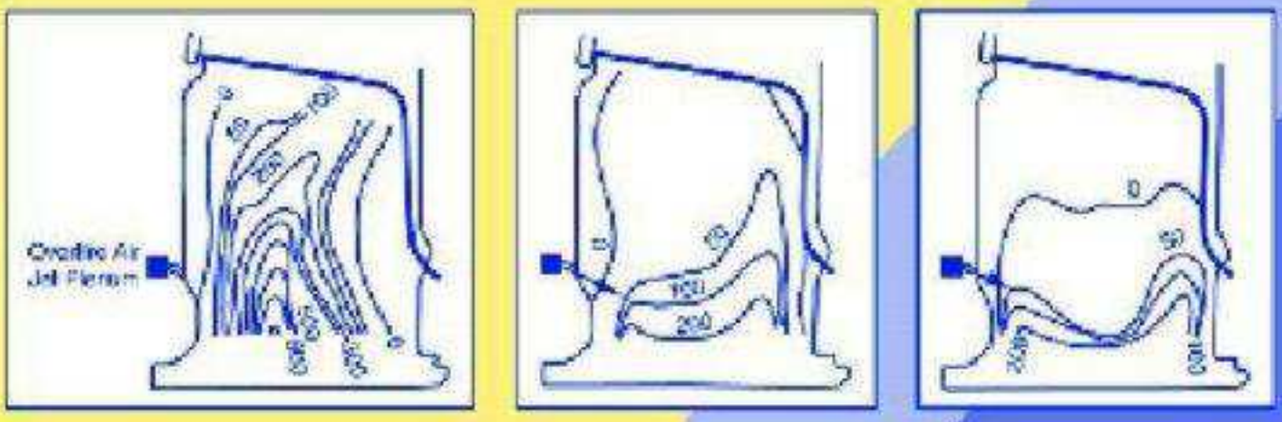
COMBUSTION AND INCINERATION PROCESSES

Third Edition, Revised and Expanded



Walter R. Niessen

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COMBUSTION AND INCINERATION PROCESSES

Third Edition, Revised and Expanded

Walter R. Niessen
Niessen Consultants S.P.
Andover, Massachusetts



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Additional Volumes in Preparation

To
my wife, Dorothy Anne,
who continues to selflessly and unreservedly support me in this and
all my other personal and professional endeavors

Preface to the Third Edition

The third edition of *Combustion and Incineration Processes* incorporates technology updates and additional detail on combustion and air pollution control, process evaluation, design, and operations from the 1990s. Also, the scope has been expanded to include: (1) additional details and graphics regarding the design and operational characteristics of municipal waste incineration systems and numerous refinements in air pollution control, (2) the emerging alternatives using refuse gasification technology, (3) lower-temperature thermal processing applied to soil remediation, and (4) plasma technologies as applied to hazardous wastes. The accompanying diskette offers additional computer tools.

The 1990s were difficult for incineration-based waste management technologies in the United States. New plant construction slowed or stopped because of the anxiety of the public, fanned at times by political rhetoric, about the health effects of air emissions. Issues included a focus on emissions of "air toxics" (heavy metals and a spectrum of organic compounds); softening in the selling price of electricity generated in waste-to-energy plants; reduced pressure on land disposal as recycling programs emerged; and the opening of several new landfills and some depression in landfilling costs. Also, the decade saw great attention paid to the potential hazards of incinerator ash materials (few hazards were demonstrated, however). These factors reduced the competitive pressures that supported burgeoning incinerator growth of the previous decade.

Chapters 13 and 14 of this book, most importantly, give testimony to the great concern that has been expressed about air emissions from metal waste combustion (MWC). This concern has often involved strong adversarial response by individuals in potential host communities that slowed or ultimately blocked the installation of new facilities and greatly expanded the required depth of analysis and intensified regulatory agency scrutiny in the air permitting process. Further, the concern manifested itself in more and more stringent air emission regulations that drove system designers to incorporate costly process control features and to install elaborate and expensive trains of back-end air pollution control equipment. A comparative analysis suggests that MWCs are subject to more exacting regulations than many other emission sources [506]. This is

not to say that environmental improvements are without merit, but in this instance the higher costs to the taxpayers and/or the dogmatic elimination of a useful option for solid waste management may not be justified by the actual benefits realized.

The situation in Europe has been quite different. Many of the countries of the European Community have passed legislation that greatly restricts the quantity and quality of materials consigned to landfills. In Germany, for example, the Closed Cycle Economy Law (refining the Waste Act of 1986) raised energy recovery from waste incineration to a level equal to that of materials recycling in the hierarchy of preference in waste management alternatives. Further, their Technical Directive for Residual Waste severely restricted the loss on ignition of waste destined for landfill to less than 5% and the total organic carbon to less than 3%. These combined factors make incineration almost a requirement. It must be said, however, that European air emission requirements are equal to or more stringent than their counterparts in the United States and, therefore, the increased use of incineration will come at a very high cost.

The incineration community has responded well to these technical, political, and economic challenges. Over the past 40 years, incineration technology, and its embodiment in processing plants, has moved from its primitive early days as a "bonfire in a box" to sophisticated, energy recovery combustion systems with effective process control capped with broad-spectrum and highly efficient air pollution control systems capable of meeting stringent emission standards. And improvements and enhancements continue to be made. This book helps engineers and scientists working in this challenging and complex field to continue the evolution of this fascinating, interdisciplinary technology.

Walter R. Niessen

Preface to the Second Edition

The second edition of *Combustion and Incineration Processes* was prepared as an update and as a substantial extension of the first edition. However, the underlying philosophy of the first edition has been retained: a focus on the fundamentals of incineration and combustion processes rather than on specific equipment. There have been many technical advances in the 15 years since this book first appeared. The application of incineration to the hazardous waste area has required new levels of process control and better and more reliable combustion performance. There is now a profound and pervasive impact of state and federal environmental regulations and guidelines on design and operation. Consequently, air pollutant emission issues have assumed a dominant position in shaping system configuration and cost.

The topics concerned with basic waste combustion processes (atomization, chemical kinetics of pyrolysis and oxidation, mixing, etc.) have been expanded. Applications are presented relevant to hazardous wastes and their incineration systems. Analysis methods and discussions of key design parameters for several additional incinerator types (especially for those burning sludges, liquids, and gases) have been significantly enlarged.

The section of the book dealing with techniques for waste data analysis and waste characterization has been substantially expanded. This reflects the strong influence of waste composition on the incineration process and the increased regulatory attention paid to emissions of toxic, carcinogenic, and otherwise environmentally significant trace elements and compounds found in wastes (the air toxics).

The first edition of *Combustion and Incineration Processes* focused on the incineration of *municipal* solid wastes. Then, resource recovery (energy recovery) was emerging as the only incineration concept, which made economic sense for large plants. Inflation had greatly increased capital and operating costs. An offset from electrical revenue had become critical to viability. Technology that fed as-received refuse to the furnace (mass burn) was competing for attention with facilities that first processed waste to a refuse-derived fuel (RDF). Still, as the research supporting the text for the first edition was prepared, few facilities of either type were operating in the United States. Data was scant and much was to be learned. This technology has matured since then.

The Clean Air Act had been long passed by 1978 and its provisions were fully implemented regarding the control of municipal incinerators. However, only total particulate emissions were regulated. Investigators in The Netherlands had reported the presence of dioxin in the collected particulate of their local refuse incinerators; acid gas, heavy metal, or NO_x controls were not incorporated into any municipal plant. However, over the past 15 years, regulatory actions (public hearings, permits, approvals, mandated design and operating guidelines, etc.) have assumed a dominant role in the design, cost, performance objectives, and implementation schedules of incineration facilities. Consequently, additional and updated methodologies are presented to estimate pollutant emission rates. Also (but modestly and in keeping with the primary focus on the incineration system), a discussion of air pollution control technology has been included.

The attention of the public and the political and regulatory establishments were just beginning to focus on hazardous wastes. The Resource Conservation and Recovery Act (RCRA), which mandated the structured and rigorous management of hazardous wastes, was new. Its full scope and requirements were still uncertain. Public Law 96-510, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), better known as the "Super-Fund Act," dealing with abandoned hazardous waste sites, had not yet been written. The challenges to incineration of RCRA and CERCLA applications are significant. Emission mitigation using both sophisticated combustion control and back-end control equipment is of great interest to both regulators and the public.

I would like to acknowledge the support given by Camp Dresser & McKee Inc. (CDM) in underwriting the preparation of many of the graphics incorporated in this edition and for their forbearance during the many months of manuscript preparation and refinement. I thank the many clients for whom I have worked over the years for their confidence and, importantly, for their support as together we addressed their problems and learned more of incineration technology. Finally, I want to thank the many colleagues I have worked with over the years—both inside and outside my employer's firm. Their professional support and help have been a constant source of stimulation.

Walter R. Niessen

Preface to the First Edition

Purification by fire is an ancient concept, its applications noted in the earliest chapters of recorded history. The art and the technology of combustion (incineration) and pyrolysis as applied to environmental engineering problems draws on this experience, as well as the results of sophisticated contemporary research. To many engineers, however, combustion systems still hold an unnecessary mystery, pose unnecessary questions, and generate unnecessary mental barriers to their full exploitation as tools to solve tough problems. This book was written in an earnest attempt to thin the clouds of mystery, answer many of the questions (those for which answers are available), and provide a clearer way for the engineer to analyze, evaluate, and design solutions to environmental problems based on combustion.

The book describes combustion and combustion systems from a process viewpoint in an attempt to develop fundamental understanding rather than present simplistic design equations or nomographs. In large part, this approach was selected because combustion systems are complex and not readily susceptible to "cook-book" design methods. Consequently, considerable space is devoted to the basics: describing the chemical and physical processes which control system behavior.

In an effort to make the book as comprehensive as possible, a large number of topics have been dealt with. Specialists in particular fields may perhaps feel that the subjects in which they are interested have received inadequate treatment. This may be resolved in part by exploring the noted references, an activity also recommended to the newcomer to the field.

The publication of this book appears timely since current trends in environmental awareness and regulatory controls will prompt increases in the use of combustion technology as the preferred or only solution. In light of escalating construction costs, the soaring expense and diminishing availability of fossil fuels used as auxiliary energy sources (or the growing value of recovered energy), and the ever more stringent regulatory insistence on high performance regarding combustion efficiency and/or air pollutant emissions, the "black box" approach is increasingly unacceptable to the designer and to the prospective owner.

This book was prepared to meet the needs of many: students; educators; researchers; practicing civil, sanitary, mechanical, and chemical engineers; and the owners and operators of combustion systems of all types—but particularly those dealing with environmental problems. To serve this diverse audience, considerable effort has been expended to provide reference data, correlations, numerical examples, and other aids to fuller understanding and use.

Last (but of the greatest significance to me, personally), the book was written because I find the study and application of combustion to be an exciting and mind-stretching experience: ever fascinating in its blend of predictability with surprise (though sometimes, the surprises are cruel in their impact). Combustion processes are and will continue to be useful resources in solving many of the pressing environmental problems of modern civilization. I sincerely hope that my efforts to share both contemporary combustion technology and my sense of excitement in the field will assist in responding to these problems.

In the preparation of this book, I have drawn from a broad spectrum of the published literature and on the thoughts, insights, and efforts of colleagues with whom I have been associated throughout my professional career. I am particularly grateful for the many contributions of my past associates at Arthur D. Little, Inc. and at the Massachusetts Institute of Technology, whose inspiration and perspiration contributed greatly to the substance of the book. Also, the many discussions and exchanges with my fellow members of the Incinerator Division (now the Solid Waste Processing Division) of the American Society of Mechanical Engineers have been of great value.

I must specifically acknowledge Professor Hoyt C. Hottel of MIT who introduced me to combustion and inspired me with his brilliance, Mr. Robert E. Zinn of ADL who patiently coached and taught me as I entered the field of incineration, and Professor Adel F. Sarofim of MIT whose technical insights and personal encouragement have been a major force in my professional growth.

I would like to acknowledge the support given by Roy F. Weston Inc. and Camp Dresser & McKee Inc. in underwriting the typing of the text drafts and the preparation of the art work. Particularly, I would thank Louise Miller, Bonnie Anderson, and Joan Buckley, who struggled through the many pages of handwritten text and equations in producing the draft.

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Introduction

For many wastes, combustion (incineration) is an attractive or necessary element of waste management. Occasionally, as for the incineration of fumes or essentially ash-free liquids or solids, combustion processes may properly be called disposal. For most solids and many liquids, incineration is only a processing step. Liquid or solid residues remain for subsequent disposal.

Incineration of wastes offers the following potential advantages:

1. Volume reduction: important for bulky solids or wastes with a high combustible and/or moisture content.
2. Detoxification: especially for combustible carcinogens, pathologically contaminated material, toxic organic compounds, or biologically active materials that would affect sewage treatment plants.
3. Environmental impact mitigation: especially for organic materials that would leach from landfills or create odor nuisances. In addition, the impact of the CO_2 "greenhouse gas" generated in incinerating solid waste is less than that of the methane (CH_4) and CO_2 generated in landfilling operations. Also, because of strict air pollution emission requirements applicable to municipal refuse incinerators, the criteria pollutant air emissions per kilowatt of power produced are significantly less than that generated by the coal- and oil-burning utility plants whose electricity is replaced by "waste-to-energy" facilities (506).
4. Regulatory compliance: applicable to fumes containing odorous or photoreactive organic compounds, carbon monoxide, volatile organic compounds (VOCs), or other combustible materials subject to regulatory emission limitations.
5. Energy recovery: important when large quantities of waste are available and reliable markets for by-product fuel, steam, or electricity are nearby.
6. Stabilization in landfills: biodegradation of organic material in a landfill leads to subsidence and gas formation that disrupts cell capping structures. Destruction of waste organic matter eliminates this problem. Incineration also forms oxides or glassy, sintered residues that are insoluble (nonleaching).

7. Sanitation: destruction of pathogenic organisms presenting a hazard to public health.

These advantages have justified development of a variety of incineration systems, of widely different complexity and function to meet the needs of municipalities and commercial and industrial firms and institutions.

Operating counter to these advantages are the following disadvantages of incineration:

1. Cost: usually, incineration is a costly waste processing step, both in initial investment and in operation.
2. Operating problems: variability in waste composition and the severity of the incinerator environment result in many practical waste-handling problems, high maintenance requirements, and equipment unreliability.
3. Staffing problems: the low status often accorded to waste disposal can make it difficult to obtain and retain qualified supervisory and operating staff. Because of the aggressive and unforgiving nature of the incineration process, staffing weaknesses can lead to adverse impacts on system availability and maintenance expense.
4. Secondary environmental impacts:

   Air emissions: many waste combustion systems result in the presence of odors, sulfur dioxide, hydrogen chloride, carbon monoxide, carcinogenic polynuclear hydrocarbons, nitrogen oxides, fly ash and particulate fumes, and other toxic or noxious materials in the flue gases. Control of emissions to very low levels has been shown to be within the capability of modern air pollution control technology.

   Waterborne emissions: water used in wet scrubber-type air pollution control often becomes highly acidic. Scrubber blowdown and wastewater from residue quenching may contain high levels of dissolved solids, abrasive suspended solids, biological and chemical oxygen demand, heavy metals, and pathogenic organisms. As for the air pollutants, control of these pollutants can be readily effected to discharge standards using available technology.

   Residue impacts: residue disposal (fly ash and bottom ash) presents a variety of aesthetic, water pollution, and worker health-related problems that require attention in system design and operation.

5. Public sector reaction: few incinerators are installed without arousing concern, close scrutiny, and, at times, hostility or profound policy conflicts from the public, environmental action groups, and local, state, and federal regulatory agencies.
6. Technical risk: process analysis of combustors is very difficult. Changes in waste character are common due to seasonal variations in municipal waste or product changes in industrial waste. These and other factors contribute to the risk that a new incinerator may not work as envisioned or, in extreme cases, at all. In most cases, the shortfall in performance is realized as higher than expected maintenance expense, reduced system availability, and/or diminished capacity. Generally, changes in waste character invalidate performance guarantees given by equipment vendors.

With all these disadvantages, incineration has persisted as an important concept in waste management. About 16% of the municipal solid waste and wastewater sludge was incinerated in the United States in the mid-1990s. Over the years, the rate of construction of new incineration units has varied greatly. Key factors in slowing construction include high interest rates, cost escalation from changes in air pollution control regulations, recession influences on municipal budgets, and surges in anti-incineration pressure from the advocates of recycling. However, increasing concern over leachate, odor, and gas generation and control in waste landfills (with consequent impacts on their availability and cost), regulatory and policy limitations on the landfilling of combustible hazardous wastes, and increases in the value of energy suggest a continuing role of incineration in the future, particularly in Europe.

Combustion processes are complicated. An analytical description of combustion system behavior requires consideration of

1. Chemical reaction kinetics and equilibrium under nonisothermal, nonhomogeneous, unsteady conditions
2. Fluid mechanics in nonisothermal, nonhomogeneous, reacting mixtures with heat release which can involve laminar, transition and turbulent, plug, recirculating, and swirling flows within geometrically complex enclosures
3. Heat transfer by conduction, convection, and radiation between gas volumes, liquids, and solids with high heat release rates and (with boiler systems) high heat withdrawal rates

In incineration applications, this complexity is often increased by frequent, unpredictable shifts in fuel composition that result in changes in heat release rate and combustion characteristics (ignition temperature, air requirement, etc.). Compounding these process-related facets of waste combustion are the practical design and operating problems in materials handling, corrosion, odor, vector and vermin control, residue disposal, associated air and water pollution control, and myriad social, political, and regulatory pressures and constraints.

With these technical challenges facing the waste disposal technologist, it is a wonder that the state-of-the-art has advanced beyond simple, batch-fed, refractory hearth systems. Indeed, incineration technology is still regarded by many as an art, too complex to understand.

The origins of such technical pessimism have arisen from many facts and practical realities:

1. Waste management has seldom represented a large enough business opportunity to support extensive internal or sponsored research by equipment vendors, universities, or research institutions.
2. Municipal governments and most industries have had neither budgets nor inclination to fund extensive analysis efforts as part of the design process.
3. As a high-temperature process carried out in relatively large equipment, incineration research is difficult and costly.
4. The technical responsibility for waste disposal has usually been given to firms and individuals skilled in the civil and sanitary engineering disciplines, fields where high-temperature, reacting, mixing, radiating (etc.) processes are not part of the standard curriculum.

Such pessimism is extreme. To be sure, the physical situation is complex, but, drawing on the extensive scientific and engineering literature in conventional combustion, the problems can be made tractable. The practical reality that pencil and paper are ever so much cheaper than concrete and steel is an important support to the argument for aggressive exploitation of the power of engineering analysis.

The remainder of this volume attempts to bring a measure of structure and understanding to those wishing to analyze, design, and operate incineration systems. Although the result cannot be expected to answer all questions and anticipate all problems, it will give the student or practicing engineer the quantitative and qualitative guidance and understanding to cope with this important sector of environmental control engineering.

The analytical methods and computational tools used draw heavily on the disciplines of chemical and, to a lesser extent, mechanical engineering. As many readers may not be familiar with the terms and concepts involved, the early chapters review the fundamental analysis methods of process engineering. Combustion and pyrolysis processes are then discussed, followed by a quantitative and qualitative review of the heat and fluid mechanics aspects of combustion systems.

Building on the basic framework of combustion technology, combustion-based waste disposal is then introduced: waste characterization, incinerator systems, design principles, and calculations.

2

Stoichiometry

Stoichiometry is the discipline of tracking matter (particularly the elements, partitioned in accord with the laws of chemical combining weights and proportions) and energy (in all its forms) in either batch or continuous processes. Since these quantities are conserved in the course of any process, the engineer can apply the principle of conservation to follow the course of combustion and flow processes and to compute air requirements, flow volumes, and velocities, temperatures, and other useful quantities. As a refinement, the engineer should acknowledge the fact that some reactions and heat transfer processes sometimes stop short of "completion" because of equilibrium limitations. Also, for some situations, the chemical reaction rate may limit the degree of completeness, especially when system residence time is short or temperatures are low.

I. UNITS AND FUNDAMENTAL RELATIONSHIPS

A. Units

In analyzing combustion problems, it is advantageous to use the molecular (atomic) weight expressed in kilograms (the kilogram mol or kilogram atom) as the unit quantity. This advantage derives from the facts that one molecular (atomic) weight of any compound (element) contains the same number of molecules (atoms) and that each mol of gas, at standard pressure and temperature, occupies the same volume if the gases are "ideal."

The concept of an ideal gas arises in the course of thermodynamic analysis and describes a gas for which intermolecular attractions are negligibly small, in which the actual volume of the molecules is small in comparison with the space they inhabit and where intermolecular collisions are perfectly elastic.

B. Gas Laws

1. The Perfect Gas Law

The behavior of "ideal gases" is described by Eq. (1a), the *perfect gas law*:

$$PV = nRT \tag{1a}$$

In this relationship P is the absolute pressure of the gas, V its volume, n the number of mols of gas, R the universal gas constant, and T the absolute temperature. Note that 273.15 must be added to the Celsius temperature and 459.69 to the Fahrenheit temperature to get the absolute temperature in degrees Kelvin (°K) or degrees Rankine (°R), respectively.

The perfect gas law was developed from a simplified model of the kinetic behavior of molecules. The relationship becomes inaccurate at very low temperatures, at high pressures, and in other circumstances when intermolecular forces become significant. In the analysis of combustion systems at elevated temperatures and at atmospheric pressure, the assumption of ideal gas behavior is sound.

The same value of the universal gas constant R is used for all gases. Care must be given to assure compatibility of the units of R with those used for P, V, n, and T. Commonly used values of R are given in Table 1.

In the mechanical engineering literature, one often finds a gas law in use where the numerical value of the gas constant (say, R') is specific to the gas under consideration. The gas constant in such relationships is usually found to be the universal gas constant divided by the molecular weight of the compound. In this formulation of the gas law, the weight w rather than the number of mols of gas is used:

$$PV = wR'T \tag{1b}$$

EXAMPLE 1. Ten thousand kg/day of a spent absorbent containing 92% carbon, 6% ash, and 2% moisture is to be burned completely to generate carbon dioxide for process use. The exit temperature of the incinerator is 1000°C. How many kilogram mols and how many kilograms of CO_2 will be formed per minute? How many cubic meters per minute at a pressure of 1.04 atm?

One must first determine the number of kilogram atoms per minute of carbon (atomic weight = 12.01) flowing in the waste feed:

$$(0.92 \times 10{,}000)/(12.01 \times 24 \times 60) = 0.532 \text{ kg atoms/min}$$

Table 1 Values of the Universal Gas Constant R for Ideal Gases

Energy	Pressure (P)	Volume (V)	Mols (n)	Temperature (T)	Gas constant (R)
—	atm	m^3	kg mol	°K	$0.08205 \frac{m^3 \text{ atm}}{\text{kg mol °K}}$
—	kPa	m^3	kg mol	°K	$8.3137 \frac{\text{kPa } m^3}{\text{kg mol °K}}$
kcal	—	—	kg mol	°K	$1.9872 \frac{\text{kcal}}{\text{kg mol °K}}$
joules (abs)	—	—	g mol	°K	$8.3144 \frac{\text{joules}}{\text{g mol °K}}$
ft-lb	psia	ft^3	lb mol	°R	$1545.0 \frac{\text{ft lb}}{\text{lb mol °R}}$
Btu	—	—	lb mol	°R	$1.9872 \frac{\text{Btu}}{\text{lb mol °R}}$
—	atm	ft^3	lb mol	°R	$0.7302 \frac{ft^3 \text{ atm}}{\text{lb mol °R}}$

Noting that with complete combustion each atom of carbon yields one molecule of carbon dioxide, the generation rate of CO_2 is 0.532 kg mol/min. The weight flow of CO_2 (molecular weight = 44.01) will be (0.532)(44.01) = 23.4 kg/min of CO_2. The temperature (°K) is 1000 + 273.15 = 1273.15, and from Eq. 1.

$$\begin{aligned} V &= \frac{nRT}{P} \\ &= \frac{0.532 \times 0.08206 \times 1273.15}{1.04} \\ &= 53.4 \text{ m}^3/\text{min CO}_2 \end{aligned}$$

In combustion calculations, one commonly knows the number of mols and the temperature and needs to compute the volume. For these calculations, it is convenient to obtain the answer by adjusting a unit volume at a specified standard condition to the conditions of interest. For such calculations one can use the gas laws expressed in terms of the volume of 1 kg or lb mol of an ideal gas at the standard conditions of 0°C or 273.15° K (32°F or 492°R) and 1 atm. The molecular volume is 22.4 m^3 (359.3 ft^3). If we denote the molecular volume as V_0, and the pressure and temperature at standard conditions as P_0 and T_0, respectively, the gas law then yields:

$$V = n \times V_0 \times \frac{P_0}{P} \times \frac{T}{T_0} \tag{2}$$

where P_0 and T_0 may be expressed in any consistent absolute units. For example, the gas volume from the preceding example could be calculated as

$$\begin{aligned} V &= 0.532 \times 22.4 \times \frac{1.00}{1.04} \times \frac{1273.15}{273.15} \\ &= 53.41 \text{ m}^3/\text{min CO}_2 \end{aligned}$$

Dalton's law (1801) of partial pressures is another useful identity derived from the ideal gas law. Dalton's law states that the total pressure of a mixture of gases is equal to the sum of the partial pressures of the constituent gases, where the partial pressure is defined as the pressure each gas would exert if it alone occupied the volume of the mixture at the same temperature. For a perfect gas, Dalton's law equates the volume percent with the mol percent and the partial pressure:

$$\begin{aligned} \text{Volume percent} &= 100 \text{ (mol fraction)} \\ &= 100 \frac{\text{partial pressure}}{\text{total pressure}} \end{aligned} \tag{3}$$

EXAMPLE 2. Flue gases from combustion of 14.34 kg of graphite (essentially, pure carbon) with oxygen are at a temperature of 1000°C and a pressure of 1.04 atm. What is the volume in m^3 of the CO_2 formed? What is its density?

$$V = \frac{14.34}{12.01} \times 22.4 \times \frac{1.0}{1.04} \times \frac{(1000 + 273.15)}{273.15} = 119.87 \text{ m}^3$$

For each mol of CO_2 formed, the mass is 12.01 + 32.00, or 44.01 kg (see Table 1 in Appendix C for atomic weights). The gas density under these conditions is

$$\rho_{CO_2} = \frac{44.12}{22.4 \times \frac{1.0}{1.04} \times \frac{(1000 + 273.15)}{273.15}} = 0.438 \text{ kg/m}^3$$

EXAMPLE 3. The carbon monoxide (CO) concentration in a flue gas stream with 10% moisture at 500°C and 1.05 atm is measured at 88.86 parts per million by volume. Does this meet the regulatory limit of 100 mg per normal cubic meter (Nm^3), established by the regulation as being a dry basis at 0°C and 1.0 atm? Adjustment to the temperature or pressure conditions of the regulatory limit does not change the mol fraction of CO in the gas. The CO concentration corresponding to the regulatory limit under dry conditions is calculated as (88.86)(1.0 − 0.1), or 79.97 parts per million, dry volume (ppmdv).

The volume of one kilogram mol of any gas at 0°C and 1.0 atm is 22.4 m^3. For CO, with a molecular weight of 28.01, the mass of one mol is 28.01×10^6 mg. Therefore, the mass concentration of CO in the flue gases is given by

$$[CO] = \frac{(79.97 \times 10^{-6})(28.01 \times 10^6)}{22.4} = 100.0 \text{ mg/Nm}^3$$

2. Standard Conditions

Throughout the published literature, in regulatory language, in industrial data sheets, etc., one frequently finds references to the term *standard conditions*. While the words imply standardization, it should be cautioned that the meaning is not at all consistent.

For example, flow calculations by U.S. fan manufacturers and the U.S. natural gas industry are referenced to 60°F (15.6°C), and 1 atm (29.92 in Hg or 14.7 lb/$in.^2$ absolute). The manufactured gas industry uses 60°F, saturated with water vapor at 30 in. of Hg absolute, for marketing but 60°F dry at 1 atm for combustion calculations.

Other important appearances of the term "standard conditions" are found in the calculations and reports associated with permits for atmospheric discharges. The standard conditions in which to report stack gas flows in the United States are often based on 20°C (68°F) and 1 atm.

The reference states used to specify and report the concentration of pollutants in air pollution regulations and permits often generate another set of standard conditions. In the United States, this may involve the calculation of volume in "standard cubic feet (scf)" at a reference temperature of 32°F and 1 atm. In Europe, the metric equivalent (0°C and 1.0 atm) is used to characterize the "normal cubic meter," or Nm^3. For particulate matter and the concentrations of gaseous pollutants, the reference volume is commonly further corrected to a specified concentration of oxygen (usually 7% O_2 in the United States but 11% O_2 in Europe and Asia) or carbon dioxide (usually 12% CO_2) by the mathematical addition/subtraction of oxygen and nitrogen in the proportions found in air.

As an alternative to specifying the oxygen or carbon dioxide concentration at standard conditions, some agencies call for adjustment to a specified "percent excess air" (the combustion air supplied in excess of the theoretical air requirement expressed as a percentage of the theoretical air). Further correction may be required to express the concentration on a dry basis.

In most real situations, the gas temperature, pressure, and state of dryness are quite different from the "standard conditions" requested. In these circumstances, the perfect gas law and its extensions (e.g., Dalton's law) are used to make the corrections.

EXAMPLE 4. A sample weight of 76 mg of particulate matter is collected in the course of sampling 2.35 actual m^3 of flue gas at 68°C and 1.03 atm. The flue gas contains 12.5% moisture. An Orsat (dry basis) analysis of the gases shows 10.03% oxygen and 10.20% carbon dioxide. The air pollution code emission limit is 60 mg/Nm^3 corrected to 7% oxygen. The emission code defines "normal cubic meter" (Nm^3) as 0°C and 1.0 atm. Is the source in conformance with the code? What if the code referenced a correction to 12% carbon dioxide? Or to 50% excess air?

Correct the gas volume to reference temperature and pressure using Eq. (2).

$$V = 2.35\left(\frac{273.15 + 0.0}{273.15 + 68.0}\right)\left(\frac{1.00}{1.03}\right)$$
$$= 1.827 \text{ m}^3 \text{ (wet)}$$

Correct gas volume to dry basis.

$$\text{corrected volume} = 1.827(1.00 - 0.125)$$
$$= 1.598 \text{ Nm}^3 \text{ (dry)}$$

Calculate gas volume and dust concentration at reference O_2 concentration.

$$C_{O_2} = \frac{21.0 - \text{measured } \%O_2}{21.0 - \text{reference } \%O_2}$$

The gas volume at 7% O_2 is calculated with the correction factor C_{O_2}.

$$C_{O_2} = \frac{21.0 - 10.03}{21.0 - 7.0} \tag{4}$$

Here $C_{O_2} = 0.784$, and the corrected gas volume is

$$1.598(0.784) = 1.252 \text{ Nm}^3(7\% \text{ O}_2)$$

The particulate concentration is, then,

$$76/1.252 = 60.7 \text{ mg/Nm}^3 \text{ at } 7\% \text{ O}_2 \quad \text{(fails the emission code)}$$

Calculate dust concentration at reference CO_2 concentration.

The gas volume at 12% CO_2 is calculated with the correction factor C_{CO_2}.

$$C_{CO_2} = \frac{\text{measured } \% \text{ CO}_2}{\text{reference } \% \text{ CO}_2} = \frac{10.2}{12.00} \tag{5}$$

Therefore, $C_{CO_2} = 0.85$, and the corrected volume is

$$1.598(0.85) = 1.358 \text{ Nm}^3(12\% \text{ CO}_2)$$

The particulate concentration is, then,

$$76/1.358 = 56.0 \text{ mg/Nm}^3 \text{ at } 12\% \text{ CO}_2 \quad \text{(passes the emission code)}$$

Calculate dust concentration at reference excess air.

By difference, the nitrogen concentration (dry) $= 100.00 - 10.2 - 10.03 = 79.77\%$. A correction factor ($CF_{50}$) may be developed that adjusts the gas volume from an initial condition with O_2, N_2, and CO volume (mol) percent oxygen, nitrogen, and carbon monoxide (dry basis), respectively, to the gas volume at 50% excess air. The accuracy of the factor depends on the assumption of negligible nitrogen content for the fuel.

$$CF_{50} = \frac{21.1 - 1.5\ O_2 + 0.75\ CO + 0.132\ N_2}{21.1} \tag{6}$$

Here, $CF_{50} = 0.786$, and the corrected volume is

$1.598(0.786) = 1.256\ Nm^3$ at 50% excess air

The particulate concentration is, then,

$76/1.256 = 60.5\ mg/Nm^3$ at 50% excess air (fails the requirement)

C. Energy

In this chapter, the basic unit of heat energy will be the kilogram calorie (kcal): the quantity of heat necessary to raise the temperature of 1 kg of water 1°C. The British Thermal Unit (Btu), the energy required to raise the temperature of 1 lb of water 1°F, is the comparable energy quantity in English units. Commonly used conversion factors are 1 kcal = 4186.8 joules or 3.968 Btu; 1 kcal/kg = 1.8 Btu/lb; 1 Btu = 1055.1 joules, and 1 Btu/lb = 2326 joules/kg. (See also Appendix B.)

1. Heat of Reaction

The heat of reaction is defined as the net enthalpy change resulting from a chemical reaction. The energy effect can be net energy release (an exothermic reaction) or energy absorption (an endothermic reaction). The heat of reaction may be calculated as the difference in the heat of formation (ΔH_{298}) between products and reactants. Heat of formation (tabulated in many handbooks) is the heat effect when the compound is formed from its constituent elements in their standard states (usually 298.15°K, at 1 atm). For example:

$$C\ (\text{graphite}) + O_2\ (\text{gas}) \rightarrow CO_2\ (\text{gas}) \qquad \Delta H_{298} = -94.03\ \text{kcal}$$

$$H_2\ (\text{gas}) + \tfrac{1}{2}O_2\ (\text{gas}) \rightarrow H_2O\ (\text{liquid}) \qquad \Delta H_{298} = -68.30\ \text{kcal}$$

$$\tfrac{1}{2}H_2\ (\text{gas}) + \tfrac{1}{2}I_2\ (\text{solid}) \rightarrow HI\ (\text{gas}) \qquad \Delta H_{298} = +5.95\ \text{kcal}$$

Heat is given off by the first two (exothermic) reactions. By convention, the heat of formation for exothermic reactions is negative. In the formation of gaseous hydrogen iodide (HI) from its elements, the reaction absorbs energy (endothermic) and ΔH_{298} is positive. Note, however, that in some of the older thermochemical literature, this convention is reversed.

It is important to note that, by definition, the heat of formation of the elements in their standard states is *zero*. Useful heat of formation values (expressed in kcal/gram mol at 25°C) include those listed in the following table:

Substance	ΔH_{298}	Substance	ΔH_{298}
$CO_{2(g)}$	−94.03	$CO_{(g)}$	−26.4
$H_2O_{(l)}$	−68.3	$C_2H_{6(l)}$	−23.4
$SO_{2(g)}$	−70.2	$CH_3OH_{(l)}$	−60.0
$NH_{3(g)}$	−11.0	$C_2H_5OH_{(l)}$	−66.2
$HCl_{(g)}$	−22.06	$CHCl_{3(l)}$	−31.5

For the special case where the reaction of interest is oxidation at elevated temperatures, we refer to the heat effect as the *heat of combustion*. The heat of combustion for carbon-hydrogen- and oxygen-based fuels and waste streams is, clearly, the release of energy when the substance(s) reacts completely with oxygen to form CO_2 and H_2O. This heat release may be calculated as the difference between the heats of formation of the products and reactants. The heat of combustion for compounds containing N, S, Cl, P, etc., may be calculated similarly, but the results may be unreliable due to the uncertainty in the specific compounds formed.

EXAMPLE 5. Using the heat of formation (ΔH_f) data given above, calculate the heat of combustion (ΔH_c) of ethyl alcohol (C_2H_5OH) and chloroform ($CHCl_3$).

Ethyl alcohol burns as follows:

$$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

$$\begin{aligned}\Delta H_c &= \Delta H_f \text{ (products)} - \Delta H_f \text{ (reactants)} \\ &= 2(-94.03) + 3(-68.3) - 1(-66.2) - 3(0.0) \\ &= -326.76 \text{ kcal per gram molecular weight (GMW)}\end{aligned}$$

For a molecular weight of 46, this corresponds to

$$\begin{aligned}&= -7.1035 \text{ kcal per gram } (-7103.5 \text{ kcal/kg}) \\ &= -12{,}786 \text{ Btu/lb}\end{aligned}$$

Chloroform may burn

(a) $CHCl_3 + \frac{3}{2}O_2 \rightarrow CO_2 + \frac{1}{2}H_2O + \frac{3}{2}Cl_2$ or
(b) $CHCl_3 + O_2 \rightarrow CO_2 + HCl + Cl_2$

For reaction (a), $\Delta H_c = -96.68$ kcal/GMW
For reaction (b), $\Delta H_c = -84.59$ kcal/GMW
Literature value: $\Delta H_c = -89.20$ kcal/GMW

A value for the heat of combustion of the feed material is often needed while analyzing combustion systems. For the complete combustion of methane, the reaction is

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O\ (l) + 212{,}950 \text{ kcal}$$

This shows that 1 kg mol of methane is oxidized by 2 kg mol of oxygen to form 1 kg mol of carbon dioxide and 2 kg mol of water; 212,950 kcal of heat are released. The subscripts g, l, and s denote the gaseous, liquid, and solid states of reactants or products, respectively. A pressure of 1 atm and an initial and final temperature of the reactants and products of 298.15 K (20°C) is assumed, unless otherwise indicated.

The heat of combustion given in this manner (*with the water condensed*) is known as the *higher heating value* (HHV). The HHV is the common way to report such data in the U.S. and British literature. Clearly, however, in a real furnace, the sensible heat content of the flue gases will be lower than would be suggested by the HHV by an amount of energy equivalent to the latent heat of vaporization of the water (10,507 kcal/kg mol at 25°C). This corresponds to 21,014 kcal/kg mol of methane. Thus, the so-called *lower heating value* (LHV) corresponds to

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g) + 191{,}936 \text{ kcal}$$

The LHV is the energy release value commonly reported in the literature of continental Europe and Asia.

For a fuel with a dry basis hydrogen content of $\%H_2$ (expressed as a percent), the HHV and LHV (dry basis) are related by

$$\text{LHV} = \text{HHV} - 94.315 \times (\%H_2) \qquad \text{for LHV, HHV in Btu/lb and} \tag{7a}$$

$$\text{LHV} = \text{HHV} - 52.397 \times (\%H_2) \qquad \text{for LHV, HHV in kcal/kg} \tag{7b}$$

EXAMPLE 6. The Chinese literature reports the heating value of a municipal refuse from the Beijing area as 1800 kcal/kg (as fired). The moisture content of the waste was 37%, and the hydrogen content of the waste (on a dry basis) was 3.69%. How do these data suggest that the heating value of the Chinese waste compares with waste burned in New York City, which is often reported to have a heating value of about 6300 Btu/lb?

As is common in such problems, there is ambiguity in the basis (wet or dry and LHV or HHV) of the two heating values. Most likely, the Chinese are reporting an LHV and the New York heating value is an HHV. A quick review of the data in Chapter 4 suggests that most U.S. refuse has an as-fired (wet basis) heating value between 4500 and 5500 Btu/lb (2500 to 3050 kcal/kg), so the New York number is probably on a dry basis. Assuming these reference conditions.

The dry basis LHV of the Chinese waste is

$$\text{LHV} = \frac{1800}{(1 - 0.37)} = 2857 \text{ kcal/kg}$$

The dry basis HHV of the Chinese waste is

$$\text{HHV} = 2857 + 52.397 \times 3.69 = 3050 \text{ kcal/kg or } 5491 \text{ Btu/lb}$$

Therefore, the Chinese waste has about 85% of the heating value of the New York refuse. Also, one might speculate that the New York refuse is about 20–25% moisture, so the as-fired (wet basis) heating value is about 70% of that for the New York waste.

This example problem vividly illustrates the difficulties and consequent uncertainties in the results that arise due to incomplete specification of the intended basis for physical and thermochemical properties. This emphasizes the importance of making the basis clear in professional publications, instructions to laboratories, specifications for equipment vendors, and so forth.

2. Sensible Heat of Gases

In analyzing combustion systems it is often necessary to calculate the sensible heat content (enthalpy) of gases at elevated temperatures or to determine the change in enthalpy between two temperatures. To make such calculations, one can draw on the approximation that Mc_p, the molal specific heat at constant pressure (in units of kcal/kg mol °C which is,

Table 2 Constants in Molal Heat Capacity (Mc_p^o) Relationship with Temperature ($Mc_p^o = a + bT + CT^2$)[a]

Compound	a	b	c
H_2	6.92	0.153×10^{-3}	$+0.279 \times 10^{-6}$
O_2	6.95	2.326×10^{-3}	-0.770×10^{-6}
N_2	6.77	1.631×10^{-3}	-0.345×10^{-6}
Air	6.81	1.777×10^{-3}	-0.434×10^{-6}
CO	6.79	1.840×10^{-3}	-0.459×10^{-6}
CO_2	9.00	7.183×10^{-3}	-2.475×10^{-6}
H_2O	7.76	3.096×10^{-3}	-0.343×10^{-6}
NO	6.83	2.102×10^{-3}	-0.612×10^{-6}
SO_2	9.29	9.334×10^{-3}	-6.38×10^{-6}
HCl	6.45	1.975×10^{-3}	-0.547×10^{-6}
HBr	6.85	1.041×10^{-3}	-0.158×10^{-6}
Cl_2	8.23	2.389×10^{-3}	-0.065×10^{-6}
Br_2	8.66	0.780×10^{-3}	-0.356×10^{-6}
CH_4	8.00	15.695×10^{-3}	-4.300×10^{-6}

incidentally, numerically identical to Btu/lb mol °F), is a function of temperature only and asymptotically approaches a value Mc_p° as the pressure approaches zero. The enthalpy change (Δh) between temperature limits T_1 and T_2 is then given by

$$\Delta h = \int_{T_1}^{T_2} Mc_p^o \, dT \text{ kcal/kg mol} \tag{8}$$

This calculation may be carried out using an analytical relationship for Mc_p° as a function of temperature. Constants for such relationships are given in Table 2 for several common gases. Alternatively, one can use a graphical presentation of the average molal heat capacity between a reference temperature of 15°C (60°F) and the abscissa temperature (Fig. 1). The average molal heat capacity is calculated and used as follows:

$$Mc_{p,av}^0 = \frac{\int_{15}^{T} Mc_p^0 \, dT}{(T - 15)} \tag{9}$$

$$\Delta h = nMc_{p,av}^0 (T - 15) \text{ kcal} \tag{10}$$

EXAMPLE 7. What is the sensible heat content of 68 kg of carbon dioxide at 1200°C relative to 15°C? How much heat must be removed to drop the temperature to 300°C? First, determine the number of mols of $CO_2 = 68/44 = 1.55$ mols. From Table 2, the heat content at 1200°C is given by:

$$\Delta h = 1.55 \int_{15}^{1200} (9.00 + 7.183 \times 10^{-3} T - 2.475 \times 10^{-6} T^2) dt$$

$$= \left[1.55 \left(9T + \frac{7.183 \times 10^{-3} T^2}{2} - \frac{2.475 \times 10^{-6} T^3}{3} \right) \right]_{15}^{1200} = 22{,}340 \text{ kcal}$$

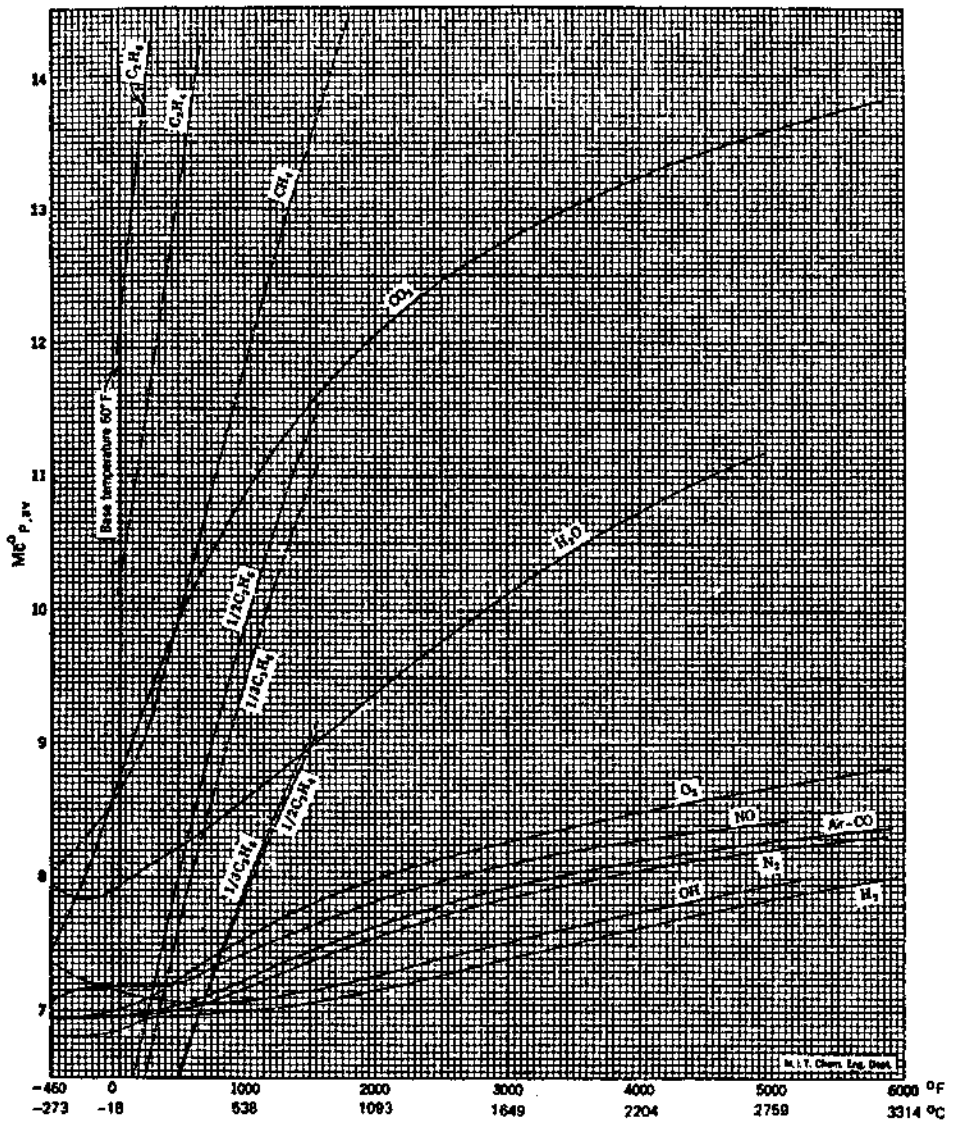


Figure 1 Average molal heat capacity between 15°C and upper temperature (Btu/lb mol, Kcal/kg mol). (Courtesy, Professor H.C. Hottel, Chemical Engineering Department, M.I.T.)

A similar calculation for an upper limit of 300°C yields 4370 kcal and a net heat extraction of 22,340 − 4370 = 17,970 kcal. Alternatively, using Fig. 1, the heat content at 1200°C is:

$$1.55(12.3)(1200 - 15) = 22{,}600 \text{ kcal}$$

and at 300°C, is

$$1.55(10.1)(300 - 15) = 4460 \text{ kcal}$$

The approximate heat loss between 1200° and 300°C is 18,140 kcal.

3. Sensible Heat of Solids

Kopp's rule [Eq. (11)] (432) can be used to estimate the molar heat capacity (Mc_p) of solid compounds. Kopp's rule states that

$$Mc_p = 6n \text{ kcal/kg mol } ^\circ\text{C} \tag{11}$$

where n equals the total number of atoms in the molecule.

Building on Kopp's rule, Hurst and Harrison (433) developed an estimation relationship for the Mc_p of pure compounds at 25°C:

$$Mc_p = \sum_{i=1}^{n} N_i \Delta_{Ei} \text{ kcal/kg mol } ^\circ\text{C} \tag{12}$$

where n is the number of different atomic elements in the compound, N_i is the number of atomic elements i in the compound, and Δ_{Ei} is the value from Table 3 for the ith element.

Voskoboinikov (391) developed a functional relationship between the heat capacity of slags C_p (in cal/gram °C) and the temperature T (°C) given as follows.

For temperatures from 20° to 1350°C:

$$C_p = 0.169 + 0.201 \times 10^{-3} T - 0.277 \times 10^{-6} T^2 + 0.139 \times 10^{-9} T^3 + 0.17 \times 10^{-4} T(1 - \text{CaO}/\Sigma) \tag{12a}$$

where Σ is the sum of the dry basis mass percentages $SiO_2 + Al_2O_3 + FeO + MgO + MnO$.

For temperatures from 1350° to 1600°C:

$$C_p = 0.15 \times 10^{-2} T - 0.478 \times 10^{-6} T^2 - 0.876 + 0.016(1 - \text{CaO}/\Sigma) \tag{12b}$$

For many inorganic compounds (e.g., ash), a mean heat capacity of 0.2 to 0.3 kcal/kg °C is a reasonable assumption.

Table 3 Atomic Element Contributions to Hurst and Harrison Relationship

Element	Δ_{Ei}	Element	Δ_{Ei}	Element	Δ_{Ei}
C	2.602	Ba	7.733	Mo	7.033
H	1.806	Be	2.979	Na	6.257
O	3.206	Ca	6.749	Ni	6.082
N	4.477	Co	6.142	Pb	7.549
S	2.953	Cu	6.431	Si	4.061
F	6.250	Fe	6.947	Sr	6.787
Cl	5.898	Hg	6.658	Ti	6.508
Br	6.059	K	6.876	V	7.014
I	6.042	Li	5.554	W	7.375
Al	4.317	Mg	5.421	Zr	6.407
B	2.413	Mn	6.704	All other	6.362

Table 4 Latent Heat Effects for Changes in State of Common Materials

Material	State change	Temperature (°C)	Latent heat of indicated state change (kcal/kg)	(kcal/kg mol)	(Btu/lb)
Water	Fusion	0	80	1435	144
Water	Vaporization	100	540	9712	971
Acetone	Vaporization	56	125	7221	224
Benzene	Vaporization	80	94	7355	170
i-Butyl alcohol	Vaporization	107	138	12,420	248
n-Decane	Vaporizatioin	160	60	8548	108
Methanol	Vaporization	65	263	12,614	473
Turpentine	Vaporization	156	69	9330	123
Zinc	Fusion	419	28	1839	51

4. Latent Heat

The change in state of elements and compounds, for example, from solid (s) to liquid (l), or from liquid (l) to gas (g), is accompanied by a heat effect: the latent heat of fusion, sublimation, or vaporization for the state changes (s)→(l), (s)→(g), and (l)→(g), respectively. Latent heat effects in many industrial processes are negligible. For example, the heat of vaporization of fuel oil is usually neglected in combustion calculations. Particularly for incinerator design calculations involving wastes or fuels with a high hydrogen content and/or high moisture content, latent heat effects are very significant. For reference, several latent heat values are given in Table 4.

5. Decomposition and Ionization

Combustion and incineration systems often experience temperatures high enough that some compounds decompose into several simpler fragments. The decomposition is not necessarily associated with oxidation reactions and often reflects the breakage of chemical or ionic bonds in the compounds purely under the influence of heat. These reactions include thermal degradation reactions of organic compounds, thermal decomposition reactions of inorganic compounds, and ionization.

The thermal degradation of organic compounds is a common and important step in the combustion process. Degradation can involve simple rupture of bonds induced by elevated temperature (pyrolysis). This is, often, an endothermic reaction. In some physical situations ("starved air incineration"), partial oxidation takes place, generating heat that triggers pyrolysis reactions in part of the combustible material. Depending on the balance between pyrolytic and oxidative reactions, the overall heat effect can be either endothermic or exothermic. This important class of decomposition reactions is covered in detail elsewhere in this book.

Thermal degradation of inorganic compounds can introduce important energy effects in some combustion and incineration processes. Also, the decomposition process may involve the shift of all or a portion of the mass of the compound to another phase. An industrially important example of such a reaction is the decomposition of calcium carbonate (limestone) to form lime (solid calcium oxide) and carbon dioxide (a gas).

Table 5 Decomposition Temperatures of Selected Compounds (°C)

Material	Solid	Gaseous	Temperature
$CaCO_3$	CaO	CO_2	897
$CaSO_4$-2 H_2O	$CaSO_4$-0.5H_2O	1.5 H_2O	128
$CaSO_4$-0.5 H_2O	$CaSO_4$	0.5 H_2O	163
$Ca(OH)_2$	CaO	H_2O	580
$Al(OH)_3$-*n* H_2O	—	2 H_2O	300
$Fe(OH)_3$-*n* H_2O	—	1.5 H_2O	500
$Fe_2(SO_4)_3$	Fe_2O_3	3 SO_3	480
$NaHCO_3$	NaOH	CO_2	270
Na_2CO_3	Na_2O	CO_2	2245

In reviewing published data on the "decomposition temperature" of chemical compounds, one must recognize that decomposition does not suddenly take place at a discrete temperature, but, in fact, is occurring to some degree at all temperatures. The degree and rate of decomposition are often strongly temperature-dependent. At any given temperature, the concentration (chemical activity) of the reactants and products tends toward or achieves a specific relationship one to another as defined by the equilibrium constant (discussed in Section V of this chapter).

Taking limestone decomposition as an example, at any instant of time some molecules of calcium carbonate are breaking apart, releasing gaseous CO_2. Also, however, CO_2 from the environment is reacting with calcium oxide in the solid matrix to reform the calcium carbonate. The equilibrium partial pressure of CO_2 over the solid and the decomposition rate are functions of temperature. As the temperature increases, the partial pressure of CO_2 increases. The approximate decomposition temperatures in Table 5 correspond to a partial pressure of 1 atm of the pertinent gaseous product.

At very high temperatures (> 2500°C), other classes of decomposition reactions occur: the thermal breakdown of polyatomic gases (e.g., O_2 and N_2 into atomic oxygen and nitrogen) and, at still higher temperatures, ionization. These reactions are confined to the very highest temperature operations. However, they can have significance (through their strongly endothermic heat effect) in affecting the peak temperature attained and on gas composition for flames of pure fuels under stoichiometric conditions or with significant air preheat or oxygen enrichment. In incineration situations when moisture, excess air, or other factors tend to favor lower operating temperatures, these reactions are usually unimportant. As for the decomposition reactions, the course of dissociation reactions as the temperature changes is described by equilibrium relationships. The dissociation characteristics of atmospheric gases are presented in Table 6.

6. Kinetic and Potential Energy

In concept, a fraction of the heat of combustion in fuels and wastes can be converted into kinetic (velocity) and potential (pressure or elevation) energy. Clearly, such a conversion is essential to the operation of rocket engines, gas turbines, and other highly specialized combustors. For the facilities of importance in this book, these energy terms are generally unimportant.

Table 6 Dissociation Behavior of Selected Molecules

Reaction	Temperature (°C)	% Dissociation	Heat effect (kcal/mol)
$O_2 \leftrightarrow 2\ O$	2725	5.950	117,500
$N_2 \leftrightarrow 2\ N$	3950	5.000	—
$H_2 \leftrightarrow 2\ H$	2200	6.500	102,200
$H_2O \leftrightarrow H_2 + 0.5\ O_2$	1750	0.370	68,390
	2200	4.100	
$CO_2 \leftrightarrow CO + 0.5\ O_2$	1120	0.014	68,000
	1540	0.400	
	2200	13.500	

7. Heat Losses

Usually, the largest energy losses from a combustion system are the sensible heat (dry gas loss) and latent heat (moisture loss) of the flue gases. The sensible heat loss is scaled by the stack gas temperature. Latent losses include the heat of evaporation of liquid water in the feed plus that of the water formed by oxidation of feed and fuel hydrogen. These losses are unavoidable, but they may be minimized. Dry gas loss is reduced through the use of an economizer and/or air heater in energy recovery systems to extract the largest possible quantity of useful heat from the flue gases before discharge. Moisture loss can be reduced through the removal of excess water from the feed (e.g., the dewatering of sewage sludge).

A second category of heat loss is associated with the fuel energy that leaves the system as unburned combustible in solid residues and as fuel gases (CO, CH_4, H_2, etc.) in the stack gas. Unburned combustible often results from low temperatures in zones of the combustor. To achieve rapid and complete burnout, high temperatures and the associated high oxidation reaction rates are necessary. Excessive moisture in the feed may prevent attainment of these temperatures. Also, rapid cooling that"quenches" combustion reactions may occur due to in-leakage of air (tramp air infiltration) or by the passage of combustion gas over heat-absorbing surfaces (cold, wet feed in countercurrent flow systems, boiler-tube surfaces, etc.).

Also, combustible may not be completely oxidized because of air supply deficiencies or ineffective mixing. Inadequate mixing leads, for example, to the appearance of unburned hydrocarbons and carbon monoxide in the off-gas from a rotary kiln. The buoyancy-stabilized, stratified flow in these units often results in high temperatures and oxygen deficiency at the top of the kiln and abundant oxygen at much lower temperatures flowing along the bottom of the kiln.

A combination of the low temperature and the air insufficiency mechanisms is responsible for the incomplete burnout of massive combustible such as stumps, mattresses, or thick books and for the incomplete burning of large metal objects. In these cases, the slow diffusion of heat and oxygen through thick ash or char layers results in incomplete oxidation before total quenching of combustion in the residue discharge system.

The third cause of unburned combustible is (often inadvertent) short transit times in the combustor. Examples of this mechanism include the material that falls, unburned, through the grates of a mass burn incinerator or the unburned paper fragments swept too quickly out of a refuse-derived fuel (RDF) incinerator by the rising combustion gases.

Radiation loss is the expression used to describe the third major heat loss: leakage of heat into the surroundings by all modes of heat transfer. Radiation losses increase in proportion to the exposed area of hot surfaces and may be reduced by the use of insulation. Since heat loss is area-dependent, the heat loss (expressed as percentage of total heat release) generally increases as the total heat release rate decreases. The American Boiler Manufacturers' Association developed a dimensional algorithm [Eq. (13)] with which to estimate heat losses from boilers and similar combustors (180). The heat loss estimate is conservative (high) for large furnaces:

$$\text{radiation loss} = \left(\frac{3.6737}{C}\right)\left(\frac{\text{HR} \cdot \text{C}}{F_{OP}}\right)^{0.6303} e^{k \cdot W_{\text{type}}} \tag{13}$$

where for the radiation loss calculated in kcal/hr (or Btu/hr):

C = constant: 1.0 for kcal/hr (0.252 for Btu/hr)
HR = design total energy input (fuel + waste heat of combustion + air preheat) in kcal/hr (or Btu/hr)
F_{OP} = operating factor (actual HR as decimal percent of design HR)
k = constant dependent on the method of wall cooling and equal to

Wall cooling method	k
Not cooled	+0.0
Air-cooled	−0.0013926
Water-cooled	−0.0028768

W_{type} = decimal fraction of furnace or boiler wall that is air- or water-cooled

II. SYSTEMS ANALYSIS

A. General Approach

1. Basic Data

The basic information used in the analysis of combustion systems can include tabulated thermochemical data, the results of several varieties of laboratory and field analyses (concerning fuel, waste, residue, gases in the system), and basic rate data (usually, the flow rates of feed, flue gases, etc.). Guiding the use of these data are fundamental relationships that prescribe the combining proportions in molecules (e.g., two atoms of oxygen with one of carbon in one molecule of carbon dioxide) and those that indicate the course and heat effect of chemical reactions.

2. Basis of Computation

To be clear and accurate in combustor analysis, it is important to specifically identify the system being analyzed. This should be the first step in setting down the detailed statement of the problem. In this chapter, the term *basis* is used. In the course of prolonged analyses, it may appear useful to shift bases. Often, however, the advantages are offset by the lack of a one-to-one relationship between intermediate and final results.

As the first step, therefore, the analyst should choose and *write down* the reference basis: a given weight of the feed material (e.g., 100 kg of waste) or an element, or a unit

time of operation. The latter is usually equivalent to a weight, however, and in general the weight basis is preferred.

3. Assumptions Regarding Combustion Chemistry

Most incinerated wastes contain the elements C, H, O, N, S, and Cl. Many contain P, Br, many metals, and unspecified "inerts." In carrying out material balance calculations, the analyst must assume the disposition of these elements in the combustor effluent streams (gaseous, liquid, and solid). Incomplete mixing, equilibrium considerations, limitations in heat transfer or reaction time, and other factors make real effluents chemically complex and of uncertain composition. However, for use as a basis for material and energy balances, the following assumptions are generally valid for the bulk flow composition in a typical oxidizing combustion environment:

Elemental or organic *carbon* + $O_2 \rightarrow CO_2$. In real systems, a fraction of the carbon is incompletely oxidized. It appears as unburned combustible or char in the solid residue, as hydrocarbons, and as CO in the effluent gases.

Depending on temperature, inorganic (carbonate or bicarbonate) *carbon* may be released as CO_2 by dissociation or may remain in the ash.

Elemental or organic *hydrogen* + $O_2 \rightarrow H_2O$ (but see chlorine, below).

Depending on temperature, *hydrogen* appearing in water of hydration may or may not be released.

Hydrogen appearing in inorganic compounds can leave in a variety of forms, depending on temperature (e.g., $2NaOH \rightarrow Na_2O + H_2O$).

Oxygen associated with the nonmetallic elements C, H, P, S, or N in organic compounds or with metals is assumed to behave as O_2 in air viz. reacting to form oxides (or remaining as the oxide).

Oxygen associated with carbonates, phosphates, etc., can leave in a variety of forms, depending on temperature.

Nitrogen usually leaves as N_2 (plus traces of NO, NO_2).

Reduced organic or inorganic *sulfur* or elemental sulfur + $O_2 \rightarrow SO_2$. A fraction will be further oxidized to SO_3.

Oxidized organic *sulfur* (e.g., sulfonates) $\rightarrow SO_2$ and/or SO_3.

Depending on temperature, oxidized inorganic *sulfur* ($SO_4^=$, $SO_3^=$) may be released as SO_2 or SO_3 (e.g., $CaSO_4 \rightarrow CaO + SO_3$).

Organic *phosphorus* (e.g., in some pesticides) $\rightarrow + O_2 \rightarrow P_2O_5$.

Depending on temperature, inorganic *phosphorus* (e.g., phosphates) may leave in a variety of forms.

Organic *chlorine* or *bromine* is usually a preferred oxidizing agent for hydrogen $\rightarrow$ HCl, HBr (HBr may $\rightarrow H_2 + Br_2$).

Inorganic *chlorine* and *bromine* (chlorides and bromides) are generally stable, although oxy-halogens (e.g., chlorates, hypochlorites) degrade to chlorides and oxygen, water, etc.

Metals in the waste (e.g., iron and steel, aluminum, copper, zinc) will, ultimately, become fully oxidized. However, incomplete burning (say, 25% to 75%) is common due to the low rate of surface oxidation and limited furnace residence time.

4. Approach to Computation

Although the skilled analyst may elect to skip one or more steps because of limited data or lack of utility, the following sequence of steps is strongly recommended:

1. Sketch a flow sheet. Indicate all flows of heat and material, including recirculation streams. Document all basic data on the sketch, including special features of analytical data and heat effects.
2. Select a basis and annotate the sketch to show all known flows of heat or material relative to that basis.
3. Apply material, elemental, and component balances. Recognize that the use of average values for quantities and characteristics is necessary but that variations from the average are most likely the norm rather than the exception. Explore alternative assumptions.
4. Use energy balances. Here, too, explore alternative assumptions.
5. Apply known equilibrium relationships.
6. Apply known reaction rate relationships.
7. Review the previous steps, incorporating the refinements from subsequent stages into the simpler, earlier work.

B. Analyses

Unlike more convention combustors, incineration systems are often charged with materials where the composition varies widely over time and that are highly complex mixtures of waste streams, off-specification products, plant trash, and so forth. The analysis of these wastes must often be a compromise.

In residential waste incineration, for example, what is a shoe? Is it (1) a shoe (i.e., a waste category easily identified by untrained field personnel)? (2) 0.5 kg in the "leather and rubber" category? (3) 0.2 kg leather, 0.18 kg rubber, 0.02 kg iron nails, etc.? (4) 8% moisture, 71% combustible, 21% residue, heating value of 3800 kcal/kg? (5) The composition as given by ultimate analysis? or (6) Properties as given by a proximate analysis? (7) A nonhazardous waste constituent? These are the questions waste engineers must ponder as they impinge upon the adequateness of their design, the need for rigorous detail (in consideration of feed variability), and, importantly, the sampling and analysis budget allocation.

The final decision should be based on the impact of errors on

Regulatory and permit definitions: hazardous or nonhazardous designations
Materials handling: bulk density, storability, explosion and fire hazard, etc.
Fan requirements: combustion air and draft fans
Heat release rate: per square meter, per cubic meter of the combustor

Materials problems: refractory or fireside boiler-tube attack, corrosion in tanks, pipes, or storage bins, etc.
Secondary environmental problems: air, water, and residue-related pollution
Process economics: heat recovery rate, labor requirements, utility usage, etc.

There are no simple rules in this matter. Judgments are necessary on a case-by-case basis. The techniques described below, however, give the analyst tools to explore many of these effects on paper. The cost is much lower than detailed field testing and laboratory analysis and far less than is incurred after an incineration furnace has been installed and fails to operate satisfactorily.

The data generated for the evaluation of waste streams present problems to the analyst. The problem begins with the largely uncontrollable characteristics of the waste generators, the unusual nature of the waste itself, and imperfections in the field sampling process. These difficulties make it problematical to secure proper samples, to adequately preserve and reduce the gross samples from the field to the relatively small quantities submitted to the laboratory, and to conduct the physical or chemical analyses themselves.

One of the first problems of concern is the need for a representative sample. Domestic waste composition has been shown to vary between urban and rural areas; between different economic and cultural groups; from month to month through the year; in different geographic, political, and climatological areas. There is a profound variation in the quantities and characteristics of wastes generated by different industries and even between different process alternatives for manufacture of the same product.

This inherent variability in the basic waste composition is only the starting point in illustrating the difficulty in securing a sample (ultimately in the 1- to 50-gram size) that properly reflects the chemistry, heating value, and other significant characteristics of "average" waste. Waste streams often include constituents that are relatively massive and hard to subdivide (e.g., tree stumps, automobile engine blocks). Other constituents may be volatile or biodegrade on standing. If trace elements or compounds are important, a single waste item (e.g., an automobile battery affecting the lead content of the waste) may be the repository of almost all of the material of interest in many tons of waste. If the item is included, the waste is "typical"; if not, the analysis is faulty.

Concern should also be given to the reported moisture level to ensure that it typifies the material "as-fired." Often wastes are supplied to the laboratory after air drying. This is either because the sampling team decided (without consultation) that such a step would be "good" or because insufficient attention was given to moisture loss during and after the waste was sampled. Not uncommonly, a waste sample may not be representative because the sampling team wanted to give the "best they could find" or because they did not wish to handle some undesirable (e.g., decaying garbage) or awkward (e.g., a large pallet) waste components.

Let us leave this topic with an injunction to the engineer:

Know the details of the sampling methodology, the sample conditioning protocols, and the laboratory analysis and reporting methods before trusting the data.

Several types of waste analysis are available to contribute to combustion system studies. They are briefly reviewed here. The different analytical protocols characterize the waste materials from different perspectives to meet different appraisal objectives.

1. Waste Component Analysis

For many waste streams, an acceptable and useful analysis is obtained by weighing the waste after separation into visually definable components. For municipal solid waste, the component categories often include newsprint, corrugated cardboard, "other paper," food waste, yard waste, aluminum, metal (excluding aluminum), glass, leather, rubber, textiles, plastics, and miscellaneous. The use of these waste categories has obvious advantages in the separation step. Further, the weights in each category are often useful in assessing recycling processes and in monitoring trends in waste sources and composition. This analysis methodology and taxonomy is discussed in greater detail in Chapter 4.

2. Proximate Analysis

The balance between moisture, combustible, and ash content, and the volatilization characteristics of the combustible fraction at high temperatures are important properties affecting combustor design. Quantitative knowledge of these properties gives considerable insight into the nature of the pyrolysis and combustion processes for sludge, solid waste, and conventional fuels. A simple and relatively low-cost laboratory test that reports these properties is called the *proximate analysis* (1). The procedure includes the following steps:

1. Heat one hour at 104° to 110°C. Report weight loss as *moisture*.
2. Ignite in a covered crucible for seven minutes at 950°C and report the weight loss (combined water, hydrogen, and the portion of the carbon initially present as or converted to volatile hydrocarbons) as *volatile matter*.
3. Ignite in an open crucible at 725°C to constant weight and report weight loss as *fixed carbon*.
4. Report the residual mass as *ash*.

It should be recognized that the value reported as "moisture" includes not only free water but also, inadvertently, any organic compounds (e.g., solvent) with significant vapor pressure at 110°C. The value for "volatile matter" includes organic compounds driven off or pyrolyzed but may also include water driven off from hydroxides or hydrates. "Fixed carbon" includes the weight of carbon left behind as a char, but the value may be reduced by weight gain in the crucible from oxidation of metals. In the civil–sanitary engineering literature concerning sewage treatment plant sludge incineration, "volatile matter" data are often treated as though they were equivalent to "combustible matter." For wastewater treatment sludge containing many hydroxides and hydrated organic and inorganic compounds, this is incorrect. It is not surprising, therefore, that one finds a wider than reasonable range in the reported "heating value" of sludge volatile matter.

3. Ultimate Analysis

For fuels the term *ultimate analysis* refers to an analysis routine that reports moisture (loss in weight, for solid fuels at 105°C), combined water (equivalent to the oxygen), and the content of several elements. Carbon, available or net hydrogen (hydrogen other than in moisture and combined water), oxygen, total sulfur, nitrogen, and "ash" are always reported. Oxygen is generally determined by difference, and thus both the value for "percent oxygen" and the "combined water" value may be in error.

In calculations relating to waste disposal systems, it may be appropriate to request analyses for chlorine and for environmentally significant elements (such as arsenic, beryllium, cadmium, chromium, nickel, and lead) and for other elements that could

influence the combustion process or would be important to air pollution or water pollution assessments. In general, several different samples are used to generate the total analysis report. Particularly for waste analysis, therefore, some numerical inconsistencies should not be unexpected.

As for the proximate analysis, the testing method can produce uncertain results for several analysis categories. The weight reported as "ash" will be changed by oxidation of metals in the sample, by release of carbon dioxide from carbonates, by loss of water from hydrates or easily decomposed hydroxides, by oxidation of sulfides, and by other reactions. Also, volatile organic compounds (e.g., solvent) can be lost in the drying step, thus removing a portion of the fuel chemistry from the sample.

4. Thermochemical Analysis

The heat of combustion of wastes is, clearly, important information in incineration system analysis. However, one must be cautious in accepting even the mean of a series of laboratory values (noting that a bomb calorimeter uses only about 1 g of sample) when there are problems in obtaining a representative sample (see below). For both municipal and industrial incineration systems, the analyst must also recognize that within the hardware lifetime waste heat content will almost inevitably change: year to year, season to season, and, even day to day. This strongly suggests the importance of evaluating the impact of waste variation on system temperatures, energy recovery, etc. Further, such likely variability raises legitimate questions regarding the cost-effectiveness of extensive sampling and analysis programs to develop this type of waste property information.

5. Special Analysis

A competent fuels laboratory offers other analysis routines that can provide essential information for certain types of combustors or process requirements.

The *forms of sulfur* analysis breaks down the total sulfur content of the material into three categories: organic, sulfide (pyritic), and sulfate. The "organic" and "sulfide" sulfur forms will oxidize in an incineration environment, thus contributing to the stoichiometric oxygen requirement. Oxidation produces SO_2 and SO_3 (acid gases) that often have significance in air pollution permits. "Sulfate" sulfur is already fully oxidized and, barring dissociation at very high temperatures, will not contribute to acid gas emissions or consume alkali in a scrubbing system.

A test for *forms of chlorine* provides a similar segregation between organically and inorganically bound chlorine in wastes. Chlorine is a very important element in waste combustion. Organic chlorine [e.g., in polyvinyl chloride (PVC) and other halogenated polymers or pesticides] is almost quantitatively converted by combustion processes to HCl: an acid gas of significance in many state and federal air pollution regulations, an important contributor to corrosion problems in boilers, scrubbers, and fans, and a consumer of alkali in scrubbers. Inorganic chlorine (e.g., NaCl) is relatively benign but contributes to problems with refractory attack, submicron fume generation, etc. Since all but a few inorganic chlorides are water soluble and few organic chloride compounds show any significant solubility, leaching and quantification of the soluble chlorine ion in the leachate provides a simple and useful differentiation between these two types of chlorine compounds.

An *ash analysis* is another special analysis. The ash analysis reports the content of the mineral residue as the oxides of the principal ash cations. A typical ash analysis is reported as the percent (dry basis) of SiO_2, Al_2O_3, TiO_2, Fe_2O_3, CaO, MgO, P_2O_5, Na_2O,

and K_2O. As discussed in the Refractories section of Chapter 5, the balance between the acidic and basic oxides in the ash is important in setting ash melting temperatures and in influencing corrosive attack of refractory (fluxing).

The *ash fusion temperature under oxidizing and reducing conditions* is another important test that provides very practical information. In this test (ASTM Standard D-1857), a sample of the material is ashed. The mineral ash is then pressed into a cone shape and placed in a muffle furnace on a tilted ceramic plate. The furnace temperature is ramped up at a set rate while the cone is observed. Four temperatures are noted:

Initial deformation temperature (IDT), where the tip of the cone just shows deformation

Softening temperature (ST), where the cone is slumped such that the height and width of the ash mass are equal

Hemispherical temperature (HT), where the mass is fluid but, due to surface tension, has a hemispherical shape with the height equal to one-half of the width

Fluid temperature (FT), where the molten ash viscosity is very low and the material flows down the plate with a thickness not greater than 1/16th in (0.15 cm).

In reducing atmospheres, the ST is often identified with the "fusion temperature" of the slag.

In combustors such as the fluid bed furnace that depend on maintaining "dry" (non-sticky) ash conditions, the IDT in the ash fusion temperature determination is a guide in setting the upper limit to the operating temperature. Similarly, the IDT is a useful guide in setting the maximum temperature where fly-ash laden furnace gases should enter a boiler-tube bank to avoid slag buildup on the tubes. For other furnaces and operating requirements, the fusion temperature is also useful both in the design and feasibility stage and in problem-solving situations.

The ash fusion test can be conducted under both oxidizing and reducing conditions. Both have utility in anticipating or understanding slag buildup problems. Although most combustors are oxidizing overall, almost any combustor has some oxygen-deficient zones. Such zones include the pyrolyzing/gasifying mass on refuse incinerator grates or sludge incinerator hearths and regions in other furnaces where the local air supply is overwhelmed by the available combustible matter. This can be very important since the fusion characteristics of ash can change dramatically as the environment shifts from oxidizing to reducing. This is particularly true for ashes containing large amounts of iron. The reduction of Fe_2O_3 to FeO involves a change in behavior of the iron oxide from an "acidic oxide" to a "basic oxide" that often leads to a lower initial deformation temperature.

A number of other useful *physical properties* may merit determination. These include melting point (to assess the potential for wastes to melt at incineration temperatures and run through openings in grates), viscosity (important in atomization of liquid wastes), and flash point (important in assessing safety problems and a key parameter in some regulatory definitions of "hazardous" combustible wastes).

Finally, the design of *materials handling* systems can benefit from data such as angle of repose (for bins and belt conveyors), particle size and density (for pneumatic conveyors), and the like.

6. Regulatory/Process Definitions

Beyond the materials tests noted above, it may be appropriate to conduct several specialized tests or develop waste characterizations to make specific distinctions that

affect the permit requirements of the combustion system or that broadly characterize the waste as a guide in basic combustion process selection.

The permit-generated characterizations are specified in the relevant regulations (e.g., the USEPA hazardous waste regulations). Such characterizations include waste chemistry or industrial process source that might denote the presence of carcinogens or toxic substances, hazardous physical properties (e.g., low flash point or corrosivity), hazardous biological properties (e.g., the presence of pathogenic organisms), or the presence of high- or low-level radioactive materials.

Process characterizations include designation as "sewage sludge," "office trash," "domestic waste," or "cafeteria waste" which aid in broad incineration concept selection.

7. Data Analysis

It is not the purpose or within the scope of this book to address in detail methodologies for the statistical analysis of waste data. However, from the discussion that introduced the analysis topic, it is to be expected that the analyst will be confronted with substantial scatter in the reported laboratory values for waste properties. Thus, it is appropriate to include some discussion of data analysis and averaging methods.

In general, the analysis of waste data seeks an estimate of the weighted average (the mean) of important waste parameters and some measure of their variability. Before statistical parameters can be estimated for the data, the basic distribution pattern of the data must be known. The distribution type defines how the mean, the variance, etc., should be calculated. Familiarity, simplicity of calculation, and convenience usually suggest that the normal distribution and its computational methods will be applied. However, for waste data, the log normal distribution (where the logarithms of the data rather than the data itself are normally distributed) is often found to fit the data as well as or better than the normal distribution. Consequently, a brief summary and comparison of the two computational methods will be presented.

The most commonly used measures of central tendency are the mean, the median, and the mode. The mean is the weighted average of the values. The median is the value that divides a data set so that one-half of the items are equal to or greater than and one-half are less than the value. The mode is the most observed value around which the items in the series tend to concentrate. There is no "best" measure of central tendency. Sometimes even the determination of these measures for a set of data is entirely improper since the data may belong to more than one population. Further, the data may not represent a meaningful set. What does the value 56.5 signify as the arithmetic mean of the four figures 2, 5, 103, and 116? Note also that expressing the mean as 56.5 rather than as "fiftyish" has imbued the value with an unwarranted aura of accuracy: far beyond its true worth. Statistical analysis of data to test the significance of trends, groupings, and other inferences is often merited.

In any event, the analyst of waste management systems is frequently presented with data sets that can be significant to the design or permitting of incineration systems. Such quantities as the heat content, the concentration of toxic elements or compounds, or the moisture and combustible contents have profound significance in system design. One rule should be kept in mind, however, in using the values derived from analyzing such data:

"*Average" is the value of a critical parameter that is never observed in practice*. Other definitions include "typical," "assumed value," and "design basis."

This definition, though tongue in cheek, should be taken to heart. Waste properties are inherently variable. Thus, the analyst is strongly encouraged to explore the impact of variations from the "average" on system behavior. "What-if?" calculations to evaluate system response to alternative property values are recommended. Fortunately, the incinerator itself is often an effective averaging device. Its size, the inventory of material being processed at any one time, the large thermal inertia of the tons of refractory comprising the incinerator chambers all act to smooth out momentary variation.

a. Probabilistic Models. As noted above, there are two probabilistic models (or distributions) often applicable to waste data that vary continuously: the normal and the log normal distributions. The arithmetic calculations associated with the normal distribution are easier to implement and are generally appropriate for bulk properties such as heating value, percent moisture, and the like. The calculations assuming the log normal distribution are more difficult but are usually superior in accuracy for trace component analyses and other properties that hover near zero.

The general shape of the normal and log normal distributions is shown in Fig. 2. For the normal distribution, the mean, median, and mode are all coincident. This provides the "comfort" that the value used for the mean falls in the midst of all the observations and, indeed, is the most observed value. For the log normal case, the mean, median, and mode differ and the mean can be significantly higher than either the median or the mode, where our intuitive "feel" for the data says the central value should be.

The Shapiro–Wilk test for normality is generally preferable for application to sets of data and to the logarithms of the data sets. The Kolmogorov–Smirnov test for normality is more common for this purpose, but the Shapiro–Wilk test should be considered for sample sizes smaller than 50. Both the test statistic and the level of significance should be computed for each form of the data (base and logarithm) to select the probability

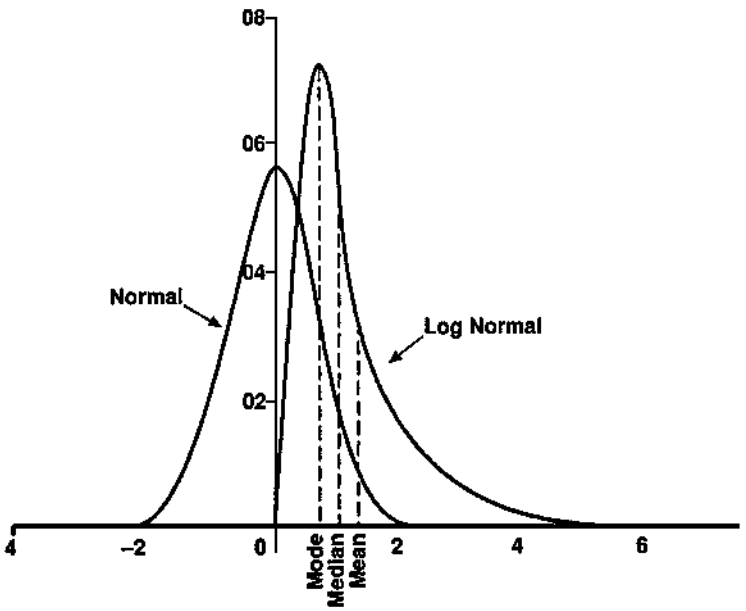


Figure 2 Normal and lognormal distribution.

distribution that best fits the situation. A 5% level of significance is a reasonable criterion to determine whether the data are normal (or log normal). If the level of significance is equal to or greater than 5%, then the hypothesis that the data are normal (or log normal) cannot be rejected.

b. Statistical Calculations. Once a probabilistic model has been selected, the mean, variance (square of the standard deviation), and other statistical quantities can be generated. For convenience, the formulas for the key statistics are summarized here for the normal and log normal cases. Additional discussions related to particle size distributions are presented in Section I.A of Chapter 13. The reader is strongly recommended to refer to more comprehensive texts on these matters (e.g., 181,182).

MEAN AND VARIANCE. For normal distributions, the population mean (M) and variance (S^2) are estimated by Eqs. (14) and (15).

$$M = \frac{1}{n_0}\sum_{i=1}^{n_0} x_i \tag{14}$$

$$S^2 = \frac{1}{n_0 - 1}\sum_{i=1}^{n_0}(x_i - M)^2 \tag{15}$$

For log normal distributions, the mean (m) and variance (s^2) of the logarithms are calculated from the transformed data $y_i = \log_e x_i$ as follows:

$$m = \frac{1}{n_0}\sum_{i=1}^{n_0} y_i \tag{16}$$

$$s^2 = \frac{1}{n_0 - 1}\sum_{i=1}^{n_0}(y_i - m)^2 \tag{17}$$

Several useful measures from log normal statistics are as follows:

$$\text{population mean:} \quad m_{\ln} = \exp[m + 0.5s^2] \tag{18}$$

$$\text{population variance:} \quad s^2_{\ln} = (\exp[s^2] - 1)(\exp[2m + s^2]) \tag{19}$$

$$\text{median at:} \quad x = \exp[m] \tag{20}$$

$$\text{mode at:} \quad x = \exp[m - s^2] \tag{21}$$

$$\text{lower quartile at:} \quad x = \exp[m - 0.67s] \tag{22}$$

$$\text{upper quartile at:} \quad x = \exp[m + 0.67s] \tag{23}$$

Often, the results of laboratory analysis of waste materials for elements or compounds present in low concentrations are reported as "nondetect" or "below detection limit." Here, limitations of the analytical protocols or the sensitivity of the apparatus produce a null or indeterminate response in detecting the material of interest. That does not mean that the correct value is zero. Nor should one, necessarily, be driven to consider the "nondetect" limit as the effective concentration for the material. For the log normal distribution case, an elegant analysis (181) supports the development of an unbiased estimator of the mean and variance from a data set with n_0 samples with discrete data values and n total samples. The unbiased estimator of the population mean and variance in the units of the observations for such "incomplete data" sets (m_{id} and s^2_{id}, respectively) is given by Eqs. (24) and (25). These relationships make use of a Bessel function P_{no} presented in Eq. (26) that is the sum of an infinite series but can be easily and accurately

estimated from the first five terms or so using a personal computer spreadsheet or hand calculator.

$$m_{\mathrm{id}} = \frac{n_0}{n}\exp[m]\left[P_{\mathrm{no}}\left(\frac{1}{2}s^2\right)\right] \tag{24}$$

$$s^2_{\mathrm{id}} = \frac{n_0}{n}\exp[2m]\left[P_{\mathrm{no}}(2s^2) - \left(\frac{n_0-1}{n-1}\right)P_{\mathrm{no}}\left(\frac{n_0-2}{n_0-1}s^2\right)\right] \tag{25}$$

$$P_{\mathrm{no}}(t) = 1 + \frac{n_0-1}{n_0}t + \frac{(n_0-1)^3}{n_0^2 2!(n_0+1)}t^2 + \frac{(n_0-1)^5}{n_0^3 3!(n_0+1)(n_0+3)}t^3 + \ldots \tag{26}$$

Note that for the special cases where n_0 is equal to zero, the mean and variance are zero. For n_0 equal to 1 and for the data value x_1, the following equations apply:

$$m_{\mathrm{id}} = x_1/n \qquad \text{and} \qquad s^2_{\mathrm{id}} = x_1^2/n$$

8. Data Cost

Data are not cheap. In planning a data collection program supporting the design of incineration design, the analyst must carefully consider the number of samples required for "representativeness" and the scope and sophistication of the data to be generated. These scalars translate into the cost and time frame for data collection and must be balanced against the utility of the information thus gained. There is no simple rule with which to strike this balance. One must recognize, for example, that changes in the composition of a waste stream over the useful life of an incinerator often place great demands on the flexibility of a system to accommodate the change. These year-to-year changes may be much more profound than the plus-and-minus "accuracy" of data that characterize the present waste. There may, therefore, be considerable merit in limiting the data collection effort in favor of more exhaustive engineering analysis to explore the consequences of change.

III. MATERIAL BALANCES

A material balance is a quantitative expression of the law of conservation of matter: What goes in comes out (unless it stays behind).

$$\text{input} = \text{output} + \text{accumulation} \tag{26}$$

This expression is always true for *elements* flowing through combustion systems (except for minor deviations in the unusual case where radioactive materials are involved). It is often not true for *compounds* participating in combustion reactions. Because of its fundamental character and intrinsic credibility, the material balance is one of the most useful tools for combustion system analysis.

A. Balances Based on Fuel Analysis

Balances on elements in the fuel or waste allow one to calculate the amount of air theoretically required to completely oxidize the carbon, net hydrogen, sulfur, etc. This quantity of air (known as the *theoretical* or *stoichiometric* air requirement) is often insufficient to achieve complete burnout in a practical combustor, and *excess* air, defined as percentage of the stoichiometric air quantity, is usually supplied. For example, an operation

at 50% excess air denotes combustion where 1.5 times the stoichiometric air requirement has been supplied. Typical excess air levels for several fuels are given in Table 7.

At a specified excess air level, elemental balances allow computation of the flue gas composition. The method of analysis is best illustrated by an example.

EXAMPLE 8. Calculate the air requirement and products of combustion when burning at 30% excess air, 75 kg/hr of a waste liquid having the ultimate analysis: 12.2% moisture, 71.0% carbon, 9.2% hydrogen, 3.4% sulfur, 2.1% oxygen, 0.6% nitrogen, and 1.5% ash. The combustion air is at 15.5°C, 70% relative humidity.

Table 7 Typical Excess Air and/or Maximum Percent CO_2 for Waste and Fossil Fuel Combustors

Fuel	Type of furnace or burner	Typical excess air (%)	Maximum % CO_2 (volume)[a]
Acid sludge	Cone and flat-flame type burners, steam atomized	10–15	—
Bagasse	All	20–35	19.4–20.5 (20.3)
Black liquor	Recovery furnaces	5–7	18.6 (without salt cake)
Blast furnace gas	Intertube nozzle-type burners	15–18	20.0–26.9 (24.7)
Carbon (pure)	—	—	20.9
Charcoal	—	—	18.6
Anthracite coal	—	—	19.3–20.0
Bituminous coal	Range for nongrate fired	—	17.7–19.3 (18.5)
Pulverized	Waterwall furnace, wet or dry bottom	15–20	—
	Partial waterwall, dry bottom	15–40	—
Crushed	Cyclone furnaces	10–15	—
Lump or crushed	Spreader stoker	30–60	—
	Vibrating grate (water cooled)	30–60	—
	Chain or traveling grate	15–50	—
	Underfire stoker	20–50	—
Coke oven gas	Multifuel burner	7–12	9.5–12.7 (11.1)
Lignite coke	—	—	19.2
Municipal solid waste (MSW)	Water-cooled/refractory covered furnace with reciprocating grate	80–100	—
	Rotary kiln	25–35	—
Natural gas	Register-type burner	5–10	11.6–12.7 (12.2)
Oil (fuel)	Register-type	5–10	14.25–15.5
	Multifuel burners and flat flame	10–20	14.75–16.35
Refinery gas	Multifuel burner	7–12	—
Refuse-derived fuels (RDF)	Completely water-cooled furnace, traveling grate	40–60	—
Tar and pitch	—	—	17.5–18.4
Softwood	—	—	18.7–20.4
Hardwood	—	—	19.5–20.5

[a]Values in parentheses are typical.

Table 8 Calculations for Example 8[a]

Line	Component	kg	Atoms or moles[b]	Combustion product	Theoretical moles O_2 required
1	Carbon (C)	71.0	5.912	CO_2	5.912
2	Hydrogen (H_2)	9.2	4.563	H_2O	2.282
3	Sulfur (S)	3.4	0.106	SO_2	0.106
4	Oxygen (O_2)	2.1	0.066	—	(0.066)
5	Nitrogen (N_2)	0.6	0.021	N_2	0.0
6	Moisture (H_2O)	12.2	0.678	—	0.0
7	Ash	1.5	N/A	—	0.0
8	Total	100.0	11.387		8.234
9	Moles nitrogen in stoichiometric air[c]			(79/21)(8.234)	
10	Moles nitrogen in excess air			(0.3)(79/21)(8.234)	
11	Moles oxygen in excess air			(0.3)(8.234)	
12	Moles moisture in combustion air[d]				
13	Total moles in flue gas				
14	Volume (mole) percent in wet flue gas				
15	Orsat (dry) flue gas analysis—moles				
16	A. With selective SO_2 testing—vol %				
17	B. With alkaline CO_2 testing only—vol %				
18	C. With SO_2 loss in testing—vol %				

Moles formed in stoichiometric combustion

CO_2	H_2O	SO_2	N_2	O_2	Total
5.912	0.0	0.0	0.0	0.0	5.912
0.0	4.563	0.0	0.0	0.0	4.563
0.0	0.0	0.106	0.0	0.0	0.106
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.021	0.0	0.021
0.0	0.678	0.0	0.0	0.0	0.678
0.0	0.0	0.0	0.0	0.0	0.0
5.912	5.241	0.106	0.021	0	11.280
			30.975		30.975
			9.293		9.293
				2.470	2.470
	0.653				0.538
5.912	5.894	0.106	40.289	2.470	54.671
10.81	10.78	0.194	73.69	4.52	100.000
5.912		0.106	40.289	2.47	48.777
12.12	N/A	0.22	82.60	5.06	100.0
12.34	N/A	N/A	82.60	5.06	100.0
12.15	N/A	N/A	82.78	5.08	100.0

[a]Basis: 100 kg of waste.

[b]The symbol in the component column shows whether these are kg moles or kg atoms.

[c]Throughout this chapter, dry combustion air is assumed to contain 21.0% oxygen by volume and 79.0% nitrogen.

[d]Calculated as follows: (0.008/18.016)[Mols N_2 in air)(28.016) + (1 + % excess air)(Mols O_2 for stoichiometric)(32)] based on the assumption of 0.008 kg water vapor per kg bone-dry air; found from standard psychrometric charts.

The calculations involved in the material balance are shown in Table 8. This type of calculation is very amenable to the spreadsheet type of analysis on a personal computer. A diskette carrying a "template" for a spreadsheet solution to a problem similar to but more complex than the Table 8 analysis (the heat and material balance problem from Example 9) is included in the back of this book. The technique for use of the template is presented in Appendix F. The spreadsheet is stored on the diskette in the Excel Office 95 format (a spreadsheet program copyrighted by Microsoft Corporation) that can often be read and used by other spreadsheet platforms.

Several elements of the analysis presented in Table 8 should be noted.

LINE 1. Carbon is assumed here to burn completely to carbon dioxide. In practice, some carbon may be incompletely burned, appearing in carbon monoxide and a range of hydrocarbons. Some may end up as unburned carbon in the solid residues comprising the bottom ash or as soot or fragments of char (pyrolyzed organic matter) carried off as a portion of the particulate matter leaving in the effluent gas. The fraction of carbon as CO ranges from negligible for well-mixed, high-temperature gaseous waste burners to several thousand parts per million in the effluent gases from poorly mixed systems burning wet waste. Carbon found as char in residue can be as high as 5% of the carbon fed to solid waste burners.

LINE 2. Hydrogen in the waste (other than the hydrogen in moisture) increases the amount of combustion air but does not appear in the Orsat analysis (lines 16 to 18). Hydrogen is assumed to burn to water vapor with the exception of the hydrogen that combines with organic chlorine or fluorine that forms the acid gases HCl and HF.

LINE 3. Sulfur present in the waste as the element, in the reduced form as sulfide, or as organic sulfur increases the amount of combustion air required in burning to SO_2. Inorganic sulfates may leave as ash or be reduced to SO_2. If SO_2 is not analyzed selectively (line 17), it is usually reported out as carbon dioxide. If care is not taken to avoid absorption of the SO_2 in the sampling and analysis steps, however, it distorts the $CO_2/N_2/O_2$ values. Consideration should be given to the use of special test methods (e.g., GC methods) for studies of waste disposal flue gases where the sulfur oxide concentration may be high.

LINE 4. Oxygen in the waste organic matter reduces the required combustion air.

LINE 12. Moisture entering with the combustion air can be seen to be small and is often neglected. As noted, psychrometric data relating the water content of atmospheric air to various conditions of temperature, relative humidity, etc., can be obtained from standard references (e.g., Ref. 4) and typical meteorological data for the region of interest from local weather stations or reference books (e.g., Ref. 5). Atmospheric moisture content should be considered in fan selection and if the resulting flue gas moisture affects the process (e.g., in sulfuric acid manufacture by the Contact Process).

Although this problem considered only carbon, hydrogen, oxygen, nitrogen, and sulfur waste components and assumed single products of combustion, the analyst should review waste composition thoroughly and consider the range of possible secondary reactions if the flue gas analysis is especially important (e.g., regarding secondary air pollution problems). A few of these concerns include the following four areas.

1. *Carbon monoxide.* As discussed later, CO may be formed in appreciable quantities in solids burning, if combustion temperatures are low, and in systems operated at or below stoichiometric conditions.

2. *Chlorine.* Chlorine appearing in the waste as inorganic salts (e.g., NaCl or $CaCl_2$) will most likely remain as the salt. Organic chlorine compounds, however, react with hydrogen to form hydrogen chloride (to the extent of the hydrogen available from all sources, including moisture in the combustion air). Excess halogen appears as the element.

3. *Metals.* Metals usually burn to the oxide, although in burning solid wastes a large fraction of massive metal feed (e.g., tin cans, sheet steel, etc.) is unoxidized.

4. *Thermal decomposition.* Some compounds in the feed may be decomposed at combustor temperatures. Carbonates, for example, may dissociate to form an oxide and CO_2. Ammonium compounds may volatilize and burn. The anionic fragment (e.g., sulfate) may appear as a particulate or gaseous component in the flue gas (e.g., SO_2 or SO_3 from sulfate). Sulfides may "roast" to form the oxide and release SO_2.

B. Balances Based on Flue Gas Analysis

Commonly, the analyst is called upon to evaluate an operating waste disposal system. In such studies, accurate data on the flue gas composition are readily obtainable and offer a low-cost means to characterize the operation and the feed waste.

The Orsat analysis is, perhaps, the easiest and most useful test of combustor performance. Indeed, it is appropriate to periodically confirm the accuracy of more sophisticated gas chromatographic (GC) gas analysis instrumentation using the Orsat apparatus.

In use, a volume of flue gas is drawn into the Orsat apparatus burette that is scribed to allow reading of the gas volume. The gas volume is recorded after allowing sufficient time for equilibration with room temperature and saturation with water vapor. Even if mercury is used as the confining fluid in the gas measuring burette, a drop of water should be maintained on top of the mercury column. By raising or lowering a vessel of confining fluid, the gases are then repeatedly bubbled through selective absorbing fluids until a constant volume reading is obtained. Relative volume changes are then reported as the percent *on a dry basis* of carbon dioxide, carbon monoxide, and oxygen. Nitrogen is reported by difference.

As a cautionary statement, it should be noted that sulfur dioxide in the flue gases will often be reported as carbon dioxide since absorption of both gases will occur in the alkaline medium used. Also, both gas percentages can be appreciably in error if water instead of mercury is used as the confining medium due to the solution of the gases (even if the water is made acid and is virtually saturated with sodium chloride to minimize gas solubility). Lastly, but far too often, the absorbent (particularly the pyrogallate used for oxygen absorption) becomes deactivated through age, overuse, or improper storage. The resulting limited absorbing capacity leads the analyst to report inaccurately.

One important combustor and combustion characteristic that can be immediately computed from the Orsat flue gas analysis is the percentage excess air:

$$\text{percentage excess air} = \frac{[O_2 - 0.5(CO + H_2)]100}{0.266N_2 - O_2 + 0.5(CO + H_2)} \tag{27a}$$

where O_2, N_2, etc., are the *volume percentages* (dry basis) of the gases. If only the CO_2 content of the flue gas is known *for a given fuel* where the concentration of CO_2 at zero

excess air (see Table 7) is CO_2^*, the percentage excess air is given by

$$\text{percentage excess air} = \frac{7900(CO_2^* - CO_2)}{CO_2(100 - CO_2^*)} \tag{27b}$$

EXAMPLE 9. The flue gas from a waste incinerator burning a waste believed to have little nitrogen or oxygen has an Orsat analysis (using alkaline CO_2 absorbent) of 12.3% CO_2, 5.1% O_2, and the rest nitrogen and inerts. From these data, calculate:

1. The weight ratio of hydrogen to carbon in the waste
2. The percent carbon and hydrogen in the dry waste
3. The kilograms dry air used per pound of dry waste
4. The percent excess air used
5. The mols of exhaust gas discharged from the unit per kilogram dry waste burned

This example is derived from Example 8. From comparison, the "actual" values based on the prior example are given in parentheses.

Basis. 100 mol of dry exhaust gas

Component	Moles	Moles O_2
$CO_2(+SO_2)$	12.3	12.3
O_2	5.1	5.1
N_2	82.6	—
Total	100	17.4
	82.6 (21/79) = 22.0 accounted from air	
	Difference = 4.6 mol O_2 disappearance	
H_2 burned	2(4.6) = 9.2 mol = 18.4 kg	
C burned	12(12.3 mol) = 147.6 kg	

Total weight of waste 166.0 (vs. 179.2 kg).

1. Weight ratio of hydrogen to carbon: (18.4/147.6) = 0.125 (vs. 0.130)
2. Percent (by weight) C in dry fuel: (147.6/166.0)(100) = 88.92 (vs. 80.86% for carbon, 84.74% for the total of carbon and sulfur)
3. Kg dry air per kg of dry waste: First, calculate the weight of air resulting in 1 mol of dry exhaust gas from a nitrogen balance:

$$\frac{1}{100}(82.6 \text{ mol } N_2)\left(\frac{1}{0.79} \text{ moles } N_2 \text{ per air mole}\right)(29 \text{ kg air/mol})$$
$$= 30.32 \text{ kg air/mol dry exhaust gas}$$

then

$$30.32\left(\frac{1}{1.66} \text{ mol dry exhaust gas per kg waste}\right)$$
$$= 18.27 \text{ kg dry air/kg dry waste (vs. 16.80)}$$

4. Percent excess air: The oxygen *necessary* for combustion is 12.3 + 4.6 = 16.9 mol. The oxygen *unnecessary* for combustion = 5.1 mol. The *total* oxygen = 22.0 mol. Note that the *necessary* oxygen would have to be increased

and the *unnecessary* oxygen decreased if incompletely burned components (such as CO) were present. The percent excess air (or oxygen) may be calculated as:

$$(100)\frac{\text{unnecessary}}{\text{total} - \text{unnecessary}} = \frac{100(5.1)}{22.0 - 5.1} = 30.2\% \text{ (vs. } 30\%) \tag{28a}$$

$$(100)\frac{\text{unnecessary}}{\text{necessary}} = \frac{100(5.1)}{16.9} = 30.2\% \tag{28b}$$

$$(100)\frac{\text{total} - \text{necessary}}{\text{necessary}} = \frac{100(22.0 - 16.9)}{16.9} = 30.2\% \tag{28c}$$

5. Mols of exhaust gas per kg of dry waste, noting that 9.2 mol of water vapor must be added to the dry gas flow:

$$\frac{100 + 9.2}{166} = 0.658 \text{ mol/kg fuel}$$

(vs. 0.623 for dry waste and 0.547 for true waste)

Lessons to be learned from comparison of the results of Example 9 with the "true" situation from Example 8 are as follows:

Waste analysis data are particularly important in calculating combustion air requirements for design.

Waste moisture data are important in determining flue gas rates (induced draft fan pollution control and stack sizing).

Nonetheless, considerable insight on the nature of the waste can be gained from stack gas analysis.

C. Cross-Checking Between Fuel and Flue Gas Analysis

In studying waste incineration processes, the skilled analyst should take all reasonable opportunities to assemble several independent data sets and, using the techniques illustrated above, cross-check for consistency. Then, when errors appear, application of insights as to probable sampling or analytical error and the potential for waste variability can allow convergence on a "best" solution. Frankly, stopping short of such cross-checking is foolish.

IV. ENERGY BALANCES

An energy balance is a quantitative expression of the law of conservation of energy. In waste incineration system analysis, five energy quantities are of prime interest:

1. *Chemical energy:* the heat of chemical reactions (importantly, oxidation reactions) that include combustion and dissociation. This quantity must be corrected for any "unreleased" fuel value in the residue or off-gases.
2. *Latent heat:* the heat to change the state of materials, which includes sublimation, fusion, and vaporization.
3. *Sensible heat:* the heat content related to the temperature of materials.
4. *Heat losses:* to the walls of combustion systems.
5. *Useful heat:* delivered to boiler tubes or to materials being heated by the combustion process.

The only truly basic energy reference condition for energy calculations is for the case where the materials are at absolute zero (−273.15°C or −459.69°F). For convenience, however, a condition of 1 atm and 15.6°C (60°F) is often used as the reference for sensible heat content. Most laboratory data on chemical reaction and latent energy are reported at reference temperatures of 15° to 25 °C. In the latter case, although theory would dictate that correction to a consistent temperature base is always appropriate, the errors incurred are generally minor. Thus, tabulated values of heat of combustion and latent heat are ordinarily used without correction.

Typically, heats of combustion are determined experimentally using a bomb calorimeter. In this method, a small quantity (often about 1 g) of material is ignited and burned with sodium peroxide in a heavy-walled, sealed container immersed in water. The resulting heat release is determined from the final temperature rise of the bomb, water, and associated container. Three consequences inherent in this methodology arise:

1. The final temperature is in the range of 20° to 30°C, such that the measured (and reported) heat effect includes the latent heat of condensation of the water vapor formed in combustion. This so-called higher heating value (HHV) is thus substantially greater than the heat appearing in the flue gas stream as sensible heat. The heating value for which the water is not condensed (the lower heating value, or LHV) is corrected for this important heat effect. Unless otherwise specified, most reported heat of combustion data in the U.S. and the United Kingdom are the higher heating value.
2. The quantity of waste tested is very small, thus greatly increasing the problem of obtaining a representative sample. This is especially so for solid wastes. Unfortunately, larger combustion bombs are highly impractical, so this problem will continue to persist. One solution, having applicability in many situations, is to analyze the waste to identify its major constituents and then "construct" the heat content of the mixed waste as a weighted average. In field studies, the entire incinerator–boiler facility may be used as a giant calorimeter. With measurement of key flow rates, material flow compositions, and temperatures, the HHV can then be calculated (432).
3. The nature of the ignition process in the combustion bomb makes tests of liquids or moist sludge very difficult. Table 9 and Appendix C give values for the heat of combustion of many common materials.

The uniformity of the higher heating value (HHV) per mol of oxygen at a stoichiometric mixture is worthy of note, particularly for the hydrocarbons where the average is about 110,000 kcal/mol O_2. This uniformity can be useful in estimating the average heat of combustion of incinerated wastes based on the air requirement determined in operating equipment. (See Table 9 here and Table 2 of Chapter 4).

EXAMPLE 10. A waste sludge is to be burned in a well-insulated combustion chamber followed by a waste heat boiler. The sludge has the following composition:

Component	Weight percent
Benzene	70.0
Carbon (coke)	8.2
Ash	9.3
Moisture	12.5

The initial concept proposed is to burn the waste using only 10% excess air (available preheated to 300°C) to maximize the heat recovered from the flue gases. Assuming 5%

Table 9 Molal Heat of Combustioin at Constant Pressure (kcal/kg mol)

Fuel	Higher heating value (HHV) (water condensed)	Lower heating value (LHV) (water uncondensed)	HHV per mole O_2	Temperature (°C)	Reference
Carbon (C to CO_2)	97,000	97,000	97,000	25	6
Hydrogen (H_2)	68,318	57,798	136,636	25	7
Carbon monoxide (CO)	67,636	67,636	135,272	25	7
Methane (CH_4)	212,950	191,910	106,475	18	8
Ethane (C_2H_6)	373,050	341,500	106,585	18	8
Ethylene (C_2H_4)	336,600	315,600	112,200	18	8
Acetylene (C_2H_2)	311,100	300,600	124,440	18	8
Propane (C_3H_8)	526,300	484,200	105,260	18–20	9
Propylene (C_3H_6)	490,200	458,700	108,933	18–20	9
Benzene (C_6H_6)	787,200	755,700	104,960	18–20	9
Sulfur (rhombic, to SO_2)	70,920	70,920	70,920	18	8

heat loss from both the combustion chamber and the boiler and neglecting dissociation, at what temperature will the flue gases enter the boiler? At a burning rate of 1100 kg/hr, what will be the steaming rate if the stack temperature is 180°C (about 250°F) and the boiler steam is saturated at 15.8 atm? Boiler feedwater is the saturated liquid at 100°C. Ambient humidity is 0.008 kg/kg dry gas. A diagram of the process is given in Fig. 3.

Let the basis be 100 kg of waste and the datum temperature 15.5°C (60°F). The chemical heat input is given by:

Component	kg	Moles	HHV (kcal)	Total heat input (kg cal)	Required mol O_2
Benzene	70.0	0.896	787,200	706,450	6.721
Carbon	8.2	0.683	9700	66,280	0.683
Ash	9.3	—	0	0	0.000
Moisture	12.5	0.694	0	0	0.000
Total	100.0			772,730	7.404

The air requirement (at 10% excess) is calculated to be

$$\begin{aligned} \text{Total mol } O_2\ (7.41)(1.1) &= \ \ 8.15 \text{ mol} \\ \text{Total mol } N_2\ (7.41)(1.1)(79/21) &= 30.66 \text{ mol} \\ \text{Total mols air} &= 38.81 \text{ mol} \end{aligned}$$

The air flow rate is, therefore, 918.8 sm^3 (standard cubic meters) at 15.5°C or 1823.5 am^3 (actual cubic meters) at 300°C. The sensible heat of the incoming air (see Fig. 1 for heat capacity) is given by

$$(38.81)(300 - 15.5)(7.08) = 78{,}170 \text{ kcal}$$

Therefore, the total energy input is $772{,}730 + 78{,}170 = 850{,}900$ kcal. The flue gas composition is calculated using a material balance. The material balance is summarized in the table below. Note that Example 9 is used in the template spreadsheet heat and material balance provided on the disk included in the back of this book. The use of the template is described in Appendix F.

Component	Required Mol O_2	Mol CO_2	Mol H_2O	Mol N_2	Mol O_2 (excess)
Benzene	6.721	5.377	2.689	27.813	0.672
Carbon	0.683	0.683	0.0	2.826	0.068
Ash	0.0	0.0	0.0	0.0	0.0
Water (in waste)	0.0	0.0	0.694	0.0	0.0
Water (in air)	0.0	0.0	0.497	0.0	0.0
Total	7.41	6.065	3.882	30.639	0.740
Volume percent (wet)		14.67	9.39	74.15	1.79
Volume percent (dry)		16.19	N/A	81.84	1.98

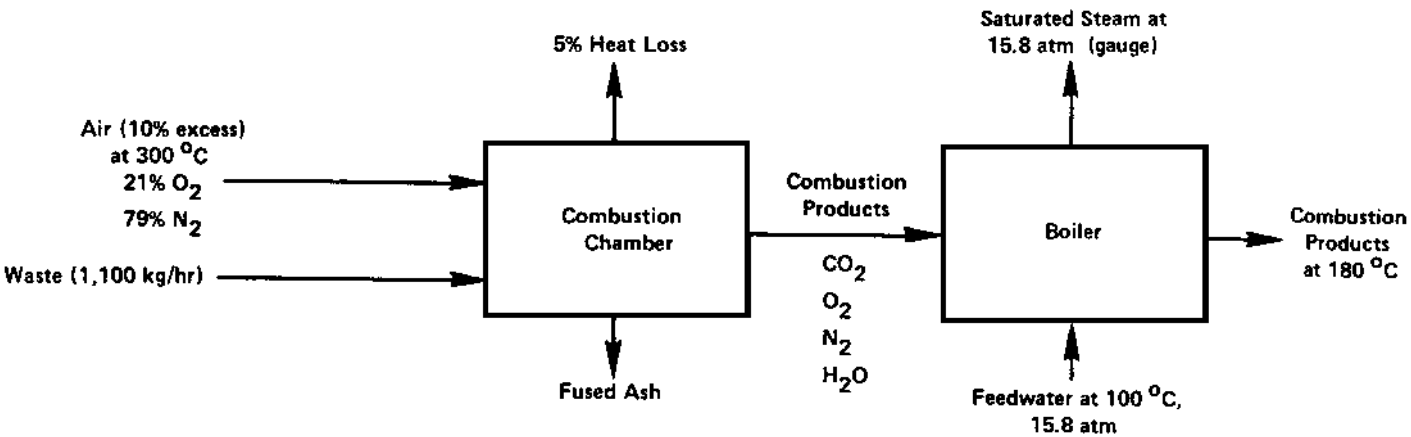


Figure 3 Process flowsheet for Example 10.

A plot of the heat content of the flue gas stream as a function of temperature provides a useful means to find the exit temperature of the combustion chamber and the steaming rate and other quantities. The sensible and latent heat content of the gases and ash is computed as shown in Table 10. The results of these computations are plotted in Fig. 4. The flows of thermal energy are, then,

		kcal	Temperature (°C)
Energy into system			
Heat of combustion		771,713	15.5
Preheated air		79,224	300
Latent heat		(35,843)	
	Total	815,093	2209[a]
Heat loss (5%) from combustion chamber		(42,489)	
Heat loss in fused residue		(4,653)	2092
Energy into boiler		767,951	2092
Heat loss (5%) from boiler		(38,398)	
Heat loss out stack gases		(86,407)	180
Net energy into steam		643,146	204

[a]The theoretical (adiabatic) flame temperature for this system (the temperature of the products of combustion with no heat loss).

For feedwater at 100°C and 15.8 atm changing to saturated steam at 15.8 atm, the enthalpy change is 567.9 kcal/kg, so the resulting steaming rate for a burning rate of 1100 kg/hr is:

$$\left(\frac{643{,}196}{567.9}\right)\left(\frac{1100}{100}\right) = 12{,}457 \text{ kg/hr}$$

Such analysis produces a number of other useful measures of the system and design values. These include:

Available results	Utility
Total air rate	Fan and duct sizing
Ash rates	Ash disposal system
Combustion chamber	
Temperature	Refractory selection
Gas flow rates	Chamber and duct sizing to obtain residence time, avoid erosion, judge pressure drop
Boiler	
Temperature	Heat transfer, steaming rate, corrosion assessment
Gas flow rates	Heat transfer, erosion protection
Energy flows	Steaming rate, feedwater system
Stack flow gas rate	Pollution control, duct and fan sizing

Note also that if the preheated air temperature is a variable, Fig. 4 could have been used to determine the preheat needed to obtain either a given flame temperature or a

Table 10 Computation of Heat Content of Flue Gases from Combustion of Benzene Waste at 10% Excess Air

A	Assumed temperature (°C)	180.0	500.0	1000.0	1500.0	2000.0	2600.0
B	A − 15.5 (°C)	164.5	484.5	984.5	1484.5	1984.5	2484.5
C	Mcp-av for N_2 at A °C[a]	6.93	7.16	7.48	7.74	7.95	8.10
D	Mcp-av for O_2 at A °C	7.17	7.48	7.87	8.13	8.26	8.26
E	Mcp-av for H_2O at A °C	8.06	8.53	9.22	9.85	10.42	10.93
F	Mcp-av for CO_2 at A °C	9.67	10.64	11.81	12.57	12.91	12.85
G	Mcp-av for Ash at A a°C[b]	0.20	0.20	0.20	0.20	0.20	0.20
H	Heat content of N_2 30.639 (B)(C)	34,905	106,299	225,670	352,249	483,394	616,461
I	Heat content of O_2 0.740(B)(D)	873	2,685	5,737	8,935	12,136	15,137
J	Heat content of H_2O 3.880(B)(E)	5,143	16,032	35,203	58,711	80,224	105,410
K	Heat content of CO_2 6.060(B)(F)	9,643	31,235	70,454	113,055	155,290	193,408
L	Heat content of ash 9.3[(B)(G) + 85][c]	306	901	2,622	3,552	4,482	5,412
M	Latent heat in water vapor 3.383(10,595)[d]	35,843	35,843	35,843	35,843	35,843	35,843
N	Total heat content of gas (H + I + J + K + L + M)[e]	86,713	192,996	375,513	570,330	771,353	971,715
O	Kcal/kg-mol of gas	2,099	4,671	9,088	13,803	18,668	23,517

[a] *Source:* Figure 1, kcal/kg mol °C.
[b] Specific heat of the ash (kcal/kg °C) for solid or liquid.
[c] The latent heat of fusion for the ash (85 kcal/kg) is added at temperatures greater than 800°C, the assumed ash fusion temperature.
[d] Latent heat of vaporization at 15.5°C of free water in waste and from combustion of hydrogen in the waste (kcal/kg mol).

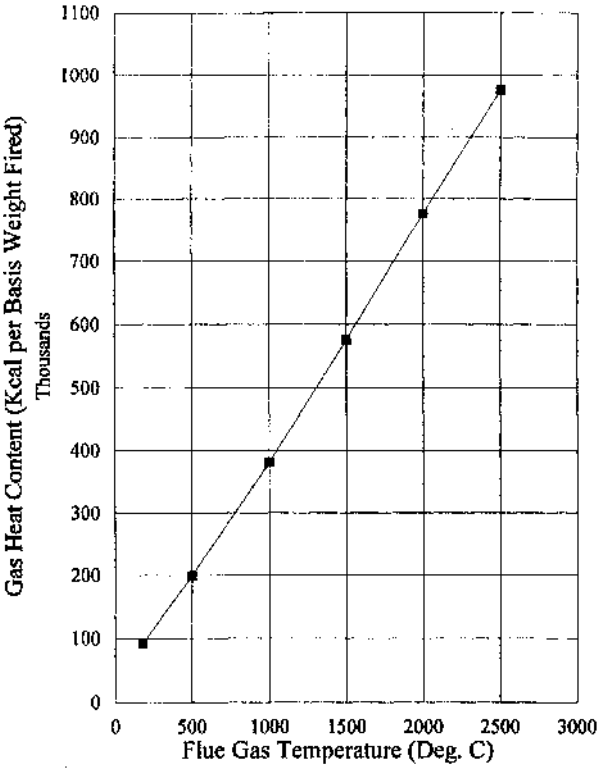


Figure 4 Heat content of the flue gases in Example 10.

desired steaming rate by the following:

Step 1 Determine energy content of combustion chamber gases at the flame temperature which (a) meets criteria that assure complete combustion, or (b) corresponds to an energy differential with that of the stack gas that produces the desired steaming rate.

Step 2 Multiply result by $(1/0.95) = 1.053$ to provide for heat loss in combustion chamber.

Step 3 Subtract the heat of combustion of the waste. The result is the energy deficiency to be satisfied by the preheated air.

Step 4 Divide the result by the combustion air mol flow rate. The result is the needed molar heat content of the combustion air (kcal/mol).

Step 5 Using Fig. 4, find (by iteration) the air preheat corresponding to the needed heat content derived in Step 4.

V. EQUILIBRIUM

It is a recognized property of chemical reactions, readily demonstrable from thermodynamic principles, that no reactions go "to completion." Of course, often the concentrations of the products are so much greater than those of the reactants that, from a practical

viewpoint, the reaction is complete. Yet, when reactants combine to form products, the products themselves begin to react in accord with the law of mass action to reform the original reactants. At the equilibrium condition, the concentrations of reactants and products are constant as the rates of the forward and backward reactions become equal.

Thermodynamic analysis shows that the extent of the reaction of ideal gases (a realistic assumption at combustion temperatures) is described by an *equilibrium constant* K_p that is a function only of temperature. The equilibrium constant for the reaction

$$aA + bB \rightleftharpoons cC + dD$$

expressed in terms of the partial pressures of reactants A and B and the products C and D is given in Eq. (29). By convention, the partial pressure terms for the reaction products are always placed in the numerator of the expression

$$K_p = \frac{p_C^c p_D^d}{p_A^a p_B^b} \tag{29}$$

The dimensions of K_p depend on the algebraic sum of the exponents given by the sum of the stoichiometric coefficients: $(c + d - a - b)$. If the total is zero, K_p is dimensionless. If the total is nonzero, K_p will have the units of pressure (atm) raised to the appropriate integer or fractional power.

The reader is directed to standard texts in physical chemistry (182) for a full development of the thermodynamic basis and relationships concerning equilibrium. In combustion system analysis relating to environmental problems, however, it is sometimes useful to understand the temperature dependence of the equilibrium constant and to know how to estimate K_p for an arbitrary reaction of interest at any given temperature.

It can be shown that K_p is related to the free energy change ΔF° when all of the reactants and products are in their standard states by

$$-\Delta F^\circ = RT \ln K_p \tag{30}$$

Further, the variation in free energy with temperature at constant pressure is given by

$$\left[\frac{\partial}{\partial T}\left(\frac{\Delta F^\circ}{T}\right)\right]_p = \frac{-\Delta H^\circ}{T^2} \tag{31}$$

Equations (30) and (31) can be combined to form an expression for the variation of K_p with temperature:

$$\left[\frac{\partial \ln K_p}{\partial T}\right]_p = \frac{d(\ln K_p)}{dT} = \frac{\Delta H^\circ}{RT^2} \tag{32}$$

Clearly, if the reaction is exothermic (ΔH° is positive), K_p increases with temperature. If the reaction is endothermic (ΔH° is negative), the reverse is true. Rearranging Eq. (32) gives

$$\frac{d(\ln K_p)}{d(1/T)} = \frac{-\Delta H^\circ}{R} \tag{33}$$

Equation (33) shows that if the logarithm of K_p is plotted against the reciprocal of absolute temperature, the slope is equal to $-\Delta H^\circ/R$. The $K_p - T$ relationships shown in Fig. 5 show almost straight lines for most reactions. This suggests that ΔH° is often approximately constant over relatively long temperature ranges.

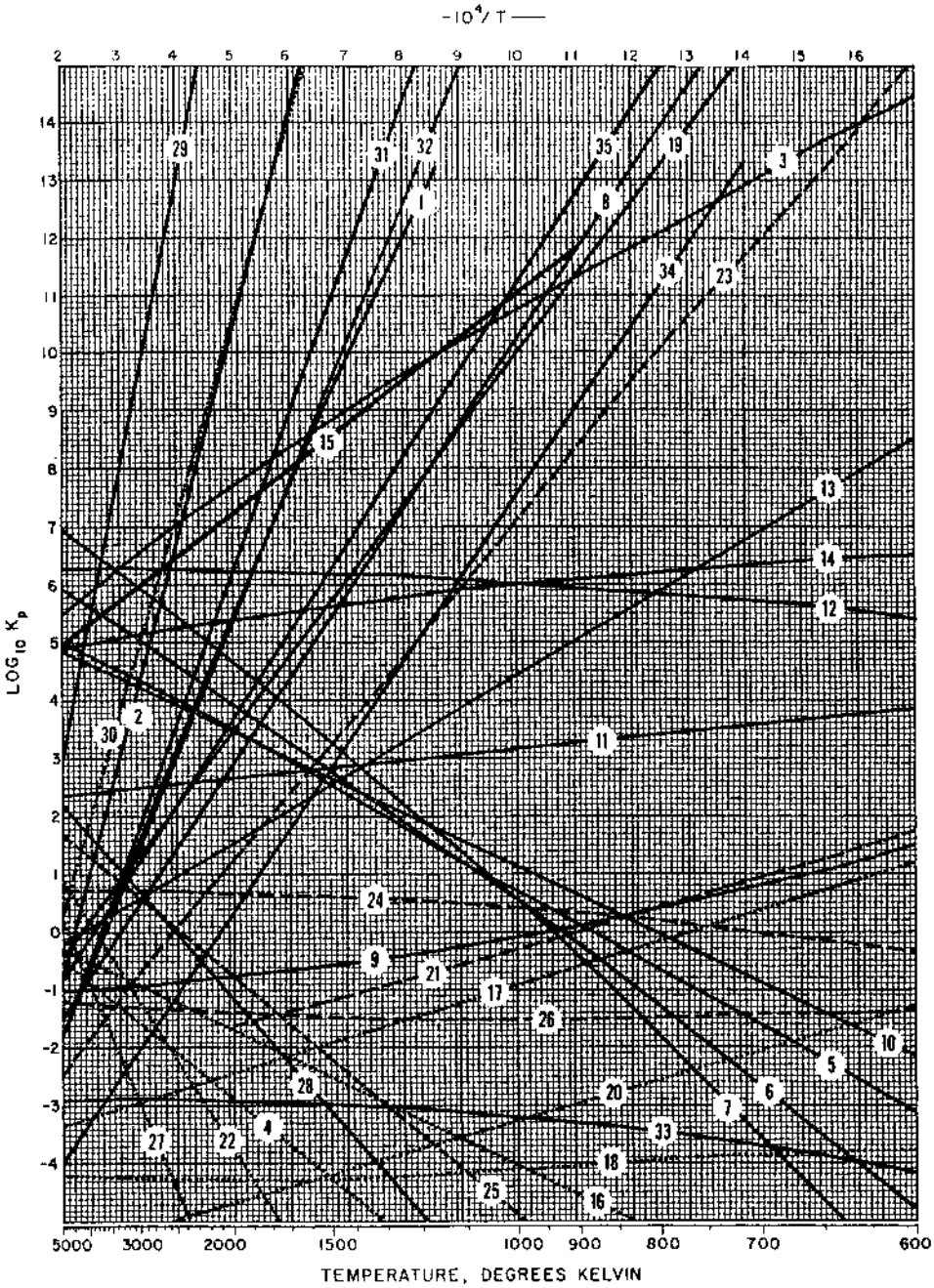


Figure 5 Equilibrium constants for reactions common in combustion systems.

A. Carbon reactions

1. $\frac{1}{2}C_2(g) \rightarrow C(s)$
2. $C(g) \rightarrow C(s)$
3. $C + \frac{1}{2}O_2 \rightarrow CO$
4. $C + \frac{1}{2}N_2 \rightarrow C_2N_2$
5. $C + H_2O \rightarrow CO_2 + 2H_2$
6. $C + H_2O \rightarrow CO + H_2$
7. $C + CO_2 \rightarrow 2CO$
8. $CO + \frac{1}{2}O_2 \rightarrow CO_2$
9. $CO + H_2O \rightarrow CO_2 + H_2$
10. $CH_4 \rightarrow C + 2H_2$
11. $\frac{1}{2}C_2H_4 \rightarrow C + H_2$
12. $HCHO \rightarrow CO + H_2$
13. $\frac{1}{2}C_2H_2 \rightarrow C + \frac{1}{2}H_2$
14. $\frac{1}{3}C_3O_2 + \frac{1}{3}H_2O \rightarrow CO + \frac{1}{3}H_2$

B. Nitrogen and oxygen reactions

15. $O_3 \rightarrow \frac{3}{2}O_2$
16. $\frac{1}{2}N_2 + \frac{1}{2}O_2 \rightarrow NO$
17. $NO + \frac{1}{2}O_2 \rightarrow NO_2$
18. $NO + \frac{1}{2}N_2 \rightarrow N_2O$
19. $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$
20. $\frac{1}{2}N_2 + \frac{3}{2}H_2 \rightarrow NH_3$

C. Sulphur reactions

21. $\frac{1}{2}S_2(g) \rightarrow S(l)$
22. $SO_2 \rightarrow SO + \frac{1}{2}O_2$
23. $SO_2 + 3H_2 \rightarrow H_2S + 2H_2O$
24. $\frac{1}{3}SO_2 + 2.3H_2S \rightarrow 1.2S_2(g) + 2.3H_2O$
25. $H_2S \rightarrow HS + \frac{1}{2}H_2$
26. $CO + H_2S \rightarrow COS + H_2$

D. Radical reactions

27. $C + \frac{1}{2}N_2 \rightarrow CN$
28. $CH_4 \rightarrow CH_3 + \frac{1}{2}H_2$
29. $2N \rightarrow N_2$
30. $N + O \rightarrow NO$
31. $2O \rightarrow O_2$
32. $2H \rightarrow H_2$
33. $\frac{1}{2}H_2 + O_2 \rightarrow HO_2$
34. $OH + O \rightarrow HO_2$
35. $OH + \frac{1}{2}H_2 \rightarrow H_2O$

Figure 5 (*continued*).

Kirchhoff's equation, developed in consideration of the first law of thermodynamics shows the dependency of reaction heats on temperature:

$$\left[\frac{\partial[\Delta H]}{\partial T}\right]_p = C_{p-\text{products}} - C_{p-\text{reactants}} = \Delta C_p \tag{34}$$

In many cases, heat capacities can be expressed (as in Table 2) as a power series:

$$C_p = a + bT + cT^2 + \ldots \tag{35}$$

Here (or, without difficulty, for other heat capacity temperature dependency functions), Eq. (34) can be integrated:

$$d(\Delta H^\circ) = \Delta C_p \, dT = (A + BT + CT^2 + \ldots)dT \tag{36a}$$

$$\Delta H^\circ = \Delta H_0^\circ + AT + \left(\tfrac{1}{2}\right)BT^2 + \left(\tfrac{1}{3}\right)CT^3 + \ldots \tag{36b}$$

Note that, for a typical reaction, the coefficients of the heat capacities differ. For example, for the reaction

$$\left(\tfrac{1}{2}\right)N_2 + \left(\tfrac{3}{2}\right)H_2 \rightleftharpoons NH_3$$

$$\Delta C_p = C_{p-NH_3} - \left(\tfrac{1}{2}\right)C_{p-N_2} - \left(\tfrac{3}{2}\right)C_{p-H_2}$$

In this instance, ΔH_0° is the constant of integration and can be evaluated from any known value of ΔH°.

An important relationship can be established by integrating Eq. (32) from a temperature where values of K_p and ΔH° are available in the literature to an arbitrary second temperature. Analytical relationships describing the heat capacities of the reactants and products as functions of temperature are useful to readily accomplish this. The reference point for these calculations is usually 298°K, where many handbooks (e.g., Ref. 4) provide data on the free energy of formation of reactants and products (allowing, with Eq. (30), calculation of K_{p298}) and heat of formation (H_{298}°). Note that if the temperature range from 298°K to the temperature of interest includes phase changes with heat effects, the enthalpy change between the limits must be incremented accordingly. For power series heat capacity functions (e.g., as shown in Table 2) then, Eq. (32) integrates to

$$\ln K_p = -\Delta H_0^\circ / RT + A \ln T + BT + CT^2 \ldots + I \tag{37}$$

The value of the integration constant I can be determined if K_p is known at any one temperature, either experimentally or by calculation from free energy data. One value of ΔH° is needed to calculate the integration constant of the Kirchhoff equation (ΔH_0°).

EXAMPLE 11. Using the methodology and equations given above, develop the general relationship for K_p as a function of temperature and calculate the K_p at a temperature of 1000°C for the water–gas reaction:

$$CO + H_2O_{(g)} \rightarrow H_2 + CO_2$$

For the water–gas reaction, the equilibrium constant is given by

$$K_p = \frac{[p_{H_2}][p_{CO_2}]}{[p_{CO}][p_{H_2O}]} \tag{38}$$

From published thermochemical data sources (4), the following are found (in cal/gram molecular weight):

Component	ΔH_{298}°	ΔF_{298}°
CO	−26,416	−32,808
$H_2O_{(g)}$	−57,798	−54,635
H_2	0	0
CO_2	−94,052	−94,260

Then from the overall reaction at 25°C, the standard free-energy change and, thus, the K_{p298} is given by

$$\Delta F^{\circ}_{298} = -94{,}260 + 0 - (-54{,}635 - 32{,}808) = -6817$$
$$\ln K_{p298} = (6810)/(298R) = 11.50 \qquad \text{and} \qquad K_{p298} = 9.90 \times 10^4$$

and, from the change in the standard enthalpies of formation,

$$\Delta H^{\circ}_{298} = -94{,}052 + 0 - (-57{,}798 - 26{,}416) = -9838$$

From the heat capacity constants in Table 2, the ΔC_p function is

$$\Delta C_p = C_{p-\mathrm{CO_2}} + C_{p-\mathrm{H_2}} - C_{p\mathrm{CO}} - C_{p\mathrm{H_2O}}$$
$$= 1.37 + 2.4 \times 10^{-3} T - 1.394 \times 10^{-6} T^2$$

From Eq. (35b),

$$\Delta H^{\circ} = \Delta H^{\circ}_0 + 1.37T + 1.2 \times 10^{-3} T^2 - 4.647 \times 10^{-7} T^3$$

Substituting $\Delta H^{\circ} = -9838$ at $T = 298$°C and solving for ΔH°_0, $\Delta H^{\circ}_0 = -10{,}321.2$. Then, the temperature relationship for the equilibrium constant [Eq. (36)] is

$$\ln K_p = \frac{10{,}321.2}{RT} + \frac{1.37}{R} \ln T + \frac{1.4 \times 10^{-3}}{R} T - \frac{4.647 \times 10^{-7}}{2R} T^2 + I$$

Using the value of $\ln K_{p298}$ from above, the integration constant I can be evaluated as

$$I = -9.9817$$

from which the final expression for $\ln K_p$ is

$$\ln K_p = -9.9817 + \frac{5223}{T} + 0.692 \ln T + 7.07 \times 10^{-4} T - 1.173 \times 10^{-7} T^2$$

For the required K_p at 1000°C (1273.15 K), $\ln K_p$ is -0.5877 and $K_p = 0.556$.

Figure 5 shows the temperature dependence of several reactions of interest in combustion analysis. K_p is based on partial pressures in atmospheres. Water is as the vapor. Carbon (solid) is beta-graphite. For combustion calculations, several reactions merit consideration in evaluating heat and material flows, especially the gas phase reactions of H_2, H_2O, CO, CO_2, O_2, with H_2O, CO_2, and O_2. Note that for reactions involving solids, the activity of the solid compounds is assumed to be unity. Thus, the "concentration" or "partial pressure" of carbon or other solids does not enter into the mathematical formulation.

The partial pressure of the gases in a mixture at atmospheric pressure can be conveniently equated with the mol fraction (mols of component divided by the total number of mols in the mixture). This equivalence (Dalton's law) and its use in the equilibrium constant formulation is strictly true only for ideal gases. Fortunately, at the temperatures and pressures typical of most combustion calculations, this is a valid assumption.

The importance of the reactions described in Fig. 5 relates to both combustion energetics and pollution control. For example, equilibrium considerations under conditions near to stoichiometric may show that substantial nitric oxide and carbon monoxide may be generated. Also, the interactions of H_2O, CO, CO_2, C, and O_2 are important in under-

standing the combustion behavior of char and in arriving at estimates of the unreleased heat of combustion of CO.

Appendix F and the associated diskette include the spreadsheet EQUILIBRIUM.XLS from which the equilibrium constant can be estimated from data on heats of formation, free energies of formation, and heat capacity relationships (e.g., Table 2).

EXAMPLE 12. For the combustion chamber conditions of Example 10, what is the emission rate of thermal NO due to the reaction $\frac{1}{2}N_2 + \frac{1}{2}O_2 = NO$? If this result indicates NO emissions are excessive, one approach to control would involve recycling stack gas at 180°C to dilute and cool the combustion chamber off-gas to 1000°C. What is the flow rate of the recycle stream and the resulting NO emission rate?

The thermal NO emission rate for a real combustor will fall somewhere between the equilibrium value calculated at combustion chamber effluent temperatures and that for stack temperatures. NO is not formed in the high-temperature zones quite to the theoretical equilibrium level due to local temperature or concentration variations and to reaction rate limitations. The NO concentration also does not follow the theoretical equilibrium curve as the gas temperature falls (in traversing the boiler) due to reaction rate limitations. The calculations below, therefore, illustrate the "worst case" scenario: equilibrium NO formation at peak furnace temperature and "frozen equilibrium" through the boiler.

From Example 10, the concentrations of N_2, O_2, and NO are:

Component	Mols	Mol percent (partial pressure)
NO	x	$x/41.32$
N_2	$30.639 - 0.5x$	$(30.639 - 0.5x)/41.32$
O_2	$0.740 - 0.5x$	$(0.740 - 0.5x)/41.32$
Total (CO_2, H_2O, O_2, N_2)[a]	41.32	

[a]Note that for this reaction, the total number of mols of gas does not change.

From Fig. 5, (Reaction Number 16), at 2065°C (2338 K), $\ln(K_p) = -1.33$ and $K_p = 0.0468$, where

$$K_p = \frac{p_{NO}}{p_{O_2}^{1/2} p_{N_2}^{1/2}} \tag{39}$$

and p_{O_2}, p_{N_2}, and p_{NO}, are the partial pressures of O_2, N_2, and NO, respectively, each expressed in atmospheres. At equilibrium, then,

$$(0.740 - 0.5x)^{1/2}(30.639 - 0.5x)^{1/2} = \frac{x}{(0.0468)(41.32)}$$

Solving this equation gives $x = 1.443$ mol of NO at equilibrium. This is equivalent to 3.490 mol percent or 34,900 parts per million (ppm) NO by volume. The heat of formation of NO is −21,600 kcal/mol of NO formed. Thus, this reaction will absorb 31,169 kcal or 3.37% of the heat of combustion calculated per basis weight in Example 10.

After review of state and local regulations, it is judged that NO emissions (regulated as "NO_X" and calculated as NO_2 since some oxidation to NO_2 will occur) could become excessive and the recycle option should be considered. Since we are trying to reduce furnace temperature, we will also save the investment and operating cost of the air preheater and use ambient (15.5°C) air.

Basis. 100 kg of waste

For ease in computation, assume the two-step system in Fig. 6. The heat input is 772,713 kcal. With 5% heat loss, and since no energy will enter the system as preheated combustion air, 734,077 kcal will be found in the combustion gas. From Fig. 4, the temperature will be 1895°C. This is also the primary furnace leaving gas temperature for Example 10 with no air preheat.

Drawing a balance around the mixing chamber, let n = number of mols of recycled gas. The heat content of the *net* products of combustion at 1000°C is found from Fig. 4 to be 380,793 kcal. Since the recycle gas has the same chemical composition as the products of combustion, the sensible heat content of the recycle gas at 1000°C is in the same ratio to the sensible heat content of the products of combustion at 1000°C as the number of mols of recycle is to the number of mols of net combustion products. At 1000°C, then, the heat content of the recycle gas is $(380{,}793)(n/41.32) = 9216n$. Since the slag heat does not appear in the recycle gas, however, a more accurate value can be taken from Table 10:

$$(380{,}793 - 2622)(n/41.32) = 9152n$$

To satisfy an energy balance around the combustion chamber, the energy in the fuel plus that in the air (zero in this case) plus that in the recycle at 180°C (see Table 10) must equal that of the mixed gas stream at 1000°C.

$$734{,}077 + 0 + 2226n = 380{,}793 + 9152n$$

$$n = 51 \text{ mol}$$

For the actual case, at 11 times the flow used as the calculation basis for Example 12, 561.1 mol/hr would be recycled.

Under the new and lower exhaust temperature, the NO generation rate may be recalculated. Noting that the recycle gas is of the same composition as the original furnace gas, the new equilibrium calculation differs from that given above only in that K_p is that for 1000°C; $\log K_p = -3.05$ at 1000°C, $K_p = 0.0009$. Solving as above, only 0.1666 mol of NO are now formed at equilibrium, or 0.403 mol %, or 403 ppm.

VI. COMBUSTION KINETICS

Combustion involves chemical reactions. Indeed, key steps in the combustion process proceed at finite rates that are dependent upon local temperature, the concentrations of the reacting species, and, in some cases, the static pressure. Combustion kinetics describe the relationships between the combustion reaction rate and basic system and environmental parameters.

Incineration applications of the combustion process pursue the ideal of 100% reaction completeness: total destruction of the feed material. An argument could be made that this goal is the same for all combustion-based processes (what utility boiler engineer wants unburned combustible in the off-gas or ash?). For incineration applications, however, the *primary purpose of the system is destruction of the feed*, not the release of energy as a means to other ends (such as the generation of electricity). For hazardous waste incineration systems, the focus on completeness of destruction is intense. This difference in the "rules" leads to a distinctive set of design objectives and evaluation tools when compared to those appropriate for nonincineration applications.

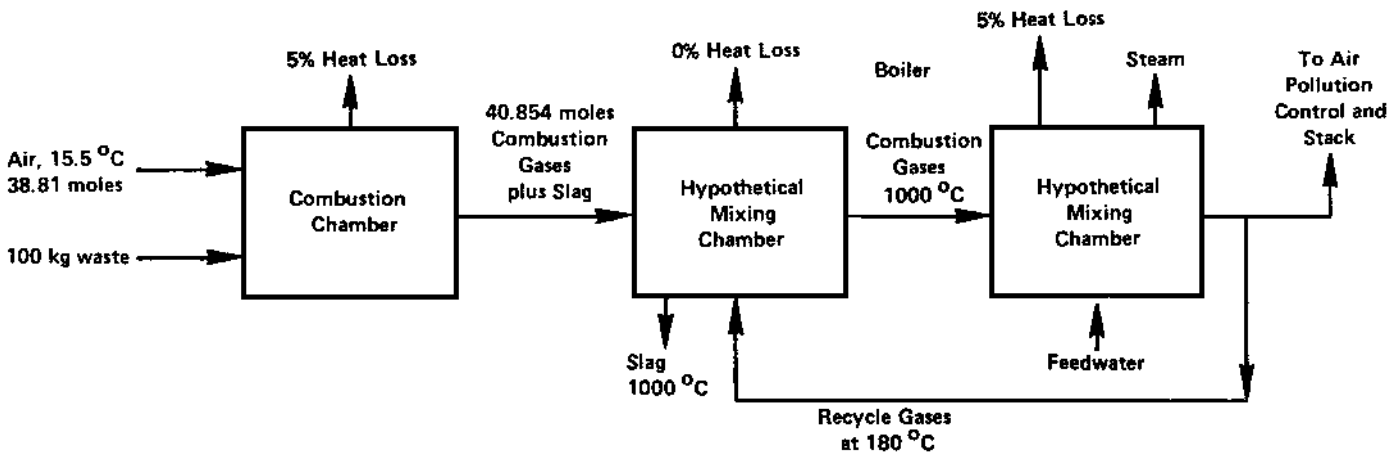


Figure 6 Process flow diagram for Example 12.

It is useful for the incinerator designer to have a basic understanding of the principles involved in combustion reaction kinetics. At a minimum, one should understand the concepts of an ignition temperature, the situations that lead to "quenching" of combustion reactions, and the significance of oxygen depletion on burnout. Also, there is merit to understanding specific kinetics relationships for common products of incomplete combustion (carbon monoxide and soot) and the oxidation and pyrolytic kinetics for a spectrum of important organic compounds.

A. Introduction to Kinetics

1. Overall Kinetics

For the generalized, gas phase chemical reaction

$$bB + cC \leftrightarrow dD + eE$$

the rate of the forward reaction (to the right) can often be described by equations of the form

$$r = k[B]^b[C]^c \tag{40}$$

where the value in the brackets (for ideal gases) is the partial pressure of the component. Similarly, for the back reaction rate (to the left)

$$r' = k'[D]^d[E]^e \tag{41}$$

At equilibrium, by definition, the forward reaction and the backward reactions proceed at the same rate:

$$r = r'$$

and

$$k[B]^b[C]^c = k'[D]^d[E]^e \tag{42}$$

$$\frac{k}{k'} = \left(\frac{[D]^d[E]^e}{[B]^b[C]^c}\right)_{\text{equilibrium}}$$
$$= K_p \text{ (the equilibrium constant)} \tag{43}$$

Van't Hoff, from thermodynamic reasoning, examined the variation of the equilibrium constant K_p with temperature T and concluded that

$$\frac{d(\ln K_p)}{dT} = \frac{\Delta H^\circ}{RT^2} \tag{44}$$

where ΔH° is the heat of reaction (kcal/mol) and R is the gas constant. Combining the two previous expressions,

$$\frac{d(\ln k_p)}{dT} - \frac{d(\ln k_p')}{dT} = \frac{\Delta H^\circ}{RT^2} \tag{45}$$

The right side of this equation can be divided into two parts, provided the overall heat of reaction is broken into an energy change for each direction:

$$\Delta H^\circ = E - E' \tag{46}$$

or

$$\frac{d(\ln k)}{dT} - \frac{d(\ln k')}{dT} = \frac{E}{RT^2} - \frac{E'}{RT^2} \tag{47}$$

The two separate expressions, one for the forward and one for the backward reaction, having a difference in agreement with the just-stated equilibrium requirement are

$$\frac{d(\ln k)}{dT} = \frac{E}{RT^2} \tag{48a}$$

$$\frac{d(\ln k')}{dT} = \frac{E}{RT^2} \tag{48b}$$

Integration yields the Arrhenius equation, Eq. (49):

$$k = Ae^{-\Delta E/RT} \tag{49}$$

The quantity ΔE was interpreted by Arrhenius as an excess over the average energy that the reactants must possess to allow the reaction to occur. He termed this the *activation energy* (actually an enthalpy) and related its significance to the critical energy required to form an activated complex or transition state between reactants and products. The exponential term is usually interpreted as the fraction of molecules that manages to obtain the necessary energy. One might picture such an intermediate as the stressed, energy-rich assembly of two colliding molecules just before the bonding electrons had shifted to form the product. The only constraint on E and E' is that their difference should be equal to the net heat of reaction. Their individual magnitudes depend on the particular structures of the molecules involved.

The term A (the "pre-exponential factor") should be interpreted as a combination of molecular collision frequency parameters, steric (orientation) factors, and other influences on reaction rate. Thus, although A appears in Eq. (49) as a constant, the value of A includes the mass and effective cross-sectional area of the specific molecules involved and, from collision theory, has a dependency on the square root of absolute temperature. The temperature sensitivity of the exponential term, however, is so powerful that, usually, A is treated as a constant.

The energy changes as a reaction proceeds are illustrated in Fig. 7 for both exothermic (heat-releasing) or endothermic (heat-absorbing) reactions.

The significant trends one can draw from an examination of the Arrhenius expression are that

Rate always increases as temperature increases.

For large ΔE (more typical of exothermic combustion reactions), the increase in rate can be very dramatic over a relatively narrow temperature range. This gives rise to the useful concept of an "ignition temperature."

The Arrhenius concept, developed in 1889 (10), has been used successfully to correlate a wide variety of kinetic data (i.e., by plotting $\ln(k)$ vs. $1/T$ to give a straight line with a slope of $-\Delta E/R$). Indeed, most failures to follow such a form have been successfully traced to previously unknown side reactions or catalytic effects.

Since the activation energy ΔE is associated with the energy required to form an activated intermediate, it is not unexpected that the value of ΔE changes if means are provided to change the amount of energy required. Specifically, the function of a catalyst is

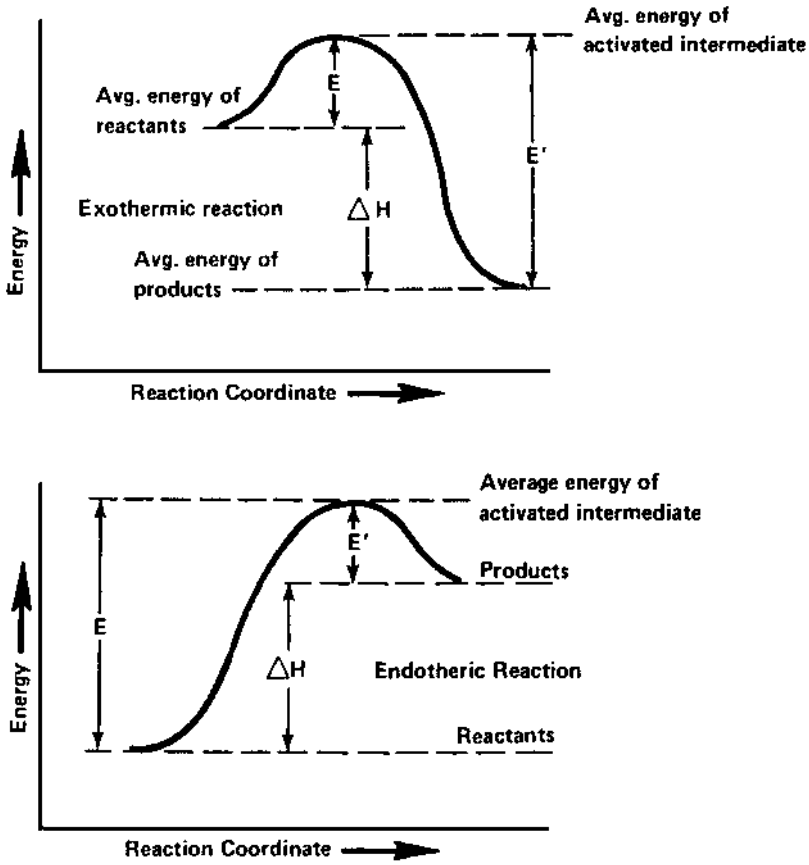


Figure 7 Energy diagram for exothermic and endothermic reactions.

to reduce the activation energy for a given reaction. This facilitates and increases the rate of the reaction at lower temperatures.

Since reaction rate is proportional to the concentrations of the reacting substances, it is reasonable to divide the study of kinetics into classes determined either by *molecularity* (the number of atoms or molecules taking part in each act leading to chemical reaction) or the *order of the reaction* (the number of atoms or molecules whose concentrations determine the rate of the process).

In a first order reaction, the rate is directly proportional to the concentration of the reacting substance, or

$$-\frac{dc}{dt} = kc \tag{51}$$

where c is the concentration of the reacting substance. For a system with an initial concentration c_0 and a concentration at time t of c_t, one has

$$x_t = c_0 e^{-kt} \tag{52}$$

Many reactions of importance in combustion studies follow the first order mathematics of Eq. (52). This includes many pyrolysis-type decomposition reactions. An important

consequence of first-order reactions is that the time taken to complete a definite fraction of the reaction is independent of the starting concentration. For example, the time required to achieve 50% destruction (the "half-life") t_{50} or the time to achieve 99% destruction (t_{99}) are

$$t_{50} = \frac{\ln 2}{k} \tag{53}$$

$$t_{99} = \frac{\ln 100}{k} \tag{54}$$

If the rate of reaction depends on two concentrations, the process is said to be of the second order. For the generalized reaction:

$$A + B \rightarrow \text{products}$$

and for the reaction at some time when the concentrations of A and B are c_A and c_B, the rate is given by

$$-\frac{dc_A}{dt} = k \cdot c_A^a c_B^b \tag{55}$$

where the powers a and b show the *degree* of the reaction. This mathematical formulation is often useful to describe combustion processes where A is, say, the fuel or feed and B is oxygen. In many cases, the process runs very fuel lean such that the oxygen concentration is almost unchanged across the flame front. For simplicity, one can describe such a case as pseudo-first order and lump the numerical value of the oxygen concentration into the k term.

2. Mechanism

The formulation of reaction rate expressions from the simple stoichiometric relationships drawn from the equation for the reaction may be in error. In such cases, the error may often be eliminated when the full sequence of reactions leading from reactants to products is more fully understood. Exploring the true route of a reaction is the study of *mechanism*. Such studies, particularly in combustion systems, often show the vital role of highly activated species, fragments of molecules, called *free radicals*. Free radicals, existing individually for only fractions of a second, are nonetheless important intermediates in the initiation and propagation of combustion reactions.

As an example of the complexity of reaction mechanisms, consider the well-studied gas phase reaction of hydrogen and bromine. The stoichiometric reaction is

$$H_2 + Br_2 \rightarrow 2\ HBr$$

Experimental data show that the rate of formation of HBr is given by

$$\frac{dC_{HBr}}{dt} = \frac{kC_{H_2}C_{Br_2}^{1/2}}{1 + k'(C_{HBr}/C_{Br_2})} \tag{56}$$

where C_x indicates the concentration of species x. This expression can be explained by *assuming* that the reaction proceeds by the following series of steps (note that observation

of the steps is impossible, and thus these steps are inferred based on their success in explaining the rate data):

Step 1 $\frac{1}{2}Br_2 \rightarrow Br\cdot$
Step 2 $H_2 + Br\cdot \rightarrow HBr + H\cdot$
Step 3 $H\cdot + Br_2 \rightarrow HBr + Br\cdot$
Step 4 $H\cdot + HBr \rightarrow H_2 + Br\cdot$
Step 5 $2Br\cdot \rightarrow Br_2$

Step 1 is the *initiating* step, generating the reactive bromine free radical (Br·). Steps 2 and 3, occurring repeatedly in a *chain reaction*, are propagating steps, producing product and reseeding the reaction mass with radicals. Since the concentration of H· in Step 3 is very small, the 0.5 power dependency on bromine concentration and the unity power on hydrogen concentration in the numerator of the overall rate equations appear reasonable.

Steps 4 and 5 are reactions that reverse or *terminate* the desired reaction processes, respectively. As HBr concentration builds, Step 4 becomes important, as indicated by the term in the denominator. If higher initial bromine concentrations are used, the importance of Step 5 is depressed, resulting in the compensatory bromine concentration term in the denominator.

An interesting example of the importance of free radical reactions in combustion processes is given by the differing behavior of heptane (C_7H_{16}) and octane (C_8H_{18}) in automobile engines. Heptane, as used as a standard test fuel, is a seven-carbon, straight-chain hydrocarbon. After losing a hydrogen atom (here, to become the *n*-heptyl radical) straight-chain hydrocarbons are relatively active radicals and readily enter into secondary combustion reactions. Thus, the combustion wave expands rapidly throughout the cylinders: so rapidly that a serious "knock" is experienced. *n*-Heptane carries an octane number (indicating the relative knock potential) of zero.

Octane, as used as a standard test fuel, is a highly branched molecule, more descriptively named 2,2,4-trimethylpentane. Free radicals arising in branched-chain structures (and also from the aromatic ring compounds and oxygenated compounds also found in unleaded but high-octane gasolines) are "stabilized"; they lose a measure of their reactivity, thus slowing combustion reaction rates, and reducing knock. 2,2,4-Trimethyl-pentane carries an octane number of 100.

Tetraethyl lead acts as a reaction inhibitor, reducing the radical concentration at the price of (1) increased pollution from lead emissions and (2) reduced activity (poisoning) of some catalytic converter catalysts.

Inhibition or radical stabilizing behavior is also shown by chlorine-containing organic compounds. This contributes to the problem of obtaining rapid combustion of halogenated compounds in combustion systems optimized for hydrocarbons that are not halogenated.

Seldom does the analyst of waste incineration systems have the opportunity or the need to study the kinetic relationships that are operative in his or her process. However, having a basic understanding of the fundamental processes involved can be useful in interpreting the underlying causes of combustion problems even if the system under study is too complex to allow a priori and quantitative evaluation of reaction rates.

B. Kinetics of Carbon Monoxide Oxidation

Carbon monoxide is an important air pollutant, is a poisonous gas in high concentrations, and can be the unwanted repository of considerable combustion energy in inefficient combustors. In many instances where hydrocarbons are burned, the oxidation reactions proceed rapidly to the point where CO is formed and then slow greatly until CO burnout is achieved. Indeed, the kinetics of methane oxidation almost duplicate the CO kinetic expressions.

CO is produced by the incomplete combustion of pyrolysis products of solid or liquid wastes, from the char in a refuse bed, or as an intermediate combustion product. The oxidation kinetics to carbon dioxide have been studied by several investigators and, although there are differences in the rate constant reported, a reasonable estimate can be made of the times required to complete the combustion. The rate expression by Hottel et al. (11) will be used to calculate the kinetics of oxidation in a combustion chamber for the condition where the CO and oxygen (air) are intimately mixed. The kinetic expression for the rate of change of CO mol fraction (f_{CO}) with time is given by

$$\frac{-df_{CO}}{dt} = 12 \times 10^{10} \exp\left(\frac{-16{,}000}{RT}\right) f_{O_2}^{0.3} f_{CO} f_{H_2O}^{0.5} \left(\frac{P}{R'T}\right)^{1.8} \tag{57}$$

where f_{CO}, f_{O_2}, and f_{H_2O} are the mol fractions of CO, O_2, and water vapor, respectively, T is the absolute temperature (K), P is the absolute pressure (atm), t is the time in seconds, R is the gas constant (1.986 kcal/kg mol K), and R' is also the gas constant, but in alternate units (82.06 atm cm^3/g mol K).

In reviewing the reaction rate expression, it is instructive to note the dependence upon the mol fraction of water vapor. This results from the participation of hydrogen and hydroxyl (OH) free radicals in the reaction.

To the extent that the combustion chamber may be considered as an isothermal reactor, the decline in CO concentration over an interval t (seconds) from an initial mol fraction $f_{CO})_i$ to a final mol fraction $(f_{CO})_f$ is given by

$$\frac{(f_{CO})_f}{(f_{CO})_i} = \exp(-Kt) \tag{58a}$$

where

$$K = 12 \times 10^{10} \exp\left(\frac{-16{,}000}{RT}\right) f_{O_2}^{0.3} f_{H_2O}^{0.5} \left(\frac{P}{R'T}\right)^{0.8} \tag{58b}$$

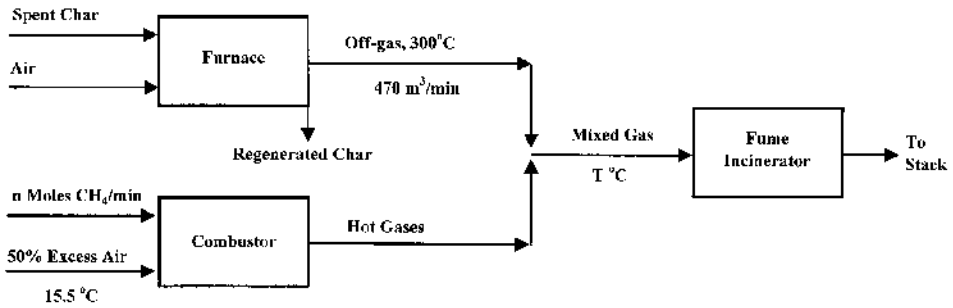
Other workers have concluded that Eq. 58 gives unrealistically high rates at low temperatures (e.g., in afterburners operating below 1000°C). A more conservative result is given by Morgan (11a):

$$\frac{-df_{CO}}{dt} = 1.8 \times 10^{13} f_{CO} f_{O_2}^{0.5} f_{H_2O}^{0.5} \left(\frac{P}{R'T}\right)^{2.0} \exp\left(\frac{-25{,}000}{RT}\right) \tag{59}$$

EXAMPLE 13. $470\,m^3/min$ of a waste gas stream from a carbon char reactivation furnace is produced at 300°C. Its composition is as follows:

Component	Mole percent
N_2	78.17
CO_2	18.71
CO	2.08
O_2	1.04
Total	100.00

The waste gas will be mixed with the flue gas from an atmospheric natural gas (methane) combustor operating at 50% excess air in a "fume incinerator" or afterburner. If CO combustion is assumed not to begin until the two gas streams are intimately mixed, plot the required residence time to reduce the CO concentration to 10 ppm (neglecting dilution effects) against the mixed-gas temperature. Note that residence time is directly related to the incinerator volume (capital cost) and mixed-gas temperature to methane consumption rate (operating cost). For ease in computation, assume the heat capacity of the two gas streams are constant, identical, and equal to about 8 kcal/kg mol °C. Neglect heat release from CO combustion. The datum for sensible heat content is 15.5°C. The system diagram is shown below:



For 1 mol of CH_4, at 50% excess air, the hot combustor gas produced has the composition:

Component	Mole percent
N_2	11.29
CO_2	1.00
CO	1.00
O_2	2.00
Total	15.29

The molal flow rate of gases from the furnace is

$$470\left(\frac{273}{300+273}\right)\left(\frac{1}{22.4}\right) = 10 \text{ mol/min}$$

Basis. 1 min of operation with a methane firing rate of n mols per minute.

MIXED-GAS TEMPERATURE

1. Total heat content
   a. Sensible heat in furnace gas $= 10\, Mc_p(300 - 15.5) = 22,760$ kcal
   b. Heat of combustion of methane (lower heating value from Table 8) $= (191{,}910)n$ kcal
2. Mixed-gas temperature (T°C)

$$T = \frac{\text{Total heat content}}{(Mc_{\text{p}})(\text{no.mols})} + 15.5 = \frac{22{,}760 + 191{,}910n}{8(10 + 15.29n)} + 15.5$$

MIXED-GAS COMPOSITION

	Moles		
Component	From furnace	From methane	Total
N_2	7.82	$11.29n$	$7.82+11.29n$
CO_2	1.87	n	$1.97+n$
O_2	0.10	n	$0.1+n$
H_2O	0.21	0	0.21
Total	10.0	$15.29n$	$10+15.29n$

REACTION TIME AND METHANE USAGE. From the relationships developed above, the reaction rate parameter K and the required residence time t can be calculated as a function of n, the methane consumption rate. Then, for a given value of n and the associated total mol flow rate and absolute temperature (T'), the volume flow rate of the mixed gas $\dot{V}$ can be calculated:

$$\dot{V} = (\text{mol/min})\ \frac{22.4}{60}\frac{T'}{273}\text{m}^3/\text{sec}$$

The chamber volume V is then given by

$$V = \dot{V}t\ \text{m}^3$$

The calculations are shown in Table 11. The results are plotted in Fig. 8.

Several points become clear upon review of Table 11 and Fig. 8: the strong influence of temperature, typical of kinetically controlled reactions. At about 650°C, the combustion rate of CO increases sharply. This could be considered an "ignition temperature" for the low oxygen concentration mixture existing in the afterburner. At normal atmospheric

Table 11 Calculations for Example 13.

n (Moles CH_4/min)	0.2	0.4	0.6	0.8	1.0
Total moles	13.06	16.12	19.17	22.23	25.29
Temperature (°C)	600	787	899	991	1076
T' (K)	874	1060	1172	1264	1350
f_{O_2}	0.023	0.031	0.037	0.040	0.043
f_{H_2O}	0.031	0.050	0.063	0.072	0.079
K (sec^{-1})	88	529	1187	2038	3095
t (sec)	0.087	0.014	0.006	0.004	0.002
$\dot{V}$ (m^3/sec)	15.6	23.4	30.7	38.4	46.7
V (m^3)	1.360[a]	0.337	0.198	0.144	0.115

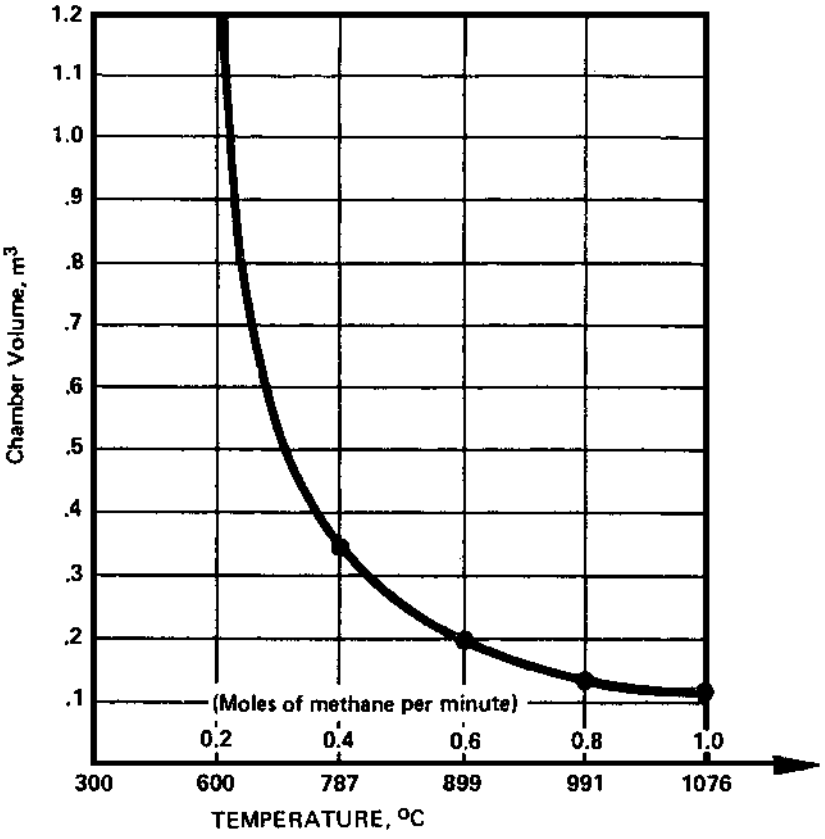


Figure 8 Capital versus operating costs trade-off anlaysis for CO afterburner (Example 13).

oxygen concentrations, the CO ignition temperature (12) is approximately 600°C (note that for $f_{O_2} = 0.2$, the chamber volume is only about 0.7 m^3 at 600°C and a $V - n$ curve such as shown in Fig. 8 would just be breaking sharply upward).

C. Kinetics of Soot Oxidation

In burning carbon-bearing wastes, conditions of high temperature and low oxygen concentration can lead to the formation of soot. The mechanisms responsible for soot formation include preferential oxidation of the hydrogen and thermally induced dehydrogenation. Whatever the cause, soot formation is a problem to the incineration system:

1. Dark, high-optical density flue gas emissions that, even when less than the applicable mass emission limits, may violate opacity restrictions.
2. The presence of carbon is a sign of poor combustion conditions and, often, is accompanied by high carbon monoxide emissions that may signal incomplete burnout of waste and/or the generation of undesirable products of incomplete combustion (PICs) such as polynuclear aromatic hydrocarbons (PNHs), dioxin compounds, and so forth.
3. Metal surfaces (e.g., the fireside of boiler tubes) exposed to gases that swing from oxidizing to reducing conditions (the region where soot is formed is often reducing) can experience high wastage rates.
4. If an electrostatic precipitator is used for air pollution control, the presence of carbon lowers the resistivity of the dust and usually lowers the collection efficiency. In fabric filter control devices, glowing, slow-burning char will significantly decrease bag life.
5. If it is necessary to burn out soot (once it is formed), the slow burnout rate of soot makes these subsequent control efforts difficult (high temperatures and long residence time may be required).
6. High concentrations of soot in the collected dust can create a fire and explosion problem.

The control of soot burnout can best be understood by examining the kinetics of combustion of carbonaceous particles. For spherical particles, review of the considerable research on this topic (13) suggests the following:

$$q = \frac{p_{O_2}}{\frac{1}{K_s} + \frac{1}{K_d}} \tag{60}$$

where

q = rate of carbon consumption (g/cm^2 sec^{-1})
p_{O_2} = partial pressure of oxygen (atm)
K_s = *kinetic* rate constant for the consumption reaction
K_d = *diffusional* rate constant

Both kinetic and diffusional resistance to reaction are thus seen to influence burnout rate.

For (small) particles of diameter d (centimeters) typical of soot, the diffusional rate constant at temperature T (K) is approximately given by

$$K_d = \frac{4.35 \times 10^{-6} T^{0.75}}{d} \tag{61}$$

The kinetic rate constant is given by

$$K_s = 0.13 \exp\left[\left(\frac{-35{,}700}{R}\right)\left(\frac{1}{T} - \frac{1}{1600}\right)\right] \tag{62}$$

where R is the gas constant (1.986 cal/g mol K).

For a particle of initial diameter d_0 and an assumed specific gravity of 2, the time (t_b) in seconds to completely burn out the soot particle is given by

$$t_b = \frac{1}{p_{O_2}}\left[\frac{d_0}{0.13 \exp\left[\left(\frac{-35{,}700}{R}\right)\left(\frac{1}{T} - \frac{1}{1600}\right)\right]} + \frac{d_0^2}{5.04 \times 10^{-6} T^{0.75}}\right] \tag{63}$$

EXAMPLE 14. The combustion of benzene and other unsaturated ring compounds is known to often result in the formation of soot. If soot is formed at 1400°C in Example 8, what are the burnout times for 2, 20, and 200 μm (1 μm = 10^{-4} cm) soot particles?

From Examples 8 and 10, at 1400°C, the equilibrium constant is 0.00617 and the oxygen partial pressure, corrected for NO formation, is

$$\begin{aligned} p_{O_2} &= [0.740 - 0.5(0.8105)]/41.34 \\ &= 0.0081 \text{ atm} \end{aligned}$$

For this condition, at a temperature of 1673 K, the burnout equation reduces to

$$t_b = 123.4\underbrace{\left(\frac{d_0}{0.212}\right)}_{\substack{\text{kinetic} \\ \text{term}}} + \underbrace{\left(\frac{d_0^2}{0.00633}\right)}_{\substack{\text{diffusional} \\ \text{term}}}$$

and

Initial diameter (μm)	Burnout time (sec)
2	0.115 (kinetic control)
20	1.084 (mixed control)
200	3.813 (diffusional control)

It can be seen that small soot particles (slightly above 2 μm in diameter) could be expected to burn out in the 0.5 to 1 sec residence time in the boiler hot zone (before a significant temperature drop occurs as the gases pass over the cool boiler tubes). Large particles or agglomerates could be a problem, since the diffusional resistance to carbon consumption is high and is the predominant influence in extending the burnout time.

D. Kinetics of Waste Pyrolysis and Oxidation

Changes in the specific hazardous materials feed to an incineration system place an important question before the operator: Will the burnout be better, the same, or worse if the waste changes from feed *A* where testing has shown acceptable burnout under their normal operating conditions (defined, say, by the temperature, oxygen concentration, and feed rate) to a new feed *B*? This is not a rhetorical question in view of the legal and moral

liability for exposed, downwind individuals. Also, there is the requirement to meet the terms of operating permits under legislation that can impose severe fines and/or perhaps invoke criminal penalties if there are excessive emissions of hazardous substances.

This practical need to be able to determine the "relative incinerability" of chemical compounds has led to considerable laboratory and field investigations of the efficiency and rate of combustion processes. Early investigators used surrogate parameters such as the heat of combustion or autoignition temperature to provide a simple, easy-to-use scale. However, data on incinerator performance showed the surrogate parameters to be unreliable. Increasing attention has been given, therefore, to the use of kinetic parameters as an appropriate and direct scale of incinerability.

1. Kinetic Limitations as Combustor Failure Modes

Incineration systems should not, ideally, be operated such that kinetics limit the degree of burnout achieved. That is, oxygen concentrations and gas temperatures should be high enough that reaction rates are very fast relative to the residence time. This is particularly important for incinerators burning hazardous wastes.

Hazardous waste incinerators are often required by their operating permits to achieve a Destruction and Removal Efficiency (DRE) of "four 9's". This means that the combined effects of the combustion process (destruction) and any settlement in ductwork or the action of air pollution control systems (removal) must ensure that the system exhaust stream contains not more than 0.01% of a preselected, environmentally significant organic material in the feed. In the acronym-rich regulatory language of the U.S. Environmental Protection Agency (EPA), the selected material is a principal organic hazardous constituent or "POHC" and 99.99% of the POHC has been destroyed and/or removed (a DRE of four "9s"). Mathematically, DRE is calculated as follows:

$$\mathrm{DRE} = [(W_{\mathrm{in}} - W_{\mathrm{out}})/W_{\mathrm{in}}] \times 100 \tag{64}$$

where W_{in} is the mass feed rate of the principal organic hazardous constituent (POHC) in the waste stream fed to the incinerator, and W_{out} is the mass emission rate of the POHC in the stack prior to release to the atmosphere.

The inability of a combustion system to attain or exceed the DRE requirement can arise from several "failure modes." These failure modes generally are not visible in the design or operating parameters that characterize the bulk flow. The "mean furnace temperature," the "mean flue gas oxygen concentration," and the "mean residence time" may all be satisfactory. However, some fraction of the system flow does not achieve the critical parameter thresholds that assure burnout. Generally, if only 99% destruction of a feed material is achieved, it is not because 100% of the flow is 99% burned but, more likely, that 99% of the flow is fully burned out and 1% did not burn at all.

One can picture the total flow through an incinerator as a composite of a large number of small, individual packets of gas each with its own unique composition and time–temperature history. Failure to achieve the target DRE could be associated with the fraction of the packets of material flowing where:

The system fails to mix sufficient air with the combustible and, in addition, fails to attain the temperature where pyrolysis reactions (thermal breakdown in the absence of oxygen) can achieve the DRE.

The system mixes sufficient air for combustion to be completed, but the passage of the packet across cold surfaces keeps or brings the temperature below the ignition threshold where fast oxidation reactions can achieve the DRE.

The system mixes an excessive quantity of air that, through dilution, brings the temperature below the ignition threshold where fast oxidation reactions can achieve the DRE.

The system includes flow paths such that some packets of gas otherwise able to burn move too quickly through the hot regions of the furnace and are quenched below combustion temperatures before achieving the DRE.

The impact of these four failure modes can be explored and addressed in design studies and in the establishment of "nominal operating conditions." Kinetic studies can help to establish the sensitivity of combustion performance to a drift in temperature, cooling by infiltration or localized incidences of poor mixing. Importantly, one can evaluate if the system is operating too close to "the edge" even if, on an overall basis, the combustion reaction rate does not appear as a DRE limitation. As in the CO combustion example above, quantitative evaluation of rate effects with an "ignition temperature" concept allows the analyst to anticipate and address these potential problems.

2. Laboratory Kinetic Data

In many cases, the kinetic parameters needed for combustion evaluations (values for A and ΔE) are unknown. The Thermal Decomposition Analytical System (TDAS) was developed and tested at the University of Dayton (183) for rapid and economical assessment of these combustion and pyrolysis rates. The TDAS has developed a significant kinetic data base for application to hazardous waste incineration.

The TDAS consists of a length of quartz capillary tubing passing through an electrically heated furnace. Prepared gas mixtures of known composition are introduced into the capillary and, very rapidly, attain a preset temperature. After a specified time period (modulated by increasing or decreasing the gas flow rate), the gas is rapidly cooled and then analyzed using gas chromatographic mass spectrometry (GCMS).

The kinetic scenario analyzed by the TDAS is somewhat atypical. In the TDAS, the reactions occur isothermally. There is no feedback of a reaction-initiating "soup" of free radicals from a flame zone to the incoming feed. The quartz "wall" acts as a free radical deactivator, thus having a reaction-quenching effect. Therefore, the TDAS data provide useful but conservative measures of reaction rates. The data are particularly useful to suggest the relative reaction rates of two compounds.

TDAS data have been taken over a range of oxygen concentrations. Often, reactions are studied in a highly diluted state (essentially, "pure air") to generate pseudo first-order kinetic constants. Other data are taken in helium or nitrogen to generate "pyrolysis mode" decomposition kinetics. Frequently the run temperature is varied over a range of flow rates that give a constant mean residence time (say, 2 sec) until the temperature corresponding to a target percent disappearance is achieved. A value for the temperature where 99% disappearance is achieved in 2 sec (T_{99}) has been proposed as an index of relative incinerability (184).

The utility of TDAS data to compare the combustion rates of organic compounds was exploited in defining a scale of relative incinerability. The University of Dayton correlated the DRE results achieved in hazardous waste incinerators with the predictions of thermal stability based on TDAS data, reaction kinetic theory, and experimental data from

the literature. They found statistically significant correlations in 7 of 10 cases using this ranking approach, which was highly superior to the heat of combustion basis for assessing relative incinerability that had been used previously (436).

From the TDAS and other data, a ranking of relative incinerability was made for 320 compounds. The compounds were grouped into seven thermal stability classes based on natural divisions in predicted stability or theory which suggested significantly different decomposition mechanisms. The list provides a basis on which to select a POHC that is as easy or more difficult to burn than any of the materials to be (or likely to be) burned in a specific incinerator and thus provides a test species that screens the "worst-case scenario." The listings of compounds sorted by both thermal stability index and alphabetically are presented in Appendix G. The thermal stability classes for U.S. EPA's "Appendix VIII" list of hazardous compounds and their associated T_{99} ranges are as follows:

Class	Compound ranking	T_{99} range (°C)
1	1–34	1590–900
2	35–77	895–800
3	78–119	790–705
4	120–193	695–604
5	194–252	600–425
6	253–271	415–360
7	272–320	320–100

Pseudo first-order TDAS kinetic data for dilute phase oxidation ($f_{O_2} \approx 0.21$) are presented in Table 12a, and other data from field tests of gas phase incineration systems (afterburners) appear in Table 12b. Kinetic constants for some compounds appear more than once. The often significant differences in the reaction rates that are frequently calculated from such data sets constitutes a warning of the dangers of using laboratory data to set operating conditions that just meet the target DRE. Clearly, a significant margin is prudent.

The use of predictive equations for combustion rates must be approached with care and appropriate conservatism. However, in the absence of specific data, correlations may be useful to make preliminary judgments or to assess the comparative performance with two different feed materials. Theodore and Reynolds (439) developed predictive equations for the temperatures in the range from 650° to 1000°C, where 99.00%, 99.90%, and 99.99% DRE would be achieved for mean residence times of 0.5, 1.0, 1.5, and 2.0 sec. The equations were derived from a combination of chemical characteristics, autoignition temperature, and laboratory kinetics constants. The predictive equations are

$$\begin{aligned} T_{99.00} &= 577.0 - 10.0V_1 + 110.2V_2 + 67.1V_3 + 72.6V_4 + 0.586V_5 - 23.4V_6 \\ &\quad - 430.9V_7 + 85.2V_8 - 82.2V_9 + 65.5V_{10} - 76.1V_{11} \\ T_{99.90} &= 594.0 - 12.2V_1 + 117.0V_2 + 71.6V_3 + 80.2V_4 + 0.592V_5 - 20.2V_6 \\ &\quad - 420.3V_7 + 87.1V_8 - 66.8V_9 + 62.8V_{10} - 75.3V_{11} \\ T_{99.99} &= 605.0 - 13.9V_1 + 122.5V_2 + 75.7V_3 + 85.6V_4 + 0.597V_5 - 17.9V_6 \\ &\quad - 412.0V_7 + 89.0V_8 - 55.3V_9 + 60.7V_{10} - 75.2V_{11} \end{aligned}$$

where $T_{99.00}$, $T_{99.90}$, and $T_{99.99}$ are the temperatures (°F) where 99%, 99.9%, and 99.99% DRE are achieved

Table 12a Kinetic Constants for Waste Materials

Compound	$T_{ignition}$(°C)	$\log_{10} A(s^{-1})$	E_a(kcal/g mol)
1,1,1-Trichloroethane	390	8.29±1.02	32±4.0
1,2-Dichlorobenzene	630	8.65±2.92	40±13
1,2,3,4-Tetrachlorobenzene	660	6.28±3.78	30±18
1,2,4-Trichlorobenzene	640	8.29±2.85	39±13
Acetic anhydride	—	12.00	34.5
Acetonitrile	760	7.17±4.57	39±23
Acrylontrile	650	6.13±4.31	31±21
Aniline	620	15.9±4.45	71±19
Azomethane	—	16.54	52.5
Benzene	630	8.63±1.36	39±6.0
Butene	538	14.57	58.2
Carbon tetrachloride	600	5.46±0.951	26±4.0
Chloroform	410	12.5±1.97	49±8.0
Dichloromethane	650	12.8±11.3	62±52
Ethane	500	5.12±1.76	24±8.0
Ethyl chlorocarbonate	—	8.96	29.1
Ethyl nitrite	—	14.15	37.7
Ethyl peroxide	—	14.71	31.5
Ethylene dibutyrate	—	10.26	33.0
Ethylidene dichloride	—	12.08	49.5
Hexachlorobenzene	650	8.38±4.59	41±22
Hexachlorobutadiene	620	12.0±2.87	55±13
Hexachlorobutane	—	12.80	59.0
Hexachloroethane	470	7.31±1.47	30±6.0
Methane	660	9.53±0.531	48±3.0
Methyl iodide	—	12.59	43.0
Monochlorobenzene	540	4.92±3.54	23±15
Nitrobenzene	570	15.1±1.72	64±7.0
Paracetaldehyde	—	15.11	44.2
Pentachlorobiphenyl	—	16.04	70.0
Propylene oxide	—	14.15	58.0
Pyridine	620	5.03±1.57	24±7.0
Toluene	536	13.36	56.5
Trichloroethane	—	8.28	32.0
Tetrachloroethylene	660	6.41±0.985	33±5.0
Vinyl chloride	472	14.55	63.3

Pseudo first-order kinetics at $f_{O_2} = 0.21$.

V_1 = number of carbon atoms in the molecule
V_2 = aromatic? (0 = no, 1 = yes)
V_3 = carbon-to-carbon double bond? (0 = no, 1 = yes)
V_4 = number of nitrogen atoms in the molecule
V_5 = autoignition temperature (°F)
V_6 = number of oxygen atoms in the molecule

Table 12b Kinetic Constants for Waste Materials

Compound	Ref.	Order	A	E_a (kcal/q mol)
1-Butene	438	P-1	3.7E14	58.2
1.2-Dichloroethane	438	P-1	4.82E11	45.6
1,2,3,5-Tetrachlorobenzene	186	P-1	3.65E08	40.00
1,2,4-Trichlorodibenzo-p-dioxin	—	2	3.155E17	72.24
1,2,Dichlorobenzene	186	P-1	1.020E10	46.60
2,7-Dichlorodibenzofuran	—	2	4.973E22	96.73
Acrolein	194	P-1	3.3E10	35.85
Acrylonitrile	194	P-1	2.130E12	52.03
Allyl chloride	438	P-1	3.98E7	29.1
Allyl alcohol	438	P-1	1.75E6	21.4
Benzene	191	2	6.010E14	36.00
Benzene	189	P-1	7.430E21	95.90
Biphenyl	194	P-1	3.55E16	66.74
Chlorobenzene	438	P-1	1.34E17	76.6
Cyclohexane	190	P-1	5.13E12	47.60
DDT	188	2	9.319E7	16.66
Ethane	438	P-1	5.65E14	63.6
Ethanol	438	P-1	5.37E11	48.1
Ethyl formate	438	P-1	1.90E16	44.7
Ethyl mercaptan	438	P-1	5.2E5	14.7
Ethyl acrylate	438	P-1	2.19E12	46.0
Ethylene	438	P-1	1.37E12	50.8
Hexachlorobenzene	186	P-1	2.48E8	41.10
Hexane	438	P-1	6.02E8	34.2
Kepone	188	2	9.554E14	40.28
Methane	438	P-1	1.68E11	52.1
Methyl ethyl ketone	438	P-1	1.45E14	58.4
Methyl chloride	438	P-1	7.43E8	40.9
Mirex	194	P-1	4.32E9	39.75
Pentachlorobiphenyl	194	P-1	5.42E13	60.27
Propane	438	P-1	5.25E19	85.2
Propylene	438	P-1	4.63E8	34.2
Toluene	189	P-1	2.28E13	56.50
Triethylamine	438	P-1	8.10E11	43.2
Vinyl acetate	438	P-1	2.54E9	35.9
Vinyl chloride	194	P-1	3.57E14	63.21

P-1 corresponds to pseudo first-order kinetics at $f_{O_2} = 0.21$, "2" to second-order kinetic expressions.
Source: From (295), (438).

V_7 = number of sulfur atoms in the molecule
V_8 = hydrogen/carbon atom ratio
V_9 = allyl compound (0 = no, 1 = yes)
V_{10} = carbon double bond–chlorine interaction (0 = no, 1 = yes)
V_{11} = natural log of the residence time in seconds

EXAMPLE 15 A gas stream containing organic vapors must be processed in a natural gas-fired afterburner to achieve at least 99% destruction of acrylonitrile (AN). AN is believed to be the most toxic and the most difficult to incinerate of the compounds present in the off-gas stream. It has been suggested that an afterburner operating at a temperature of 850°C with a mean residence time of 0.3 sec achieves this objective. Is this correct?

Table 11 includes two sets of kinetic constants for acrylonitrile. Both sets were derived from TDAS data at high and relatively constant oxygen concentrations and are based on the first-order mathematics of Eq. (42):

Set 1:	Activation energy	31.0 kcal/g mol
	Pre-exponential constant	1.3×10^6
	Reference temperature	1053 K
	Reference O_2 partial pressure	0.21 atm
Set 2:	Activation energy	52.03 kcal/g mol
	Pre-exponential constant	2.13×10^{12}
	Reference temperature	865 K
	Reference O_2 partial pressure	0.20 atm

Unfortunately, the data are presented as pseudo first-order data taken in a highly diluted condition, but the actual combustion conditions probably cover a range of oxygen concentrations that are not very "lean." Further, and very importantly, from the literature it is seen that AN combustion is second order. (This accounts, in part, for its position as one of the more difficult compounds to burn in the USEPA's "relative incinerability" list as shown in Appendix G.) Therefore, one should use the reported oxygen concentration and temperature at which the pre-exponential constant was developed to generate the basic, second-order kinetic constants. Then the kinetics mathematics can be rewritten in second-order form so that the oxidation rate equations properly account for oxygen concentration effects.

The relationships between the pseudo first-order rate constant (k_{P-1}) and the second-order rate constant (k_2) and the respective pre-exponential constants A_{P-1} and A_2 are:

$$k_{P-1} = k_2 \left[\frac{p_{O_2}}{R'T}\right]_{\text{ref}} \tag{65}$$

$$A_2 = A_{p-1} \left[\frac{R'T}{p_{O_2}}\right]_{\text{ref}} \tag{66}$$

where the Universal gas constant R' is 0.08206 atm liters/K gram mol. Thus, the second-order pre-exponential constants are

Data Set 1 $A_2 = 5.349 \times 10^8$ l/gram mol-sec
Data Set 2 $A_2 = 7.560 \times 10^{14}$ l/gram mol-sec

If one examines a gas-fired thermal oxidizer for a dilute fume, one sees the following situation:

> The bulk gas temperature rises quickly to the set point. The average oxygen concentration is dependent on flame temperature: Higher temperatures are associated with lower overall excess air (lower oxygen concentration). This relationship is shown in Fig. 9 for a natural gas- (CH_4)

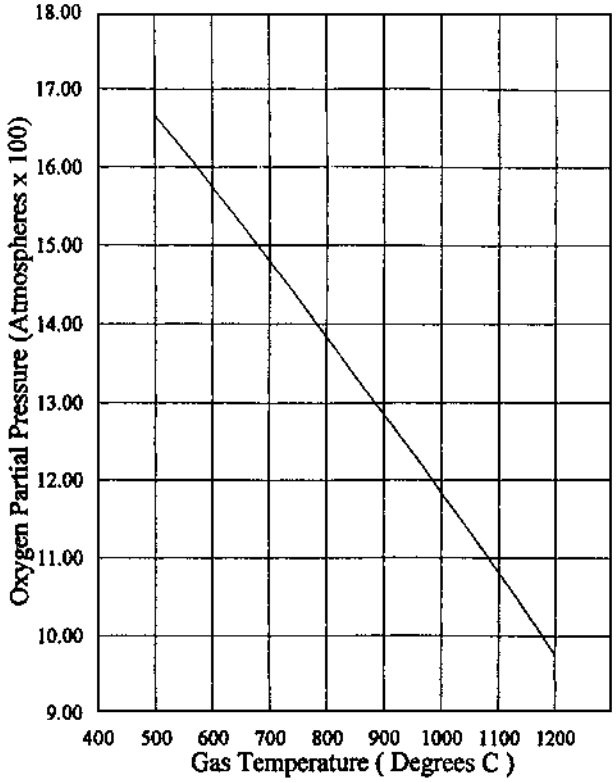


Figure 9 Temperature-oxygen relationship for natural gas combustion in dilute fume afterburner.

fueled system with a modest heat loss allowance. The AN oxidation kinetics under these circumstances can be analyzed as pseudo first-order with the pre-exponential A varying as the temperature and O_2 concentration change. A quadratic equation adequately fits the oxygen partial pressure (p_{O_2}) and gas temperature (T°C) relationship:

$$[p_{O_2} = 0.2089 - 7.8771 \times 10^{-5} T - 1.1726 \times 10^{-8} T^2 \text{ atm}$$

The fume moves through the system in what is usually close to plug flow. In this example, back-mixing or other flow irregularities will not be quantified. There will be eddy recirculation and back-mixing in most real situations. For example, there may be recirculation zones in the entrance region where the burner discharge and fume enter the system. This situation is illustrated in Fig. 22(a) and (b) of Chapter 6.

Calculations can be made for the 99% burnout goal using Eq. (46) with k_{P-1} values calculated from the two sets of kinetic constants and the oxygen–temperature correlation above. The results are shown in Figs. 10 and 11. The Set 2 kinetic data produce much shorter burnout times than the Set 1 data. The calculations illustrated in Fig. 10 (Set 1) suggest that the unit would fail to meet the burnout objective for a 0.3-sec, 850°C operating condition. Figure 11 (Set 2) data indicate achievement of the goal. However, the shape of the Fig. 11 curve shows that if any significant fraction of the flow is at a

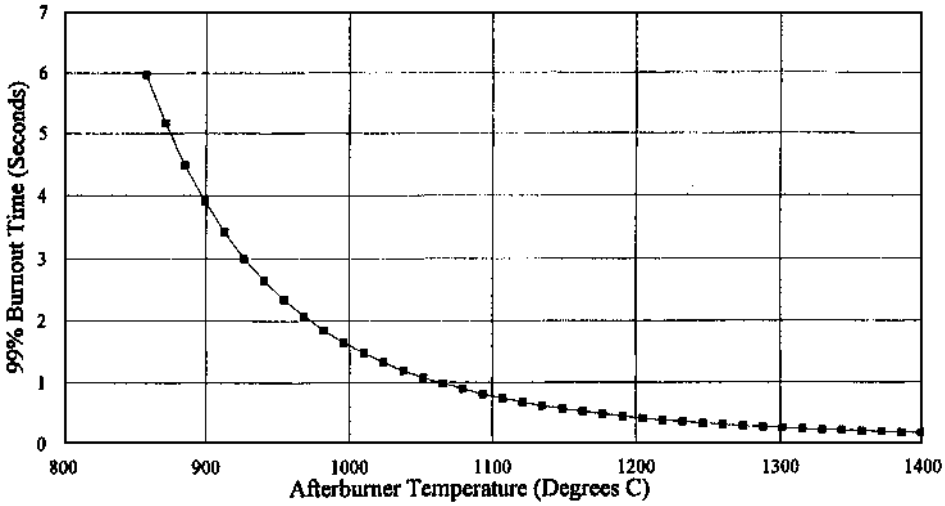


Figure 10 Acrylonitrile burnout time (data set 1).

substantially lower temperature, the 99% requirement will not be met even for this case. Thus, under the best of conditions, the suggested design condition is marginal and some data indicate a total failure. It would appear, therefore, that to avoid gross overdesign or failure, additional test data (perhaps in a pilot unit) are needed.

The consequences of kinetic failure in this case will include emission of unburned AN and a mix of products of incomplete combustion (PICs). These will include a wide range of partial oxidation products. Characteristically, such PICs are odorous aldehydes, ketones, and ethers. If identified by name in a GCMS analysis, one often finds them to be "environmentally problematical." In general, however, although the PIC chemistry can

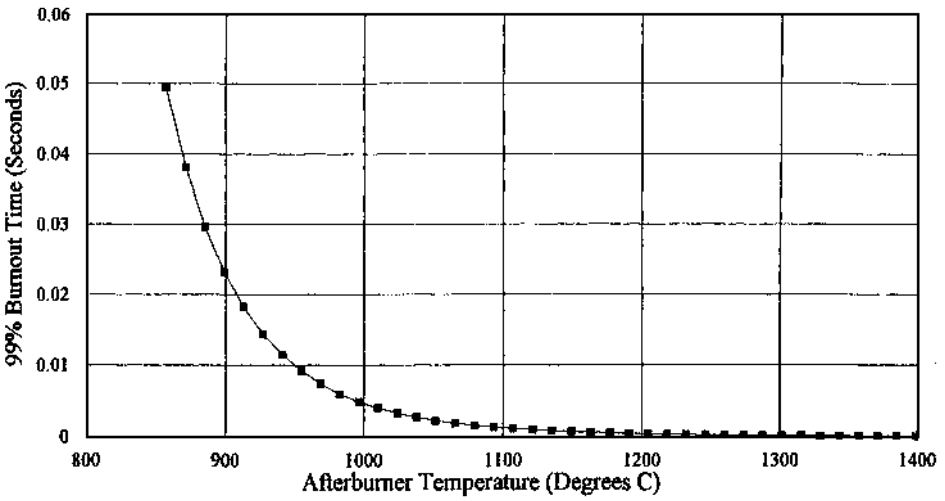


Figure 11 Acrylontrile burnout time (data set 2).

Table 13 Ignitition Temperatures of Selected Compounds [195]

Compound	Ignition temperature (°C)	
	Thermal	Catalytic
Benzene	580	302
Toluene	552	302
Xylene	496	302
Ethanol	392	302
Methyl isobutyl ketone	459	349
Methyl ethyl ketone	516	349
Methane	632	500
Carbon monoxide	609	260
Hydrogen	574	121
Propane	481	260

suggest problems with significant adverse impacts, the real health risk consequence is often modest to (practically) none. This is due to the low concentration of individual PICs in the flue gases and, thus, the very low ambient concentrations experienced by even the "most exposed individual."

3. Ignition Temperature Data

Based on both kinetic data and data from dilute fume afterburner performance, the ignition temperature can be determined. Ignition temperature data for both direct flame and catalytic afterburners are shown in Table 13.

4. Flash Point Estimation

The flash point is the lowest temperature at which a liquid gives off sufficient vapor to form an ignitable mixture with air near the surface of the liquid. Several standard methods are available using a closed cup (the preferred method) or an open cup. Flash point is suggested as a measure of "ignitability" by the U.S. EPA and by regulatory agencies elsewhere. The EPA defines a liquid as hazardous as a consequence of ignitability if the closed-cup flash point is less than 60°C. To be protective, the lowest flash point temperature is usually taken.

Several flash point values are shown in Table 14. Flash points can be estimated using the method of Shebeko (441) according to the following methodology:

Step 1. From Eqs. 67a and 67b, calculate the vapor pressure of the substance at the flash point ($P_{sat\text{-}fp}$) as related to the total system pressure P and the numbers of atoms of carbon (N_C), sulfur (N_S), hydrogen (N_H), halogen (N_X), and oxygen (N_O) in the molecule.

Table 14 Values of the Flash Point (°C) for Several Substances

Compound	T_{flash} (°F)	T_{flash} (°C)	Compound	T_{flash} (°F)	T_{flash} (°C)
Acetic acid	104.0	40.0	Diethyl ether	−20.0	−28.9
Acetone	0.0	−17.8	Ethyl acetate	24.0	−4.4
Benzene	12.0	−11.1	Ethylene glycol	232.0	111.1
Butyl acetate	216.0	102.2	Furfural	140.0	60.0
Chlorobenzene	90.0	32.2	Methyl alcohol	54.0	12.2
Cottonseed oil	590.0	310.0	Methyl ethyl ketone	30.0	−1.1
o-Cresol	178.0	81.1	Naphthalene	174.0	78.9
Cyclohexanol	154.0	67.8	Phenol	175.0	79.4
Decane	115.0	46.1	Toluene	40.0	4.4

Step 2. From data or correlations of vapor pressure and temperature, find the temperature corresponding to the calculated vapor pressure

$$p_{\text{sat-fp}} = \frac{P}{1 + 4.76(2\beta - 1)} \tag{67a}$$

$$\beta = N_C + N_S + \frac{(N_H - N_X)}{4} - \frac{N_O}{2} \tag{67b}$$

EXAMPLE 16. Using the method of Shebeko, estimate the flash point of methyl ethyl ketone (MEK). Compare the estimated value to the literature value of −1.1°C.

MEK has the atomic formula $CH_3C_2H_5CO$ and, from Eq. 67b, $\beta = 5.5$ and $P_{\text{sat-fp}} = 15.6$ mm Hg at a total pressure of 1 atm. From vapor pressure correlations available from the literature (e.g., (442)], the vapor pressure of MEK (P_{vap}) may be approximated by

$$P_{vap} = \exp\left[72.698 - \frac{6143.6}{T} - 7.5779 \ln(T) + 5.6476 \times 10^{-6} T^2\right]$$

By successive approximation, $T = -8$°C.

3

Selected Topics on Combustion Processes

Combustion processes involve mass and energy transport and chemical reaction. Depending on the relative pace of these necessary steps, the process characteristics change. Such changes can affect the degree of success of the combustion system in performing according to expectations.

It is the goal of design engineering to apply an understanding of the physical and chemical processes that govern systems of interest in order to quantitatively predict performance. Alternatively, we may wish to translate performance goals into system hardware designs and operating set points. A first-principles approach to these tasks is difficult and time-consuming. Yet exploration of the fundamental processes involved gives valuable insight into the appropriateness of designs and into the interpretation and solution of operating problems.

To this end, complete combustion processes for gaseous, liquid, and solid fuels are described. Also, intentionally incomplete combustion (or pyrolysis) is described to aid in understanding waste processing concepts that are based on this interesting but less common concept in waste pyroprocessing.

I. GASEOUS COMBUSTION

Although most wastes requiring incineration are not gaseous, most combustion is completed through gas phase reactions. Many liquids vaporize in the hot furnace environment, and it is the resulting gas molecules that actually engage in combustion. Heavier liquids and solids are pyrolyzed by intense heating. This generates lower-molecular-weight volatile fragments that burn in the gas phase. Even carbon char (appearing as the waste of interest or as a product of the pyrolysis process) is usually gasified (by oxygen or water vapor) to carbon monoxide that burns in the gas phase.

In reviewing gas phase combustion, systems may be divided into those where fuel and stoichiometric oxidant enter the combustion environment separately and where the combustion rate is almost always mixing limited, and those where combustion is initiated in homogeneous fuel–oxidant mixtures, with the flame reactions propagating through the

system in a substantially continuous (although, perhaps, smudged by turbulence) flame front. The latter case is found primarily only in premixed gas burners. The former is by far the most common.

The mechanism by which oxidant and fuel are brought together provides a second classification of flame type. When molecular diffusion predominates, the flame is known as a *laminar diffusion flame*. When eddy diffusion predominates, the flame is known as a *turbulent diffusion flame*. The Reynolds number of the stream—a measure of the ratio of momentum forces (scaling eddy mixing) to viscous forces (scaling molecular mixing)—can be a useful indicator of the regimes where one or the other flow conditions exist.

A. The Premixed (Bunsen) Laminar Flame

Visual examination of simple, premixed conical hydrocarbon–air flames indicates three regions: preluminous, luminous, and postluminous. In the *preluminous zone*, the cold feed gas undergoes preheating and some "seeding" with reactive species due to thermal and mass diffusion against the direction of convective flow. At some point the combination of temperature and mixture reactivity reaches a level where rapid heat release begins. Activated radicals (e.g., OH·, C=C, and others) appear in high concentration and account for much of the visible light released in the blue *luminous zone*. Gouy suggested in 1881 (14) that the conical shape of the luminous zone could be explained by assuming that the flame propagates normal to itself at a constant rate, known as the *burning velocity* or *flame speed*. This simple concept has withstood the testing of many investigators and appears to be able to quantitatively explain flame front geometry. For most hydrocarbon fuels, the flame speed falls in the range from 35 to 60 cm/sec at normal atmospheric temperatures and pressures.

The combustion reaction is seldom complete within the luminous zone. Particularly for the combustion of complex fuels, heat release from CO and H_2 oxidation extends into the *postluminous zone* (an afterburning region). In the postluminous zone, the temperature falls due to radiation heat loss and to the assimilation of cool ambient fluid into the flame flow, and combustion is completed.

Figure 1 illustrates the heat release for a stoichiometric propane–air flame at 0.25 atm (15). The low pressure increases the thickness of the luminous zone. A similar thickening is observed as the degree of premix (air-to-fuel ratio) is decreased.

B. The Diffusion Flame

In a diffusion flame, fuel combustion reactions must await the arrival of oxidant. Preparatory steps such as pyrolysis, evaporation, or thermal cracking, however, may proceed under the influence of radiative heat transfer from the (typically) hot surroundings, the heating due to turbulent mixing of hot burned gases into the fuel stream, and conduction from the flame regions.

For most burner systems, the fuel is introduced into the combustion chamber in a jet, with or without swirl. Since combustion is mixing limited, the flow characteristics (especially entrainment) of the jet are prime determinants of combustion rate, flame length, and flame shape. Since jet behavior is very important to diffusion flame and combustor fluid mechanics, it is discussed in detail below. One important flame quantity, the flame length, will be mentioned here for the more common case, the turbulent diffusion flame.

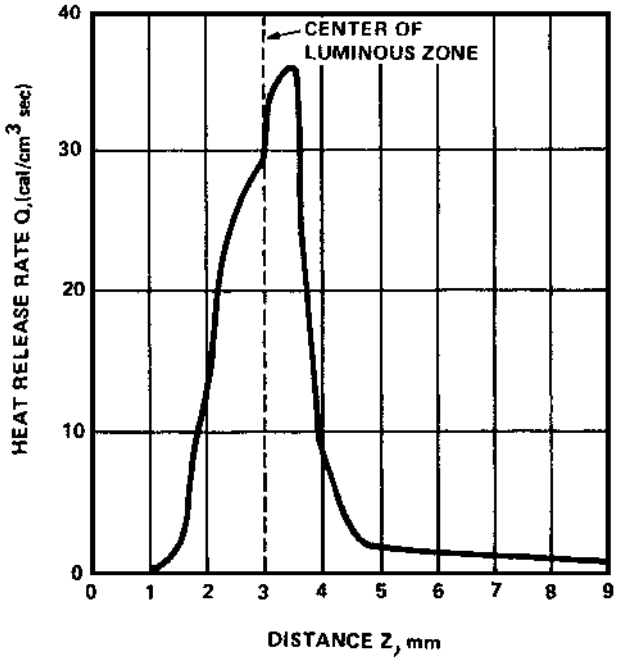


Figure 1 Heat release rate in stoichiometric propane-air flame at 0.25 atm. Curve calculated from the temperature profile using estimated thermal conductivities.

Based on a simplified model for jet mixing, Hottel (16) proposed and tested the following relationship defining the flame length L, corrected for the distance X^+ from the nozzle face to the break point where turbulence is initiated:

$$\frac{L - X^+}{d} = \frac{5.3}{f_s}\left\{\left[f_s + (1 - f_s)\left(\frac{M_a}{M_0}\right)\right]\frac{T_F}{\theta_m T_0}\right\}^{1/2} \tag{1}$$

where

L = flame length (meters)
X^+ = distance from nozzle face to initiation of turbulence (meters)
d = nozzle diameter (meters)
f_s = mole fraction of nozzle gas in a stoichiometric gas–air mixture
M_a, M_0 = molecular weight of air and nozzle gas, respectively
T_F = adiabatic flame temperature (Kelvin) of a stoichiometric mixture
T_0 = nozzle gas temperature (Kelvin)
θ_m = moles of reactants per mole of product in a stoichiometric mixture

Estimation of X^+ is necessary if total flame length is to be determined. Generally, X^+ is small compared to $(L - X^+)$ except for CO flames for which $X^+/(L - X^+)$ is as high as 0.4. On the average, X^+ is about $0.05L$, is less than $0.09L$ in the turbulent range, and decreases with increasing nozzle Reynolds number.

This correlation is useful in that it allows anticipation of flame jet impingement problems and allows estimates of the effect of fuel changes (changes in f_s, M_0, T_F, and θ_m)

and of preheat (changes in T_0) on flame length. Its accuracy for a variety of gaseous fuels ranged within 10% to 20% of the experimental values. It should be recognized that devices that increase the rate of entrainment of oxidant will act to shorten the flame. Thus, swirl in particular will significantly shorten flame length.

EXAMPLE 1. Natural gas at 15°C (methane, with a flame temperature of 2170 K) is to be burned in air from a port 4 cm in diameter at a velocity of 3 m/sec. The furnace is 8 m wide. Flame impingement has been a problem at other plants, and so the plant engineer suggests cutting back on the fuel flow by up to 20% to reduce flame length. Will this work? What will?

First, the jet should be evaluated to determine if it is, indeed, turbulent.

$$\text{Reynolds no.} = N_{\text{Re}} = \frac{d_0 u_0 \rho_0}{\mu_0} \tag{2}$$

where

$d_0 =$ nozzle diameter $= 4$ cm
$u_0 =$ discharge velocity $= 3$ m/sec $= 300$ cm/sec
$\rho_0 =$ density of methane at 15°C $= 6.77 \times 10^{-4}$ g/cm^3
$\mu_0 =$ viscosity of methane at 15°C $= 2.08 \times 10^{-4}$ g/cm sec

$$N_{\text{Re}} = \frac{4(300)(6.77 \times 10^{-4})}{2.08 \times 10^{-4}}$$
$$= 3900 \text{ (dimensionless)}$$

Since the Reynolds number exceeds that required for turbulent flow (2100), the flame length relationship should hold.

Since 1 mol of methane burns stoichiometrically with 2 mol of oxygen, and $2(79/21) = 7.52$ mol of nitrogen, $f_s = 1/(1 + 2 + 7.52) = 0.095$.

Methane burns according to the reaction

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
(3 mols) (3 mols)

so

$$\theta_m = 3/3 = 1.$$

Assuming that X^+ is much less than L,

$$\frac{L}{d} = \frac{5.3}{0.095}\left\{\left[0.095 + (1 - 0.095)\left(\frac{29}{16}\right)\right]\frac{2170}{(1)(288)}\right\}^{1/2}$$
$$= 202$$

and

$$L = 8.07 \text{ m}$$

Will dropping the firing rate help? The lower inlet velocity will lower the air entrainment rate in proportion, and the flame length will remain essentially constant.

What could be done?

1. Use a 3-cm nozzle diameter. This will cut the flame length to 3/4 of the base case with an increase in gas compression costs. Alternatively, use two or more nozzles.

2. Preheat the fuel. If the methane is introduced at 250°C (523 K), the flame length will decrease to 6 m.
3. Partially premix air with the gas (changing f_s and M_θ), being careful to avoid flashback problems.
4. Explore the possibility of tilting the burner.
5. Explore the use of swirl-type burners.

Use of the equation presented should cause no problems in many situations. If, however, the burner discharges into hot furnace gases where the oxygen concentration is depleted, or operates as part of a bank of fuel nozzles where the zone of influence of fuel jets overlaps, a lengthening of the flame can be anticipated.

II. LIQUID COMBUSTION

The combustion of liquids begins with the accumulation of heat in the liquid mass from radiation from the flame or from hot refractory walls, from recirculating burned gases, or from a pilot burner. Eventually, the fuel approaches its boiling point and it begins to vaporize. The fuel vapors then diffuse from the liquid surface, mixing with oxygen in the air and increasing in temperature. At some point, the rate of oxidation reactions and associated heat release is high enough that full ignition and combustion ensues.

In most situations it is desirable to subdivide the oil into small droplets in order to enhance vaporization rate (increasing the combustion rate per unit volume), to minimize smoking, and to ensure complete combustion. In some simple "pot-type" heaters, in pit incinerators, and occasionally in highly unusual waste disposal situations, sludge or liquids are burned in a pool.

A. Pool Burning

Fires above horizontal liquid pools have been studied both experimentally and analytically to clarify the relationship between burning rate and the properties and characteristics of the system.

In small pools (up to 3 cm in diameter), burning is laminar and, unexplainedly, the burning rate per unit area $\dot{m}''$ decreases in approximate proportion as diameter increases. In a 3- to 5-cm-diameter pool, the flame is still laminar but regular oscillations occur.

For diameters greater than 7 cm and less than 20 to 30 cm, a transition to turbulent burning takes place. Convection is the primary source of feedback energy influencing $\dot{m}''$ in this pool size range, and the overall $\dot{m}''$ is essentially independent of pool diameter. For flames that yield little radiation (e.g., methanol), the constant $\dot{m}''$ range extends to diameters over 100 cm.

A constancy of $\dot{m}''$ (average) for a range of pool diameters does not imply a constant $\dot{m}$ with radius. Akita and Yumoto (17) report a 44% maximum radial mass flux variation for a 14.4-cm diameter methanol fire, and Blinov and Khudakov (18) report an 18%, 18%, and 27% maximum radial variation for benzene, gasoline, and tractor kerosene, respectively, in a 30-cm tank. These variations, however, may be considered small.

Studies by DeRis and Orloff on pool burning rates in the convectively controlled region (19) identified a relationship between burning rate and characteristics of the fuel which appears to satisfactorily correlate several sets of data for values of B (a dimensionless mass transfer driving force) greater than unity. Below $B = 1$, the burning rate $\dot{m}''$ is lower than predicted, apparently due to the onset of unexplained extinction processes.

DeRis and Orloff's correlation is

$$\dot{m}'' = 0.15\left(\frac{\lambda_1}{C_{p1}}\right)\frac{g(\rho_a - \rho_3)^{1/3}}{\mu_2\alpha_2}B\left[\frac{\ln(1+B)}{B}\right]^{2/3} \text{ kg/sec-m}^2 \tag{3a}$$

and

$$B = \frac{\Delta H_c}{\theta \Delta H_v} - \frac{H_s}{\Delta H_v} \quad \text{(an enthalpy driving force)} \tag{3b}$$

where

$\dot{m}''$ = burning rate (kg/sec m^2)
g = acceleration of gravity (m/sec^2)
ΔH_c = heat of combustion (HHV) of fuel (kcal/kg)
θ = kilograms oxidant (air) per kilogram fuel (kcal/kg)
ΔH_v = heat of vaporization of fuel (kcal/kg)
H_s = heat content (sensible) of 1 kg of oxidant (air) at the liquid temperature at the surface of the burning pool (kcal/kg)
ρ_a = density of air at ambient temperature (kg/m^3)

and where the following are the properties of the gas mixture formed upon stoichiometric combustion of the fuel and subscripted 1, 2, or 3 to correspond to evaluation at 25%, 50%, and 100%, respectively, of the total enthalpy of a stoichiometric mixture:

λ = thermal conductivity (kcal m^{-1} sec^{-1} °C^{-1})
C_p = specific heat (kcal kg^{-1} °C^{-1})
ρ = density (kg/m^3)
μ = viscosity (kg/m sec^{-1})
α = thermal diffusivity (m^2/sec)

To use this correlation, the temperatures corresponding to various enthalpies are easily determined, using a plot such as Fig. 4 in Chapter 2. Mixture properties at a temperature T are calculated for mole fractions f_i of components with molecular weights MW_i:

$$\rho = \sum_i f_i \rho_i \tag{4}$$

$$\mu = \frac{\sum_i f_i (MW)_i^{1/2} \mu_i}{\sum_i f_i (MW)_i^{1/2}} \tag{5}$$

$$\lambda = \frac{\sum_i f_i (MW)_i^{1/3} \lambda_i}{\sum_i f_i (MW)_i^{1/3}} \tag{6}$$

$$C_p = \frac{\sum_i f_i C_{pi} (MW)_i}{\sum_i f_i (MW)_i} \tag{7}$$

$$\alpha = \frac{\lambda}{\rho C_p} \tag{8}$$

As the pool diameter increases beyond the 20- to 30-cm range, radiation from the flame plume plays an increasingly important role in setting the evaporation (burning) rate. For these larger pools where the flame plume is optically thick, the burning rate of a liquid with a density $\rho_\ell(\mathrm{g/cm^3})$ is given by

$$\dot{m}'' = \frac{0.076\rho_\ell \Delta H_c}{\Delta H_v} \text{ kg m}^{-2} \text{ sec}^{-1} \tag{9}$$

where terms are defined as for Eq. (3). An analysis by Steward (20) of the data of several investigators developed a relationship correlating the height of the visible flame plume with the pool size and burning characteristics. Steward's relationship showed that the tip of the visible flame plume corresponded to a condition of 400% excess air.

B. Droplet Burning

For most liquid waste incineration and liquid fuel burning equipment, atomization is used to subdivide the feed for more efficient and complete burning (see Fig. 2). Atomization is effected by a number of means, including

Low-pressure (0.03 to 0.35 atm) air atomization
High-pressure (2 atm or more) air or steam atomization
Mechanical atomization of fluid through special orifices at pressures from 5 to 20 atmospheres
High-speed rotating conical metal cups

The power requirements and characteristics of each atomizing method are described in the chapter relating to liquid waste incinerators.

Early analysis of droplet burning was based on analogies with coal combustion. These studies viewed droplet combustion as involving the diffusion of oxidant to the droplet surface followed by heterogeneous (two-phase) reaction. Later work led to the

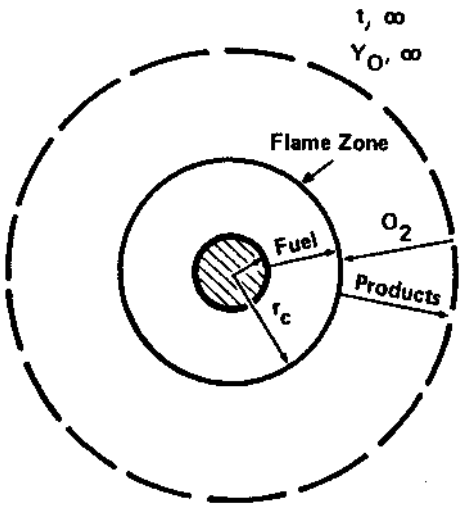


Figure 2 Typical model of droplet burning.

presently accepted concept that combustion occurs in a homogeneous diffusion flame surrounding an evaporating droplet (Fig. 2).

A review by Williams (20a) suggested the following as the burning time t_b (sec) of a droplet of initial diameter d_ρ (cm) of a hydrocarbon oil of molecular weight M_W at a temperature T (K) in an atmosphere with an oxygen partial pressure p_{O2} (atm) as

$$t_b = \frac{29{,}800 M_w d_o^2}{p_{O2} T^{1.75}} \tag{10}$$

A more detailed theoretical analysis of the evaporation and burning of individual droplets was presented by Kanury (435) who considered the two-step process: gasification or vaporization of a liquid waste or fuel followed by gas phase combustion. For lightweight liquids, gasification is a purely physical (evaporation) process. For heavier fuels or wastes, pyrolysis or destructive distillation may be involved.

One of the key steps in the analysis is the establishment of the conditions at the surface of the droplet. For lighter fuels, it is useful and usually accurate to assume that the surface temperature of the evaporating droplet approaches (but is always slightly lower than) the boiling temperature of the liquid at the extant total pressure. If pyrolysis is involved, there is often no discrete boiling temperature and the surface temperature is usually much higher.

For the lighter liquid fuels or wastes, Kanury's analysis considered the heat transfer and mass transfer processes involved in droplet evaporation. In most incineration scenarios, the temperature of the gaseous environment into which the droplet is sprayed (T_∞) is significantly higher than the liquid's boiling point T_B. Under these conditions, the mass transfer number (B) is given by

$$B = \frac{c_g(T_\infty - T_B)}{L + c_1(T_B - T_R)} \quad \text{(dimensionless)} \tag{11}$$

The evaporation constant λ_v is given by

$$\lambda_v = \frac{8\rho_g \alpha_g}{\rho_1} \ln(B+1) \text{ cm}^2/\text{sec} \tag{12}$$

And the droplet evaporation time t_v is equal to

$$t_v = \frac{d_0^2}{\lambda_v} = \frac{\rho_1 d_0^2}{8\ \rho_g \alpha_g \ln(B+1)} \text{ sec} \tag{13}$$

where

c_g = specific heat of the liquid's vapor (cal/gm °C)
T_∞ = temperature of the surrounding air (°C)
T_B = boiling point of the liquid (°C)
L = heat of vaporization of the liquid (cal/g)
c_l = specific heat of the liquid (cal/gm °C)
T_R = bulk temperature of the liquid
ρ_g = density of the liquid's vapor (gm/cm^3)
α_g = thermal diffusivity of the liquid's vapor cm^2/sec = $k_g/\rho_g c_g$
k_g = thermal conductivity of the vapor at T_B cal cm/sec cm^2 °C
ρ_l = density of the liquid (g/cm^3)
d_0 = initial diameter of the droplet (cm)

Kanury's extension of the analysis to include the effects of combustion leads to a modification of the mass transfer number to

$$B = \frac{\Delta H f Y_{0\infty} + c_g(T_\infty - T_B)}{L + c_1(T_B - T_R)} \quad \text{(dimensionless)} \tag{14}$$

where the definitions are as above and

ΔH = heat of combustion of the liquid (cal/g)
f = mass stoichiometric ratio (grams of liquid/g of O_2)
$Y_{0\infty}$ = mass concentration of oxygen in the environmental gas (grams/gram) and equal to 0.232 (23.2%) for air

The mass transfer driving force for several liquid fuels burning in air are illustrated in Table 1.

For the burning constant λ_b defined by

$$\lambda_b = \frac{8\rho_g \alpha_g}{\rho_1} \ln(B+1) \text{ cm}^2/\text{sec} \tag{15}$$

Table 2 indicates the accuracy of prediction of λ_b in contrast to experimental determinations.

The burning time t_b of an individual droplet is given by

$$t_b = \frac{d_0^2}{\lambda_b} \text{ sec} \tag{16}$$

Table 1 Mass Transfer Driving Force for Combustion of Liquids in Air

Liquid	$c_g(T_\infty - T_B)$	$\Delta H f / Y_{0\infty}$	$c_l(T_B - T_R)$	L	T_B	B
n-Pentane	−4.95	785	8.91	87.1	36.0	8.15
n-Hexane	−14.80	770	25.80	87.1	68.0	6.70
n-Heptane	−24.30	770	41.20	87.1	98.5	5.24
n-Decane	−47.70	770	80.50	86.0	174.0	4.34
Benzene	−18.60	790	24.70	103.2	80.0	6.05
Methanol	−13.80	792	25.20	263.0	64.5	2.70
Ethanol	−18.10	776	32.60	200.0	78.5	3.25
Kerosene	−71.20	750	106.00	69.5	250.0	3.86
Light diesel	−71.20	735	103.50	63.9	250.0	3.96
Medium diesel	−74.30	725	107.50	58.4	260.0	3.94
Heavy diesel	−77.50	722	109.00	55.5	270.0	3.91
Acetone	−11.40	770	23.60	125.0	56.7	5.10
Toluene	−28.00	749	35.00	84.0	110.6	6.06
Xylene	−34.00	758	45.30	80.0	130.0	5.76

Assumed values:
$c_g = 0.31$ cal/gram °C
$T_\infty = 20$°C
$Y_{0\infty}$ assumed 0.232
T_R assumed 20°C
Source: From (435).

Table 2 Burning Constant for Various Hydrocarbons Oxidant (Air at 20°C and 1 atm)

	$\lambda_{calculated}$	$\lambda_{measured}$	
Fuel/Liquid	10^{-3} cm^2/sec		Reference
Benzene	11.2	9.9	443
Toluene	11.1	6.6	444
o-Xylene	10.4	7.9	444
Ethyl alcohol	9.3	8.6	443
n-Heptane	14.2	8.4	443
n-Heptane	14.2	9.7	444
iso-Octane	14.4	9.5	444
Petroleum ether	—	9.9	444
Kerosene	9.7	9.6	444
Diesel oil ($\rho = 0.850$)	8.5	7.9	444

The application of burning time predictions based on Kanury's analysis must be cautious and conservative. Extrapolating from the single droplet model to the analysis of real, large-scale combustors requires addition of four rather complex refinements to the theory:

1. In dense sprays, evaporation and diffusion burning of the vapor become the dominant mechanism.
2. Relative motion between droplet and the gaseous surrounding medium removes the simplifying assumptions of radial symmetry.
3. Initial droplet particle sizes are not uniform, and the evaporation characteristics are poorly described using models based on mean droplet sizes.
4. Mixing processes of fuel and oxidant take place in the aerodynamically complex flow in the burner and furnace (not in a simplified, one-dimensional reactor).

Unfortunately, such studies have not yet produced quantitatively useful correlations for use in combustion chamber design. However, the parameters in the equations give considerable insight as to the effect of user-controllable variables in enhancing the combustion rate. For example, droplet combustion rate is increased by reducing drop size, increasing the temperature of the ambient atmosphere, operating at high oxygen concentration, and preheating the fuel.

As a starting point in burner analysis, the flame length relationship in Eq. (1) could be used for jets of liquid fuel droplets. Application of Eq. (1) is subject to the qualification that the flame will be longer than predicted with the difference in predicted and actual decreasing as

The number of coarse droplets decreases.
The latent heat of evaporation (less any preheat) decreases. And/or
The mean droplet diameter decreases.

Also, the flame will be considerably shortened by swirl effects.

III. SOLID COMBUSTION

The combustion of solid phase wastes, as with liquids, is largely a process of gasification followed by combustion of the gaseous products (see Fig. 3). Even in the cases where heterogeneous attack of the solid by a gaseous oxidant such as O_2, CO_2, or H_2O occurs (e.g., in combustion of coke), the initial by-product is often carbon monoxide rather than fully oxidized CO_2.

The development of furnaces to burn solids has let to three characteristic firing modes:

1. *Suspension burning.* Solids burn while entrained in a fast-moving air stream. In some embodiments, the particles of solids are finely divided and dry. This is the case for the burning of pulverized coal, rice hulls, etc. In other instances, the feed is introduced as a semiliquid sludge that dries, gasifies, and burns in suspension. This is the case for wastewater treatment plant sludges in a fluid bed combustor. The gaseous environment is hot and often oxygen rich. Combustion is completed while the particles are suspended in the gas flow. In some configurations, the solids leaving the combustion zone are captured and reinjected to improve burnout. Much of the residue leaves the system still entrained in the flue gases.
2. *Semisuspension burning.* Coarsely subdivided solids are injected mechanically or pneumatically into the combustion space. Drying and combustion occur partially while the solids are airborne and are completed after the particles fall to a grate. This technology is used for spreader stoker-fired coal and prepared refuse derived fuel (RDF). Residue is dumped periodically or is continuously withdrawn.
3. *Mass burning.* Unsubdivided or coarsely subdivided solids are moved into the combustion space by mechanical means (e.g., by hydraulic ram, manual charging, or drawn in on a grate) and are pushed, are dragged, or tumble through the furnace until a satisfactory degree of burnout is obtained. In some small, low-capacity units, the feed remains substantially undisturbed in the combustion space while it burns. Residue is discharged periodically or continuously.

In waste disposal practice, each of these techniques has been used. Quantitative descriptions of the processes involved are still under development and are costly to apply in most conceptual and final design efforts. However, several of the important steps in combustion are subject to analysis, particularly if graphical tools and modern microcomputers are used. A summary of the results are given below to give insight into the processes and their control.

In suspension burning, entering particles of fuel are almost instantly exposed to intense radiant, convective, and conduction heat transfer as hot combustion products are entrained into the jet of suspending fluid. In mass burning, much of the mass is shielded from radiant heating. Thus, fuel particles deep within the bed must await the arrival of the ignition front before rapid temperature increases are experienced.

Semisuspension burning processes fall between the extremes. As the temperature of a fuel particle increases, free moisture is lost, and then decomposition of organic matter begins. The volatile matter includes a wide variety of combustible hydrocarbons, carbon monoxide, carbon dioxide, water vapor, and hydrogen. The weight loss and composition of the volatiles developed by gasification of the solid depend on the time and temperature history. The heating rates in pulverized coal furnaces are very high (10^4 °C/sec or more). In such cases, decomposition is complete in less than 1 sec for particles smaller than about 100 μm.

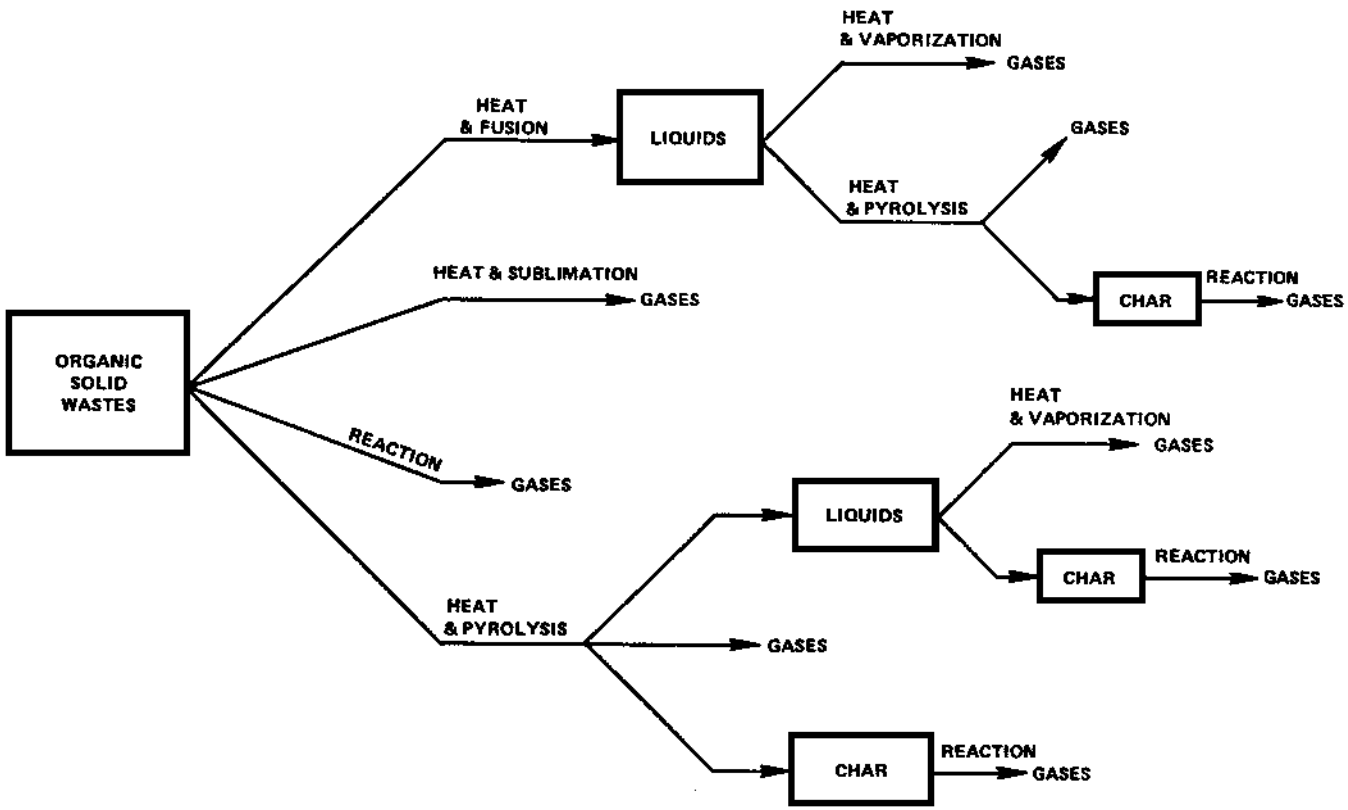


Figure 3 Phase changes in the combustion of organic solids.

At the other extreme, a slower rate of heating (less than 10°C/min) characterizes carbonization process in charcoal manufacture. Intermediate heating rates would be found in waste incineration by mass burning (say, 1000°C/min) or the proximate analysis test (about 300°C/min).

The significance of these processes to the incinerator designer arises from their impact on the spatial distribution of volatile release, and thus combustion air requirement within the furnace. If, for example, volatile release is extremely rapid, the region near the charging point of a mass burning system would behave as an intense area source of fuel vapors, driven out of the fuel bed by undergrate air flow. Combustion air requirements, therefore, would be largely in the overbed volume in this region of the furnace and the high, localized heat release rate must be taken into account in developing the design of the enclosure. If, on the other hand, volatilization is slow or limited, heat release will be confined largely to the bed and the majority of the combustion air should be underfire. With a perversity not uncommon in the analysis of waste disposal problems, the intermediate situation appears to be the case.

The introduction of oxidant only in localized areas of the incinerator environment introduces a second complication. In the situation where a mass of ignited solid waste sits upon a grate through which air is passing, the gaseous environment varies with distance above the grate line. In the *idealized* case, the following processes occur:

At and near the grate, air supply is far above stoichiometric, and released volatiles burn rapidly and completely to CO_2 and water vapor. Heat release rates per unit volume are high. One could call this the *burning zone*.

Just ahead of the fully involved burning zone and closer to the feed point, the waste mass includes both wet and dry material. The ignited, burning dry material generates heat and hot gases that supply the heat needed to dry and preheat the wet material. A portion of the drying energy may be supplied by preheated undergrate combustion air. This is the *drying zone*.

At some point away from the grate, the free oxygen is exhausted, but both CO_2 and H_2O act as oxidizing agents to produce CO and H_2 in both heterogeneous and homogeneous reactions. This is the *gasification zone*.

Further up in the bed, no oxidizing potential remains in the gases, and the effect is one of immersion of solid waste in a hot gas flow with pyrolysis reactions predominating. This is the *pyrolysis zone*.

In real situations, the bed is often split open in places due to the heterogeneous form of solid wastes. This leads to channeling or bypassing effects. Also, some air may be entrained into the bed from the overbed space. Further, differences in the point-to-point underfire air rate ($m^3/sec\ m^{-2}$) due to grate blinding and spatial variation in the density of combustible throughout any vertical plane in the bed lead to irregularity in volatilization patterns. The net result of these factors is to smudge the boundary between zones and to produce, at the top of the bed, a gas flow that varies moment to moment from fuel-rich to air-rich.

A. Thermal Decomposition

The thermal decomposition or pyrolysis of waste solids in the absence of air or under limited air supply occurs in most burning systems. Pyrolysis is a destructive distillation process effected by the application of heat in an insufficiency of air to yield gaseous, liquid

(after cooling), and solid products. In comparing suspension burning and mass burning processes, both involve pyrolysis of incoming solids, but for suspension burning the physical scale of the fuel-rich zone is smaller, and the pyrolysis products will differ due to the differences in heating rate. Figure 4 illustrates the sequence of steps in pyrolyzing an organic char-forming material.

Both physical and chemical changes occur in solids undergoing pyrolysis. The most important physical change in materials such as bituminous coal and some plastics is a softening effect resulting in a plastic mass, followed by resolidification. Cellulosic materials increase in porosity and swell as volatiles are evolved.

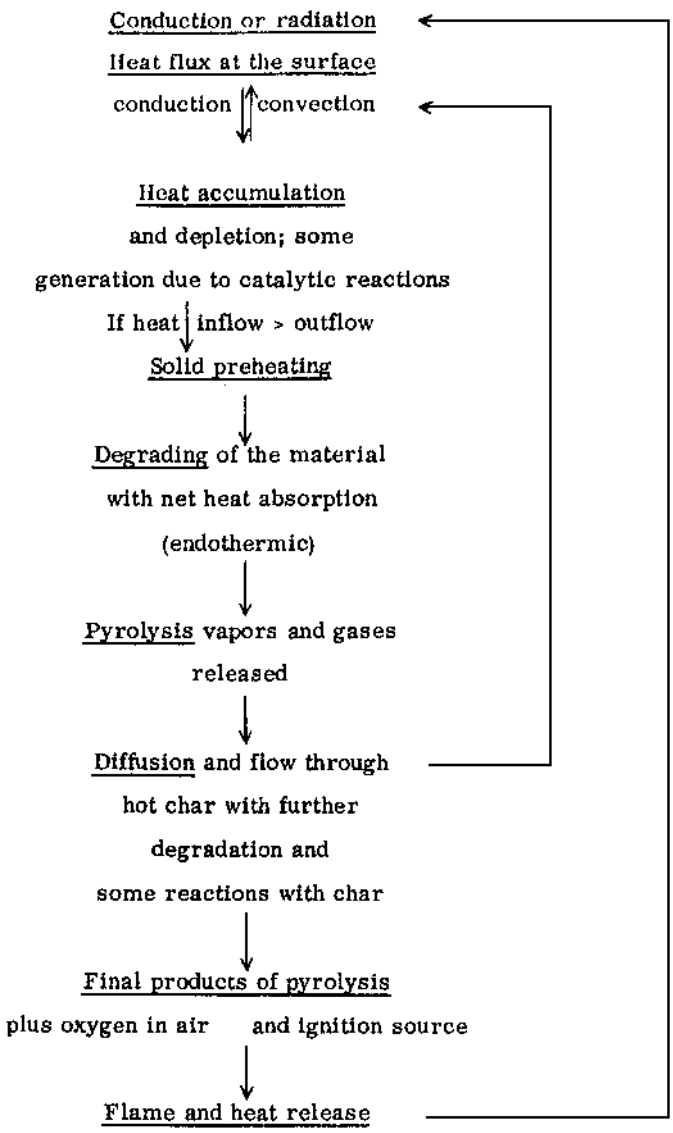


Figure 4 Process sequence in pyrolysis.

As cellulose pyrolysis begins (at about 200°C), complex, partially oxidized tars are evolved. As the temperature increases, these products further decompose or crack, forming simpler, more hydrogen-rich gaseous compounds and solid carbon. The solid residue approaches graphitic carbon in chemical composition and physical structure.

Whether the overall pyrolysis process of a given solid is endothermic or exothermic depends on the ultimate temperature attained. For most materials, the process is endothermic at lower temperatures and exothermic at higher temperatures.

The rate-controlling step in pyrolysis (the rate of heat transfer into the waste or the pyrolysis reaction rate) is dependent upon the temperature and the physical dimensions of the waste. Below 500°C, the pyrolysis reactions appear rate-controlling for waste pieces smaller than 1 cm in size. Above 500°C, pyrolysis reactions proceed rapidly, and heat transfer and product diffusion are rate-limiting. For large pieces (greater than 5 cm), heat transfer probably dominates for all temperatures of practical interest.

The upper temperature limit for pyrolysis weight loss is a function of the material being heated. For bituminous coal the weight loss achieved at 950°C is about as high as will be obtained at any practical temperature. Cellulose pyrolysis is essentially completed between 575° and 700°C.

1. Pyrolysis Time

The time required for pyrolysis of solid wastes can be estimated by assuming that the rate is controlled by the rate of heating. Neglecting energy absorption or generation by the reactions, one may estimate pyrolysis time by assuming the refuse piece (a plate or a sphere) is suddenly plunged into a hot reactor maintained at a high temperature. The pyrolysis (heating) time is defined here as the time required for the center temperature to rise by 95% of the initial temperature difference between the specimen and the surroundings. A thermal diffusivity of 3.6×10^{-4} m^2/hr was used; it is roughly equal to that of paper, wood, coal, and many other carbonaceous solids. Radiation and contact conduction are neglected. The results for thin plates or spheres (21) are shown in Figs. 5 and 6.

The effect of specimen size is evident, thus showing differences expected with size reduction. The effect of gas velocity is also significant and illustrates that in mass burning, where relative gas–solid velocities may range from 0.1 to 0.4 m/sec, slow pyrolysis times would be expected. The relatively long pyrolysis time calculated for small particles at very low (0–0.1 m/sec) relative velocity (as would be found in suspension burning) suggests strongly that other heat transfer mechanisms (especially radiation) can become of primary importance. The results for entirely radiant heating to the plate or sphere starting at an initial temperature of 20°C is shown in Figs. 5 and 6 as the heating time at infinite cross-flow velocity (V_∞). The indicated heating time requirement is seen to be large compared to the residence time in the radiant section of a boiler (approximately 1–2 sec) and thus, without considerable reduction in particle size of the feed, unburned material can enter the convection tube banks.

2. Pyrolysis Products

a. Liquid Products. The liquid product of pyrolysis is known to contain a complex mixture of alcohols, oils, and tars known as pyroligneous acids. Pyrolysate liquids from municipal refuse contain from 70% to 80% water with the remainder being a wide range of (often oxygenated) organic compounds. Specific compounds found in the pyrolysate include acetic acid, methanol, 2-methyl-1-propanol, 1-pentanol, 3-pentanol, 1,3-propane-

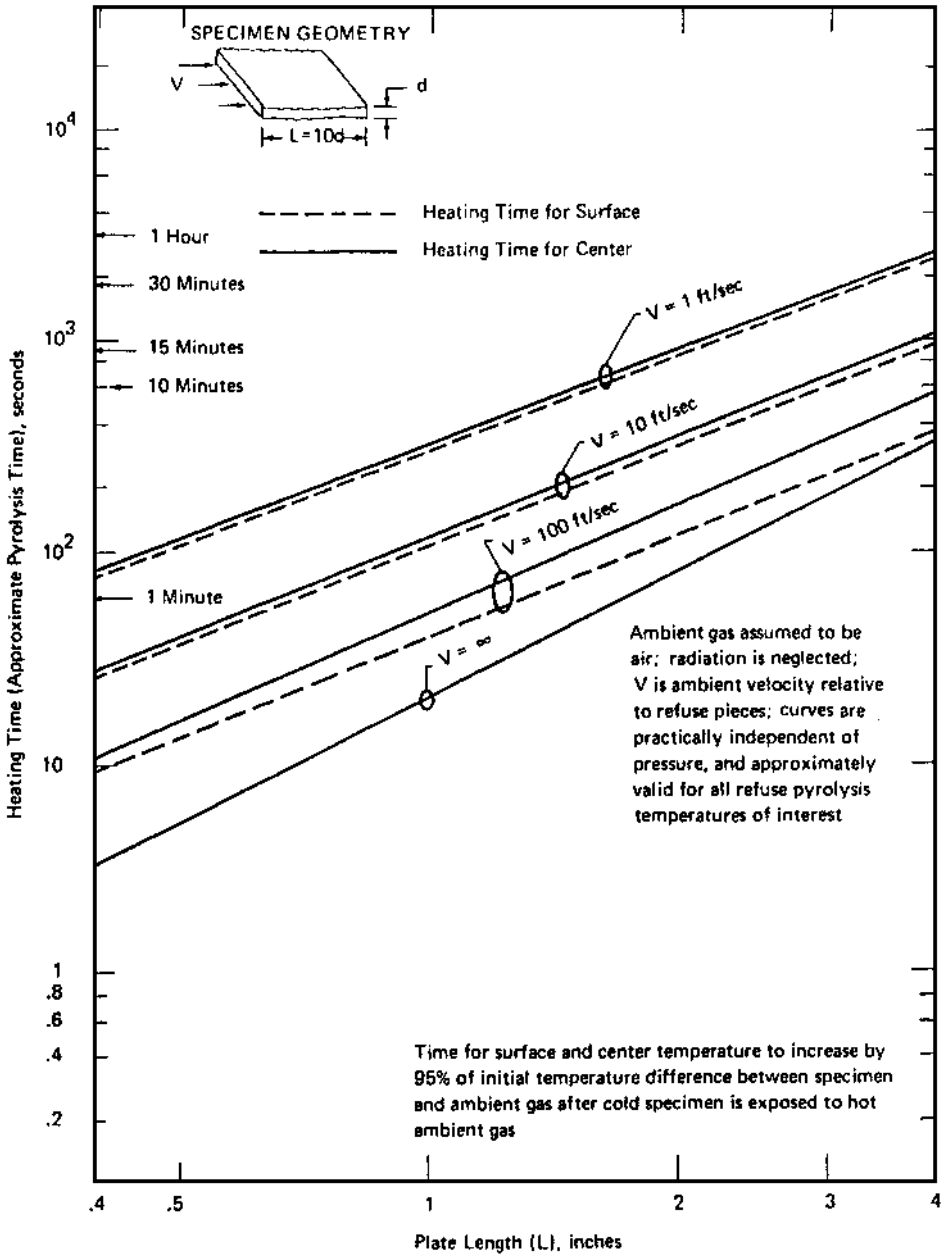


Figure 5 Radiative and convective heating time for a thin plate. (From Ref. 21.)

diol, and 1-hexanol. The composition is highly dependent upon refuse composition, heating rate, and ultimate temperature (see Tables 3, 4, and 5). The yield of liquid is approximately 50% to 60% of the air-dried, ash-free refuse, decreasing with increasing ultimate temperature. The heat content of the liquid per pound of refuse decreases as the pyrolysis temperature increases.

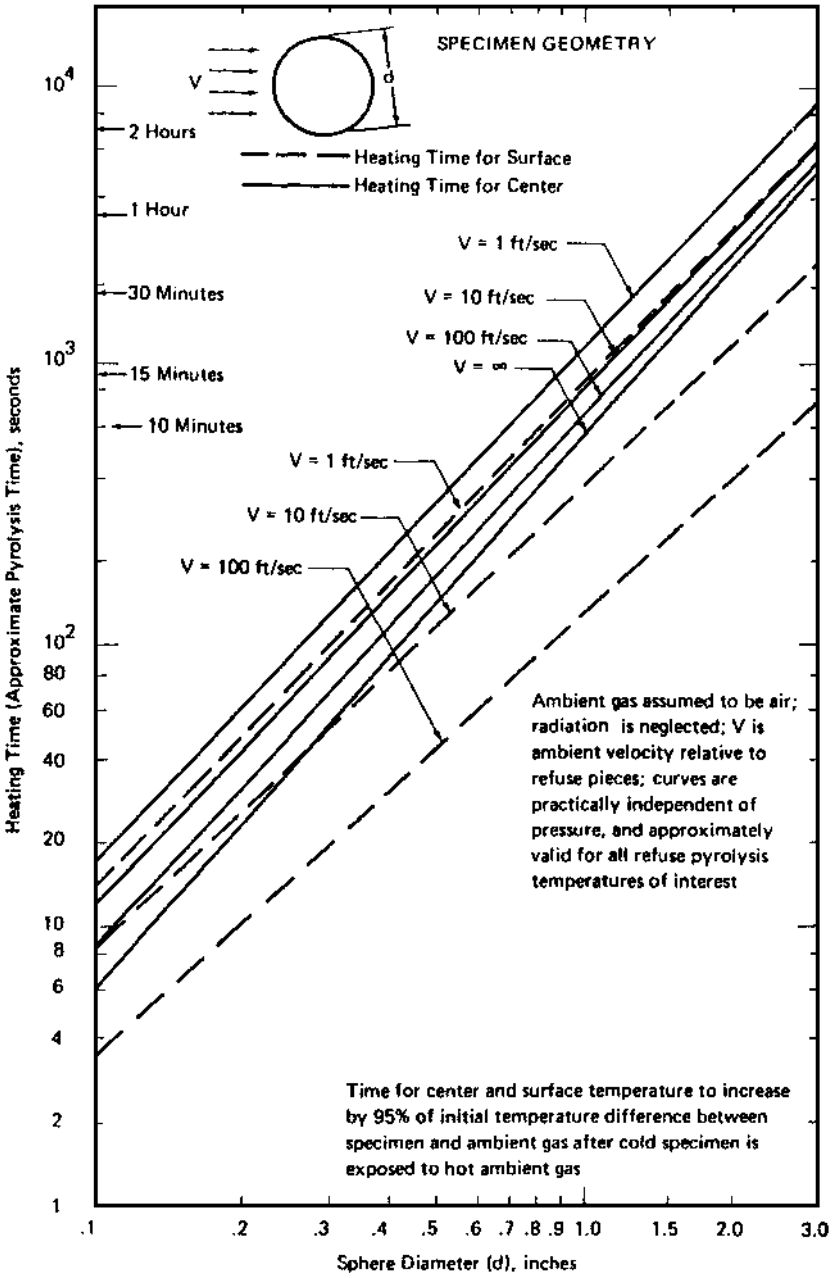


Figure 6 Radiative and convective heating time for a sphere. (From Ref. 21.)

A set of pyrolysis data were collected by Folks et al. (345) for thermophilic and mesophilic biological wastewater treatment sludge from the Hyperion treatment plant in Los Angeles. The pyrolysis experiments were run from 765° to 1004°C and produced char, pyrolysis oil, and gaseous products in the proportions 48.0%, 4.73%, 24.44% and 41.35%,

Table 3 Yields of Pyrolysis Products from Different Refuse Components (Weights Percent of Refuse)[a]

Component	Gas	Water	Other liquid	Char (Ash-free)	Ash
Cord hardwood	17.30	30.93	20.80	29.54	0.43
Rubber	17.29	3.91	42.45	27.50	8.85
White pine sawdust	20.41	32.78	24.50	22.17	0.14
Balsam spruce	29.98	21.03	28.61	17.31	3.07
Hardwood leaf mixture	22.29	31.87	12.27	29.75	3.82
Newspaper I	25.82	33.92	10.15	28.68	1.43
Newspaper II	29.30	31.36	10.80	27.11	1.43
Corrugated box paper	26.32	35.93	5.79	26.90	5.06
Brown paper	20.89	43.10	2.88	32.12	1.01
Magazine paper I	19.53	25.94	10.84	21.22	22.47
Magazine paper II	21.96	25.91	10.17	19.49	22.47
Lawn grass	26.15	24.73	11.46	31.47	6.19
Citrus fruit waste	31.21	29.99	17.50	18.12	3.18
Vegetable food waste	27.55	27.15	20.24	20.17	4.89
Mean values	24.25	23.50	22.67	24.72	11.30

[a]Refuse was shredded, air-dried, and pyrolyzed in a retort at 815°C. From Ref. 22.

Table 4 Yields of Pyrolysis Products from Refuse at Different Temperatures (Percent by Weight of Refuse Combustibles)[a]

Temperature (°C)	Gases	Liquid (including water)	Char
480	12.33	61.08	24.71
650	18.64	59.18	21.80
815	23.69	59.67	17.24
925	24.36	58.70	17.67

[a]From Ref. 23.

3.45%, 20.81% for the thermophilic and mesophilic sludges respectively. Table 6 shows a comparison between the characteristics of the pyrolysis oil in comparison to No. 6 fuel oil.

b. Gaseous Products. The yield, composition, and calorific value of gaseous pyrolysates depend upon the type of material, the heating rate, and the ultimate temperature. Table 3 shows that for typical refuse components, gas yield ranges from 17% to 31% of the air-dried feed. From Table 4 it can be seen that a doubling in gas yield occurs as the ultimate temperature is raised from 480° to 925°C. Table 5 indicates that the yield decreases, then increases with heating rate.

As the ultimate temperature increases, more of the combustion energy in the feed material appears in the gas product, although the data indicate that the gas calorific value does not show a regular variation (Table 7). Table 8 shows an increase in hydrogen and a

Table 5 Effect of Heating Rate on Pyrolysis Products and Heating Value of the Pyrolysis Gas from Newspaper[a]

Time taken to heat to 815°C (min)	Yield, weight percent of air-dried refuse				Heating value of gas, kcal/kg of newspaper
	Gas	Water	Other liquid	Char (Ash-free)	
1	36.35	24.08	19.14	19.10	1136
6	27.11	27.35	25.55	18.56	792
10	24.80	27.41	25.70	20.66	671
21	23.48	28.23	26.23	20.63	607
30	24.30	27.93	24.48	21.86	662
40	24.15	27.13	24.75	22.54	627
50	25.26	33.23	12.00	28.08	739
60	29.85	30.73	9.93	28.06	961
71	31.10	28.28	10.67	28.52	871

[a]From Ref. 22.

Table 6 Sewage Sludge Pyrolysis Oil Properties[a]

Property	No. 6 fuel oil	Sludge pyrolysis oil
Sulfur content (%)	0.7–3.5	0.72–1.35
kcal/kg	10,100	1,020–9,280
Specific gravity	0.98	0.79–0.84
kg/liter	0.985	0.796–0.846
kcal/liter	9,939	5,220–7,830

[a]From Ref. 345.

Table 7 Calorific Value of Pyrolysis Gases Obtained by Pyrolyzing Refuse at Different Temperatures[a]

Temperature (°C)	Gas yield per kg of refuse combustibles, (m^3)	Calorific value	
		kcal/m^3 gas	kcal/kg refuse combustibles
480	0.118	2670	316
650	0.173	3346	581
815	0.226	3061	692
925	0.211	3124	661

[a]From Ref. 23.

Table 8 Composition of Pyrolysis Gases Obtained by Pyrolyzing Refuse at Different Temperatures[a]

Temperature (°C)	Gas composition, % by volume					
	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6
480	5.56	12.43	33.50	44.77	0.45	3.03
650	16.58	15.91	30.49	31.78	2.18	3.06
815	28.55	13.73	34.12	20.59	2.24	0.77
925	32.48	10.45	35.25	18.31	2.43	1.07

[a]From Ref. 23.

drop in carbon dioxide as the ultimate temperature increases. Table 5 suggests that the heating value of cellulosic materials (represented by newsprint) first decreases, then increases with increasing heating rate. In general, pyrolysis of 1 kg of typical refuse combustibles yields from 0.125 to 0.185 m^3 of gas having a calorific value of about 3000 kcal/m^3; about one-third the calorific value of natural gas. Table 9 shows the composition of the gaseous products from pyrolysis of sewage sludge (345).

c. Solid Products. The solid product or char resulting from pyrolysis is an impure carbon. The proximate analysis of the char is similar to coal, with the rank of the corresponding coal increasing as the ultimate pyrolysis temperature increases. Char formed at 480°C is comparable to certain bituminous coals, whereas pyrolysis at 925°C produces an anthracite-like product. The yield of char ranges from 17% to 32% of the air-dried, ash-free feed, decreasing with increasing heating rate and ultimate temperature (Table 10). The calorific value of refuse char is around 6600 kcal/kg of air-dried char and decreases slowly as the ultimate temperature increases (Table 10). Data for the carbon and sulfur content and the heating value of the char formed by pyrolysis of sewage sludge (345) are shown in Table 11.

3. Thermal Decomposition Kinetics

Although the details of the complex chemistry and heat transfer processes controlling pyrolysis reactions in wastes (thick sections, often compounded of several materials,

Table 9 Composition of Pyrolytic Gases (Average Percent by Volume)

Temp. (°C)	Min.	H_2	O_2	N_2	CH_4	CO	C_2H_6	CO_2	C_2H_4
Thermophilic sludge									
795	105	25.0	2.2	18.9	18.8	12.7	3.6	26.5	1.9
849	75–165	31.5	7.4	14.3	12.55	19.6	1.27	15.25	0.67
854	15–165	30.6	6.82	13.9	14.1	16.88	1.32	10.56	1.88
927	15–45	26.6	0.9	15.25	13.3	16.55	0.7	23.9	1.4
1004	15–45	30.0	0.85	14.8	12.85	20.45	0.25	12.45	0.15
Mesophilic sludge									
867	30–60	13.4	1.75	61.2	3.25	7.4	0.2	13.3	0
860	30–60	17.95	1.8	53.2	4.65	8.4	0.25	14.4	0.15

Table 10 Comparison of Char Produced by Refuse Pyrolysis with Certain Coals[a]

Proximate analysis of air-dried material	Bituminous coal from lower Freeport Seam	Char resulting from refuse pyrolysis at different temperatures				Pennsylvania anthracite
		480°C	650°C	815°C	925°C	
Volatile matter %	23.84	21.81	15.05	8.13	8.30	8.47
Fixed carbon %	65.36	70.48	70.67	79.05	77.23	76.65
Ash %	8.61	7.71	14.28	12.82	14.47	11.50
kcal/kg of air-dried material	7880	6730	6820	6410	6330	7565

[a]From Ref. 21.

Table 11 Characteristics of Char from Pyrolysis of Sewage Sludge[a]

Pyrolysis temperature (°C)	Percent carbon	Percent sulfur	kcal/kg dry sludge	kcal/kg char
Thermophilic sludge				
593	17.0	0.82	626	1332
765	15.0	0.81	576	1193
849	16.3	0.76	628	1278
854	14.7	0.70	547	1152
927	13.3	0.57	541	1130
1004	13.0	0.40	494	1018
Mesophilic sludge				
867	7.8	0.58	253	613
860	8.1	0.54	261	633

[a]From Ref. 345.

anisotropic and heterogeneous in thermal and chemical properties) are not known, pyrolysis has been extensively studied for wood and synthetic polymers. Much of the general body of literature concerned with this topic is found under the heading "Fire Research" and derives its support from an interest in the basic processes that start and feed (or stop) conflagrations in manmade and natural combustible materials.

Studies by Kanury (24) using an x-ray technique to monitor density changes during the pyrolysis of wooden cylinders subjected to convective and radiative heating provide useful insight into pyrolysis kinetics. As a consequence of the x-ray technique, Kanury's analysis, summarized below, is based on density change rather than mass.

Based on convention (25, 27), surface pyrolysis of wood may be assumed to follow a first-order Arrhenius-type rate law

$$\frac{d\rho}{dt} = -k_1(\rho - \rho_c)\exp\left(\frac{-\Delta E}{RT}\right) \tag{17}$$

where

ρ = instantaneous density (g/cm) and subscripts c = char, v = virgin solid
t = time (min)
k_1 = pre-exponential factor (min^{-1})
ΔE = activation energy (kcal/kg mol)
R = universal gas constant (1.987 cal mol^{-1} K^{-1})
t = Absolute temperature (K) and subscript 0 indicates initial conditions

Kanury plotted $(\rho - \rho_c)^{-1}$ $(d\rho/dt)$ versus $1/T$ on semi-log paper to test the validity of Eq. (17) and found good agreement with an activation energy (ΔE) of about 19,000 kcal/kg mol and a pre-exponential frequency factor of about 10^6 min^{-1}.

Observation of the surface temperature with a microthermocouple indicated an approximately linear change with time:

$$T = T_0 + a_1 t \tag{18}$$

Combining Eq. (17) and (18) and integrating yield

$$\ln\left[\frac{\rho - \rho_c}{\rho_v - \rho_c}\right] = \frac{-k_1 \Delta E}{a_1 R}[\gamma_0(\zeta) - \gamma_0(\zeta_0)] + \int_{\zeta_0}^{\zeta} \gamma_0(\zeta) d\zeta \tag{19}$$

where

$$\zeta = \frac{\Delta E}{RT}$$

$$\gamma_0(\zeta) \equiv \frac{1}{\zeta}\exp(-\zeta)$$

Integration of $\gamma_\theta(\zeta)$ yields

$$\int \gamma_0(\zeta) d\zeta = \ln \zeta + \sum_{n=1}^{\infty} \frac{(-1)^n \zeta^n}{(n)(n!)} \tag{20}$$

The right side of Eq. (20) converges for positive ζ, and the exponential integral of the first-order $\gamma_1(\zeta)$ is defined as

$$\int \gamma_1(\zeta) = -0.5772 - \left(\ln \zeta + \sum_{n=1}^{\infty} \frac{(-1)^n \zeta^n}{(n)(n!)}\right) = \int_{\zeta}^{\infty} \gamma_0(\zeta) d\zeta$$

Therefore

$$\int_0^{\infty} \gamma_0(\zeta) d\zeta = \gamma_1(\zeta_0) - \gamma_1(\zeta) \tag{21}$$

Substituting Eq. (21) into Eq. (19)

$$\ln\left(\frac{\rho - \rho_c}{\rho_v - \rho_c}\right) = \frac{-k_1 \Delta E}{a_1 R}[\gamma_0(\zeta) - \gamma_0(\zeta_0) + \gamma_1(\zeta_0) - \gamma_1(\zeta)]$$

Since ζ_0 is usually $\gg 30$, $\gamma_0(\zeta_0)$ and $\gamma_1(\zeta_0)$ are of the order of 10^{-10} and may be neglected, yielding

$$\ln\left(\frac{\rho - \rho_c}{\rho_v - \rho_c}\right) \approx \frac{-k_1 \Delta E}{a_1 R}[\gamma_0(\zeta) - \gamma_1(\zeta)] \tag{22}$$

$\gamma_0(\zeta)$ and $\gamma_1(\zeta)$ are tabulated in standard texts.

Kanury's experimental data on the surface density–time function was in excellent agreement with a prediction based on the experimentally determined value for a_1 of 50 K/min.

Kanury's data also showed two plateaus in the pyrolysis rate: at 100° and 350°C. The plateau at 100°C is, most likely, associated with supply of the latent heat of evaporation of moisture in the wood. The plateau at 350°C is suspected to be due to the resistance to mass flow and diffusion of the pyrolysis gases offered by the char layer. It was noted, in support of this hypothesis, that the 350°C plateau was absent in pyrolysis of the surface layers or when major cracks and fissures appeared as the solid near the axis of the cylinder pyrolyzed.

Kanury also observed that if the pyrolysis rate becomes constant (in the plateau region), then from Eq. (18):

$$\frac{d\rho}{dt} = \text{constant} = -a_2(\rho_v - \rho_c)$$

A plot of the data from $\Delta E/R = 9500$ K gave satisfactory agreement for

$$\left(\frac{\rho - \rho_c}{\rho_v - \rho_c}\right) = \frac{a_2}{k_1}\exp\left(\frac{\Delta E}{RT}\right) = 1.436 \times 10^{-7}\exp\left(\frac{\Delta E}{RT}\right) \tag{23}$$

The slope of the plot of the log of the l.h.s. of Eq. (23) versus $1/T$ K had a slope of unity, thus providing additional confirmation of the first-order reaction rate expression.

Another observation was that the pyrolysis rate, after attaining its maximum value, fell in a manner somewhat like an exponential, namely,

$$\left(\frac{\rho - \rho_c}{\rho_v - \rho_c}\right)\frac{d\rho}{dt} = -a_3\exp(-a_4 t) \tag{24}$$

Integration yields

$$\left(\frac{\rho - \rho_c}{\rho_v - \rho_c}\right) = \frac{a_3}{a_4}\exp(-a_4 t) + a_5 \tag{25}$$

Since, as t becomes large, the exponential tends to zero and ρ approaches ρ_c, a_5 is 0. Plotting the data for the pyrolysis rate in the inner layers $a_3 = 1.404\ \text{min}^{-1}$ and $a_4 = 0.216\ \text{min}^{-1}$ or

$$\left(\frac{\rho - \rho_c}{\rho_v - \rho_c}\right) = 6.5\exp(-0.216t) \tag{26}$$

Eliminating the exponential between Eqs. (24) and (26), and substituting into Eq. (17), yield

$$k_1\exp\left(\frac{-\Delta E}{RT}\right) \approx 0.216 \quad \text{(a constant)} \tag{27}$$

For $k_1 = 10^6\ \text{min}^{-1}$ and $\Delta E/R = 9500$ K, $T = 619$ K or 346°C, the observed plateau temperature. In summary, then, it would appear that the wood cellulose pyrolysis process consists first of an essentially nonreacting thermal heating stage with moisture loss to about 350°C. Then, pyrolysis occurs at a rapid rate, followed by further heating of the char residue through conduction and radiation from the exposed surface.

Data by Shivadev and Emmons on thermal degradation of paper (28) also showed a plateau in a temperature range about 350°C. Their experiments involved radiant heating of

filter paper samples. They deduced reaction rate constants and energy release terms by radiating preweighed specimens for progressively longer time periods and then determining the total weight loss as a function of time. Temperatures in the specimen were evaluated by considering the specimens to be thermally thin and thus rapidly attaining an equilibrium temperature related to the radiative flux level, the absorptivity of the surface, and material properties, all of which were either known or measured.

Shivardev and Emmons fitted their mass-loss (surface density m) and temperature data with two expressions. The first, for temperatures below 655 K (382°C) is

$$\frac{dm}{dt} = -5.9 \times 10^6 \exp\left(\frac{-26{,}000}{RT}\right) \text{ g cm}^{-2} \text{ sec}^{-1} \tag{28a}$$

For temperatures above 655 K they found

$$\frac{dm}{dt} = -1.9 \times 10^{16} \exp\left(\frac{-54{,}000}{RT}\right) \text{ g cm}^{-2} \text{ sec}^{-1} \tag{28b}$$

They speculated that the expression for the high-temperature reaction may incorporate combustion effects of the pyrolysis gases. It is noteworthy here that in associated studies of ignition, the inflection temperature associated with ignition was 680 ± 15 K. The numerical values obtained are in rough agreement with the Kanury data.

Chiang et al. (445) studied the kinetics of petrochemical sludge pyrolysis. In an isothermal reactor, sludge was heated with nitrogen to temperatures from 400° to 800°C for times from 1 to 60 minutes. Pyrolysis products (both solid residues and volatilized liquids) were analyzed.

The pyrolysis process was characterized using the equation

$$r = \frac{dx}{dt} = k(1-x)^n = A \exp\left[-\frac{E_a}{RT}\right] \cdot (1-x)^n \tag{29}$$

where

r = reaction rate of pyrolysis
x = transformation rate given as

$$x = \frac{W - W_f}{W_0 - W_f}$$

t = pyrolysis time (sec)
k = Arrhenius constant
W_0 = sludge weight at $t = 0$
W_f = sludge weight at $t = \infty$
a = frequency factor sec^{-1}
E_a = activation energy (kcal/kg mol)
R = universal gas constant
T = absolute temperature (K)
n = apparent order of reaction

The composition of sludge and the solid residues are shown in Table 12. The reaction order and activation energy were 2.5 and 2,640 kcal/kg mol, respectively. The average Arrhenius constant was 0.0616 sec^{-1}.

Table 12 Elemental Composition of Sludge at Differing Pyrolysis Temperatures[a]

Temperature (°C)	Residue	%C	%O	%H	%N	%S	%Ash
105 (raw sludge)	18.9	39.0	24.4	5.7	4.75	1.18	24.97
400	13.8	42.4	24.4	2.79	6.38	1.87	22.16
500	10.7	41.5	18.1	2.36	3.42	2.41	32.21
600	9.7	40.6	11.6	1.92	2.59	1.96	41.33
700	8.2	39.3	9.17	1.62	2.00	2.45	45.46
800	8.6	38.5	8.54	1.50	1.92	2.50	47.04

[a]Sludge dried at 105°C for 24 hours. Sludge pyrolysis time: 30 minutes.
Source: From (445).

Table 13 Kinematic Parameters of Scrap Tire Materials

Material	$\ln A$ (min^{-1})	ΔE (kJ/g mol)
Processing oils in natural and polybutadiene rubber	7.84	48.0
Processing oils in styrene–butadiene rubber	7.56	43.3
Natural rubber	38.20	207.0
Butadiene rubber	34.08	215.0
Styrene–butadiene rubber	24.02	148.0

Source: From (448).

Scrap automobile tires were also subjected to pyrolytic conditions using derivative thermogravimetric (DTG) and thermogravimetric analysis. In their investigations, Kim et al. (446) studied the pyrolysis kinetics and mechanisms for the compositional components of two different sections of scrap tire rubbers: sidewall and tread. They found that the breakdown of each of the compounds comprising the tires followed a irreversible, one-step decomposition mechanism.

The tires used in their experiments involved tread (comprised of two types of styrene-butadiene rubber) and sidewalls (a mixture of natural rubber and polybutadiene rubber). The resulting kinetic constants are shown in Table 13. The decomposition left a residue approximating 34% of the initial weight: approximately 28% of the carbon black originally in the tire compounds and not lost in the pyrolysis event, plus about 6% ascribed to char residues of the thermal decomposition.

B. Particle Burning Processes

The combustion of solids as finely divided solid particles is most commonly seen in pulverized coal boilers. Also, however, many agricultural residues (e.g., sawdust) and other wastes (e.g., dried sewage sludge) are pneumatically conveyed and blown into combustors.

In the combustion of most solid particles, the rate is most strongly influenced by the rate of heat transfer to the surface. This leads to surface heating, pyrolytic breakdown and gasification, and combustion in a diffusion flame surrounding the particle. Surface heating by radiation from the flame accelerates pyrolysis, finally yielding a residue devoid of

Table 14 Combustion Properties of Carbon and Metals

Fuel	Oxide	Fuel density (g/cm^3)	M_{fuel}	M_{oxide}	B.P.$_{fuel}$ °C	B.P.$_{oxide}$ °C	f	B_{oxygen}	B_{air}	$t_b \times 10^{-5}$(sec)* (in O_2)	$t_b \times 10^{-5}$(sec)* (in air)
Al	Al_2O_3	2.700	27.000	101.900	2,467	2,980	1.120	1.120	0.260	0.900	2.930
Be	BeO	1.840	9.000	25.000	2,970	3,900	0.564	0.564	0.131	1.040	3.790
B	B_2O_3	2.340	10.800	69.600	2,550	1,860	0.451	0.451	0.105	1.570	6.150
Ca	CaO	1.550	40.100	56.100	1,487	2,850	2.500	2.500	0.580	31.000	0.850
C	CO	1.50[a]	12.000	28.000	4,827	(191)	0.750	0.750	0.174	0.670[b]	2.280[c]
C	CO_2	1.50[a]	12.000	44.000	4,827	(79)	0.375	0.375	0.087	1.160[d]	4.160[e]
Hf	HfO_2	13.300	178.500	210.600	5,400	—	5.590	5.590	1.300	1.760	3.980
La	La_2O	6.160	139.000	325.800	3,469	4,200	5.790	5.790	1.341	0.810	1.820
Li	Li_2O_3	0.530	6.900	29.900	1,317	1,200	0.865	0.865	0.200	0.210	0.730
Mg	MgO	1.740	24.300	40.300	1,107	3,600	1.520	1.520	0.353	0.470	1.450
Pu	PuO_2	19.840	242.000	274.000	3,235	—	7.560	7.560	1.755	2.310	4.900
K	K_2O	0.860	39.000	94.200	774	—	4.890	4.890	1.134	0.120	0.280
K	K_2O_2	0.860	39.000	110.200	774	—	2.440	2.440	0.567	0.170	0.480
Si	SiO_2	2.350	28.100	60.100	2,355	2,230	0.879	0.879	0.204	0.930	3.230
Na	Na_2O_2	0.970	23.000	78.000	892	657	1.437	1.437	0.334	0.270	0.850
Th	ThO_2	11.300	232.000	264.100	4,000	4,400	7.260	7.260	1.685	1.340	2.870
Ti	TiO_2	4.500	48.000	79.900	3,260	2,750	1.497	1.497	0.347	1.230	3.750
U	UO_2	19.050	238.000	270.000	3,818	2,500	7.430	7.430	1.726	2.230	4.740
U	U_3O_8	19.000	238.500	842.000	3,818	—	5.580	5.580	1.294	2.520	5.730
Zr	ZrO_2	6.440	91.200	123.200	3,578	5,000	2.850	2.850	0.662	1.200	3.190

*For 1 micron (10^{-4} cm) particles, $\rho_g D$ is assumed as 5×10^{-4} g/cm/sec.
[a]1.30–1.70
[b]0.58–0.76
[c]1.97–2.58
[d]1.01–1.32
[e]3.78–4.95
Source: From (435).

volatiles. Oxygen diffuses to the solid surface, releasing heat and further raising the solid temperature.

Kanury (435) analyzed the process of solid particle combustion to yield an estimate of the time required to completely burn a particle of initial diameter d_0 as

$$t_b = \frac{\rho_F d_0^2}{8\rho_g D_0 \ln(B+1)} \tag{29}$$

where

ρ_F = density of the particle (g/cm^3)
d_0 = initial particle diameter (cm)
$\rho_g D_0$ = product of density and diffusivity of the surrounding gas (g/cm/sec)
B = mass transfer number (dimensionless) = $fY_{O\infty}$
f = normalized oxygen requirement of the waste (g O_2/g waste)
$Y_{O\infty}$ = mass concentration of oxygen in the surrounding gas (0.232 for air)

Values of the key variables are shown in Table 14.

C. Mass Burning Processes

In the idealized mass burning model described above it was postulated that in thick beds the upper regions could behave as a true pyrolyzer. Evidence (29, 30) for coal and refuse beds would tend either to discount the existence of the pyrolysis zone or, more probably, to suggest that this zone does not appear in beds of practical thickness. Thus, the off-gas from a bed would be a mixture of gases from both burning and gasification zones.

Studies (30, 377) of the off-gas from beds of burning refuse in a municipal incinerator have confirmed the earlier data of Kaiser (31) and the hypothesis (21) that the off-gas composition is controlled by the water–gas shift equilibrium. This equilibrium describes the relative concentration of reactants in the following:

$$\mathrm{H_2O + CO \leftrightarrows CO_2 + H_2}$$
$$K_p = \frac{p_{H_2O}\, p_{CO}}{p_{CO_2} p_{H_2}} \tag{30}$$

The importance of this equilibrium in mass burning is the incremental gasification potential given to the underfire air. In tests in Newton, Massachusetts (30), refuse and off-gas stoichiometry were studied. Average refuse was given the mole ratio formula $CH_{1.585}O_{0.625}(H_2O)_{0.655}$. For this formula and assuming that the water–gas shift equilibrium holds, over 1.5 times as much refuse can be gasified by a given quantity of air as would be predicted for stoichiometric combustion to CO_2 and H_2O. Burning/gasification rate data showed rates 1.7 to 2.1 times those corresponding to stoichiometric combustion.

A second result coming from the water–gas shift reaction is that a definite and relatively large combustion air requirement will necessarily be placed on the overfire volume. The air requirement for the CO, H_2, distilled tars, and light hydrocarbons can, indeed, be as much as 30% to 40% of that expended in gasification, thus creating a need for effective overfire air injection and mixing.

4

Waste Characterization

The first step in solving waste management problems is to abandon the hopeless view that "waste" is an indefinite state of matter tied to its genesis as the unusable residue of a process or an unwanted discard of human activity. Instead, waste should be regarded in its own right as a feedstock, a fuel, and/or a potentially useful material. In this new light, the analyst then must seek to determine values for the physical and chemical engineering properties that, though less consistent than those of conventional materials and fossil fuels, nonetheless are the defining measures that characterize behavior.

Supporting this line of thought, one must discard the sense that "waste" is so heterogeneous in its composition and so variable in its properties that problems with its proper management and use cannot be defined, let alone solved. To be sure, waste streams will often exhibit great variability point to point and over time. The designer must, therefore, provide processes with more operating flexibility, reserve capacity, and materials "stamina" than conventional process equipment. But the development of a working estimate of average waste composition and properties along with a sense of the expected excursions from those averages is the necessary starting point of design.

Several properties important in waste characterization are shown in Table 1 (107). Although it is seldom necessary to characterize wastes in all the areas in Table 1, such a checklist can be useful in alerting the waste manager to processing constraints and opportunities, permitting requirements, or safety hazards.

Desired data are often lacking to precisely define the design basis for waste processing systems. Many waste studies have demonstrated the large errors possible from desk-top estimates of the generation rate, composition, or properties of waste. It is strongly recommended, therefore, that especially commissioned waste surveys and analyses should be incorporated into the problem definition phase of the design effort.

Careful consideration should also be given to the range of variation in composition. For municipal waste, for example, seasonal changes in yard waste content and local precipitation patterns lead to day-to-day fluctuations in moisture content. Economic class, geographical region, culinary preferences, and residential styles (homes, apartments, hotels, and campgrounds) are significant. In industry, seasonal shifts in production patterns or periodic housekeeping activity leads to variation.

Table 1 General, Physical, and Chemical Parameters of Possible Significance in the Characterization of Solid Wastes[a]

General parameters	
Compositional weight fractions	Process weight fractions
Domestic, commercial, and institutional	Combustible
Paper (broken into subcategories)	Compostable
Food waste	Processable by landfill
Textiles	Salvageable
Glass and other ceramics	Having intrinsic value
Plastics	
Rubber	
Leather	
Metals	
Wood (limbs, sawdust)	
Bricks, stones, dirt, ashes	
Other municipal	
Dead animals	
Street sweepings	
Catch-basin cleanings	
Agricultural	
Field	
Processing	
Animal raising	
Industrial	

Mining/metallurgical

Special
Radioactive
Munitions, etc.
Pathogenic

Physical parameters

Total wastes	Solid wastes	Liquid wastes	Gaseous wastes
Size	Souble (%)	Turbidity	Temperature
Shape	Suspendable (%)	Color	Pressure
Volume	Combustible (%)	Taste	Volume
Weight	Volatile (%)	Odor	Density
Density	Ash (%)	Temperature	Particulate (%)
stratification	soluble (%)	Viscosity data	Liquid (%)
Surface area	suspendable	specific gravity	
Compaction	Hardness	stratification	
Compactibility	Particle-size distribution	Total solids (%)	
Temperature	shape	soluble (%)	
Color	surface	suspended (%)	
Odor	porosity	settleable (%)	
Age	sorption	Dissolved oxygen	
Radioactivity	density	Vapor pressure	
Physical state	aggregation	Effect of shear rate	
total solids		Effect of temperature	
liquid		Gel formation	
gas			

Table 1 (continued)

Chemical parameters		
General	Organic	Inorganic and elemental
pH	Soluble (%)	Moisture content
Alkalinity	Protein nitrogen	Carbon
Hardness ($CaCO_3$)	Phosphorus	Hydrogen
MBAS (methylene blue active substances)	Lipids	(P_2O_5 and phosphate)
BOD (biochemical oxygen demand)	Starches	Sulfur content
COD (chemical oxygen demand)	Sugars	Alkali metals
Rate of availability of nitrogen	Hemicelluloses	Alkaline-earth metals
Rate of availability of phosphorus	Lignins	Heavy metals
Crude fiber	Phenols	especially Mercury
Organic (%)	Benzene oil	Lead
Combustion parameters	ABS (alkyl benzene sulfonate)	Cadmium
Heat content	CCE (carbon chloroform extract)	Copper
Oxygen requirement	PCB (polychlorinated biphenyls)	Nickel
Flame temperature	PNH (polynuclear hydrocarbons)	Toxic materials
Combustion products (including ash)	Vitamins (e.g., B-12)	Chromium
Flash point	Insecticides (e.g., Heptachlor,	especially Arsenic
Ash fusion characterization	DDT, Dieldrin, etc.)	Selenium
Pyrolysis characterization		Beryllium
Toxicity		Asbestos
Corrosivity		Eutrophic materials
Explosivity		Nitrogen
Other safety factors		Potassium
Biological stability		Phosphorus
Attractiveness to vermin		Precious metals

[a]Source: Ref. 107.

Such changes in waste characteristics must be provided for in the design and operating protocols of waste processing systems. Even with such relatively obvious foresight, however, the worst (live ammunition, cans of flammable solvent, containers of toxic chemical, etc.) should be anticipated.

> The cardinal rule in waste management design is to ask, "What happens when. . .?" rather than "What if. . .?"

Although the analysis of the specific wastes to be processed is desirable, it is useful to have some general data for preliminary screening of concepts. The data presented below meet this need. In general, these data were generated by methodical sampling, segregation, weighing, and/or analysis of the waste streams. More comprehensive data can be found elsewhere (108).

I. GENERAL

A. Chemistry

The relative importance of the chemical composition of a waste is generally greater for sludge/solid wastes than for liquids and much more so than for gases. This generalization derives from the usually large fraction of noncombustible inorganic constituents in solid wastes and the frequently important impact of these elements on system design. The presence of toxic elements and compounds also is important through the resulting impact on worker safety, combustion system efficiency requirements, air pollution control, and/or designation of the unit as a "hazardous waste incinerator."

Carbon, hydrogen, and oxygen are clearly important as the primary elements constituting the fuel fraction of a waste. From data on CHO alone, most of the contribution to the heating value may be estimated.

Nitrogen is modestly important as it appears in fuel value calculations but can be significant as it affects the generation of NO_x air pollution (via the "fuel nitrogen" mechanism).

Sulfur in the waste as the element, and that appearing in organic sulfur compounds or inorganic sulfides, is important as it can result in the generation of the acid gases SO_2 and SO_3 during incineration, which impacts on air pollution and corrosion.

Chlorine content as organic chlorides generating HCl is also important as it affects air pollution and boiler corrosion. Note that the high-temperature corrosion caused by chloride in the ash layer on the tubes has been observed to decrease as the sulfur content of the waste increases.

Phosphorous can be important primarily as it affects the melting point of residues and slag deposits. Incineration of organophosphate pesticides produces phosphorous pentoxide that significantly depresses the slag fusion temperature. Some inorganic phosphates depress the ash melting point. Insoluble ferric phosphate, for example, is often formed as a reaction product to remove soluble phosphates as a step in wastewater treatment. Unless lime ($Ca(OH)_2$) is added in slight excess of the amount stoichiometrically balanced with the ferric phosphate to form calcium triphosphate, the sludge ash fusion temperature can be depressed below 800°C and slagging problems can develop in sludge incineration systems.

Potassium and sodium content are important as they indicate the presence of low-melting compounds (e.g., NaCl, $NaSO_4$) which affect slag fusion temperature. The sodium

chloride–sulfate eutectic is particularly troublesome in burning refinery and petrochemical sludges.

Toxic organic compounds are clearly important as they impact worker safety and the requirement for effective combustion and combustion control. Stack emission of many specific organic compounds that have demonstrable health effects at low concentrations (e.g., benzene and vinyl chloride monomer) is limited in many countries by the air pollution regulations.

Heavy metals and other toxic elements (especially Cd, Hg, Pb, Zn, Cr, Cu, Be, As, Se, Ni, and Ag) are important since combustion will not destroy them: They will appear in the residue and in the fly ash, thus, perhaps, rendering the residues subject to the hazardous waste regulations with consequent ballooning of the cost, liability, and administrative complexity of residue disposal.

Those toxic elements with compounds that volatilize at combustion temperatures (especially the chlorides and some oxides of Cd, Hg, Pb, Zn, As, Se, and Ag) are of interest since they will often be emitted from the stack as a submicron particulate and as a deposit on other finely divided particulates. Most data indicate a significant "enrichment" of the content of these volatile elements in the particulate relative to that in the raw waste (see Chapter 13).

Ash chemistry can be used to give insight into possible problems with refractory attack and ash fusion (slagging) problems.

B. Heat of Combustion

In the analysis and design of incineration systems, few waste parameters are as important as the heat of combustion. A fundamental approach to estimation of this quantity is described in Chapter 2, Section I. The correlations and estimation tools supplied here are more tailored to the waste incineration field and, in some cases, may be more easily applied.

All of the estimation methods are based on use of the ultimate analysis to synthesize the mean heat of combustion. As such, their accuracy is dependent on the accuracy of the underlying ultimate analysis. Several of the methods are refinements of the Dulong formula. The original application of Dulong's formula was in estimation of the heat of combustion of coal. The underlying assumption of the Dulong formula (2) assumes a negligible heat of formation of the organic matter relative to the heat of combustion of the elements:

$$\begin{aligned}\text{kcal/kg (dry basis)} = {} & 8{,}080\ (\text{weight fraction carbon}) \\ & + 34{,}460\ (\text{weight fraction hydrogen}) \\ & - 4{,}308\ (\text{weight fraction oxygen}) \\ & + 2{,}250\ (\text{weight fraction sulfur}) \end{aligned} \tag{1}$$

A more complete expression (3) developed for municipal solid wastes incorporates compensation for the heat losses in calcining carbonate carbon and for nitrogen. Its use requires knowledge of the weight fraction (dry basis) of organic and inorganic (carbonate)

carbon, oxygen, sulfur, hydrogen, and nitrogen (denoted C_{org}, C_{inorg}, O, S, H, and N, respectively) in the waste sample. The equation is

$$\text{kcal/kg (dry basis)} = 7{,}831\ C_{org} + 35{,}932\ (H_2 - O_2/8) + 2{,}212\ S - 3{,}545\ C_{inorg} + 1{,}187\ O_2 + 578\ N_2 \quad (2)$$

EXAMPLE 1. Using the Dulong equation, estimate the heating value of a waste with the composition: 45.85% organic carbon, 0.83% inorganic carbon, 6.61% hydrogen, 35.94% oxygen, 1.03% nitrogen, 0.1% sulfur, and 9.64% ash.

$$\text{kcal/kg (dry basis)} = 7{,}831(0.4585) + 35{,}932\left(0.066 - \frac{0.3594}{8}\right) + 2{,}212(0.001) - 3{,}545(0.0083) + 1{,}187(0.3594) + 578(0.0103) = 4{,}747\ \text{kcal/kg}$$

The three heating value estimation relationships that follow were developed to estimate the heat of combustion (ΔH_c) of the combustible fraction of industrial and municipal wastes (kcal/kg) on a moisture and ash-free or "MAF" basis. *One must use the weight percent of hydrogen* (H), *oxygen* (O), *sulfur* (S), *etc.*, *on a dry, ash-free basis and substitute the percent* (not *the decimal percent*) *value in the equations*. The Vondracek value is on an as-fired basis and the waste analysis is input as noted.

Chang equation

$$\Delta H_c = 8561.11 + 179.72\text{H} - 63.89\text{S} - 111.17\text{O} - 90.00\text{Cl} - 66.94\text{N} \quad (3)$$

Modified Dulong equation

$$\Delta H_c = 78.31\text{C} + 359.32(\text{H} - \text{O}/8) + 22.12\text{S} + 11.87\text{O} + 5.78\text{N} \quad (4)$$

Boie equation

$$\Delta H_c = 83.22\text{C} + 275.48\text{H} - 25.8\text{O} + 15.0\text{N} + 9.4\text{Cl} + 18.5\text{F} + 65.0\text{P} + 12.2\text{Fe} \quad (5)$$

Vondracek equation

$$\Delta H_c\ \text{(as fired)} = \text{C}(89.17 - 0.0622\text{C}_1) + 270(\text{H} - \text{O}/10) + 25\text{S} \quad (6)$$

For the Vondracek equation, C_1 is the carbon content on a moisture and ash-free basis and C, H, O, and S are the percents of the elements on an as-fired (wet) basis.

The Chang equation (205), the modified Dulong equation, the Boie equation, and the Vondracek equation were tested against one another for the prediction of the heat of combustion of 150 pure organic compounds where laboratory data were available to test the accuracy of prediction. In this comparison, the average error relative to the laboratory value was for Chang, 1.48%; for Dulong, 5.54%; and for Boie, 11.38%.

Chang's equation was clearly superior for this task. However, the Boie equation was originally developed and is well regarded for estimation of the heat of combustion of mixed wastes (especially high cellulosic material) such as refuse or wood. An analysis by Rigo (206) suggests that Vondracek and Boie are, statistically, equivalent estimators of

heat content. The modified Dulong equation is generally best for fuel-like, high-carbon/hydrogen materials such as coal, peat, or lignite, but Rigo (206) found it less accurate for refuse predictions.

Each of the prediction equations relates heat content to waste chemistry. It is not surprising, therefore, that an evaluation of data for wastes and fuels shows that the heat release and the air requirement (also derived from waste chemistry) are, approximately, in a constant proportion (Table 2). Although the stoichiometric air requirement per million kcal for refuse is in line with that for other fuels, refuse has a relatively low air requirement per kilogram of fuel. Since refuse is now burned at bed depths that approximate coal heat release rates (kcal hr^{-1} m^{-2}), the air rates (m^3 sec^{-1} m^{-2}) could, in principle, be similar to those used for coal stokers. In practice, however, much higher air rates are used in incinerators to assist with drying and to temper ultimate combustion temperatures.

Incineration is often considered for the disposal of wastewater containing high concentrations of organic material. The contaminant concentration of these wastes is often determined as the chemical oxygen demand, or COD. For this test, the oxygen uptake from a highly oxidizing chemical (often chromic acid) is used. The results are reported in milligrams (of oxygen) per liter. As noted in Table 2, the higher heating value for a wide variety of fuels is approximately the same per unit weight of oxygen: about 1360 kg of air per million kcal heat release. This equivalence can, therefore, be used to estimate the heat content of such aqueous wastes. It should be noted that some classes of organic compounds (e.g., many aromatic compounds) are incompletely oxidized in the COD test procedure. Thus, estimates of combustion parameters from COD determinations may be in error (on the low side) depending upon the concentration of these chemically refractory materials.

Lastly, it should be noted that due to the approximate equivalence of heating value with air requirement, not only can one estimate heating value from combustion stoichiometry but the reverse may also be useful: estimation of the theoretical combustion air requirement from bomb calorimeter or other data on heating value.

EXAMPLE 2. Estimate the theoretical air requirement and the heating value for methane (CH_4), which has a HHV of 13,275 kcal/kg. Also, estimate the theoretical air requirement for a waste of unknown composition that, from bomb calorimeter tests, has a heating value of 2900 kcal/kg.

Table 2 Theoretical Air Requirements of Municipal Refuse and Other Fuels

Fuel	kg Air/kg fuel	kg Air/MM kcal[a]	sm^3 Air/M kcal
Refuse	3.22	1303	1.10
Wood	3.29	1265	1.07
Peat	2.33	1300	1.10
Lignite	5.27	1343	1.13
Sub-bituminous B	7.58	1332	1.12
Bituminous high volatile	9.08	1336	1.13
Bituminous volatile	10.99	1368	1.15
Anthracite	9.23	1496	1.26
Fuel oil	13.69	1350	1.14
Methane	17.26	1300	1.10

[a]MM = millions, M = thousands.

Methane will burn according to the stoichiometric relationship

$$CH_4 + 2O_2 \rightarrow CO_2 + H_2O$$

$$\frac{\text{kg air}}{\text{kg fuel}} = \frac{2 \text{ mol } O_2}{\text{mol } CH_4} \times \frac{\text{mol } CH_4}{16 \text{ kg } CH_4} \times \frac{100 \text{ mol air}}{21 \text{ mol } O_2} \times \frac{29 \text{ kg air}}{\text{mol air}} = 17.3$$

$$\text{Approximate heating value} = \frac{17.3 \text{ kg air}}{\text{kg fuel}} \times \frac{10^6 \text{ kcal}}{1360 \text{ kg air}} = 12{,}720 \text{ kcal/kg}$$

Based on the approximate equivalence of 1360 kg of air with one million kcal, the estimated stoichiometric air requirement of the waste is

$$\frac{2900 \text{ kcal}}{\text{kg fuel}} \times \frac{1360 \text{ kg air}}{10^6 \text{ kcal}} = 3.94 \frac{\text{kg air}}{\text{kg fuel}}$$

C. Ash Fusion Characteristics

The ash melting point is often a waste property that limits the burning rate on hearths and grates. The same is true for hand-fired and stoker-fired coal boiler furnaces. Ash fusion is a fearsome matter in fluid bed furnaces where continued operation of the system depends on maintaining "dry" bed grains. Accumulation of ash on boiler tubes and in ductwork is another operating problem where the key variable is the temperature at which the ash becomes "tacky,"

As a consequence of the importance of ash fusion temperature, the prediction of the onset of slagging (fusion of the ash) and fouling (accumulation of fused deposits) has been and remains an important concern to fuels technologists. Since "ash" contains seven major and numerous minor constituents in several hundred different mineral compositions and crystal forms, analysis of the problem and formulation of reliable prediction tools is difficult.

In the course of burning off the combustible matter, the mineral matter in coal is converted into the oxides. These are principally SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O and K_2O for coal. In the case of coal, TiO_2 and P_2O_5 are also present but in small quantities. For biological sludge, the P_2O_5 can be over 10% of the ash and refuse phosphorous is variable, but probably less than 5%. Often, the SO_3 content of ashes is reported since, under the ASTM ashing procedure, SO_3 is captured by the alkaline earth and alkali metal oxides. These sulfates decompose above 1000°C and, therefore, analytical data used for prediction of ash melting behavior should be normalized to a sulfur-free basis.

Coal technologists have often made use of the "silica percentage" concept or "silica ratio" method (199). The silica percentage method for the estimation of slag viscosity, based on linear regression analysis of viscosity data on 35 coal slags (correlation coefficient 0.989), predicts the viscosity in poises a reference temperature (2600°F or 1427°C) as a function of the percentage of silica in the slag as

$$\log_e \text{viscosity (at } 1427^\circ\text{C)} = 0.05784(\%SiO_2) - 1.8452 \quad (7)$$

A somewhat more precise prediction of viscosity based on composition was developed by Watt and Fereday (202) and Hoy (203). Their prediction considered the effect of Al_2O_3 on viscosity and gives some improvement in predictive accuracy but at the price of

mathematical complexity. Reid and Cohen (199) extended the prediction equation based on the silica percentage estimation of slag viscosity at one temperature to a general formula giving the viscosity (η) in poise as a function of the temperature (°C) and the percentage of silica (expressed as a decimal) as

$$\eta^{-0.1614} = 0.0008136T - 1.1607 + \exp[0.2989 - 0.9335(\%\mathrm{SiO_2})] \tag{8}$$

The ash fusion prediction formula estimates the "temperature of critical viscosity" (T_{cv}) that marks the temperature where behavior shifts from glass-like to a pseudoplastic solid that resists flow under gravity. The T_{cv} probably signifies the presence of a solid phase within the melt. Above this temperature, the slag behaves as a Newtonian fluid with linear stress–strain relationships. The T_{cv} value is higher than the "sticky point" by from a few degrees to somewhat over 100°C. The estimate by Hoy et al. (200) is

$$T_{cv} = 2990 - 1470A + 360A^2 - 14.7B + 0.15B^2 \tag{9}$$

where, using the percentages of the several oxides in the ash analysis,

$$A = \mathrm{SiO_2}/\mathrm{Al_2O_3}$$
$$B = \mathrm{Fe_3O_3} + \mathrm{CaO} + \mathrm{MgO}$$

and the analysis is normalized such that

$$\mathrm{SiO_2} + \mathrm{Al_2O_3} + \mathrm{Fe_2O_3} + \mathrm{CaO} + \mathrm{MgO} = 100$$

The relationship in Eq. 9 is satisfactory for most coal ash compositions, but there can be significant error when the ratio of SiO_2 to Al_2O_3 exceeds about 3.0.

The prediction equation presented below as Eq. (10) is a combination of a correlation by Hoy (200) based on analysis of an extensive data base (201) for coal ash with a correlation by this author based on data for biological wastewater treatment plant sludge. The sludge data are summarized in subsequent sections of this chapter (Table 34). The coal ash data on which the Hoy correlation was based were obtained in a Margules-type viscometer operating up to 1600°C using a platinum crucible and bob and with a controlled atmosphere. Atmospheric control is necessary because under reducing conditions some of the oxides in the ash become less highly oxidized (e.g., Fe_2O_3 shifting to FeO). This can lead to significant changes in the fusion temperatures. Typically, fusion occurs at a significantly lower temperature under reducing conditions.

Niessen (204) analyzed 26 sets of sewage sludge ash melting point data to allow more accurate estimation of the ash melting point for application to incinerators burning biological wastewater treatment plant sludge. Particularly for the fluid bed systems but also for multiple hearth furnaces, ash fusion or "stickiness" to any significant degree can create severe operational difficulties. The correlation in Eq. (9) greatly overestimates fusion temperatures for this ash type. Niessen used Eq. (8) to estimate the temperature where the ash viscosity was 1000 poise. He then compared the resulting temperature with the initial deformation temperature (oxidizing conditions) which is a benchmark for "stickiness". He found that the temperature from Eq. (8) (T_8) predicted a value that was too high. The error correlated with the ratio of basic to acidic oxides in the ash. An improved estimate of the temperature of incipient fusion T_{id} (standard deviation of the error in the adjusted estimate of T_{id} equals 55°C) is given by

$$T_{id} = T_8 - 206.03 + 377.56\left(\frac{\mathrm{Fe_2O_3} + \mathrm{CaO} + \mathrm{MgO} + \mathrm{Na_2O} + \mathrm{K_2O}}{\mathrm{SiO_2} + \mathrm{Al_2O_3} + \mathrm{TiO_2}}\right) \tag{10}$$

An exhaustive regression analysis of the ash fusion characteristics of 260 samples of coal ash from the United States, Italy, Spain, Germany, Australia, Poland and Africa and 35 samples of biomass ash was made by Seggaini (475). He developed correlating equations for the ASTM standard ash fusion conditions under both oxidizing and reducing conditions with variables formulated as combinations of the weight and/or percentages of ash constituents. Not surprisingly, he found that the mol percentages of constituents was always preferred to the weight percentage. Thus, unlike the equations presented above, composition data substituted into his correlations should be calculated as mol percentages. He also obtained the best results when iron was calculated as FeO rather than Fe_2O_3 and when the data were normalized to an SO_3-free basis. The final equations are of the form

$$T = \text{constant} + ax_1 + bx_2 + cx_3 + \cdots$$

The form of the variables and the several constant terms are presented in Table 3 noting the following:

Compositions are mol percents, normalized to an SO_3-free basis.

The silica value (SV) differs, however, and is calculated using the compositions calculated as weight percentages as

$$\text{SV} = \text{SiO}_2/(\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO})$$

The dolomite ratio is the fraction of bases present as CaO and MgO also calculated using the compositions calculated as weight percentages:

$$\text{dolomite ratio} = (\text{CaO} + \text{MgO})/(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O})$$

Percent base equals the sum of mol percent Fe_2O_3, CaO, MgO, K_2O, and Na_2O.

Percent acid equals 100 minus percent base or the sum of the mol percent SiO_2, Al_2O_3 and TiO_2.

R_{250} is a ratio calculated first by normalizing the sum of SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO to 100% and then calculating the ratio:

$$R_{250} = (\text{SiO}_2 + \text{Al}_2\text{O}_3)/(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{CaO})$$

The notation "abs" indicates absolute value.

Table 3a Variables in Ash Fusion Temperature Correlation

Variable	Meaning	Variable	Meaning
x_0	$\exp[(\text{silica value})^2 \times 10^{-1}]$	x_{10}	% Na_2O on coal[a]
x_1	% P_2O_5 on ash[a]	x_{11}	% base[a]
x_2	% SiO_2 on ash[a]	x_{12}	% acid[a]
x_3	% Fe_2O_3 on ash[a]	x_{13}	R-250[a]
x_4	% Al_2O_3 on ash[a]	x_{14}	dolomite ratio[b]
x_5	% TiO_2 on ash[a]	x_{15}	% base/% acid[a]
x_6	% CaO on ash[a]	x_{16}	silica value[b]
x_7	% MgO on ash[a]	x_{17}	$\exp[10^{-4} \cdot x_2 \cdot x_4]$
x_8	% K_2O on ash[a]	x_{18}	$\exp[10^{-2} \cdot (x_2 + x_4)]$
x_9	% Na_2O on ash[a]	x_{19}	$\exp[0.1(x_{15} - 1)^2]$

[a] Concentrations are in mol percent on an SO_3-free basis.

[b] Concentrations are in weight percent.

Source: From (475).

Table 3b Coefficients of Ash Fusion Temperatures—Reducing Conditions

No.	Variable	Initial deformation (IDT)	Height = width (ST)	Height = width/2 (HT)	Fluid (FT)	T_{cv}
1	x_0	—	—	16451.	—	−8484.1
2	x_1	93.944	—	−54.286	−101.77	−1882.3
3	x_2	—	—	−15.194	—	43.26
4	x_3	—	—	111.47	—	230.41
5	x_4	—	—	—	—	274.77
6	x_5	19.55	—	—	—	—
7	x_6	—	—	—	34.747	—
8	x_7	—	−214.3	—	—	—
9	x_8	−25.546	−232.0	—	—	—
10	x_9	−45.160	−237.68	—	—	—
11	$(x_1)^2$	−5.8404	—	—	3.4543	5375.0
12	$(x_2)^2$	−1.5985	−0.61899	0.75485	—	—
13	$(x_3)^2$	—	−1.5323	−1.1018	−0.10266	−1.6596
14	$(x_4)^2$	−1.5816	—	—	0.58836	−1.52
15	$(x_5)^2$	1.2348	−2.7719	−7.5792	−6.6806	—
16	$(x_6)^2$	0.0814	−1.4701	−0.18652	—	1.479
17	$(x_7)^2$	—	1.276	—	1.1486	3.84
18	$(x_8)^2$	—	−0.48885	—	—	—
19	$(x_9)^2$	2.3959	—	—	−1.5312	—
20	x_2x_3	—	−1.967	—	−0.3235	−0.802
21	x_2x_4	−6.2074	—	−0.26758	—	−2.99
22	x_2x_6	—	−1.1638	0.55503	−0.1355	1.182
23	x_3x_4	—	−1.2297	−2.177	−0.4545	−2.487
24	x_3x_6	−0.39542	−2.8610	−1.1151	—	—
25	x_3x_7	−0.27112	−1.3607	−2.0264	0.35805	—
26	x_4x_6	—	−1.5470	−1.470	−1.0598	−2.0326
27	x_6x_7	—	−0.8958	−0.3688	—	—
28	$x_2 + x_4$	—	—	—	—	—
29	$x_6 + x_7$	−4.4499	—	23.859	−37.946	—
30	x_3/x_6	−5.0069	—	—	—	—
31	$(x_2/x_4)^2$	—	0.00919	—	—	—
32	$(x_2 + x_4)^2$	—	—	—	—	—
33	$(x_2 + x_4)/x_3$	−0.0912	—	—	−0.09338	−1.685
34	x_{11}	—	160.32	−63.820	−47.717	—
35	$(x_{11})^2$	0.42422	0.47624	—	—	0.619
36	x_{19}	—	—	—	—	343.39
37	$(x_{14})^2$	−0.019822	—	—	—	—
38	x_{15}	—	—	—	20137.	−1616.2
39	$(x_{15})^2$	15.973	—	—	−10104.	—
40	$(x_{15} - 1)^2$	−16.478	0.091314	8.2745	10106.	—
41	x_9x_{15}	—	—	—	—	71.576
42	x_3/x_{11}	—	—	—	—	—
43	x_{13}	—	6408.0	—	−12124.	—
44	Abs $(x_{15} - 1)$	—	—	−165.61	—	1045.3
45	x_{16}	227.08	—	—	−23613.	6158.1
46	$(x_{16})^2$	735.56	1748.2	—	1849.3	—

Table 3b (continued)

47 x_{14}	2.3436	−441.27	—	127.71	—
48 x_{17}	29298.	−11481.	—	—	—
49 x_{18}	11306.	2307.1	—	−2576.6	—
Constant term	−43699.	4745.2	−8456.4	—	—
Standard deviation (°C)	84.5	66.8	56.8	73.8	52.2
r^2 of Correlation	0.82	0.83	0.88	0.82	0.86

Source: From (475).

Table 3c Coefficients of Ash Fusion Temperatures—Oxidizing Conditions

No. Variable	Initial deformation (IDT)	Height = width (ST)	Height = width/2 (HT)	Fluid (FT)	T_{cv}
1 x_0	−20730.	543.46	24484.	−15946.	−164526.
2 x_1	186.5	17.125	44.583	−68.941	−12900.
3 x_2	18084.	−16209.	2154.3	−15276.	−960594.
4 x_3	8195.	4563.7	−1088.2	2449.7	−735233.
5 x_4	18065.	−16193.	2016.6	−15252	−959798.
6 x_5	99.951	−10.867	175.12	53.762	−11798.
7 x_6	−9539.8	6311.1	15582.	6913.5	−333078.
8 x_7	−9669.5	6147.8	15543.	6709.7	−332825.
9 x_8	8072.0	4349.0	−1139.2	2173.9	−736015.
10 x_9	8060.6	4351.7	−1206.4	2171.9	−736002.
11 $(x_1)^2$	−13.198	−8.6585	8.936	16.583	3419.6
12 $(x_2)^2$	−19.497	−1.2099	−2.358	0.19781	−16.020
13 $(x_3)^2$	−0.60209	−1.5299	−0.79626	−2.1125	−7.0293
14 $(x_4)^2$	−1.6574	−0.79718	0.27981	0.78967	−23.841
15 $(x_5)^2$	0.4122	−3.5648	−10.858	−5.2889	6.1493
16 $(x_6)^2$	−0.82549	−1.2347	−0.59307	−1.1161	4.0657
17 $(x_7)^2$	0.57076	1.1538	0.38648	1.8361	4.1022
18 $(x_8)^2$	−0.23092	−0.7556	−2.4847	0.5194	6.6166
19 $(x_9)^2$	1.9088	−0.98841	11.37	−1.3338	−5.5105
20 x_2x_3	−0.068062	−0.76729	−1.5117	−2.0645	−2.1615
21 x_2x_4	−2.9676	−2.3044	−3.4773	2.2167	−56.430
22 x_2x_6	−0.11222	−0.78797	−0.18977	−1.4414	3.0119
23 x_3x_4	−0.2231	−0.78288	−3.2271	−2.7169	−0.97246.
24 x_3x_6	−1.9808	−2.4232	−2.1618	−3.1316	−0.71224
25 x_3x_7	0.51986	−1.8214	−1.1611	−0.92908	−4.1939
26 x_4x_6	−0.48264	−0.99078	−0.97349	−2.4124	0.90895
27 x_6x_7	−0.45071	−1.0683	−0.9715	−0.39195	2.0637
28 $x_2 + x_4$	−18143.	16074.	−2098.1	15429.	947414.
29 $x_6 + x_7$	17755.	−1768.9	−16717.	−4551.0	−403047
30 x_3/x_6	−2.3786	4.9007	−27.432	5.7066	3.8785
31 x_2/x_4	0.	0.012824	−41.134	0.002178	739.05
32 $(x_2 + x_4)^2$	0.	0.	0.60352	0.	−50.349
33 $(x_2 + x_4)/x_3$	−0.12371	0.0042819	0.18732	−0.082176	−0.66483

(*continued*)

Table 3c (continued)

No.	Variable	Initial deformation (IDT)	Height = width (ST)	Height = width/2 (HT)	Fluid (FT)	T_{cv}
34	x_{11}	−8039.3	0.0044444	1252.6	−2179.2	724118.
35	$(x_{11})^2$	0.60247	0.54954	0.20981	0.14651	−2.6125
36	x_{19}	0.	0.	0.	0.	1265.3
37	$(x_{14})^2$	264.68	327.72	348.26	−135.52	−632.4
38	x_{15}	8223.	−17163.	−16789.	−11896	−302980.
39	$(x_{15})^2$	−4158.7	8490.2	8046	5967.4	156124.
40	$(x_{15} - 1)^2$	4157.7	8490.0	−8027	−5965.0	−157814.
41	$x_9 x_{15}$	−4.9830	1.4096	−3.4407	4.6028	225.37
42	x_3/x_{11}	−633.55	−492.93	173.34	−284.06	−889.43
43	x_{13}	8401.3	5326.4	224.92	1296.4	−8178.4
44	Abs $(x_{15} - 1)$	153.15	185.39	412.17	−135.48	2713.9
45	x_{16}	−2519.7	2391.7	−13677.	761.88	44555.
46	$(x_{16})^2$	3810.6	196.24	4504.7	2807.6	2408.7
47	x_{14}	−693.63	−871.62	−575.95	−22.048	519.42
48	x_{17}	−3922.2	−3381.9	−993.51	−19165	148605.
49	x_{18}	19389	11931.	18014.	−7482.3	180164.
Constant term		−12986.	−1697.6	−38446.	42543.	1137313.
Standard deviation (°C)		79.3	64.2	46.0	69.0	47.0
r^2 of correlation		0.84	0.84	0.92	0.84	0.89

Source: From (475).

The surface tension (γ) of coal slags (and, by extrapolation, other slags) is typically 300–400 dyne/cm in air and may be estimated at 1400°C in air (392) from

$$\gamma = 3.24(SiO_2) + 5.85(Al_2O_3) + 4.4(Fe_2O_3) + 4.92(CaO) + 5.49(MgO) + 1.12(Na_2O) + 0.75(K_2O) \quad (11)$$

where the indicated compositions are on a weight percent basis and total to 100%. Extrapolation to other temperatures is made using a temperature coefficient of surface tension of minus 0.017 dyne/cm per °C.

In addition to the general ash fusion characterizations described previously, one must be alert for the special cases where particular mixes of compounds form a low-melting eutectic. This is shown in Table 4 for several common (and, often, problem) alkali salt systems.

D. Smoking Tendency

Although not an unfailing rule, the tendency of a material to form soot under less-than-optimal combustion conditions appears to be generally related to the ratio between the unbound hydrogen and the carbon content of a material. This ratio is calculated as

$$\text{unbound hydrogen-to-carbon ratio} = \frac{\%H_2 - \dfrac{\%O_2}{8}}{\%C} \quad (11)$$

Table 4 Melting Points of Common Eutectic Mixtures

Compound #1	Compound #2	Mol percent #1	Mol percent #2	Melting point (°C)
NaCl	—	100%	—	800
Na_2SO_4	—	100%	—	884
Na_2CO_3	—	100%	—	851
$Na_2O–SiO_2$	—	100%	—	800
$MgSO_4$	—	100%	—	1185
$MgSO_4$	Na_2SO_4	41	59	660
$Na_2O–SiO_2$	Na_2SO_4	55	45	635
NaCl	Na_2SO_4	35	65	623
NaCl	Na_2CO_3	38	62	633
Na_2SO_4	Na_2CO_3	53	47	828

Table 5 Comparative Sooting Tendency of Waste Materials

Waste material	Unbound H-to-C ratio
Mixed paper	0.0065
Softwood	0.0191
Linoleum	0.0625
Polyurethane	0.0641
Polystyrene	0.0913
Waxed paper carton	0.0927
Polyvinyl chloride	0.1200
Cooking fats	0.1325
Rubber	0.1333
Oils, paints	0.1343
Polyethylene	0.1677

For wastewater sludge, this ratio is about 0.0032; for comparison with other materials, see Table 5.

II. SOLID WASTE

Most of the material that is incinerated falls within the class "solid waste." Unfortunately, this class of wastes is very difficult to deal with as an "engineering material." Securing a representative sample is often most problematical. Materials handling is difficult and can expose workers to risk. Blending is slow and incomplete. However, for incinerator analysis and design purposes, even highly heterogeneous solid wastes can usefully be considered as a relatively discrete "material" with acceptably reproducible properties and characteristics. Clearly, a somewhat long averaging time may be needed before this constancy is apparent. The data and correlations given below are an attempt to summarize useful information regarding the characteristics of several classes of solid wastes. As with other information in the waste management engineering field, one must recognize that significant excursions from these mean values are to be expected.

A. Solid Waste Composition

In this context, composition refers to the category of material (paper, glass, etc.) in the waste streams. Composition data are reported in this form since the "analysis method," (visual categorization) is low-cost and can rapidly and economically be applied to large quantities of waste. This latter point is important if a meaningful characterization is to be made on a stream that is grossly heterogeneous. Data in this form may be translated into mean overall chemical compositions and the like by taking the weighted average of the chemical compositions of specified components. Lastly, data on a categorical basis are directly usable to estimate the potential for materials recovery.

1. Mixed Municipal Refuse

In many instances, the waste stream of interest cannot be directly sampled. Under such circumstances, data from other municipalities can be useful as an indicator of mean refuse composition. Generally, municipal refuse is categorized as shown in Table 6.

An examination of refuse composition data from across the United States shows great variability, reflecting local practices regarding the wastes accepted at landfills or incinerators, seasonal effects (e.g., on yard waste quantities), economic level of the citizens, incorporation of commercial or industrial waste, etc. These data can be rationalized, however (109, 110), into an estimated national average composition.

These results are more useful if the moisture levels of the components are adjusted, category by category, to a moisture basis corresponding to the manufactured state of the materials entering the refuse storage bunker, that is, changing from the mixed or "as-fired" basis to an "as-discarded" basis. The moisture content values shown in Table 7 can be used to effect this basis shift.

Carrying out the moisture adjustment does not materially change the total moisture content of the refuse mix, only the distribution of moisture among the refuse categories. Discarded solid waste, as it is mixed together with other refuse materials, may either lose or absorb moisture. Food wastes, for example, may transfer significant quantities of moisture to paper and textiles. The as-discarded basis is useful in indicating the true relative magnitude of waste generation for the various categories, as the appropriate basis for estimating salvage potential, and as the basis for forecasting refuse generation rates and chemical and physical properties. Such basis adjustments can become critical for wastes

Table 6 Primary Constituents of Categories of Mixed Municipal Refuse

Category	Description
Glass	Bottles (primarily)
Metal	Cans, wire, and foil
Paper	Various types, some with fillers
Plastics	Polyvinyl chloride, polyethylene, styrene, etc., as found in packing, housewares, furniture, toys and nonwoven synthetic fabrics
Leather, rubber	Shoes, tires, toys, etc.
Textiles	Cellulosic, protein, woven synthetics
Wood	Wooden packaging, furniture, logs, twigs
Food wastes	Garbage
Miscellaneous	Inorganic ash, stones, dust
Yard wastes	Grass, brush, shrub trimmings

Table 7 Estimated Average Percent Moisture in Refuse on an "As-Discarded" and "As-Fired" Basis[a]

Component	As-fired	As-discarded
Food wastes	63.6	70.0
Yard wastes	37.9	55.3
Miscellaneous	3.0	2.0
Glass	3.0	2.0
Metal	6.6	2.0
Paper	24.3	8.0
Plastics	13.8	2.0
Leather, rubber	13.8	2.0
Textiles	23.8	10.0
Wood	15.4	15.0

[a]From Ref. 109.

where a substantial fraction of the waste is very moist and, thus, where profound effects of moisture transfer occur.

An excellent example of a geographical area where these circumstances occur to a significant degree is found in the Pacific Rim (e.g., China, Korea, Japan, Taiwan). In these countries, large quantities of very moist (>85% moisture) food waste are combined with relatively little absorbent paper material. As a result, the categorical solid waste composition data are greatly distorted. A spreadsheet model to reallocate waste compositions using the measured moisture content on an "as-fired" basis to the "as-discarded" basis useful in estimating waste properties, heating value, etc., is described in Appendix F and provided as a file on the diskette provided with this book.

The seasonal and annual average compositions shown in Table 8 were derived from an analysis of over 30 data sets from municipalities throughout the United States. Based on

Table 8 Estimated Average Municipal Refuse Composition, 1970 (Weight Percent, as Discarded)[a]

					Annual average	
Category	Summer	Fall	Winter[b]	Spring	As-discarded	As-fired
Paper	31.0	39.9	42.4	36.5	37.4	44.0
Yard wastes	27.1	6.2	0.4	14.4	13.9	9.4
Food wastes	17.7	22.7	24.1	20.8	20.0	17.1
Glass	7.5	9.6	10.2	8.8	9.8	8.8
Metal	7.0	9.1	9.7	8.2	8.4	8.6
Wood	2.6	3.4	3.6	3.1	3.1	3.0
Textiles	1.8	2.5	2.7	2.2	2.2	2.6
Leather, rubber	1.1	1.4	1.5	1.2	1.2	1.5
Plastics	1.1	1.2	1.4	1.1	1.4	1.4
Miscellaneous	3.1	4.0	4.2	3.7	3.4	3.6
Total	100.0	100.0	100.0	100.0	100.0	100.0

[a]From Ref. 110.
[b]For southern states, the refuse composition in winter is similar to that shown here for fall.

Table 9 Estimated Average Generated Refuse Composition 1960–1995 (Weight Percent As-Described, Mixed Refuse)

	Year				
Component	1960	1970	1980	1990	1995
Paper & paperboard	34.1	36.7	36.6	35.4	38.5
Yard wastes	22.8	19.1	18.2	17.0	14.1
Food wastes	13.9	10.5	8.5	10.2	10.2
Glass	7.5	10.5	9.9	6.4	6.1
Metal	12.4	11.4	10.2	8.0	7.5
Wood	3.4	3.1	4.7	6.0	5.0
Textiles	1.9	1.5	1.7	2.9	3.4
Leather & rubber	2.2	2.5	2.8	2.9	2.9
Plastics	0.4	2.5	4.4	8.4	8.8
Other	1.5	2.2	3.0	2.9	3.4
Estimated Rate (kg/person/day)	1.21	1.47	1.65	2.05	2.00

Source: From (450).

estimates of forecast manufacturing rates of paper, metal cans, and other consumer and industrial products and estimates of the prompt and delayed disposal rate of these commodities for the United States overall, composition forecasts can be prepared (Table 9). In the forecasts (450), consideration was given to the mean useful life of the products. Table 9 also shows the estimated per capita waste generation rate patterns over the period from 1960 through 1995.

Waste sampling and analysis data are shown in Tables 10a and 10b to illustrate the high degree of variation to be expected in waste sampling. In addition to these regional differences, one can expect seasonal variation in the composition and quantity of wastes. The average of three years of data from New Jersey (384) from a region where the waste was about 54% residential and 46% commercial and industrial showed 122% of the annual average volumetric monthly waste quantity was received in May; about the average from July through October; then declining almost linearly to only 78% of the average in February and climbing back to the peak in May. The refuse density varied from 435 kg/m^3 in the summer to 390 kg/m^3 in the winter.

The data in Table 11 are given for comparison with the U.S. refuse composition estimates. For the U.S. refuse data, the decline in the use of coal for home heating is shown in the change in refuse ash content between 1939 and 1970.

A review of Table 9 shows the dramatic increase in the plastics content of the waste stream. "Plastics" is a generic term referring to a wide range of different resin bases, each with differing chemistries and properties. The estimated U.S. average distribution of plastics, as found in the waste stream, is summarized in Table 12 (450).

2. Construction and Demolition Waste

Wastes generated in the course of construction and demolition (C&D) activities can comprise a large fraction of the total waste disposal requirement in metropolitan areas. Estimation of the quantities and composition of this waste can be made (451) based on the floor area of the building to be constructed or demolished and the general structural type of the building. In general, the original data underlying the waste estimates were volumetric

Table 10a Solid Waste Weight Percent Characterization Data (1988, 1990) [291]

Waste category	Indian-apolis, IN	Kauai, HI	King Co., WA	Bergen Co., NJ	Monroe Co., NY
Paper	38	26	27	44	42
Plastics	8	7	7	9	10
Yard debris	13	20	19	9	7
Miscellaneous organics	22	24	31	17	24
Glass	7	5	4	7	10
Aluminum	1	1	1	1	1
Ferrous metal	4	6	3	5	5
Nonferrous metal	0	1	1	4	0
Miscellaneous inorganics	0	3	7	5	0
Other	0	9	0	3	0

Waste category	Ann Arbor, MI	Portland, OR	San Diego, CA	Santa Cruz Co., CA	National estimate
Paper	29	29	26	33	34
Plastics	8	7	7	8	9
Yard debris	8	11	21	15	20
Miscellaneous organics	39	33	23	18	20
Glass	4	3	4	7	7
Aluminum	1	1	1	1	1
Ferrous metal	5	7	3	5	7
Nonferrous metal	2	0	0	0	0
Miscellaneous inorganics	2	9	6	6	2
Other	2	1	10	7	0

Table 10b Standard Deviations of Solid Waste Characterization Data (Percent of Reported Average Weight Percent Values) [291]

Waste category	Portland, OR	Cincinatti, OH	Bergen Co., NJ	Rochester, NY	Sacremento, CA
Paper	6	20	19	13	14
Plastics	14	10	35	19	3
Yard debris	11	26	28	26	17
Misc. organics	12	52	86	32	17
Glass	24	16	32	46	2
Aluminum	35	48	50	76	56
Ferrous metal	13	27	54	29	15
Nonferrous metal	63	137	48	161	80
Misc. inorganics	11	54	59	—	30

Table 11 A Summary of International Refuse Composition Data (Weight Percent, Mixed Refuse)

Country	Ref.	Paper	Metal	Glass	Food	Plastic
Australia	300	38.0	11.0	18.0	13.0	0.1
Austria	300	35.0	10.0	9.0	24.0	6.0
Bangladesh	307	2.0	1.0	9.0	40.0	1.0
Belgium	314	30.0	5.3	8.0	40.0	5.0
Bulgaria	314	10.0	1.7	1.6	54.0	1.7
Burma	302	1.0	3.1	6.0	80.0	4.0
China[c]	449	3.1	0.3	0.8	60.0	4.5
Colombia	302	22.0	1.0	2.0	56.0	5.0
Czechoslovakia	314	13.4	6.2	6.6	41.8	4.2
Denmark[a]	314	32.9	4.1	6.1	44.0	6.8
United Kingdom	302	37.0	8.0	8.0	28.0	2.0
Finland[a]	314	55.0	5.0	6.0	20.0	6.0
France	310	30.0	4.0	4.0	30.0	1.0
Gabon[a]	314	6.0	5.0	8.0	77.0	3.0
Western Germany[b]	302	20.0	5.0	10.0	21.0	2.0
Hong Kong	307	32.0	2.0	10.0	9.0	11.0
India[b]	302	3.0	1.0	8.0	36.0	1.0
Indonesia[b]	302	10.0	2.0	1.0	72.0	6.0
Iran	314	17.2	1.8	2.1	69.8	3.8
Italy[a]	310	31.0	7.0	3.0	36.0	7.0
Japan[b]	309	21.0	5.7	3.8	50.0	6.2
Kenya	314	12.2	2.7	1.3	42.6	1.0
Netherlands[b]	313	22.2	3.2	11.9	50.0	6.2
New Zealand	307	28.0	6.0	7.0	48.0	0.1
Nigeria[b]	302	15.5	4.5	2.5	51.5	2.0
Norway	301	38.2	2.0	7.5	30.4	6.5
Pakistan[b]	312	2.2	2.2	1.75	52.5	1.2
Philippines	311	17.0	2.0	5.0	43.0	4.0
Saudi Arabia	306	24.0	9.0	8.0	53.0	2.0
Singapore	307	43.0	3.0	1.0	5.0	6.0
Spain[b]	314	18.0	4.0	3.0	50.0	4.0
Sri Lanka	302	8.0	1.0	6.0	80.0	1.0
Sudan	308	4.0	3.0	—	30.0	2.6
Sweden[b]	314	50.0	7.0	8.0	15.0	8.0
Taiwan	307	8.0	1.0	3.0	25.0	2.0
United States[b]	303, 304, 305	28.9	9.3	10.4	17.8	3.4

[a]Major cities.
[b]Data averaged for two or more cities.
[c]Data for Qingdao municipal government.
Source: From (315).

(since the generators were concerned with the numbers of trucks needed to haul off the material). Conversion factors are provided to readily convert between the volumetric and mass bases.

Table 13 presents the waste generation intensity in the course of demolition of buildings of various types.

In the course of construction activity, waste is generated in proportion to the usage of various building materials. The fraction lost, thus contributing to the municipal waste

Table 12 Estimated Average Mix of Plastics in Municipal Refuse (1966)

Resin	Abbreviation	Estimated thousands of short tons disposed/year	Percent of total plastics discarded
Polyethylene terephthalate	PET	900	7.4
High-density polyethylene	HDPE	1440	11.8
Polyvinyl chloride	PVC	870	7.1
Low-density, very low density polyethylene	LDPE/LLDPE	2510	20.5
Polypropylene	PP	1670	13.7
Polystyrene	PS	1790	14.6
Other resins	—	3050	24.9

Source: From (450).

Table 13 Estimated Waste Generation in Demolition Activities

		Building type				
Material	Units	Brick	Steel[b]	RC[c]	SRC[d]	Wood
Concrete	m^3/m^2	0.348	0.292	0.460	0.565	—
Steel[a]	ton/m^2	0.031	0.058	0.031	0.051	—
Tile	m^2m^2	0.050	0.098	0.461	0.224	0.483
Brick	$piece/m^2$	292	101	75	43	105
Glass	m^2m^2	2.370	0.131	0.203	0.006	2.370
Wallpaper	m^2/m^2	1.131	—	1.717	—	1.131
Paper floor	m^2/m^2	0.344	—	0.332	—	0.344
Wood floor	m^2/m^2	2.800	2.21	3.43	2.79	—
Concrete block	$piece/m^2$	—	—	2.17	11.2	—
Wood	m^2m^2	0.076	0.039	0.045	0.033	0.175
Mortar	m^2/m^2	3.210	0.855	3.54	0.850	—

[a]Total steel in construction work.
[b]Steel-frame type. [c]Reinforced concrete construction type.
[d]Steel-framed reinforced concrete structure.
Source: From (451).

Table 14 Rate of Loss of Building Materials in Construction Activities

Materials	Sources	Losses (Range, Average) as %
Concrete	Reinforced concrete work	1–2 (1.5)
Tile	Masonry work	2–3 (2.5)
Brick	Masonry work	1–5 (3.0)
Glass	Window frame work	2–15 (6.0)
Wallpaper	Decoration work	1–20 (11.0)
Wood	Carpenter's work	10–30 (13.0)
Mortar	Masonry, waterproofing work	0.3
Formwork	Reinforced concrete, building work	16.7[a]

[a]Data obtained from speciality contractors.
Source: From (451).

Table 15 Conversion Factors for Building Materials

Material	Units	Conversion factor
Concrete	kg/m^3	2300
Tile	kg/m^2	28.8
Brick	kg/piece	2
Glass	kg/m^2	9.9
Wallpaper	kg/m^2	0.3
Paper floor	kg/m^2	2.6
Woodform	kg/m^2	6.7
Concrete block	kg/piece	6.7
Mortar	kg/m^2	33
Wood	kg/m^2	573

Source: From (451).

stream, differs widely between these materials (Table 14). Using the volume-to-mass conversion factors from Table 15, the waste generation intensity from construction activity can be estimated and is shown in Table 16. Data from Germany (453) indicate that the average compositional breakdown of typical construction site waste is 64.85% mineral matter, 31.24% combustible matter, and 3.91% metal.

3. Institutional, Commercial, and Industrial Waste

Solid wastes from institutional and commercial sources (schools, office buildings, stores, small businesses) almost equal that generated by residences. Industrial waste generation

Table 16 Estimated Waste Generation from Construction Activities (kg/m^2 floor area)

	Building type		
Materials	Concrete[a]	Block	Wood
Concrete	15.870	12.000	0.000
Tile	0.333	0.035	0.348
Brick	4.530	17.490	6.270
Glass	0.120	1.410	1.410
Wallpaper	0.055	0.037	0.037
Woodform	3.841	3.156	0.000
Wood	3.380	5.668	13.000
Mortar	0.351	0.318	0.318
Fiber	0.317	0.240	0.279
Packing	1.428	1.080	1.250
Plastic	2.904	2.196	2.550
Steel	5.174	3.912	4.543
Miscellaneous	9.522	7.200	8.361

[a]This is a summary of data for reinforced concrete, steel-framed, reinforced concrete, and steel-frame building types.
Source: From (451).

can exceed the combination of residential and commercial wastes. Yet, with their importance apparently obvious, little published data exist.

The information on industrial and commercial waste generation rates and compositions is difficult to obtain, correlate, and/or to generalize because of the following factors:

Manufacturing establishments, even those in the same type of business, may differ widely in their waste-generating practices.
Most firms are reluctant to reveal production and related statistics for fear of the data being used to the competitive advantage of others.
Some firms are reluctant to provide information on waste volumes and composition for fear the data will indicate noncompliance with pollution control regulations. Regardless of their wastes' pollution-related characteristics, there is also a tendency for firms to underestimate its quantity.
Some industrial activities are subject to seasonal fluctuations.
The extent of salvaging, recycling, sale to scrap dealers, or other reclamation of wastes differs greatly among manufacturers.
Many firms have little understanding of and few records on their waste generation and characteristics.

Data for mixed commercial refuse and for a variety of industries have been prepared, however (Tables 17, 18, and 19 and Ref. 108), but considerable care should be exercised in their application to any specific industrial establishment or geographic region.

B. Solid Waste Properties

The categorical composition is the starting point for the development of parameters of interest to the incinerator designer. Although the manipulation of gross categorical data to

(*text continues on p. 129*)

Table 17 Composition of Commercial Refuse (Weight Percent, Mixed)

Component	Commercial wastes		Residential wastes[c]
	Kentucky[a]	Michigan[b]	
Metal	10.6	6	8.6
Paper	60.4	57	44.0
Plastics	9.4	1	1.4
Leather, rubber			1.5
Textiles		1	2.6
Wood		2	3.0
Food waste	7.1	24	17.1
Yard waste		0	9.4
Glass	11.3	6	8.8
Miscellaneous	1.2	3	3.6
Total	100.0	100	100.0

[a] *Source:* Ref. 114 (sampling and analysis).
[b] *Source:* Ref. 115 (engineering estimates).
[c] *Source:* Table 27.

Table 18 Industrial Waste Composition[a]

	Component (wt %)									
SIC number	Paper	Wood	Leather	Rubber	Plastics	Metals	Glass	Textiles	Food	Miscellaneous
20 Food and kindred products										
Data points	30	30	30	30	30	30	30	30	30	30
Average	52.3	7.7	—	—	.9	8.2	4.9	0	16.7	9.2
Standard deviation	32.7	10.9	—	—	.4	3.7	2.8	0	29.9	21.1
Confidence limits	11.7	3.9			.1	1.3	1.0		10.7	7.5
22 Textile mills										
Data points	18	18	18	18	18	18	18	18	18	18
Average	45.5	—	0	—	4.7	—	—	26.8	—	—
Standard deviation	40.3	—	0	—	10.7	—	—	38.1	—	—
Confidence limits	18.6				4.9			17.6		
23 Apparel products										
Data points	17	17	17	17	17	17	17	17	17	17
Average	55.9	—	0	0	—	0	0	36.5	1.35	—
Standard deviation	37.4	—	0	0	—	0	0	37.3	2.8	—
Confidence limits	17.8							17.7	1.3	
24 Wood products										
Data points	9	9	9	9	9	9	9	9	9	9
Average	16.7	71.6	0	0	0	—	—	0	0	7.8
Standard deviation	33.6	34.8	0	0	0	—	—	0	0	19.7
Confidence limits	22.0	22.7								12.9
25 Furniture										
Data points	7	7	7	7	7	7	7	7	7	7
Average	24.7	42.1	0	—	—	—	0	—	—	—
Standard deviation	12.3	16.2	0	—	—	—	0	—	—	—
Confidence limits	9.1	12.0								

26 Paper and allied products										
Data points	20	20	20	20	20	20	20	20	20	20
Average	56.3	11.3	0	0	—	9.4	—	—	—	14.0
Standard deviation	8.7	15.5	0	0	—	18.2	—	—	—	27.5
Confidence limits	3.8	6.8				8.0				12.1
27 Printing and publishing										
Data points	26	26	26	26	26	26	26	26	26	26
Average	84.9	5.5	—	0	—	—	0	—	—	—
Standard deviation	5.3	12.3	—	0	—	—	0	—	—	—
Confidence limits	2.2	4.7	—	0	—	—	0	—	—	—
28 Chemical and allied										
Data points	48	48	48	48	48	48	48	48	48	48
Average	55.0	4.5	—	—	9.3	7.2	2.2	—	—	19.7
Standard deviation	34.0	6.2	—	—	17.0	13.9	4.2	—	—	32.8
Confidence limits	9.6	1.7			4.8	3.9	1.2			9.3
29 Petroleum and allied										
Data points	5	5	5	5	5	5	5	5	5	5
Average	72.1	6.8	0	0	15.3	4.4	0	0	—	1.0
Standard deviation	35.7	4.4	0	0	30.7	5.2	0	0	—	1.3
Confidence limits	31.4	3.9			27.0	4.6				1.1
30 Rubber and plastics										
Data points	13	13	13	13	13	13	13	13	13	13
Average	56.3	5.2	0	9.2	13.5	—	0	—	—	—
Standard deviation	31.5	6.2	0	20.3	20.7	—	0	—	—	—
Confidence limits	17.2	3.4		11.0	11.3					
31 Leather manufacturing										
Data points	3	3	3	3	3	3	3	3	3	3
Average	6.0	3.9	53.3	—	—	13.5	—	0	0	—
Standard deviation	4.2	5.4	47.3	—	—	19.2	—	0	0	—
Confidence limits	4.7	6.1	53.6			21.7				

(*continued*)

Table 18 (continued)

SIC number	Component (wt %)									
	Paper	Wood	Leather	Rubber	Plastics	Metals	Glass	Textiles	Food	Miscellaneous
32 Stone, clay, and glass										
Data points	16	16	16	16	16	16	16	16	16	16
Average	33.8	4.3	0	—	—	8.1	12.8	—	0	40.0
Standard deviation	37.5	8.4	0	—	—	24.8	29.6	—	0	44.8
Confidence limits	18.4	4.1				12.2	14.5			22.0
33 Primary metals										
Data points	12	12	12	12	12	12	12	12	12	12
Average	41.0	11.6	0	—	5.4	5.5	2.0	0	—	29.0
Standard deviation	27.4	12.4	0	—	9.8	7.8	4.3	0	—	40.0
Confidence limits	15.5	7.0			5.5	4.4	2.4			22.7
34 Fabricated metals										
Data points	36	36	36	36	36	36	36	36	36	36
Average	44.6	10.3	0	—	—	23.2	—	—	—	12.2
Standard deviation	37.7	20.8	0	—	—	34.5	—	—	—	31.0
Confidence limits	12.3	6.8				11.3				10.1
35 Nonelectrical machinery										
Data points	48	48	48	48	48	48	48	48	48	48
Average	43.1	11.4	—	—	2.5	23.7	—	0	—	—
Standard deviation	34.3	19.5	—	—	6.8	30.8	—	0	—	—
Confidence limits	9.7	5.5			1.9	8.7				

36 Electrical machinery										
Data points	19	19	19	19	19	19	19	19	19	19
Average	73.3	8.3	0	—	3.5	2.3	—	0	1.2	—
Standard deviation	24.4	10.1	0	—	7.0	3.5	—	0	2.4	—
Confidence limits	11.0	4.5			3.1	1.6			1.1	
37 Transportation										
Data points	8	8	8	8	8	8	8	8	8	8
Average	50.9	9.4	0	1.4	2.1	—	—	0	—	19.5
Standard deviation	34.2	6.3	0	1.5	2.9	—	—	0	—	33.3
Confidence limits	23.8	4.4		1.0	2.0					23.1
38 Scientific instruments										
Data points	8	8	8	8	8	8	8	8	8	8
Average	44.8	2.3	0	0	6.0	8.4	—	0	—	—
Standard deviation	34.0	3.6	0	0	6.4	17.2	—	0	—	—
Confidence limits	23.6	2.5			4.4	11.9				
39 Miscellaneous manufacturing										
Data points	20	20	20	20	20	20	20	20	20	20
Average	54.6	13.0	—	—	11.9	5.0	—	—	—	8.1
Standard deviation	38.7	23.7	—	—	22.2	10.3	—	—	—	14.0
Confidence limits	17.0	10.4			9.7	4.5				6.1

[a] *Source:* Ref. 110; confidence limits are 95%.

Table 19 Typical Waste Composition of Institutional, Commercial and Light Industrial Generators (Weight Percent)

	Generator type (see Notes for key)										
Component	A	B	C	D	E	F	G	H	I	J	K
Mixed paper	10.3	11.3	28.6	43.0	11.8	12.9	15.9	8.5	19.8	13.1	2.2
Newsprint	33.7	11.5	2.5	3.5	6.7	7.2	13.2	19.8	1.7	0.4	0.5
Corrugated paper	10.0	27.5	26.1	21.5	37.4	35.6	44.9	10.3	29.4	27.8	17.4
Plastic	8.6	13.7	6.9	3.7	8.0	11.1	5.6	2.0	7.3	22.2	3.8
Yard waste	5.3	0.5	0.0	0.0	2.8	0.5	0.7	3.2	3.6	0.0	3.2
Wood	1.7	0.7	0.1	8.5	3.6	15.0	9.4	46.6	0.5	27.2	27.1
Food Waste	13.0	4.9	6.7	2.2	12.4	0.7	0.2	0.2	1.6	0.4	1.0
Other organics	7.4	7.5	0.1	1.2	1.9	2.0	0.2	5.8	8.3	2.0	2.3
Total combustibles	90.0	77.6	71.0	83.6	84.6	85.0	90.1	96.4	72.2	93.3	57.5
Ferrous	2.5	6.9	8.2	0.6	3.6	10.0	3.9	0.6	16.4	0.8	17.5
Aluminum	1.1	2.7	1.5	0.4	0.7	0.4	0.3	0.1	1.5	0.9	0.1
Glass	5.9	11.9	6.2	0.8	2.7	1.5	1.4	0.1	9.9	4.9	1.0
Other inorganics	0.3	0.9	13.1	14.6	8.6	3.1	4.3	2.8	0.0	1.0	23.9
Total noncombustibles	9.8	22.4	29.0	16.4	15.6	15.0	9.9	3.6	27.8	6.7	42.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

A—multifamily dwelling; B—hotels; C—schools; D—office buildings; E—shopping center, F—warehouse; G—electric manufacturers; H—wood products manufacturers; I—dealers/repair shops; J—plastic manufacturers; K—construction. (Totals may not sum exactly due to rounding.)
Source: From (453).

establish average chemical composition, heat content, and the like requires assumptions of questionable accuracy, it is a necessary compromise. Typically, several (perhaps one to three) tons of waste from a 200 to 1000 ton/day waste flow are analyzed to produce a categorical composition. Then a still smaller sample is hammermilled and mixed, and a 500-mg sample is taken. Clearly, a calorific value determination on the latter sample is, at best, a rough reflection of the energy content of the original waste.

1. Chemical Analysis

Stepping from the categorical analysis to a mean chemical analysis provides the basis for stoichiometric calculations. The macrochemistry of waste (the percentage of the major chemical constituents carbon, hydrogen, oxygen, sulfur, nitrogen, chlorine, and ash) is an important input to estimates of heat content, combustion air requirements, incinerator mass balances, etc. The microchemistry of waste (the content of heavy metals and other environmentally important species present at the parts per million level) is also important in revealing potential air or ash emission problems.

a. Mixed Municipal Refuse

MAJOR Chemical Constituents. Chemical data for average municipal refuse components based on the mixed refuse of Table 8 are presented in Tables 20 and 21. Although these data may not be at all representative of the material of interest in a given design effort, the general approach to data analysis presented here may be used. The process begins with refuse categorical compositions (such as Table 6) and incorporates the effects of the moisture exchange processes discussed above to produce the baseline refuse elemental statistics used in heat and material balance computations, etc.

MINOR Chemical Constituents. Increasing interest in the emission rate of metals with health effects (an important part of the class of air pollutants called “air toxics") leads to a need to understand the sources and typical concentrations of many of the trace elements in waste streams. These concentrations, clearly, vary widely in different waste components and even within relatively narrow categories of waste. Thus, data on “typical” concentrations must be used with appropriate caution. Table 22 indicates the result of three extensive analyses of the trace metal concentrations in mixed municipal refuse (455, 456, 457).

A detailed breakdown of several of the important trace elements was made for wastes delivered to the Burnaby, British Columbia (serving greater Vancouver) MWC (454). The analytical results for a wide range of individual waste components are shown in Table 23.

b. Specific Waste Components. Data for specific waste components are given in Table 24. These data may be used when detailed categorical analyses are available or when one wishes to explore the impact of refuse composition changes.

It is of importance to distinguish between the two types (soluble and insoluble) of chlorine compounds found in refuse. The most important soluble chlorine compounds are sodium and calcium chloride. These compounds (substantially) remain as solid inorganic salts in the bottom ash and fly ash. The insoluble chlorine compounds are principally chlorine-containing organic compounds [e.g., polyvinyl chloride (PVC), polyvinylidene chloride (Saran), etc.] that form HCl in combustion processes and thus generate a requirement for acid gas control. Data on the distribution of the two forms of chlorine (378) are shown in Table 25.

(*text continues on p. 140*)

Table 20 Estimated Ultimate Analysis of Refuse Categories (% Dry Basis)[a]

Category	C	H	O	N	Ash	S	Fe	Al	Cu	Zn	Pb	Sn	P**	Cl	Se	% Fixed carbon (dry basis)
Metal	4.5	0.6	4.3	0.05	90.5	0.01	77.3	20.1	2.0	—	0.01	0.6	0.03	—	—	0.5
Paper	45.4	6.1	42.1	0.3	6.0	0.12	—	—	—	—	—	—	—	—	Trace	11.3
Plastics	59.8	8.3	19.0	1.0	11.6	0.3	—	—	—	—	—	—	0.01	6.0	—	5.1
Leather, rubber							—	—	—	2.0	—	—	—	—	—	6.
Textiles	46.2	6.4	41.8	2.2	3.2	0.2	—	—	—	—	—	—	0.03	—	—	3.9
Wood	48.3	6.0	42.4	0.3	2.9	0.11	—	—	—	—	—	—	0.05	—	—	14.1
Food wastes	41.7	5.8	27.6	2.8	21.9	0.25	—	—	—	—	—	—	0.24	—	—	5.3
Yard wastes	49.2	6.5	36.1	2.9	5.0	0.35	—	—	—	—	—	—	0.04	—	—	19.3
Glass	0.52	0.07	0.36	0.03	99.02	—	—	—	—	—	—	—	—	—	—	0.4
Miscellaneous	13.0*	2.0*	12.0*	3.0*	70.0	—	—	—	—	—	—	—	—	—	—	7.5

[a]From Ref. 21; (*) estimated (varies widely); (**) excludes phosphorus in $CaPO_4$.

Table 21 Ultimate Analysis of Annual Average 1970 Mixed Municipal Waste[a]

Category	(wt %) "As-fired"	(wt %) "As-discarded"	(% moisture) "As-discarded"	Composition of average refuse (kg/100 kg dry solids)						
				Ash	C	H_2	O_2	S	N_2	Weight
Metal	8.7	8.2	2.0	10.13	0.50	0.067	0.481	0.0011	0.0056	11.19
Paper	44.2	35.6	8.0	2.74	20.70	2.781	19.193	0.0547	0.1368	45.59
Plastics	1.2	1.1	2.0	0.17	0.90	0.125	0.285	0.0045	0.0150	1.50
Leather, rubber	1.7	1.5	2.0	0.24	1.23	0.170	0.390	0.0062	0.0205	2.05
Textiles	2.3	1.9	10.0	0.08	1.10	0.152	0.995	0.0048	0.0523	2.38
Wood	2.5	2.5	15.0	0.09	1.43	0.178	1.260	0.0033	0.0089	2.96
Food waste	16.6	23.7	70.0	2.17	4.13	0.574	2.730	0.0248	0.2772	9.90
Yard waste	12.6	15.5	50.0	0.54	5.31	0.701	3.890	0.0378	0.3129	10.79
Glass	8.5	8.3	2.0	11.21	0.06	0.008	0.041	—	0.0034	11.32
Miscellaneous	1.7	1.7	2.0	1.62	0.30	0.046	0.278	—	0.0696	2.32
Total	100.0	100.0		28.99	35.66	4.802	29.543	0.1372	0.9022	100.00

Average Refuse Summary (As-fired Basis: 100 kg Average Refuse)

Component	wt %	Mol
Moisture (H_2O)	28.16	1.564
Carbon (C)	25.62	2.135
Hydrogen (H_2-bound)	2.65	1.326
Oxygen (O-bound)	21.21	1.326
Hydrogen (H_2)	0.80	0.399
Sulfur (S)	0.10	0.003
Nitrogen (N_2)	0.64	0.023
Ash	20.82	—
Total	100.0	

Higher heating value (water condensed): 2472 kcal/kg
Lower heating value (water as vapor): 2167 kcal/kg

Table 22 Summary of Elemental Concentrations of Various Fractions of MSW

	Charlestown, PEI (Combustibles fraction) $n = 12$[a]			Quebec City, PQ (Combustibles fraction) $n = 12$			Hartford, CT (RDF) $n = 12$		
Element	Mean	Std. dev.	Median	Mean	Std. dev.	Median	Mean	Std. dev.	Median
Al	12,050	4,060	22,225	5,530	1,740	5,233	72,220	19,930	66,200
Ba	1.2	4.04	0	147	66.9	145	385	130	395
Ca	5,140	1,375	5,125	20,060	6,470	17,250	76,260	14,460	79,700
Cd	0.7	1.14	0	8.06	7.39	5.5	30.3	10.1	29.0
Cr	21.8	16.3	16.5	172	215	112	433	495	275
Co	0.17	0.58	0	3.71	1.76	2.8	52.8	34.2	42.9
Cu	48.3	25.4	41	430	660	108	8,930	17,130	1,720
Fe	2,365	1,830	1,960	6,050	1,385	5,970	31,930	20,205	23,050
Pb	82.4	47.4	79	732	1,080	255	2,760	2,155	1,820
Hg	0.17	0.39	0	1.23	1.04	0.74	0.11	0.10	0.08
Na	3,040	2,070	2,400	2,470	1,010	2,170	71,960	63,550	53,000
Ni	4,25	2.22	4	45.1	8.01	43	442	407	280
Sn	14.2	5.51	12.5	54.9	108	20	889	337	875
Zn	146	61.5	134	429	243	39	5,870	9,050	2,560

[a] n = number of samples.

Source: From (458). Charlestown data from (455). Quebec City data from (456). Hartford data from (457).

Table 23 Metal Concentrations in Components of Municipal and Commercial Waste Materials

Category		Elemental composition in ppm (grams/ton of component)															
Major	Minor	Al	As	B	Ba	Be	Cd	Cr	Cu	Hg	Mn	Ni	Pb	Sb	Se	Sn	Zn
Paper group																	
Fine papers		3283	1.3	2.2	7.7	0.1	0.1	3.4	8	0.3	24.6	7.9	4.5	2.3	0.25	8	208
Books		2874	0.4	37.6	62.6	0.01	0.4	8.7	40	0.2	48.2	1.4	0.005	0.03	0.13	24	88
Magazines	Glued	9808	1.1	2.5	24.2	7.4	0.001	16.6	26	0.3	50.9	17.6	0.4	1.6	0.08	36	36
	Not glued	22413	1.8	7.6	36.9	0.2	0.3	5.8	37	0.3	50.9	8.2	5.9	98.9	0.13	31	18
Laminates	Wax/plastic	5603	0.7	3.7	22.3	0.1	0.3	3.2	7	0.1	25.5	5.4	7.1	3.7	0.05	12	16
	Foil	101,262	0.8	15.4	25.1	7.2	0.1	44.6	226	0.1	64.5	8.7	92.3	20.2	0.02	11	119
Newsprint	Glued	3772	0.8	6.1	9.3	0.3	0.1	1.3	10	0.3	19.5	4.3	2.4	1.2	0.11	18	8
	Not glued[a]	4203	0.7	6.9	18.4	1.0	0.1	3.8	13	2.9	45.0	6.2	7.2	2.5	0.11	24	19
	Not glued[b]	4282	0.6	16.5	23.2	6.3	0.1	215.1	36	0.3	81.9	106.5	5.7	1.8	0.07	25	29
Browns	Corrugated	1030	0.6	3.1	6.3	0.3	0.1	1.8	3	0.1	17.3	3.8	3.8	1.5	0.04	4	10
	Kraft	1687	0.8	4.7	11.3	1.0	0.1	4.7	11	0.5	28.1	7.7	9.3	1.6	0.05	13	22
	Box board	3319	0.7	6.0	31.0	1.1	0.2	5.4	12	0.2	41.0	6.8	12.0	2.8	0.04	11	29
Residual mixed		1505	1.2	6.6	14.3	0.1	1.7	33.0	24	0.4	51.2	7.5	229.4	5.0	0.03	25	81
Plastic group																	
Film	Color	3236	0.5	13.7	169.8	0.1	6.6	115.1	25	0.2	34.1	8.0	361.5	27.1	0.01	92	1132
	Flexible	980	1.7	29.7	11.0	0.1	2.8	86.0	20	0.2	33.0	5.9	279.3	10.7	0.02	31	67
	Rigid	12,451	1.3	5.4	128.5	0.1	37.2	119.6	75	0.1	53.0	27.2	33.7	17.1	0.04	179	52
Food/beverage[c]	No. 1 PETE	1394	0.8	193.5	8.0	1.9	5.3	16.7	31	0.2	60.0	8.3	61.5	174.1	0.05	6	97
	No. 2 HDPE	2438	1.5	29.4	83.5	2.7	2.9	15.0	24	0.2	36.5	7.0	60.6	52.0	0.005	14	142
	No. 3 PVC	90	1.1	7.2	0.0	0.02	4.5	2.6	2	0.1	11.7	2.6	2160	29,700	0.03	17	3
Food/bev. (cont.)[c]	No. 4 LDPE	262	0.2	12.0	5.0	4.0	2.5	4.7	10	0.1	9.4	4.2	56.0	16.0	0.03	0.01	89
	No. 5 PP	736	0.5	5.3	4.5	0.04	1.9	31.6	16	0.1	31.9	6.0	69.3	51.2	0.03	18	40
	No. 6 PS	36	0.2	3.9	3.4	0.03	4.7	7.1	9	0.1	3.6	5.7	25.0	44.0	0.02	25	96
	Other	19688	1.2	20.0	117.9	0.5	79.3	44.1	57	0.4	41.7	38.2	157.7	101.3	0.15	96	273

Footnotes on p. 136.

Table 23 (continued)

Category		Elemental composition in ppm (grams/ton of component)														
Major	Minor	Al	As	B	Ba	Be	Cd	Cr	Cu	Hg	Mn	Ni	Pb	Sb	Se	Sn	Zn
Plastic group (cont.)																	
Housewares	Clear	406	0.1	0.5	18.5	0.5	0.9	6.4	7	0.1	6.1	15.6	61.7	24.9	0.02	316	108
	White	856	0.2	7.1	8.5	1.5	2.5	595.	44	0.2	249.5	146.	41.8	24.9	0.02	66	129
	Blue	1686	3.1	16.9	565.0	0.03	289.7	8.7	80	0.1	11.2	16.3	64.3	90.3	0.03	106	76
	Yellow	826	0.3	8.1	227.1	0.1	104.8	1287	17	0.1	22.7	9.0	2479	62.9	0.08	145	277
	Other	1154	0.3	5.9	168.1	0.5	100.9	359.	29	0.3	14.1	2.8	647.3	254.7	0.22	62	199
Toys & Other		565	0.5	9.5	83.1	1.5	75.8	229.	98	0.1	219.5	27.7	102.8	93.4	0.03	66	349
Videotape		136	14.3	64.7	27.4	0.0	2195	94.1	38	0.2	338.1	17.6	882.0	211.7	0.02	60	774
Organics group																	
Yard & garden	Lawn & plant	15547	7.3	527.1	132.8	2.6	6.0	101.	690	1.4	498.4	23.6	153.6	52.2	0.07	79	365
	Branches	4328	0.9	22.5	54.2	9.7	1.1	24.1	45	0.4	184.7	10.8	61.9	7.8	0.04	19	124
Food waste	Organic	2910	1.2	328.7	17.4	0.0	2.0	22.6	43	0.3	101.2	4.8	72.0	12.8	0.05	38	186
	Shells & bone	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Wood	Finished	431	5.1	14.6	46.3	16.1	1.1	113.	109	0.2	258.3	8.3	562.9	0.2	0.02	18	117
	Unfinished	415	34.0	20.9	27.9	17.4	0.04	56.1	46	0.4	117.2	0.8	324.3	0.5	0.01	31	205
Textiles		894	0.4	6.9	23.0	2.2	2.8	440.	67	1.1	36.7	0.8	128.2	96.4	0.03	43	142
Leather		—	—	—	—	—	—	—	—	—	—	—	——	—	—	—	—
Rubber		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Footwear		2648	0.7	5.6	91.9	2.7	11.9	1831	25	0.1	25.2	5.5	133.8	4.0	0.03	37	764
Other		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Metals group																	
Ferrous	Beer cans	120,400	8.8	125.6	43.0	0.004	61.9	302.7	323	36.4	4690	166.0	230.5	68.8	0.06	986	886
	Soft drink cans	120,400	8.8	125.6	43.0	0.004	61.9	302.7	323	36.4	4690	166.0	230.5	68.8	0.06	986	886
	Food cans	1348	7.0	161.0	1.8	0.004	43.1	158.8	99	5.6	3459	160.4	344.3	88.2	0.04	793	1566
	Band & Strap	626	40.0	372.0	2.2	0.1	15.0	492.0	119	0.02	(d)	41.7	596.0	163.0	0.09	216	30
	Manufactured	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Bimetallic	Beer cans	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Soft drink cans	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Food cans	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Electric motor	181,300	9480	98.0	1274	0.0	9.1	289.1	(e)	5.4	1056	38.9	609.6	74.5	20.58	137	7332
	Other	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Nonferrous	Beer cans	750,000	0.2	9.0	67.0	0.01	3.0	95.0	1141	0.3	7694	27.9	68.0	20.0	0.01	80	170
	Soft drink cans	585,583	0.4	19.7	157.7	0.3	6.0	89.3	1094	0.4	7307	19.1	32.3	18.0	0.01	81	248
	Food cans	731,000	7215	17.2	10.3	0.4	1.7	172.0	645	0.2	3059	34.1	95.5	25.8	16.34	114	445
	Manufactured	370,000	199	20.0	34.0	0.1	5.6	1354	194	0.2	132	7.2	94.0	23.0	5.00	297	(h)
	Foil pack	337,500	0.8	15.0	27.0	0.2	51.0	134.3	279	0.8	2367	40.4	0.004	0.03	0.01	53	120
	Other	850,000	8369	20.0	12.0	—	2.0	200.0	750	0.2	3557	0.0	111.0	30.0	19.0	132	518
Glass group																	
Combined	Clear	13,449	1.0	88.8	340.8	1.0	4.8	943.0	22	0.2	179	10.1	109.3	144.7	0.77	50	60
	Green	10,819	9.8	44.6	486.6	0.4	0.3	46.2	6	0.1	250	62.7	2.0	36.5	0.06	166	21
	Brown	9796	6.9	29.2	190.7	0.2	1.7	91.5	92	.06	256	22.8	103.1	25.4	0.48	27	251
	Other color	6036	0.4	21.5	784.7	0.01	0.4	—	29	0.1	76	12.5	90.0	154.3	0.16	74	1671
Light Bulbs																	

Table 23 (continued)

Category		Elemental composition in ppm (grams/ton of component)															
Major	Minor	Al	As	B	Ba	Be	Cd	Cr	Cu	Hg	Mn	Ni	Pb	Sb	Se	Sn	Zn
Inorganic group																	
Light construction	Rock/sand/dirt	71,574	6.0	2850	807.8	0.01	20.0	187.0	134	0.3	1074	155.8	1545	200.4	0.79	126	5118
	Drywall/plaster	490	0.6	288	31.0	0.9	2.0	8.6	7	0.3	21.0	4.2	38.0	38.0	0.20	26	21
	Glass insulation	977	0.7	53.6	296.7	0.1	0.05	14.1	48	1.1	102.5	8.2	40.8	5.2	0.03	114	12
	Other insulation	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Other	3150	17.0	13.2	61.1	0.2	0.4	34.0	112	0.1	111.2	23.5	30.1	0.8	0.003	89	57
Small appliances group																	
Electrical parts	Brass & copper	—	—	13.2	—	—	—	—	—	—	—	—	—	—	—	—	—
	Plastic	34,368	777.1		1.4	0.04	3.6	251.3	915	0.1	29.6	4.4	662.3	4802	3.05	80	63
	Other metals	—	—	11.8	—	—	—	—	—	—	—	—	—	—	—	—	—
Household hazardous																	
Batteries	Lead acid	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Carbon	6500	2.8	18.0	14.0	0.3	31	38.0	140	20.5	(f)	278.0	40.0	23	0.04	354	(i)
	Ni-cadmium	10000	4.4	70.0	12.0	0.0	12%	64.0	53	0.3	2788	315.0	113.0	670	0.11	53	685
	Alkaline	815	1.0	59.0	7.6	0.3	1940	74.0	(g)	242.	(f)	726.0	143.0	60	0.02	342	(j)

(a) Black and white.
(b) colored.
(c) PETE = polyethylene terephthalate; HDPE = high-density polyethylene; PVC = polyvinyl chloride.
(d) 14,000
(e) 744,800
(h) 400,000
(f) 179,999
(g) 12,000
(i) 63,000
(j) 14,000
LDPE = low-density polyethylene; PP = polypropylene; PS = polystyrene.
Source: From (454).

Table 24 Proximate and Ultimate Analyses and Heating Value of Waste Components

	Proximate analysis (as-received) weight %				Ultimate analysis (dry) weight %						Higher heating value (kcal/kg)		
Waste component	Moisture	Volatile matter	Fixed carbon	Non-comb.	C	H	O	N	S	Non-comb.	As received	Dry	Moisture and ash free
Paper and Paper Products													
Paper, Mixed	10.24	75.94	8.44	5.38	43.41	5.82	44.32	0.25	0.20	6.00	3778	4207	4475
Newsprint	5.97	81.12	11.48	1.43	49.14	6.10	43.03	0.05	0.16	1.52	4430	4711	4778
Brown Paper	5.83	83.92	9.24	1.01	44.90	6.08	47.34	0.00	0.11	1.07	4031	4281	4333
Trade Magazine	4.11	66.39	7.03	22.47	32.91	4.95	38.55	0.07	0.09	23.43	2919	3044	3972
Corrugated Boxes	5.20	77.47	12.27	5.06	43.73	5.70	44.93	0.09	0.21	5.34	3913	4127	4361
Plastic-Coated Paper	4.71	84.20	8.45	2.64	45.30	6.17	45.50	0.18	0.08	2.77	4078	4279	4411
Waxed Milk Cartons	3.45	90.92	4.46	1.17	59.18	9.25	30.13	0.12	0.10	1.22	6293	6518	6606
Paper Food Cartons	6.11	75.59	11.80	6.50	44.74	6.10	41.92	0.15	0.16	6.93	4032	4294	4583
Junk Mail	4.56	73.32	9.03	13.09	37.87	5.41	42.74	0.17	0.09	13.72	3382	3543	4111
Food and Food Wastes													
Vegetable Food Wastes	78.29	17.10	3.55	1.06	49.06	6.62	37.55	1.68	0.20	4.89	997	4594	4833
Citrus Rinds and Seeds	78.70	16.55	4.01	0.74	47.96	5.68	41.67	1.11	0.12	3.46	948	4453	4611
Meat Scraps (cooked)	38.74	56.34	1.81	3.11	59.59	9.47	24.65	1.02	0.19	5.08	4235	6913	7283
Fried Fats	0.00	97.64	2.36	0.00	73.14	11.54	14.82	0.43	0.07	0.00	9148	9148	9148
Mixed Garbage I	72.00	20.26	3.26	4.48	44.99	6.43	28.76	3.30	0.52	16.00	1317	4713	5611
Mixed Garbage II	—	—	—	—	41.72	5.75	27.62	2.97	0.25	21.87	—	4026	5144
Trees, Wood, Brush, Plants													
Green Logs	50.00	42.25	7.25	0.50	50.12	6.40	42.26	0.14	0.08	1.00	1168	2336	2361
Rotten Timbers	26.80	55.01	16.13	2.06	52.30	5.5	39.0	0.2	1.2	2.8	2617	3538	3644

(*continued*)

Table 24 (continued)

Waste component	Proximate analysis (as-received) weight %				Ultimate analysis (dry) weight %						Higher heating value (kcal/kg)		
	Moisture	Volatile matter	Fixed carbon	Non-comb.	C	H	O	N	S	Non-comb.	As received	Dry	Moisture and ash free
Demolition Softwood	7.70	77.62	13.93	0.75	51.0	6.2	41.8	0.1	<.1	0.8	4056	4398	4442
Waste Hardwood	12.00	75.05	12.41	0.54	49.4	6.1	43.7	0.1	<.1	0.6	3572	4056	4078
Furniture Wood	6.00	80.92	11.74	1.34	49.7	6.1	42.6	0.1	<.1	1.4	4083	4341	4411
Evergreen Shrubs	69.00	25.18	5.01	0.81	48.51	6.54	40.44	1.71	0.19	2.61	1504	4853	4978
Balsam Spruce	74.35	20.70	4.13	0.82	53.30	6.66	35.17	1.49	0.20	3.18	1359	5301	5472
Flowering Plants	53.94	35.64	8.08	2.34	46.65	6.61	40.18	1.21	0.26	5.09	2054	4459	4700
Lawn Grass I	75.24	18.64	4.50	1.62	46.18	5.96	36.43	4.46	0.42	6.55	1143	4618	4944
Lawn Grass II	65.00	—	—	2.37	43.33	6.04	41.68	2.15	0.05	6.75	1494	4274	4583
Ripe Leaves I	9.97	66.92	19.29	3.82	52.15	6.11	30.34	6.99	0.16	4.25	4436	4927	5150
Ripe Leaves II	50.00	—	—	4.10	40.50	5.95	45.10	0.20	0.05	8.20	1964	3927	4278
Wood and Bark	20.00	67.89	11.31	0.80	50.46	5.97	42.37	0.15	0.05	1.00	3833	4785	4833
Brush	40.00	—	—	5.00	42.52	5.90	41.20	2.00	0.05	8.33	2636	4389	4778
Mixed Greens	62.00	26.74	6.32	4.94	40.31	5.64	39.00	2.00	0.05	13.00	1494	3932	4519
Grass, Dirt, Leaves	21–62	—	—	—	36.20	4.75	26.61	2.10	0.26	30.08	—	3491	4994
Domestic Wastes													
Upholstery	6.9	75.96	14.52	2.62	47.1	6.1	43.6	0.3	.1	2.8	3867	4155	4272
Tires	1.02	64.92	27.51	6.55	79.1	6.8	5.9	0.1	1.5	6.6	7667	7726	8278

Leather	10.00	68.46	12.49	9.10	60.00	8.00	11.50	10.00	0.40	10.10	4422	4917	5472
Leather Shoe	7.46	57.12	14.26	21.16	42.01	5.32	22.83	5.98	1.00	22.86	4024	4348	5639
Shoe, Heel & Sole	1.15	67.03	2.08	29.74	53.22	7.09	7.76	0.50	1.34	30.09	6055	6126	8772
Rubber	1.20	83.98	4.94	9.88	77.65	10.35	—	—	2.00	10.00	6222	6294	7000
Mixed Plastics	2.0	—	—	10.00	60.00	7.20	22.60	—	—	10.20	7833	7982	8889
Plastic Film	3–20	—	—	—	67.21	9.72	15.82	0.46	0.07	6.72	—	7692	8261
Polyethylene	0.20	98.54	0.07	1.19	84.54	14.18	0.00	0.06	0.03	1.19	10,932	10,961	11,111
Polystyrene	0.20	98.67	0.68	0.45	87.10	8.45	3.96	0.21	0.02	0.45	9122	9139	9172
Polyurethane	0.20	87.12	8.30	4.38	63.27	6.26	17.65	5.99	0.02	4.38(a)	6224	6236	6517
Polyvinyl Chloride	0.20	86.89	10.85	2.06	45.14	5.61	1.56	0.08	0.14	2.06(b)	5419	5431	5556
Linoleum	2.10	64.50	6.60	26.80	48.06	5.34	18.70	0.10	0.40	27.40	4528	4617	6361
Rags	10.00	84.34	3.46	2.20	55.00	6.60	31.20	4.12	0.13	2.45	3833	4251	4358
Textiles	15–31	—	—	—	46.19	6.41	41.85	2.18	0.20	3.17	—	4464	4611
Oils, Paints	0	—	—	16.30	66.85	9.63	5.20	2.00	—	16.30	7444	7444	8889
Vacuum Cleaner Dirt	5.47	55.68	8.51	30.34	35.69	4.73	20.08	6.26	1.15	32.09	3548	3753	5533
Household Dirt	3.20	20.54	6.26	70.00	20.62	2.57	4.00	0.50	0.01	72.30	2039	2106	7583
Municipal Wastes													
Street Sweepings	20.00	54.00	6.00	20.00	34.70	4.76	35.20	0.14	0.20	25.00	2667	3333	4444
Mineral (c)	2–6	—	—	—	0.52	0.07	0.36	0.03	0.00	99.02	—	47	—
Metallic (c)	3–11	—	—	—	4.54	0.63	4.28	0.05	0.01	90.49	—	412	4333
Ashes	10.00	2.68	24.12	63.2	28.0	0.5	0.8	—	0.5	70.2	2089	2318	7778

[a]Remaining 2.42% is chlorine.
[b]Remaining 45.41% is chlorine.
[c]Heat and organic content from labels, coatings, and remains of contents of containers.
Source: Refs. 38–40, 116–118.

Table 25 Soluble and Insoluble Chlorine Content of Refuse Constituents [378] (Mass Percent—Dry Basis)

A. Baltimore County, MD

Waste category	Total % Cl_2	Std. dev.	Soluble % Cl_2	Std. dev.	Insoluble % Cl_2	Std. dev.
Paper	0.251	0.0063	0.088	0.0077	0.163	0.0099
Plastics, soft	0.055	0.0100	0.004	0.0013	0.051	0.0101
Plastics, hard	0.083	0.0326	0.000	0.0000	0.083	0.0326
Wood/vegetable	0.005	0.0018	0.003	0.0007	0.002	0.0009
Textiles	0.019	0.0090	0.006	0.0031	0.013	0.0095
"Fines"	0.042	0.0053	0.009	0.0011	0.033	0.0054
Total	0.455	0.0363	0.110	0.0085	0.344	0.0373

B. Brooklyn, NY

Waste category	Total % Cl_2	Std. dev.	Soluble % Cl_2	Std. dev.	Insoluble % Cl_2	Std. dev.
Paper, unbleached	0.211	0.0702	0.140	0.0618	0.071	0.0935
Paper, bleached	0.013	0.0015	0.007	0.0017	0.007	0.0023
Plastics, soft	0.123	0.0427	0.007	0.0014	0.117	0.0427
Plastics, hard	0.332	0.1038	0.009	0.0049	0.323	0.1039
Wood/vegetable	0.056	0.0145	0.023	0.0026	0.034	0.0147
Textiles	0.020	0.0102	0.007	0.0028	0.013	0.0106
"Fines"	0.131	0.1141	0.022	0.0114	0.109	0.1147
Total	0.886	0.1757	0.215	0.0632	0.674	0.1869

2. Bulk Density

In many smaller municipalities, weighing scales for refuse vehicles are not available. In such circumstances, data is often gathered on a volumetric basis. Bulk density data are presented in Table 26.

3. Thermal Parameters

Once a weight-basis generation rate is established, data on the heating value of waste components are of great interest to the combustion engineer. The information in Table 27 is presented to supplement the data in Table 24.

4. Municipal Refuse as a Fuel

Electric power plants and industrial combustion systems represent a rich source of data and proven design experience for understanding and improving incineration systems. To use these data, however, it is necessary to appreciate the similarities and differences between municipal refuse and its associated combustion parameters and those for other fuels.

a. Heat Content. Municipal refuse, though quite different from high-rank coals and oil, has considerable similarity to wood, peat, and lignite (Table 28). It would be reasonable, therefore, to seek incinerator design concepts in the technology developed for the combustion of the latter materials. Refuse does, however, have distinguishing characteristics, such as its high total ash content, which may require more extensive ash-handling

(*text continues on 146*)

Table 26 Bulk Density of Mixed Wastes and Waste Components (kg/m^3)

	Unspecified average	Loose	Other	Range	Reference
Mixed residential wastes					
Garbage, kitchen waste	370	185		300–450	119
Mixed refuse with garbage		185	195[a]		119
Mixed refuse without garbage		140	280[a]		119
Residential	145			60–255	120
Residential in paper sacks	115			80–160	120
Wet residential	170			115–255	120
Damp residential	130			90–215	120
Dry residential	120			55–145	120
Bunkered refuse (8–11 m high)					
10% Moisture	155				121
20% Moisture	180				121
30% Moisture	225				121
40% Moisture	275				121
50% Moisture	345				121
Single-family dwelling	105				121
Multiple-family dwelling	110				122
Apartment house	150				122
Residential waste components					
Grass and trimmings		130			119
Metal cans		95			119
Unbroken glass and bottles		415			119
Broken glass		1190			123
Rags		115			124
Paper and cardboard		110	215[b]		119
Paper		140			124
Wet paper		165			124
Rubber		270			124
Bulky wastes					
Household bulky	100				125
Average bulky	190				125
Tree cuttings	135				125
Logs and stumps	400				119
Green logs		320	800[c]		121
Limbs and leaves		160	190[d]		119
Brush		30			119
Furniture		50			119
Major appliances		180			119
Wood crates		110			119
Battery case and miscellaneous auto	715				119
Auto bodies		130			119
Wood pallets, driftwood	210				125
Tires and rubber products		240			119

(*continued*)

Table 26 (continued)

	Unspecified average	Loose	Other	Range	Reference
Construction-demolition					
Mixed demo, nonburnable		1430			119
Mixed demo, burnable		360			119
Mixed const, burnable		255			125
Mixed construction I		965			119
Mixed construction II	160				125
Broken pavement, sidewalk		1520			119
Municipal					
Street dirt		1370			119
Alley cleanings		150			126
Street sweepings, litter		250			125
Catch-basin cleaning		1445			119
Sewage-sludge solids		1040			119
Sewage screenings		950			119
Sewage skim (grease)		950			119
Industrial waste					
Sawdust		290			123
Bark slabs		400			123
Wood trimmings		580			123
Wood shavings		240			123
Mixed metals		120			123
Heavy metal scrap		2410			119
Light metal scrap		800			119
Wire		320			119
Dirt, sand, gravel		1445			119
Cinders		900			124
Fly ash		1285			119
Cement industry waste		1425			119
Other fine particles		965			119
Oils, tars, asphalts		965			119
Mixed sludges (wet)		1190			123
Chemical waste, dry		640			119
Chemical waste, wet		965			119
Leather scraps		180			123
Shells, offal, paunch, fleshings		300			123
Textile wastes		180			123
Rubber		300			123
Plastics		30			123
Agricultural waste					
Pen sweepings		650			119
Paunch manure		1030			119
Other meat-packing waste		1030			119
Dead animals		355			119
Mixed vegetable waste		355			123
Mixed fruit waste		355			123

(*continued*)

Table 26 (continued)

	Unspecified average	Loose	Other	Range	Reference
Agricultural waste (continued)					
Beans or grain waste		775			119
Potato-processing waste		670			119
Chaff		60			123
Mixed agricultural		585			119
Residues					
Liquid slag				240–288	180
Dense solid slag				224–272	180
Solid ash				192–256	180
Loose powder ash				24–56	180
Fine ground slag				96–144	180

[a]Dumped packer truck density, expanded from 215 kg/m^3 in packer truck.
[b]Compacted in packer truck.
[c]Density of wood.
[d]Chipped.

Table 27 Higher Heating Value of Refuse Components (kcal/kg)[a]

	Ash content (dry basis)	Higher heating value (kcal/kg)	
		Dry basis	Dry, ash-free
Paper, paper products			
Books, magazines	24.05		4198
Cardboard			4652
Mixed paper I	6.55		4488
Mixed paper II	4.02		4283
Waxed paper			6111
Waxed cartons			6667
Food, food wastes			
Garbage (California)	6.53		4044
Cooking fats			9000
Sugar (sucrose)	0.00	3943	3943
Starch	0.00	4179	4179
Coffee grounds		5588	
Corn on the cob		4500	
Brown peanut skins		5795	
Oats		4443	
Wheat		4184	
Castor oil	0.00	8861	8861
Cottonseed oil	0.00	9400	9400
Trees, wood, brush, plants			
Brush (California)	8.87		4732
Excelsior	0.77		4792
Greens (California)	10.57		4396

(*continued*)

Table 27 (continued)

	Ash content (dry basis)	Higher heating value (kcal/kg)	
		Dry basis	Dry, ash-free
Trees, wood, brush, plants (continued)			
Lignin			5850
Wood (California)	1.13		4678
Pitch		8406	
Wood (Washington, D.C.)	1.65		4925
Sawdust (pine)		5376	
Sawdust (fur)		4583	
Wood, beech (13% H_2O)		3636	
Wood, birch (11.8% H_2O)		3717	
Wood, oak (13.3% H_2O)		3461	
Wood, pine (12.2% H_2O)		3889	
Domestic wastes			
Linoleum	27.4		6361
Rags, linen		3962	
Rags, cotton			4000
Rags, silk		4662	
Rags, wool			5444
Rags, mixed	2.19		4189
Rags, cellulose acetate	2.19		4444
Rags, nylon			7328
Rags, rayon			416
Rubber	48.0		7111
Shellac			7544
Asphalt			9533
Plastics			
Phenol formaldehyde			6217
Polyethylene			11083
Polypropylene			11083
Polystyrene			9906
Polyurethane foam			5700
Styrene-butadiene copolymer			9833
Vinyl chloride/acetate copolymer			4906
Metals			
Aluminum (to Al_2O_3)			7417
Copper (to CuO)			603
Iron (to $FeO_{.947}$)			1200
Iron (to Fe_3O_4)			1594
Iron (to Fe_2O_3)			1756
Lead (to PbO)			250
Magnesium (to MgO)			5911
Tin (to SnO_2)			1169
Zinc (to ZnO)			1275

[a] *Source:* Refs. 40, 127, 128; see also Table 4.16.

Table 28 Heat Content of Municipal Refuse and Other Fuels

Fuel	Moisture (%)	Ash (%)	Volatile (dry basis %)	(Higher heating value) (kcal/kg)				As-fired (lower heating value) (kcal/kg)
				As-fired	Ash-free	Dry basis	Dry, ash-free basis	
Refuse	28.16	20.82	62.3	2470	3120	3440	4845	2185
Wood	46.9	1.5	78.1	2605	2645	4910	5050	2170
Peat	64.3	10.0	67.3	1800	2000	5030	6995	1330
Lignite	36.0	12.1	49.8	3925	4465	6130	7560	3585
Sub-bituminous B	15.3	6.7	39.7	5690	6100	6720	7200	5375
Bituminous-high volatile B	8.6	8.4	35.4	6800	7420	7440	8190	6520
Bituminous-volatile	3.6	4.9	16.0	8030	8450	8330	8780	7775
Anthracite	4.5	14.4	7.4	6170	7205	6460	7600	6010
Methane	0	0	100.0	13,275	13,275	13,275	13,275	11,975
#2 Fuel oil	0	0	100.0	10,870	10,870	10,870	10,870	10,210
#6 Fuel oil	1.5	0.08	100.0	10,145	10,300	10,300	10,375	9,600

equipment. Excluding the massive ash (metal and glass), however, the fine ash content (that capable of being suspended in the flue gas) is only 5.44%, suggesting that incinerators may require less efficient particulate air pollution control devices for comparable combustion situations. Clearly, refuse is also a lower energy fuel than most conventional solid fuel alternatives.

As noted above, heat content can be expected to change over time and, especially, if the character of the domestic and commercial culture is in a state of rapid evolution. This circumstance is seen in many countries and regions where burgeoning economic development has led to revolutionary changes in buying habits and, consequently, in the character (and quantity) of solid waste. Figure 1 shows this evolutionary development for Kaohsiung City in southern Taiwan over the period 1983 through 1993 (511).

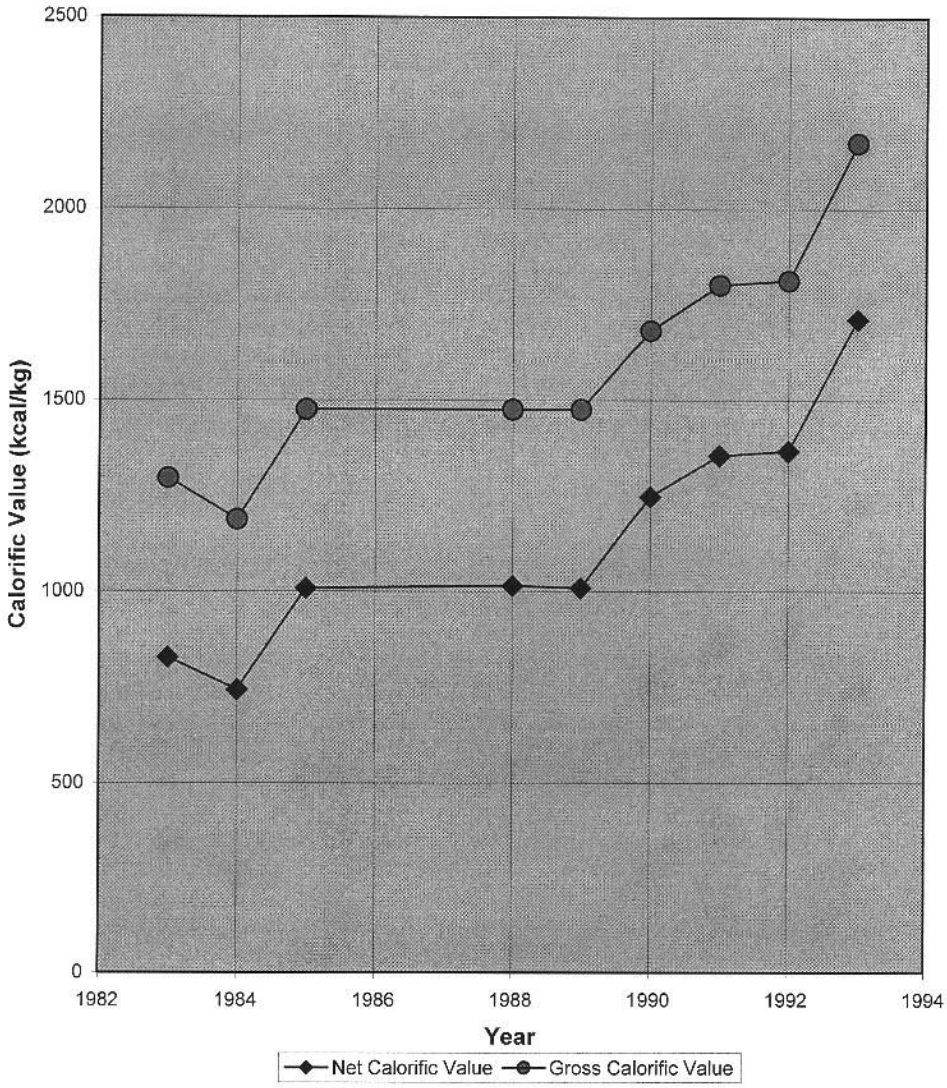


Figure 1 Change in MSW calorific value for Kaohsiung City, Taiwan.

b. Density. Refuse density is similar to that of wood, peat, and lignite (Table 28). Since, in grate-fired systems, coal and refuse grate retention times are comparable (40–50 min), refuse bed depths would be much greater than those for coal at comparable grate burning rates. A typical coal stoker, for example, burns at the rate of 9,300 to 12,000 kcal hr^{-1} m^{-2}. This corresponds, for the bituminous coal energy density and for typical stoker speeds, to a bed height of 12.7 to 17.7 cm. In order to provide comparable specific burning rates for refuse, bed heights from 110 to 150 cm are required.

Table 29 indicates the average density of municipal refuse in comparison with other fuels. The "ultimate density" for refuse was calculated as the weighted average of the densities of the refuse components. Comparing the ultimate density with the as-fired density yields an approximate void fraction that is much higher for refuse than for any other fuel shown. The high void fraction, aside from reaffirming the need for a deep bed, also indicates the difficulties in obtaining uniform refuse distribution to avoid "blowholes" or open spaces on the grate.

In summary, municipal refuse burning practices should be comparable with those for low-rank carbonaceous solid fuels such as wood, peat, and lignite. Although incinerator designs reflect a portion of the technology developed to burn these other materials, application of spreader stoker and suspension burning techniques and some aspects of furnace design and fuel feeding have not yet found their way into conventional incinerator practice. However, refuse does present some unique problems to the furnace designer, particularly as a result of its high ash content, relatively low energy density ($kcal/m^3$), and high moisture content.

5. Other Wastes

Data are often tabulated for many different wastes such as those from both specific and general commercial and industrial sources or from specialized sources such as hospitals. Since these data often reflect highly specific processes, manufacturing techniques, raw material choices, and so forth, etc., one must be very cautious about using such tabulated "typical" data for detailed design. In general, at least some waste sampling and analysis is merited to form a project-specific basis for design, to observe potential materials handling or safety problems, and the like. In some cases, however, the source characteristics are similar enough to benefit from tabulated data.

a. Automobile Shredder "Fluff" Waste. Data were generated on the "fluff" fraction of the waste generated in shredding automobile bodies. The waste is about 16% of the weight

Table 29 Density of Material Refuse and Other Fuels

Fuel	Density (as-fired kg/m^3)	$kcal/m^3$	Density (ultimate) kg/m^3)	Mean void fraction (%)
Refuse	273 (av)	676,000	963 (est)	72
Wood (chips)	280	730,000	562 (av)	50
Peat	400 (est)	712,000	802	50
Bituminous coal (sized)	802	5,783,000	1405	43
#6 Fuel	987	10,010,000	987	0
Methane	0.67	9,000	N/A	N/A

Table 30 Characteristics of Automobile Shredder "Fluff" Waste (386)

Property (units)	Low value	High value	Average value
Moisture (% as-received)	2	34	10
Ash (% as-received)	25	72	47
Volatiles (% as-received)	24	66	44
Fixed carbon (% as-received)	0	12	3
Sulfur (% as-received)	0.2	0.5	0.4
Chlorine (% as-received)	0.7	16.9	3.4
HHV (kcal/kg—MAF)*	5,517	7,128	6,444
Density (kg/m^3)			320
Size consist −6 mm	19	55	35
Size consist +6 to −12 mm	16	29	20
Size consist plus 12 mm	27	64	46
Component weight %			
Fiber			42.0
Fabric			3.1
Paper			6.4
Glass			3.5
Wood splinters			2.2
Metals			8.1
Foam			2.2
Plastics			19.3
Tar			5.8
Wiring			2.1
Elastomers			5.3
Stack gas inlet HCl (12% O_2)			600 ppm
Stack gas inlet SO_2 (12% O_2)			100 ppm
Stack gas NO_x (12% O_2)			111 ppm

*MAF = Moisture and ash free.

of the total auto body and consists mainly of the nonmetallic portion of automobiles (excluding tires, batteries, and radiators, which are customarily removed prior to shredding). Thus, fluff is generated from interior plastic trim, upholstery fabric and filler, insulation, and padding. Data on the characteristics of this waste are presented in Table 30.

III. BIOLOGICAL WASTEWATER SLUDGE

The biological treatment of wastewater from domestic and many industrial sources involves a series of process steps aimed at either converting undesirable pollutants from a solubilized state to a solid form or removing the solids from the bulk flow. Although the processes used may involve some reduction in the pollutants (e.g., through biological oxidation), the majority of the pollutant mass that enters the plant exits the wastewater treatment plant as a constituent of "biological sludge" or "biosolids."

The categories of biosolids include

Primary treatment sludge—the sludge generated through settling early in the treatment sequence

Secondary treatment sludge—the excess biomass generated in the activated sludge tanks under aerobic conditions through biological reproduction and growth whereby soluble pollutants are converted into cell mass

Tertiary treatment sludge—biomass generated in advanced wastewater treatment such as denitrification.

Other solid streams are often generated in the course of treatment though in lesser quantities than the sludges: "scum" (the floatable material accumulating on clarifiers); "screenings" (the rags, twigs, and other large solids screened from the entering wastewater), and "grit" (the coarse sandy/silty solids removed following screening).

Having captured the solids, some plants move directly to some kind of ultimate disposal system such as landfill or direct land application. Most plants interpose one of several processes ahead of disposal in order to accomplish several ends: pasteurization or other step to kill off pathogenic organisms and "stabilization" of the sludge such that continued vigorous biological activity stops or is slowed. Common processes to accomplish these ends include lime addition or "digestion."

Lime addition involves mixing lime (calcium oxide) with the sludge to raise both the temperature (from the heat of hydration/slaking) and the pH to kill pathogenic organisms and stop biological activity. This often involves addition of 20% to 30% lime (by weight on dry solids), so a considerable increase in both mass and ash content occurs.

Digestion involves continuing biological degradation of organic compounds bound in the sludge. The process can be conducted under aerobic conditions (with excess oxygen) or anaerobic conditions (oxygen-deficient). The latter involves thermophylic, methane-forming organisms and, consequently, generates fuel values as "digester gas" that have potential application in incineration or other energy-intensive processes as well as for sludge preheating. Clearly, the conversion of a portion of the biomass to methane fuel (the digester gas is about 50% methane and 50% CO_2) results in some depletion of the fuel value (higher ash-to-combustible ratio) of the stabilized sludge solids. Further, digestion adversely impacts the dewatering characteristics of the sludge.

The means for ultimate disposal of wastewater treatment solids has evolved over the years. For wastewater treatment plants that are in or near to rural areas with easy access to farmlands and that generate sludge having low concentrations of the heavy metals mercury, cadmium, chromium, lead, and nickel, application of liquid sludge (2% to 5% solids), dried sludge products or composted sludge to croplands has been encouraged by many regulatory authorities and found to be cost-effective and generally acceptable to the sludge users. In more urbanized areas where the distance to and scale of land application would be unreasonable and/or where intensive industrialization has led to the presence of significant concentrations of heavy metals in the sludge, incineration followed by ash landfilling is often practiced.

As one might suspect from the above, the characteristics of wastewater treatment sludge are strongly related to (1) the mix of domestic, commercial, and industrial wastewater types involved and (2) the process flowsheet of the treatment plant. Thus, a "bedroom-community" wastewater plant usually generates a highly organic, clean sludge, whereas a heavily industrialized city generates a sludge that can be heavily contaminated with undesirable heavy metals and, even, toxic organic pollutants. Some communities use "combined sewers" where runoff from storms is carried (and treated) through the same sewer system as the sanitary sewage. Thus, contaminants and the content of inert, soil-derived materials in the sludge (scoured from the sewer lines during high storm flows) are

dependent on rainfall patterns. Changes and upsets in the treatment plant can significantly alter the characteristics of treatment and the performance of dewatering equipment. The conclusion one must draw is that the characteristics of wastewater sludges are exceedingly variable. Therefore, flexibility in the ability to respond to changes is an important process feature of a satisfactory sludge incineration system.

A. Sludge Composition

The solids in sludge fall into two broad categories: the combustibles and the ash. Combustibles include the organic cell mass and other organic matter (scum, leaves, etc.). In this category are also the (usually) trace amounts of pesticides and other toxic anthropogenic organic compounds. Often, workers in the field mistakenly equate the combustible content of sludge to the reported "volatile solids" (VS) content of the sludge. VS is a sludge characterization variable often reported in the literature. One must be cautious, however, since the protocols used in sludge analysis result in a portion of the inorganic sludge mass associated with lime and ferric chloride treatment (used to enhance dewatering) and of some other inorganic compounds to be reported as VS.

The ash component of sludge includes the relatively inert inorganic materials associated with the wastewater flow (grit, silt, and sand, etc.) but also includes the insoluble toxic metal compounds, which can be environmentally significant.

As noted above, digestion reduces the VS content of the sludge. Wet oxidation is another process often applied to sludge to assist in disposal. There, partially dewatered sludge is heated to high temperatures at elevated pressures and treated with hot, compressed air. The combination of conditions ruptures the cells and oxidizes (in the wet condition) a portion of the VS. The resulting sludge solids dewater exceedingly well in relatively low-cost dewatering devices (to, say, 34%–40% solids) and often show an increase in the fuel value of the organic fraction (presumably, from a shift in the relative proportions of carbon, hydrogen, and oxygen). The high-strength liquid stream that must be recycled to the headworks of the treatment plant is a disadvantage to wet oxidation.

B. Sludge Properties

1. Chemistry

The chemistry of biosolids differs significantly from that of most other wastes. This derives from its nature as a biomass comprised very importantly of myriad microscopic organisms. This tends to increase the phosphorous, nitrogen, and, to a degree, sulfur content when compared to typical "refuse" materials.

Data showing the range of sludge chemistry and heat content are shown in Tables 31 and 32. Please note that this table is not an exhaustive compilation and that significantly different sludge compositions are, undoubtedly, to be found.

2. Physical Properties

a. Percent Solids and Dewatering. The percentage of solid matter is the most important sludge parameter in the design and operation of incineration systems. For most municipal treatment plants (often referred to as Publicly Owned Treatment Works or POTWs), dewatering is seldom able to produce a sludge with more than a 25% to 27% solids cake. Thus, the burning of sludge is more the "burning" of water than of organic biomass. Further, in many plants, the sludge percent solids is allowed to be the dependent variable in

Table 31 Wastewater Treatment Sludge Data

Type	No.	Vol. Mat.	Fixed C	Ash	S	C	H	N	O	Cl	kcal/kg
Dig. P + S	1	50.54%	11.77%	37.69%	2.02%	34.04%	4.16%	5.79%	16.29%	1.06%	3461
Dig. P + S	1	50.04%	12.83%	37.13%	1.88%	34.24%	4.10%	4.52%	18.13%	0.80%	3529
Dig. P + S	1	57.55%	11.99%	30.46%	1.93%	38.38%	4.93%	1.86%	22.44%	0.80%	4009
Dig. P + S	1	47.31%	10.74%	41.95%	2.04%	32.29%	3.94%	4.91%	14.88%	0.84%	3292
Dig. P + S	1	50.91%	15.01%	34.08%	1.50%	37.13%	4.28%	6.25%	16.76%	2.22%	3727
Dig. P + S	1	49.61%	10.26%	40.13%	1.76%	33.10%	4.07%	5.35%	15.60%	0.81%	3366
Dig. P + S	1	60.71%	10.83%	28.46%	2.03%	39.38%	5.16%	6.29%	18.68%	0.83%	4167
Dig. P + S	1	59.68%	12.88%	27.44%	1.92%	40.67%	5.36%	5.77%	18.84%	0.82%	4294
Dig. P + S	1	45.96%	15.40%	38.64%	1.54%	35.00%	3.66%	5.64%	15.52%	0.84%	3402
Dig. P + S	1	49.34%	10.52%	40.14%	1.61%	33.63%	4.20%	4.93%	15.48%	0.74%	3463
Dig. P + S	2	56.29%	7.84%	35.87%	1.02%	35.32%	5.10%	5.29%	17.40%	0.40%	3808
Raw DI	3	49.89%	0.00%	50.11%	0.16%	26.91%	2.86%	1.19%	18.77%	—	2057
Raw P + S	4	61.67%	9.33%	28.78%	—	38.08%	3.43%	2.99%	24.32%	0.82%	3966
Raw P + S	4	60.52%	9.64%	29.84%	—	37.36%	8.28%	2.67%	24.45%	0.67%	3857
Raw P + S	4	56.94%	9.92%	33.14%	0.38%	36.16%	5.02%	2.67%	22.65%	0.51%	3516
Raw P + S	4	59.15%	8.87%	31.98%	0.38%	36.17%	5.35%	2.52%	23.60%	0.76%	3572
Raw P + S	4	44.80%	7.66%	47.54%	0.12%	27.92%	4.03%	2.08%	18.31%	0.59%	2717
Raw P + S	5	69.60%	8.30%	22.10%	0.91%	50.06%	7.00%	4.82%	15.05%	0.11%	5500
Raw P + S	6	83.20%	17.20%	9.60%	0.71%	45.88%	6.46%	3.70%	9.60%	—	4518

(*continued*)

Table 31 (continued)

Type	No.	Vol. Mat.	Fixed C	Ash	S	C	H	N	O	Cl	kcal/kg
Raw P + S	6	72.38%	18.44%	9.18%	0.73%	46.05%	6.48%	3.59%	9.18%	—	4551
Raw P + S	6	71.93%	15.20%	12.87%	0.08%	44.91%	5.05%	3.92%	12.87%	—	3931
Raw P + S	6	69.52%	18.21%	12.17%	0.77%	43.08%	6.14%	4.19%	12.17%	—	4150
Raw P + S	6	70.70%	17.55%	11.75%	0.76%	45.66%	6.48%	4.18%	11.75%	—	4656
Raw P + S	6	70.14%	15.34%	14.52%	0.85%	44.03%	6.00%	4.32%	14.52%	—	4309
Raw P + S	6	69.14%	17.46%	13.40%	0.83%	43.66%	5.89%	4.36%	13.40%	—	4162
Raw P + S	6	69.17%	13.76%	17.07%	1.00%	45.64%	5.50%	4.23%	17.07%	—	4210
Raw P + S	7	56.10%	2.20%	41.70%	0.42%	26.32%	3.28%	2.77%	25.44%	0.11%	2305
Raw P + S	8	68.30%	9.31%	22.39%	0.50%	45.39%	5.39%	3.56%	22.55%	0.80%	4645
Zimpro	4	43.20%	7.61%	49.19%	—	26.95%	3.73%	2.84%	17.06%	0.65%	2655
Zimpro	4	59.31%	10.01%	30.68%	0.37%	36.66%	5.36%	2.12%	24.81%	0.75%	3705
Zimpro	4	43.04%	7.03%	49.73%	—	25.91%	3.71%	2.42%	17.99%	0.58%	2465
Zimpro	4	42.35%	7.26%	50.39%	0.33%	26.95%	3.86%	1.64%	16.84%	0.29%	2367
Zimpro	4	43.52%	7.51%	48.97%	0.16%	27.12%	4.23%	1.59%	17.93%	0.56%	2587
Zimpro	9	41.49%	2.67%	55.84%	0.77%	26.42%	3.67%	1.89%	11.41%	0.12%	2681

Notes: P = primary, S = secondary, Zimpro = heat conditioned, Dig. = digested, DI = Deinking plant.
Data for plants 3 and 6 are for wastewater treatment sludge from paper mills.

Table 32 Typical Higher Heating Value for Wastewater Treatment Solids

Sludge type	Typical sludge higher heating value (kcal/kg-dry basis)
Raw primary sludge	5,500–7,000
Activated (secondary) sludge	4,700–5,500
Anaerobically digested primary sludge	3,050
Raw, primary sludge, $FeCl_3$-lime conditioned	3,900
Biological trickling filter solids	4,700–5,500
Grease and scum	9,250
Fine screenings	4,300
Ground garbage	4,550
High organic grit	2,200

the plant with detention times, effluent quality, and almost all other process variables held to narrow tolerances. From the standpoint of thermal processing systems, this means that the most important process variable is "out of control." Clearly, in view of the increases in fuel expense, increased environmental impacts, and other adverse consequences of the uncontrolled swings in operating conditions which are often associated with such a plant management strategy, the decision to implement a thermal processing system should be the occasion to seriously reevaluate plant wet-end operating priorities and practices.

The dewatering of sludges can be affected by a number of technologies. Table 33 indicates the range of performance of such equipment. One must remember in considering such generalizations on dewatering performance that biological sludge is a collection of living organisms. As such, it can be "young" or old, sickly or healthy, highly aerobic and vigorous or devoid of oxygen (septic) and in decline. Further, each of these characterizations of sludge "state" is associated with different dewatering behavior. Therefore, the same treatment plant can, from time to time, experience wide swings in dewatering performance due to changes in wastewater characteristics, temperature changes, plant process upsets, or equipment malfunctions, etc.

Table 33 Typical Sludge Dewatering Effectiveness Levels

Gravity settling	Percent solids
Clarifier	0.5–4
Thickener	3–8
Hydrocyclones	3–8
Sludge drying bed	85+
Mechanical dewatering	**Percent solids**
Vacuum filter	14–23
Belt filters	16–34
Filter press	30–45
Centrifuge (conventional)	14–23
Twin-roll nip press	15–25
Centrifuge (high "g")	23–35

To assist in gravity or mechanical dewatering, a variety of coagulation and/or conditioning aids may be used. These include alum, polymers, lime, lime and ferric chloride, and even recycled incinerator ash. For some of the filtering devices, precoats or filtering aids are sometimes used. While any or all of these may increase the percent solids, it is noteworthy, with respect to the use of inorganic chemicals, that often a marginal improvement in cake percent solids is obtained with an *increase* in energy parameter (see subsection 3, "Thermal Properties," ahead) and, thus, becomes less energy-efficient as a feed to combustion systems due to the dilution of sludge combustibles with inert matter.

b. Surface Chemistry. Wastewater treatment sludges (chemical or biological) consist of solids (organic and/or inorganic) that carry a charged outer layer. The zeta potential is a measurable indication of the charge. The zeta potential may be used as an indicator of the probable response of the water–solids mixture to added ionic species such as lime, alum, or certain polyelectrolyte polymers used to coagulate and flocculate the solids. These coagulation aids are often needed to improve the dewatering characteristics of the sludge. While not directly relevant to the incineration process, the complex surface chemistry of sludges also significantly impacts their rheological properties and storage characteristics. Thus, a basic recognition of the surface-active nature of the materials can provide a starting point for problem solving associated with materials-handling systems for sludge materials.

c. Biology. The particular species of biological organisms in wastewater sludge may be important. Of particular importance are the pathogens (disease-causing organisms) that could result in operational problems and hazards and/or limitations in disposal (pasteurization or other treatment may be required by regulatory agencies in order to effect a pathogen kill). The population of any specific organisms in sludge depends on many factors: the source of the sludge solids, the pH and temperature, the dissolved oxygen concentration, and other process features that encourage or discourage growth of particular organisms. Clearly, any substantial pathogen content that develops is pertinent. Note, however, that most pathogens are relatively vulnerable to stressed conditions. In those situations where the sludge is stored over a prolonged time and, particularly, in the course of composting operations, spores of certain fungi may be formed that exacerbate respiratory problems.

For most biological sludges, anaerobic organisms are present. On standing, the aerobic species rapidly consumes available oxygen within the sludge mass. Diffusion of atmospheric oxygen is too slow to renew it. Therefore, after an induction period, the anaerobic organisms begin to thrive and, in a short time, achieve dominance within the sludge mass. This can rapidly cause odor problems during storage due to generation of hydrogen sulfide and a spectrum of mercaptans and organic sulfides and disulfides.

d. Ash Fusion Temperature. Table 34 summarizes data (204) on the ash chemistry and ash fusion temperature for several sewage sludge samples. The data illustrate the range of typical values for these parameters and the variation to be expected within the same plant.

3. Thermal Properties

a. Heat of Combustion. The heat of combustion of sludge combustible is roughly comparable to that of peat, as Table 28 shows. The heat of combustion is somewhat elevated by the presence of excess oils and greases. Often, sludge heat content is reported in the literature in units of kcal/kg VS, but this is not desirable since the VS content can be

Table 34 Ash Composition and Fusion Temperatures for Biological Wastewater Treatment Plant Sludge Ash

		Fusion data (Deg. C)—reducing conditions				Fusion data (Deg. C)—oxidizing conditions			
Sludge type	Plant no.	T-ID (R)	T-S (R)	T-Hem (R)	T-F (R)	T-ID (O)	T-S (O)	T-Hem (O)	T-F (O)
Dig. P + S	1	982	1071	1104	1148	1154	1204	1232	1260
Dig. P + S	1	1037	1087	1115	1143	1148	1198	1226	1251
Dig. P + S	1	1021	1093	1126	1165	1115	1173	1198	1223
Dig. P + S	1	1004	1107	1148	1176	1148	1198	1223	1248
Dig. P + S	1	982	1073	1110	1148	1160	1207	1232	1260
Dig. P + S	1	1004	1093	1137	1162	1148	1204	1226	1248
Dig. P + S	1	987	1076	1112	1154	1160	1210	1235	1260
Dig. P + S	1	996	1085	1121	1160	1165	1215	1240	1265
Dig. P + S	1	1026	1093	1118	1154	1093	1148	1176	1221
Dig. P + S	1	1004	1093	1126	1165	1148	1204	1226	1248
Dig. P + S	2	1104	1204	1237	1260	1215	1260	1285	1310
Raw DI	3	1365	1379	1393	1407	1390	1401	1410	1418
Raw P + S	4	1204	1271	1298	1315	1304	1360	1387	1410
Raw P + S	4	1148	1235	1271	1310	1260	1315	1346	1371
Raw P + S	4	1148	1237	1271	1315	1260	1321	1348	1371
Raw P + S	4	1093	1148	1173	1198	1148	1193	1218	1243
Raw P + S	4	1093	1148	1173	1210	1160	1204	1229	1260
Raw P + S	5	1365	1415	1482	1482	1393	1482	1482	1482
Raw P + S	6	1137	1190	1243	1293	1198	1218	1237	1257
Raw P + S	6	1160	1185	1207	1223	N/A	N/A	N/A	N/A
Raw P + S	6	1176	1198	1221	1243	N/A	N/A	N/A	N/A
Raw P + S	6	1171	1198	1223	1246	N/A	N/A	N/A	N/A
Raw P + S	6	1171	1193	1210	1223	N/A	N/A	N/A	N/A
Raw P + S	6	1143	1182	1218	1254	N/A	N/A	N/A	N/A
Raw P + S	6	1143	1165	1187	1207	N/A	N/A	N/A	N/A
Raw P + S	6	1126	1151	1176	1201	1168	1187	1207	1223
Raw P + S	7	1482	1482	1482	1482	1482	1482	1482	1482
Raw P + S	8	1004	1093	1129	1171	1093	1148	1182	1210
Zimpro	4	1148	1215	1243	1260	1204	1260	1293	1315
Zimpro	4	1260	1315	1348	1376	1315	1376	1398	1426
Zimpro	4	1037	1118	1160	1204	1226	1276	1304	1326
Zimpro	4	1282	1260	1398	1426	1398	1460	1487	1515
Zimpro	4	1287	1371	1401	1432	1404	1460	1490	1518
Zimpro	9	1160	1187	1221	1254	1204	1235	1260	1282

(*continued*)

Table 34 (continued)

Sludge type	Plant no.	Ash analysis								
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	MgO	Na_2O	K_2O
Dig. P + S	1	39.61%	12.0%	8.6%	1.2%	15.0%	11.2%	6.5%	3.5%	1.6%
Dig. P + S	1	35.92%	10.3%	9.4%	1.8%	13.9%	10.9%	7.1%	3.7%	2.4%
Dig. P + S	1	28.07%	10.4%	8.4%	1.4%	15.6%	14.6%	3.0%	7.2%	4.5%
Dig. P + S	1	28.14%	9.9%	7.6%	1.5%	21.0%	18.7%	4.2%	2.9%	1.5%
Dig. P + S	1	36.78%	12.5%	9.1%	1.5%	16.7%	13.7%	5.5%	3.2%	1.7%
Dig. P + S	1	28.35%	8.9%	7.9%	1.5%	23.1%	14.0%	4.9%	4.7%	2.7%
Dig. P + S	1	42.79%	12.2%	8.4%	1.4%	14.9%	13.2%	4.2%	2.0%	1.0%
Dig. P + S	1	39.47%	13.3%	9.1%	1.5%	12.4%	15.7%	3.6%	3.3%	1.4%
Dig. P + S	1	39.49%	11.1%	10.1%	1.4%	13.0%	11.8%	3.8%	5.5%	2.3%
Dig. P + S	1	31.54%	10.4%	8.6%	1.2%	18.1%	13.6%	3.3%	3.5%	2.6%
Dig. P + S	2	37.83%	10.6%	7.1%	1.3%	22.9%	8.4%	3.6%	2.1%	3.8%
Raw DI	3	26.63%	21.0%	1.4%	4.9%	1.3%	40.6%	2.1%	0.5%	0.5%
Raw P + S	4	43.28%	30.1%	3.0%	4.5%	5.9%	6.4%	2.9%	0.6%	0.7%
Raw P + S	4	41.69%	32.8%	2.4%	3.4%	6.4%	6.8%	4.0%	1.3%	0.8%
Raw P + S	4	42.73%	32.4%	2.8%	3.5%	5.9%	7.4%	3.4%	0.9%	0.6%
Raw P + S	4	47.00%	23.6%	3.2%	2.6%	5.9%	6.9%	8.2%	1.6%	1.0%
Raw P + S	4	45.63%	26.8%	3.1%	3.3%	5.0%	8.6%	3.9%	1.4%	1.1%
Raw P + S	5	11.80%	4.1%	8.1%	—	19.6%	39.1%	3.3%	—	—
Raw P + S	6	34.15%	14.1%	9.3%	2.0%	12.0%	9.4%	6.0%	2.9%	2.6%
Raw P + S	6	34.10%	18.0%	4.0%	1.0%	14.4%	12.3%	6.2%	3.6%	2.2%
Raw P + S	6	28.78%	17.6%	4.0%	0.9%	17.6%	13.8%	6.0%	4.0%	2.6%
Raw P + S	6	33.96%	18.2%	3.9%	1.1%	14.6%	12.4%	6.2%	3.5%	2.2%
Raw P + S	6	34.54%	18.8%	3.4%	1.2%	14.4%	10.9%	6.5%	3.6%	2.5%
Raw P + S	6	29.35%	15.8%	4.2%	1.0%	17.6%	14.0%	6.6%	4.0%	2.8%
Raw P + S	6	33.38%	16.2%	4.6%	1.2%	14.0%	12.8%	6.8%	3.1%	2.7%
Raw P + S	6	36.98%	20.1%	5.3%	1.8%	8.7%	10.1%	5.5%	2.9%	1.8%
Raw P + S	7	6.29%	2.1%	1.8%	—	4.7%	45.2%	2.7%	—	—
Raw P + S	8	39.80%	20.1%	7.1%	2.4%	11.6%	7.8%	2.3%	1.7%	3.9%
Zimpro	4	50.38%	24.6%	2.9%	3.1%	6.2%	7.6%	2.6%	0.8%	0.7%
Zimpro	4	46.87%	26.6%	3.2%	5.1%	5.1%	6.9%	4.1%	0.6%	0.6%
Zimpro	4	40.23%	27.0%	3.1%	4.0%	6.2%	9.6%	3.2%	1.7%	1.3%
Zimpro	4	42.43%	34.4%	2.8%	3.6%	5.6%	6.1%	3.2%	0.5%	0.6%
Zimpro	4	46.23%	32.1%	2.7%	3.5%	5.1%	6.0%	2.2%	0.5%	0.4%
Zimpro	9	41.01%	13.1%	5.7%	0.8%	9.4%	21.5%	4.6%	0.6%	1.6%

Notes: P = primary. S = secondary. Zimpro = heat conditioned. Dig = digested. DI = Deinking plant. Data for plants 3 and 6 are for wastewater treatment sludge from paper mills.

significantly different than the combustible content due to a high calcium and/or ferric hydroxide content.

The heat of combustion of wastewater sludges can be estimated from the ultimate chemical analysis of the sludge using the Dulong, Chang, or Boie relationships [Eqs. (3), (4), and (5)]. However, comparison (204) of predictions using these relationships with data from fuels laboratories for a set of over 80 sludge samples from a variety of wastewater plants showed that these equations always predict high by an average of about 9%, 17%, and 12%, respectively. A modification of the Dulong equation for application to sludge that, on average, predicts low by only about 6% develops the moisture, ash-free heat of combustion by

$$\text{kcal/kg} = 5{,}547\text{C} + 18{,}287\text{H}_2 - 1{,}720\text{O}_2 + 1{,}000\text{N}_2 + 1{,}667\text{S} + 627\text{Cl} + 4{,}333\text{P} \tag{12}$$

where C, H, S, etc. are the decimal percents of carbon, hydrogen, sulfur, etc., evaluated on a dry, ash-free basis.

The heat of combustion can be expected to vary over time. Data indicate that digested sludges fall into the low end of the heat of combustion range and heat-treated (e.g., wet oxidation) sludges fall into the high range.

b. Energy Parameter. In comparison to many other combustion systems, the sludge incinerator must cope with a fuel having an exceptionally high ash and moisture content. Thus, the balance between the fuel energy in the combustible, the burdensome latent heat demand of the moisture, and the dilution effect of the ash is especially important and powerful. Consequently, numerous thermal studies are inevitably conducted where the percent solids is carried as the independent parameter and dependent parameters such as fuel use, steam generated, etc., are derived. It is both inconvenient and aggravating that the use of "percent solids" as a correlating variable (1) produces nonlinear plots and (2) does not represent a sludge property that truly is a measure of quality. That is, it is not always beneficial to increase percent solids (as, say, through adding an inorganic sludge condition aid). A more useful variable for such investigations is the "energy parameter" (EP), which combines in a single term the heat and material balance for the combustion of sludge or other fuels or wastes. The EP is calculated as follows:

$$\text{EP} = \frac{(1 - S) \times 10^{-6}}{SBV} \text{ kg } \text{H}_2\text{O per million kcal} \tag{13}$$

where

S = decimal percent solids
V = decimal percent volatile
B = heat of combustion (kcal/kg volatile)

The advantage in using the EP instead of percent solids to correlate thermochemical calculations is that EP correlations are usually linear, whereas, over broad ranges, the percent solids correlations are strongly curved. It can be noted that for a given percent excess air the EP collapses the heat effects of water evaporation, flue gas heating, and waste-derived energy supply into a single term. Using the energy parameter, for example, fuel requirement and steam-raising potential for sludge incineration correlate linearly. Further, a reduction in EP is always a benefit: Less fuel is always needed or more energy recovered.

5

Combustion System Enclosures and Heat Recovery

Waste incineration typically occurs as a hot turbulent flow within a refractory lined or water-cooled (boiler) enclosure. This chapter provides a basic understanding of the characteristics, key properties, materials, and heat transfer processes that should be incorporated into the design of such systems.

I. ENCLOSURES

The enclosure, the furnace shell itself, plays a key role in assuring adequate performance of a thermal processing system. Specifically, the enclosure and its characteristics affect the process in the following ways:

Shape—Enclosure shape affects the radiative flux onto incoming fuel. This flux affects ignition time and flame length, the gross flow pattern in the furnace (including recirculation and bulk mixing), and the heat absorption patterns in boiler-type enclosures.

Volume—Enclosure volume determines the mean residence time, affecting burnout of CO, H_2, soot, tars, and other combustible pollutants.

Accessory features—The enclosure may include (1) heat-absorbing surfaces for energy recovery, (2) burners for auxiliary fuel to maintain temperature or for the burning of atomizable liquid wastes, (3) air jets for overfire combustion and temperature control in units burning solid wastes or secondary and tertiary combustion air jets for liquid or gas fired units, (4) means to feed waste and withdraw slag or solid residues, (5) water sprays to cool the combustion gases as a precursor to temperature-sensitive air pollution control devices, and so forth.

The design of incinerator enclosures is not yet a rigorous engineering discipline, especially for mass burning systems. In the geometrically simple case of axially fired cylindrical chambers, a number of analytical tools are available to describe the flow patterns (see Chapter 6). Perhaps the greater challenge to the analyst is to *simplify* the problem to one susceptible to analysis.

A. Refractory Enclosure Systems

Refractories are defined as nonmetallic materials suitable for the construction or lining of furnaces operated at high temperatures. Stability (physical and chemical) at high temperatures is the primary material requirement, as the refractory system may be called upon, while hot, to withstand compressive and (limited) tensile stresses from the weight of the furnace or its contents, thermal shock resulting from heating or cooling cycles, mechanical wear from the movement of furnace contents (or even the furnace structures themselves due to thermal expansion or, in a kiln, for the entire furnace), and chemical attack by heated solids, liquids, gases, or fumes.

In most incineration systems, refractory materials constitute an important part of the furnace enclosure, ducting, and/or stack. The functions of refractory materials include

- Containment of the combustion process and flue gases in an enclosure resistant to failure from thermal stresses or degradation from high-temperature abrasion, corrosion, and erosion
- Reradiation of heat to accelerate drying, ignition, and combustion of incoming feed
- Protection of plant personnel from burn injury by their insulating qualities
- Enhancement of combustion by incorporation into refractory baffles that increase turbulence in high-temperature flue gas passages
- Support of the burning mass or residues (hearth burning systems)
- Protection of vulnerable system components in unusually severe environments (e.g., incinerator boiler superheater surfaces or sidewalls alongside grates)

To serve these many functions, a wide range of refractory materials have been developed. Art and science must be combined for proper application of refractory systems. This is particularly true for incineration systems where frequent and sometimes unanticipated changes in waste character can result in wide swings in temperature and ash (or slag) and gas composition.

The data and discussions presented here (drawn especially from Ref. 55) must then be recognized as only a brief introduction to the field of refractory selection and design. In the course of system design, the engineer is encouraged to consult with firms and individuals (including owners and operators of existing facilities) with experience *closely paralleling* the intended application. As an indication of the difficulty in evaluating refractories, it is noteworthy that refractory life or maintenance requirements for a given plant cannot be reliably forecast from pilot-scale experience, even when similar wastes or fuels, system geometry, etc., are used. This simulation problem reflects the complexity of the processes that induce refractory failure.

Refractory materials are supplied mainly in

- *Preformed shapes*, including standard sizes of brick, most commonly $22.9 \times 11.5 \times 6.4$ cm ($9 \times 4.5 \times 2.5$ in.) and $22.9 \times 11.5 \times 7.6$ cm ($9 \times 4.5 \times 3$ in.) "straights"; arch, wedge, kiln block, and other shapes used to build arches or to line cylindrical chambers and flues; special and often proprietary designs incorporating hangers for suspended wall and roof construction; and special application shapes such as ignition tiles or checker brick. They are traditionally installed using mortar and occasional metal anchors to tie the refractory to the structural supports.
- *Plastic refractories* (a mixture of aggregate, clays, and bonding materials premixed with sufficient water for workability and ready to use) and dry, *ramming mix* (to

be mixed with water before using), which can be rammed into place to form monolithic structures.

Castable and gunning mixes, which are poured or sprayed (gunned), respectively, to form large monolithic structures.

Mortar and high-temperature cements.

Granular materials such as dead-burned dolomite, dead-burned magnesite and ground quartzite.

1. Composition of Refractories

Table 1 indicates the primary constituents of many refractories commonly used in incineration applications. It can be seen that most fireclay alumina and silica refractory materials are composed of mixtures of alumina (Al_2O_3) and silica (SiO_2) with minor constituents, including titania (TiO_2), magnesite (MgO), lime (CaO), and other oxides. In high-abrasion areas or where resistance to thermal shock and/or high-thermal conductivity is important, silicon carbide is also incorporated.

The minerals that constitute refractory materials exhibit properties of acids or bases as characterized by electron donor or receptor behavior. Acidic oxides include silica, alumina, and titania, and basic oxides include those of iron, calcium, magnesium, sodium, potassium, and chromium. The fusion temperatures and compatibility of refractory pairs or slags and refractory is related especially to the equivalence ratio of the basic to acidic constituents.

The mineral deposits from which the fire clays are obtained include (1) the hydrated aluminum silicates (e.g., kaolinite) and flint clays, which contribute strength, refractoriness, and dimensional stability, and (2) the plastic and semiplastic "soft clays," which contribute handling strength. Bauxite or diaspore clays, precalcined to avoid high shrinkage in the firing of refractory products, are the principal source of alumina for high-alumina refractory (greater than 45% alumina).

Basic refractories incorporate mixtures of magnesite (usually derived from magnesium hydroxide precipitated from sea water, bitterns, or inland brines), chrome ore, olivine [a mineral incorporating mixed magnesium, silicon, and iron oxides with forsterite ($2MgO{\cdot}SiO_2$) predominating], and dolomite, a double carbonate of calcium and magnesium.

2. Properties of Refractories

a. Refractory Structure. At room temperature, refractory products consist of crystalline material particles bonded by glass and/or smaller crystalline mineral particles. As the temperature increases, liquid phase regions develop. The mechanical properties of the refractory at a given temperature depend on the proportion and composition of the solid minerals, glassy structure, and fluid regions.

In the manufacture of refractory products, unfired or "green" refractory masses are often heated or "fired" in a temperature-controlled kiln to develop a ceramic bond between the larger particles and the more or less noncrystalline or vitrified "groundmass." In firing, a high degree of permanent mechanical strength is developed. For any given refractory composition, however, there exists an upper temperature limit above which rapid and sometimes permanent changes in strength, density, porosity, etc., can be expected. This upper limit is often a critical parameter in the selection of refractory for a given service.

The evaluation of the high-temperature softening behavior of fireclay and some high-alumina refractory materials is often accomplished by determination of the pyrometric

Table 1 (Part 1) Properties of Selected Refractory Brick[a]

Type	Class	Primary constituents (wt %) Silica (SiO_2)	Alumina (Al_2O_3)	Titania (TiO_2)	Pyrometric[b] cone equivalent	Density (kg/m^3)
Fire clay[c]	Superduty	40–56	40–44	1–3	33–34	2240–2320
Fire clay[e]	1. High duty	51–61	40–44	1–3	33–33.5	1920–2325
	2. Medium duty	50–57	25–38	1–2	29–31	1920–2325
	3. Low duty	60–70	22–33	1–2	15–29	1920–2325
Fire clay[f]	Semi-silica	72–80	18–26	1–2	29–31	1840–2000
High alumina[g]	1. 45–48%	44–51	45–48	2–3	35	
	3. 60%	31–37	58–62	2–3	36–37	2240–2565
	5. 80%	11–15	78–82	3–4	39	2485–2885
	7. 90%	8–9	89–91	0.4–1	40–41	2645–3045
	8. Mullite	18–34	60–78	0.5–3	38	2325–2645
	9. Corundum	0.2–1	98–99+	Trace	42	2725–3205
Silica[h]	1. Superduty	95–97	0.1–0.3[i]		N/A*	1680–1890
	2. Conventional	94–97	0.4–1.4[i]		N/A*	1680–1890
	3. Lightweight	94–97	0.4–1.4[i]		N/A*	960
Silicon carbide[j]	1. Bonded	Silicon carbide			38	2325–2645
	2. Recrystallized					—
Insulating[k]	1. 870°C	Variable:			N/A*	580
	3. 1260°C	alumina,			N/A*	740
	5. 1540°C	fireclay,			N/A*	940
	6. 1650°C	perlite, etc.			N/A*	960
Chrome[l]	1. Fired	Cr_2O_3 (28–38), MgO (14–19)			N/A*	2960–3285
	2. Chemically bonded	Al_2O_3 (15–34), Fe_2O_3 (11–17)			N/A*	—

Type	Modulus of rupture (kg/m^2)	Cold crushing strength (kg/m^2)	Thermal conductivity $kcal\,hr^{-1}\,m^{-2}\,(°C/cm)^{-1}$ @ 500°C	@ 1000°C	@ 1500°C	Thermal expansion (% at 1000°C)
Fire clay[c]	2930–7900	7320–29,300	1.16	1.25	N/A[d]	0.6
Fire clay[e]	2440–14,650	7320–34,200	1.11	1.22	N/A*	0.6

	3900–12,200	8300–29,300	N/A	N/A	N/A	0.5–0.6
	4880–12,200	9760–29,300	N/A	N/A	N/A	0.5–0.6
Fire clay[f]	1460–4400	4880–14,650	0.89	1.09	N/A*	0.7
High alumina[g]	4880–7800	12,200–29,300	—	—	—	—
	2930–8790	8790–34,200	1.20	1.25	1.29	0.6
	5370–14,650	19,530–43,900	—	—	—	0.7
	5860–17,100	19,520–43,900	1.92	1.65	1.65	0.7
	4880–17,100	17,100–43,900	—	—	—	—
	8790–14,650	24,400–43,900	3.40	2.25	2.32	0.8
Silica[h]	2440–4880	7320–17,100	1.19	1.55	1.90	1.3
	2930–5860	8790–19,530	1.00	1.25	1.61	1.2
	N/A	N/A	0.40	0.65	1.00	—
Silicon carbide[j]	9760–19,530	12,200–73,200	15.61	12.22	8.47	0.5
	N/A	N/A	—	—	—	
Insulating[k]	340–490	440–540	0.137	0.275	N/A*	Low
	490–830	540–930	0.251	0.338	N/A*	Low
	830–1465	830–1470	0.312	0.395	0.482	Low
	1950–2930	3900–4880	0.344	0.426	0.512	Low
Chrome[l]	3420–6350	9760–19,530	2.04	1.83	1.75	0.8
	3420–8790	9760–24,400	—	—	—	—

[a] Source: selected manufacturers data.

[b] See Appendix C.

[c] These materials exhibit the highest refractoriness of any fireclay brick; stable volume; good spall resistance; good load bearing properties; fair resistance to acid slags, but only moderate reistance to basic slags.

[d] N/A = not available; N/A* = not applicable or beyond meaningful range.

[e] High duty has low thermal expansion, fair resistance to acid slags and spalling, lower resistance to basic slags. Properties degrade for lower duty brick.

[f] These materials exhibit rigidity under load, volume stability, and high resistance to structural spalling, and to attack by volatile alkalis.

[g] These materials exhibit high refractoriness increasing with alumina content; high mechanical strength; fair to excellent spall resistance; high resistance to basic slags, and fair resistance to acid slags.

[h] These materials exhibit high refractoriness, mechanical strength, and abrasion reistance; and low thermal spalling above 650°C. “Hot patch” brick has good spall resistance. This brick is resistant to acid slag but is attacked by basic slag.

[i] Remainder primarily lime.

[j] These materials exhibit high refractoriness, thermal conductivity, resistance to spalling, slagging, and abrasion. They begin to oxidize at specific temperatures.

[k] These materials exhibit resistance to thermal spalling but are degraded rapidly by abrasion or slag. Most often used as a backing for more resistant bricks.

[l] These materials exhibit high resistance to corrosion by basic and moderately acid slags. Iron oxide can cause spalling.

cone equivalent, or PCE (see Table 1 and Appendix E). In this test, a ground sample of material is molded into a test cone, mounted on a ceramic plate tilted to a slight angle, and heated at a definite rate. PCE standards mounted adjacent to the test cone are observed. The PCE of the material being tested is defined as that of the standard cone whose tip touches the plaque at the same time as that of the test specimen. Since softening of refractory is affected by the chemical nature of the surrounding atmosphere, the test is always carried out in an oxidizing atmosphere. If the situation under design is reducing in nature, consideration should be given to evaluation under similar atmospheric conditions.

b. Melting Behavior. Alumina–silica refractories (e.g., fireclay and high-alumina brick) contain both crystalline and glassy material. At temperatures above approximately 980° to 1095°C, the glassy bond begins to become progressively less rigid and, indeed, becomes a viscous liquid. As viscosity drops, the glass lubricates relative motion of the crystalline particles and, under stress, deformation can occur. At higher temperatures, the crystalline material begins to dissolve in the glass and, finally, the mass is unable to retain its original shape, deforming under its own weight.

The temperature level at which deformation becomes critical to structural integrity depends particularly on the stress level, on the availability of cooler regions within the refractory shape which, since more rigid, will accept the load, and on the alumina content (since the crystalline alumina granules are the last to melt). Also, a past history of long-term, high-temperature heat-soaking may have resulted in the solution of solid material into the glassy phase with a consequent increase in the observed viscosity at a given temperature. This phenomena may explain in part why a hard-burned fireclay is generally more resistant to deformation than a light-burned or unused brick.

Silica refractories that are almost wholly crystalline when cold differ greatly from fireclay-based refractories in their melting behavior. In silica refractories, the melting is due especially to the fluxing action of alumina, titania, and alkali. Indeed, if the flux content is less than 0.5%, the formation of a substantial (>10%) liquid fraction (and associated deformation and strength losses) occurs abruptly over a 50°C temperature range near 1705°C.

c. Dimensional Changes. Almost all green refractory materials exhibit *permanent* dimensional changes on initial heating. As firing proceeds, the rate of change of dimensions diminishes. If actual use reflects a careful choice of refractory (and, naturally, a specific curing cycle), little significant dimensional change will be observed in service.

As with most materials, refractories also exhibit *reversible* expansion and contraction when heated and cooled, respectively. An indication of the linear expansion at elevated temperatures for refractory materials is given in Table 1.

Thermal expansion must be given careful consideration in the design of refractory structures. As described below, inadequate provision for expansion leads to pinch spalling. Excessive expansion allowances may unduly weaken the refractory wall or roof structures. Appropriate allowances for thermal expansion in refractory brick in high-temperature service range from 8 mm/m for fireclay and 50% to 80% alumina brick, 10.5 mm/m for 90% alumina brick, and 13 mm/m for 99% alumina brick. The importance of providing for expansion increases as the length or height of walls increases. For fireclay walls 5 m or more in length, expansion joints are customarily staggered 1 to 2 m apart. For low walls, the joints may be 3 to 4 m apart. Expansion joints would typically be formed of ceramic fiber material firmly packed into openings in the brickwork.

Castable fireclay refractories are not fired until they enter service, but, due to offsetting changes within the material, the designer generally need not expect significant changes as the structures enter service. This balance of dimensional changes includes expansion of the fired aggregates, shrinkage of the cement paste with dehydration, and a mix of changes (both expansion and contraction) as mineralogical reactions occur within the components comprising the brick. Expansion provisions in castable refractory concrete would usually be accounted for within the cast panels, although certain applications require the use of expansion joints at the interface between large panels.

Castable refractory concrete materials typically shrink during installation and curing but expand once heated. Control joints scored onto the surface or cold joints installed between sections will allow cracking to be controlled at specific areas, allowing for a neater appearance. Any shrinkage cracks noticed after initial curing of castable refractory concrete will close on heating. It is imperative to note that small cracks (1–5 mm in width) observed in refractory materials when cold will close on heating. These small cracks should be thoroughly cleaned of any ash or other accumulations and must never be filled with any "patching" material.

d. Abrasion and Impact. In the incineration of solids, refractories are often subject to the impact of heavy pieces of material charged into the furnace, abrasion by moving solids, or direct impingement by abrasive fly ash suspended in fast-moving gas streams. Abrasion and impact resistance are often evaluated using standard rattler tests (ASTM C-7) and, more recently, by blasting the surface using silica or silicon carbide grit. Performance in the latter test has been shown to correlate well with modulus of rupture data.

e. Spalling. Excessive thermal or mechanical stresses applied near to the face of a refractory brick or monolithic structure or adverse changes in the internal structure of the refractory in zones paralleling the hot face can lead to the loss of fragments (or spalls) of surface material. If the newly exposed refractory material is also overstressed or undergoes a second cycle of internal structural change, the degradation process will continue until structural failure occurs or until heat losses through the thinned brick require shutdown. The loss of face refractory through cracking and rupture is known as *spalling*. Spalling is of three general types: thermal, mechanical, and structural.

THERMAL SPALLING. Thermal spalling results from stresses generated within the refractory arising from the unequal extent of thermal expansion (or contraction) due to temperature gradients. Failure of the refractory is usually associated with rapid changes in temperature. Thus, thermal spalling failures can be traced to material and/or operational factors.

Refractory with low thermal expansion properties, high tensile strength, and a maximum extensibility (the ratio of tensile strength to modulus of elasticity) shows superior thermal spalling resistance.

For fireclay brick, spalling characteristics are largely dependent upon the proportion of free silica in the constituent clays, the size and size distribution of the particles, and upon the amount and composition (softening temperature) of the glassy bond. Up to 980° to 1095°C (1800° to 2000°F), for example, a high glass content will result in a high spalling tendency. Above these temperatures, the glassy materials soften (allowing stress relief), and the fireclay brick becomes very resistant to spalling.

Since the extent and composition of the glassy bond are affected by the time and temperature history of the brick during its manufacture and by the temperatures

experienced in service, consideration must be given to both factors in evaluating the potential for spall failure. Table 2 indicates some general trends.

The specific temperature (650°C) where spall sensitivity is abruptly improved for silica brick reflects the abrupt volume change accompanying the crystalline inversion of the cristobalite. Above 650°C, spalling resistance is excellent.

Among the basic brick compositions, the best spall resistance is found in brick with a high periclase content: bonded with magnesium aluminate spinel or a chrome spinel. In some applications, the basic brick is encased in a metal sheath. At low temperatures, the case holds the fragments in place. At higher temperatures, the metal oxidizes, reacts with the magnesia, and bonds adjacent brick together.

MECHANICAL SPALLING. Rapid drying of wet brickwork, inadequate provision for thermal expansion, or pinching of hot ends (especially in arches) can lead to stress concentration and failure. "Pinch spalling" is common on the inner surfaces of sprung arches since the hot faces expand more than the cold ends or when inadequate provision for expansion has been made in the refractory design.

STRUCTURAL SPALLING. Structural spalling refers to losses of surface material due to changes (in service) in the texture and composition of the hotter portions of the brick.

Table 2 Thermal Spall Resistance of Refractory Materials[a]

Type of brick	Comparative spall resistance[b]
Fire clay:	
Superduty:	
Spall resistant	Superior
Regular	Excellent
High Duty:	
Spall resistant	Good
Regular	Fair
Semi-silica	Good
High alumina:	
45 to 60% alumina	Superior to good
>60% alumina	Superior to fair
Silica:	
All types	Excellent above 650°C
General duty	Poor below 650°C
Spall-resistant	Fair below 650°C
Basic:	
Chrome, fired	Fair
Chrome-magnesite (chemically bonded or fired)	Good to fair
Magnesite, fired or chemically bonded	Fair
Magnesite, fired (high periclase)	Excellent
Magnesite-chrome (chemically bonded)	Superior to excellent
Magnesite-chrome, fired	Very superior to excellent
Spinel bonded magnesite, fired	Superior
Forsterite	Fair

[a] Source: Ref. 55.

[b] Spall resistance ratings are comparative *only* within groups.

These changes can be brought about through the action of heat, through reactions with slags or fluxes, or through the reactions of or with gases that permeate the brick (see "Reactions with Gases", p. 169). The changes resulting in spalling are those where zoned structures are formed that show markedly different thermal expansion characteristics, increased sensitivity to rapid temperature change, or the presence of shrinkage or expansion cracks.

f. Chemical Reactions. At the temperatures found in incinerators and many other combustion systems, chemical action can be one of the greatest factors contributing to the ultimate destruction of refractory structures. The mineral constituents of wastes (or fuels) or the gases in the furnace enclosure may penetrate the refractories, changing the size and orientation of crystals, forming new minerals or glass, altering the texture and physical or chemical properties of the brick, or dissolving (corroding) granules or bonding structures. The chemical agents that participate in these chemical reactions are known as *fluxes* and the corrosive melting action that ensues as *fluxing*.

The chemistry of the mineral residues from the incineration of wastes and the products derived from reactions between the residues and refractory materials are exceedingly complex. Indeed, the chemical, physical, and temporal parameters affecting corrosion in refractories are so complex that it has not been found possible to adopt a single screening test of general utility. Experience, however, gives insight into general principles of refractory–residue compatibility.

ACIDIC AND BASIC FLUXES. In evaluating the potential for refractory reactions, the most useful general concept matches acidic slags with acidic refractories and basic slags with basic refractories. In this context, the oxides of the following elements show acidic or basic properties, as shown in Table 3.

Since fluxing involves chemical reactions, the analyst should take care to evaluate the acid–base balance using composition expressed in *mol percent* instead of the commonly reported weight percent.

Refractory brick falls into acidic or basic categories, as Table 4 shows. The use of the net acidic or basic chemistry of a slag is a good but not perfect criterion for refractory selection. Exceptions are common due to differences in operating and reaction temperatures, reaction rates, viscosities of reaction products, and the formation of protective glazes and coatings on the refractories. For example, the relative concentrations of the elements in a slag could at, say, low concentrations yield a reaction product of high melting point while at high concentrations, a different reaction product would be formed with a very low

Table 3 Acidic and Basic Properties of Refractory Fluxes

Acidic oxides	Basic oxides
Silicon (as SiO_2)	Iron (as FeO)
Aluminum (as Al_2O_3)	Calcium (as CaO)
Titanium (as TiO_2)	Magnesium (as MgO)
Phosphorous (as P_2O_5)	Potassium (as K_2O)
	Sodium (as Na_2O)
	Chomium (as Cr_2O_3)

Table 4 Acidic and Basic Properties of Refractory Categories

Acidic brick	Basic brick
Fireclay	Chrome brick
High alumina	Magnesite
Silica	Forsterite

melting point. This example is found in practice in the pattern of attack of silica refractories by ferrous oxide slags.

CORROSION RATE. The corrosion rate of refractories depends on a number of factors that the rate at which reactants are brought together, react, and are carried away.

The rate at which reactants are brought together is *inhibited* by (1) low concentrations of fluxes, (2) the diffusion resistance of protective layers or dense brick structure, (3) the adherence or high viscosity of reaction products, (4) the inability of the flux to "wet" the surface of the refractory, (5) temperatures low enough so that the flux is in the solid state, and (6) lack of agitation or turbulence in the molten fluxing agent (usually induced by impinging or shearing gas flows).

The rate of reaction, as with other chemical reactions, is strongly dependent on temperature. In some cases, only a few degrees' rise in temperature will cause the destruction of an otherwise satisfactory lining. This sensitivity emphasizes the importance of making prompt and thorough evaluation of refractory response to changes in the operation of combustion systems that increase average temperatures or that increase the thermal loading in "hot spot" regions (e.g., at flame impingement points).

The rate at which reaction products flow away (thus exposing fresh surface to attack) is *reduced* by (1) high-viscosity reaction products (note that molten minerals increase in viscosity as the temperature falls so that wall cooling, obtained with natural or forced convection or imbedded water-filled cooling coils, will freeze the slag and impede corrosion). If this approach is used, however, consideration must be given to thermal spalling when the furnace is cooled off or to mechanical spalling if slag accumulations become heavy, and (2) special selection of brick composition, texture, and/or permeability to avoid spalling due to the increased volume of reaction products. Such structural spalling can occur upon the reaction of chrome bearing basic brick with Fe_2O_3 or the reaction of soda or potash fumes with fireclay and some high-alumina brick.

REACTIONS WITH ALKALI METAL COMPOUNDS. The alkali metal-containing wastes (most commonly, sodium and potassium compounds) are often critical relative to fluxing reactions. In setting incinerator orientation (down-fired or horizontal), the potential for the formation of eutectics of these compounds can force design decisions such as orienting the chamber to assure gravity flow of molten salt reaction products (see, also, Chapter 4, I.C). Sodium compounds enter into reactions with common refractory materials (220), as shown in Table 5.

REACTIONS BETWEEN REFRACTORIES. Just as "foreign materials" such as fly ash can react with refractories, so refractory bricks and/or mortars of different compositions can enter into reactions with one another. The potential for reaction depends on (1) physical contact, (2) the existence of low-melting eutectics such as the alumina–silica eutectic with a melting point of 1595°C, (3) the impurities within either refractory that can

Table 5 Reactions of Refractories with Alkali Metal Compounds

Sodium compound[a]	Refractory constituent	Temp. (°C)	Results
Na_2O	Chromium	730	Liquid formation
Na_2CO_3	Alumina	730	Volume expansion
Na_2SiO_4	Alumina	750	Liquid formation
Na (metal)	Silicate	800	Liquid formation
Na_2CO_3	Magnesia	840	Volume expansion
Na_2CO_3	Alumina	1090	Volume expansion

[a] Applies equally for potassium compounds.

form an interstitial liquid phase even though the brick as a whole appears strong and rigid, (4) the availability of mechanisms such as gravity, diffusion, or capillary action to mingle the brick components, and (5) the temperature level at the interface.

Engineering guidelines for the abutting of different refractories and for the choice of mortars at the interface are best developed with refractory manufacturers in consideration of the overall system requirements.

REACTIONS WITH GASES. Furnace gases can have a major impact on refractory–slag and refractory–refractory reactions, can affect the melting range and viscosity–temperature properties of slags, and can, themselves, participate in refractory attack. From the sections of this book dealing with combustion system fluid flow, it should be recalled that the composition of furnace gases is seldom constant at any one point in the system and certainly varies from point to point in the system. Thus, if refractory attack by gases can be a factor in a given design, the refractory selection will include consideration of the *range* of furnace atmospheres to be encountered and not only the "average."

The most important measure of furnace atmosphere corrosive impacts relates to its oxidizing or reducing nature. For most refractory oxidizing atmospheres are preferred. An exception is silicon carbide, which slowly oxidizes above 900°C. Oxidizing agents for silicon carbide include oxygen, carbon dioxide, and water vapor. To retard these oxidation reactions, the silicon carbide grains are usually coated with ceramic material.

Reducing atmospheres tend to enhance the corrosivity of iron-bearing slags, perhaps due to the greater basicity of FeO versus the more fully oxidized forms. The relative ease with which iron oxides are reduced and oxidized and the resulting changes in chemical reactivity and density of the oxides accompanying these changes can weaken brick exposed to alternating oxidizing and reducing atmospheres. Also, between 370° and 540°C, carbon monoxide can decompose (catalyzed by iron oxides) into carbon and carbon dioxide. Iron oxides may also be partially reduced to metallic iron or iron carbide. The consequent volume changes can lead to rapid disintegration of the brick. Some superduty and high-duty fireclay brick and high-alumina brick, if fired to Cone 18 or higher under controlled conditions, offers high resistance to carbon monoxide effects. This appears to be due to conversion of iron oxides into catalytically inactive silicates.

Unburned or partially cracked natural gas undergoes decomposition and carbon deposition within refractories in the temperature range of 480° to 820°C.

Chlorine reacts with some components of various refractories (e.g., alumina) at about 950°C to form volatile chlorides. Alumina also reacts with sulfur oxides (in the presence of water vapor) in the cooler parts of the linings to form aluminum sulfate. The volume increase accompanying the "sulfating" reaction will weaken the brickwork.

Clearly, the permeability to gases of refractory brick will provide a useful measure of the potential extent and importance of reactions with furnace gases. While permeability is related to porosity, the relationship is not direct since the orientation and diameters of pores and the extent to which they interconnect affect gas diffusion rates. Operating history, which could include sealing of the surface with a relatively continuous glaze or the loss of binders (such as occurs with chemically bonded basic brick), also influences gas permeability. Thus, experience is often the only means to assess performance.

3. Selection of Refractories

In most furnaces, and particularly in incinerators, it is of value to give careful attention to the selection of "optimal" refractory. "Optimal" in this sense is not universal but reflects the special needs and values of each application. Thus, total cost per unit of production (taking into account initial materials and installation costs, interim maintenance costs, and the value of lost production during refractory-related maintenance or major rebricking) may be a prime consideration. For waste disposal systems, reliability and availability of the incineration system often have value that far exceeds the differential material costs between inferior and superior refractory grades, especially since both transportation and installation expense is essentially equal for each grade.

Beyond economic factors, refractory selection should involve a detailed analysis of operational, design, and construction factors and expectations. Ideally, the designer should carefully analyze the chemical, fluid flow, and heat flow parameters that characterize the proposed system and then interact with specialists in refractory design and selection. Often, parallel experience will be available to guide the selection process. Also, it is usually found that only one or two among the several refractory properties are keys to success (e.g., refractoriness, resistance to thermal shock, or resistance to fluxes). As mentioned in the introduction to this discussion and restated here for emphasis, refractory selection is an expert's game, derived from broad, in-depth experience in full-size equipment that is just now emerging as a quantitative technology.

Selection of refractory for a particular high-temperature incineration application must address a number of refractory service parameters:

1. Temperature—The chosen refractory must demonstrate a temperature resistance rating in excess of the maximum service temperature to be expected in the process. Typical refractory chosen for incineration processes would exhibit a temperature rating of not less than 900°C.
2. Atmosphere—The chosen refractory must possess characteristics that will ensure successful operation under both reducing and oxidizing service conditions. Typical refractory chosen for incineration processes would be of a fine-grain structure with minimal iron impurities in the material.
3. Slag resistance—The chosen refractory must be resistant to penetration and adhesion of slags or molten metals that may contact the refractory surface during operation. Typical refractory chosen for incineration processes would be of a high-density, fine-grain structure.
4. Abrasion resistance—The chosen refractory must exhibit a physical strength under service temperatures that would be satisfactorily resistant to abrasion. Typical refractory chosen for high-abrasion areas within incineration processes would exhibit an

extremely fine-grain structure and/or a silicon carbide makeup, depending upon the severity of abrasion and working temperature.

5. Physical arrangement—The choice between refractory brick and castable refractory concrete must be made to suit the various shapes of chambers, ducts, and openings desired in the system. Typical refractory chosen for incineration processes could be either refractory brick or castable refractory concrete. In areas where abrasion resistance is of importance, brick structures are preferred.

No single refractory product presents all of the characteristics that would provide a long service life in all areas of the incineration system. Although a high heat-duty refractory brick is generally acceptable in all gas phase areas of the system, such as furnace and duct walls and roof, consideration should be given to increasing the quality to superduty brick in areas of severe reducing atmosphere or slag attack. Ninety-nine percent silicon carbide or 70+% alumina refractory brick should be considered for areas adjacent to moving waste, such as the sidewalls of the grate area.

In areas where furnace geometry makes it very difficult or impossible to use refractory brick, castable refractory concrete possessing the same or better characteristics as the adjacent brickwork should be chosen. Castable refractory concrete would be used in areas such as burner cone extensions, observation port cones, access door jambs and lintels, and around other refractory penetrations.

In some highly specialized situations, the use of molded, prefired refractory shapes or blocks would allow for a complete refractory brick application. However, the availability of these shapes is sometimes uncertain and the price is considerably higher than alternate methods such as castable refractory concrete.

Proper installation and anchorage of the refractory will ensure that repairs can be easily and economically accomplished, requiring replacement of no more than the failed or worn material.

4. Refractory Design and Construction Practices

a. Monolithic Refractories. Historically, monolithic, cast refractories were used because less skill was required to install them than prefired brick shapes (459). However, they definitely provide certain advantages over brick construction in yielding joint-free, less permeable construction and in providing quicker return to service following maintenance and general ease of installation. Monolithic types of refractory are available to cover the entire spectrum of physical and chemical properties. Careful selection should be made considering these properties relative to the conditions of intended service. It is also important that they be properly installed using established methods of mixing, placing, casting, drying, and heatup.

Proper storage of the refractories is important. If possible, castable refractories should be stored indoors. However, they can be stacked outdoors and covered. In either case, the refractory must be protected from water because premature wetting will ruin it. Regardless of outside temperature, castables should be installed in environments ranging in temperature between 16° and 27°C (both the refractory material and the water used to mix with it). If either material or water is outside this range, setting and resulting properties can be adversely affected.

ANCHORS. In most cases, monolithic refractory installations require anchors to ensure that the refractory material remains securely in place. A variety of anchors are

Table 6 Grades of Steel Required for High-Temperature Service

Maximum temperature of metallic component (°C)	Type of steel
600	Carbon steel
1000	304 stainless steel
1100	310 or 309 stainless or Cr–Ni casting
>1100	Refractory anchors

Source: From (459).

manufactured to meet all application requirements. Anchors are made from wire, rod, cast metal, and refractory shapes. Wire anchors are normally used for refractory linings less than 23 cm thick. For linings thicker than 23 cm, or for higher temperatures, ceramic or cast metal anchors are used. For temperatures below 600°C, carbon steel anchors can be used. Stainless steel grades are chosen for higher temperatures as shown in Table 6.

Anchor length—Length of wire anchors should be 80% of the depth of the lining. This figure is rounded upward to the next-longest available anchor size.

Anchor spacing—Distance between anchors should be considered carefully. Edges, roof, and nose and areas where vibration, mechanical movement, or gravity impose loads on the lining require more anchors. Standard spacing for various areas is suggested in Table 7. The tines of metal rod anchors should be rotated 90° from neighboring anchors. The base section of the anchors should be securely welded to the steel supports in a square pattern.

Anchor welding—Wire anchors require at least 1.3 cm of weld fillet across both sides of the base leg. Tack welding is inappropriate and insufficient for wire anchors. Heavier rod anchors also may require more fillet weld on both sides of the base leg. Welds can be tested by striking half of them with a hammer. A ringing sound indicates a good weld. A dull thud indicates a potential failure. To check for weld quality, flatten out about 1% of the anchors and, if the test shows poor welds, check all the anchors and replace those that fail.

Table 7 Wire and Rod Anchor Spacing

Location	Lining thickness (cm)	Anchor centers (cm)
Walls, cylinders, slopes	5–7.5	15
	10–12	23
	15–34	30
Roof, bull noses	5–7.5	15
	10–12–15	23
	18–20–23	30
	5–7.5–10	23
	12–23	38
	23+	60

Source: From (459).

Table 8 Ceramic and Cast Metal Anchor Spacing (cm)

Location	Lining	Anchor
Vertical and circular units	23–30	38
	30–38	46
	38+	60
Roof, bull noses, and arches	15+	30

Source: From (459).

Refractory anchors for high temperatures—For temperatures above 1100°C, an anchoring system employing refractory anchors should be used. Available in lengths from 23 to 46 cm, refractory anchors are designed to accept either slip-over anchor castings or welded-on support studs. Welded-on support studs are recommended for wall construction, while metal castings are recommended primarily for roof construction. Roof refractory anchoring systems are made to engage either pipe or I-beam supports. They maintain some flexibility between the anchor and casting to accommodate thermal expansion and movement of the lining. The length of refractory anchors usually equals the lining thickness. Suggested spacing for ceramic or cast metal anchors is covered in Table 8. Guidelines from which to estimate the quantities of anchors required are given in Table 9.

MIXING CASTABLE REFRACTORIES. Castable refractories should be mechanically mixed in a mortar or paddle mixer with a capacity of 0.37 to 1.1 m^3. Such mixers ensure a rapid, thorough mix, discharge the full batch, and virtually clean themselves from batch to batch. A clean mixer is a must when working with castables. Some substances found in dirty mixers may cause flash setting or otherwise lower the ultimate strength by combining with the cement in the castable.

Water to be used in mixing castable refractories must be of a quality equivalent to that of drinking water. Water may need to be warmed in cold weather to raise the temperature to between 16° and 27°C. In hot weather, the water and castable may need to be cooled so the temperature does not exceed 27°C at the mixer.

Table 9 Estimating Anchor Quantities

Anchor spacing, cm × cm	Anchors/m^2
15 × 15	43
20 × 20	25
23 × 23	19
23 × 30	14
25 × 25	16
30 × 30	11
30 × 46	7

Note: To determine the total number of anchors required, multiply the anchors per m^2 by the total area in the lining.

To begin a mix, one pours one-half to three-quarters of the total amount of water required for a batch into the mixer with the paddles turning. Entire bags of dry castable are then added as required. Segregation of castable components within the shipping bags may occasionally occur during transportation. Thus, if a partial bag is to be used, the contents of a full bag should be carefully dry-mixed before any of the contents are used. After the castable in the mixer comes to a uniform color, one then adds the balance of the water (in small increments) to bring the mix to casting consistency. It is important not to use more than the amount of water recommended by the castable refractory manufacturer since decreased castable refractory strength results.

Excessive mixing generates heat, speeds up setting time, reduces strength, and breaks down the aggregate. The material should remain in the mixer only long enough to produce a uniform mix. Mixing time should never exceed 5 minutes. An efficient paddle mixer should do the job in $1\frac{1}{2}$ to $2\frac{1}{2}$ minutes.

Castable refractories tend to stiffen somewhat after leaving the mixer. Judgment on whether the mix has reached proper consistency should be made at the point of placement. The "ball-in-hand" test, for castable installations, provides a useful guide to proper consistency. Tossed 15 to 30 cm into the air, a ball of properly mixed castable approximately 8 to 10 cm in diameter should adapt to the shape of the hand when it is caught. It should not flow through the fingers or disintegrate. Disintegration may indicate insufficient water in the mix.

Particularly when installed under high-temperature and/or high-humidity conditions, castables should be poured into forms immediately after the castable is mixed. In no case should the time between mixing and casting exceed 30 minutes. Castable containing high-purity calcium–aluminate cements should be placed within 15 minutes.

FORMS AND MOLDS. To prevent premature loss of moisture from the mix, forms or molds used for casting refractories must be thoroughly oiled or greased. The ultimate strength of the refractory will be reduced by premature loss of water required for hardening by hydration of the mix. Casting should be carried out fast enough to ensure that the exposed surface of the castable does not dry out.

All high-strength castable should be vibrated into place. This is especially important for coarse aggregate mixes. An immersion vibrator should be drawn slowly up through the castable so it does not leave holes or channels behind. The mix is too stiff if the vibrator leaves holes. Extended vibration will segregate components and weaken the castable.

Regardless of the outside temperature, the temperature of the material and water should be between 16° to 27°C. This is the ideal temperature range. When the material is cold, water is sometimes heated but not over 30°C. In cold weather it is always important to have warm materials; otherwise the materials will have an "ice cube" effect on the water.

Whenever possible, especially for large areas, an alternating section concept should be used for construction. This reduces total linear shrinkage within the lining and permits initial shrinkage to take place prior to installation of the adjacent section.

Slow reaction time between the water and the cement is needed. Noting that high temperatures accelerate the set, the exothermic hydration reaction of the cement cannot be slowed down once it starts. Therefore, refractory castable should not be stored in a hot or cold warehouse, in a railroad car, or next to a furnace before placement. If stored materials are especially hot or cold, they may need approximately 3 to 7 days to obtain the desired temperature range when stored in full pallets. Breaking down pallets can speed this up to 16 to 24 hours.

After placing, castable materials should be kept above 10°C for 24 hours to maximize properties. If, for some reason, exterior shell temperatures are below 4°C, insulation on the shell exterior should be considered. If castable does not reach 25°C during curing, it is more prone to explosion during heatup. If proper temperatures are maintained during mixing and for 24 hours after placing, subsequent freezing conditions (even freezing and thawing conditions) will not materially affect the properties.

To prevent surface water loss and ensure proper cement hydration and strength development, the exposed surfaces of a cast section should be sprayed with a resin-based curing compound or covered by plastic sheets or damp burlap.

Forms can normally be stripped 8 to 12 hours after casting. Most cements contained in refractory castable reach almost all of their ultimate strength in 24 hours. Curing is substantially complete in one full day.

INITIAL HEATUP. A controlled heatup schedule is required for castable linings. This is especially true for those containing high-strength, high-purity binders. Heat will remove the free water as steam at around 100°C. Water of hydration will be driven off between 200° and 870°C. Initial firing rates should raise the temperature about 10°C/hour. Holds (1 hour each per 2.5 cm of thickness) should be incorporated at 200° to 260°C, at 540° to 650°C, and at the maximum preheat temperature. If, at any point during heatup, steaming is noticed, the temperature should be held until all steaming subsides. Avoid direct flame impingement on the refractory surfaces during heatup.

b. Brick Refractory Structures. Courses of brick laid in a wall so that the lengths parallel the face of the wall are called *stretchers*. Brick whose length runs at right angles to the face of the wall are *headers*. In *soldier* courses, the brick stand on end, and in *rowlock* courses they lie on edge. Header courses tend to spall less than stretchers at the hot face of a furnace wall because they expose a smaller area to the high temperature. However, stretcher courses expose fewer joints than headers, and this provides an advantage in applications where joints tend to wear more rapidly than the brick.

Bonding—tightening construction through combinations of headers and stretchers and off-setting vertical joints—strengthens and stabilizes furnace walls. The type of bond selected for any particular type of furnace depends upon the design of the furnace, the thickness of the walls, the need for gastight construction, the severity of operating conditions, and the need for easy maintenance. In any case, the wall should be bonded so loads will be transferred to the cooler part of the wall when the inner, hotter portion loses its ability to carry them. Walls must be designed to carry structural loads at high temperatures.

All stretcher walls—one brick thick—usually have the least structural stability, but they are sometimes used in smaller furnaces and in furnaces where heat must pass through the walls. Alternate header and stretcher courses probably provide the most common arrangement for standard incineration furnaces. Large, 23-cm brick break joints, start ends of walls, and turn corners.

Courses mostly consisting of headers are often used advantageously in 23- and 34-cm walls subject to high temperatures, heavy loads, and abrasion. This bond provides stability and easy replacement, but expansion joints pass entirely through 23-cm walls.

Courses consisting mainly or entirely of headers on the inner face and mainly stretchers on the cold face are sometimes considered desirable when spalling conditions are severe. Three or four stretcher courses to one header provide a wall to which an

11.5-cm *skin wall* can be tied for repairs. However, it should not be used where stretcher courses may fall into the furnace.

In composite wall construction consisting of two or more kinds of brick in inner and outer courses, the courses are sometimes tied together. Usually, the brick possessing the higher refractory qualities goes into the interlocking courses. However, when the two types of brick have marked differences in rates of thermal expansion, the backup courses should not be tied to the inner courses. This is especially true when the temperature gradient through the wall makes a significant difference in total expansion.

Wall thickness must bear some relation to height and unsupported length. In straight, unsupported walls, an 11.5-cm thickness will carry heights up to 1 m. Twenty-three-cm walls will carry heights of 1 m to 2.5 m. Thirty-four-cm walls will carry heights of 2.5 m to 3.5 m. And 46-cm walls will carry heights higher than 3.5 m.

Walls with unsupported length more than one and one-half their height should be somewhat thicker, and thermal spalling conditions may indicate additional thickness. Walls of cylindrical furnaces and stacks, with adequate backing, may be somewhat thinner for a given height than straight walls.

Cylindrical walls, arches, and domes are built with brick tapered to turn circles. Arch brick slope from edge to edge so that the length of the brick parallels the furnace wall like a stretcher while the wedge brick tapers from end to end so that it faces into the furnace like a header. A 23 × 11.5 × 6.35-cm arch brick makes an 11.5-cm thick lining, while the same wedge shape makes a 23-cm lining.

Castable refractory materials are often used to fill places where brick would be cut to fit. For example, the irregular space between roof or wall brick and thermocouple, observation ports or other small furnace penetrations is filled with castable refractories.

The thickness of the joints between refractory brick depends on the brick, the mortar, the need for preventing gas leakage, and the requirements for thermal expansion. When there is no need for an especially strong bond, they can be laid with no mortar. In some cases, the fusion that takes place on the hot face will provide the bond required. Generally, however, the use of mortar is desirable to level courses and to provide smooth bedding for the brick.

Brickwork laid with heat setting mortars should have thin joints, either dipped or poured. The brick should be rubbed or tapped into place to produce as much brick-to-brick contact as possible. Joints made with an air setting mortar generally can be made somewhat thicker, but such joints should be completely filled.

In furnace construction, proper allowance must be made for thermal expansion. Usually, vertical expansion allowances permit walls to move freely upward, and horizontal expansion allowances appear at joints in the brick.

ARCH CONSTRUCTION. Refractory brick arches form the roof of most furnaces, combustion chambers, and flues, providing the standard solution to the problem of spanning the high-temperature process with refractories. Sometimes arches span wall openings, and sometimes they carry the weight of walls or checkerwork. Most arches are built of brick, although it is not uncommon to form an arch of castable refractory.

In a true arch, the design of the whole determines the shape of each brick or structural unit. Theoretically, each joint is a small piece of the radius of the circle of which the arch is a segment. Each end of the arch rests on a special shape brick called a skewback. The arch becomes self-supporting after all of the pieces go into place, but it must be supported until the final center shapes—the keys—go into place. When it is complete, the arch springs from the sloping faces of the skewback shapes. The skewbacks cut off the arc of the circle on the outside radii of the arc.

The sprung arch exerts—on the skewbacks—a downward vertical force and an outward horizontal force, a distribution of its weight. The vertical force may be carried by steel beams or by the furnace walls or by a combination of walls and steel buttresses. The horizontal thrust of the roof arch travels through the skewbacks to a steel supporting system known as the binding that is composed of beams and tie rods. The tie rods, usually above the furnace, link one side of the furnace to the other and balance opposing forces one against the other.

In traditional furnace design, the binding consists of

Horizontal buttress beams running lengthwise of the furnace in contact with the skewbacks where possible

Vertical beams called buckstays spaced at intervals along the furnace walls and usually set in concrete

Horizontal tie rods, I-beams, or channels extending across the furnace above the roof to connect the upper ends of opposite buckstays

In ring arches, each course of brick forms a separate ring running across the roof, and the joints are continuous across the roof. Ring arches require somewhat less labor for initial construction. Cold repairs are easier to make and they offer better resistance to spalling. However, ring arches require support at the end of the furnace to forestall outward displacement.

In bonded arch construction, all joints are broken and the rings help bond one another in a stronger construction. Bonded roofs are better adapted for hot repairs, but they demand more skill of the brick masons and more uniformity in the individual brick.

B. Water-Cooled Enclosures and Heat Recovery Systems

Containment of combustion processes in refractory lined chambers limits the peak temperatures that can be permitted (requiring increased excess air levels and, consequently, larger air pollution control and fan equipment). An alternative enclosure concept uses metal surfaces protected against overheating by water cooling. In small units or where energy recovery is economically unsound, simple water sprays on the outside of a metal furnace wall may be reasonable. Although not strictly an enclosure concept, heat removal in waste heat boilers is often used in small and medium-sized incinerators both as a means to recover useful heat and/or to cool the gases ahead of air pollution control. In larger units, the walls are constructed of tubes welded in an air-tight membrane wall (a "waterwall"), and considerably more complex strategies of energy recovery are implemented.

1. External Cooling

In its simplest embodiment, cooling of the metal furnace walls is accomplished by flowing water, uncontained, over the outside surface. For example, a small, unlined rotary kiln-type furnace with coarse water sprays playing on the shell has been successfully used for industrial waste incineration. Scale, the deposit of minerals in the makeup water, builds up over time and spontaneously (or with "help") cracks off.

Systems using such a cooling technique are limited in size and heat release rate because of uneven heat transfer in areas where adherent scale is formed. In such "insulated" areas, wall temperatures increase rapidly and metal wastage occurs. The low capital cost and ease of repair of these furnaces, however, make them attractive in special cases.

2. Waste Heat Boilers

In smaller incinerators (say, with a heat release rate between 1 and 5 million kcal/hr), the quantity of heat released is large enough to make energy recovery potentially attractive yet economic considerations argue against use of the more complex and costly waterwall enclosure concept.

a. Fire-Tube Waste Heat Boilers. Fire-tube boilers are so-named because the products of combustion pass through tubes or flues that are surrounded by water. These boilers produce only saturated steam. Generally, incinerator fire-tube boilers are of the horizontal type with a long cylindrical shell set on saddles equipped with rollers to permit movement of the boiler as it expands and contracts or suspended from hangers and supported by overhead beams. Because the outer shell of the fire-tube boiler must contain the full steam pressure, economics and practicality of fabrication limit the maximum pressure available. Boilers with steaming rates from 500 to 20,000 kg/hr at pressures from 1 to slightly over 15 atm are available. These boilers are usually shop fabricated and are low in first cost. They find common application for smaller incinerators burning nonhazardous plant trash. They have the disadvantage of requiring a large water volume and their circulation is poor, resulting in slow response to changes in firing rate. Also, their capacity, pressure, and steam temperature are limited.

b. Water-Tube Waste Heat Boilers. In a water-tube boiler, the products of combustion pass around tubes containing water. The tubes are welded into one or more cylindrical drums. The uppermost drum (the "steam drum") receives the rising froth of steam and liquid water and is the point of entry of the feedwater. In order to provide high-purity water for processes, for a subsequent superheater or a turbine, the steam drum also includes steam scrubbers and separators to aid in separating the gaseous steam from liquid water. The steam drum also mixes the saturated water remaining after steam separation with the incoming feedwater, mixes any chemicals added for corrosion control, and provides a point of water accumulation to accommodate rapid changes in furnace heat release or boiler load. If there are no other drums, the steam drum is the point where a portion of the boiler water is drawn off as a blowdown stream to purge accumulated solids from the system. In boilers with two or more drums, the lowest drum (the "mud drum") accumulates scale and other solids and is the preferred source of the blowdown stream.

3. Waterwall Boiler Enclosures

In larger combustors, convective heat transfer surface, as in a waste heat boiler, is used to withdraw heat by boiling water. In addition, however, feedwater, under pressure, is also passed into tubes in panels lining the furnace wall. These panels of wall tubes are welded together with a narrow steel strip between the individual tubes to form a continuous, gas-tight membrane or "waterwall" enclosure. The waterwalls are backed with insulation. To better understand the system, let us follow the course of the water entering the boiler plant.

a. Water Treatment. Proper treatment of boiler feedwater and recycled condensate is critically important to on-line availability and maintenance cost control for the boiler enclosure. Water treatment programs for steam-generating systems have two primary objectives: to control deposition and to minimize corrosion. Several chemical treatment options are available for each component of the boiler system. Which is applied depends on the treatment objectives for that particular component. The selection of the optimum treatment strategy for incinerator boilers involves consideration of cost effectiveness, the

anticipated performance in comparison to the objectives, and monitoring and control objectives. If the steam is to be used by others, there may also be other requirements (regulatory issues, other industry standards) that must be met. Table 10a indicates the basic objectives for the various portions of the boiler system.

RAW WATER TREATMENT. Raw water, containing dissolved minerals and suspended matter, would be an unsatisfactory feed to a boiler. Therefore, raw water entering the plant must be treated prior to use as boiler feedwater to protect the boiler from scaling and corrosion. The required quality of the feedwater increases as the steam pressure and temperature increase. Table 10b presents the recommended quality of feedwater and boiler drum water for water-tube and fire-tube boilers at various operating pressures.

As indicated, the critical feedwater and boiler water quality parameters controlled to reduce boiler corrosion include total iron, total copper, total hardness (mg/l of $CaCO_3$), silica, dissolved oxygen, conductivity, and pH. Other parameters, such as turbidity and total solids (suspended and dissolved), can reduce the heat transfer efficiency of the boiler if not properly controlled.

Traditionally, refuse incinerators with boilers have utilized clarification and filtration followed by ion-exchange demineralizers to control most of the impurities in the boiler feedwater. The demineralizer removes all inorganic salts from solution by ion exchange using a cationic, anionic, and mixed-bed ion exchange vessel, a decarbonator, and the equipment to regenerate the ion-exchange units.

The raw municipal water first enters the cation vessel where the dissolved cations (Ca^{++}, Na^{+}, etc.) salts are captured and replaced with hydrogen ions (H^{+}) leaving the anions as acids; the water then enters the anion-exchange vessel where the anions (SO_4^{--}, Cl^{-}, etc.) are removed and replaced with hydroxyl ions (OH^{-}) leaving purified water. The ion-exchange beds must be periodically regenerated with sulfuric acid (cation bed) and sodium hydroxide (anion bed). The conductivity of the treated feedwater is monitored to indicate when the ion-exchange beds require regeneration.

Reverse osmosis (RO) is an alternative technology for removing impurities in feedwater. This technology uses high pressure to force the water through membranes, which filter out the impurities at the ionic level. The capital and operating (pump power) costs are usually higher with the RO feedwater treatment systems.

DEAERATOR-WATER TREATMENT. Beyond the action within the deaerator to remove dissolved air and, importantly, its oxygen, from the feedwater, additional control is needed to remove the remainder. The chemicals used for this purpose are reducing agents in the class of products called oxygen scavengers. They fall into two categories: inorganic and organic. Oxygen scavengers are fed on demand in proportion to the dissolved oxygen. Table 11 summarizes their characteristics.

Sulfite is the most commonly used inorganic scavenger. Usually, it is complexed with sodium, but, in some formulations, with ammonia. Sulfites are fast and low in cost, but they add solids to the boiler water. Hydrazine, although quite toxic, is used where high-purity feedwater is essential such as the power and nuclear industries. Complexing the hydrazine with an organic compound reduces the toxicity. However, the complex decomposes over time, releasing CO_2 that converts to carbonate alkalinity in the boiler and reduces the pH of the boiler water. These inorganic scavengers are fed in slight excess to the oxygen demand and controlled based on the measured residual.

Organic scavengers involve a range of chemistry. The optimum selection is based on the specific requirements for oxygen control and the impact of the particular treatment chemical on the ultimate boiler-water chemistry as it may be constrained by regulations.

Table 10a Recommended Boiler Feedwater Treatment Specifications

Boiler Type:	Industrial fire tube and water tube, high duty, primary fuel fired, drum type
Makeup Water Percentage:	Up to 100% of feedwater
Conditions:	Includes superheater, turbine drives or process restrictions on steam purity

Saturated Steam Purity Target[a]

	Drum operating pressure[b] MPa (psig)				
Feedwater[c]	0.0–2.07 (0–300)	2.08–3.10 (301–450)	3.11–4.14 (451–600)	4.15–5.17 (601–750)	5.18–6.21 (751–900)
Dissolved oxygen (mg/l O_2) measured before O_2 scavenger addition[d]	< 0.04	< 0.04	< 0.007	< 0.007	< 0.007
Total iron (mg/l Fe)	≤0.100	≤0.050	≤0.030	≤0.025	≤0.020
Total copper (mg/l Cu)	≤0.050	≤0.025	≤0.020	≤0.020	≤0.015
Total hardness (mg/l $CaCO_3$)	≤0.300	≤0.300	≤0.200	≤0.200	≤0.100
pH range @ 25°C	7.5–10.0	7.5–10.0	7.5–10.0	7.5–10.0	7.5–10.0
Chemicals for preboiler system protection. Nonvolatile TOC mg/l C[e]	< 1	< 1	< 0.5	< 0.5	< 0.5
Oily matter (mg/l)	< 1	< 1	< 0.5	< 0.5	< 0.5
Boiler water (in drum)					
Total solids (ppm)	3500	3000	2500	2000	1500
Silica (mg/l SiO_2)	≤150	≤90	≤40	≤30	≤20
Total alkalinity (mg/l $CaCO_3$)	< 350[f]	< 300[f]	< 250[f]	< 200[f]	150[f]
Free hydroxide alkalinity (mg/l $CaCO_3$)[g]			Not Specified		
Specific conductance (μmho/cm) @ 25°C without neutralization	< 3500[h]	< 3000[h]	< 2500[h]	< 2000[h]	< 1500[h]

[a] No values given because steam purity achievable depends upon many variables, including boiler water total alkalinity and specific conductance and the design of boiler, steam drum internals, and operating conditions (Note *h*). Since boilers in this category require a relatively high degree of steam purity, other operating parameters must be set low enough to achieve this high purity for protection of the superheaters and turbines and/or to avoid process contamination.

[b] With local heat fluxes >473.2 kW/m^2 (>150,000 Btu/hr/ft^2), use values for the next-higher pressure range.

[c] Boilers below 6.21 MPa (900 psig) with large furnaces, large steam release space, and internal chelant, polymer, and/or antifoam treatment can sometimes tolerate higher levels of feedwater impurities than those in the table and still achieve adequate deposition control and steam purity. Removal of these impurities by external pretreatment is always a more positive solution. Alternatives must be evaluated as to practicality and economics in each individual case.

[d] Values in table assume existence of a deaerator.

[e] Nonvolatile TOC is that organic carbon not intentionally added as part of the water treatment regime.

[f] Maximum total alkalinity consistent with acceptable steam purity. If necessary, should override conductance as blowdown control parameter. If makeup is demineralized water at 4.14 MPa (600 psig) to 6.89 MPa (1000 psig), boiler-water alkalinity and conductance should be that in table for 6.90 to 10.34 MPa (1001 to 1500 psig) range.

[g] Minimum level of OH^- alkalinity in boilers below 6.21 MPa (900 psig) must be individually specified with regard to silica components of internal treatment.

[h] Maximum values often not achievable without exceeding suggested maximum total alkalinity values, especially in boilers below 6.21 MPa (900 psig) with >20% makeup of water whose total alkalinity is >20% of TDS naturally or after pretreatment by lime-soda, or sodium cycle ion exchange. Actual permissible conductance values to achieve any desired steam purity must be established for each case by careful steam purity measurements. Relationship between conductance and steam purity is affected by too many variables to allow its reduction to a simple list of tabulated values.

Source: ASME.

Table 10b Treatment Program Objectives for Boiler System Components

Component	Objective	Comments
Pretreatment	Prevent deposition in boiler	Remove soluble species: Ca, Mg, Si In demineralized systems, remove additional soluble species: NO_3^-, $CO_3^=$, $SO_4^=$
Deaerator	Prevent corrosion	Remove corrosive agents: dissolved O_2, acidic gases such as CO_2 Maintain system pH
Boiler	Prevent deposition and corrosion	Disperse or complex Fe, Ca, Mg, Si; remove via blowdown Maintain system pH
Condensate	Prevent corrosion	Maintain system pH

Source: From (500).

Table 11 Characteristics of Oxygen Scavenger Programs

Program	Advantages	Disadvantages
Inorganic: Sulfite	Easy to monitor product concentration	Contributes solids to feedwater
	Economical for high O_2 concentrations	May limit boiler energy efficiency
	Fastest reaction with O_2	Cannot attemperate with feedwater
Inorganic: Hydrazine	All volatile species	Hydrazine is highly toxic
	Easy to monitor product concentration	Low thermal stability
		Hydrazine generates NH_3 and acids
Organic: Carbohydrazide	Lower cost than other organics	Carbohydrazide generates NH_3, CO, and organic acids
		Reaction with O_2 is pH- and temperature-dependent
Organic: Hydroquinone	Of all organics, fastest reaction with O_2, especially at ambient temperatures	Does not mix well with other chemicals in feed tanks
Organic: Hydroxyl amines	Simple to feed, blends well	Difficult to monitor concentration
	Reduces feedwater Fe concentration	Reaction with O_2 is pH-dependent
Organic: Methyl ethyl ketoxime	Simple to feed, blends well	Reaction with O_2 is pH-dependent
	Reduces feedwater Fe concentration	
Organic: Ascorbic acid	Acceptable for food plant customers	Low thermal stability
		Most expensive organic product
		Concern about use for attemperation

Source: From (500).

Unlike the inorganic scavengers, the organic compounds are fed in direct relationship to the oxygen demand. Aside from their cost, the organic acid decomposition products of these materials can be problematical in sensitive applications such as steam turbines.

BOILER-WATER TREATMENT. Water quality is critical for successful boiler operation. To avoid scale buildup and/or corrosion from contaminants, the water must be treated. The level of treatment increases with the severity of the water-side environment (as characterized by the temperature and pressure of the product steam). In a typical steam–condensate–feedwater cycle, a portion of the flow is blown down (drained) to the sewer to control the buildup of solids in the boiler-water inventory. Various chemicals are added to the steam drum and to the recycled feedwater and condensate to control pH and to reduce carbon dioxide, calcium, and magnesium. Their characteristics are summarized in Table 12.

Control of pH is critical to avoid acid corrosion. Caustic soda is used to keep the pH in an alkaline range. Softened makeup water often contains calcium, magnesium, and silica. Iron and copper are added to the boiler water with the condensate return. Sodium phosphate added to react with calcium and magnesium forms a precipitate in the steam drum, which is removed with the boiler blowdown operation. Addition of dispersants assists in keeping the precipitates suspended. Some of the newer dispersants also aid in preventing deposition of iron and copper.

An alternative strategy uses chelants to complex the calcium and magnesium ions. The result is an unusually clean boiler tube with consequent benefits in heat transfer efficiency.

Boiler steam drum blowdown rates vary with the quality of the feedwater but are usually 1% to 3% of the total feedwater flow to the boiler.

CONDENSER-WATER TREATMENT. Condensate return is economically important to conserve the value added in water treatment. However, condensation processes can release considerable iron and copper contaminants, which return to the boiler. Neutralizing

Table 12 Characteristics of Internal Treatment Programs

Program	Advantages	Disadvantages
Precipitating (softened feedwater)	Easy to monitor concentration Fewest risks from overfeed	Adds solids to boiler system May limit boiler energy efficiency
Solubilizing (softened feedwater)	Maintains tubes cleanest Most economical for hardness <1.0 ppm	Overfeed is corrosive Difficult to monitor concentration
Precipitating with solubilizing (softened feedwater)	Easy to monitor concentration Most economical for hardness >1.0 ppm	Overfeed is corrosive
Dispersing (softened feedwater)	Flexible feedpoint Tolerant of changes in hardness	Not economical for hardness >1.0 ppm Difficult to monitor concentration
Coordinated phosphate/pH (high-purity feedwater)	Best corrosion protection for high-purity feedwater	More difficult to control feed rate within narrow range of pH and phosphate concentration

Source: From (500).

Table 13 Characteristics of Condensate Treatment Programs

Program	Advantages	Disadvantages
Neutralizing amines	Simple application of product Many alternatives available	Cost is proportional to concentration of acids and can be higher than filming amines
Filming amines	Lowest cost	Intolerant of overfeed or poor pH May require satellite feedpoints
Passivating agents	Some blended with neutralizing amines Can reduce O_2 and Fe in condensate	Cost > neutralizing or filming amines
Neutralizing + filming amines	Ideal for complex systems	Tight control required May require satellite feedpoints Intolerant of overfeed or poor pH
Neutralizing amines + passivating agents	Can reduce O_2 and Fe in condensate	More expensive than neutralizing amines alone

Source: From (500).

amines, filming amines, and passivating agents, individually or in combination, are used to control these problems, as summarized in Table 13.

Filming amines are injected at a constant rate into the steam header ahead of the condenser to coat the condenser tubes to prevent attack from acidic species or oxygen. The filming action is pH-dependent, and tight control to a pH below 7.5 is necessary to prevent solubilization of the amine and tube attack.

Neutralizing amines react with acidic species to stop corrosion. Soluble carbon dioxide can be removed by adding morpholine, cyclohexamine, diethylaminoethanol amine, or other neutralizing amines (alone or in blends) to the feedwater circuit. In some cases, other satellite-feed locations are added to ensure control throughout the water circuit. A disadvantage of these amines is that no control of dissolved oxygen is present. To add this feature, oxygen scavengers known as passivating agents are fed to supplement the protective action of the neutralizing amines.

b. Deaeration. Water also contains dissolved gases (air components, CO_2, etc.) that would accumulate in the boiler after a time and that increase the minimum pressure obtainable when the water is condensed. (In steam turbines operated with a condenser, the steam can, theoretically, be expanded to the pressure corresponding to the vapor pressure of water at the condenser temperature. Noncondensable or "fixed" gases accumulate and pressurize this area and must be pumped out. Their net effect is to reduce the efficiency of the turbine.) Also, oxygen participates in corrosion reactions leading to tube wastage.

The treated feedwater is heated with steam or electricity to the atmospheric boiling point in a deaerator. The deaerator uses steam scrubbing and mass transfer across a set of flat trays or spray nozzles to remove the bulk of the dissolved air and, importantly, its oxygen, from the feedwater. In some steam plants, low-pressure "waste steam" is condensed to preheat the boiler feedwater after the deaerator but prior to entering the boiler proper.

c. Feedwater Pumping. The water leaving the deaerator is ready for introduction into the boiler using the feedwater pumps to raise the pressure to the boiler's working level. Electrical pumps are commonly used in this service. In larger plants, pumps driven by small steam turbines are often used once the boiler has reached its normal operating conditions.

d. Feedwater Heating. Feedwater heating is effected using boiler product steam or extraction steam taken at a location in the turbine intermediate between the feed steam generated in the boiler and superheater (throttle steam) and the condenser. The number of feedwater heating stages is selected as a balance between the associated capital cost and the capitalized energy value of improved thermodynamic efficiency in power cycles.

e. Boiler. At the point of introduction into the boiler, the feedwater is treated, deaerated, and, perhaps, somewhat preheated such that its temperature is in the range from 100° to 200°C. In passing the water through the boiler, it is desirable to optimize the temperature difference between the water and the hot combustion gases (maximum heat transfer rate) to minimize the required amount of heat transfer area (capital cost) while still extracting the maximum amount of heat from the combustion gases. In larger boilers, this will include the following components.

RADIANT BOILER. The water walls and, in some cases, banks of tubes exposed to the high-temperature combustion zone. Heat transfer rates are very high, and radiant energy transport from the incandescent refuse bed, flame, and/or hot gases (see subsequent sections of this chapter) is the predominant means of heat transfer.

SLAG SCREEN. Banks of specialized boiler tubes at the entrance to the convection passes that are designed to accept and cope with the accumulation of slag deposits.

CONVECTION BOILER. One or more banks of tubes (or "passes") between which the hot flue gases flow where the water (from the economizer) is evaporated. Heat transfer is predominantly by convection. Flow of the water through the tubes may be due to buoyancy effects (a natural convection boiler) or pumps (a forced convection boiler) and is two-phase: containing both liquid water and steam. Erosion of the tubes by fly ash is proportional to both the quantity and abrasive character of the fly ash and, exponentially, on the flue gas velocity. Typical limits range from 19.8 m/sec for a nonabrasive or low ash concentration to 13.7 m/sec for an abrasive or high ash concentration.

STEAM DRUM. One or more large accumulators with disengagement space and mechanical devices to separate the gaseous steam from the liquid water. The liquid is recirculated to the convection or radiant boiler sections. The product steam, in thermodynamic equilibrium with liquid water, is "saturated" at the temperature and pressure of the steam drum contents. Saturated steam may be the desired product, or the steam may be further heated in the superheater.

SUPERHEATER. One or more radiantly and/or convectively heated tube banks where the saturated steam is further heated to produce dry steam with a higher heat content (enthalpy) than saturated steam at the same pressure. When steam is to be piped long distances, superheating reduces the amount of liquid condensate from heat losses in transmission. When steam is used for power production, superheating the steam allows recovery of more mechanical energy in the turbine than for saturated steam.

ECONOMIZER. One or more banks of tubes between which the hot flue gases flow and convectively transfer heat to the feedwater. The feedwater supplied to the economizer is usually heated near or to the boiling point such that the fireside metal temperatures are safely above the dew point of the flue gases. The economizer is located in the part of the

boiler where the flue gas temperature is the lowest. Generally, economizers are arranged for the downward flow of gases and the upward flow of water. In boilers fired with low-ash fossil fuels, fins or other extended surface methods are sometimes used to increase the heat recovery effectiveness of economizer tubes. With few exceptions, the use of extended surface tubing is not recommended for sludge or solid waste incineration systems.

SOOTBLOWERS. Mechanical devices used for on-line cleaning of gas-side boiler ash and slag deposits. Sootblowers clean the tubes using a cleaning medium (saturated or superheated steam, compressed air, or water singly or in combination) directed at the fouled surfaces. Although there are advantages to each, superheated steam at from 4.8 to 24.1 bar gauge is generally preferred. If air is used, pressures from 4.1 to 15.2 bar gauge are normal. Water is used at 10.3 to 20.7 bar gauge. Sootblower type and frequency of use depend on the location within the boiler and on the severity of deposits.

Sootblowers to remove dusty or lightly sintered ash can be of the fixed- position type (either rotating or nonrotating) in low-temperature areas of the boiler. Short and long retractable wall blowers auger themselves into the boiler from their storage point at the wall. The short travel blower is used principally to clean furnace water wall tubes and reaches and extends considerably less than 0.5 m into the furnace. The long, retractable blowers extend far into a boiler to clean tube banks, extending from about 0.6 m to as much as 17 m.

In refuse applications, the frequency of application of the sootblowers must be judiciously selected. Retractable blowers, used in the superheaters and convection banks, are spaced about 2.4 to 3.0 m apart (532) and are operated at steam rates comparable to that used in bituminous coal boilers. However, if sootblowing is too frequent, the tubes will be so clean that high corrosion rates are often experienced. If too seldom, heat transfer degrades and back-end temperatures increase and energy generation efficiency decreases. In some units, mechanical rapping has been used as an alternative to sootblowing in both the superheater and the economizer.

AUXILIARY BURNERS. In many countries, auxiliary burners must be provided to ensure that furnace temperatures exceed preset minimums during startup, during shut-down, or during upset conditions. Such burners are usually equipped for oil or gas firing and are used only when needed to adhere to regulatory minimums. Typical designs are for a firing rate of 25% to 30% of the boiler's maximum continuous rating (MCR). The burners are mounted in the sidewalls just above any bull nose and after the overfire air jet introduction elevation.

To avoid efficiency degradation from air cooling of the auxiliary burners when they are not in service, some installations use a burner mounting that allows the burner to be retracted when not in service.

f. Metal Wastage. In boilers using wastes as fuels (and for conventional fuels as well), metal wastage due to corrosion and erosion and tube fouling due to the buildup of deposits present serious problems to the system designer and operator. Detailing the nature and cures for such problems is beyond the scope of this book and is still a matter of intense study and speculation. Several basic concepts, however, merit qualitative description.

LOW-TEMPERATURE CORROSION. Metal temperatures in some regions of the boiler may be low enough such that condensation of moisture in the flue gases will occur. This includes the economizer (if the feedwater is too cold), surfaces used to transfer heat to incoming combustion air (the air heater), slow-flow zones (low heat transfer rates), and in underinsulated locations. If a given gas mixture is cooled, condensation will occur at a

relatively discrete temperature. This is the dew point of the gas mixture and is uniquely related to the composition of the gas mixture. The presence of mineral acids (e.g., sulfuric or hydrochloric acid) in the flue gas (especially sulfur trioxide) leads to condensation at temperatures considerably *above 100°C*. The resulting metal wastage rate is accelerated by the presence of soluble chlorides or acids and can become unacceptably high. Clearly, such corrosive mechanisms are always operative during boiler startup and shutdown. Of particular importance is the sulfuric acid dew point, which is considerably higher than the water-related dew point.

The sulfuric acid dew point T_{SAD} (degrees K) may be estimated (197) from

$$1000/T_{SAD} = 1.7842 + 0.0269 \log P_{H_2O} - 0.1029 \log P_{SO_3} + 0.0329 \log P_{H_2O} \log P_{SO_3} \quad (1)$$

where P_{H_2O} and P_{SO_3} are the partial pressure (atmospheres) of water vapor and sulfur trioxide, respectively, and logarithms to the base 10 are used.

The sulfurous acid dew point $T_{H_2SO_3}$ (degrees K) may be estimated (477) from

$$1000/T_{H_2SO_3} = 3.9526 - 0.1863 \ln P_{H_2O} - 0.000867 \ln P_{H_2SO_3} + 0.000913 \ln P_{H_2O} \ln P_{H_2SO_3} \quad (2)$$

where $T_{H_2SO_3}$ is in degrees Kelvin, the partial pressures of water vapor and sulfurous acid are in mm of mercury, and natural logarithms are used.

The hydrofluoric acid dew point T_{HF} (degrees K) may be estimated (489) from

$$1000/T_{HF} = 2.8723 - 0.0386 \ln P_{H_2O} - 0.0686 \ln P_{HF} + 0.00099 \ln P_{H_2O} \ln P_{HF} \quad (3)$$

where T_{HF} is in degrees Kelvin, the partial pressures of water vapor and hydrofluoric acid are in mm of mercury, and natural logarithms are used.

The hydrochloric acid dew point T_{HCl} (degrees K) may be estimated (477) from

$$1000/T_{HCl} = 3.7368 - 0.1591 \ln P_{H_2O} - 0.0326 \ln P_{HCl} + 0.00269 \ln P_{H_2O} \ln P_{HCl} \quad (4)$$

where T_{HCl} is in degrees Kelvin, the partial pressures of water vapor and hydrochloric acid are in mm of mercury, and natural logarithms are used.

The hydrobromic acid dew point T_{HBr} (degrees K) may be estimated (477) from

$$1000/T_{HBr} = 3.5639 - 0.1350 \ln P_{H_2O} - 0.0398 \ln P_{HBr} + 0.00235 \ln P_{H_2O} \ln P_{HBr} \quad (5)$$

where T_{HBr} is in degrees Kelvin, the partial pressures of water vapor and hydrobromic acid are in mm of mercury, and natural logarithms are used.

The nitric acid dew point T_{HNO_3} (degrees K) may be estimated (477) from

$$1000/T_{HNO_3} = 3.6614 - 0.1446 \ln P_{H_2O} - 0.0827 \ln P_{HNO_3} + 0.00756 \ln P_{H_2O} \ln P_{HNO_3} \quad (6)$$

where T_{HNO_3} is in degrees Kelvin, the partial pressures of water vapor and nitric acid are in mm of mercury, and natural logarithms are used.

The "cure" for these types of corrosion is straightforward: design to avoid dead zones and to maintain metal temperatures safely above the dew point of the flue gases.

Also, minimize the frequency and duration of cooldowns. Chloride-rich deposits on tube surfaces are hygroscopic and become moist during out-of-service periods. Samples of deposits (1 g in 100 g of water) exhibited a pH of 4.0 (379): a level where corrosion of carbon steels would proceed rapidly and where stress corrosion problems would occur with austenitic stainless steel overlays and cladding.

HIGH-TEMPERATURE CORROSION. In regions of the furnace where the fireside tube metal temperature is above, say, 250°C, a variety of mechanisms for chemical attack of the metal tube surfaces becomes operative.

Chlorine and sulfur attack. Chlorine, appearing in the flue gases as hydrochloric acid (often from the combustion of chlorinated hydrocarbon wastes or polyvinyl chloride) or in salts such as sodium or potassium chloride, has been shown to participate in corrosive attack of metal tubes. The chlorine may act independently or in conjunction with lead, zinc, sodium, and potassium present as several salts. The metal salts appear to facilitate chlorine attack by producing low-melting eutectics that act as fluxes for the naturally protective deposits on the tube metal surface. Although the problem has been severe and large sums of money have been spent in research, the root causes of the corrosion are still uncertain. It is clear that a reducing condition at the tube surface is important. It is unclear whether HCl or Cl_2 is the corrosive agent or, perhaps, merely participates as metal salts that flux the deposits and expose the native metal to attack.

Sulfur, appearing as the dioxide or trioxide or as sulfates, appears to slow the rate of attack of the metal by chlorides (59). While the exact mechanism of attack is still in question, it is clear that fireside metal temperature is the single most important parameter in evaluating the potential for rapid metal wastage. The flue gas temperature, however, is a second, though less important, variable at gas temperatures of interest.

Data reported by Battelle (56–61) indicate that a maximum fireside metal temperature of 205°C (400°F) should give very long carbon steel boiler tube service (say, more than 15 years) for systems burning 100% municipal refuse. It is reasonable to assume a 25°C temperature drop across the tube wall for tubes with boiling heat transfer rates on the inner wall. On this basis, high-temperature corrosion should not be a problem up to a maximum (saturated) steam pressure of 9.85 atm (130 psig) for surface in the radiant or convective boiler sections. For higher steam pressures and temperatures, increased wastage must be accepted and/or more costly tube metal alloys or other corrosion control strategies must be used. For metal temperatures up to 480°C, carbon steel corrosion increases rapidly with chlorine concentration up to about 1% in the waste and then levels off. At higher temperatures, the corrosion rates increase linearly with chlorine content (321).

Excessive furnace wall and superheater corrosion is presently being responded to by the use of co-extruded tubes or cladding. In the furnace and convective regions of the boiler, AISI 310 gives a benefit factor of about three. In superheaters, 50% Cr–50% Ni gives a benefit factor of ten (320). In other instances, Inconel, as a weld overlay or in a bimetallic tube construction, has been effective (532) for lower furnace corrosion protection in RDF-fired boilers.

The problems of accelerated metal wastage are of special concern for superheater surfaces. The lower heat transfer rates of gaseous steam flowing through a pipe (compared to liquid water undergoing nucleate boiling) results in higher fireside tube temperatures and greatly accelerated corrosion. For tubes flowing gaseous steam, a average tube wall temperature drop of 50–70°C is realistic. Excursions to higher fireside temperatures can occur more frequently and with greater severity than for boiler tubes. Some postconstruc-

tion relief from the superheater corrosion problem has been found by the use of rammed silicon carbide-type refractory coatings on the tubes (62). This "solution" comes at the cost of lowered heat transfer rates and increased investment and maintenance expense. A strategy that has been found useful in new plants moves the superheater surface to follow a convective boiler pass that lowers the gas temperature to about 800°C at the entry to the superheater.

Oxidizing and reducing conditions. In the incineration of heterogeneous fuels such as raw municipal refuse and especially for mass burning configurations, it is common to produce flue gases that fluctuate in composition between oxidizing (having an excess of oxygen) and reducing (devoid of oxygen and with significant concentrations of reducing gases such as carbon monoxide, hydrogen, or mixed hydrocarbons). Metal surfaces exposed to such changing gas compositions are subject to rapid wastage. In large part, this wastage is due to the effects of repeated cycles of surface metal oxide formation and then reduction. Flaking of the weak, reduced metal structure is accelerated by the "shot blasting" effect of entrained particulate.

The problem of reducing conditions (CO) is synergistic with HCl attack. Under such conditions, strong efforts to correct the substoichiometric condition are warranted. Data from an industrial RDF boiler (367) indicated the value of Inconel 182 alloy weld overlay (310 stainless next, 312/347 stainless least durable) and suggested the use of clad tubes with Incoloy 825 in highly corrosion-prone areas.

In mass burning systems, the bed processes always produce reducing gases; consequently, sidewalls and radiant tube banks are particularly prone to this type of attack. Protection of the sidewalls up to a distance 9 to 10 m above the grate line has been used successfully to cure the sidewall corrosion problem. Near the grate, armour blocks or refractory blocks have been used successfully. Also, pin stud and silicon carbide (SiC) refractory is used in this zone due to its combination of high abrasion resistance and high thermal conductivity. Introduction of sufficient secondary air above the fire and stimulation of high levels of turbulence can greatly assist the burnout of reducing gases prior to their entry of the tube banks.

RDF systems present a difficult problem in lower furnace sidewall attack because of the inherent high flame temperatures in the furnace occasioned by the high heat release in the over fire space: semisuspension burning. By protecting the sidewalls with pin studs and refractory, heat removal in the lower furnace area is reduced, thus tending to increase the flame temperature still further. This leads to aggravation of the slagging problem on the sidewalls. High-nickel alloy cladding of the tubes (Inconel is recommended) (532) is a preferred solution.

Abrasion (erosion) wastage. The mechanical erosion of tube surfaces by fast-moving fly-ash particles can rapidly lead to tube failure. The fly ash from municipal refuse combustion has been shown to be particularly abrasive (more so than, for example, most coal ash). This problem can be mitigated by reducing the velocity of the flue gases between the tubes (say, to 3.5–4.5 m/sec) by coating the tubes with refractory (or letting slag build up to a degree) and by careful design of tube bank geometry and flow patterns. In general, these remedies lead to larger, more costly boiler facilities.

Steam thermodynamics. Calculations regarding rates of steam generation and power generation from steam in turbines require values for the enthalpy and entropy of feedwater and steam at various temperatures and pressures. These thermodynamic data are available

in standard texts (e.g., 442, 460). Estimates can be found using the computer program included on the diskette provided with this text and described in Appendix F.

II. HEAT TRANSFER

It is beyond the scope of this chapter to deal with the complex problems of heat transfer analysis for combustors. Texts such as *Radiative Transfer* (27) and others are more appropriate resources. However, several heat transfer-related considerations should be noted.

A. Conduction

The primary areas of application of conduction heat transfer analysis in the design of incineration systems are in estimating fuel heating rates and in predicting heat losses and outside wall temperatures for the combustion chamber. Although the heat flux in combustion systems is largely radiative (except the convective heating of boiler tubes), heat loss by conduction through the refractory walls can exceed 2% to 8% of the total heat release and can result in unsafe outside wall temperatures.

In refractory-lined systems where worker comfort or safety requires cool outside wall temperatures, an analysis of wall heat loss is appropriate. Boundary conditions for the analysis would include the following considerations:

1. Assume that the inside wall temperature will be maintained within a few hundred degrees of the hottest large areas or volumes in the combustion chamber. This assumption recognizes the fact that since wall conduction is relatively poor, the inside temperature will approach radiative equilibrium with such intense radiation sources.
2. Allow for both convective and radiative losses from the outer wall. Rather than introducing the mathematical complexity of the fourth power of temperature dependency of radiation, use an overall natural convection plus radiation coefficient, available from standard texts (5). Note, however, that if outside temperatures exceed, say, 200°C, a more careful consideration of radiation is appropriate.

For one-dimensional heat transfer by conduction in the x-direction, the heat transfer rate per unit area is given by

$$\dot{Q}_a = -\lambda \frac{dT}{dx} \quad \text{kcal hr}^{-1}\ \text{m}^{-2} \tag{7}$$

where λ is the thermal conductivity and dT/dx is the thermal gradient. The minus sign acknowledges the fact that heat flow in the positive x-direction requires a decline in temperature with increasing x. The conversion factor for λ from the commonly tabulated values (e.g., Ref. 4) of $\text{Btu hr}^{-1}\ \text{ft}^{-2}\ (^\circ\text{F/ft})^{-1}$ to $\text{kcal hr}^{-1}\ \text{m}^{-2}\ (^\circ\text{C/m})^{-1}$ is 1.487.

For steady, one-dimensional conduction in isotropic solids, the thermal gradient will be linear and Eq. (7) becomes

$$\dot{Q}_a = -\lambda \frac{\Delta T}{\Delta x} \tag{8}$$

where Δx is the thickness of the slab and ΔT the surface-to-surface temperature difference.

It should be noted that the thermal conductivity often varies appreciably over the temperature extremes common to combustion systems, and a suitable average must often be selected. More complex problems that relax the assumptions indicated above (isotropic materials, one-dimensionality, etc.) may often be solved by the use of special texts (e.g., Ref. 64).

EXAMPLE 1. A horizontal, cylindrical incinerator 4 m in diameter is burning liquid waste in a chamber with 20-cm-thick insulating firebrick walls, sheathed with 6-mm-thick steel. The mean radiative temperature of the flame is 1100°C. What is the approximate outside skin temperature?

Assume that the equilibrium temperature of the inside wall is 1000°C and that the ambient is 25°C. Simplify the analysis by assuming that the thermal gradient within the wall and within the steel shell is linear. Figure 1 illustrates the situation.

$$[\dot{Q}_a]_R = \text{conduction through refractory} = \frac{\lambda_R(T_1 - T_2)}{X_R} \text{ kcal hr}^{-1} \text{ m}^{-2} \tag{9}$$

$$[\dot{Q}_a]_S = \text{conduction through steel (neglecting conduction of air film)} = \frac{\lambda_S(T_2 - T_3)}{X_S} \text{ kcal hr}^{-1} \text{ m}^{-2} \tag{10}$$

$$[\dot{Q}_a]_{a,c} = \text{conduction to ambient} = h_c(T_3 - T_a) \text{ kcal hr}^{-1} \text{ m}^{-2} \tag{11}$$

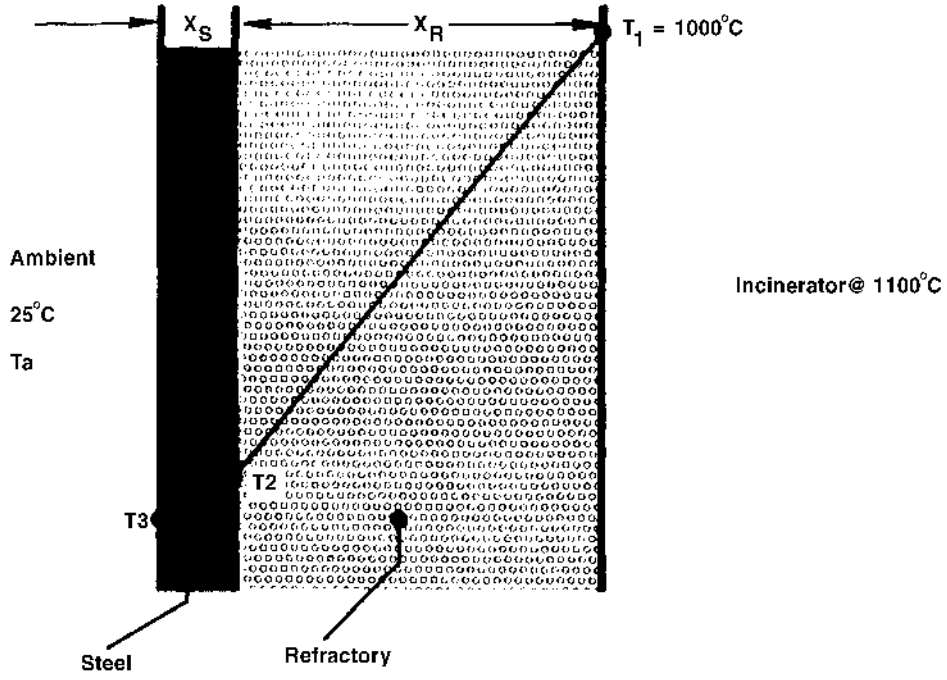


Figure 1 Schematic of process in Example 1.

where

$$h_c = 2.84\left(\frac{\Delta T_s}{D_0}\right)^{0.25} \text{ kcal hr}^{-1}\text{ m}^{-2}\ ^\circ\text{C} \tag{12}$$

Note that Eq. (12) is a *dimensional* equation, with ΔT_s being the temperature difference between surface and ambient in °C and D_0 is the outside diameter in meters. The equation applies to horizontal cylinders or to long vertical cylinders only. For other configurations:

Vertical plates higher than 1.0 m:

$$h_c = 4.23(\Delta T_s)^{0.25} \text{ kcal hr}^{-1}\text{ m}^{-2}\ ^\circ\text{C}^{-1} \tag{13}$$

Horizontal plates:

Facing upward:

$$h_c = 5.93(\Delta T_s)^{0.25} \text{ kcal hr}^{-1}\text{ m}^{-2}\ ^\circ\text{C}^{-1} \tag{14}$$

Facing downward:

$$h_c = 3.12(\Delta T_s)^{0.25} \text{ kcal hr}^{-1}\text{ m}^{-2}\ ^\circ\text{C}^{-1} \tag{15}$$

$$[\dot{Q}_a]_{a,r} = \text{radiation to ambient} = h_r(T_3 - T_a) \text{ kcal hr}^{-1}\text{ m}^{-2} \tag{16}$$

where

$$h_r = \frac{4.92 \times 10^{-8}(T_{3'}^4 - T_{a'}^4)(\varepsilon_S)}{(T_3 - T_a)} \text{ kcal hr}^{-1}\text{ m}^{-2}\text{ K}^{-1} \tag{17}$$

$T_{3'}$ and $T_{a'}$ are the surface and ambient temperatures (respectively) expressed in degrees Kelvin, and ε_S is the emissivity of the outer steel shell. Property values of use are

$$\lambda_R = 0.15 \text{ kcal hr}^{-1}\text{ m}^{-2}\ (^\circ\text{C/m})^{-1}$$
$$\lambda_S = 37 \text{ kcal hr}^{-1}\text{ m}^{-2}\ (^\circ\text{C/m})^{-1}$$
$$\varepsilon_S = 0.8 \text{ (oxidized steel, rough oxide coat)}$$

Note that

$$\dot{Q}_a|_R = \dot{Q}_a|_S = \dot{Q}_a|_{a,c} + \dot{Q}_a|_{a,r}$$

Rather than attempting to solve a fourth-order equation, assume T_3, calculate h_c and h_r, calculate T_3, and iterate to acceptable convergence:

Assume

$$T_3 = 120^\circ\text{C (393 K)}$$
$$h_c = 2.84\left(\frac{120 - 25}{4}\right)^{0.25} = 6.27 \text{ kcal hr}^{-1}\text{ m}^{-2}\ ^\circ\text{C}$$
$$h_r = \frac{4.92 \times 10^{-8}(393.15^4 - 298.15^4)(0.8)}{(120 - 25)} = 6.62 \text{ kcal hr}^{-1}\text{ m}^{-2}\text{ K}^{-1}$$
$$h_{c+r} = h_c + h_r = 12.89 \text{ kcal hr}^{-1}\text{ m}^{-2}\ ^\circ\text{C}^{-1}$$

Eliminating T_2 between the steel-to-refractory and the refractory-to-ambient heat loss terms and using the notation

$$C_1 = 1 + \frac{\lambda_S X_R}{\lambda_R X_S} = 8223$$

$$C_2 = \left(\frac{X_R}{\lambda_R}\right) h_{c+r} = 17.19$$

then

$$T_3 = \frac{(C_1 - 1)T_1 + C_1 C_2 T_a}{(C_1 - 1 + C_1 C_2)}$$

$$T_3 = 78.6^\circ\text{C} \quad \text{and} \quad T_2 = 78.7^\circ\text{C}$$

Clearly, the conductive resistance of the steel is negligible in comparison to that of the firebrick and the problem could be simplified by neglecting it.

Recomputing h_c and h_r for the new T_3 yields

$$h_c = 5.43 \text{ kcal hr}^{-1} \text{ m}^{-2} \,^\circ\text{C}^{-1}$$

$$h_r = 5.43 \text{ kcal hr}^{-1} \text{ m}^{-2} \,^\circ\text{C}^{-1}$$

$$h_{c+r} = 10.86 \text{ kcal hr}^{-1} \text{ m}^{-2} \,^\circ\text{C}^{-1}$$

and

$$T_3 = 88^\circ\text{C (acceptable convergence)}$$

It is noteworthy that changing the assumed inside wall temperature by 100°C would change T_3 by less than 10°C. Also, if the outside wall is as hot as 90°C (194°F), care should be exercised to prevent worker contact or consideration should be given to lagging the wall with insulation to bring the temperature within safe limits.

B. Convection

Convection, though important in boiler design, is usually less important than radiation in combustion system analysis. A particular exception occurs when jets of heated air or flames impinge upon a surface. This can happen when sidewall overfire air jets are discharged across narrow furnaces or burner flames impinge on the opposite end of the furnace. The heat transfer rates at the point of impingement can be extremely high. Consequent damages to refractory or to boiler tubes can be excessive. For this reason, flame length or jet penetration calculations should be used to ensure a reasonable margin of safety.

C. Radiation

In high-temperature combustors, radiation is the dominant mechanism for heat transfer. The relationship defining the total radiant emissive power W_B from a black body at a temperature T is known as the Stefan–Boltzmann law:

$$W_B = \sigma T^4 \text{ kcal m}^{-2} \text{ hr}^{-1} \tag{18}$$

where

$$\sigma = \text{the Stefan–Boltzmann constant}$$
$$= 4.88 \times 10^{-8} \text{ kcal m}^{-2} \text{ hr}^{-1} \text{ °K}^{-4} \quad \text{or} \quad 0.171 \times 10^{-8} \text{ Btu ft}^{-2} \text{ hr}^{-1} \text{ °R}^{-4}$$

One should note that the emissive power is spectral in nature (being different at different wavelengths). For black bodies (which absorb and emit fully at all wavelengths), this is unimportant. For solids, liquids, or gases that absorb or emit preferentially in one or more spectral regions, however (importantly including carbon dioxide and water vapor), the spectral characteristics of both emitter and absorber must be taken into account. To simplify computation, the concept of a "gray body" has been developed. At the same temperature, the total emissive power of a gray body W is somewhat less than a black body. The ratio of emissive power of the gray body to the black body at the same temperature is known as the *emissivity*, i.e.,

$$\frac{W}{W_B} = \varepsilon \tag{19}$$

The emissivity of surfaces generally increases as tarnish or roughness increases (e.g., oxidized steel or refractory) and may change with temperature.

Radiation follows straight lines. Thus, the geometrical relationship between surfaces and volumes has a direct impact on the net flux. Also, surfaces will absorb and reradiate and may reflect heat, thus compounding the difficulty of analysis.

Gases and luminous flames are radiators. Although carbon dioxide and water vapor (particularly) are essentially transparent in the visible region of the spectrum, they absorb strongly in other spectral regions and participate significantly in radiant heat transfer in furnaces. It should be noted that the overall characteristics of gas emissivity (a "gray gas") may be conveniently approximated with an exponential formulation

$$\varepsilon_{\text{gas}} = 1 - \exp(-apx) \tag{20}$$

where a is a constant characteristic of the gas, p is the partial pressure of the gas, and x is the thickness of the gas layer. Thus, thick sections of gas at high concentrations will have relatively higher emissivity than the converse. As an indication of the importance of these effects, at 1100°C, a 3-m thickness of water vapor at a partial pressure of 0.1 atm in air has an emissivity of 0.2, about 25% of that of a refractory wall.

Similarly, flames emit a significant radiative flux due both to the radiative emission of gases and to the hot particulate matter (ash and soot) contained within it.

For a thorough treatment of radiative transport, the serious student is directed to texts in the field (e.g., Refs. 27 and 63).

D. Heat Transfer Implications in Design

Although a detailed treatment of heat transfer in furnaces is beyond the scope of this chapter, several general observations should be made.

The designer should be aware that in many cases (e.g., burning wet refuse) there is a significant heat requirement to initiate and maintain a steady burning condition. When heat recovery is of no interest, no serious compromises are required and the shape and operating temperature of the surfaces in radiative "touch" with the incoming waste can be readily designed such as to ensure rapid and stable ignition. When heating of boiler

surfaces or stock is an objective, care should be given to avoid robbing the feed zone of the heat flux required to maintain steady ignition and burning.

The designer should consider the heat fluxes within and through the furnace as they may affect wall temperatures. Often, in waste-burning systems, the ash materials may react with the refractory at elevated temperatures to yield low melting eutectics. Such processes result in rapid, even catastrophic, wall degradation. Also, high wall temperatures may foster adherence of ash (slag buildup), which can cause mechanical damage to walls and, in mass burning systems, to the grates when the accumulated slag brakes off and falls. Such slag deposits can build up to the point where the flow of gases and even waste moving on grates can be impeded as, for example, by completely bridging across a 3-m-wide furnace.

The designer should also be aware that cold surfaces are heat sinks, draining away the radiative energy from within a furnace. Many furnaces are constructed with (from a radiative heat loss standpoint) clear "views" of cold zones from the hot primary chamber. The result is a chilling of the combustion zone with noticeable increases in soot and carbon monoxide generation.

III. SLAGGING AND FOULING

Ash is an important component of waste. Ash dilutes the combustible content of the waste, and the presence of significant quantities of ash requires a large investment in facilities to capture, handle, and store the material following the combustion process. However, the most significant ash-related problems arise due to the ash deposits on the sidewalls and boiler tubes of the combustion enclosure and heat recovery equipment. Deposition of ash leads to problems with structural integrity arising from both the mass of the slag accumulations and the damage that can be done to grates and materials-handling equipment from falling chunks of ash. Ash deposits also contribute to tube corrosion and, through chemical interaction, attack (fluxing) of refractory. Accumulation of slag insulates the tubes and reduces the heat transfer rate. In severe cases, accumulated deposits interfere with the flow of flue gases through the boiler passes.

Ash particles below the initial deformation temperature (see Chapter 2) can be expected to be in a dry and solid state. Under these conditions, the particles simply bounce off tubes and, at worst, build up in corners and crevices as a dusty deposit. However, when the temperature exceeds the initial deformation temperature, impacting particles become more plastic and have a greater tendency to stick and accumulate. At the fluid temperature, the ash will run off and deposits will be limited in thickness. Between these two extremes, as the differential between the initial deformation and the hemispherical temperature increases, the ash deposits are both sticky and too viscous to flow under the influence of either gravity or soot blowing. This can lead to rapid buildup of deposits.

The potential for ash deposition problems is characterized in two ways: with a *slagging indices* used to judge the potential severity of problems with the high-temperature radiant surface and the *fouling indices* used to judge the potential severity of problems with the convective surface in the boiler.

Analysis of the slagging characteristics of ash have been studied extensively with respect to coal applications (532). For coal, the ash behavior is characterized in two categories: bituminous ash and lignitic ash. Ash is denoted bituminous when

$$Fe_2O_3 > CaO + MgO$$

and lignitic when

$$Fe_2O_3 < CaO + MgO$$

A slagging index (R_s) giving an indication as to the probable severity of slagging can be formed from the ratio of basic oxides to acidic oxides and the sulfur content (for bituminous ash). Using the definition based on weight percent of oxides:

$$B = CaO + MgO + Fe_2O_3 + Na_2O + K_2O \tag{21a}$$

$$A = SiO_2 + Al_2O_3 + TiO_2 \tag{21b}$$

$S =$ weight percent sulfur on a dry basis

$$R_s = BS/A \tag{22}$$

and the slagging potential is given as follows:

$R_s < 0.6$	low	$2.0 < R_s < 2.6$	high
$0.6 < R_s < 2.0$	medium	$2.6 < R_s$	severe

For lignitic ash, the slagging index R_s^* is based on the ash fusibility temperatures given IT as the initial deformation temperature and HT as the hemispherical temperature:

$$R_s^* = \frac{(\text{maximum HT}) + 4(\text{minimum IT})}{5} \tag{23}$$

Babcock and Wilcox (532) have found that the most accurate method to predict slagging potential is based on a viscosity index R_{vs} based on measurements of the temperature (°F) where the slag viscosity is 250 poise in an oxidizing atmosphere and 10,000 poise in a reducing atmosphere ($T_{250\text{-oxid}}$ and $T_{10,000\text{-reduc}}$, respectively). The viscosity index is given by

$$R_{vs} = \frac{(T_{250\text{-oxid}}) - (T_{10,000\text{-reduc}})}{54.17 f_s} \tag{24}$$

where f_s is a correlation factor given by

$$f_s = 0.5595 \times 10^{-16} T^{5.3842} \tag{25}$$

and the slagging potential is given as follows:

$R_{vs} < 0.5$	low	$1.0 < R_{vs} < 2.0$	high
$0.5 < R_{vs} < 1.0$	medium	$2.0 < R_{vs}$	severe

For bituminous ash, the fouling index R_f is based on the basic and acidic oxide ratios [Eqs. (21a) and (21b)] and the percentage of sodium oxide in the ash:

$$R_f = \frac{B}{A} x Na_2O \tag{26}$$

and the fouling potential is given as follows:

$R_f < 0.2$	low	$0.5 < R_f < 1.0$	high
$0.2 < R_f < 0.5$	medium	$1.0 < R_f$	severe

For lignitic ashes, the fouling classification depends on the balance of calcium, magnesium, iron, and sodium oxides, when $CaO + MgO + Fe_2O_3 > 20\%$ by weight and

$Na_2O < 3$	low to medium
$3 < Na_2O < 6$	high
$Na_2O > 6$	severe

and when $CaO + MgO + Fe_2O_3 < 20\%$ by weight and

$Na_2O < 1.2$	low to medium
$1.2 < Na_2O < 3$	high
$Na_2O > 3$	severe

Slagging can be avoided by designs that maintain fireside metal temperatures below the range where the slag becomes tacky. For municipal refuse, this range is approximately 600° to 700°C. Alternatively, the boiler passes can be equipped with soot blowers using steam, compressed air jets, or metal shot to periodically dislodge adherent slag. Note, however, that cleaning the tube surface can also result in the removal of coatings that perform a protective role with respect to tube attack. Thus, following soot blower activation, corrosive wastage will be initiated, typically at very high rates, until a protective coating of slag and/or corrosion products is reestablished.

6

Fluid Flow Considerations in Incinerator Applications

Furnace fluid mechanics are complex. Flows in real systems are often driven by burner or air jets and by buoyancy. They interact in swirling, recirculating eddys, all while traversing complex geometrical sections. Yet a basic understanding of furnace flow processes gives great insight into the design of air jets and the anticipation of burner-chamber interactions, mixing problems, and other effects that are vital elements of the combustion process.

This chapter is divided into two sections: driven flows (those directly at the command of the designer) and induced flows (those arising from driven flows and those arising from buoyancy effects).

I. DRIVEN FLOW

The designer has within his or her control an effective and flexible flow control tool: jets of air or steam and/or, for gaseous, liquid, or pulverized fuels, jets of fuel or burner flames. These jetting flows serve to introduce fuel or the sensible heat of combustion products, introduce combustion or temperature control air, or, particularly for the steam jet, serve to inject energy to mix and/or direct the furnace gas flow.

A. Jet Flow

The following analysis of jet flow is drawn heavily from the portions of Refs. (21) and (65) dealing with the interrelationships between furnace flow and pollutant emissions.

1. Introduction

The gasification behavior of refuse beds and the need to induce mixing of furnace gases indicate that situations exist within incinerator furnaces where jet systems could be of assistance in realizing better burnout of combustible pollutants and in controlling furnace temperature distributions. A review of the design and operating characteristics of existing incineration systems (21) and discussions with incinerator designs suggest the need for better correlations supporting the design of these jet systems. As discussed below, the

fluctuating conditions of gas movement and composition within incinerator furnaces present a considerable challenge to those contemplating a detailed analysis of any device that interacts with the flow and combustion processes. Therefore, the analyses are necessarily somewhat simplified. However, the results will support the design of practical systems that will perform effectively and in accord with the expectations of the designers (65).

a. Use of Jets. Jets have been utilized for many years as an integral part of furnaces, boilers, and other combustion systems. In boilers fired with pulverized coal, for example, air jets are used to convey the fuel into the combustion chamber, to control the heat release patterns, and to supply secondary air for complete combustion. In processes with a burning fuel bed, properly placed air jets supply secondary air where needed above the fuel bed to complete combustion. Also, jets of air and/or steam are used to induce turbulence and to control temperature by dilution of furnace gases.

The important characteristics of jets that underlie all of these uses are as follows:

The controlled addition of *mass* to contribute to the oxidation process (air jets) or to serve as a thermal sink to maintain gas temperatures below levels where slagging, corrosion, or materials degradation may occur (air or steam jets).

The controlled addition of *linear* and/or *angular momentum* to promote mixing of the jet-conveyed gas with gases in the combustion chamber or to promote mixing of gases from different parts of the combustion chamber. In the latter case, high-pressure steam jets are often used to provide high-momentum fluxes with a minimum introduction of mass.

The basic challenge to the combustion system designer is to use these characteristics to maximum advantage in meeting his or her overall design goals.

b. General Characteristics of Jets. Because of the longstanding practical interest in the use of jets, a body of literature has been developed that quantitatively characterizes the nature of jet flow. Jets are conveniently categorized, according to flow regime (laminar or turbulent, supersonic or subsonic) and geometry (round or plane). Laminar jets occur only at very low jet velocities and are of no interest here. Supersonic jets, for describing high-pressure steam flows, are of potential interest but are not considered here. Plane jets, which issue from a slot finite in one dimension and effectively infinite in the other, are primarily of academic interest. We will, therefore, focus in this discussion on round, low subsonic, turbulent jets and return later to the fact that a row of closely spaced round jets behaves, to a degree, like a plane jet.

Other important parameters characterizing jet flow behavior include the relative densities of the jet and ambient fluids, the velocity of the ambient fluid relative to the jet velocity, and the degree to which the space into which the jet issues is confined by walls. Also, in situations where combustion can occur (jets of fuel into air as in burners and jets of air into fuel vapors, the so-called inverted flame), the initial temperature and combustible content of the jet and ambient fluid are of interest. All of these factors are important in the application of jets to incinerators, and their effects, singly and in combination, on jet characteristics are discussed. To set the stage for this discussion, we consider here the basic characteristics of jets issuing into an infinite atmosphere of quiescent fluid of the same density as the jet fluid.

The round, isothermal turbulent jet shows three characteristic regions (Fig. 1). Immediately adjacent to the nozzle mouth is the *mixing region*. Fluid leaves the nozzle

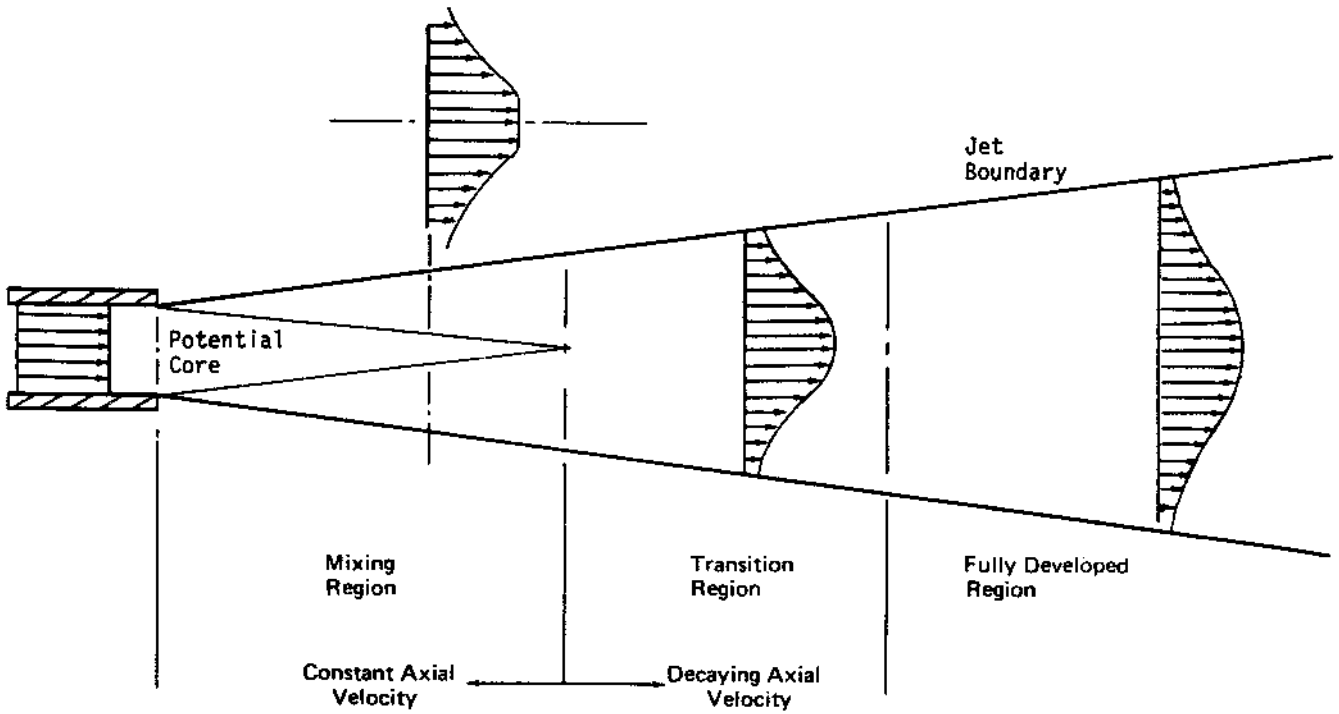


Figure 1 Regions of jet flow.

with an essentially flat velocity profile. The large velocity gradients between this *potential core* and the ambient fluid induce turbulence that causes ambient fluid to mix into the jet. The mixing results in momentum transfer between the jet and ambient fluids and progressively destroys the flat velocity profile. At a distance of about 4.5 jet nozzle diameters downstream, the influence of shear forces reaches the centerline of the jet and eliminates the potential core (13).

It is important to note that the "nozzle diameter" characterizing jet flow is not necessarily the physical dimension of the orifice from which the jet issues. If, for example, the jet issues from a sheet metal plenum, a flow contraction to about 60% of the open discharge area (the area of the vena contracta), characteristic of the flow past a sharp edged orifice, will define the effective nozzle diameter and the location of the effective jet discharge plane will be displaced about two-thirds of a diameter downstream of the orifice (the location of the vena contracta). If a relatively long (2–3 diameters) constant area section lies upstream of the discharge plane, the nozzle diameter may be taken as the orifice diameter. Attention should be given, therefore, to the geometry of the entire nozzle fluid delivery system in analysis of jet behavior.

In the region from 4.5 to about 8 diameters downstream, the transition of the flat entrance velocity profile to a fully developed profile is completed. Beyond this *transition region* the velocity profile retains a more or less constant shape relative to the velocity of the axis of the jet and is referred to as "self-preserving". This is the *fully developed* region.

Important jet characteristics include

- The centerline velocity and concentration changes with axial distance from the nozzle mouth
- The shape of the radial velocity and concentration profiles in the fully developed region
- The intensity of turbulence in the jet
- The rate of entrainment of ambient fluid into the jet

These characteristics are all interrelated: Turbulence generated by high-velocity gradients induces entrainment, which causes momentum and mass transfer between the jet and the ambient fluid. These characteristics are important in practice because they determine the quantitative effect of firing a jet into a combustion chamber. The axial decay of velocity establishes how far the jet penetrates into the chamber. The radial velocity distributions determine how large a volume is affected by the jet. The entrainment rates determine how effectively furnace gases are mixed along the jet path.

2. The Use of Jets for Combustion Control

Municipal incineration is an important source of combustible pollutants. Studies discussed in (21) showed that these pollutants would necessarily arise in the gasification zone of the grate and could possibly arise in the discharge zone.

These observations lead to the conclusion that systems are needed to provide air near the gasification zone and/or to induce high-intensity turbulence at strategic locations within the incinerator furnace. Although passive mixing systems, such as baffles or checkerwork, may have some value in the inducement of turbulence, they clearly are not useful in supplying air and are not alterable to cope with changes in the distribution of combustible pollutant release along the bed or throughout the chamber.

a. Jet Design for Incinerators—A Statement of the Problem. Combustible pollutants appear to be generated along the full length of a mass burning incinerator grate, although their discharge rate into the overfire volume is relatively low in the drying and ignition zones prior to the introduction of underfire air. From the standpoint of a $kg/hr\,m^2$ release rate, the gasification zone probably qualifies as the single most important source of carbon monoxide, soot, and hydrocarbons in the system. Carbon monoxide and coked ash material will be evolved in the region between the gasification zone and the burnout region. Overfire air is definitely required in the region of gasification and char burnout. Reduced undergrate air flows and turbulence inducement are required in the area over the discharge grate. Also, some means may be required to increase the general level of turbulence throughout the upper regions of the incinerator furnace.

In incinerators for liquid or gaseous wastes, mixing processes often depend on jet systems, both to introduce the waste and to ensure complete combustion. This latter concern is particularly important if the waste is a toxic material or includes pathogenic organisms.

The specification of jets for incinerator applications meeting the requirements listed above places great demands upon the designer. It is clear that the jet behavior should be known in a flow field where combustion, crossflow, and buoyancy effects are all potentially important, and, for some systems, the jets must operate over long distances. This latter characteristic arises from the shape of most continuous-feed mass burning incinerators, which tend to be long and narrow. Thus, jets directed over the discharge grate region that are expected to carry bed off-gases back toward the pyrolysis region must act over distances of 3 to 10 m (20 to 100 or more jet diameters). The location, number, and flow parameters appropriate to these jets should be consistent with the overall furnace geometry, should be easily maintained and operated, and should be controllable to the extent demanded by the fluctuations in refuse composition and burning characteristics. Particularly, when jets are used for secondary air addition, the jet design should add sufficient air to meet the oxygen requirement of the rising fuel vapors, yet not provide so much air as to overly cool the gases, thus quenching combustion. Also, the draft capabilities of the furnace must be considered in determining the amounts of air introduced.

b. Experience in Jet Application for Coal-Burning Systems. Overfire air systems have been used for over 100 years in coal-burning practice. In some respects, the combustion characteristics of coal burning on a grate are similar to those of refuse. Typically, however, coal ignites more readily (partly due to its lower moisture content), burns with more regularity and predictability, and, for overfeed or crossfeed situations, is typically burned in furnaces with grates that are short relative to those used in many continuous-feed refuse-burning incinerators. Therefore, although the problems are not identical, it is of value to review experience in coal-burning practice as an indication of the potential of jet systems for combustion control.

The use of controlled overfire air in industrial solid fuel combustion systems was stimulated by the desire to improve boiler efficiency through complete combustion of soot and carbon monoxide and to reduce smoke emissions. Although the historical pattern of technological development of overfire air systems is unclear, Stern (66) mentions that patents and active marketing of steam-air jets, primarily for smoke control, began in 1880. Quantitative appreciation of the benefits of smokeless combustion on overall fuel economy was widely argued until documented by Switzer (67) in 1910. Switzer's work, carried out at the University of Tennessee, involved measurements of jet system steam consumption,

smoke intensity, and boiler efficiency on a hand-fired return-tubular boiler fired with bituminous coal. The results of his tests showed an increase in thermal efficiency from 52.6% to 62.1%, an increase in the effective range of the boiler from 80% to 105% of its rated capacity before smoking occurred, and a steam consumption for the overfire jet system of only 4.6% of the total steam raised.

Recognition of the importance of overfire air and mixing stimulated considerable research in the first decade of the 1900s. Some of the more completely documented and detailed laboratory and field data were produced by the Bureau of Mines, which was conducting "investigations to determine how fuels belonging to or for the use of the United States Government can be utilized with greater efficiency." Kreisinger et al. (68) studied the combustion behavior of several coals in a special research furnace under a variety of combustion air and firing rate conditions. Their work showed a strong relationship between the burnedness of the flue gas, the properties of the coal, and the size of the combustion space (Fig. 2). Their results were interpreted in agreement with prior suggestions of Breckenridge (69), to result from differences in the emission of volatile between coal varieties and the rate-limiting effects of inadequate mixing. Their correlating parameter, which they called the "undeveloped heat of combustible gases," represented the remaining heat of combustion of the flue gases. Relative to Fig. 2 and the composition data in Table 1 it would appear that the volume requirements for complete burnout in refuse incineration may be considerably in excess of those acceptable in coal-fired combustors. Quantitative extrapolation from their data to incinerators, however, would be highly speculative. Unfortunately, within the scope of the USBM experimental program, generalized design guides for the flow rate and locations appropriate for overfire air systems were not developed.

Some of the earliest test work directly aimed at finding the benefits of overfire air in utility combustion systems was conducted in 1926 by Grunert (70) on forced draft chain grate stokers at the Commonwealth Edison Company in Chicago. Grunert's data showed that overfire jets discharging over the ignition zone could reduce the carbon monoxide levels at the entrance to the first pass of boiler tubes from an average value of 1% to essentially zero. Also, the gas temperature and composition profile could be made considerably more uniform. Of importance to fuel economy, it was found that although additional air was introduced through the overfire air jets, the total combustion air was susceptible to reduction. Similar work in Milwaukee reported by Drewry (71) also showed performance improvement (an increase of 7.2% in boiler efficiency), smoke elimination, and complete burnout of combustibles within the firebox. Once again, however, design correlations generally applicable to the coal-burning industry were not presented.

Major contributions to the overfire jet design art were published in the mid-1930s. Of particular importance were reports on a number of meticulous test programs carried out in Germany, perhaps typified by the work of Mayer (72). Although still not providing generalized design criteria, Mayer made gas composition traverses (45 points) within a traveling grate stoker furnace firing low-volatile bituminous coal. His results are shown in Fig. 3.

As a measure of the completeness of combustion in the overfire space, Mayer determined the heating value of the gases ($kcal/m^3$) as calculated from the complete gas analysis. Without overfire air, as seen in Fig. 3(a), strata of combustible gases rise into the combustion chamber and persist as the gases leave the combustion space and enter the first boiler pass. This is indicated by the zero heating value curve, which is not closed. Figure 3(b) shows the effect of medium-pressure overfire air jets. It can be seen that combustion is

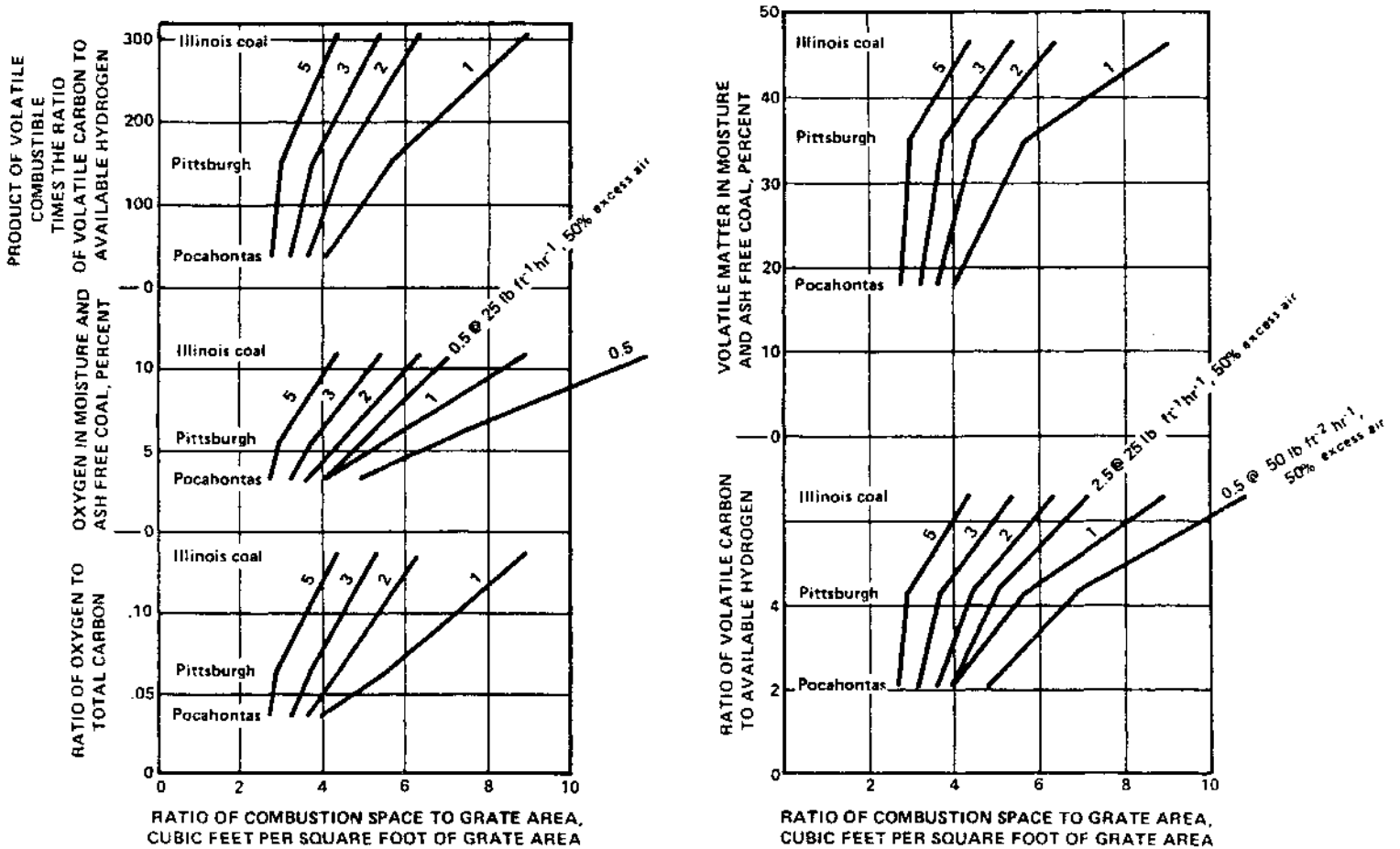


Figure 2 Relation between coal characteristics and size of combustion space required in USBM test furnace at combustion rate of 50 lb hr^{-1} ft^{-2} and 50% excess air. Numbers on graphs are the percentage of the heat of combustion of the original coal which appears as unreleased heat of combustion in the furnace gases. [From (68).]

Table 1 Chemical Characteristics of Coal and Refuse[a]

Item	Characteristics[b]	Pocahontas coal	Pittsburgh coal	Illinois coal	Refuse
1	Volatile matter	18.05	34.77	46.52	88.02
2	Fixed carbon	81.95	65.23	53.48	11.99
3	Total carbon	90.50	85.7	79.7	50.22
4	Volatile carbon (item 3 minus item 2)	8.55	20.47	26.22	38.22
5	Available hydrogen	3.96	4.70	3.96	1.57
6	Ratio volatile C to available H_2	2.16	4.35	6.60	24.34
7	Oxygen	3.32	5.59	10.93	41.60
8	Nitrogen	1.19	1.73	1.70	1.27
9	Percentage of moisture accompanying 100% of MAF coal or refuse	2.53	2.88	22.07	55.19
10	Product of items 1 and 6	39	151	307	2142
11	Ratio of oxygen to total carbon	0.0367	0.0652	0.137	0.828
12	Total moisture in furnace per kilogram of coal or refuse reduced to MAF basis (kilogram)	0.409	0.501	0.700	1.161

[a] Data on coal are from Ref. 68; data on refuse are from Ref. 21.
[b] Items 1 through 8 and 11: percent on moisture and ash-free basis (MAF).

improved, yet some fraction of the combustible still enters the boiler passes. Figure 3(c) shows the effect of further increases in the overfire air plenum pressure. Under these latter conditions, combustion is complete within the furnace volume. For these tests, Mayer employed jets directed toward the bed just beyond the ignition arch.

Also in the 1930s, developments in fluid mechanics by Prandtl and others provided mathematical and experimental correlation on the behavior of jets. Application of this

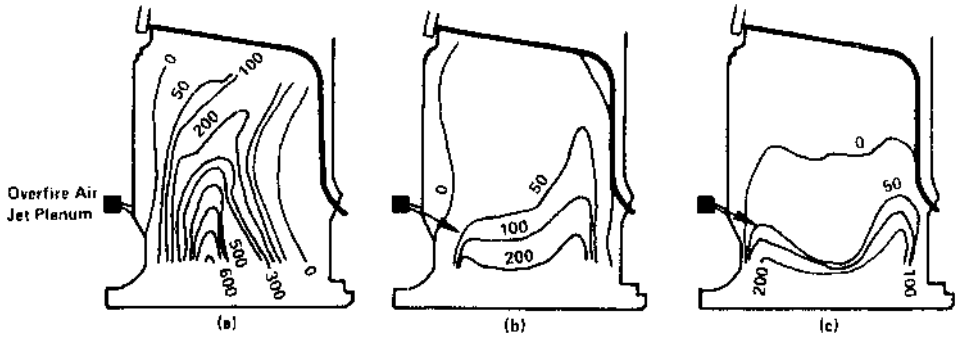


Figure 3 Lines of equal heating value (kcal per standard cubic meter) of flue gas firing low-volatile bituminous coal at a rate of 137 kg m^2 hr^{-1}: (a) No overfire air, (b) overfire air pressure 13 mm Hg (7 in. H_2O), (c) overfire air pressure 18.7 mm Hg (10 in. H_2O). [From (72).]

understanding to furnace situations was presented in some detail by Davis (73). His correlations, although based on greatly simplified assumptions, were of considerable interest to furnace designers at that time. As an example of the applicability of his work, Davis explored the trajectories anticipated for jets discharging over coal fires and compared his calculated trajectories with data by Robey and Harlow (74) on flame shape in a furnace at various levels of overfire air. The results of this comparison are shown in Fig. 4. Although general agreement is shown between the jet trajectory and the flame patterns, correlation of the meaning of these parameters with completeness of combustion is unclear and not supported by Robey and Harlow's data. The results do give confidence,

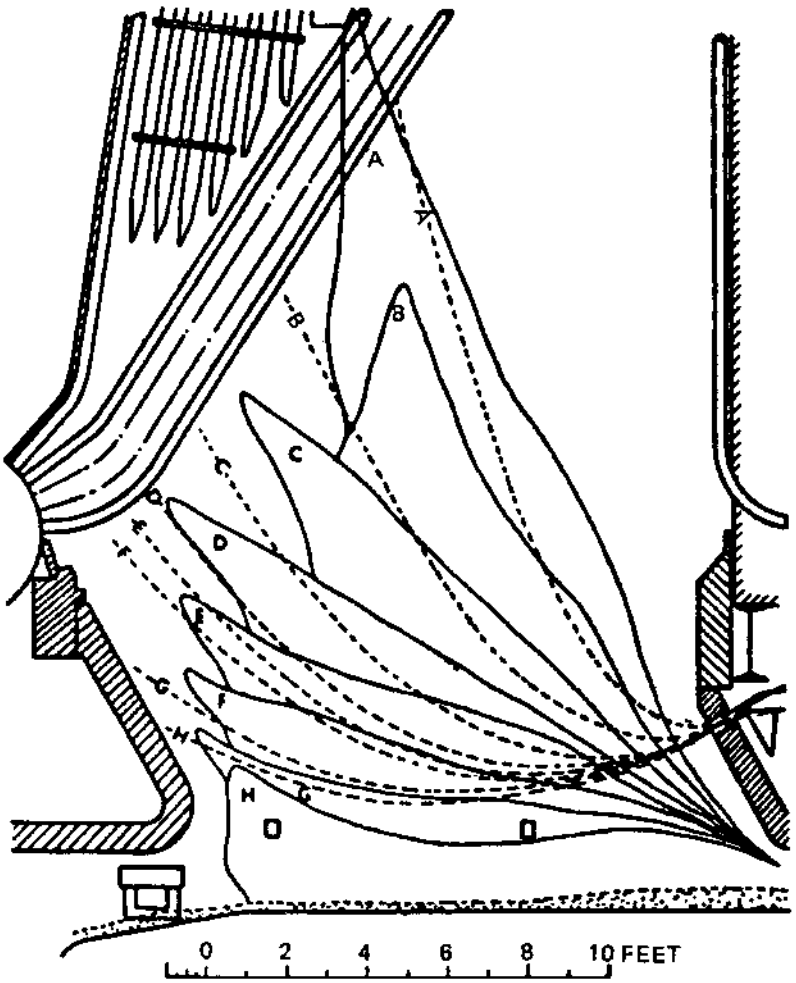


Figure 4 Comparison of observed flame contours and calculated trajectories of overfire jets. Percentage of overfire air at the following points: A, 565; B, 10.5; C, 16.6; D, 20.0; E, 21.4; F, 22.8; G, 26.8; H, 28.8. [From (73).]

however, that jet trajectories can be calculated under a variety of furnace conditions to produce reasonable estimates of behavior and thus permit avoidance of impingement of the jet in the bed.

Work on the applications and advantages of overfire air continued through World War II, particularly with reference to avoidance of smoke in naval vessels to preclude easy identification and submarine attack (66). However, the wide introduction of pulverized coal firing in electric utility boilers and the rapid encroachment of oil and gas into the domestic commercial and industrial fuel markets rapidly decreased the incentive for continued research into overfire jet systems for application in stoker-fired combustors. Indeed, the number of literature references on this topic falls off rapidly after 1945.

In summary, during the 70 or more years during which overfire air jet application to stoker-fired systems was of significant importance, no generalized design criteria of broad applicability had been developed. An art had arisen regarding the use of overfire jets, typically over the ignition arch and in the sidewalls of traveling grate stokers burning bituminous coal. Sufficient jet design technology had been developed to allow specification of jets that would adequately penetrate the upflow of gases arising from the bed and that served to smooth the temperature and gas composition profiles at the entrance to the boiler passes above. Even in 1951, however, the comment was made by Gumz (75), a well-recognized contributor to combustion technology, that "the number of nozzles, their location and direction are the most disputed factors in the use of overfire air jets."

3. Jet Dynamics and Design Guidelines

In 1880, the first patents were issued for steam-air jet devices to supply overfire air and induce turbulence in hand-fired furnaces burning bituminous coal. The development and marketing of these proprietary jet systems reflected a need for improvements in combustion efficiency and for means to reduce smoke emissions. Since that time, a number of refinements in the physical arrangements and design characteristics of overfire jets have been offered to the technical community. However, few instances can be found where comprehensive design correlations are presented in the literature. In the great majority of cases (e.g., 76–78), the technical content of the papers is limited to documentation of improvements in performance (particularly with reference to smoke abatement) resulting from the use of specific arrays of overfire jets in a specific combustor. Most published design information deals with such topics as the pumping efficiency or the estimation of steam consumption in steam ejectors. One can find few instances where attempts were made to couple an analysis of jet behavior to an analysis of furnace behavior.

To some extent, the tendency of early workers to report only empirical results reflected the limitations of theoretical understanding or mathematical treatment techniques of their time. Also, the complexity of furnace dynamics presents a considerable challenge to the analyst, and thus generalization is difficult. It is noteworthy, for example, that the rigorous mathematical treatment of the behavior of two-dimensional plane jets has only recently been solved in detail (79). Solution of this problem required the use of high-speed computers and complex numerical techniques. Efforts at a similar analysis of the asymmetrical round jet are now in process, but solutions require very large amounts of core storage and computation time.

Ideally, the design basis used in overfire air jet designs for incinerator applications should recognize the effects of buoyancy, crossflow, and combustion as they are experienced in real incineration systems. The work of Davis (80) and Ivanov (81),

though concerned with coal-fired systems, produced correlations resting heavily on experimental results that provide a starting point for a design methodology.

a. Round Isothermal Jets. The behavior of circular jets discharging into a quiescent, nonreacting environment at a temperature similar to that of the jet fluid provides the starting point in any review of jet dynamics. Indeed, the behavior of jets under such conditions has often been the primary guideline in the design of overfire jets for incinerator applications (82). Because of the relatively simple nature of jet structure under such conditions, this configuration is perhaps the most studied, both analytically and experimentally, and good correlations are available describing jet trajectory, velocity, entrainment, turbulence levels, and the like.

Correlation of data taken by many experimenters leads to the following expressions for the axial decay of centerline velocity and concentration (13):

$$\frac{\bar{u}_m}{\bar{u}_0} = 6.3\left(\frac{\rho_0}{\rho_a}\right)^{1/2}\frac{d_0}{(x+0.6d_0)} \tag{1}$$

$$\frac{\bar{c}_m}{\bar{c}_0} = 5.0\left(\frac{\rho_0}{\rho_a}\right)^{1/2}\frac{d_0}{(x+0.8d_0)} \tag{2}$$

where $\bar{u}_m$ and $\bar{c}_m$ are the time-averaged centerline velocity and concentration of jet fluid at distance x downstream from the nozzle; $\bar{u}_0$ and $\bar{c}_0$ are the comparable parameters at the nozzle; and d_0 is the nozzle diameter. ρ_0 and ρ_a are the densities of the jet and ambient fluids, respectively. These equations apply *only* in the fully developed region (i.e., $x/d_0 > 8$) and are confirmed by other investigators (e.g., Ref. 83).

The experimentally measured *radial velocity* and *concentration profiles* in the fully developed region can be represented by either Gaussian or cosine functions. The Gaussian representations (13) are

$$\frac{\bar{u}_{x,r}}{\bar{u}_m} = \exp\left[-96\left(\frac{r}{x}\right)^2\right] \tag{3}$$

$$\frac{\bar{c}_{x,r}}{\bar{c}_m} = \exp\left[-57.5\left(\frac{r}{x}\right)^2\right] \tag{4}$$

where $\bar{u}_{x,r}$ and $\bar{c}_{x,r}$ are the time-averaged velocity and concentration at distance x downstream and distance r from the jet centerline.

The spread of the jet is defined in terms of the half-angle to the half-velocity point (i.e., the angle subtended by the jet centerline and the line from the centerline at the nozzle mouth to the point where the velocity is one-half of the centerline velocity). This angle is independent of distance from the nozzle mouth in the fully developed region, a consequence of the self-preserving nature of the velocity profile. The half-angle of the half-velocity point is approximately 4.85°, based on concentration in the same way, the half-angle is 6.2° (13).

The turbulent intensity of the jet is defined in terms of u' and v', the r.m.s. fluctuating velocity components in axial and radial directions, respectively. Data of Corrsin (84) show that the intensity ratio $u'/\bar{u}_m$ and $v'/\bar{u}_m$ depend on the ratio r/x. At $x/d_0 = 20$, each velocity ratio varies from about 27% at the centerline to about 5% to 7% at $r/x = 0.16$.

Ricou and Spaulding (85) measured entrainment rates and determined that the mass flow rate (m_x) in the jet is linearly related to x according to

$$\frac{m_x}{m_0} = 0.32\left(\frac{\rho_a}{\rho_0}\right)^{1/2}\left(\frac{x}{d_0}\right) \tag{5}$$

This relationship holds for all values of nozzle Reynolds number greater than 2.5×10^4 and for $x/d_0 > 6$. At $x/d_0 < 6$, the entrainment rate per unit jet length is lower, increasing progressively with distance until it stabilizes at the constant value corresponding to Eq. (5). Entrainment is an inherent characteristic of jet flows. Equation (5) indicates that the magnitude of the entrained flow exceeds the nozzle flow in only a few nozzle diameters. The importance of the entrainment phenomena is felt most strongly in ducted flows (e.g., an axially mounted burner discharging into a cylindrical chamber) when an insufficiency of fluid relative to the entrainment requirement leads to significant recirculation flows (see Section III.B.1).

The relationships describing the behavior of isothermal jets entering a quiescent fluid are well documented and form the basis for design criteria relative to the use of jets in incinerators. In this application, however, the effects of crossflow of the ambient fluid and density differences between the jet and ambient fluids are important. These effects are less well documented, and their inclusion in the design criteria poses some difficult problems. These matters are dealt with below.

b. Buoyancy Effects. When the jet and ambient fluids are of different density, the buoyant forces acting on the jet can cause deflections of the jet trajectory. This effect is potentially important in incinerator applications since the air introduced by the jets will be much colder than the furnace gases and hence of higher density. From an incinerator design and operating standpoint, this could be critical: Jets could "sink" from an anticipated flow trajectory passing above the bed to one causing entrainment of particulate from the bed or causing overheating of the grates with a "blowpipe" effect.

Relatively little experimental or theoretical work has been done to characterize jet performance under these conditions. Figure 5 shows the geometry of the system considered and defines symbols used in the discussion. A jet of density ρ_0 issues at a velocity of u_0 from a circular nozzle of diameter d_0. The ambient fluid is at rest of density ρ_a.

Abramovich (83) analyzed the trajectory of a heated jet issuing into a cold ambient fluid and compared his theoretical result with the data of Syrkin and Lyakhovskiy (86). The resulting expression is

$$\left(\frac{y}{d_0}\right) = 0.052\left[\frac{gd_0}{\overline{u}_0^2}\right]\frac{(\rho_a - \rho_0)}{\rho_0}\left(\frac{x}{d_0}\right)^3 \tag{6}$$

Figure 6 shows a comparison of this expression with experimental data in which the ratio $(\rho_a - \rho_0)/\rho_0$ was varied in the approximate range of 0.2 to 0.8. Equation (6) generally underestimates the buoyancy-induced deflection of the jet.

Field et al. (13) considered the behavior of a buoyant jet and obtained the expression

$$\frac{y}{d_0} = \left(\frac{x}{d_0}\right)\tan\alpha_0 + \frac{0.047}{\cos\alpha_0}\left(\frac{gd_0}{\overline{u}_0^2}\right)\left(\frac{\rho_a - \rho_0}{\rho_0}\right)\left(\frac{\rho_a}{\rho_0}\right)^{1/2}\left(\frac{x}{d_0}\right)^3 \tag{7a}$$

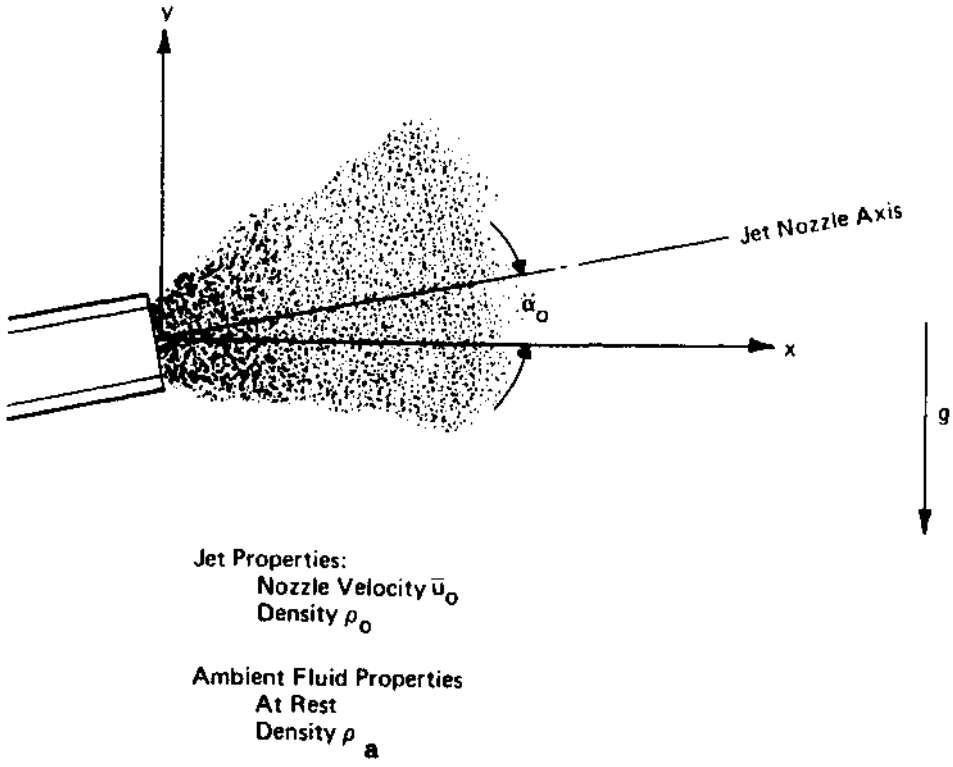


Figure 5 Schematic of jet flow.

For a jet injected normal to the gravity field ($\alpha_0 = 0$), Eq. (7a) reduces to

$$\frac{y}{d_0} = 0.047\left(\frac{gd_0}{\bar{u}_0^2}\right)\left(\frac{\rho_a - \rho_0}{\rho_0}\right)\left(\frac{\rho_a}{\rho_0}\right)^{1/2}\left(\frac{x}{d_0}\right)^3 \tag{7b}$$

which differs from Eq. (6) in the value of the leading constant (0.047 as opposed to 0.052) and in the presence of the term $(\rho_a/\rho_0)^{1/2}$. In incinerator applications, where the jet and ambient temperatures are approximately 40°C (313°K) and 1430°C (1703°K), respectively, this term has the value of

$$\begin{aligned}\frac{\rho_a}{\rho_0} &= \left(\frac{T_0}{T_a}\right)^{1/2} \\ &= (313/1703)^{0.5} \\ &= 0.43\end{aligned} \tag{8}$$

The deflections predicted by the two equations will differ by a factor of 2.

Figure 6 compares Eq. (7b) with the data of Syrkin and Lyakhovskiy (86). In these data, the term $(\rho_a/\rho_0)^{1/2}$ varies from about 1.1 to 1.4. The inclusion of the term $(\rho_a/\rho_0)^{1/2}$ results in better agreement with the data, particularly at the larger values of x/d_0.

c. Crossflow Effects. The need to understand the behavior of a jet issuing into a crossflow normal to the jet axis arises in the analysis of furnaces, plume dispersion from chimneys,

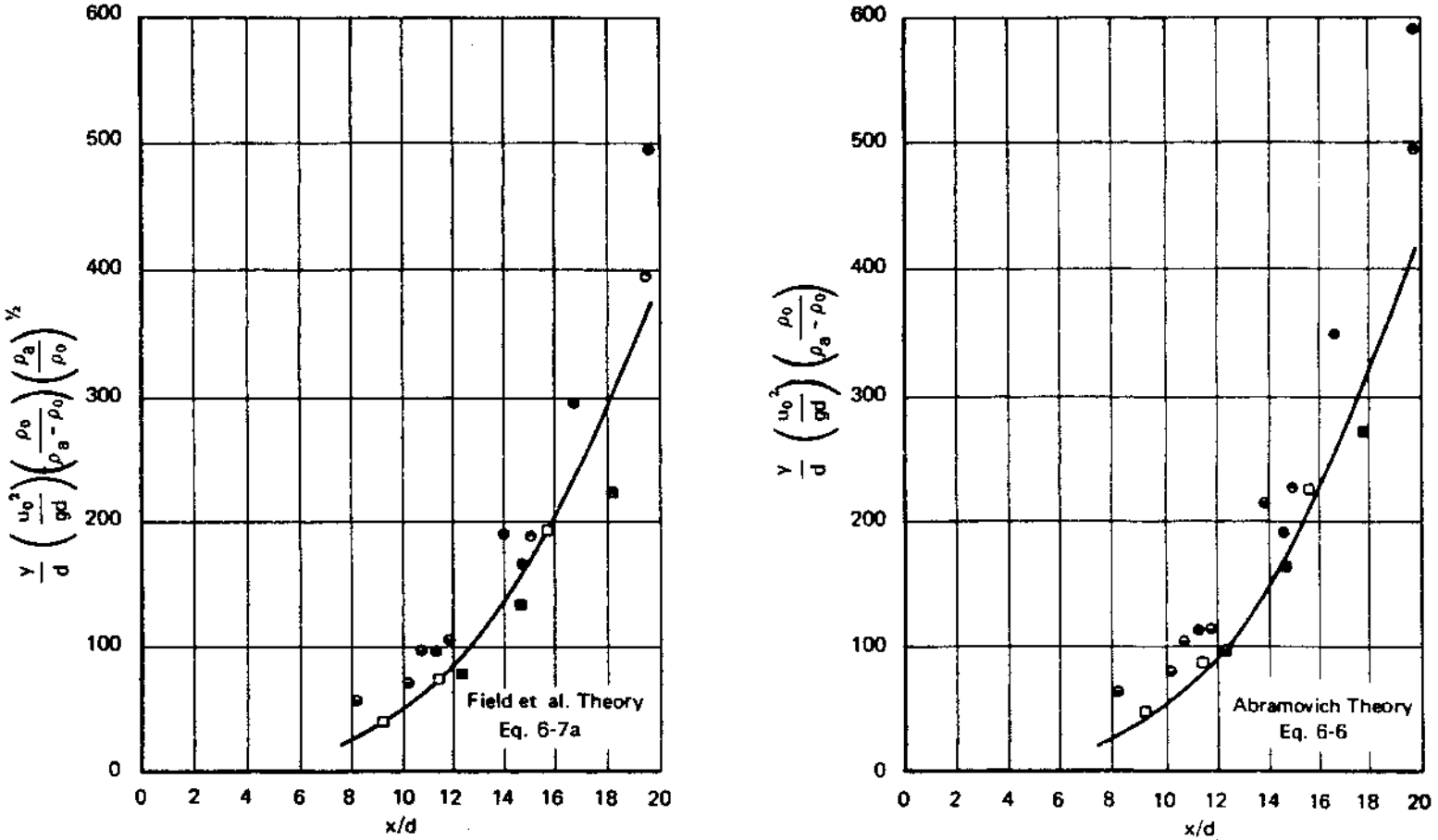


Figure 6 Comparison of the predictions of Abramovich and Field et al. with the data of Syrkin and Lyakhousky on buoyant jet behavior. [From (13, 83, and 86).]

and elsewhere. The deflection of the jet by the crossflow has been studied extensively, both experimentally and analytically, although most workers have limited their work to descriptions of centerline trajectory and gross entrainment rates. A review of the literature (55) indicated that no analysis has been carried out, either experimentally or theoretically, that characterizes the radial distribution of velocity or concentration in detail.

With crossflow, the interaction of the flow deflects the jet and alters the cross-sectional shape of the jet. Figure 7 is a diagram of the jet cross-section several nozzle diameters along the flow path. The originally circular cross-section has been distorted into a horseshoe shape by the shearing action of the external flow around the jet, and internal patterns of circulation have been set up. Measurements in the external flow around the jet show a decreased pressure downstream of the jet, recirculation of the external fluid, and a process leading to the periodic shedding of vortices into the wake of the jet. These phenomena are similar to those observed in the wake of a solid cylinder exposed to crossflow.

Dimensional analysis considerations suggest that the coordinates of the jet axis $(x/d_0, y/d_0)$ should depend on the ratio of momentum fluxes in the external and jet flows

$$M = \frac{\rho_a u_1^2}{\rho_0 u_0^2} \tag{9}$$

and the Reynolds number.

$$N_{\mathrm{Re}} = \frac{\rho_0 \bar{u}_0 d_0}{\mu_0} \tag{10}$$

For turbulent jets in the Reynolds number range above 10^4, correlation of experimental data suggests that the Reynolds number effect is negligible and the momentum ratio is the predominant variable characterizing the flow.

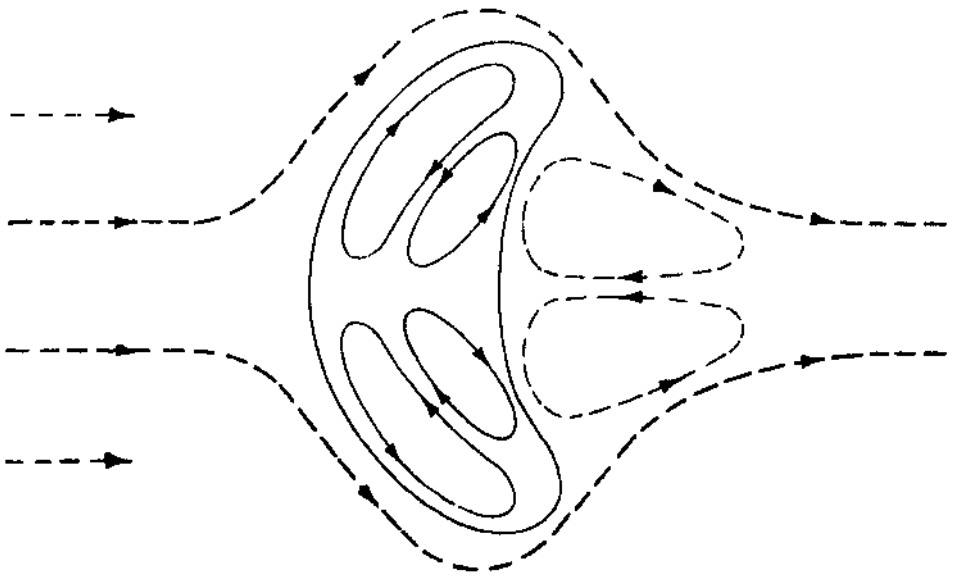


Figure 7 Jet cross-section and circulation patterns for round jets in crossflow.

In terms of the geometry illustrated in Fig. 8, the following expressions for computing the axial trajectory of a single jet have been reported. The jet axis is taken to be the locus of maximum velocity (13, 81, 83, 87–89).

$$\frac{y}{d_0} = 1.0(M)^{1.12}\left(\frac{x}{d_0}\right)^{2.64} \qquad 0 < M \leq 0.023, \quad \alpha_0 = 0 \tag{11}$$

$$\frac{y}{d_0} = M\left(\frac{x}{d_0}\right)^{2.55} + (1+M)(\tan\alpha_0)\left(\frac{x}{d_0}\right) \qquad 0.046 \leq M \leq 0.5 \tag{12}$$

$$\frac{y}{d_0} = M^{1.3}\left(\frac{x}{d_0}\right)^{3} + (\tan\alpha_0)\left(\frac{x}{d_0}\right) \qquad 0.001 \leq M \leq 0.8 \tag{13}$$

$$\frac{y-y^+}{d_0} = 5.5M^{1.175}\left(\frac{x-x^+}{d_0}\right)^{2.175} \qquad 0.01 \leq M \leq 0.028, \quad \alpha_0 = 0 \tag{14}$$

where y^+/d_0 and x^+/d_0 denote the end of a zone of establishment. Values vary somewhat with M but are of the order of 1 or less.

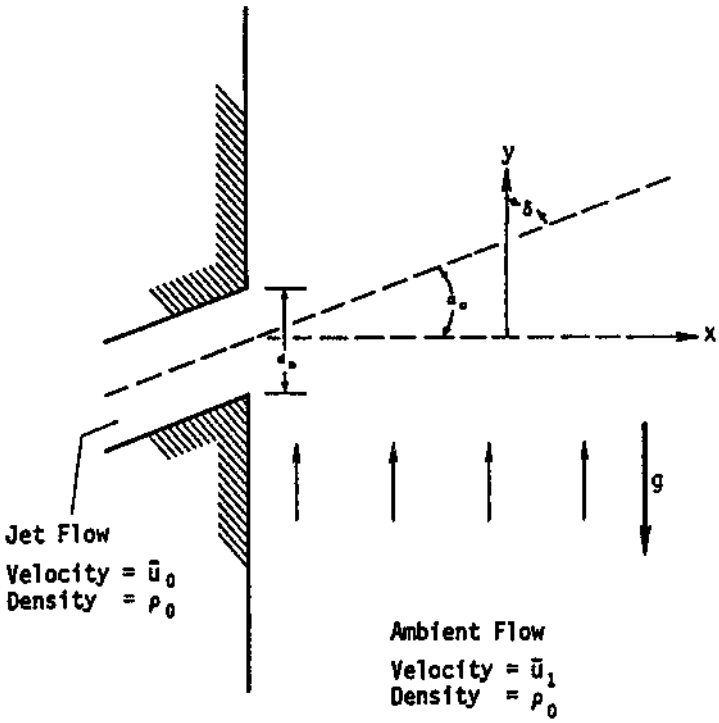


Figure 8 Coordinate system for round jet in crossflow.

Abramovich (83) derived an analytical relation of the form

$$\frac{x}{d_0} = \sqrt{\frac{39}{MC_x}} \ln\left[\frac{10 + y/d_0 + [(y/d_0)^2 + 20(y/d_0) + (7/MC_x)\tan^2\ \alpha_0]^{1/2}}{10 + \sqrt{(7/MC_x)}\tan\alpha_0}\right] \tag{15}$$

where C_x is an effective drag coefficient relating drag on the jet to the momentum flux in the external flow and has a value (dimensionless) of approximately 3.

A simplified treatment of jet behavior in crossflow with temperature effects was presented by Davis (80) in 1937. The crossflow effect was introduced by the assumption that the jet rapidly acquired a velocity component equal to the crossflow velocity. The jet was then seen to follow a path corresponding to vector addition of the crossflow velocity to the jet centerline velocity [the latter being calculated using a simplified velocity decay law by Tollmien (90)]. Temperature effects were introduced as being reflected in increases in jet velocity due to expansion of the cold nozzle fluid (initially at T_0) after mixing with the hot furnace gases (at T_a). Davis' final equation for the deflection (y) is given by

$$y = \frac{u_1 x(x + 4d_0\cos\alpha_0)}{2a_1 d_0 \bar{u}_0 \cos^2\alpha_0}\left(\frac{T_0}{T_a}\right)^{1/3} + x\tan\alpha_0 \tag{16}$$

where a_1 is a constant depending on nozzle geometry (1.68 for round jets and 3.15 for long, narrow plane jets). The many rough assumptions in Davis' analysis (some of which have been shown to be in error) would indicate that its use should be discouraged. Comparison of calculated trajectories with observed flame contours (Fig. 4) suggests it may have some general value. Interpretation of the meaning of the general agreement between calculated jet trajectory and flame contour as shown in Fig. 4 is uncertain, however, and use of the Davis equation in incinerator applications is questionable.

Patrick (87) reported the trajectory of the jet axis (defined by the maximum concentration) to be

$$\frac{y}{d_0} = 1.0M^{1.25}\left(\frac{x}{d_0}\right)^{2.94} \qquad (\alpha_0 = 0) \tag{17}$$

Figure 9 shows a plot of the velocity axis [Eq. (12)] and the concentration axis [Eq. (17)] for a value of $M = 0.05$. The concentration axis shows a larger deflection than does the velocity axis. This is probably due, in part, to the asymmetry of the external flow around the partially deflected jet. Also, recent calculations by Tatom (79) for plane jets suggest that under crossflow conditions, streamlines of ambient fluid can be expected to cross the jet velocity axis.

For our purposes, we are interested in jets that penetrate reasonably far into the crossflow (i.e., those that have a relatively high velocity relative to the crossflow). The empirical equations of Patrick (87) [Eq. (11)] and Ivanov (81) [Eq. (13)] were developed from data that satisfy this condition. Figures 10 and 11 show comparisons of these two equations for values of M of 0.001 ($\bar{u}_0/u_1 = 30$) and 0.01 ($\bar{u}_0/u_1 = 10$). Ivanov's expression predicts higher deflections at large x/d_0 (particularly at $M = 0.01$).

Ivanov (81) also investigated the effect of the spacing between jets (s) in a linear array on jet trajectory. He measured the trajectories of jets under conditions where $M = 0.01$ for $s = 16$, 8, and 4 jet diameters. His results are shown in Fig. 12 along with the trajectory of a single jet (infinite spacing). The data show that reducing the spacing between jets causes greater deflection of the jets. As spacing is reduced, the jets tend to merge into a curtain. The blocking effect of the curtain impedes the flow of external

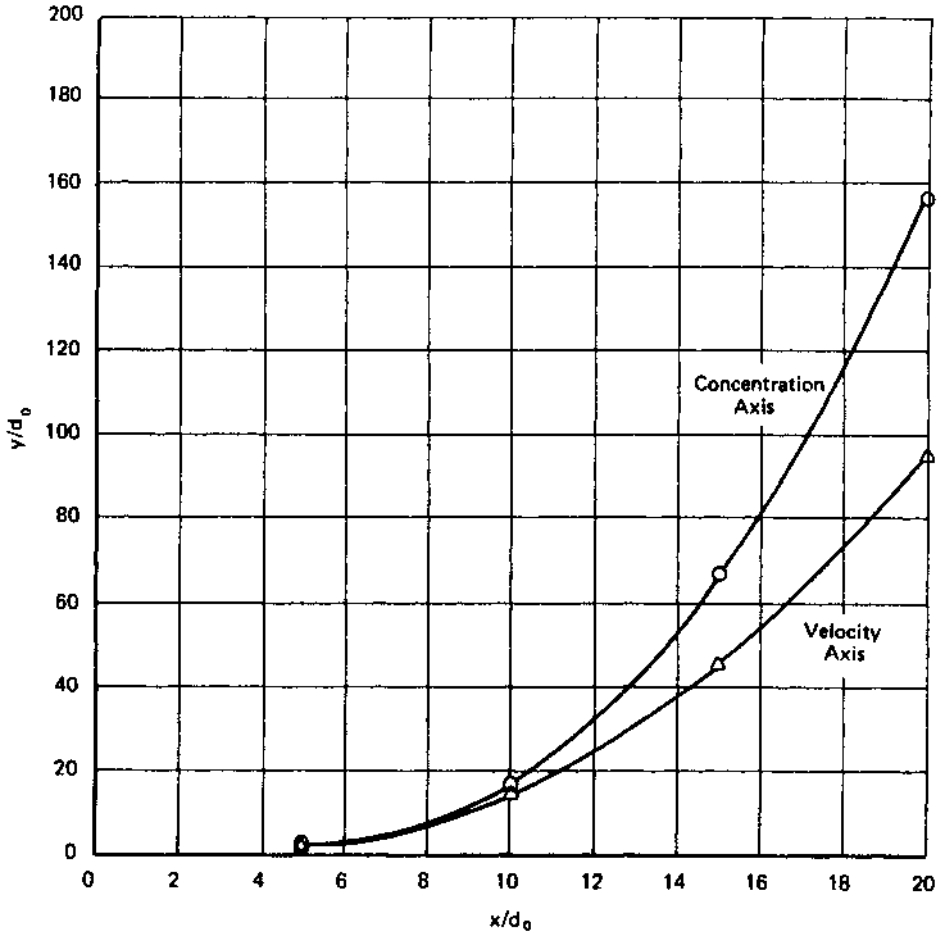


Figure 9 Trajectory of concentration and velocity axes for jets in crossflow, $M = 0.05$. [Data from (87).]

fluid around the jets and increases the effective deflecting force of the external fluid. The increase in deflection is most notable as s/d_0 is reduced from 16 to 8. Above $s/d_0 = 16$, the merging of the jets apparently occurs sufficiently far from the nozzle mouth to have little effect on the external flow. At $s/d_0 = 8$, the jet merge apparently takes place sufficiently close to the nozzle mouth that further reduction in spacing has little added effect.

Earlier data [Abramovich (83)] on water jets colored with dye issuing into a confined, crossflowing stream were correlated in terms of jet penetration distance. The penetration distance L_j was defined as the distance between the axis of the jet moving parallel to the flow and the plane containing the nozzle mouth. The axis was defined as being equidistant from the visible boundaries of the dyed jet. The resulting correlations was

$$\frac{L_j}{d_0} = k\frac{\bar{u}_0}{u_1} \tag{18}$$

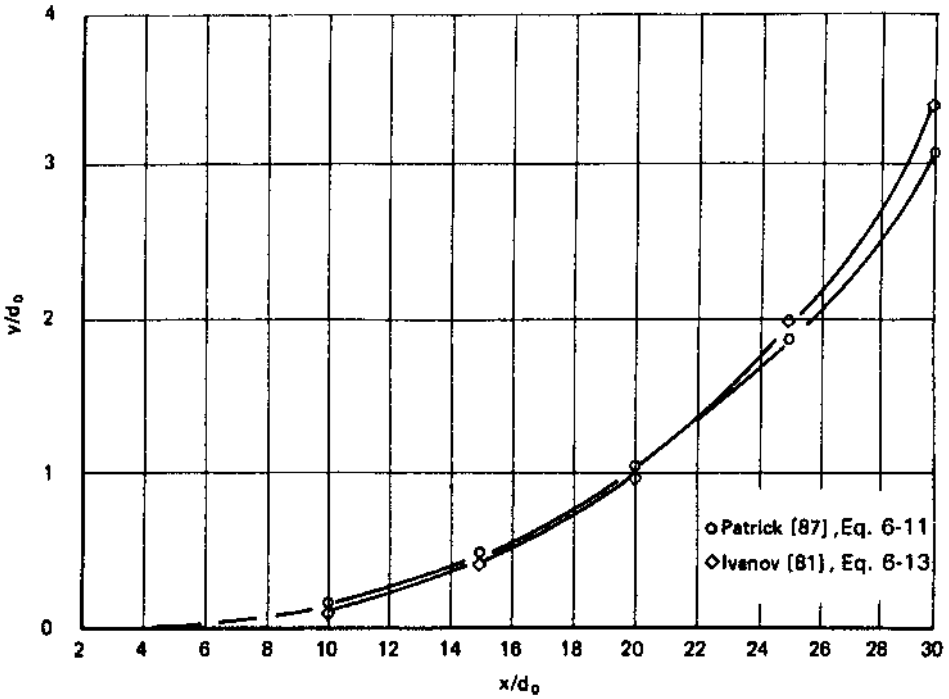


Figure 10 Comparison of trajectories at $M = 0.001$ ($u_0/u_1 = 31.6$) for jets in crossflow.

where k is a coefficient depending on the angle of attack and the shape of the nozzle. Defining the angle of attack δ as the angle between the jet and the crossflow velocity vectors and equal to $(90 - \alpha_0)$ in the terminology shown in Fig. 8, the recommended values of k are presented in Table 2.

Figure 13 shows a comparison of Ivanov's correlation [Eq. (13)] with the jet penetration correlation [Eq. (18)] for $M = 0.001$ and $M = 0.01$.

Equation (18) predicts a smaller jet penetration than does Eq. (13). There are two possible explanations for this discrepancy.

The data on which Eq. (13) was based do not extend to large values of x/d_0, and extrapolation of the data may be in error; and

The data on which Eq. (18) was based were taken in a confined crossflow in which the lateral dimension (normal to both the jet axis and the crossflow) was sufficiently small to interfere with normal jet spreading. The jet effectively filled the cross-section in the lateral dimension, behaving like a series of jets at low spacing.

Ivanov's data (Fig. 12) show that penetration is reduced at lower spacing. The penetration given in Eq. (13) for $M = 0.01$ was reduced by 25% (see dotted trajectory marked $s/d_0 = 4$, $M = 0.01$ in Fig. 13). Agreement between this adjusted trajectory and the penetration given by Eq. (18) is better.

d. Buoyancy and Crossflow. When a cold air jet is introduced into a cross-flowing combustion chamber, both buoyancy and crossflow forces act simultaneously on the jet.

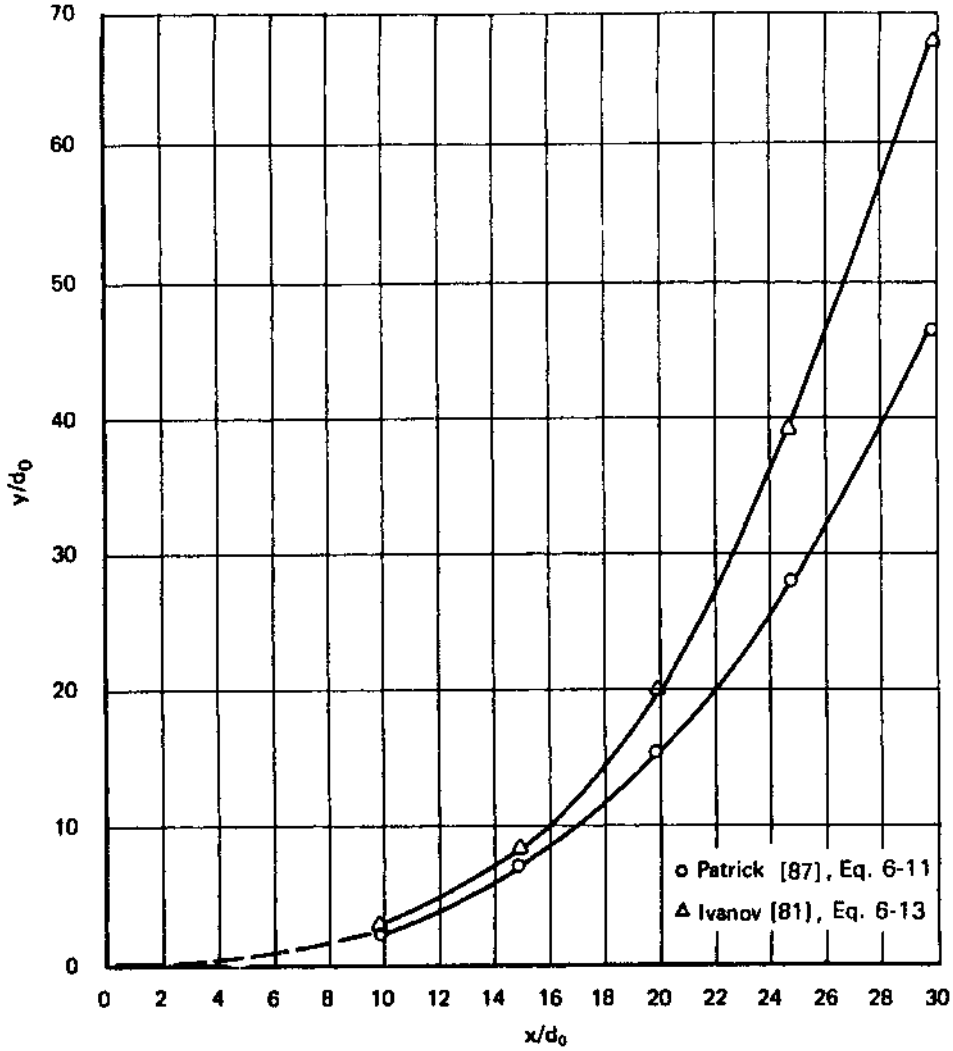


Figure 11 Comparison of trajectories at $M = 0.01$ ($u_0/u_1 = 10$) for jets in crossflow.

Abramovich (83) reports the results of experiments conducted by injecting cold jets into a hot crossflow. Temperature ratios of as much as 3 to 1 were used (corresponding to the jet fluid having a density three times that of the crossflowing fluid), with the values of M in the range of 0.045 to 0.5. The normal crossflow trajectory equation correlated the data

Table 2 Nozzle Coefficients

For $\delta = 90^\circ$ for round and square nozzles	$k = 1.5$
For $\delta = 90^\circ$ for rectangular nozzles	$k = 1.8$
For $\delta = 120^\circ$ for all nozzles	$k = 1.85$

Source: From (83).

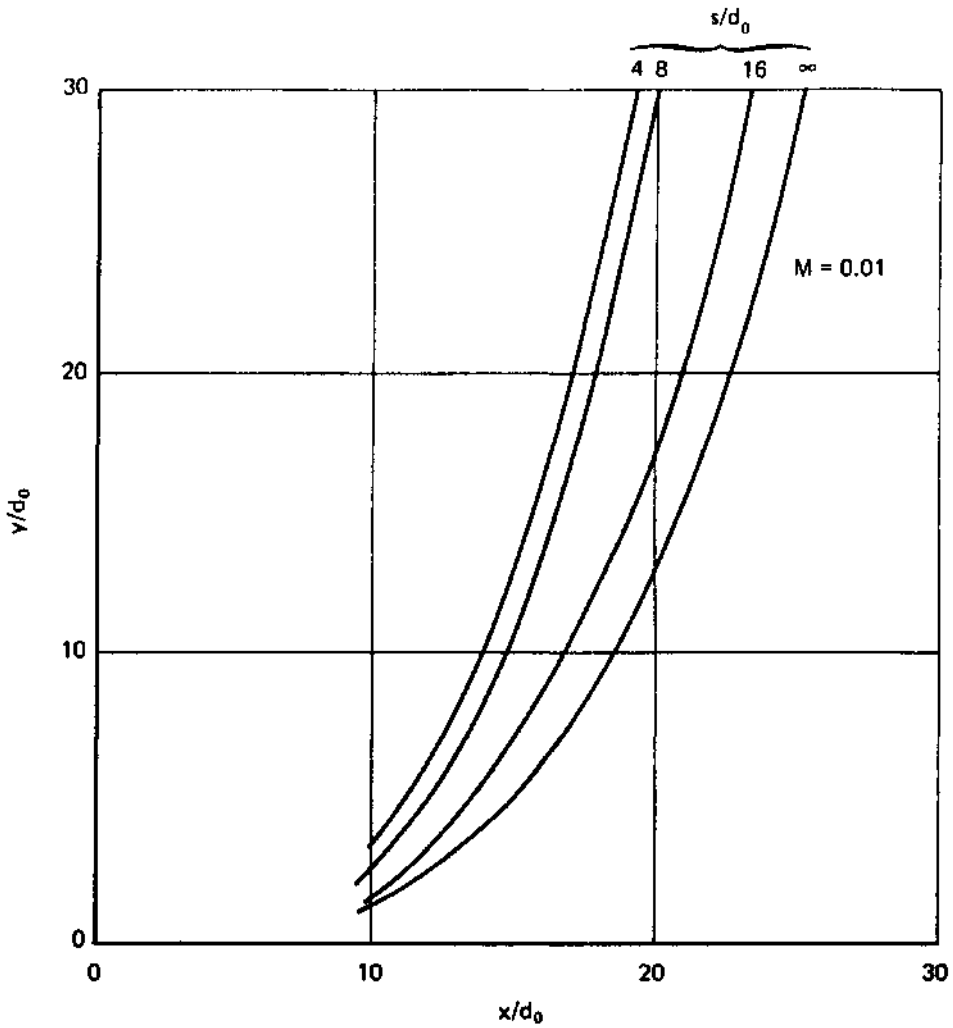


Figure 12 Effect of jet spacing on trajectory for jets in crossflow. [After (81).]

when the value of M was computed using actual fluid densities. From these data, Abramovich concluded that buoyancy effects could be neglected, other than as density differences were incorporated into the crossflow parameter M.

The same conclusion was drawn by Ivanov (81) it who injected hot jets into a cold crossflow. The ratio of temperature (and density) between jet and ambient fluids was 1.9, and M ranged from 0.005 to 0.02. The geometry of the tests was not clearly stated by either Abramovich or Ivanov. It appears that the buoyancy force acted in the same direction as the crossflow force in Ivanov's tests (i.e., a hot jet discharging into an upflow).

Application of these conclusions to incinerator design practice, however, is subject to question because of the large geometrical scale-up involved. Physical reasoning suggests that the ratio of buoyant force to drag force acting on a nonisothermal jet in crossflow depends on scale. The buoyant force F_b is a body force and is, therefore,

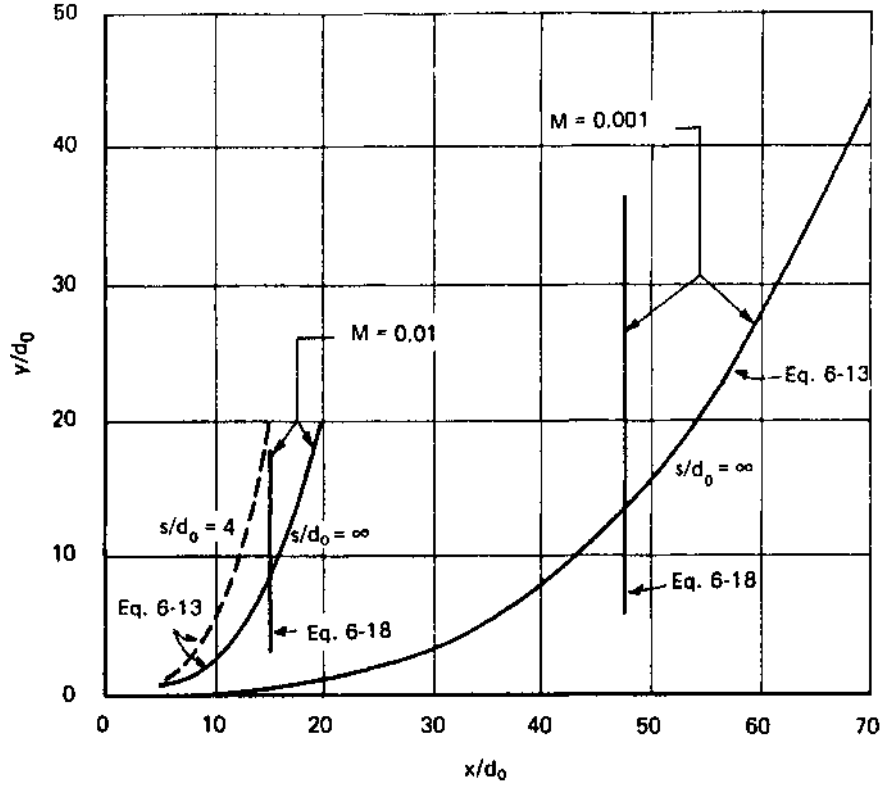


Figure 13 Comparison of Ivanov's trajectory correlation (Eq. 13) with jet penetration correlation (Eq. 18). [From (81).]

proportional to jet volume. The drag force F_d exerted by the crossflow has the characteristics of a surface force and is, therefore, proportional to the effective cylindrical area of the jet. Therefore, the ratio of buoyant force to drag force is proportional to jet diameter. A simple analysis, discussed in (63), gives

$$\frac{F_b}{F_d} = \frac{\pi}{2C_x}\left(\frac{gd_0}{u_1^2}\right)\left(1 - \frac{\rho_0}{\rho_a}\right) \tag{19}$$

where C_x is the effective drag coefficient.

The value of the effective drag coefficient C_x is believed to be in the range of 1 to 5; analysis given in (63) suggests that 4.75 is an acceptable value.

Typical values of the physical parameters in Ivanov's experiments (81) are

$$\begin{aligned} d_0 &= 5 \text{ to } 20 \text{ mm} \\ \bar{u}_0/u_1 &= 10 \text{ to } 20 \\ T_0/T_a &= \rho_a/\rho_0 = 2 \\ \rho_0\bar{u}_0^2/\rho_a u_1^2 &= 100 \text{ to } 200 \\ u_1 &= 3.68 \text{ to } 4.16 \text{ m/sec} \end{aligned}$$

The maximum value of F_b/F_d results from the maximum value of nozzle diameter d_0 and the minimum value of crossflow velocity u_1. Substitution of these values into Eq. (19) yields a force ratio of 0.003, which indicates that the crossflow effect completely dominated the buoyant effect on the small jets used in Ivanov's tests. Therefore, one would speculate that his results (no buoyancy effect) could be anticipated under his test conditions.

In incinerator applications, jet diameters in the neighborhood of 0.1 m are commonplace, along with crossflow velocities in the order of 0.6 to 1.5 m/sec. For a 0.1-m jet in a 0.6-m/sec crossflow with the same 1.91 density ratio as in Ivanov's tests,

$$\frac{F_b}{F_d} = \frac{3.14}{2(4.75)} \frac{9.81(0.1)}{(0.6)^2} \left(1 - \frac{1}{1.91}\right)$$
$$= 0.43$$

which suggests that the buoyant and crossflow forces are of the same order of magnitude.

e. Design Methods. The correlations given above provide the basic tools for the analysis of jet behavior in real furnace environments. In general, the correlations are based in theory and corroborated with data. Translation of behavioral relationships into designs can be approached in two ways:

Detailed analysis of the actions and interactions of each component of the system under design, "building" an understanding of system behavior from an understanding of its parts

Assembly of generalized correlations into "rules of thumb" and the like that show applicability to a number of systems similar to the device in question

The jet design correlations above, when coupled with the bed-burning and chamber flow analyses, are supportive of the first approach. As such, they are broadly applicable, but their use makes demands upon the designer for data and understanding he or she may not possess.

Approaches to a rule-of-thumb, generalized method for overfire air jet design have been proposed by Ivanov (81) and by Bituminous Coal Research, Inc. (91). Although these design guides were developed for coal-fired boilers, they are presented here as an indication of approaches successful in other applications. Their applicability to incineration systems, however, has been demonstrated only in one installation (30).

THE METHOD OF IVANOV. Ivanov conducted a number of experiments in a noncombusting model furnace to determine the effects of various jet configurations on the temperature profiles above a burning coal bed. The system being studied involved a rectangular furnace through which a single, flat chain grate stoker drew a level fuel bed into the furnace at the front wall and discharged ash just outside the rear wall. He concluded that

It is preferable to position overfire jets in the front wall of the furnace rather than in the rear wall.

Close spacing of the jets is desirable in order that the jets form an effective curtain. Above this curtain, a rotary motion of the gases is induced, which contributes greatly to the mixing process.

If maximum temperatures occur near the center of the grate, rather than near the front, the design depth of penetration of the jet should be increased by 5%.

Slightly better mixing is obtained if jets are fired from one wall, rather than if the same flow is divided between jets on opposite walls, whether the opposing sets of jets are directly opposed, staggered but on the same horizontal level, or on different horizontal levels.

A given level of mixing is achieved at lower power cost and with less air if small-diameter jets are used rather than large ones.

For conditions that gave good mixing, Ivanov computed the jet penetrations (L_j) from Eq. (20) and normalized the values obtained with respect to L_T, the axial length of the model furnace.

$$L_j = d_0 k \left(\frac{\bar{u}_0}{u_1} \right) \tag{20}$$

Using the k values recommended by Abramovitch (Table 2) to compute L_j, he correlated L_j/L_T with the relative jet spacing s/d_0 (where s is the center-to-center jet spacing and d_0 is the jet diameter) and obtained the following values:

s/d_0	Front arch furnace (L_j/L_T)	Rectangular furnace (L_j/L_T)
4	0.90	0.80
5	0.95	0.90
6	1.10	1.0

This correlation is the basis for his design method. Ivanov's design method is as follows:

Nozzles should be located not less than 1 m nor more than 2 m above the fuel bed.

The angle of inclination of the jets is determined by aiming the jets at a point on the grate 1.2 m to 2 m from its far end. Jets fired from the underside of a front arch may be angled downward as much as 50° from the horizontal if the fuel bed is not disturbed by the resulting jet.

The relative jet spacing should be in the range of $s/d_0 = 4$ to 5.

The velocity of gases in the furnace at the cross-section where the jets are located is computed from known overall air rates and grate areas and corrected for temperature. This velocity is the crossflow velocity u_1 and the density is ρ_a.

The jet velocity is set by the capability of the overfire fan but should always be 60 m/sec for cold jets and 70 m/sec for heated jets. He assumes a fan outlet pressure of about 25 mm Hg and computes the jet velocity from

$$\bar{u}_0 = \sqrt{\frac{2gP}{1.2\rho_0}} \tag{21}$$

where ρ_0 is the density of the nozzle fluid and the factor of 1.2 compensates for 20% pressure drop through the ducting.

The required jet diameter is computed from Eq. (22):

$$d_0 = \frac{L_j}{k_1(\bar{u}_0/u_1)\sqrt{\rho_0/\rho_a}} \tag{22}$$

where k_1 is 1.6 for $s/d_0 = 4$ to 5, and L_j is taken to be a factor times L_T the axial length of the furnace. The factors were given above and range from 0.8 to 1.10.

The number of nozzles in the row N is then calculated from the furnace width Z and the jet spacing s according to

$$N = \frac{Z - 4s}{s} \tag{23}$$

The required fan capacity Q_t is then computed from

$$Q_t = N\frac{\pi d_0^2}{4}\bar{u}_0 \tag{24}$$

THE BITUMINOUS COAL RESEARCH (BCR) METHOD. The National Coal Association has published a design handbook for *Layout and Application of Overfire Jets for Smoke Control*, based on work by the BCR (91).

The NCA recommends

Sidewall placement

Location of nozzles about 0.5 m above the fuel bed in modern furnaces and from 0.2 m to 0.3 m above the bed in older, small furnaces

Introduction of from 10% to 30% theoretical air via jets depending on whether the smoke formed is "light" or "heavy"

The design method is as follows:

Read the required volume of air (cubic feet per minute per pound coal burned per hour) from a table, given the heating value of the coal and whether the smoke is light, moderate, or heavy. Compute the air requirement in cubic feet per minute.

Decide where nozzles will be located (front, side, or back wall).

Read the number of nozzles required from a table, given the dimension of the wall on which the jets are to be located and the penetration distance (equal to the axial dimension of the furnace).

Compute the air requirement per nozzle by dividing the result of the first step and result of the third step.

Read nozzle diameter and required fan pressure from graphs, given the air requirement per nozzle (fourth step) and the penetration distance from the third step.

Determine duct size from a nomograph, given total air requirement from the first step.

The design criteria on which this method is based are not readily apparent. Examination of the tables and graphs included in the reference shows that (1) the number of jets is approximately proportional to the length of the furnace wall where the jets are installed and is approximately proportional to the desired penetration distance and (2) the penetration distance appears to be defined as that distance required to reduce the velocity of a jet, issuing into a quiescent chamber, to 2.5 m/sec.

Several qualitative statements can be made. First, the crossflow velocity does not enter explicitly into the design method. Second, working out several examples shows that relative spacing s/d_0 of up to 10 or more result. This is at odds with Ivanov's finding that spacings of four to five jet diameters are optimal.

The design methods cited above apply to furnaces burning coal or shale and are generally used in boiler design. These applications are characterized by

A uniform and predictable fuel supply that burns in a regular and repeatable pattern along the grate
Use of high heating value fuel (in the range of 5500 to 8300 kcal/kg), with low moisture and ash content
The desirability of minimizing excess air so that high combustion temperatures and high heat recovery efficiency can be obtained
Relatively low combustion volume per Btu per hour capacity

In contrast, mass burning incinerators are characterized by

A variable and generally unpredictable fuel supply; the composition and moisture content vary seasonally in a somewhat predictable manner and hourly (as fired) in an unpredictable manner.
Use of low heating value fuel (2475 kcal/kg average as fired), with relatively high ash (20%) and moisture (28%) content (21).
No general requirement for high-combustion gas temperature, except in heat-recovering incinerators or as may be required to achieve emission requirements for carbon monoxide, volatile hydrocarbons, dioxins, etc.
Relatively large combustion volumes per kcal/hour capacity.

In both cases, complete fuel burnout is desirable and combustion gas temperatures must be kept below the point where slagging or damage to the refractory occurs. Both types have fly-ash problems, although the incinerator problem is more severe since relatively large pieces of unburned paper can be lifted into the combustion volume.

The difference in characteristics place different requirements on the overfire jets. Jet systems in mass burning incinerators must contend with

A shifting combustion profile caused by variations in the upflow gas temperature, composition, and velocity, and in the moisture content and composition of the fired refuse
Large pieces of partially burned refuse in the combustion volume
Large combustion volumes per kcal/hour, which increases the difficulty of mixing the combustion gases
Typical excess air levels, even in incinerator boilers, of about 100%

In meeting these conditions, minimization of excess air introduced in the jets is not as important as in heat-recovering boilers. The principal factors that mitigate for low excess air in incinerators are draft limitations, higher costs of air pollution control, fan and stack equipment, power costs, and the general requirement that the overfire air not quench the combustion reaction. Although these factors are important, realization of complete combustion of pollutants, materials survival, and inhibition of slagging are predominant concerns.

f. Combustion Effects. The analysis in (21) and experimental data (30) indicate that under almost all conditions the flow of air through a refuse bed will produce gases containing unburned combustible. Although bypassing (channeling) of air through the bed can provide some of the needed oxidant to the fuel-rich gases, the data by Kaiser (31) indicate that the gases, on the average, remain fuel-rich. As a consequence, it should be expected that some combustion will occur as the oxygen-bearing overfire air jet penetrates the hot gas flow rising from the bed. This results in a so- called inverted flame where a jet of oxidant discharges into, "ignites," and burns in a fuel-rich environment.

This phenomenon has been observed in both coal- and refuse-burning practice, where impingement of a jet on the opposite side wall has resulted in refractory overheating and slagging, contributing to premature wall failure. In another case, a jet of air moving beneath a long arch over the discharge grate of an incinerator furnace yielded temperatures of over 1375°C in the brickwork. Because of the potential importance of this combustion effect, a simplified mathematical model of jet behavior under these conditions was developed (63), and the effect of the pertinent variables was explored.

The analysis makes use of jet concentration correlations describing the axial c_m and radial c weight concentration of nozzle fluid as functions of the distance from the nozzle plane x and the radial dimension r. The concentration at the nozzle is c_0 and the nozzle diameter is d_0. The ambient T_a, nozzle fluid T_0, and mixture T_m temperatures are those prior to combustion. For noncombusting jets, in the absence of crossflow and buoyancy, these variables are related by

$$\bar{c}_m = 5\bar{c}_0\left(\frac{T_a}{T_0}\right)^{1/2}\left(\frac{d_0}{x}\right) \tag{25}$$

$$\bar{c} = \bar{c}_m \exp\left[-57.5\left(\frac{r}{x}\right)^2\right] \tag{26}$$

Assuming equal and constant specific heats for the nozzle and ambient fluid, an energy balance yields

$$T_m = T_a + 5\left(\frac{T_a}{T_0}\right)^{1/2}(T_0 - T_a)\frac{d_0}{x}\exp\left[-57.5\left(\frac{r}{x}\right)^2\right] \tag{27}$$

Using Eq. (27), one can calculate the mixture temperature. Then, by comparison with an assumed minimum ignition temperature T_i (say 590°C), it can be determined whether combustion will occur. (Note that this procedure takes account of "quenching" of combustion reactions in the cold core of the jet.)

The oxygen demand θ (kg of oxygen per kg of ambient fluid) and heat of combustion ΔH_c (kcal/kg of oxygen reacting) of the furnace gases can be estimated. Defining Ω as the concentration of nozzle fluid in the mixture relative to the nozzle concentration c/c_0, we find that if $T_m \geq T_i$ and if $\Delta(1-\Omega) - \Omega c_0 \geq 0$, combustion will occur to the extent of the available oxygen releasing $\Delta H_c \Omega c_0/\theta$ kcal/kg of mixture. The resulting gas temperature T_F is given by

$$T_F = T_R + \frac{1}{c^\circ_{p,\mathrm{av}}}\left[(1-\Omega)(T_1 - T_R)c^\circ_{p,\mathrm{av}} + \frac{\Delta H_c \bar{c}_0}{\theta}\right] \tag{28}$$

where T_R is the reference temperature for enthalpy (say 15°C) and $c^\circ_{p,\mathrm{av}}$ is the average specific heat of the gases between the reference temperature and T_F.

For the oxygen-rich case, if $T_m \geq T_i$ and if $\theta(1-\Omega) - \Omega c_0 < 0$, combustion will occur to the extent of the available fuel, releasing $\Delta H_c(1-\Omega)$ kcal/kg of mixture. The resulting gas temperature is given by

$$T_F = T_R + \frac{1}{c^\circ_{p,\text{av}}}[(1-\Omega)(T_1 - T_R)c^\circ_{p,\text{av}} + \Delta H_c(1-\Omega)] \tag{29}$$

Calculation of the radial profiles of temperature according to the above was carried out, and the results are plotted in Figs. 14, 15, and 16, at various distances from the nozzle plane. The depressed temperature (600°C) near the discharge plane is the subignition temperature or "quenched" region. The peaks of temperature found along a radial temperature "traverse" identify the stoichiometric point. The peak temperature (about 1400°C) reflects the assumptions

T_a = 1094°C (2000°F)
ΔH_c = 206 kcal/kg (370 Btu/lb)
θ = 0.0545 kg O_2/kg ambient
$\bar{c}_0$ = 0.23 kg O_2/kg nozzle fluid (air)
$c^\circ_{p,\text{av}}$ = 0.31 kcal/kg °C^{-1} relative to 15.5°C

Note that only absolute temperatures are to be substituted in the equations.

It can be seen that a hot zone is rapidly developed with a diameter of about 30 cm (1 ft) and this zone endures, for large jets, for distances that approximate the widths of many incinerator furnaces (2 to 3 m). This problem is greatly reduced as the jet diameter is decreased, thus adding additional incentive to the use of small-diameter jets.

The rapid attainment of stoichiometric mixtures within the jet is in agreement with the theory developed by Thring (92), which roughly approximates the spread in velocity and concentration using the same mathematical formulations as in Eqs. (1) through (4), but

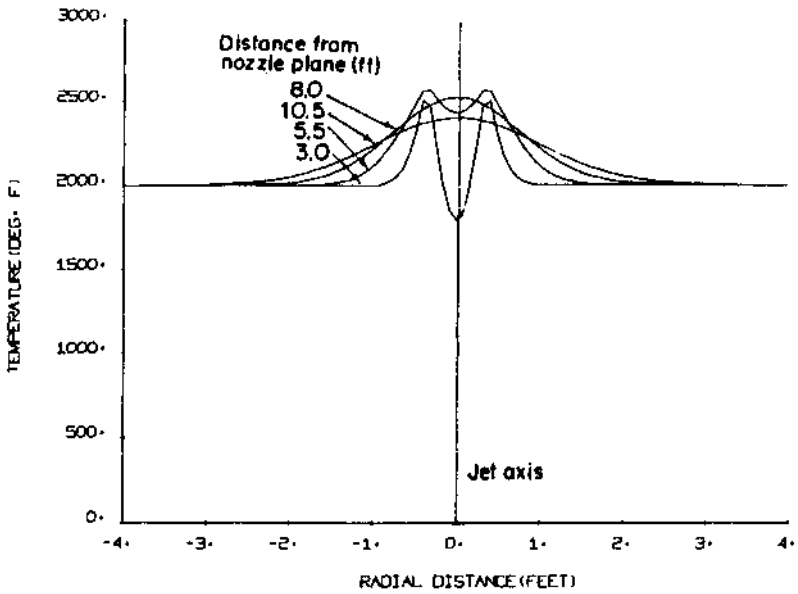


Figure 14 Temperature versus radial distance (jet diameter = 1.5 in.). [From (63).]

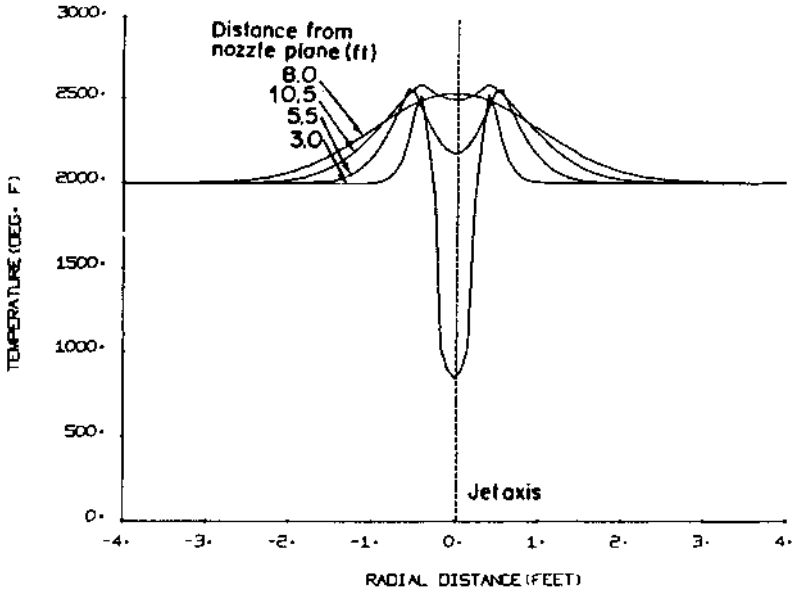


Figure 15 Temperature versus radial distance (jet diameter = 2 in.). [From (63).]

using an effective nozzle diameter equal to $d_0(\rho_0/\rho_f)^{1/2}$, where ρ_f is the gas density at the temperature of the flame.

The above illustrates the characteristics of "blowtorch" effects from air jets and shows that temperatures near 1400°C, such as have been experienced with jets, could be anticipated. However, the quantitative accuracy of the above calculations is limited to

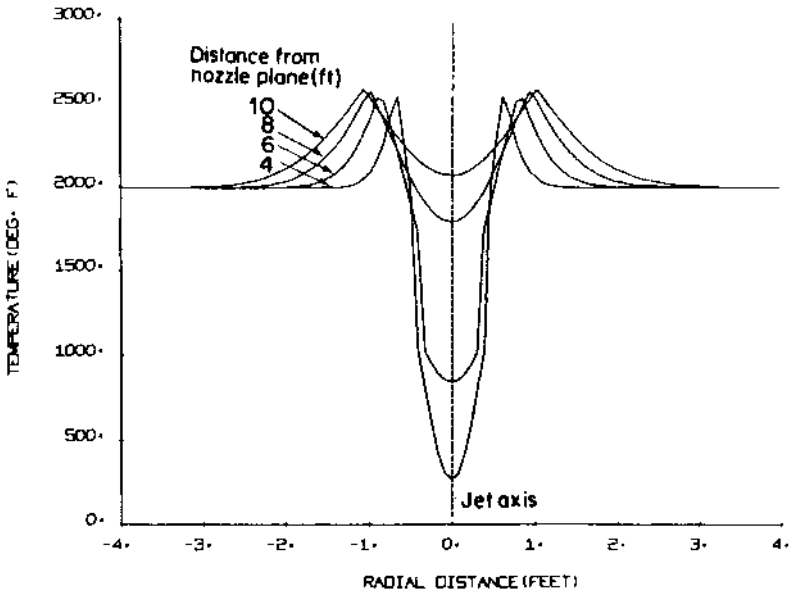


Figure 16 Temperature versus radial distance (jet diameter = 4 in.). [From (63).]

providing only an initial estimate of the nature of air jet behavior in incinerators. No allowance is made in the analysis, for example, of crossflow effects, which are known to increase jet entrainment rates and thus "shorten" the inverted flame described by the analysis. The method, therefore, can be expected to produce a conservative result.

The correlations of axial concentration by Patrick (87) provide a means to estimate the effect of crossflow in shortening the distance to the point of completion of the combustion reactions. From Eq. (25) an analysis readily shows the distance from the nozzle plane to the point where the gas on the axis is at a stoichiometric ratio to be given by

$$\frac{x}{d_0} = 5\left(\frac{T_a}{T_0}\right)^{1/2}\left(\frac{\bar{c}_0}{\theta} + 1\right) \tag{30}$$

Patrick found the centerline concentration to vary along the jet path length l in crossflow according to

$$\frac{\bar{c}_0}{\bar{c}_m} = \left[\left(\frac{l}{d_0}\right)\exp(7.8M^{1/2} - 1.856)\right]^{1.18} \tag{31}$$

and, for no crossflow, according to

$$\frac{\bar{c}_0}{\bar{c}_m} = 0.112\left(\frac{x}{d_0}\right)^{1.18} \tag{32}$$

Combining Eqs. (31) and (32) establishes the relationship between the centerline distance x for noncrossflow, which corresponds to the same concentration ratio as for a jet in crossflow that has traveled over a path length l

$$\frac{x}{d_0} = 1.42\left(\frac{l}{d_0}\right)\exp(7.8M^{1/2} - 1.856) \tag{33}$$

The path length can be easily calculated by numerical integration of Eq. (34), which also can be derived from Patrick's trajectory relationships:

$$\left(\frac{l}{d_0}\right) = \int_0^{x/d_0}\left[9M^{2.55}\left(\frac{x}{d_0}\right)^4 + 1\right]^{0.5} d\left(\frac{x}{d_0}\right) \tag{34}$$

Therefore, to find the distance from the nozzle plane to the point where such peak (stoichiometric) temperatures will be obtained on the centerline, the noncrossflow distance is calculated from Eq. (30); the resulting value is substituted into Eq. (33) to yield the crossflow path length at an equivalent degree of mixing; and the integration given in Eq. (34) is carried out to define the dimensionless distance x/d_0 integration limit, which causes the integral to assume the value of the calculated path length. This latter x/d_0 value corresponds to the horizontal distance from the nozzle to the plane where peak temperatures exist. The vertical displacement of the jet in this plane may then be calculated by substitution into Eq. (35).

$$\frac{y}{d_0} = M^{1.28}\left(\frac{x}{d_0}\right)^3 \tag{35}$$

The analysis shows that jet temperatures can be considerably elevated by combustion effects. Therefore, when analyzing jet operation in regimes where a buoyancy analysis

(neglecting combustion) suggests jet drop will be important, these effects could provide counterbalancing jet temperature increases.

g. Incinerator Overfire Air Jet Design Method. The basic parameters to be selected in design of an overfire air jet system are

The diameter (d_0) and number (N) of the jets to be used
The placement of the jets
The quantity of the air to be added over the fire

Related but not independent variables are the jet velocity $\bar{u}_0$ and the head requirements for the overfire air fan P.

The tentative design method is based on that of Ivanov (81), which was discussed above. It is important in using this method to substitute the values of d_0 and u_1 obtained into Eq. (19) to determine if buoyant forces might be important. Values should fall in the "drag forces" predominate region.

The basic equations on which the design method is based are as follows:

Air Flow Relation

$$Q_T = 47Nd_0^2\bar{u}_0 \tag{36}$$

where

Q_T = the overfire air rate (m^3/min)
N = the number of jets
d_0 = the jet diameter (m)
$\bar{u}_0$ = the jet velocity (m/sec)

Ivanov's Penetration Equation

$$\frac{L_j}{d_0} = 1.6\left(\frac{\bar{u}_0}{u_1}\right)\sqrt{\frac{\rho_0}{\rho_a}} \tag{37}$$

where

L_j = the desired jet penetration
u_1 = the estimated crossflow velocity in the incinerator
ρ_0 and ρ_a = the jet and crossflow gas densities, respectively

Jet Spacing Equation

$$z = \left(\frac{s}{d_0}\right)Nd_0 \tag{38}$$

where

z = the length of furnace wall on which the jets are to be placed
s/d_0 = the desired value of jet spacing (measured in jet diameters)

Inherent in Eq. (38) is the assumption that the jets are placed in a single line. Ivanov recommends that s/d_0 be in the range of 4 to 5, although values as low as 3 can probably be used without invalidating the penetration equation [Eq. (37)].

The form of these equations sheds some light on the options open to the systems designer. For a given set of furnace conditions, Eq. (37) can be rearranged to give

$$d_0\bar{u}_0 = \text{constant} \tag{39}$$

The product of jet diameter and velocity is fixed by furnace conditions. Substitution of Eqs. (38) and (39) into Eq. (36) yields

$$\frac{Q_T}{z} = \frac{0.326 d_0 \bar{u}_0}{s/d_0} \tag{40}$$

The air flow per length of wall is fixed by furnace conditions, except that s/d_0 can vary from 3 to 5.

EXAMPLE 1. Consider an incinerator with the following characteristics:

Capacity, 250 metric tons per day (24-hr basis)
Total stoichiometric air requirement, 425 m^3/min
Length of wall for jet placement L, 9 m
Desired depth of penetration L_j, 2.5 m
Crossflow velocity u_1, 1.25 m/sec

Jet and furnace temperatures are 40°C (313 K) and 1090°C (1363 K), respectively, so that

$$\sqrt{\frac{\rho_a}{\rho_0}} = \sqrt{\frac{T_0}{T_a}} = \sqrt{\frac{313}{1363}} = 0.48$$

Develop the design of the overfire jet system.

Step 1. Compute the product $d_0\bar{u}_0$ from Eq. (37):

$$d_0\bar{u}_0 = L_j u_1 \left(\frac{1}{1.6}\right)\sqrt{\frac{\rho_a}{\rho_0}} = \frac{(2.5)(1.25)(0.48)}{1.6} = 0.94\ \text{m}^2/\text{sec} \tag{41}$$

Step 2. Select value of $\bar{u}_0$. Using Ivanov's guidelines, set $\bar{u}_0 = 60$ m/sec (cold jet).

Step 3. Compute d_0 from the result of Step 1.

$$d_0 = 0.94/60\ \text{m} = 0.0157\ \text{m} = 1.57\ \text{cm}$$

The pressure requirement for the overfire air fan depends mainly on $\bar{u}_0$. Equation (34) may be used to calculate the required velocity head as a function of $\bar{u}_0$.

$$\Delta P = 1.2\left[\frac{\rho_0 \bar{u}_0^2}{2g}\right] \tag{42}$$

for air at 40°C, $\rho_0 = 1.12\ \text{kg/m}^3$, and for $\bar{u}_0 = 60$ m/sec, $\Delta P = 247\ \text{kg/m}^2$ (46.2 cm Hg).

Step 4. Compute the number of jets N. Setting $s/d_0 = 4$, Eq. (38) yields

$$N = \frac{9}{(4)(0.0157)} = 143\ \text{jets}$$

Step 5. Compute Q_T from Eq. (36).

Step 6. Compare Q_T with the theoretical air requirement. The theoretical air requirement is 425 m^3/min, so that the overfire air rate is equivalent to

$(99.4/425)(100) = 23\%$ of theoretical. The soundness of this value can be checked by comparison with the air requirements defined by the bed-burning process and by reference to experience. Note, however, that few data exist to allow confident valuation of the performance of existing plants with respect to combustible pollutant emissions and the design and operating parameters of the overfire air systems.

The amount of overfire air can be increased or decreased within limits without seriously affecting the performance of the jets by changing the jet spacing parameter [s/d_0 in Eq. (38)] within the range of 3 to 5. It should be recognized that the design method described has as its goal the complete mixing of fuel vapors arising from the fuel bed with sufficient air to complete combustion. Two other criteria may lead to the addition of supplementary air quantities: the provision of sufficient secondary air to meet the *combustion air requirement* of the fuel vapors, and the provision of sufficient air to *temper furnace temperatures* to avoid slagging (especially in refractory-lined incinerators). In the example given, both criteria act to greatly increase the air requirement and would suggest the installation of additional jets (although the discharge velocity criteria are relaxed). Nonetheless, the Ivanov method is intended to ensure the effective utilization of overfire air and, in boiler-type incinerators where tempering is not required, will permit optimal design and operating efficiency.

h. Isothermal Slot Jets. The discussions above have dealt with the round jet, the configuration found almost exclusively in combustion systems. In designs where a multiplicity of closely spaced round jets are used, however, the flow fields of adjacent jets merge. The flow then takes on many of the characteristics of a jet formed by a long slot of width y_0.

For use in analyzing such situations, the flow equations applicable to such a slot jet (or plane jet) are as follows.

Centerline velocity:

$$\frac{\bar{u}_m}{\bar{u}_0} = 2.48\left(\frac{x}{y_0} + 0.6\right)^{-1/2}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \tag{43}$$

Centerline concentration:

$$\frac{\bar{c}_m}{\bar{c}_0} = 2.00\left(\frac{x}{y_0} + 0.6\right)^{-1/2}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \tag{44}$$

Transverse velocity:

$$\frac{\bar{u}}{\bar{u}_m} = \exp\left[-75\left(\frac{y}{x}\right)^2\right] \tag{45a}$$

$$= 0.5\left[1 + \cos\left(\frac{\pi y}{0.192x}\right)\right] \tag{45b}$$

Transverse concentration:

$$\frac{\bar{c}}{\bar{c}_m} = \exp\left[-36.6\left(\frac{y}{x}\right)^2\right] \tag{46a}$$

$$= 0.5\left[1 + \cos\left(\frac{\pi y}{0.279x}\right)\right] \tag{46b}$$

These functions correspond to a velocity half-angle of 5.5° and a concentration half-angle of 7.9°.

Entrainment:

$$\frac{\dot{m}_x}{\dot{m}_0} = 0.508\left(\frac{\rho_a}{\rho_0}\right)^{1/2}\left(\frac{x}{y_0}\right)^{1/2} \tag{47}$$

where $\dot{m}_x$ and $\dot{m}_0$ are for a unit length of slot and $\dot{m}_0 = \rho_0 \bar{u}_0 y_0$.

B. Swirling Flows

In waste and fuel burners and within furnaces, swirl is often used to modify flow characteristics. Because of the intense recirculation patterns in swirling flows (burning gases travel back toward the burner, bringing heat energy and reactive species to promote ignition in the entering fuel–air mixture), rotation is found to shorten the flame. The recirculation and flame-shortening effects may be exploited to reduce the size and cost of the enclosure or to increase the postflame residence time.

1. The Axial Swirl Burner—Isothermal Performance

Velocities in axially symmetrical swirling jets (the axial swirl burner) can be defined in terms of three components. Axial velocity $\bar{u}$ is the component parallel to (but not necessarily on) the jet axis, radial velocity $\bar{v}$ is the velocity toward or away from the axis, and $\bar{w}$ is the velocity tangent to a circle centered on the axis.

The intensity of swirl in a jet has been characterized using the swirl number N_s, which is defined as the dimensionless ratio of jet angular momentum $\dot{L}_0$ to linear momentum $\dot{G}_0$.

$$\dot{L}_0 = 2\pi\rho_0 \int_0^{r_0} (\bar{u}\bar{w})_0 r^2 \, dr \tag{48}$$

$$\dot{G}_0 = 2\pi \int_0^{r_0} (P + \rho\bar{u}^2)_0 r \, dr \tag{49}$$

$$N_s = \frac{2\dot{L}_0}{\dot{G}_0 d_0} \tag{50}$$

where the static pressure P (gauge) in Eq. (49) allows for pressure variations over the nozzle cross-section due to centrifugal forces. Swirl numbers of typical burners are usually in the range from 0.6 to 2.5 (93).

The swirl burner can be constructed in a number of different configurations, including straight or profiled vanes, tangential entry with radial vanes, a movable block system (94), or a scroll-type tangential inlet. These systems, though geometrically different, lead to highly similar flow patterns.

A large, toroidal recirculation zone is formed in the exit, occupying up to 75% of the exit diameter, with up to 80% of the initial flow being recirculated.

The kinetic energy of turbulence is given by

$$KE = \frac{\bar{u}'^2 + \bar{w}'^2 + \bar{v}'^2}{\bar{u}_0^2} \tag{51}$$

It is observed that very high levels of kinetic energy of turbulence are formed (up to 300% of the kinetic energy at the nozzle plane) with a rapid decay (to less than 50%) within one exit diameter.

The swirling flow exhibits a three-dimensional, time-dependent instability called the precessing vortex core (PVC), which can lead to the generation of tonal combustion noise or lead to blowout and other instabilities (93).

The axial reverse flow (initiating at $N_s > 0.6$) is, surprisingly, virtually nonswirling and has a magnitude M_r relative to the nozzle flow (for straight exits) given by

$$N_s = 0.508 + 5.66M_r - 6.25M_r^2 + 2.28M_r^3 \tag{52}$$

The presence of an oil gun or other source of nonswirling axial flow can reduce M_r by up to 50%, while a divergent exit nozzle can increase M_r by 500% to 600% over that for straight exits, with M_r increasing with increasing divergence angle (say, 24° to 35° half-angle) up to an as-yet undefined limit where M_r ultimately begins decreasing (as detachment occurs).

The shape of the reverse flow zone is dependent upon the type of swirler with more compact, smaller-volume zones being formed with tangential inlet swirlers and longer, thinner zones being formed with vane swirlers. Thus, the tangential inlet swirlers have higher reverse flow velocities and steeper velocity gradients (more intense turbulence and consequent mixing), since the M_r for both swirlers are comparable.

The rate of entrainment of ambient fluid and jet half-angle is much higher for swirling flows than that in nonswirling jets. Experimental data by Kerr and Fraser (95) indicate approximately linear entrainment and half-angle laws:

$$\frac{\dot{m}_x}{\dot{m}_0} = (0.35 + 0.7N_s)\frac{x}{d_0} \tag{53}$$

$$\tan \varphi_s = (1 + 2.84N_s)\tan \varphi_0 \tag{54}$$

where

$\dot{m}_x$, $\dot{m}_0$ = the mass flows at a distance x and at the plane of the nozzle of diameter d_0, respectively

φ_s, φ_0 = the jet half-angle with and without swirl, respectively

Especially at high N_s and when the ratio of the cross-sectional dimension of the burner d_0 to that of the enclosure d_c is high, a second recirculation zone is established at the wall. The mass flow of this outer recirculation may be greater or less than the central zone. Although the central zone is of greater interest to combustion engineers, the existence of the wall flow can be of great influence on wall heat transfer rates and consequent materials problems.

The relationship between pressure drop and N_s is dependent upon swirler design, although, in all cases the pressure loss coefficient $\Delta P/(\frac{1}{2}\rho_0 u_0^2)$ increases with increasing N_s. Annular vaned swirlers are particularly sensitive to N_s variations, with the pressure loss coefficient (PLC) increasing from 8 to 50 as N_s increases from 1.0 to 2.8. Tangential entry swirlers showed a threefold increase in PLC as the Reynolds number (based on swirler diameter) increased from 0.3×10^5 to 2.3×10^5. Studies on the effect of an axial oil gun (96) showed a threefold increase in PLC if a gun was used. Considerable reduction of PLC was shown for small values of d_0/d_c. Typical ranges of d_0/d_c lie between 0.4 and 0.7 (96). A divergent outlet also appears to reduce the PLC, typically by 10% to 20%.

2. The Cyclone Combustion Chamber—Isothermal Performance

A second type of swirling combustor is the *cyclone combustion chamber*, where air and fuel are injected tangentially into a large, usually cylindrical chamber and exhausted through a centrally located exit hole in one end. These combustors are often used for the combustion of materials that are normally considered difficult to burn efficiently, such as damp vegetable refuse, high-ash content, and brown coals, anthracite, and high-sulfur oils.

There are two main types of such chambers. The first (Type A) has two or more tangential inlets into the top of a cylindrical chamber, with exit through a constricted orifice in the bottom, and is commonly used for higher-calorific-value fuels where slag and ash generation and removal are not serious problems. The second (Type B) has one to four tangential inlets at the top, a baffled exit at the top, and a slag tap at the bottom and is used with high-ash-content fuels.

The swirl number for such systems, assuming a uniform exit axial velocity profile, can be related to dimensional parameters:

$$N_{sc} = \frac{\pi d_e d_c}{4A_t} \tag{55}$$

where d_e is the diameter of the diameter of the exit throat and A_t is the area of the tangential inlet.

On this basis, Type A systems usually operate at an N_{sc} from 2 to 11, a length-to-exit diameter L_T/d_e of from 1 to 3, and a ratio of d_e/d_c of from 0.4 to 0.7. Type B systems operate at an N_{sc} from 8 to 20, an L_T/d_e from 1 to 1.25, and a d_e/d_c from 0.4 to 0.5. At these N_{sc}, very high residence times are achieved, and most of the combustion processes appear to occur inside the chamber.

The flows within Type A and Type B chambers are complex and sensitive to the inlet and outlet configurations, to relative inlet, outlet, and chamber dimensions, and to the presence of vanes or other flow modifiers on the sidewalls or end piates (93).

The pressure drop through both types of cyclones has been expressed by Tager (97) as the sum of inlet losses (ΔP_i) and losses across the chamber (ΔP_{cc}):

$$\Delta P = \Delta P_i + \Delta P_{cc} \tag{56}$$

$$\Delta P_i = \xi_a \frac{\bar{w}_{\text{in}}^2 \rho_0}{2g} \tag{57a}$$

$$\Delta P_{cc} = \xi_{cc} \frac{\bar{u}_e^2 \rho_0}{2g} \tag{57b}$$

where

$\bar{w}_{\text{in}}$ = the tangential inlet velocity
$\bar{u}_e$ = the average exit velocity

Values of the coefficients ξ_a and ξ_{cc} can be taken from Fig. 17 for d_e/d_c of 0.45. Tager's correlation to other values of this parameter (97) showed for d_e/d_c from 0.3 to 1.0:

$$\Delta P_{cc} = (\Delta P_{cc})_{0.45} \left(\frac{0.9}{d_e/d_c} - 1.0 \right) \tag{58}$$

The efficiency of swirl generation in cyclone combustors is usually in the range 4% to 15%. This is to be compared with efficiencies as high as 70% to 80% in swirl burners. For Type A cyclones, Fig. 18 shows the effect of variation in constructional parameters on efficiency (98).

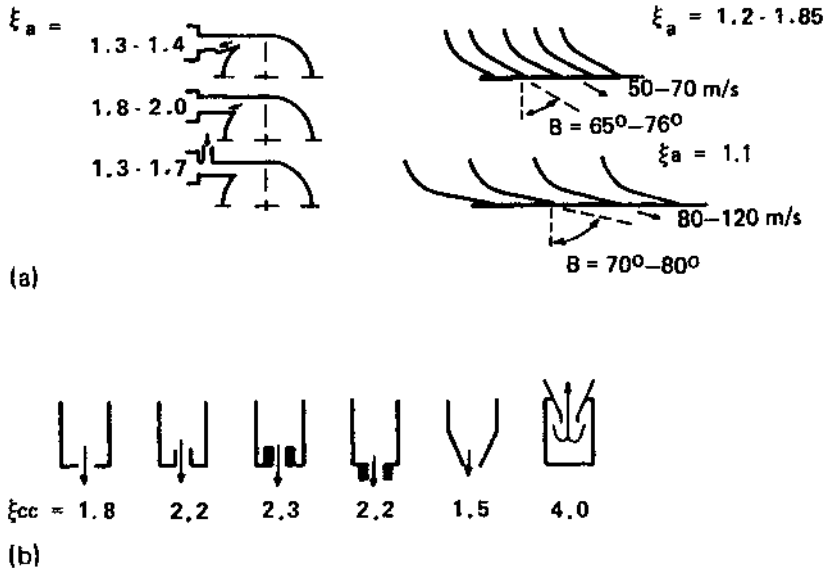


Figure 17 (a) Inlet losses for various types of swirlers. (b) Chamber-friction, swirl, and outlet losses. [From (97).]

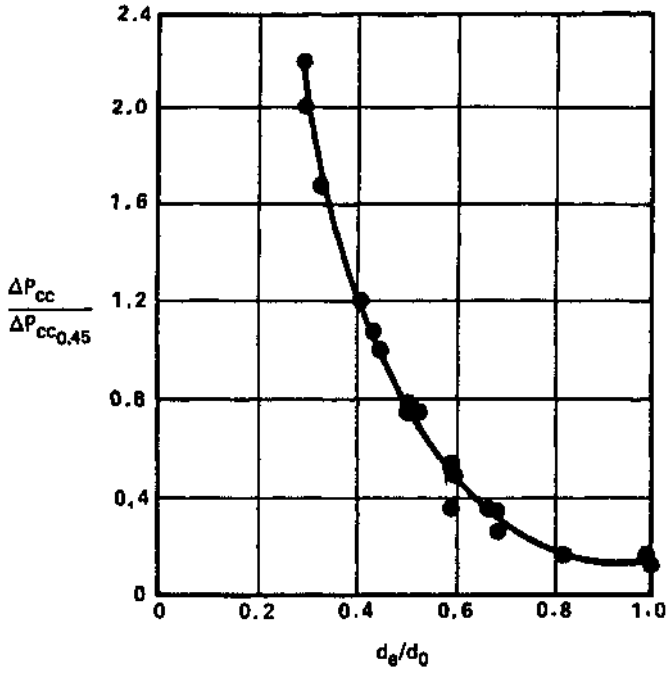


Figure 18 Dependence of the aerodynamic efficiency on the constructional parameters of Type A cyclone combustors. Points obtained from tests on eight different cyclones in self-similarity Reynolds number range (Re > 50,000) by Tager. [From (97).]

3. The Axial Swirl Burner—Combustion Effects

Combustion processes (especially volumetric expansion) exert a great influence on swirling flows. Few data are available to quantify the impact of combustion (especially ϕ, the mixture ratio relative to stoichiometric). An example for unenclosed swirl burners is presented in Table 3.

It is apparent, however, from these and other data (99, 100) that with combustion in comparison to the isothermal case:

A considerable reduction in M_r occurs, particularly near $\varphi = 1$ and with premix.

The maximum axial velocity is almost twice that in the isothermal case, although the decay of velocity is similar.

The density changes from combustion cause the initial jet spread to be greater.

The recirculation zones are shorter and wider from premixed burners. With burner mixing, the mode of fuel entry and φ can lead to either narrower or wider zones. Limited data (93) suggest that very high values of φ or axial/radial fuel entry produces zone widths less than the isothermal case.

The effect of enclosure upon a swirl burner is, as in the isothermal case, dependent upon the ratio of furnace d_c to burner d_e diameter. Although the various interactions are complex functions of φ, mode of fuel entry, and geometry, one can determine that the impingement point of the flame on the wall lies between $0.2d_c$ and $0.5d_c$ in the range

$$0.7 < N_s < 1.3 \qquad 3 < d_c/d_e < 5 \qquad 0.9 < \varphi < 1.7$$

The swirl parameter N_s tends to decrease due to combustion, which increases the axial momentum flux. Beltagui and Maccallum (100) have suggested a 10% decrease may be appropriate.

Pressure drop increases to between 125% and 300% of the isothermal case, the larger values being obtained in premixed systems.

In understanding the behavior of swirl burner combustion the concept of a well-stirred zone followed by a plug flow zone has proven to be a powerful concept. The well-stirred zone, brought about by intense back-mixing and turbulence, is of uniform composition and temperature. The burnedness β, the degree to which combustion is completed, in the well-stirred zone is generally less than unity. Thus, the plug flow zone is important in providing the time for combustion to be completed.

Similarity between flows in hydraulic (water) models and actual furnaces has been studied by Beér et al. (101), and their results are shown in Figs. 19 and 20. Note that $\bar{t}$ is the mean residence time, t is the actual time following cessation of tracer injection, and $\bar{t}_s$ is the residence time in the well-stirred section. Further, N_s in the combus tion cases has to be multiplied by the density ratio $(\rho_f/\rho_{\text{iso}})^{1/2}$ to compensate for effect of combustion.

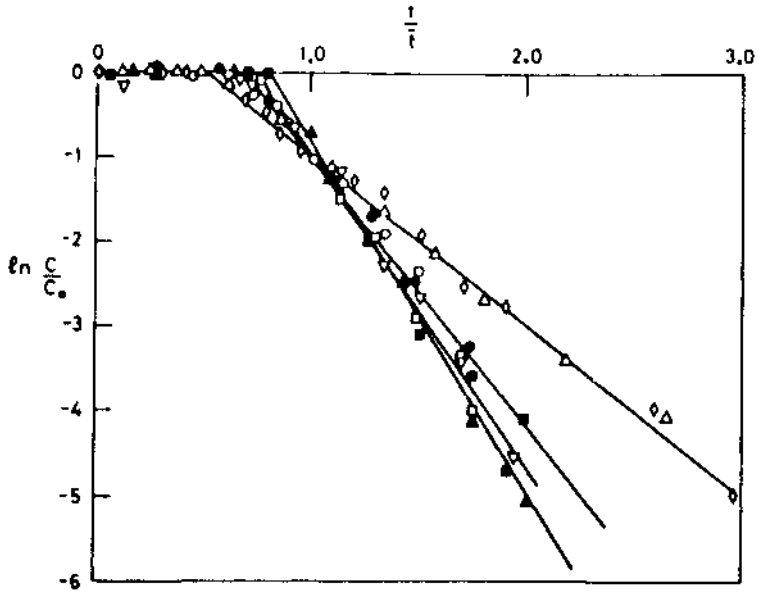
Figure 19 shows the decay rates of injected tracers in a pulverized coal furnace and in a 0.1-scale water model. It can be seen that the effect of swirl is to lengthen the time until decay of tracer concentration commences and then to result in a more rapid concentration decay rate than the nonswirl case.

Figure 20 shows that the residence time distribution between the stirred zone and the plug flow zone may be controlled by swirl, going through a minimum as N_s increases. Some data (102) have shown that for oil-fired combustion, operation at the minimum point

Table 3 Characteristics of Unenclosed Swirl Burners[a]

N_s	ϕ[b]	Combusting M_r	Isothermal M_r	Length of recirculating zone[c]		Width of recirculating zone[c]		Type of fuel entry	Type of swirler
				Combusting	Isothermal	Combusting	Isothermal		
0.7	1.63	0.005	0.04	0 to $2d_e$	$3.5d_e$	$0.83d_e$	$0.4d_e$	Premix	Annular vaned
1.25	1.63	0.06	0.16	0 to $3d_e$	$5d_e$	$1.8d_e$	$0.6d_e$	Premix	Annular vaned
2.2	13.8	0.64	1.00	$-1d_e > L > 2d_e$	$\sim 5d_e$	$0.6d_e$	$\sim 0.7d_e$	Axial	Tangential

[a] From Ref. 93.
[b] Town gas ($\approx$ 50% H_2) was used for all of these results.
[c] Distances expressed in exit throat diameters.



	$2L_0^*/G_0^*d_e$		τ, sec
◊	0	FURNACE	15.2
△	0	MODEL	20
■	1.56	FURNACE	18.3
▲	1.56	MODEL	20
□	2.24	FURNACE	17.9
▽	2.24	MODEL	20
○	3.9	FURNACE	19.3
●	3.9	MODEL	20

Figure 19 Tracer concentration decay as a function of swirl number in model and prototype furnace. [From (101).]

in well-stirred residence time yields maximum performance with minimum smoke emissions.

4. The Cyclone Combustion Chamber—Combustion Effects

Data on cyclone systems with combustion are few; this is due, importantly, to the experimental difficulties encountered with the high-ash or slagging fuels most often fired in this type of equipment. Some conclusions, however, can be drawn:

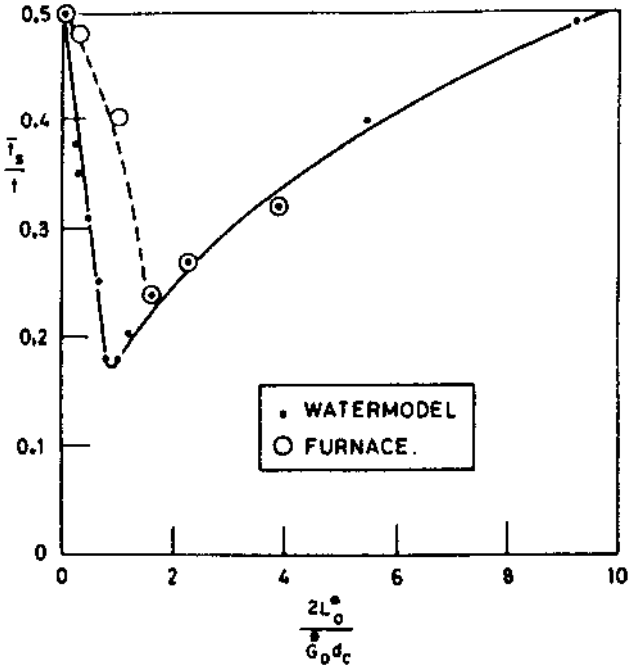


Figure 20 Ratio of residence time in stirred section to total residence time as a function of swirl number. [From (101)]

Optimum combustion can be obtained by admitting 2% to 3% of the combustion air on the axis. Axial introduction of fuel leads to incomplete mixing and poor combustion.

At least two symmetrically arranged tangential inlets should be used to avoid uneven burning and excessive pressure drop.

In combustion situations, up to three major zones of oxygen deficiency occur, one commonly occurring in the region of the exit throat. This phenomenon, perhaps due in part to centrifugal stratification effects, leads to the need for an afterburning chamber to obtain complete burnout.

Comparisons between isothermal and combusting system regarding flow pattern and pressure drop show strong similarity. For evaluating N_s in the combusting state, the following correction is recommended:

$$(N_s)_{\text{combusting}} = (N_s)_{\text{isothermal}} \left[\frac{T_{\text{inlet}}\ ^\circ\text{K}}{T_{\text{outlet}}\ ^\circ\text{K}} \right] \tag{59}$$

II. INDUCED FLOW

For the combustion systems and subsystems described above, emphasis was placed on the flow elements directly within the control of the designer, the axial and sidewall jet and the swirled jet or cyclonic flow. This section explores the consequential effects of these flows (recirculation) and the impact of buoyancy forces on furnace flow. Each of these induced

flows has a significant effect on combustor performance and should be understood by both the designer and the trouble-shooter.

A. Jet Recirculation

As a consequence of viscous and (at higher Reynolds numbers) turbulent momentum transfer, gradients in velocity always produce an acceleration of the slower flow and proportional deceleration of the faster flow. This process leads to the generation of recirculation patterns within furnaces that can, in several circumstances, cause problems. It is not always vital that the designer be able to quantify these effects, but an awareness of their existence and potential impact is of use in anticipating and diagnosing problems. Since sidewall and axial jets are commonplace in combustors, their behavior merits special attention.

1. Sidewall Jets

Recirculation patterns are generated within furnaces with sidewall jets by the entrainment of furnace gases into the jet flow. The entrainment coefficient J, defined as the ratio of the influx velocity component perpendicular to the jet axis $\bar{v}_m$ to the centerline jet velocity $\bar{u}_m$, can be estimated for round jets as follows:

Identify the jet's outer surface as that bounded by the points where the velocity is one-half of the centerline velocity. This surface is conical and may be characterized by the jet half-angle φ_0. The jet diameter is then $2x\tan\varphi_0$, and the area of influx over a distance dx is $2\pi x\tan\varphi_0\,dx$.

The influx mass rate is m_x, given by Eq. (5) where $m_0 = \frac{1}{4}\bar{u}_0\rho_0\pi d_0^2$. The influx volume flow is $\dot{m}_x/\rho_x$. Then the influx velocity and the entrainment coefficient are given by

$$\bar{v}_m = \frac{1}{2\pi\rho_a x\tan\varphi_0}\left(\frac{d\dot{m}_x}{dx}\right) \tag{60}$$

$$J = \frac{\bar{v}_m}{\bar{u}_m} = 0.0063\cot\varphi_0 \tag{61}$$

and for $\varphi_0 = 4.85^\circ$, $J = 0.075$ and

$$\bar{v}_m = 0.47\bar{u}_0\left(\frac{\rho_0}{\rho_a}\right)^{1/2}\frac{d_0}{x} \tag{62}$$

In many instances, a linear array of round jets is used. For many small jets, positioned close together, the jet flows merge a short distance from the nozzle and the flow field becomes similar to that of a long slot jet.

For an array of round jets of diameter d_0 and for a distance s center to center, the width y_0 of a slot jet of equivalent mass flow is given by

$$(y_0)_{\text{equivalent}} = \frac{\pi d_0^2}{4s} \tag{63}$$

For this situation or for the slot jet itself:

$$J = 0.051 \tag{64}$$

$$\bar{v}_m = 0.127\bar{u}_0\left(\frac{y_0}{x}\right)^{1/2}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \tag{65}$$

EXAMPLE 2. A round jet with a diameter of 10 cm is situated on the sidewall of a furnace. Air at 27°C is discharged into the furnace at a velocity of 15 m/sec. Calculate the influx velocity as the jet moves across the furnace. Do the same for a linear array of 1.5-cm-diameter jets on 6-cm centers with a $\bar{u}_0$ of 60 m/sec.

The mean temperature of the furnace gases is 1027°C and has a mean molecular weight approximately the same as air.

For the round jet, noting that with similar molecular weights the density ratio is given by the inverse of the absolute temperature ratio, Eq. (62) indicates

$$\begin{aligned}\bar{v}_m &= 0.47(15)(1300/300)^{1/2}(0.1)(1/x)\\ &= 1.47/x\end{aligned}$$

For the array of jets, the equivalent slot width is given by Eq. (63) as

$$\begin{aligned}(y_0)_{\text{equivalent}} &= \pi(0.015)^2/(4)(0.06)\\ &= 0.00295 \text{ m} = 0.295 \text{ cm}\end{aligned}$$

and from Eq. (65)

$$\begin{aligned}\bar{v}_m &= 0.127(60)(0.00295)^{1/2}(1300/300)^{1/2}(1/x)^{1/2}\\ &= 0.861(1/x)^{1/2}\end{aligned}$$

The resulting velocity field is show in Fig. 21.

The primary significance of these calculations lies in the demonstration that, in the region of the nozzle face, a substantial velocity field will exist, with furnace gas moving along the wall toward the jet. This flow increases the convective heat flux to the wall in the vicinity of the nozzle (raising wall temperature) *and* scours the wall with entrained fly ash.

If the resulting wall temperature is below the fly-ash sticking temperature, some (though probably minor) wall erosion may occur. If the wall temperature is high enough so that the fly ash adheres, a buildup of slag mass will occur. This phenomenon (known as "bearding") is well known in refractory municipal refuse incinerators where slag accumulations often surround sidewall jet orifices. Slumping or melting of the slag can occur until the overhanging mass is chilled by the cold air jet. The resulting overhang of slag can deflect the jet into the refuse bed, increasing the entrainment of fly ash and, if severe deflection occurs, resulting in a blow-pipe heating effect with consequent destruction of the metal grate.

Beyond the specific effects of jet-driven recirculation noted above, it is well to keep in mind the more general concept that regions of steep velocity gradients will always lead to an inspiration effect with consequent perturbation of the flow field.

2. Axial Jets

The discharge of a jet of fuel and/or air down the axis of a combustor induces recirculation flow, which, in extreme cases, can be the controlling influence in establishing combustor

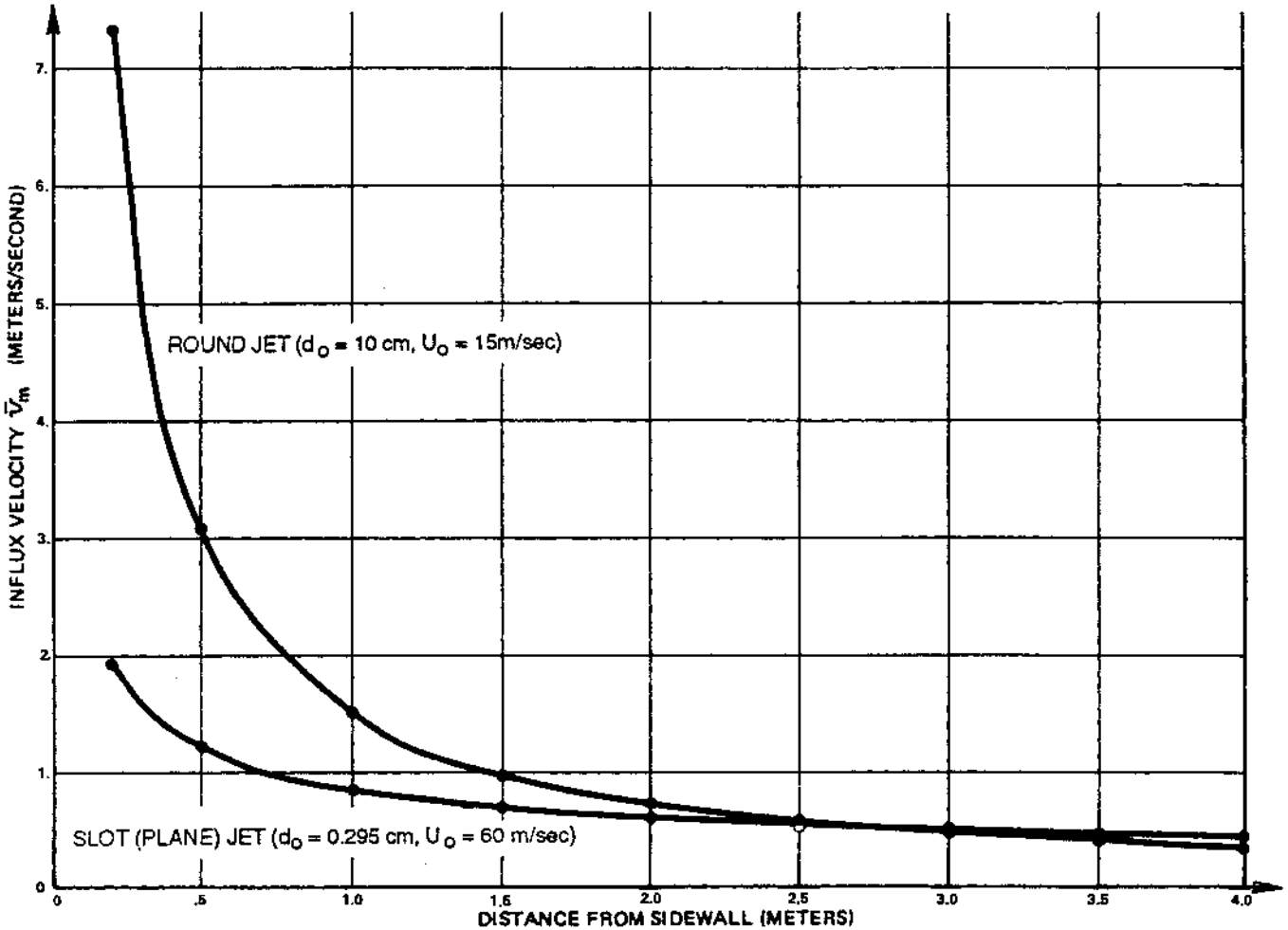


Figure 21 Entrainment velocities of side-wall jets.

performance. Such cases include the long, cylindrical axially fired liquid waste incinerator and most rotary kilns.

The theory of Thring and Newby (103), though supplanted in refinement and accuracy by the work of Craya and Curtet (104), Barchilon and Curtet (105), and Hill (106), provides for relatively simple formulations to identify the approximately location of the point C where disentrainment begins (Fig. 22a).

The Thring–Newby theory [here, modified by Field et al. (13)] assumes that the jet entrains as a free jet up to the point C (at $x = x_c$). Thus, the total entrainment up to this point (the net recirculation flow m_r) is given, using Eq. (5), as

$$\dot{m}_r = \left[0.32 \left(\frac{\rho_a}{\rho_0} \right)^{1/2} \frac{x_c}{d_0} \dot{m}_0 \right] - \dot{m}_0 \tag{66}$$

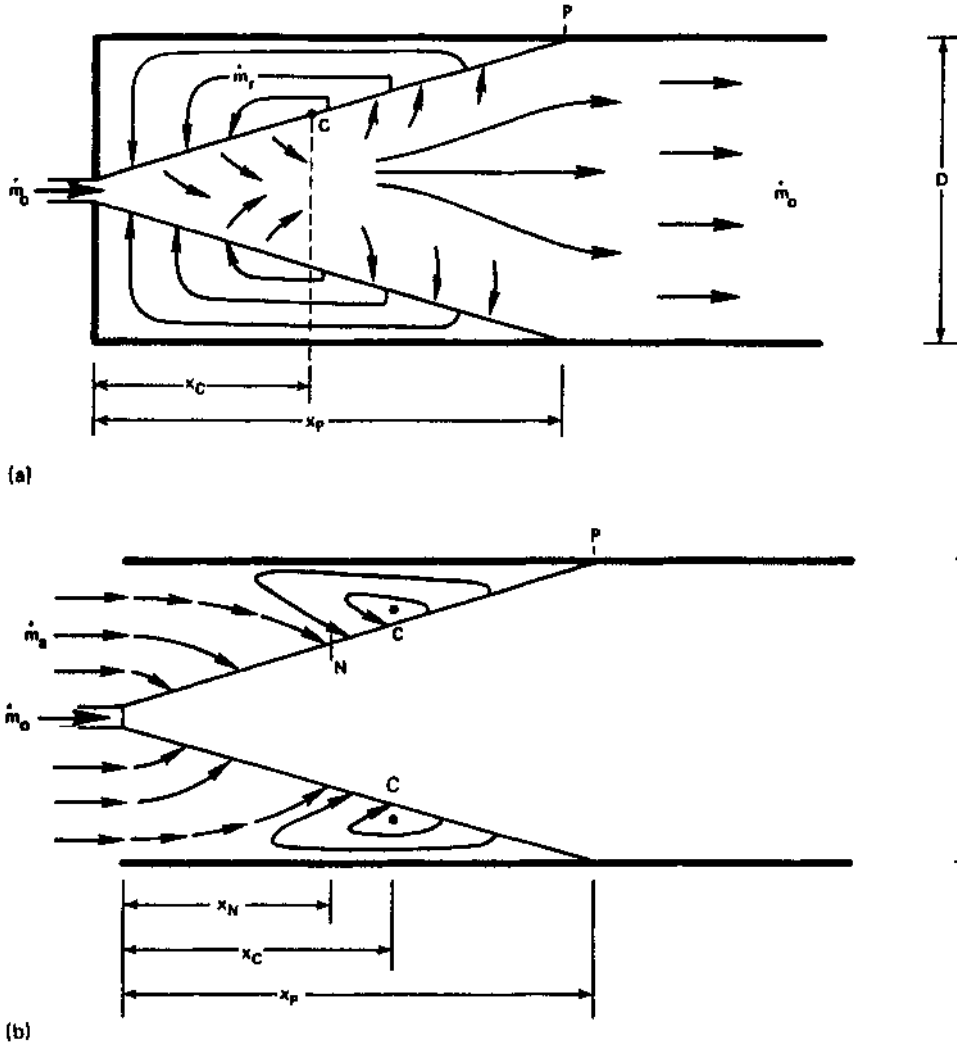


Figure 22 Recirculation flows in cylindrical chamber: (a) flow in chambers with one end closed; (b) flow in open-ended chamber.

The point C is postulated to lie midway between the point x_0 where entrainment begins ($\dot{m}_x = \dot{m}_0$), according to Eq. (5), and the point P where the envelope of an unconfined jet would strike the wall. From Eq. (5),

$$x_0 = \frac{d_0}{0.32}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \tag{67}$$

Assuming a jet angle of 9.7°, the jet strikes the wall at a distance x_P, which, relative to the duct diameter D, is given by

$$x_P = 2.925D \tag{68}$$

Thus, x_C is given by

$$x_C = \frac{1}{2}\left[x_P + \frac{d_0}{0.32}\left(\frac{\rho_0}{\rho_a}\right)^{1/2}\right] \tag{69}$$

A parameter ω is then defined:

$$\omega = \frac{d_0}{D}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \tag{70}$$

hence

$$x_C = \frac{1}{2}\left(x_P + \frac{D\omega}{0.32}\right) \tag{71a}$$

$$= D\left(1.467 + \frac{\omega}{0.64}\right) \tag{71b}$$

$$\frac{\dot{m}_r}{\dot{m}_0} = \frac{0.47}{\omega} - 0.5 \tag{72}$$

For the case where a secondary air flow of mass flow $\dot{m}_a$ but a negligible momentum is introduced (as in a kiln), it is assumed that the secondary air is entrained by the primary jet flow before any recirculating gas is entrained. For this situation, an equivalent nozzle diameter d_0 is calculated as

$$d_0' = \frac{2(\dot{m}_0 + \dot{m}_a)}{(\pi\rho_0 m_0 \bar{u}_0)^{1/2}} \tag{73}$$

Equation (72) still holds, but now the left side is $\dot{m}_r/(\dot{m}_0 + \dot{m}_r)$, and ω' is given by

$$\omega' = \left(\frac{\dot{m}_a + \dot{m}_0}{\dot{m}_0}\right)\frac{d_0'}{D}\left(\frac{\rho_0}{\rho_a}\right)^{1/2} \tag{74}$$

The theory then gives the position N, where recirculation entrainment begins (x_N), and the position C, which is the core of the recirculation eddy (x_C), as

$$x_N = 3.125\omega' D \tag{75a}$$

and

$$x_C = 1.56(\omega' + 0.94)D \tag{75b}$$

The distance to the point P where the jet strikes the wall (x_P) is as in Eq. (66) and

$$\frac{\dot{m}_r}{\dot{m}_0 + \dot{m}_a} = \frac{0.72}{\omega'} - 1 \tag{76}$$

Data from cold models and hot furnaces show that Eq. (72) fits the slope of the data but is consistently high in its estimation by an increment of about 0.25 in a plot of $\dot{m}_r/\dot{m}_0$ vs. $1/\omega$. A similar comparison of data using Eq. (76) (plotting vs. $1/\omega'$) overpredicts the mass flow ratio by up to a factor of 1.7 (at $1/\omega' = 7$) but joins the data at $1/\omega' = 2$.

The position of points N, C, and P, in data compared by Field et al. (13), gave a reasonable fit. The fit was improved, however, by using a narrower effective jet angle (9.2° vs. 9.79°) in estimating x_P.

It should be noted that these analytical expressions are valid only for d_0'/D less than about 0.05.

B. Buoyancy

In many incinerator furnaces, it is desired to minimize gas velocities. This design objective is usually established to minimize entrainment of particulate matter. When boiler tubes are immersed in the flow, avoidance of erosion metal wastage is also important.

One approach to estimating the velocities in the furnace imagines all heat to remain in the gas (thus giving the gases a maximum volumetric expansion), and to calculate the mean velocity by dividing the volumetric flow rate by the furnace cross-sectional area. Although such an approach may be useful for preliminary estimates, the potential impact of buoyancy forces, accelerating the gases to many times the "average" velocity, should be carefully considered.

The acceleration of gases from an initial velocity u_0, elevation y_0, and pressure P_0 is described by Bernoulli's equation:

$$u^2 = u_0^2 + \frac{2(P_0 - P)}{\rho_0} g_c - 2g(y - y_0) \tag{77}$$

Case 1. The furnace may be considered to be well sealed and to consist of two zones: (1) a hot gas flow and (2) a cold, stagnant (or slowly moving) gas zone.

This case might be typified by a sealed municipal incinerator with the hot gases arising from the refuse bed and the colder gases (over the residue quench tank) moving out slowly. Here, the change in static pressure ($P_0 - P$) for the cold gas, as the flows rise through a vertical outlet flue, is also experienced by the hot gas. Noting that the ratio of absolute temperatures is the inverse of the ratio of densities, writing Eq. (77) for both flows and combining yield

$$(u^2)_{\text{hot}} = (u_0^2)_{\text{hot}} + 2g(y - y_0)\left(\frac{T_{\text{hot}}}{T_{\text{cold}}} - 1\right) \tag{78}$$

Case 2. As for Case 1 but with a "leaky" furnace so there is ready communion with the atmosphere.

This case is common for many older municipal incinerators. Under these conditions, there is an interaction between the hot and cold gases and ambient with both the furnace gas

streams accelerating, but with the acceleration of the hot zone being more pronounced. In this case:

$$(u^2)_{\text{hot}} = (u_0^2)_{\text{hot}} + 2g(y - y_0)_{\text{hot}}\left(\frac{T_{\text{hot}}}{T_a} - 1\right) \tag{79a}$$

$$(u^2)_{\text{cold}} = (u_0^2)_{\text{cold}} + 2g(y - y_0)_{\text{cold}}\left(\frac{T_{\text{cold}}}{T_a} - 1\right) \tag{79b}$$

and for roughly equal elevation changes

$$(u^2)_{\text{hot}} - (u^2)_{\text{cold}} = (u_0^2)_{\text{hot}} - (u_0^2)_{\text{cold}} + 2g(y - y_0)_{\text{average}}\left(\frac{T_{\text{hot}} - T_{\text{cold}}}{T_a}\right) \tag{79c}$$

EXAMPLE 3. In a large, well-sealed furnace, 6000 m^3/min of gases leave the burning refuse bed at a temperature of 1100°C (1373 K), at elevation 12.5 m, and at velocity 1.2 m/sec. At the end of the furnace, 25 m^3/min of quench tank vapors rise from the tank surface at 300°C (573 K) and 0.1 m/sec. The two gas flows leave through a vertical outlet flue at the top of the chamber. The entrance to the flue is at elevation 17.5 m and the flue cross-sectional area is 65 m^2. Estimate the average velocity through the flue and the possible peak velocity in consideration of buoyancy effects. Neglect the flow area for the cold gases.

Mean velocity:

$$\begin{aligned}\bar{v} &= \frac{\text{volumetric flow rate}}{\text{flue area}} \\ &= \frac{6000}{65}\ \text{m/min} \\ &= 92.31\ \text{m/min, or } 1.54\ \text{m/sec}\end{aligned} \tag{80}$$

Buoyancy-affected velocity from Eq. (78):

$$(u^2)_{\text{hot}} = (1.2)^2 + 2(9.807)(17.5 - 12.5)\left(\frac{1373}{573} - 1\right)$$

$$u_{\text{hot}} = 11.76\ \text{m/sec}$$

Clearly, the almost eightfold increase in velocity will not fill the outlet flue: There will be a "necking down" of the hot gas flow envelope in accord with the basic continuity equation:

$$\text{(density)(velocity)(area)} = \text{constant} = \text{mass flow rate} \tag{81}$$

Note also that for a "leaky" furnace and an ambient temperature of 20°C (293 K):

$$u_{\text{hot}} = 19.05\ \text{m/sec}$$

$$u_{\text{cold}} = 9.68\ \text{m/sec}$$

Beyond these conclusions (which could allow the designer to make judgments regarding such matters as tube erosion effects at the entrance to a boiler-tube bank in the outlet flue) it should also be evident that such accelerations will significantly shorten the residence time of the burning/burned gases in the furnace chamber. Thus, just as volumetric flow rate and flue area did not produce a good estimate of exit velocity, neither will volumetric flow rate and chamber volume necessarily produce a good estimate of mean residence time unless (1) the furnace is well sealed, and (2) the system is of relatively uniform temperature.

III. MIXING AND RESIDENCE TIME

Vague references to the "3 T's" of time, temperature, and turbulence are often made as if this secret provides the key to the achievement of good combustion performance. Unfortunately, the effluent streams from real combustors do not have a single, unique time or temperature characterizing their history in the system. The real case is one where the flow is described best with distribution functions of stay-time and of temperature. The mathematical characteristics of the two distributions (e.g., the standard deviation and skewness of the distribution) differ, and neither is routinely measured. Also, "turbulence" is a concept well understood in theory and readily observed in the fluid flow laboratory but difficult to quantify, measure, and design for in practice. Thus, it is appropriate to look more closely at these critical system characteristics as an aid to design and performance troubleshooting.

Attaining a temperature high enough to stimulate vigorous reaction rates, a degree of mixing (with oxygen) complete enough to ensure rapid oxidation, and a stay-time long enough for substantial burnout is vital in hazardous waste incineration. The achievement of destruction-removal efficiencies at the 99.9999% level is required in the United States for polychiorinated biphenyl (PCB) and a few other designated compounds. Performance to the 99.99% level is mandated for all others. For the PCBs this means that only one part in one million of PCB in the feed stream can fail to meet or exceed the minimum temperature/stoichiometry/time scenario that completes the destruction reactions.

However, it is likely that most of the unoxidized, emitted material is not a residual "heel" of an overall reaction that is quenched just short of completion by the reaction-quenching effect of a wet scrubber or the like. Instead, the unreacted material is more likely to be contained in those packets of chamber gases that never made it to satisfactory combustion conditions: "failure modes" brought about by chilling at cold walls, excessive dilution and cooling by air in-leakage, weak mixing with combustion air so only the (slower) pyrolysis reactions were operative, etc. Thus, when one speaks of the problem of achieving a high efficiency of destruction, one is concerned not with the temperature, residence times (say, calculated from the chamber volume and average volumetric gas flow rate), and the oxygen concentration of the bulk flow, but rather with the "low-end tails" of the temperature, time, and oxygen distribution functions: that is, the fraction of the flow that experiences temperatures below the ignition temperature, substoichiometric oxygen concentrations, etc. Thus, a part of understanding this type of "failure" will come from improved understanding of the distribution functions of time, temperature, and oxidant concentration that characterize the system behavior. Residence time provides a useful model for this investigation.

A. Fundamental Distribution Relationships

Each packet of gas in the effluent from an incineration system possesses a history. The duration of the packet's stay in the system is one such type of history, and it is definable in statistical terms. With each distribution of residence times we can associate a function $F(t)$ with the property that it is equal to the fraction of packets possessing a residence time t or less. There is a complementary function $F^*(t)$ such that

$$F^*(t) = 1 - F(t) \tag{82}$$

The functions $F(t)$ and $F^*(t)$ can be viewed as probabilities: $F(t)$ is the probability that a given packet remains in the system for a time t or less and $F^*(t)$ the probability of its

residence time exceeding t. The derivative of $F(t)$ with t is the probability that the residence time falls between t and $t + dt$. That is,

$$f(t) = \frac{dF(t)}{dt} = -\frac{dF^*(t)}{dt} \tag{83}$$

and the fraction of material that has been in the system for a time between t_1 and t_2 is given by

$$Y_{1,2} = \int_{t_1}^{t_2} f(t)dt \tag{84}$$

The expected or "average" residence time $E_f(t)$ equals (420)

$$E_f(t) = \int_0^\infty t \cdot f(t)dt = \int_0^\infty F^*(t)dt \tag{85}$$

B. Common Distribution Functions

The residence time distributions in real systems are complex. In the analysis of these distributions, however, it is often found that the real case can be evaluated as though it were comprised of a system of several common, simplified flow scenarios modified by possible "failure modes." For convenience in these evaluations, we make use of a reference residence time. For isothermal operation and with a system volume of V and a volumetric flow rate (at the system temperature) of v, the reference residence time (θ) is given by

$$\theta = V/v \tag{86a}$$

For a time of interest t, a dimensionless measure of time may be formed as

$$\xi = t/\theta \tag{86b}$$

1. Plug Flow

The simplest distribution is that of plug flow. When the system operates in plug flow, there is no back-mixing of gas.

For this case, $F(t) = 0$ for $\xi \leq 1$ and $F(t) = 1$ for $\xi > 1$.

2. Perfect ("Well-Stirred") Mixing

For perfect mixing, the concentration throughout the vessel is constant and the residence time distribution is given by

$$F(t) = 1 - e^{-\xi} \tag{87a}$$

and

$$f(t) = \frac{1}{\theta} e^{-\xi} \tag{87b}$$

C. Failure Modes

If one analyzes real systems, two conceptual "failure modes" are useful: dead space and short-circuiting (421).

The concept of *dead space* takes account of circumstances when, due to the character of the flow field, a portion of the chamber volume is not in steady flow but contains a recirculating eddy. Thus, the effective volume of the chamber is less than that calculated from the physical dimensions. Examples of such dead space include the outside corner and the downstream wall on the inside corner for a right-angle turn in a rectangular duct or the recirculating eddy in the larger duct just after a sudden expansion before the entering jet attaches at the wall.

The concept of *short-circuiting* presumes that a portion of the flow passes through the chamber to the effluent with "infinite velocity." This type of bypassing was observed by Guilliland and Mason (347) in fluid beds and was associated with large bubbles that moved rapidly through the bed with little or no contact with the bed solids. In combustion analyses, this might also be a useful representation of a portion of the flow below the ignition temperature.

D. Residence Time Scenarios

1. Perfect Mixing with Plug Flow

This combination is the ideal scenario from the standpoint of combustion: a well-mixed zone where reactions are fast (accelerated by the feedback of heat and free radicals to the incoming feed stream) followed by a burnout, plug-flow zone. Note that a system that is 100% well mixed is *not* optimal since, by definition, unless the volume is infinite, the composition of the reaction mass (a blend of reaction products and raw feed) in the volume must include unreacted feed.

If we assume that the system consists of two parts: a fraction $(1-p)$ in which the material moves with perfect mixing followed by a fraction p in plug flow. For this case (421), the residence time F function is given by:

$$F(t) = 1 - e^{-[1/(1-p)](\xi - p)} \qquad F(t) \geq 0 \tag{88}$$

Figure 23 shows the system response for several values of the parameter p.

2. Perfect Mixing with Dead Space

This system is, in essence, a perfectly mixed zone that is smaller by the fraction d: The perfectly mixed volume is $(1-d)V$ and the dead space dV. The F function for this scenario (421) is given by

$$F(t) = 1 - e^{-[\xi/(1-d)]} \qquad F(t) \geq 0 \tag{89}$$

Figure 24 shows the system response for several values of the parameter d.

3. Perfect Mixing with Partial Short-Circuiting

This system considers a fraction f of the entering feed to pass to the outlet with an infinite velocity and the fraction $(1-f)$ to move through a perfect mixing zone. The distribution F function for this scenario (421) is given by

$$F(t) = (1-f)e^{-\xi(1-f)} \qquad F(t) \geq 0 \tag{90}$$

Figure 25 shows the system response for several values of the parameter f.

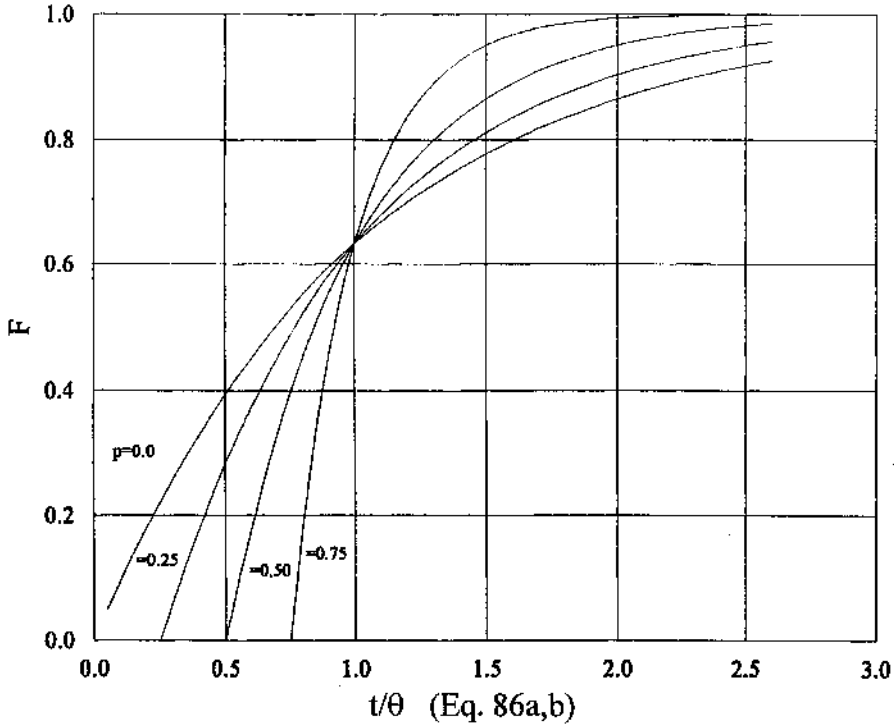


Figure 23 Perfect mixing with plug flow. [From (421)]

4. General Case

Wolf and Resnick (421) considered the general case where one was analyzing experimental data in an evaluation of a system comprised of a mixture of plug flow and perfect mixing with dead zones and short-circuiting. Their consideration included the effects of uncertainties in the calculated residence time due to experimental errors and, in addition, lag times between actual effluent gas composition changes and reported changes (e.g., as through holdup in sampling lines). Their assessment of the resulting F function was given by

$$F(t) = 1 - e^{-\eta[\xi-(\varepsilon/\theta])} \qquad F(t) \geq 0 \tag{91}$$

The term η can be considered as a measure of the efficiency of mixing: equal to unity for perfect mixing and approaching infinity for the plug flow case. Dead space also results in η greater than unity. Short-circuiting results in η less than unity. Errors in the evaluation of the average residence time could make η greater than or less than unity.

The term ε is a measure of the phase shift in the system. If $\varepsilon/\theta > 0$ (the case for plug flow or a system lag), the system response lags behind that expected for perfect mixing. Short-circuiting gives a negative value for ε.

If one analyzes reported residence time distributions for single-stage systems, one finds that the data can be replotted as $\ln[1 - F(t)]$ vs. ξ to yield a straight line. Then η and ε can be determined from the slope and intercept. Note, however, that behavior inferred from

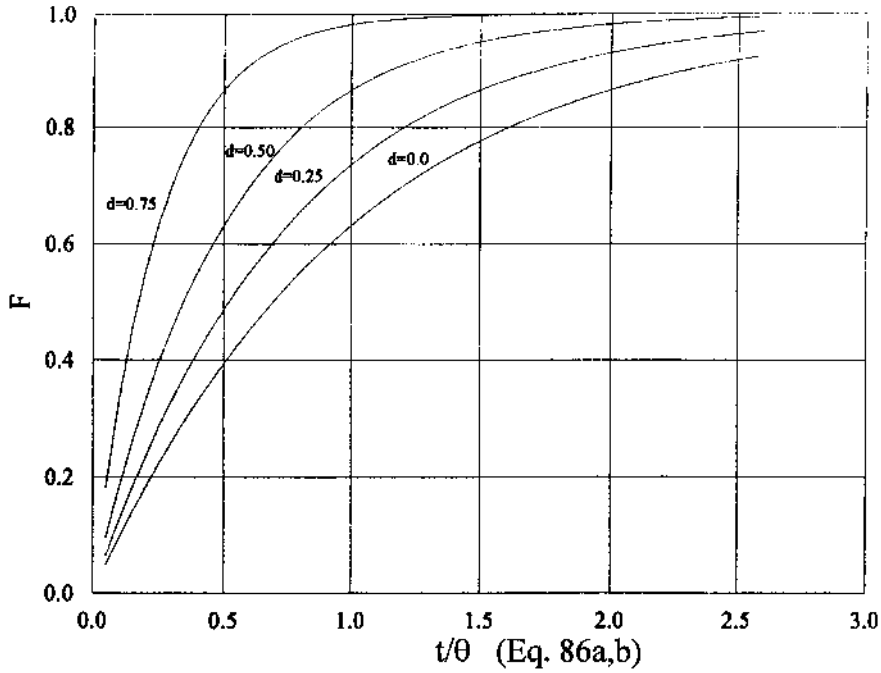


Figure 24 Perfect mixing with dead space. [From (421).]

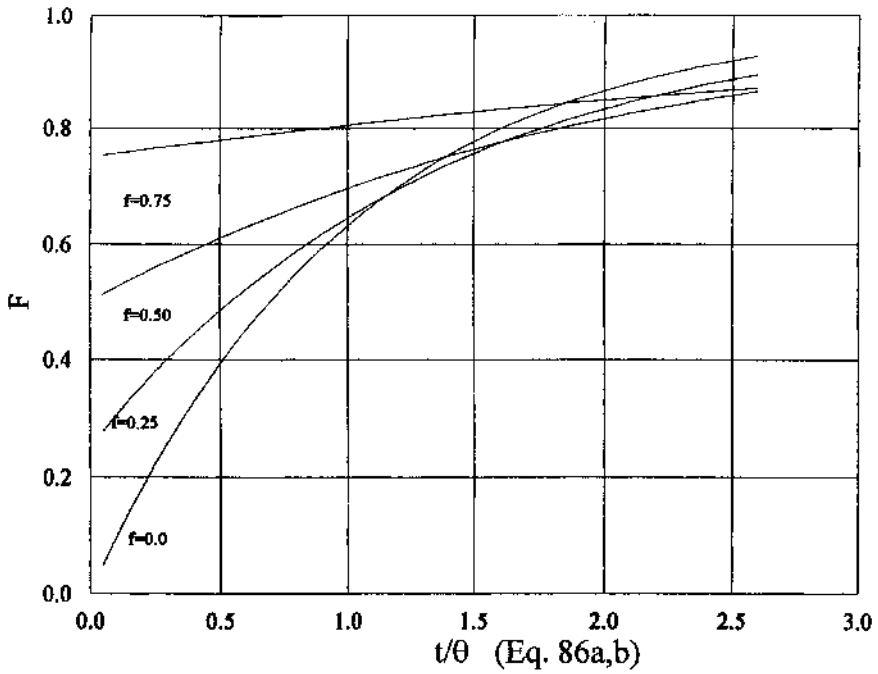


Figure 25 Perfect mixing with short circuit. [From (421).]

Table 4 Residence Time Data and Correlating Parameter Values

Ref.	Flow System	Derived Values η	Derived Values ε	a Perfect mixing of effective volume %	p Plug flow of effective volume %	d Dead Space of total volume %	f Short circuiting of flow rate %	L Lag of θ %
422	Turbulent oil in pipe	0.00	1.00	0	100			
423	Laminar oil in pipe	2.56	0.50	44	56	11		
424	Gas fluidized bed	1.74	0.42	58	42			
347	Gas fluidized bed	1.30	0.30	77	23			7
347	Gas fluidized bed	1.20	0.16	84	16			
347	Gas fluidized bed	1.10	0.08	92	8			
347	Gas fixed bed	7.95	0.84	13	87	3		
347	Gas in pipe	13.40	0.92	8	92			
425	Gas fluidized bed	1.15	0.17	87	13			4
425	Gas spherical stirred reactor	1.00	0.00	100				
426	Gas fluidized bed	2.12	0.34	58	42	19		Indefinable
427	Gas fluidized bed	1.50	0.29	70	30	4		
427	Gas fluidized bed	2.05	0.25	58	42	20	5	9
428	Liquid fixed bed	3.15	0.70	32	68			2
429	Gas fluidized bed	2.20	0.55	45	55			
430	Gas fluidized bed	0.70	−0.25	100			30	25
430	Gas fluidized bed	0.74	−0.30	100			26	10
430	Gas fluidized bed	0.68	−0.20	100			32	36
431	Solid fluidized bed	1.23	0.10	89	11	9		

the η and ε values based on a given mathematical model of the situation is not necessarily an accurate representation of the physical situation. For example, a model represented by a combination of perfect mixing, plug flow, and dead space could equally well be represented by perfect mixing, dead space, and sampling lag. However, such an analysis may give some insights and/or allow the testing of various hypothetical scenarios.

Table 4 presents the result of an analysis of published residence time data (421). The derived values for η and ε were taken from plots of $\ln[1 - F(t)]$ vs. ξ. Further, a flow model was postulated that would give the measured result as a combination of perfect mixing, plug flow, and dead space plus a lag time. The factor a is the percentage of the total volume assumed to be perfectly mixed. The factor L was the lag of the residence time θ as a percent.

7

Materials Preparation and Handling

Probably no single element of incineration systems causes more problems than those related to the handling of wastes. One of the most significant differences between liquid and gaseous waste incineration systems and those for sludges and solids concerns the equipment used to collect, transport, store, reclaim, and fire the wastes. In many cases, weaknesses or failures in the design of materials handling subsystems have greatly reduced the utility and increased the operating and maintenance problems and costs of solid or sludge waste management facilities.

I. SOLID WASTES

A. General

In comparison with sludges, most solid wastes usually have a low bulk density and, except for process wastes, include a substantial fraction of cellulose (wood, paper, cardboard). The low bulk density requires relatively large storage space and often involves rehandling of the waste (stacking) to increase storage capacity. For hazardous waste materials that present a toxicity problem to plant personnel, enclosed storage such as single-outlet bins, multiple-outlet silos, and portable bins are required. Municipal solid wastes can be stored using a number of techniques, as shown in Table 1.

Multiple-outlet silos are useful to store small or medium quantities since they rely on gravity to discharge the solids. Therefore, hopper slopes and outlet dimensions must be generous enough to ensure uninhibited flow. Single-outlet bins are common in industry. These bins use funnel-flow with steep, pyramidal hoppers sloping 60° or less from the horizontal. Portable bins are commonly used for on-site waste accumulation at industrial and commercial sites. In many instances, the container is equipped with a hydraulic compactor to increase capacity and reduce the frequency of pick-up.

In small facilities, domestic solid wastes are often dumped on a tipping floor and pushed about or stacked using a front-end loader. In larger plants, a concrete pit and bridge crane system is more common. Pit and crane systems are much more costly than the floor dump approach.

Table 1 Types and Characteristics of Dry Bulk Storage

Storage technique and method of reclaim/discharge	Storage capacity		
	Small (<550 m^3)	Medium	Large (>20,000 m^3)
Stockpiles			
Bottom tunnel		X	X
Bucket wheel			X
Scraper truck			X
Front-end loader	X	X	
Multiple-outlet silos			
Mass flow	X	X	
Expanded flow	X	X	
Funnel flow	X	X	
Single-outlet bins			
Mass flow	X		
Expanded flow	X	X	
Funnel Flow	X	X	
Portable bins			
Funnel flow	X	X	
Mass flow	X		
Concrete pits			
Grapple	X	X	X

Source: From (501).

Rubber belt and steel apron or vibrating conveyors have been used to transport raw and shredded solid waste for short distances. Pneumatic systems have been used with shredded wastes for transport for over 300 m. Frequent and severe problems with abrasion wastage of the piping and with plugging indicate that pneumatic conveyors should be selected only when absolutely necessary and designed with an absolute minimum of turns. Conveyors of any type for solid wastes can be counted on to present a continuing problem with maintenance and housekeeping.

Storage and reclaim of solid wastes is also a problem area. Frequent bridging problems in chutes or in bins, compaction on standing, and other operating difficulties in confined flow situations are common. These problems result from the tendency of solid wastes to interlock, catch on minute projections, and compress. Forced expulsion through flaring cross-sections (e.g., with a ram) or open storage in pits or on open floors are preferred. For bunkered shredded waste, bins with vertical screws (to keep the bed uncompacted) and "live bottom" design have been effective.

The most common materials handling options and problem areas in solid waste management facilities are summarized in Table 2.

B. Pit and Crane Handling of Solid Wastes

The pit and crane approach for refuse receiving, storing, and charging is used worldwide in large incinerator plants. The crane operator is a key member of the incinerator staff. His or her duties include diversion of troublesome bulky items; mixing of segregated, highly combustible and noncombustible wastes to even out the heat release rate in the furnace;

Table 2 General Practices in Materials Handling for Domestic Solid Waste

Step	Small plant	Large plant	Problem areas
Receipt	Manual scale	Automatic scale	Delays
Storage	Floor dump	Pit/crane	Cleanout, vectors, fires, mixing
Reclaim	Front-end loader from storage	Grapple	Personnel hazard
Feed	Ram	Ram, chute	Outage, jams
Support during burn	Hearth	Metal grate	Overheating, clinker
Residue	Water quench, drag conveyer	Water quench, hydraulic ram and vibrating conveyer	Jams
	Special processes		
Shredding	Impractical	Hammermill, shear shredder	Explosions
Ferrous separation	—	Belt or drum magnet	Contamination
Battery removal	Floor dump and visual check	Floor dump and visual check	Delays

and relocating and stacking the pile of waste that builds directly below the tipping positions in order to increase the usable storage capacity of the pit.

In most plants, the pit is sized to hold waste corresponding to three days' production. The pit is usually constructed to match the *ultimate* capacity in plants laid out with expansion in mind. The type of construction and the cost of outages for expansion of the pit at a later time make this a cost-effective investment decision. The usable volume of the pit certainly includes all volume below the tipping floor. By stacking the waste against the back wall, about 50% of the pit volume above the tipping floor level can also be assumed to be available.

The pit is approximately 9 to 14 m deep (from the tipping floor to the bottom). This allows several vehicles to dump before crane action to restack the waste is necessary. The pit length is determined by the space for the feed hoppers and the furnace boiler spacing. In some instances, the number of available tipping bays is specified. A rule of thumb (361) for the required number of tipping bays is given by

$$\text{number of bays} = (1/6) \times \text{maximum number of trucks per hour} \quad (1)$$

This allows about 10 minutes' average for truck positioning, dumping, cleanup, and departure. Data on the intensity of truck arrivals may be extracted from records in existing facilities (such as the landfill). A conservative assumption suggests that the plant's rated capacity in solid waste will be delivered in 5-tonne packer trucks, delivering 7 days' worth of plant capacity in a 5-day period, and that one-half of this delivery will take place in two rush-hour periods per day, each of 90 minutes' duration. Back-calculating from this scenario, one tipping bay is needed for each 125 tonnes of capacity. Tipping bays should be not less than 410 cm wide. Year-long tests at three large mass burn plants in the United

States (361) indicate that an average refuse density of 325 kg/m^3 should be used to calculate both the above- and below-tipping-floor volume. Empirical estimates of the in-place density of settled refuse after approximately two days' storage showed a logarithmic relationship to bed depth. The relationship describing the average density ρ_{refuse} for domestic, U.S. refuse is given in Eq. (2) for bunkers loaded to a uniform depth D_1. For a bunker with a pile sloped from a front wall depth D_1 to the back wall at D_2, the relationship is given in Eq. (3).

$$\rho_{refuse} = \frac{\ln D_1}{0.019721} + 250 \text{ kg/m}^3 \tag{2}$$

$$\rho_{refuse} = \frac{50.734[D_2(\ln D_2 + 1.1881) - D_1(\ln D_1 + 1.1881)]}{D_2 - D_1} \text{ kg/m}^3 \tag{3}$$

In plants built before 1980, many of the cranes used in the United States were controlled by an operator located in an air-conditioned cab attached to the crane bridge. The operator is located in a stationary pulpit in more recent designs. The pulpit is located on the front side of the pit over the tipping floor, at the end of the pit, or on the back side of the pit between the furnace hoppers in order to provide a view of the tipping area, the storage pit, and the furnace hoppers. In larger plants, the pulpit is sized for two operator stations. The tipping area is very dusty, and care must be given in the design of the environmental systems (air conditioning, fresh air make-up, etc.) to maintain a positive pressure within the pulpit work space.

In most plants, combustion air is drawn from the pit area both for dust control and to minimize the emission of odors. To minimize clogging of inlet screens by airborne dust, fiber, and paper, the air intakes should be located as high as possible above the pit. The capture velocity of the air intake openings should be in the range of 2.5 to 5.0 m/sec (preferably closer to the lower value).

Motor controls for remote-operated refuse handling cranes are, preferably, located off-board the crane in a clean, well-ventilated room (360). This eliminates vibrations, shock, and impact loads and reduces maintenance difficulty and cost. With such an arrangement, conductors are required to deliver current to the individual motors of each motion located on the crane and to control other devices such as limit switches located on the crane. The current-carrying conductors are high-voltage conductors and consist of between 6 and 10 conductors *per motion*. The control conductors are low voltage and use 2 to 6 conductors *per control device*. Most often, the pulpit and control center are linked to the crane using festooned conductor systems rather than a rigid-type conductor system with sliding shoe-type collectors.

In many modern plants, a number of the crane motions have been reduced to automated sequences called by the operator. These include hoisting of the loaded grapple, homing movements of the trolley and bridge to bring the loaded grapple to a selected hopper, lowering of the loaded grapple into the hopper, discharging the refuse, hoisting the empty grapple, and returning to a selected pit position.

The changing nature of refuse size consist, density, and mechanical properties demands much of the equipment used to grasp, lift, and drop waste. The types of grabs used are most conveniently grouped by the actuation method and basic shape of the device. Opening and closing are either by a wire rope system or an electric-hydraulic (EH) system. The principal shapes are the two-jaw clamshell or the multi-tine "orange peel" type.

The long tine, clamshell grapple was preferred in United States practice for many years. The grapple consists of two cutaway jaws with long, pitchfork-type tines fastened to

the bottom lip of the jaws. The better digging capability of this design led it to replace conventional clamshell buckets with short teeth. Most still in use are of the three-rope suspension (two holding ropes and one closing rope) or four-rope suspension (two holding and two closing ropes). They are suspended from the overhead traveling crane having both a holding and a closing hoist. Some plants use EH actuation. Although the capital cost is higher, there is a partially off-setting benefit in increased on-line availability and rope costs (360) because of the superior 3- to 6-month mean time before failure of the hoisting lines (found in both rope-operated and EH devices) in comparison to the 1- to 3-month life of the closing lines (only on the rope-operated grapples).

The orange peel grapple consists of 6 to 8 tines evenly spaced radially. Rope-actuated orange peels are of the four-rope type using an overhead crane with both holding and closing hoists. The EH embodiment has each claw operated by an individual hydraulic ram or a central ram with very rugged linkages to the tines. The capacity of the device is reported to be 15% to 20% higher than the clamshell grapple. Further, the clamshell grapples themselves are approximately 40% to 50% heavier than equivalent orange peel systems. This increased dead weight decreases the refuse lifting capacity by 25% to 35% in comparison to that of the orange peels (360).

C. Size Reduction of Municipal Solid Wastes

Size reduction is a necessary step in the production of refuse-derived fuel (RDF). Also, limited breakdown of as-received waste is sometimes used ahead of mass burning systems to facilitate precombustion materials recovery. The characteristic dimension of refuse after processing for size reduction is often referred to as the "top-size." Clearly, both raw and processed waste is found in a range of particle sizes: from fine dust, with dimensions expressed in microns, to mattresses and furniture dimensioned in meters. The "top size," as most often used, refers to the particle dimension such that only 10% of the mass of the material exceeds the top size. Note that the top size refers to the longest dimension of any given waste element.

Size reduction for solid wastes is a complex process. Unlike coal and most mineral material, only a small fraction of municipal waste breaks down under crushing forces (e.g., glass). Most of the materials in waste deform, stretch, or are simply compressed by crushing forces. Not only is the material not subdivided, but considerable energy is absorbed. This increases the cost of processing without providing the benefit. Thus, we must add shearing, ripping, and cutting action.

In the late 1970s, the U.S. EPA sponsored several studies of size reduction (284, 285). The results of these studies are most interesting and useful. However, one must exercise care in that the structured experiments and limited test objectives that guided the research work may suggest design principles that yield marginal facilities in practice. Refuse is inconsistent in its characteristics. Sudden shifts in waste properties that places unanticipated, heavy demands on undersized equipment operating at high speed with considerable rotating energy can do damage or otherwise shut down critical processes.

Four classes of equipment are commonly used for MSW size reduction:

Swing hammer-type hammermills (horizontal or vertical shaft)
Vertical ring grinder shredders
Flail mill (a lightweight swing hammermill for very coarse reduction)
Rotary shear (a slow-turning cutting-type device with circular cutter disks)

1. Horizontal Shaft Hammermill Shredders

Horizontal shaft hammermills are the most common size-reduction devices used in refuse applications. By adjustment of the spacing in the grate bars at the discharge, the particle size can be varied from very coarse (say, 10 to 15 cm) to fine (2 to 3 cm). The equipment is very rugged, and little presorting is needed. The three basic types of horizontal shaft shredders are shown in Fig. 1. In the early 1960s and 1970s, U.S. practice favored hammer designs involving periodic retipping of the hammers with special weld rod material. Improved materials and increasing labor costs have shifted the preference of many plants to a no-weld, discard concept using a hammer with a replaceable wear cap with a Brinnel hardness over 500.

The topfeed, single-direction configuration is appropriate as the primary (first pass) size reduction device to bring residential or light commercial refuse to a 5- to 15-cm top size. In these devices, the in-feed is generally a free fall down a chute inclined between 60° and vertical. These devices are effective for a wide range of feed characteristics (paper, cans, glass containers, clothing, brush and smaller branches). Disadvantages include their tendency to reject or throw back feed materials (requiring effective containment hoods and curtains), high shock loading on equipment, and surging output rates due to uneven feed rates.

Also, these devices inherently generate "windage," an air flow engendered by the rotating hammers. Windage aggravates housekeeping and can be a matter of concern when materials are shredded that present an inhalation hazard (pharmaceuticals, toxic materials, etc.). Importantly, windage also contributes to the severity of explosions occasioned by shredding containers filled with volatile, combustible liquids. The explosion problem is serious and has taken the lives of workers and caused severe damage to facilities in many plants. Explosion control using fast-acting halon (or equivalent) explosion suppression devices has shown to be effective.

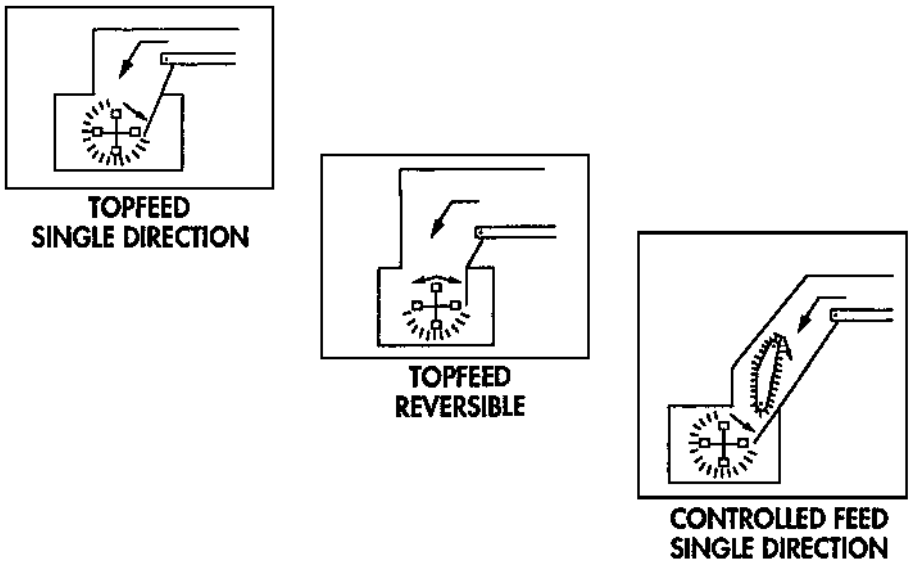


Figure 1 Horizontal shaft shredder types.

Secondary shredders, producing a 2- to 5-cm product, can be of the single-direction or reversible center feed design. The feed to the center feed devices is a free fall close to the rotor center line. The center feed concept was developed on the hypothesis that with reversible motor operation, hammer wear is more even and hammer replacement is less frequent. In fact, most shredding facilities have considerable time available for hammer rotation, and the downtime needed to turn the hammers is not significant. However, the reversible system presents several problems: increased tendency for rejection of feed (due to the more open feed throat) and increased rotor windage.

Heavier, bulky trash or demolition wastes are processed best in the controlled feed configuration where the compression feed device provides positive feed and more uniform power load. The feed enters down a chute at an angle of 45° or more, is gripped by a crawler apron feeder or a drum roller, and is forced at a steady rate into the hammer circle. This design has minimal rejection and shrapnel back-fling, even power consumption, and lesser rotor windage due to the constricted feed throat opening.

Analysis of horizontal shaft shredder data (355) showed that power consumption varied with product particle size according to the following:

$$E_{ow} = 17.91\, X_0^{-0.90} \qquad (r^2 = 0.87) \tag{4}$$

$$E_{ow} = 35.55\, X_{90}^{-0.81} \qquad (r^2 = 0.89) \tag{5}$$

where E_{ow} is the specific energy consumption (kilowatt hours per metric ton processed) on a wet waste basis as a function of X_0 and X_{90}: the product sizes (in cm) corresponding to the 63.2% and 90% cumulative passing, respectively. An effect of the mass of the material being "held up" in the mill was also seen to increase power consumption. No consistent pattern of power consumption with refuse mean moisture content was found, although a "lubricating" effect from the moisture was expected. The power relationships were developed from facilities handling from 4 to 90 metric tons per hour. They are, however, "generalizations" and variations should be expected with design and feed differences.

Typically, motor sizes for shredding are estimated as a combination of the net power for shredding plus the idle power (freewheeling power). Motor size can be estimated from the power demand per ton from Eqs. (4) or (5), the desired throughput, and then division by a factor of 0.9 kwh/hp. Clearly, a considerable safety margin is appropriate. Table 3 provides a selection chart for both shredders and motors.

Hammer wear (and consequent maintenance expense in either replacing or retipping hammers) is second only to power in its importance in shredding economics. Analysis of hammer wear test data (355) showed a range of 0.013 to 0.106 kg/tonne. The wide range reflects the effects of hammer material and hardfacing alloys tested. The greatest wear was sustained by nonhardfaced manganese steels (with a hardness as-cast of 14 R_c). The limiting factor for very hard alloys is the chipping of the welds under high-impact loads. Optimum alloy hardness appears to lie in the range $48 \leq R_c \leq 56$, with the upper value limited by chipping tendencies. In general, this Rockwell range resulted in specific weight loss between 0.015 to 0.03 kg/tonne.

2. Vertical Shaft Mills

Vertical shaft mills use either swing hammers or ring grinders to reduce refuse. Larger mills use a top-mounted, direct drive motor. Most such mills incorporate a conical shell with a progressively smaller clearance between the shell and the rotating grinding units as one moves toward the base. In the vertical shaft, swing hammer device, the in-feed

Table 3 Selection Chart for Shredders and Motors

Shredder size (cm) (Hammer swing diam. × feed width)	106 × 150	150 × 150	150 × 200	180 × 252	216 × 252
	Processing rate (T/hr)				
Packer truck waste (residential)	22.7	36.4	54.5	90.0	136.4
Bulky waste (residential/commercial)	—	18.2	22.7	40.9	54.5
Motor size (hp) (for 10-cm nominal top size)	600	800	1250	2000	3000

Source: From (461).

penetrates the hammers in a converging, conical section reaching a minimum clearance at the "neck." Reduction is by attrition between the hammer tips and anvils spaced around the inner shell. The discharge involves a 90° turn and, due to the rotating action of the mill, the leaving stream tends to load up one side of the discharge conveyor.

Studies of a 746-kW (1000-hp) vertical shaft machine (363) indicated that the Rosin–Rammler equation was adequate as a descriptor of the particle-size distribution. The equation was originally developed in studies of coal grinding (364) and is stated as

$$Y = 1 - \exp[-x/x_0]^n \tag{6a}$$

where

Y = cumulative fraction of particles by weight less than size "x"
n = a constant
x_0 = a constant known as the "characteristic size" defined as the size at which 63.2% of the particles are smaller

Rearranging, one notes that

$$\ln\left(\frac{1}{1-Y}\right) = \left(\frac{x}{x_0}\right)^n \tag{6b}$$

Thus, plotting $\ln[1/(1-Y)]$ vs. "x" on log-log paper yields the slope n and the characteristic size at $\ln[1/(1-Y)] = 1$. The shredder data showed the average $x_0 = 30$ mm (range from 23 to 38 mm) and the average slope $n = 0.7$ (range from 0.6 to 0.9). There was no observable trend in either x_0 or n over the testing period (12,600 metric tons). There was no observable effect of average waste moisture content on the particle-size analysis.

Power consumption averaged 5.71 kwh/tonne comprised of 0.08 kwh/tonne of "freewheeling power" and 5.79 kwh/tonne for the shredding energy. This measure of freewheeling power is much lower than the 10% estimated by other researchers for horizontal shaft mills (355). Hammer wear averaged 4.74 kg/100 tonnes processed and was approximately linear with the quantity of refuse processed.

The ring grinder mills rotate at about one-half the speed of the vertical shaft hammermills (say, 300 vs. 600 rpm) but are otherwise similar. The rotor of these devices is commonly driven from the bottom via a bull gear and pinion.

3. Flail Mills

A flail mill is, in general, a horizontal shaft hammermill with lightweight hammers. The primary function of the mill is for coarse bag breaking and limited size reduction. As such, flail mills have considerably lower horsepower, windage, and space requirements and can process large quantities of material at low cost. Their operation does not produce a highly controllable size consist. Also, their low power makes them more vulnerable to interruptions unless care is given to presorting.

4. Rotary Shears

Rotary shears are low-speed devices (say, 20 to 40 rpm) characterized by two parallel counterrotating shafts (turning toward one another). Disks incorporating one to six cutter teeth (two or three teeth per disk are common) are mounted on the shafts using keys. The shafts rotate at different speeds, often about 2 : 1. Size reduction involves a shearing or tearing action rather than the impact or crushing reduction common in the hammermill. The differences in rotational speed and reduction method lead to a much lower power consumption for waste processing (generally 10% to 20% of the power consumed by a hammermill performing the same reduction). One or more pairs of shredding shafts are mounted at the bottom of a simple, rectangular feed hopper. They discharge to a pan or apron conveyor mounted below.

Shear shredders are particularly well suited to the processing of pallets, drums, automobile tires, furniture, demolition waste, and other relatively large items where coarse size reduction is sought (289). Because of their low speed (few sparks and little heating of the material being processed), open construction, and negligible windage, they are not prone to explosions. Also, in comparison to the hammermills, they are a low-noise and low-dust potential device. They are less applicable to processing paper or ductile sheet materials, especially where small or controlled particle sizes are sought.

5. Noise Levels During Waste Processing

Many of the devices used in waste processing are inherently noisy. This presents problems to neighboring land users and, in the plant, may present hazards to employees. Measured noise levels associated with waste processing are shown in Table 4.

D. Conveying of Solid Wastes

For many bulk solids, the physical and descriptive properties affecting conveying and other materials handling operations fall within a rather narrow band. Those properties fall outside the “normal” range for mixed solid waste, for processed refuse-derived fuel (RDF), and for many waste components. Beyond their unusual “average” characteristics, refuse and refuse component properties often vary widely. Generalizations concerning materials handling, therefore, must be made with care. Further, such generalizations should be used in design with a strong measure of conservative interpretation.

The design of conveyors relies on engineering data on material properties and material handling interactions. The tables that follow present such information for samples of (1) “raw,” municipal solid waste (MSW), (2) shredded, air-classified RDF, (3) a

Table 4 Measured Noise Levels for Refuse Processing Systems

Location	Noise levels (dBA)
Tipping floor	85–92
Shredder in-feed	85–90
Primary shredder	96–98
Magnetic separator	90–96
Secondary shredder	91–95
Air classifier fan	95–120
Shop	78
Control room	70
Offices	67
Maintenance laborer[a]	89
Shredder operator[a]	83
U.S. OSHA[b] (8-hr standard)	90
U.S. OSHA[b] (4-hr standard)	95

[a]Average worker exposure.
[b]Occupational Safety & Health Standards.
Source: From (462).

densified RDF (d-RDF) manufactured in a 13-mm diameter by 10-mm mean length compressed but friable pellet, (4) the "heavy fraction" produced in air classification, (5) the "ferrous fraction" produced by magnetic separation, and (6) a 1 : 1 (by volume) mixture of d-RDF and coal. The data were collected in a comprehensive study of the engineering aspects of conveying (287).

Table 5 indicates the complete list of properties and characteristics that affect conveyability. Table 6 presents a compact descriptor code referencing several key characteristics and properties (287). The confidence with which one can extend the conclusions and recommendations that follow to other refuse types with higher or lower moisture content, with a different content of light commercial or industrial waste, or with other critical variations is uncertain. However, the data provide a starting point for consideration of the materials handling parameters of mixed MSW and its derivatives.

A key measure is the angle of maximum inclination (Table 7) that measures (for a belt conveyor) the angle relative to the horizontal at which an empty conveyor belt will successfully transport the material fed to it. If the belt is inclined at or above this angle, the material being fed will roll back on the belt. Forward motion of material becomes impossible.

The angle of maximum inclination differs from the angle of repose (Table 8), which measures the angle between the horizontal and a sloping line from the top of the pile to the base. It was noted (287) that waste materials seldom form conical piles, so several "angles of repose" appear in a given pile. For d-RDF, the angle varied as the pellets broke down. Loose, degraded pellets produced higher angles than hard, stable pellets. The angle of surcharge is similar to the angle of repose: the angle to the horizontal the surface of the material assumes while at rest on a moving conveyor belt. The results in Table 8 reflect several experimental difficulties. Specifically, the belt was at rest during the measurements

Table 5 Properties and Characteristics of Solid Wastes Affecting Conveyability

Properties (measured)
Abrasiveness[a]
Angle of external friction[a]
Angle of internal friction[a]
Angle of maximum inclination (of a belt)
Angle of repose
Angle of slide
Angle of surcharge
Bulk density, loose
Bulk density, vibrated
Cohesiveness[a]
Flowability, flow function[a]
Lumps: size, weight
Moisture content
Particle hardness[a]
Screen analysis and particle size consist
Sized and unsized material
Characteristics (assessed)
Builds up and hardens
Corrosive
Degradable, size breakdown
Deteriorates in storage, decomposition
Dusty
Explosiveness
Flammability
Harmful dust, toxic gas or fumes
Interlocks, mats and agglomerates
Packs under pressure
Particle shape
Stickiness, adhesion
Contaminable
Very light and fluffy, may be windswept

[a] Test methods for processed solid waste fractions yet to be developed.
Source: From (279).

and, for economy, both the quantity of waste handled and the dimensions of the test belt conveyors were relatively small.

The angle of slide (Table 8) is that angle to the horizontal of an inclined flat surface on which an amount of material will begin to slide downward due to its own weight: an important measurement in design of chutes or diverters. The data in the table show the effects of the type and condition of the underlying surface. The state of compaction and rate of change of tilt in the measurement process also affect the results.

The loose bulk density and the bulk density after vibration for consolidation (Table 9) are other important properties.

Table 6 Material Class Descriptor Codes

	Material Characteristics	CEMA Code[a]
Size	Very fine—less than 100 mesh	A_{100}
	Fine—3 mm or less	B_6
	Granular—75 mm or less	D_3
	Lumpy—containing lumps 400 mm or less	D_{16}
	Irregular—stringy, interlocking	E
Flowability	Very free flowing—angle of respose $<19^\circ$	1
	Free flowing—angle of repose 20° to 29°	2
	Average flowing—angle of repose 30° to 39°	3
	Sluggish—angle of repose 40° and over	4
Abrasiveness	Nonabrasive	5
	Abrasive	6
	Very abrasive	7
	Very sharp—cuts or gouges belt conveyors	8
Characteristics (assessed)	Builds up and hardens	F
	Deteriorates in storage	H
	Corrosive	T
	Degradable—size breakdown	Q
	Dusty	L
	Explosiveness	N
	Flammability	J
	Harmful dust, toxic gas or fumes	R
Characteristics interlocks	Mats down or agglomerates	V
	Packs under pressure	X
	Stickiness—adhesion	O
	Very light, fluffy	Y

[a]Conveying Equipment Manufacturers Association.

Table 7 Angle of Maximum Inclination

Solid waste fraction	Flow rate (ton/hr)	Angle of maximum inclination
MSW	0.9	19
RDF	0.9	21
d-RDF	4.5	30
Heavy fraction	4.5	28
Ferrous fraction	4.5	28
d-RDF/coal (1 : 1 by volume)	9.1	27

Note: Belt width, 45.7 cm, belt idlers, 35 degrees, belt speed, 0.51 m/sec.
Source: From (287).

Table 8 Materials Handling Properties

Solid waste fraction	Angle of repose		Angle of slide		Angle of surcharge		CEMA Code[a]
	Range	Ave.	Steel plate	Conveyor belting	20° idler	35° idler	
MSW	25 – 52	39	29.3	30.0	55	54	E36HJVO
RDF	29 – 49	40	31.0	35.0	51	65	E35HJLXY
d-RDF	27–46	38	32.8	34.5	N/A	49	$D_3$35HJQL
Heavy fraction	30–59	40	27.5	28.5	48	59	E47HQVO
Ferrous fraction	N/A	N/A	N/A	N/A	N/A	52	D_{16}6
d-RDF/coal (1 : 1 by volume)	40–50	42	22.0	24.0	N/A	40*	$D_3$45HJQL

*This data point is of uncertain accuracy.
All angles in degrees.
[a]Conveying Equipment Manufacturers Association.
Source: From (287)

Table 9 Bulk Density $(kg/m)^3$

Fraction	Loose		Maximum	
	Range	Average	Range	Average
MSW	61–152	66	66–200	134
RDF	34–50	43	37–72	54
d-RDF	361–387	374	402–486	445
Heavy fraction	366–598	482	334–451	435
Ferrous fraction	N/A	N/A	194	194
d-RDF/coal (1 : 1 by volume)	712	712	590	590

Source: From (287)

1. Belt Conveyors

Belt conveyors are used for residue in smaller mass burn incinerators and are used extensively for waste handling in RDF preparation systems. Although this type of conveyor appears to be simple and its economy prompts frequent selection, there are many inappropriate and problematic applications in refuse service. In some cases, the problems are reflections of the irregular or problematic properties of refuse. In other cases, however, the problem reflects a lack of understanding of the basic principles and working relationships between the key design variables of the conveyor itself.

Spillage—The loss of material from the belt at transfer points and losses distributed along the belt path is an important failure mode. For a given material and at constant mass flow rate, the fraction of the flow that is spilled per unit length of belt increases rapidly when the belt speed decreases below a critical level. This is due to the progressive increase in the height of material on the belt as velocity is reduced. Ultimately, the load begins to overflow. As belt speed increases,

however, spillage also increases due to aerodynamic effects and the vibration and shock as the load passes the idlers. In general, it is preferred to operate a belt at higher velocity with a minimum load than the reverse.

In the test program (287), it was observed that belts transporting solid waste fractions, unless at very low throughput, always generated spillage. Also, it was noted that 35° idlers were superior to 20° idlers in obtaining increased carrying capacity for the same velocity and spillage rate. Further, a definite increase in spillage was observed as the incline of the belt increased. This was especially the case for the lighter (e.g., fluff RDF) fractions where rollback and slippage precipitate increased spillage.

Trajectory—Knowledge of the trajectory of material discharging from a belt is important in the design of discharge chutes, wear plates, and splitters. Studies (288) of discharge trajectory compared field measurements with a calculation methodology available in the United States from the Conveying Equipment Manufacturers Association (CEMA). Agreement was quite satisfactory for RDF ("fluff"), MSW, and both heavy and ferrous fractions over a belt speed range from 0.56 to 2.24 m/sec.

Dust generation—Data generated in the course of studies of dust generation were inconclusive. However, a pattern of increasing dust concentration as the conveyor speed and inclination increased was generally followed. Although the data were irregular, it appeared that dust control is necessary at transfer points for RDF, d-RDF, and RDF-coal blends.

2. Vibrating Conveyors

Vibrating conveyors are in common use for residue handling in incinerator plants and find extensive use as in-feed or out-feed conveyors in RDF facilities.

In a vibrating conveyor, a eccentric drive device imparts an acceleration with both vertical and horizontal components to the conveying pan. Particles on the pan are lifted upward and pushed forward. Design and operating variables include the frequency and amplitude (stroke) of the drive. For these conveyors, conveying speed increases as the frequency and stroke increase.

Since these devices are constructed entirely of metal, they are not damaged by impact of hot or abrasive materials discharging from a shredder or incinerator grate. Their inherent operating characteristics lead them to level and distribute the material being conveyed, which can be beneficial in smoothing out the discharge rate to the next process step. One should note, however, the consistent tendency among solid waste fractions to compact due to the vibration of the pan, with MSW and RDF fractions showing the highest degree of compaction.

3. Apron Conveyors

Apron conveyors are most often used in resource recovery plants as receiving conveyors for unprocessed waste or at the discharge of size-reduction equipment where loading or ballistic impact of material on the conveyor is of concern. The conveyor is made up of a series of hinged steel pans on a chain and roller assembly. The pans ride on tracks underneath or outboard of the pans.

The static angle of surcharge on belts is the same as the angle of repose (Table 8) for steel surfaces. As with a belt conveyor, the maximum carrying capacity is linearly related to the apron velocity on the flat. Capacity declines with increasing conveyor inclination,

especially at angles above 15°. Spillage is quite limited until angles of inclination are used where rollback ensues (typically above 30°).

E. Size Classification and Screening

Several devices are used to remove fines and to concentrate combustible and noncombustible fractions. These include air classifiers, disk screens, and trommels.

1. Air Classification

Air classifiers use the influence of a high-velocity air flow to effect separation by exploiting differences between the aerodynamic and inertial properties of the constituents of solid waste. The efficiency with which an object subjected to the force applied by the air flow responds with a directed movement is affected by interference from other objects in the air stream. Thus, the sharpness of separation is inversely related to the loading rate of the classifier. The basic separation mechanism of the air classifier is not based on properties related directly to composition. Thus, the air classifier products streams are not necessarily greatly enriched in inorganic or organic content. For example, an air classifier cannot tell the difference between a discarded hammer and a peach or between a piece of paper and small glass shards. Particles with the same ratio of aerodynamic drag to inertia tend to end up in the same outlet stream. Nonetheless, air classifiers are very commonly used in RDF processing as a low-cost first step to achieve a measure of separation of "lights" (targeted on paper, textiles, and plastics) from "heavies" (targeted on stones, wet materials, glass, and massive metal).

Air classifiers are designed with solids flow predominantly in the horizontal direction, in the vertical direction, inclined, and in a vertical "zig-zag" pattern. In all cases, the design details of practical and effective systems have evolved through trial and error. However, some general principles have emerged from comprehensive parametric studies of separation. Table 10 reports the results of studies by the U.S. Bureau of Mines on the lifting effect of gas flows on several waste categories in a vertical classification column (411). However, after over 25 years of analytical studies and testing in both laboratory and field equipment, the ability to confidently predict performance or to design hardware offering sharp separation is yet elusive (412).

2. Screens

Screens separate mixed materials into classes based on the ability of particles to pass through or to be retained on an aperture of a given size. Screens are used alone or in sets to

Table 10 Separation Groupings in Air Classifiers

Velocity (m/min)	Materials separated
90–120	Light fines, dust balls, film plastics
215–245	Newspapers and magazines, paper towels and tissue, film plastic, more groundwood than chemically pulped paper, styrofoam
275–305	Some corrugated, more chemically-pulped than groundwood paper
335–400	Mostly corrugated
400–425	Kraft and corrugated, aluminum, tire fragments, glass, tin cans

Source: From (411)

produce either a simple pass–don't pass split or to produce an "overs" stream of too large particles, an "unders" stream of too small particles, and a product stream containing particles in a defined mid-range.

The major types of screens are flat (vibrating, shaking, inclined, or air assisted), disk screens, and rotary screens (trommels). The last category is described below. The primary function of screens in RDF processing is to separate oversize for return to size reduction equipment and to remove undersize that, often, is a concentrate of noncombustible glass, metal, and mineral matter.

Flat-deck screens are very useful for granular material (sand, ores, etc.) but are prone to blinding (plugging) with platelike or flaky materials (such as RDF paper fragments) and to snagging when wires are present. For these reasons, they have found limited use in RDF applications.

Disk screens are comprised of a series of disks of alternating lesser and greater diameter that are attached to rotating shaft assemblies arranged perpendicular to the flow of material. The "fines" are those particles with a characteristic dimension smaller than the spacing between the disks. The rotary motion of the disks moves the material along through the screening cavity. These screens are often used to separate oversize for secondary shredding (414) and for removal of fines from RDF and from incinerator ash.

3. Trommels

A trommel is a rotating drum perforated along part or all of its length with circular holes or slots. Trommels are common and effective elements of many RDF processing schemes. In this service, they are useful to act as a bag breaker, as a means to break most (not all) of the glass bottles, and to remove sand, glass, and other fines from shredded RDF streams. The basic screen construction parameters include the diameter, total length, screening surface length, inclination angle, aperture size and shape, and open area fraction. The operating variables are mass feed rate and rotational speed. In a few installations, provision for variation in the inclination angle is possible. The range of these parameters in trommels used in RDF applications is illustrated in Table 11.

Analytical studies and tests (376) using raw refuse and the air-classified, light fraction of MSW were conducted. Comparisons between predicted and experimental data showed general correspondence between model and test results, but more work was clearly needed in the analytical development. It was shown that the screening efficiency increases with decreasing inclination angle (over the range from 2° to 8°). Thus, using a smaller inclination angle would be expected to shorten the length of the trommel for equivalent screening efficiency.

It was indicated that screening efficiency increases with increasing rotational speed. Also, the rate of change of screening efficiency with respect to rotational speed decreases with increasing rotational speed within the range of 29% to 73% of the "critical rotational speed" (where the material is held on the wall by inertial or centrifugal forces). The critical speed N_c for diameter (D) in meters is given by the dimensional formula

$$N_c = \frac{251.1}{D} \quad \text{(rpm)} \tag{7}$$

This suggests that, to a degree, poor screening efficiency due to overloading or insufficient length of screen can be compensated for by increasing the rotational speed.

Table 11 Dimensions and Capacities of Trommels

No.	Diameter (m)× length (m)	Hole size (mm)	Capacity (ton/hr)	Power (hp)	Speed (rpm)
1	3.35 × 12.19	120, 63, 19, 6	68.2	40	11
2	3.66 × 8.53	32	40.9	20	9
3	3.66 × 11.58	34	90.9	120	10.5
4	3.05 × 15.54	57	50.1	60	10
5	3.05 × 13.72	120	56.8	80	11
6	3.05 × 7.92	40, 210×254	9.1	6	9–30
7	3.05 × 6.40	Various	4.5	—	0–20
8	2.74 × 9.14	120	22.7	17	14
9	2.44 × 6.10	16	22.7	25	14
10	2.74 × 9.14	19	36.4	20	11
11	2.44 × 13.41	10 × 51, 25 × 101, 203 × 254, 152	30	88	
12	2.44 × 10.67	70, 26	45.5	50	—
13	2.13 × 6.10	Various, 13	40.9	2	—
14	2.13 × 6.10	102, 51	45.5	10	13
15	2.13 × 4.54	22	9.1	12	28
16	1.83 × 7.32	19	18.2	15	11
17	1.52 × 6.10	102, 32, 16	4.5	15	25
18	1.22 × 5.49	19 or 76	13.6	15	20
19	1.22 × 2.44	13	4.1	7.5	8–16
20	1.22 × 3.66	132	6.8	7.5	22
21	1.22 × 3.35	19	12.3	7.5	10–30
22	1.22 × 2.44	76, 19	13.6	15	1–20
23	0.91 × 4.88	10, 13	9.1	2	12–36
24	0.91 × 3.05	102, 51	3.6	1.5	4–43

Source: From (413)

F. Ferrous Metal Separation

Ferrous metal separation is practiced both ahead on (in the preparation on an RDF) and after combustion. In both cases, either permanent or electromagnets are used to effect separation. Figure 2 shows the relationship between the diameter of the magnet and the working distance to an object containing ferrous metal. The separation effectiveness of the magnet depends on the distance between magnet and metal, the weight of the object relative to the magnetic force, and the depth and weight of any overburden of nonmagnetic refuse material covering and/or entangled with the magnetic material.

The layout of ferrous metal separations is usually of two types:

1. A continuous belt fitted with magnets (a "belt magnet") operating above a conveyor handling mixed waste and pulling ferrous metal from the conveyor.
2. A drum fitted with electromagnets (a "drum magnet") operating at the end of a conveyor. The magnet is energized only for a preset fraction of the drum rotation such that ferrous metal is held longer than nonferrous material and, thus, is released with a different trajectory. The ferrous is directed to a special receiving chute.

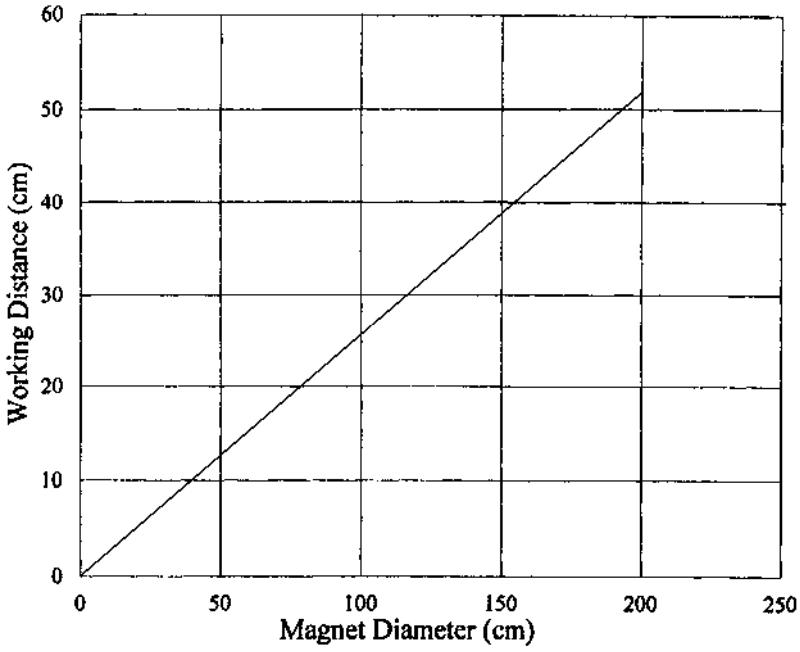


Figure 2 Working distance of magnets.

In both cases, some nonferrous is inevitably included in the product stream due to entanglement, physical trapping, etc. Thus, if a high-quality scrap is desired, a second separation of the ferrous-enriched product is needed.

II. SLUDGE HANDLING

A. General

Pumps of most conventional designs can, in some circumstances, be used in (dilute) sludge pumping service. With wastewater sludges, progressive cavity (for sludge up to about 20% solids) or piston pumps (for the range of sludge solids content) have shown the best performance. The special rheological properties of sludge require special analysis, however, for the reliable estimation of pressure drop (see below).

Conveyance of dewatered sludges via belt, tubular, and screw conveyors, slides and inclines, and elevators has been demonstrated. Because the consistency of the sludges is so variable, however, the design selected must consider performance under conditions widely variant from "average."

Belt conveyors using field-vulcanized seams are simple and reliable and, for semisolid sludges, can operate at up to an 18° incline. Skirtboards are recommended at critical areas. Adjustable-tension finger-type scrapers mounted beyond the idler on the flattened portion of the belt are recommended. Splashing and impact at transfer points should be minimized. In this regard, the thixotropic character of sludge (significant decreases in apparent viscosity under shear) can produce surprising results when, after a splashing impact at a transfer point, a "stiff" sludge cake can turn to watery liquid.

Screw conveyors are useful for sludge conveyance on the horizontal and, depending on the sludge consistency, up inclines. Abrasion-resistant construction, provision for easy inspection, and maintenance ingress are recommended. In most cases, internal, intermediate bearings are undesirable, thus limiting the maximum conveyor length to approximately 20 ft.

B. Sludge Pumping in Pipes

Many sludges can be pumped; perhaps after heating to reduce the viscosity. However, the high-pressure drop associated with sludge pumping requires that careful attention be given to estimation of the flow characteristics.

Unless a sludge has been dewatered to a significant degree, it can be transported most efficiently and economically by pumping through pipelines. Further, the use of pumps to feed sludge to incineration systems has become the method of choice for three commanding reasons:

1. Feeding through a pump produces a stable feed rate that results in lower air emissions, reduced fuel use, and more troublefree operation of the incinerator.
2. Feeding through a pump eliminates several limitations in layout over the use of conventional screw or belt conveyors.
3. Feeding through a pump introduces sludge to the incinerator without admission of any unwanted "tramp air" and with little or no exposure of the sludge, thus facilitating the containment of odors.

Head losses must be estimated for sludge pumping, preferably using rheological data for the specific sludge of interest, since friction pressure drop behavior is often not the same as for water; especially for sludges of greater than 2% solids content. Head requirements for elevation and velocity, however, do parallel those for water.

In the well-behaved, "Newtonian flow" of water, oil, and most single-component, single phase fluids in laminar flow situations, the pressure drop is directly proportional to the velocity and the viscosity. Further, the viscosity is a constant, independent of velocity (velocity being a measure of the shear rate in the fluid). The relationship between the laminar flow pressure drop ΔP (atm) per length L (m) of pipe of diameter D (m) for a fluid of viscosity μ (centipoise) flowing at a velocity V (m/sec) is given by "Poiseuille's" law:

$$\Delta P = \frac{3.157 \times 10^{-7} \mu V L}{D^2} \tag{8}$$

As the velocity increases in a given flow situation, it is found that the flow behavior departs from purely laminar characteristics through a transition region where eddy formation increases in frequency and severity until a turbulent condition is attained. The onset of eddy formation is associated with the attainment of a Reynold's number (N_{Re} and dimensionless) of about 2000, and fully turbulent flow is observed at Reynold's numbers above 4000. The Reynold's number is calculated as

$$N_{\mathrm{Re}} = \frac{\rho_0 \overline{u_0} d_0}{\mu_0} = \frac{d_0 G}{\mu_0} \tag{9}$$

where the fluid density ρ_0, the mean velocity u_0, the characteristic dimension of the flow (typically the diameter d_0 for pipe flow), the fluid viscosity μ_0, and/or the mass flow per square meter G are in consistent units. The Reynold's number is one of several

dimensionless groups of process variables used in the characterization of fluid flow and other processes. Analysis (and, confirming experiment) often shows that these groups are physically meaningful parameters such that similitude between two situations is found if the numerical value of the group is maintained identical. The Reynold's number can be viewed as the ratio of momentum forces in the flow field (characterizing turbulent eddy processes) and viscous forces (characterizing laminar processes). Thus, Reynold's number similitude is aimed at maintaining a similar balance between eddy and laminar flow behavior.

In turbulent flow, the pressure drop ΔP (atm) per length L (m) of pipe of diameter d_0 (m) for a fluid of density ρ (kg/m^3) and viscosity μ (centipoise) at a velocity V (m/sec) is given by:

$$\Delta P = \frac{fV^2 L\rho}{35.46 g_c d_0} \tag{10}$$

where g_c is a conversion factor equal to 98.06 kg-mass meters per kg-force sec^2. The variable f, the "Fanning friction factor," is a function of the Reynold's number and pipe roughness.

Different behavior is observed for the flow of sludge. The basic fluid behavior is "non-Newtonian" for wastewater sludges, Specifically, viscosity is not constant, as determined by tests in a rotational viscometer. In this type of machine, the test liquid is placed between concentric cylinders, one of which rotates. The torque on the non-rotating cylinder is measured as a function of rotational speed. In such a device, sludge shows a reduction in apparent viscosity under shear (thixotropic characteristics).

When testing sludges, it is usually found that there is a yield stress τ_0 below which the cylinder will not start to rotate (see Fig. 3). Then, as the rotational speed (shear rate) is increased, the resistance at first increases and then decreases. Such a reduction in apparent viscosity with shear rate is typical of thixotropy and results from the breakdown of physical structures and interparticle attractive forces. Once these structures are broken down, one can characterize the fluid property akin to and having the same units as viscosity as η, the coefficient of rigidity. This flow behavior is known as that of a "Bingham plastic." For such materials at high shear stress, the flow behavior compares to that of a Newtonian fluid, as shown in Fig. 4.

To describe the pressure drop in such systems, one must calculate the starting pressure needed to overcome the yield stress and the pressure to overcome friction. The starting pressure is given by

$$\Delta P = \frac{4L\tau_0}{d_0} \tag{11}$$

It should be noted that, often, the yield stress (τ_0) increases with time as the material rests in the pipe in the no-flow situation. Therefore, startup pressure requirements may be considerably greater than those calculated based on the τ_0 developed as shown in Fig. 3. Since the development of such high-yield stresses is time-dependent, consideration should be given to purging the line (especially pump suction lines) if extended periods of no flow are encountered.

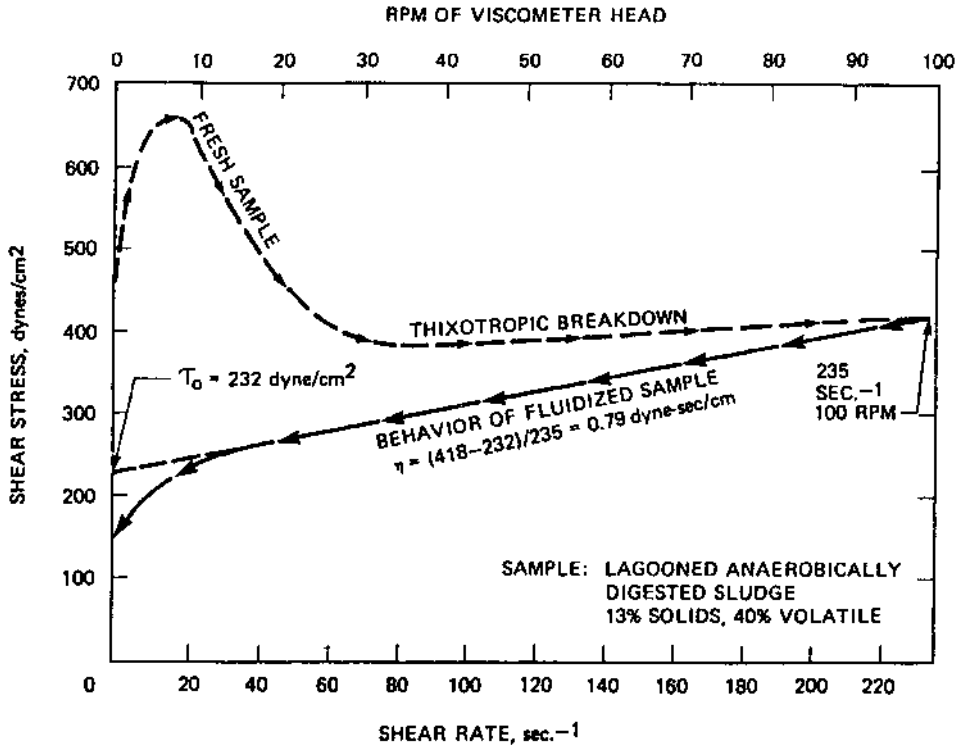


Figure 3 Viscometer test of sewage sludge. (From [223]).

To calculate the pressure drop for steady flow, two dimensionless numbers are used: a modified Reynold's number given by

$$N'_{\mathrm{Re}} = \frac{\rho_0 \overline{u_0} d_0}{\eta_0} = \frac{d_0 G}{\eta_0} \tag{12}$$

and the Hedstrom number N_{He} (the product of the Reynold's number and the ratio of the yield stress to the viscous force) as given by

$$N_{\mathrm{He}} = \frac{d_0^2 \tau_0 g_c \rho_0}{\eta_0^2} \tag{13}$$

Equation (9) can be used to estimate the pressure drop ΔP in atm for ρ_0 in kg/m^3, the length L in m, the velocity V in m/sec, and using η_0 in centipoise as the Bingham plastic limiting value (at high shear rate) for the coefficient of rigidity. The overall Fanning friction factor (f) in Eq. (9) should be developed (207) as a function of the friction factor for laminar (f_L) and turbulent (f_T) flow by:

$$f = (f_L^b + f_T^b)^{1/b} \tag{14}$$

where f_L is the (iterative) solution to Eq. (15):

$$f_L = [16/N_{\mathrm{Re}'}][1 + (1/6)(N_{\mathrm{He}}/N_{\mathrm{Re}'}) - (1/3)(N_{\mathrm{He}}^4/f^3 N_{\mathrm{Re}'}^7)] \tag{15}$$

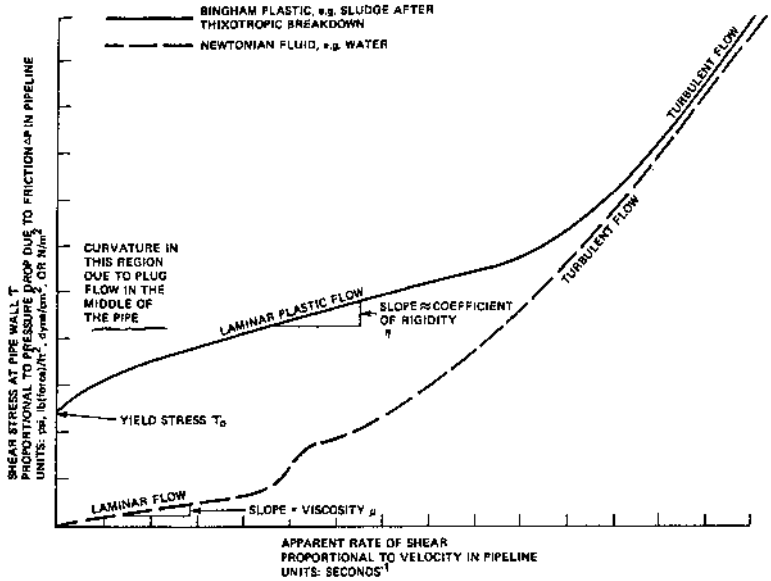


Figure 4 Comparison of behaviors of wastewater sludge and water flowing in circular pipelines. (From [223]).

with

$$f_T = 10^a N_{\mathrm{Re}'}^{-0.193} \tag{14}$$

and where

$$a = -1.47[1.0 + 0.146\exp(-2.9 \times 10^{-5} N_{\mathrm{He}})] \tag{15}$$

and

$$b = 1.7 + 40{,}000/N_{\mathrm{Re}'} \tag{16}$$

An estimate of the friction factor can also be taken from Fig. 5.

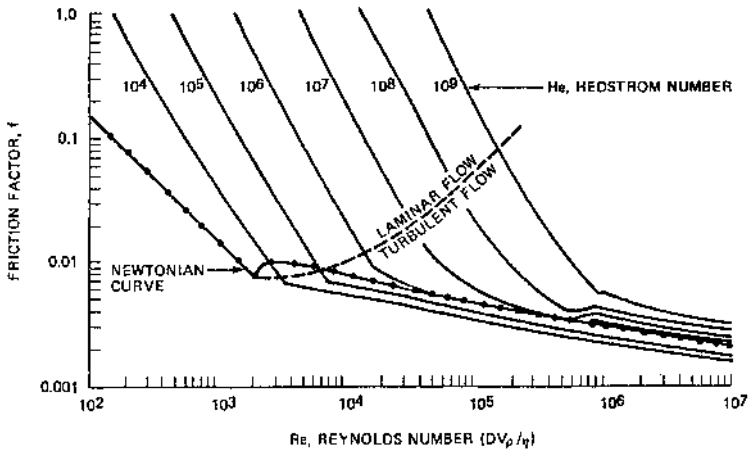


Figure 5 Friction factor for sludge analyzed as a Bingham plastic. (From [223]).

8

Incineration Systems for Municipal Solid Wastes

If a gas- or oil-fired boiler is compared with boilers for the combustion of coal, one observes substantial differences beginning with fuel receipt, handling, and storage through to the stack. Clearly, departing from a pumpable, atomizable fluid to a solid and from a low-ash to a high-ash fuel introduces pervasive and costly changes to the design, construction, and operating procedures. A similar comparison in the area of waste incineration yields more dramatic results.

Even more profound differences between systems for gases or liquids and those for solid wastes are seen if one examines the individual unit processes and unit operations that take place from the time a waste enters the disposal facility to the time its combustion products leave. Generally, it is found that more steps and steps of greater complexity occur for the solids. In kind, the design problem for the sludge or solid waste incineration systems is found to be more empirical, less tractable to confident prediction, and more subject to partial or total failure than their counterparts for gaseous or liquid wastes. Further, in many cases key solid waste parameters are subject to unpredictable short- and long-term variation. Municipal solid waste is heterogeneous, irregular in key materials handling properties, highly and unpredictably changeable, and always problematic. One facility engineer expressed his frustration with the challenges of waste handling with the caution, "If the waste can possibly 'get you', it will!" That word of warning should be particularly heeded in the design of materials handling equipment.

The following discussions are intended to describe contemporary incineration practice for municipal solid waste combustors (MWC). In a few instances, particularly relating to flue gas temperature control for refractory systems, some additional process analysis methodology is presented.

The predominant concern here is on incinerators for municipal solid waste. Because of the wide variation in waste character in industrial situations, systems for industrial wastes often require designs where materials handling, construction materials selection, effluent gas quality goals, and other features must be tailored to the unique nature of the industrial disposal problem. The complexity of the resultant designs and the many new dimensions in combustor configuration are generally beyond the scope of this volume.

The objective of this section is to answer the difficult question: What is a municipal incinerator? In the early years of refuse incineration in the United States, incinerators were designed in a technical collaboration between the public works department of the owner city (county, etc.), its consulting engineer, and the major component vendors (especially the grate and/or boiler manufacturer). The 1970s saw the emergence of a new entity: the system vendor. Unlike the earlier situation, the governmental entity with a waste disposal requirement now found itself in a commercial environment where single-point, overall responsibility for the design and, often, the operation of the facility could be placed in the hands of one of several competing firms. The final working relationship was codified and detailed in a comprehensive contract document (the Service Agreement). The role of the consulting engineer had largely shifted to project planning, assistance in financing, preparation of permitting, and preparation of performance specifications for competitive bidding by several of the system vendors. Elsewhere, entrepreneurial system vendors took the lead in developing a project.

The Service Agreement often goes beyond a simple documentation of a contract to provide waste incineration services. Since the lifetime of the agreement is often 15 to 20 years, many of the circumstances defining the nature of the service, economic factors, environmental requirements, and other important parameters will change. Thus, the agreement defines the set of reference system characterizations that were the basis of the original procurement and indicates methods and guidelines with which to update the cost and/or performance basis from the baseline. The characterizations include a "reference waste" composition and heat content; unit costs for labor, utilities, taxes, and reagents; environmental requirements; and daily and annual processing rates and energy recovery targets.

The new, system vendor-dominated incineration business employs a wide variety of designs to do the same job. This individuality reflects both the growth of incineration technology in recent years and the large number of basic design parameters that are somewhat flexible and can be bent to the prejudices of the design firm. The systems used can be divided into two broad categories: "mass burn technology" burning raw, substantially unprocessed refuse and "refuse-derived fuel" (RDF) technology, where a prepared, refuse-based fuel is burned. Although mass burn technology dominates the market in the United States and Europe, both approaches have their strong points and their advocates.

The discussion that follows outlines the options in mass burn incinerator design and the special characteristics of RDF-based combustion systems. The RDF preparation technology is, substantially, left to other books although refuse processing is briefly covered in Chapter 4. Any one of the pages or even paragraphs would require expansion to a chapter or book in its own right if the subject were dealt with at a level of detail fully supporting hardware design. It is hoped, however, that after reading this section the reader will have familiarity with many of the terms involved in describing an incinerator and with the wide variability possible between systems.

I. PERFORMANCE OBJECTIVES

The performance objectives of a municipal waste incineration system are

- To process each normal operating day not less than the quantity of waste with an analysis and heat content specified in the Service Agreement

To process the minimum weekly, monthly, and/or yearly quantity of waste specified in the Service Agreement

To consistently operate within the emission limits and other legal constraints of all applicable environmental regulations to include restrictions on the concentrations or mass rates of air or water pollutants, sound pressure levels, and/or the maintenance of specified system operating parameters within designated limits

To protect the health and well-being of incinerator employees and of the commercial and residential community that abuts the operation

To protect the capital investment reflected in the equipment, buildings, roads, etc., comprising the incineration facility such that the useful operating life and maintenance and operating expenses of the incinerator are not adversely impacted

To meet any production guarantees regarding residue quality and quantity; export rates of power, steam, or other energy-related products; or other commercial promises

The achievement of these objectives is strongly supportive of a healthy plant operation, good customer relations, and good financial performance.

A. Throughput and Refuse Heat Content

Many of these performance objectives are strongly influenced by the characteristics of the waste. The most basic connection is through the heat content of the waste material since, in essence, an incinerator is a system to process heat. Therefore, the capacity of an incinerator is intrinsically associated with a maximum heat release rate (the maximum continuous rating, or MCR) and not a mass throughput rate (except as the mass rate, multiplied by the waste heat content, is equivalent to a heat release rate). Unfortunately, many municipal clients believe that their contract relationship with the incinerator operator is a commitment to process a given mass of material (e.g., 400 tons per day) rather than to process a specified number of millions of kilocalories per day. Experience has shown that if this potential misperception is not clearly addressed in the Service Agreement, changes in waste heat content over the contract life will lead to customer dissatisfaction and, even, lawsuits.

Why is heat release the "real variable"? Figure 1 illustrates the process and hardware connections that spring from the MCR heat release parameter. The heat release rate, because of the approximate equivalence between heat release and combustion air quantity, is strongly related to the volumetric flow rate of combustion air and of the products of combustion. Thus, the heat release rate sets the size of the forced draft and induced draft fans, sets the size of the air pollution control system, and sizes the ductwork and dampers, pressure drops, etc., throughout the flow system. Also, the heat release rate, for a given combustion chamber, strongly impacts the heat transfer rates (both convective and radiative), which affects the temperature of surfaces in boilers and on refractory walls. Thus, exceeding the design heat release rate can result in overheating of critical system components. All these factors illustrate why incinerator capacity is quite properly equated to the MCR rather than the tons fed.

Another limitation on capacity relates to the structural strength and materials handling capabilities of the grate and the physical dimensions and capacity of the residue and fly-ash handling systems. These physical limitations generally limit the furnace throughput to approximately 110% of the basic design capacity.

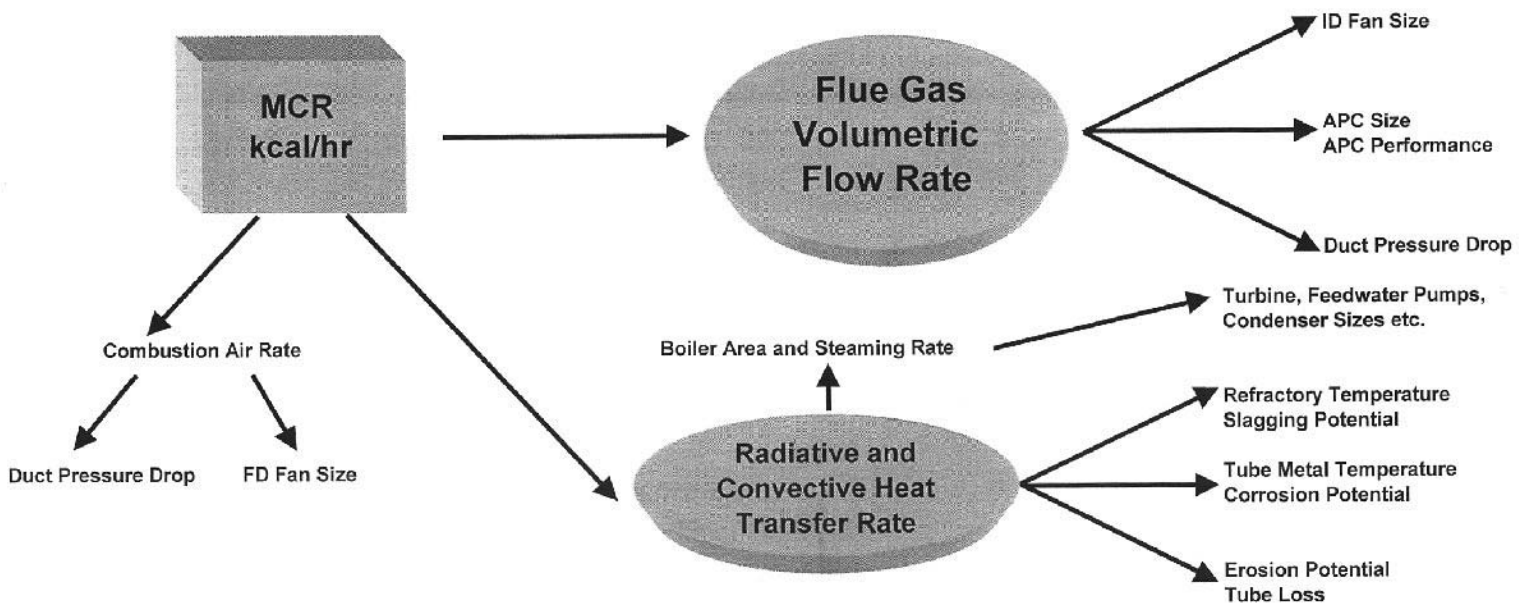


Figure 1 Maximum continuous rating (MCR).

B. The Firing Diagram: The Overall Process Envelope

The firing diagram shown in Fig. 2 provides a concise, graphical statement of the operating process envelope of an incineration system. Specifically, the area bounded by the dotted lines represents the combinations of mass feed rate and refuse heat content supported by the referenced incineration furnace. For all points within the dotted area, the furnace can meet its design mass disposal rate and still remain at a technically sound fraction of MCR and the physical throughput limitations.

Let us consider the various elements of the boundary of the operating zone:

Maximum heat release—The horizontal "top line" of the zone is the MCR. Heat release rates over this limit unduly stress the equipment or exceed design limits for fans, air pollution control equipment, etc. Also, in waterwall boiler systems, operation above this heat release rate may lead to boiler-tube failures, tube erosion, etc., contributing to unscheduled outage.

50% of MCR—The horizontal "bottom line" of the zone is set at 50% of the MCR. While somewhat arbitrary, burning at less than one-half the design heat release is often accompanied by poor mixing (increasing CO and hydrocarbon pollutant emissions), degradation in residue quality, furnace control problems, draft control problems, etc.

110% of maximum throughput—The vertical "rightmost boundary" of the zone is set at 110% of the design mass throughput. This is a reasonable estimate of the maximum feed rate that can be accommodated by the grate and residue handling system.

50% of maximum throughput—The vertical, "leftmost boundary" of the zone is set at 50% of the design mass throughput, reflecting the constraint that as the throughput drops from the design level, it becomes more likely that the grate will be exposed to furnace radiation. Also, the breakdown in the performance of the solids materials handling equipment becomes more likely.

Maximum rate of highest heat content refuse—The "sloped top boundary" of the zone is set by the heat release–throughput line for the highest heat content refuse. This line intersects the MCR line at the design throughput line. This is the maximum heat content refuse used as the basis of design in setting the MCR. Note that for this heat content refuse, the system can just meet the design throughput rate (often equal to the minimum rate set in the service agreement) and stay within the MCR.

Maximum rate of lowest heat content refuse—The "sloped bottom boundary" of the zone is set by the heat release–throughput line for the lowest heat content refuse that intersects the 50% MCR line and extends to the design capacity limit.

Since the operating zone described in the firing diagram is a simple, graphical statement of the maximum operational capabilities of the incineration system, there are merits to including the diagram as part of the Service Agreement.

C. Plant Availability

Plant availability is a critical characteristic of an incineration facility. Reliable waste disposal is, clearly, important to public health and community sanitation. From the standpoint of the facility contract operator, processing waste is, generally, the only way the facility generates revenue. If the facility is off-line, cash inflow stops while fixed costs,

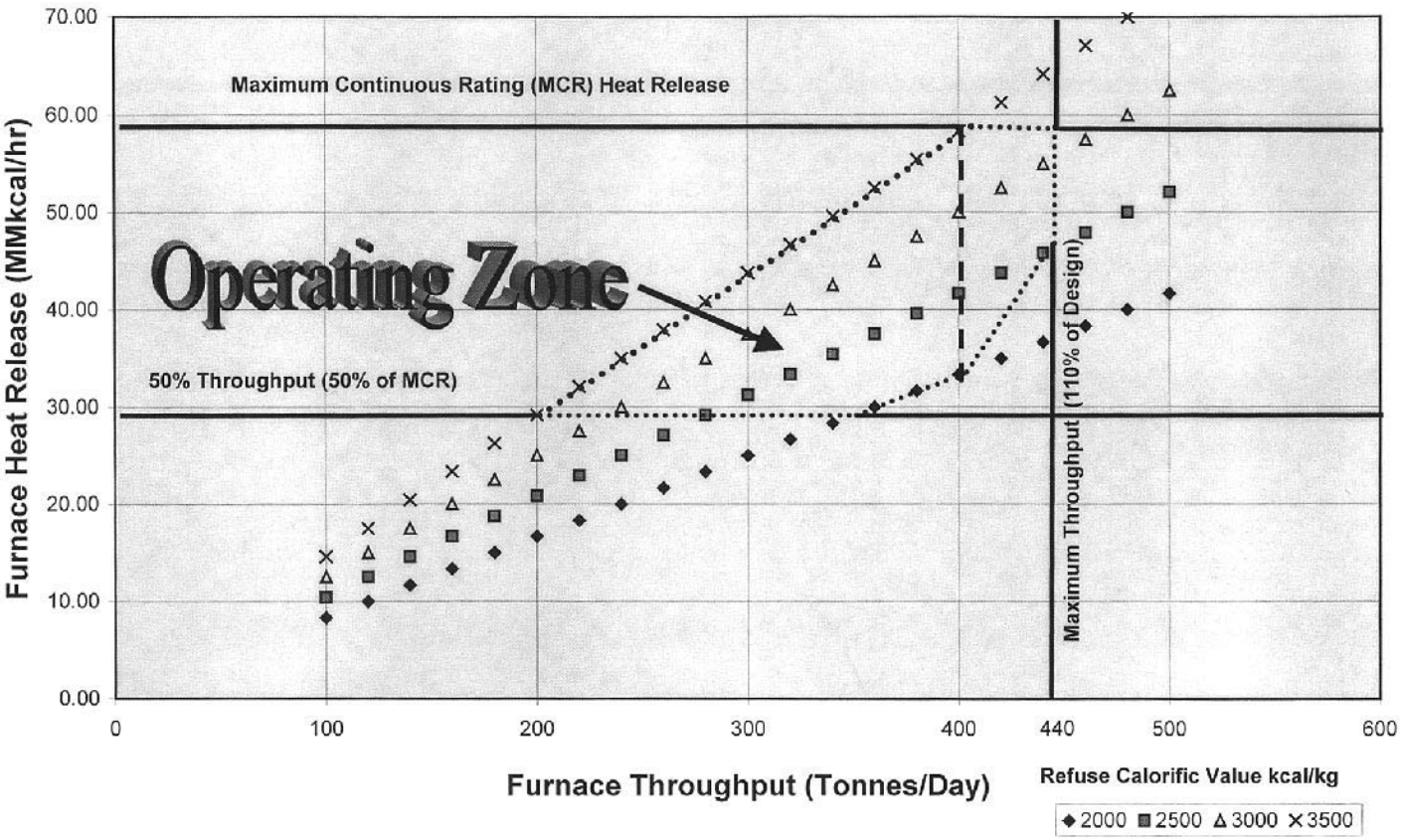


Figure 2 400 TPD incinerator firing diagram.

labor, taxes, and other expenses continue. Thus, the design process must give careful consideration to the tradeoffs between increased capital investment operating expense and improvements in on-line availability.

1. Power Outages

Although the effects of reduced plant throughput on annual throughput guarantees due to electrical power outages may fall within the force majeure clauses of the service agreement (referring to "acts of God" for which no blame is assessed), the facility still suffers from the cessation of the revenue stream. If the historical pattern of outages in a proposed electrical service area suggests that outages may be frequent and of extended duration, there may be ready justification for some measure of protection. This could include:

Equipping major power users (e.g., forced and induced draft fans, boiler feedwater pumps, stokers) with both electrical and steam turbine drives. The electrical system would be necessary for initial "black" startup. Thereafter, the systems could be switched to steam drive for sustained operation. Although this approach increases capital investment, it insulates the plant from the impact of power outages and reduces the cost for purchased electricity.

Installing on-site diesel power generation (for the computer, install a battery pack as a noninterruptible power supply) for minor electrical users (small motors, critical lighting, etc.) as well as for the furnace grates and cranes. Alternatively, one could increase the standby power capacity to a size sufficient to operate the entire plant.

In the design process, the degree to which the facility is provided protection against power outages should be drawn from an engineering tradeoff analysis. Such an analysis looks at life cycle costs with installed power generation equipment (including consideration of the avoided cost for electricity that did not have to be purchased) in comparison to the lost revenue for disposal fees and energy.

2. Equipment Outages

A comprehensive analysis of the mechanical reliability of all proposed structural and process components can serve to pinpoint the subsystems that could potentially shut down an incinerator line or the entire plant. These could include, for example, outages of the crane and grapple, refractory failure, feedwater pump failures, and so forth. If possible, maintenance data summarizing the frequency and severity of outage experience in similar plants should be reviewed. Solutions to such problems can include several strategies:

Installed backups: Many plants install parallel components if outages are frequent or prolonged and, especially, if the overall plant availability is impacted. Examples of such components include the bridge crane, cables and grapple, and boiler feedwater pumps. For the air pollution control (APC) system, redundancy (e.g., spare modules in the fabric filter) may be appropriate even though the capital cost is high since in most jurisdictions, APC outages trigger immediate shutdown.

Spare parts: If the turn-around time to install a new item is short, consideration can be given to maintaining a larger inventory of spare parts to facilitate rapid return to operations. This option is usually more appropriate for components of a single line (e.g., a combustion air fan motor) than for assemblies that impact the overall plant. An inventory of replacement refractory bricks and castable material is clearly necessary. Spare grate bars are similarly appropriate.

Response strategy: The importance of plant availability warrants detailed planning for all significant outage scenarios. Plant operators and maintenance staff should receive training in the most effective and rapid response to minimize collateral damages and to reduce the time to return to service. Such planning along with regular inventory and restocking of spare parts and maintenance supplies and tools will keep the staff both ready and capable to respond to problems.

Preventive maintenance: The working environment in an incineration facility is aggressive and unrelenting. Consequently, the availability of individual items of equipment and of the plant is closely tied to the commitment of the facility management and staff to an aggressive and effective program of preventive maintenance. This means expenditure planning, staff scheduling and training, strict maintenance scheduling, and appropriate prioritizing of the maintenance function.

In the design process, the degree to which the facility provides protection against equipment outages is drawn from an engineering tradeoff analysis. The analysis should look at the life cycle costs with backups, spares, etc., and include consideration of lost revenue for disposal fees and energy.

II. SITE DESIGN CONSIDERATIONS

The design of the incinerator site significantly impacts the cost of the facility, the control of storm water runoff, and the efficiency of the truck traffic flow. Site development costs typically represent 2% to 4% of the total cost of a plant, but can increase if substantial earth moving is required for the site. Storm water must be controlled to limit the impacts of plant runoff on nearby receiving waters (streams, rivers, and lakes). Traffic backups (queuing) can occur if the plant roadway system is not configured properly. The designer must consider all of these site issues when evaluating different sites for the plant and in orienting the plant on the selected site.

A. Site Grading

The incinerator structures should be located to minimize the need for extensive site grading. Grading is expensive and requires substantial time to complete. The waste receiving area (tipping floor or pit charging level) of the plant is generally located at a higher elevation than the combustion system to allow the waste to be fed into the incinerator by gravity. Thus, the plant is usually oriented so that the waste receiving area is located on the highest elevation of the site, and the combustion and air pollution control equipment are located toward the lower elevations.

The roadway grades should be limited to allow loaded waste delivery trucks to easily start and stop when the waste delivery area is backed up. Typically, roadway grade is limited to 5% or even less if many uncovered, open-top delivery trucks are expected at the plant and spillage could occur.

The grade of planted areas should be limited to minimize soil erosion during heavy rains. Typically, planted area grading should be limited to a slope of 4 : 1. Steeper slopes may be employed, but special measures for slope stability and erosion control may be necessary.

B. Site Drainage

The drainage system design should control storm water runoff from the plant site. Since uncontrolled storm water can carry pollutants from the ash loading, chemical handling, truck washdown, and waste receiving areas into nearby receiving waters, containment and diversion to sewers or on-site treatment or holding facilities are appropriate. Typically, the control of storm water runoff is most critical at the ash handling areas. Many plants have installed first flush collection and sedimentation tanks and sand, oil, water separators to collect the ash from the storm water runoff.

Chemical handling and spill containment areas must control the runoff of storm water so that spilled or residual chemicals cannot be washed off-site. To restrict the flow of rainwater if chemicals are present in the containment area, valves are often placed on the spill containment area drains. Holding ponds can be used to temporarily store large quantities of storm water runoff if the off-site drainage systems do not have sufficient capacity

C. Site Traffic and Road Considerations

The plant roadway system should minimize traffic congestion and allow adequate room for queuing of trucks at the scale house and at the tip area. The plant traffic should all flow in one direction around the plant. Roadways should allow the waste delivery trucks to enter and exit without stopping or crossing the plant roadways. Roadways used by waste delivery and ash haul trucks should have a minimum turning radius sized for the largest expected vehicle in use and should be wide enough for two trucks to pass. Truck congestion is common at the scale house and at the entrance to the tipping area, and plant roadways should provide space for at least 10 trucks to line up at both locations.

III. COLLECTION AND DELIVERY OF REFUSE

In the incinerator system, the handling of refuse begins with the delivery of materials to the site. In the United States, most refuse is delivered to the site in motor vehicles although railroads, private automobiles, or barges are sometimes involved. Delivery vehicles can include open dump trucks, commercial vehicles, and private cars. By far, however, most of the waste delivered to incineration sites is conveyed using specialized trucks with equipment for compression and densification. In some instances, very large (50- to 70-m^3) compaction truck trailers are employed to ferry refuse from centrally located transfer stations to a distant incinerator site. Such transfer stations are serviced by smaller collection vehicles.

The refuse loaded into the original collection vehicles usually has a density of about 80 to 240 kg/m^3, depending on the nature of the refuse and how it has been packed at the refuse generation point. Refuse can be loosely placed in collection receptacles, manually stamp-packed, or compacted at the site by hydraulic compression and/or baling devices. In a few cases, the waste is ground or shredded. A power compaction unit can compress the refuse at the generation site (such as at commercial establishments, hospitals, apartments, hotels, etc.) to a density of about 500 to 1000 kg/m^3. However, most refuse loaded into vehicles at the collection site is compacted in the truck body to 250 to 500 kg/m^3 by means of mechanical and/or hydraulic systems using power takeoffs from the vehicle engine. Compaction is employed in most municipal and private collection vehicles to increase the payload capacity of the vehicle.

Most incinerators have a scale to weigh the incoming refuse. Various types of scales are available. Some are manually operated with the weights recorded by the scale operator. Others furnish a printout of the gross, tare, and net weights, together with the license or code number of the vehicle. Larger modern installations use a computerized scale for automatic weighing: The driver of the incoming vehicle inserts a coded card to supply the vehicle code number and the tare weight of the vehicle, and the automatic system prints the gross weight and net weight, as well as the date and time of the delivery.

The plant should have an accurate and reliable truck scale to weigh and record all incoming waste deliveries and outgoing ash trucks. Plant personnel and/or local municipal officials must supervise the scale operations to ensure that all trucks travel over the scale and are weighed properly. The tare (empty) weight of the waste delivery trucks is used to calculate the net weight of the waste in each waste delivery load. Weigh scale systems can be connected to a computer that records the waste delivery data. Such a scale data recording system can print a ticket to provide the truck driver with a record of the delivery.

The scale operator is also responsible for determining if the trucks are authorized to deliver waste to the plant and is the first line of defense in assuring that the type of waste is compatible with the environmental permits and the technical capabilities of the system. Clearly, the reliability and integrity of the scale operator are key to a successful operation.

Typically, a small building (the scale house) is provided adjacent to the scale to provide shelter for the plant personnel and for the weigh scale computer system. Several plants house the scale operator and weigh scale computer system in the plant administrative offices when the scale has been located adjacent to the administrative building and the lines of sight are designed with this function in mind. A typical weigh scale is 10 m long and 3 m wide and has a gross (total) capacity of 55,000 kg.

The waste loads should be periodically inspected when they are dumped to identify material that, in accord with the operating permit of the incinerator and the provisions of the Service Agreement, cannot or should not be processed. Any oversized or hazardous material should be removed immediately and temporarily stored in a safe area. In some plants, hand-held radiation detectors are used to identify and remove radioactive material. Since the charging of material to the incinerator which is forbidden by air permits or other regulatory limitations places the incinerator operator at risk for fines, penalties, or shutdown, the importance of a “good faith” implementation of waste load monitoring is critical.

The receipt of refuse also presents the key to preventing fires and hazardous events. Some plants use hand-held combustible gas detectors to identify and remove potentially explosive items. Such screening is particularly important for plants that process the refuse to a fuel (RDF) since the shredding stages of fuel preparation often expose the waste to sparks and other potential ignition sources. Provisions and penalties should be clearly understood, prohibiting the delivery of all unacceptable wastes. These would include hazardous materials, explosives, chemical waste, flammable liquids, and, perhaps, medical and\or pathological wastes. Plant policies (and permit provisions) should be visibly displayed in signs posted at the point of entry. These passive reminders need to be reinforced with regular visual inspections by the truck scale operators, random selection of incoming trucks for dumping and visual inspection of contents, and constant vigilance by tipping floor personnel and crane operators.

IV. REFUSE HANDLING AND STORAGE

Refuse is a perverse material with unusual physical and mechanical properties. Unlike many solids, it does not cone when piled up and often exhibits a negative angle of repose (an overhang). Because of its source and moisture content, portions of the waste can be sticky so it may not discharge cleanly from belt or apron conveyors. This can cause housekeeping problems along the return run. Waste compresses, which can result in binding at points of close tolerance in moving machinery. Since the compressed material is not brittle and thus does not break off, the tough, compressed waste can keep gates and doors from closing fully.

Waste physical forms include fine powders, sometimes dry and dusty and sometimes wet or even watery; long streamers (e.g., plastic ribbons); individual pieces of paper that are easily blown about and heavy, thick telephone books; cans, bottles, and other containers carrying explosive, toxic, corrosive, or flammable liquids; long and tough shapes such as long steel bars, thick wood planks or beams; and massive materials from engine blocks to furniture and mattresses. This variability emphasizes the special need for rugged and flexible materials handling equipment.

A. Tipping Floor-Based Waste Storage and Reclaim Systems

In small incinerator plants (say, less than 150 tons per day), a paved tipping floor is sometimes used instead of a receiving pit. Under this concept, the refuse is dumped directly onto the floor by the collection vehicles and marshaled into piles using front-end loaders. On demand, the waste is reclaimed from the storage piles and charged to the incinerator(s).

The tip floor area for the storage piles must include a concrete push-wall so that the pile does not move when a front-end loader picks up a load. In order to avoid exceptionally long holding times, the storage area should be large enough to create two separate storage piles so that new waste deliveries can be stored in one pile as the incinerator is fed from a pile of older waste. Otherwise, the waste storage pattern is on a "first in, last out" basis that encourages fly and other vermin infestation, odor, and even spontaneous combustion. Typically, the maximum pile height is 3.5 to 4 m depending, importantly, on the maximum lifting capacity of the front-end loader. Typical waste density is 200 to 250 kg/m^3 depending on the moisture content and makeup of the material.

The preferred location of the two storage piles is in the corners of the storage floor on each side of the incinerators. The area between the incinerators should be left open to allow the front-end loaders to maneuver and to provide access for fire control. The maximum reach of the front-end loader and the height of the concrete push-walls determine the height of the storage piles on the tip floor. The concrete push-walls should be a minimum of 3.6 m high and designed to withstand a force of 600 kg/m^2.

The floor surface area in front of the waste feed hoppers can be expected to wear down from the scraping of the front-end loader bucket. Regular reinforced concrete usually wears down to the steel reinforcing bars in 8 to 10 years. There are options to eliminate the expensive repairs of a new tipping floor section, including

- A concrete hardening additive can be used in front of the hopper to minimize the wear.
- A steel plate can be located above the hydraulic waste loading ram in front of the loading hopper that can easily replaced. Steel rails can also be cast in the concrete

approximately 1 to 2 cm above the concrete to keep the front-end loader bucket above the concrete surface.

The floor dump approach is low in initial capital cost in comparison to the pit and crane design. Also, the floor dump facilitates visual checking of incoming refuse for excluded wastes (e.g., hazardous materials and automobile batteries). However, fire control is difficult in the floor dump situation (especially if the fire starts at some distance from the front face). The floor becomes slippery from the dumping and presents a safety hazard to employees. Another hazard comes from the high levels of dust swirling about the workers who, perforce, must work for long periods of time in the dumping areas.

B. Pit and Crane-Based Waste Storage and Reclaim Systems

In larger incinerator plants, refuse is most often received and stored in a pit below ground level. A traveling crane with a bucket is used to pile the refuse for storage and to move it away from the area just below the unloading area so that the pit can accommodate additional refuse. The bridge travel covers the entire length of the storage pit, and the trolley travel covers the width of the pit. The bridge crane design criteria must take into consideration the reliability needs of the incinerator, which are comparable to cranes designed for steel mill duty (class F): nearly the most stringent in the industry. Industrial or modified industrial-duty cranes are unacceptable in incinerator service.

The crane and bucket are also used to feed the incinerator furnace. Generally, the pit is sized to hold the quantity of refuse that can be burned in 2 to 3 days. In most modern plants, the crane is controlled by one or two crane operators working from a pulpit mounted on one of the end-walls or in the middle of the back wall of the pit. The duty cycle of a refuse handling crane should conform to minimum requirements established by experience, which show a charging time of 30% to 35%, a restocking time of 35% to 50%, and an idle time of 15% to 35% (461). All bridge and trolley motors should be sized for at least 115% of the design load, and the hoisting and grapple motors should have a rating of at least 125% of the design load.

Three types of buckets are in common use for handling municipal refuse: the clamshell bucket, the grapple bucket, and the “orange peel” bucket. The clamshell and grapple buckets can be equipped with teeth to assist in digging into the refuse for a full bucket. The orange peel bucket does not require teeth to grab the refuse, even for unusual or large pieces. With the orange peel, it is difficult to thoroughly clean the floor of the receiving pit. The clamshell and the grapple are well suited to a clean-out of the pit, providing the teeth are first removed. A steel plate is sometimes used to cover the teeth when cleaning the floor of the pit with a grapple bucket. Pit cleaning is important for sanitation, good housekeeping, and elimination of odors from decomposing refuse. It is prudent to design the pit and crane facility so that undesirable material inadvertently dumped into the pit can be grasped by the bucket and carried to a point where the reject material can be easily shunted to a truck or otherwise eliminated.

While open receiving areas are possible, they are infrequently used. The receiving area should be enclosed to avoid windblown refuse from causing a nuisance, to control dust and odors, and to prevent snow and ice from interfering with the movement of vehicles. Enclosing the refuse receiving area also assists in refuse moisture control by keeping the rain off. Moisture stability is helpful in obtaining uniform combustion temperatures in the furnaces.

Fires in the pit are not uncommon. Generally, the fires are started by dumping material that is already smoldering or burning (a “hot load"). Spontaneous combustion or buildup of heat from composing of refuse components is another potential cause. It is therefore necessary to equip the pit area with fire hoses at several strategic and accessible locations surrounding the pit. Hoses permit focused application of water to particular “hot spots” rather than the more general quenching effects of sprinklers. If circumstances support this approach, the fire may often be extinguished without undue flooding of the pit.

Sprinkler system installations are common in pit and crane systems and are extremely important in facilities that store refuse on the tipping floor. The tipping bay area should be provided with an automatic sprinkler system covering the first six meters of the tipping floor adjacent to the refuse pit (387), and an automatic sprinkler system should be provided over the entire refuse pit area (including the charging hoppers and the crane park area at both ends). A minimum water density of 10 l/min/m^2 should be provided (388). This provides a discharge rate of at least 62 l/min/m of pit opening. In plants where the crane operator rides in a cab on the bridge, care should be given to the facility design to assure easy and rapid escape from the cab, noting that the upper regions of the building will rapidly fill with dense, acrid smoke during a pit fire.

C. Bin Storage and Reclaim Systems for RDF

Systems to store and retrieve RDF are critical to the operational success of all classes of RDF combustion systems. Because of the unique physical properties of RDF, experience has shown the importance of dynamic storage. That is, processed RDF, sitting quiescently in a bin or other storage bunker, has a tendency to “knit” together into a coherent structure that, often, will not behave in a predictable and desirable manner when outtake conveyors or another withdrawal mechanism is started. For example, it may be found that, after a period of time, a conveyor mounted under the RDF pile simply bores a hole into the mass and the structure overhead fails to collapse into the void. Thus, after only a small quantity is withdrawn, the RDF flow rate drops to zero.

Dynamic storage involves both continuous operation of the withdrawal mechanism and continuous recycle of the unfed RDF flow. Therefore, when RDF is not being fired, there is 100% recycle. Then, as the firing rate increases, the recycle stream diminishes but does not stop. A second aspect of successful dynamic storage has sometimes involved the installation of vertical screws in bins to continuously “fluff” the RDF. Parallel paired counterrotating withdrawal screws in the bin bottom provide a “live bottom” feature that also has proven successful. Note, however, that continuous movement exacerbates the wear problems fostered by the highly abrasive nature of waste and its accompanying sand and grit. Also, rotating elements (such as the screws) become fouled by ribbon-type waste materials.

The RDF storage bin is important because, in most instances, the RDF preparation system is only operated on a one- or two-shift basis. As noted above, the RDF processing capacity is often considerably greater than the needs of the combustion facility. Thus, a facility is needed to hold a relatively large working volume of waste to bridge over the shift outages and maintenance outages of the processing system.

Ideally, a surge storage bin is interposed between the long-term storage bin and the combustor. The quantity of material in the surge bin usually corresponds to 5 to 10 minutes of firing at the design rate. This bin should respond quickly to changes in boiler demand.

V. SIZE CONTROL AND SALVAGE

In some plants, oversize or otherwise undesirable refuse is controlled by exclusion at the tipping location or by selective removal from the pit by the crane operator. Under supervision, bulky articles can be deposited in a specific area of the pit, or they can be carried directly to the residue disposal site without passing through the incinerator furnace. The latter method is often used for bulky metal items such as refrigerators, stoves, and large metal parts ("white goods") that contain little or no combustible material. If the item contains biodegradable material, it may be cleaned before it is taken to the residue disposal site. Combustible oversize items are preferably broken up and incinerated.

Most refuse can be reduced in size by shearing or shredding. Shearing is a controlled method for reducing all refuse to a given maximum size by passing it through a shear or series of shears, or through a single or multiple guillotine. Shredding, which is rapidly coming into increased use, commonly makes use of horizontal or vertical shaft hammermills or shear shredders. Coarse shredding (say to a top size of 25 cm) improves the efficiency of recovery of ferrous metal with magnetic drums or belts. Finer shredding, although necessary for applications where the refuse will be burned in suspension, presents problems when burning on conventional incinerator grates.

VI. INCINERATOR FEED SYSTEMS

A. Feed Systems for Floor Dump Receipt and Storage

Most floor dump receipt and storage systems use a front-end loader to reclaim refuse from the storage piles and deposit it into feeding hoppers. The front-end loaders are operated continuously to feed waste into the incinerators. The front-end loader bucket should have sufficient capacity to fill the waste feed hopper completely with one load. The bucket capacity should have a minimum volume of 1 m^3 to accommodate the maximum dimension of typical wastes but must be sized to be compatible with the incinerator unit size. Because of the high dust level on the charging floor, the radiator on the front-end loader should be extra heavy-duty. Also, the tires should be solid rubber. Since the loader is critical to continued plant operation, the plant should either have two loaders on-site or have arrangements with local heavy equipment firms to assure reliable and fast delivery of rental vehicles.

The refuse is ultimately recovered from the piles (last in, first out) and deposited at the same grade as the storage floor. This design approach is simple and is the easiest to work with, but it requires that the elevation of the tipping floor must be considerably higher than the floor of the incinerator system. This may present problems with the site layout but is greatly preferred from an operational standpoint. The refuse is then

Pushed onto a conveyor that loads the feed hopper of an incinerator furnace or a shredding or compacting device.

or

Pushed through an opening in the floor either to directly feed an incinerator furnace or to load a hopper equipped with a hydraulic ram for feeding to an incinerator furnace in a batchwise fashion. There are two closures on the hopper to ensure that there is always a seal between the incinerator environment and the tipping area. The seal limits or stops the flow of cold air into the furnace (usually under draft) on charging. An inrush of cold air is detrimental to the inside refractory

walls of the furnace and can cause CO and smoke by cooling and quenching the burning process.

The first closure is a hydraulically actuated, reasonably airtight top closure to the charging hopper cavity (a lid) that closes to isolate the hopper from the tipping floor after the waste is fed into the hopper. The second closure is a guillotine damper that opens to allow the hydraulic ram to push the waste from the hopper into the incinerator. The face of the guillotine door that is exposed to the furnace is refractory-protected. After the charge of waste is pushed into the furnace, the feed ram retracts and the guillotine closes to isolate the hopper from the incinerator. The hopper top closure then is opened to allow the hopper to be reloaded with waste from the tipping floor for another feed cycle.

In a few cases, the waste must be scooped into the bucket of a front-end loader and lifted to the dumping point. Such handling should be avoided if possible since it is slow and, including the cleanup of spillage, labor-intensive.

The rate of feed is controlled by a time cycle or plant instrumentation that indicates more waste is required. For example, "modular, starved-air incinerators" operate with a fixed air flow to the primary chamber. The flow is low and the chamber is maintained in the reducing mode (with less than a stoichiometric oxygen supply). As the combustible burns down, the air supply comes into better balance with the heat release and the flue gas temperature increases, thus signaling the need to charge new waste. In many plants a light located directly above the incinerator-loading hopper indicates to the front-end loader operator that the hopper is empty and positioned to receive a load of waste. The waste feed cycle time varies depending on the design capacity of the incinerator. Typically, waste is fed into the hopper every 2 to 4 minutes.

With a hopper-feed system, either the ram can clear the hopper at each stroke or an oversized hopper can be filled with refuse and the ram used to shear a horizontal section of refuse at selected intervals. The ram feeder provides an air seal at the feed to the furnace, an improvement over the bucket or the front-end loader systems of batch feeding, which often let in undesirable quantities of cold air, as well as releasing occasional puffs of flames or hot gases when the charging gate was open.

B. Feed Systems for Pit and Crane Receipt and Storage Systems

1. Mass Burn Systems

Modern-design mass burn incinerator systems nearly always specify continuous or semicontinuous feeding of refuse to the incineration furnace (Fig. 3). In larger mass burning plants, a hopper and a gravity chute supply a mechanical feeder, such as a pusher ram. RDF systems use a mechanical or pneumatic conveyor to transport the refuse from a storage bunker and then continuously cast the RDF into the furnace using an air-swept chute and high-pressure jets of air.

In the hopper and gravity chute systems (Fig. 4), a rectangular hopper receives refuse delivered by the crane and bucket. The bottom of the hopper terminates in a rectangular section chute leading downward to the furnace grate or other feeder conveyor at the entrance to the furnace chamber itself. This gravity chute is either of uniform cross-section or flared slightly toward the lower end to minimize bridging. It is either refractory-lined, made of water-cooled steel plate, or both, to prevent heat damage when the occasional burn-back occurs or at shutdown. The inside walls should be carefully

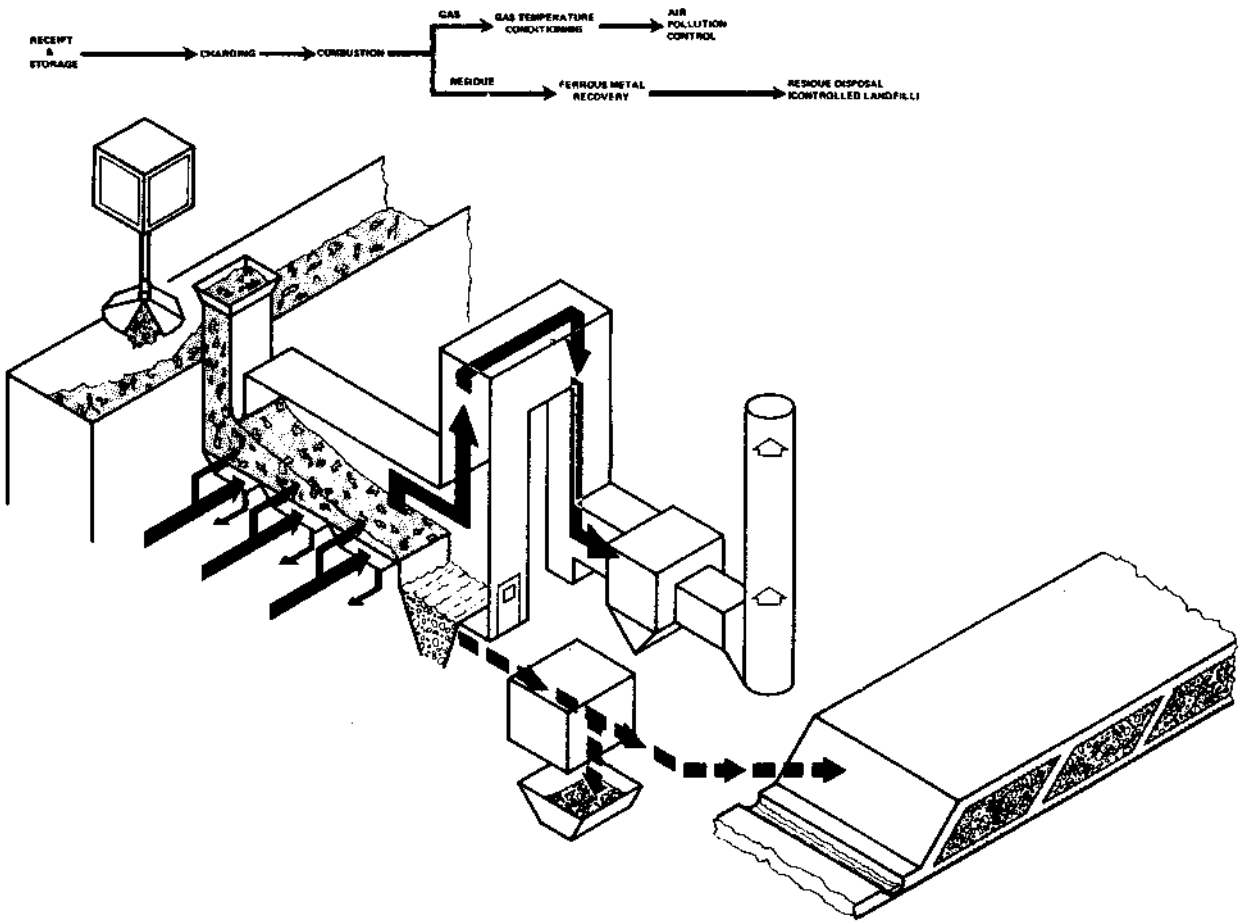


Figure 3 Continuous-feed incinerator.

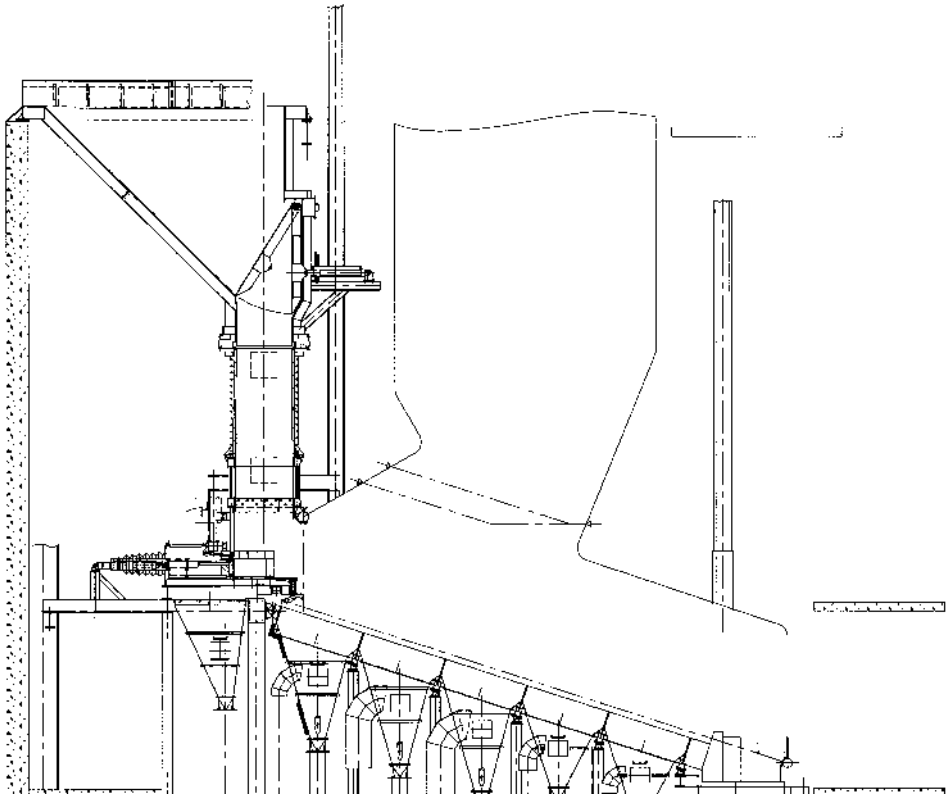


Figure 4 Detail of hopper and chute system. (Courtesy of Von Roll, Inc.)

ground and otherwise smoothed to avoid even small irregularities and ledges that will catch refuse components and hold back the flow of refuse. Fires in the chute may be caused by faulty chute design (too short or too narrow), by the presence of large or irregular refuse, which can provide flues for combustion gases and flame to ascend the chute, or by having insufficient material in the chute.

2. RDF Burning Systems

Floor dump and pit and crane/grapple feed systems have the relatively simple and predictable task of moving a unit volume of raw waste from a pile or pit to the charging hopper. However, RDF handling technology must go far beyond this and must effectively and reliably master the vagaries of waste physical form (ribbons, massive "chunks," powders, wet sludge, etc.) and provide the combustion system with a relatively uniform energy feed rate (kcal/min).

Selecting equipment for storage and retrieval of RDF is an inexact process. The designer must be cognizant of the physical and chemical characteristics of both the RDF and the original raw feed. Of special importance are the handling problems (hangups,

choking, etc.) from rags, streamers, wires, hard plastics, and metals. Also, one must recognize that RDF is not uniform. Moisture content will vary, particle size will change, unexpected materials will appear from time to time. RDF can be fluffy or dense and is relatively incompressible. Although the RDF preparation system is supposed to remove many of the problem materials and minimize RDF variations, the expectation should be that this protection will fail from time to time. When it does, the consequences will exact a toll on the steadiness of feed (and, thus, the combustion and steam generation rate) and the distribution to the several feed spouts (and, thus, the distribution of RDF on the grate), etc.

Unlike the mass burn systems, heat release (and steaming rate) within RDF combustors tracks much more closely the energy feed rate to the system. Although there is a certain amount of "heat release inertia" from the mass of material burning on the grate, an estimated 20% to 30% of the heat is released in the suspension burning part of the two-step combustion process. This close coupling of feed rate with steaming rate emphasizes the importance of designing hardware that minimizes stop–start flow, frequent blockage of one or more feed points, etc. Experience to date has often shown that the design process involves substantial trial and error. Success is seldom achieved in the early phase of plant startup and shakedown.

a. Spreader Stoker (RDF) Burning Systems. A spreader stoker system consists of a feeding device, a mechanism for throwing the RDF into the furnace, and a simple flat traveling grate with suitable openings through which to admit underfire air. In some designs tailored to handle high-moisture, high-ash wastes, a reciprocating, water-cooled grate is used. The RDF feeding and distributing mechanism is located at the front wall of the furnace (usually a waterwall boiler enclosure), above the grates. The grates move toward the feeder assembly and discharge the ash just below the front wall. The speed of the grates is set to give sufficient time for combustion to be completed before the ash is discharged at the front. The residue is continuously discharged from the furnace into a hopper. Normally, the ash is relatively cool and clinkerfree.

After injection, the RDF transits the volume above the burning material on the grate. The hot, still-burning gases rising from the grate pass through and about the stream of entering waste. As the flue gases sweep past the incoming waste fragments, the waste dries, ignites, and begins to burn. The burning waste stream then falls to the grate for burnout. This two-step combustion process is sometimes called "semisuspension burning."

The feed system usually begins with a conveyor system drawing from the surge bin that may incorporate a weigh feeder device to meter the mass rate of RDF. In most cases, the materials handling system is a "run-around" design where the mass rate of material withdrawn from storage is significantly larger than the net feed rate. The excess is returned to storage. This strategy helps to minimize irregularities in the feed rate. The conveyor discharges into a distribution device that divides the feed into the 2 to 8 chutes leading to the feeding devices. Alternatively, the system can be designed with multiple discharge points from surge bins interposed between the large, long-term storage RDF holding bins and the boiler. Whatever the design, the feeder design must provide for easy and rapid access for routine inspection, for preventive maintenance, and for operator intervention to break up bridging and other flow-interrupting problems.

The spreader stoker feeder functions to vary the supply of RDF to the furnace and to provide even distribution on the grate. The mechanisms that propel the RDF into the furnace include steam and air injection as well as mechanical rotors. Mechanical spreader stoker feeders are divided into two classes: overthrow, where the RDF comes into contact

with the upper part of the rotor blade assembly, and underthrow, when it comes into contact with the lower part.

Pneumatic feeders are most often used with RDF. A widely used technique for distribution of RDF uses a swinging spout that services multiple feed chutes. The RDF is fed into the top of the unit and the swinging spout proportions the RDF into 2, 3, or 4 chutes running to the feeders. Rollers at the nexus between the chutes avoid hangup of ribbons and rags and break up bridges.

Figure 5 shows a pneumatic system used for RDF firing. Air, under pressure, enters the distributor inlet under control with a damper. The direction of the air flow in the horizontal plane is set with adjustable air vanes in the air distributor nozzle. Waste, falling by gravity from a distribution system above, is caught up in the powerful air jet and swept toward the furnace opening. The final fuel trajectory is controlled by angling the distributor tray by means of the distributor tray control. Figure 6 shows the boiler system, including the pneumatic feeder and traveling grate stoker.

b. Suspension (RDF) Burning Systems. If suspension burning is to be employed in the incinerator furnace, the refuse should be prepared by suitable shredding or grinding. The most desirable feeding method is air injection. Suspension burning has been used successfully in waterwall boilers for the generation of steam from waste products such as wood bark, bagasse, and similar materials. In conformance with practices in the fossil fuel-fired boiler industry, air injection of shredded refuse has been used for corner firing, for spreader stoker firing, or for "cyclone" firing, all of which are in commercial use for the generation of steam from powdered or crushed bituminous coal. With suspension burning, a burnout grate should be provided at the bottom of the waterwall furnace chamber for completion of combustion of large particles and/or slow-burning materials.

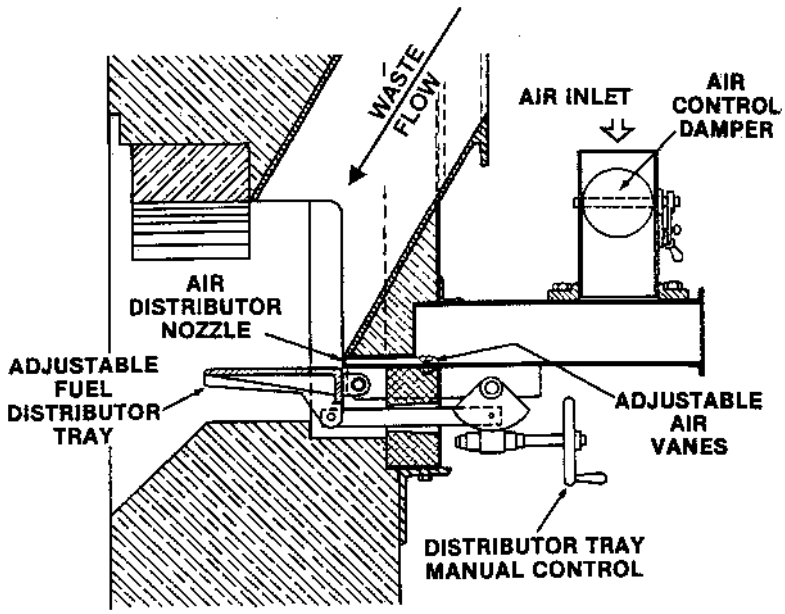


Figure 5 Pneumatic refuse fuel feed system. (Courtesy of Babcock Borsig Power, Inc.)

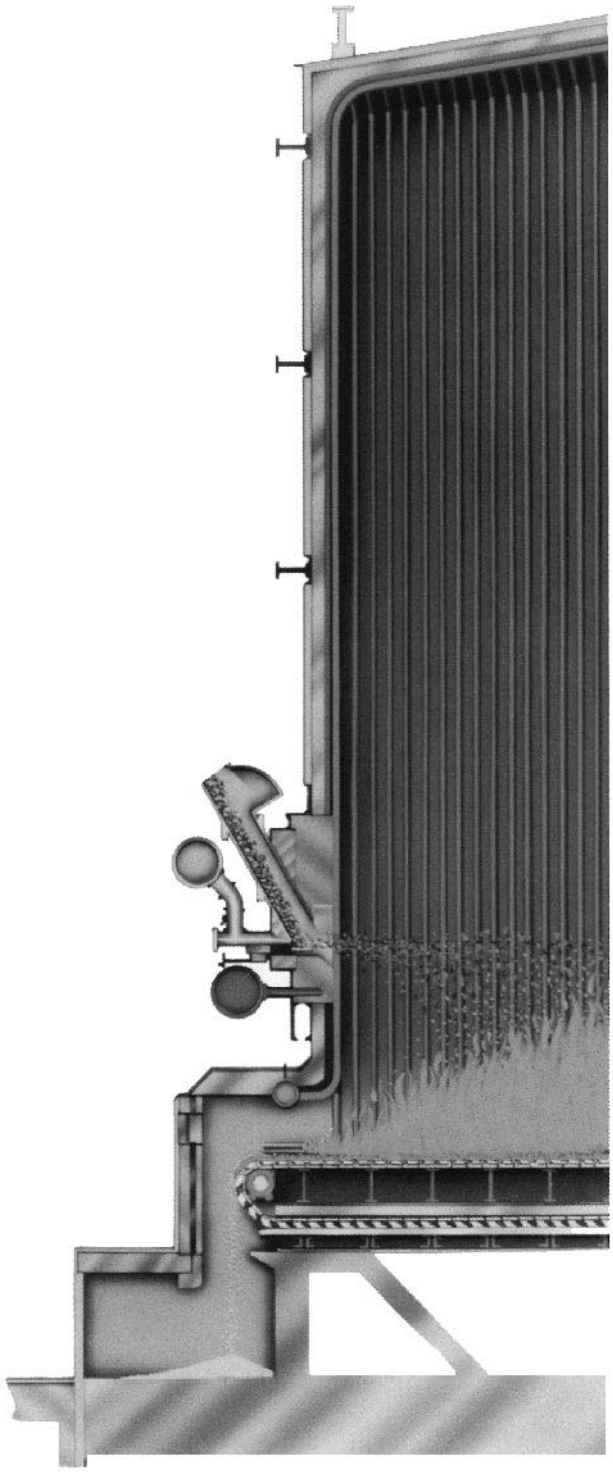


Figure 6 Pneumatic RDF fed boiler system. (Courtesy of Babcock Borsig Power, Inc.)

VII. GRATES AND HEARTHS

In general, small incineration furnaces use a stationary grate or refractory hearth to support the burning refuse. Most larger plants use one of several available grate types to support and transport the refuse while simultaneously stoking or mixing the refuse during the combustion process. Suspension burning is the only process that does not necessarily require a hearth or grate, since most of the refuse is oxidized while in suspension in furnace gases. But even for suspension burning, a burnout grate is often provided at the bottom of the furnace chamber to provide for more complete burnout of combustibles in the residue. Experience suggests that only when the refuse has been shredded to 95% < 1 cm should consideration be given to abandoning the burnout grate.

There are many different types of hearths or grates, each of which has its own special features.

A. Stationary Hearth

Those incinerator furnace systems that operate without grates include the stationary hearth, rotary hearth, and rotary kiln. The stationary hearth is usually a refractory floor to the furnace, which may have openings for the admission of air under slight pressure below the burning material on the hearth, in the manner of the blacksmith's forge. In the absence of underfire air ports, air is admitted along the sides or from the top of the furnace, and combustion proceeds in the same, surface-burning manner as in a bonfire, but with improved conditions due to the reradiation of heat from the surrounding furnace walls and roof. Unless the refuse being processed provides a porous burning mass (as may be the case with bulky refuse), it is necessary to provide manual stoking with slice bars to stir the mass of refuse in order to achieve a reasonable burning rate and degree of burnout.

Stationary hearth furnaces are used for most commercial and smaller industrial incinerators. They are also used almost exclusively in crematories and for hospital wastes. For the latter applications, auxiliary gas or oil burners are used to maintain the furnace temperature in the range of 650° to 900°C in the presence of adequate quantities of oxygen from air, well dispersed throughout the gas. In burning such high-moisture waste, primary chamber burners are needed to ensure complete oxidation of combustible solids and vapors for the elimination of smoke and odors. Confident smoke and odor control requires auxiliary fuel burners under automatic temperature control in a secondary combustion chamber.

Bulky refuse incinerators constructed in the mid-1970s (117,118,121) used a refractory chamber with a refractory floor equipped with a number of air inlet gratings, similar to floor drains. One side or end of the chamber was connected to the hot combustion chamber of another incinerator installation. If not, a secondary combustion chamber was installed prior to the breeching and stack to ensure burnout of combustible gases and particulate. A refractory door permitted the opposite side of the combustion chamber to be opened for access. A special extended bulldozer blade was used to load the hearth with refuse from a paved platform outside the chamber and to drag out ash residue. Alternatively, it was possible to remove the ash residue by raking with a hoe or by pushing the ash residue beyond the hearth into a depressed area from which the ash could be removed.

B. Rotary Kiln

The rotary kiln hearth system has been used for several hundred years in the pyroprocessing industry. The rotary kiln concept accomplishes two objectives simultaneously:

moving solids into and out of a high-temperature combustion zone and mixing and stoking the solids during combustion. In its classical embodiment, a kiln is comprised of a steel cylindrical shell lined with abrasion-resistant refractory to prevent overheating of the metal. A kiln is generally inclined slightly toward the discharge end, and the movement of the solids being processed is controlled by the speed of rotation.

In some instances, special provisions have been made for air cooling or water cooling the kiln shell, thus eliminating the use of refractory. For example, a steel kiln cooled with external water sprays known as the Lantz Converter was developed for pyrolysis applications in the mid-1960s. In the late 1970s, a new kiln technology emerged involving a water-cooled kiln cylinder fabricated of steel boiler tubes welded together and manifolded for the introduction of feedwater and withdrawal of steam. This system (The "O'Connor Rotary Combustor") is described in Section F. The design and operating features of kilns for the destruction of hazardous wastes are described in Chapter 11.

There has been little use of the refractory-lined rotary kiln for municipal incinerator furnaces except to enhance residue burnout *after* the burning of refuse on a multiple-grate system. The rotary kiln normally requires all of the air for combustion to enter the unit with the refuse at the feed end. Therefore, the cooling flow of ambient combustion air is a deterrent to the temperature increase necessary for rapid ignition. Further, the inherent construction of a kiln emphasizes the suspension of particulate in the gas stream and tends to limit mixing of pyrolyzed refuse combustible matter with combustion air. For kiln-based incinerators, these features result in high particulate and hydrocarbon concentrations in the flue gases entering the APC system in comparison with conventional grate systems. The few rotary kilns that have been used for incineration of refuse have been relatively stubby (length limited to only about four to five times the diameter) and are commonly provided with a bypass duct to reduce the gas volumetric flow rate (and particulate entrainment) through the kiln.

C. Stationary Grates

Stationary grates have been used in incinerator furnaces for a longer time than any grate system except the stationary hearth, which was used in incinerators and crematories prior to the Middle Ages. The original stationary grates were probably metal bars or rails supported in the masonry side-walls of the furnace chamber. Subsequently, these bars were replaced with cast metal or fabricated metal grates with mechanical linkages to rotate the grate sections to dump the ash residue. While some stoking action can be obtained by shaking the grate, as in partial dumping, stationary grates normally require manual stoking with a slice bar to stir the burning bed of refuse in order to obtain a reasonably complete burnout of ash residue. Such stationary grates are not in wide use in modern facilities but were common in many of the older cell-type incinerators. The latter have usually been constructed with a multiplicity of furnace sections or cells, with an opening above each cell for charging.

D. Mechanical Grates: Batch Operations

Mechanically operated grates installed in batch-type furnaces were a natural evolution from the stationary grate furnaces. Although batch-type incineration furnaces have given way to continuous furnaces for new, large installations, many of the new small-capacity incinerators still utilize batch-fed furnaces, either with stationary or intermittently operated grates or without grates, the latter in small commercial and industrial installations.

1. Cylindrical Furnace Grates

Cylindrical batch furnaces were common in the United States in the 1950s and early 1960s. In these furnaces, the grates form annuluses inside the vertical cylindrical walls of the furnace. A solid grate or "dead plate" covers the central area of the annulus. A hollow rotating hub with extended rabble arms rotates slowly above the circular dead plate to provide mechanical stoking or mixing. A center post provides the bearing support of the hub and rabble arms. The rotating hub is covered with a hemispherical "cone" with one or more consecutively smaller cones stacked on top of the first one. Forced air (called "cone air") for combustion is supplied through the hub to the hollow rabble arms and then through openings in the arms to the space just above the dead plate. Additional cone air is supplied to each of the cones, to cool the metal. The annular grate area is divided into pairs of keystone-shaped segments; each pair is arranged to open downward for dumping the ash residue into the ash hopper below. These segmental grates are either hand-operated or hydraulically operated under manual control. It is frequently necessary to poke and slice the ash residue using the access doors around the furnace, in order to clean the fires and to assist in the dumping of the ash residue.

When circular grates are used, the cylindrical furnace is fed intermittently or batchwise through an opening in the top at the centerline of the furnace. A charging door is used to close the opening between additions of refuse. In the usual method of operation, refuse is placed in the hopper above the charging door or gate preparatory to the next charging cycle. At a signal from the operator, the charging gate is opened, the refuse drops into the bonfire of previously ignited refuse, and the charging gate closes immediately after the hopper is emptied. Additional refuse is charged in repeated cycles at the discretion of the operator until the accumulated ash residue in the furnace requires dumping through the circular grates.

2. Rectangular Batch Furnace Grates

Mechanically operated grates in rectangular batch-operated incinerator furnaces include reciprocating (pusher) grates, and rocking grates. The grates are usually installed in a slightly inclined position from the horizontal, with the lower end of the incline at the ash discharge point. With these grates, the furnace is fed intermittently through an opening in the top and at the higher end of the grate, and the fresh refuse is deposited over the bonfire of previously ignited refuse. These systems were contemporaries of the cylindrical furnaces in the United States during the 1950s and 1960s.

As the burning continues, the grates are operated under manual control to move the burning bed of refuse toward the discharge; the manual control is to prevent (ideally) the discharge of residue that has not been completely burned. In some instances a dump grate is installed at the ash discharge point to hold back ash residue that is still burning, with manual operation of the dump grate after the accumulated ash has been completely burned. At times it is necessary to manually stoke or slice the fire in order to spread the burning refuse over the grate or remove larger pieces of metal or clinkers that interfere with the desired flow of burning refuse across the grate.

E. Mechanical Grates: Continuous Operations

Mechanical constant-flow grates have been and are being used in most of the newer continuous-burning municipal-scale incinerators. This constant-flow grate feeds the refuse continuously from the refuse feed chute to the incinerator furnace, provides movement of

the refuse bed and ash residue toward the discharge end of the grate, and does some stoking and mixing of the burning material on the grates. Underfire air passes upward through the grate to provide oxygen for the combustion processes, while at the same time cooling the metal portions of the grate to protect them from oxidation and heat damage. Typical grate designs correspond to an average heat release rate of 13,500 to 16,000 kcal m^{-2} min^{-1}. Clearly, the actual rate in different portions of the grate differs widely from this average.

The grate device is only one part of the overall primary furnace system. The primary furnace system includes the hopper/chute/feeder, the grate and underfire air system, the furnace enclosure with its protective side walls, the overfire air system (including design features such as the shape of the lower regions of the enclosure and the direction and discharge velocity of the air jet nozzles), and the bottom ash and siftings equipment. While each vendor makes claims as to the benefits of its particular grate design, most firms have invested considerable time and money in developing an optimized, overall primary furnace system that works together as a successful, integrated package. If one takes the grate of one vendor and inserts it into the furnace envelope of another, success is no longer as certain.

1. Reciprocating Grate

Reciprocating grates involve cast alloy grate bars, actuated in sequence to push, mix, and help to break up (stoke) the refuse. Since the early 1970s, the reciprocating grate system has become the most commonly used type in mass burn incinerator service. The plane of the grates provided by the several grate vendor firms throughout the world ranges from flat to inclined downward toward the ash discharge point. The grate bar actuation devices include those that push toward the ash discharge (the preponderance of grates are of this design) and those that push toward the feed end.

a. Grates on the Flat or Pushing "Downhill". In this embodiment, the reciprocating or pusher grate is installed stepwise in rows on the flat or on a slight downward incline toward the discharge (generally up to about 15° depression). Alternate rows of high chromium–nickel alloy grate bars are stationary or move to convey the refuse from the feed point (under the feed chute or at the discharge plane of a feeder ram) through the combustion area to the ash hopper or other ash discharge equipment. Stoking action comes as a result of the separate motion of the alternate rows of grates. Additional stoking and mixing (breaking open packed refuse masses) is obtained in some designs by providing one or more dropoffs, causing tumbling from one grate section to the next. Two, three, or four grate sections are commonly included in this type of grate for a continuous-flow incinerator. This design is illustrated in Fig. 7.

b. Grates Pushing "Uphill." The reverse acting reciprocating grate (Fig. 8) is also inclined downward, though at a steeper angle, toward the discharge end. However, in this system, the cast metal grate elements reciprocate uphill against the downward flow of refuse, thereby producing some rolling of the burning material as a result of the upward reverse thrust. Again, these grates form a steplike configuration rather than a steady incline, so that additional mixing is obtained as the refuse tumbles from one level to the next.

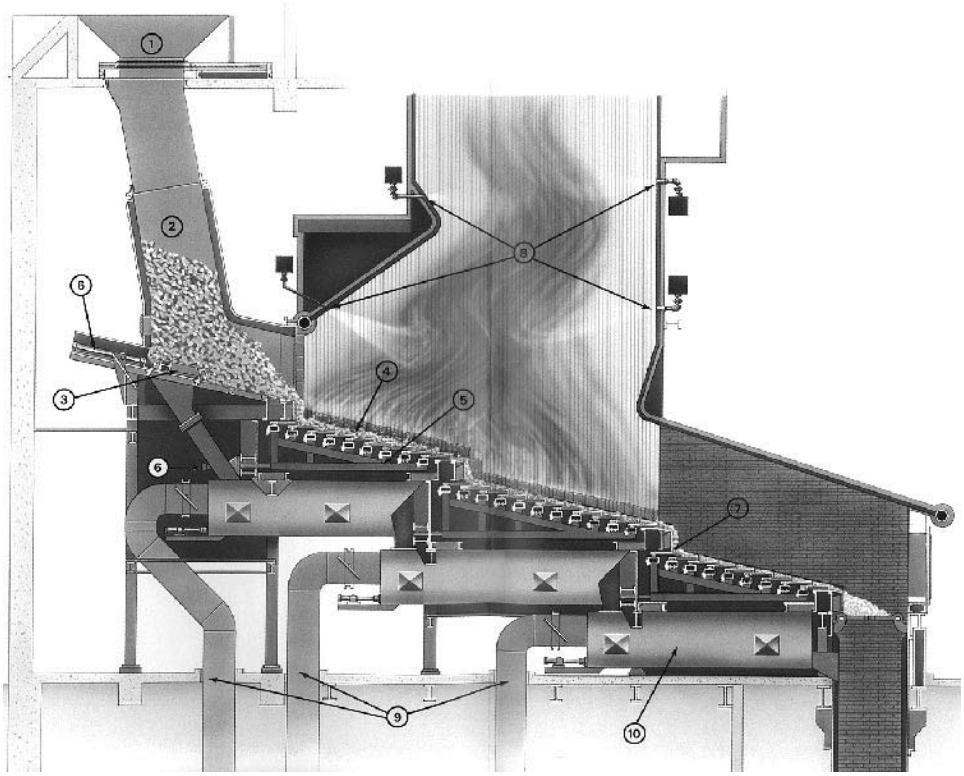


Figure 7 Detroit Reciprograte® refuse fired stoker. 1, refuse charging hopper; 2, refuse charging throat (refractory-lined or water-cooled); 3, hydraulic charging ram; 4, grates (high Cr–Ni alloy); 5, tapered roller bearings (shielded from siftings); 6, hydraulic power cylinders and control valves; 7, vertical dropoff (lined with alloy tuyères to admit air); 8, overfine air jets; 9, undergrate combustion air supply ducts; 10, automatic siftings removal system (discharges to bottom ash system). (Courtesy of Detroit Stocker Company.)

2. Rocking Grate

The rocking grate slopes downward from the feed toward the discharge end. Two, three, four, or more grate sections are installed in series. There is little or no (e.g., <3 cm) dropoff between sections. The rocking grate sections are comprised of a rectangular array of grate segments each of which is approximately quarter-cylindrical. Each segment has 20% to 30% open area to pass siftings to a hopper or conveyor system mounted below the grate and to admit undergrate air. Alternate rows of grate segments are rotated approximately 90° about the edge toward the discharge of the grates.

As the grate face rises up into the burning bed, the refuse mass is broken up and thrust forward toward the discharge. These grate segments each rotate back to a rest position and alternate segments rotate as before, causing a similar stoking action and pushing of the refuse bed forward. This two-cycle action is similar to the previously described pusher and reverse-acting grates, except that it seems to mix the material more effectively. Further, it redistributes the refuse and ash on the grate to cover local areas

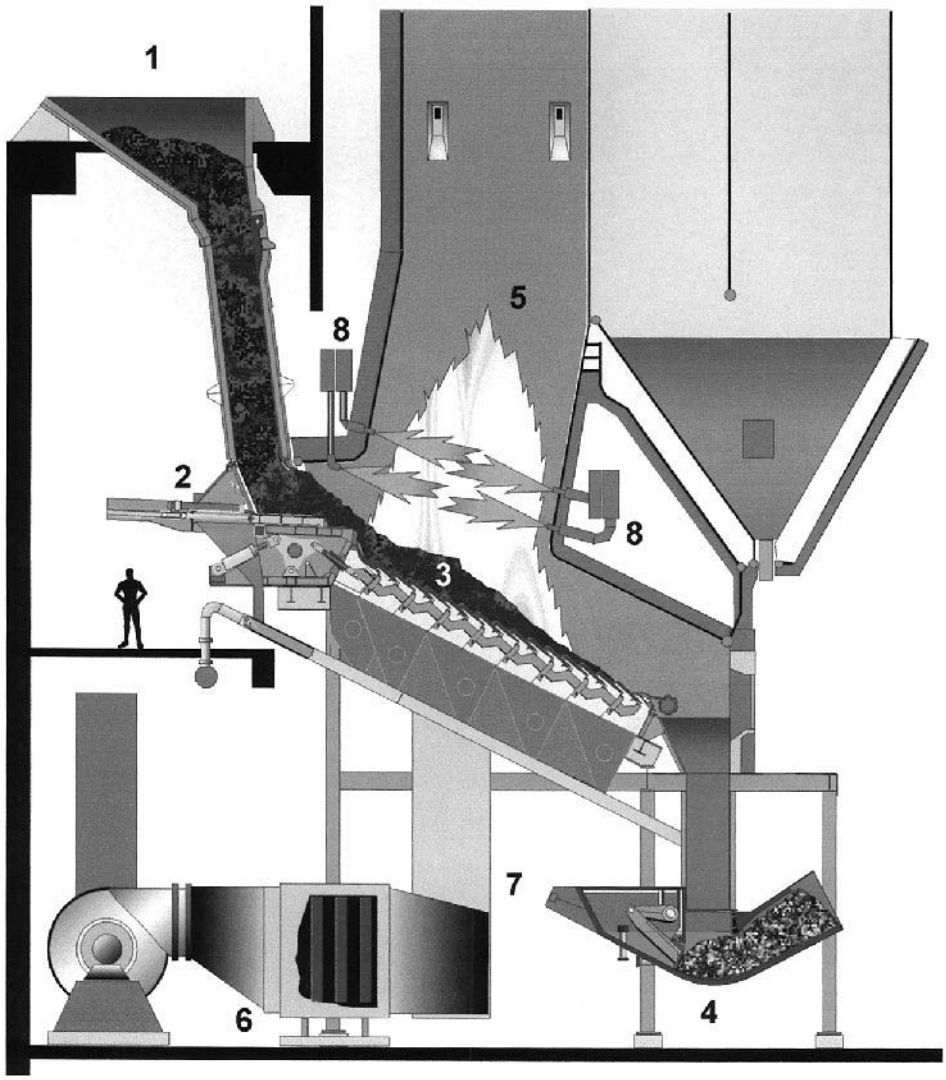


Figure 8 MARTIN® reverse-acting grate. 1, feed hopper; 2, feeder; 3, MARTIN® reverse-acting grate; 4, MARTIN® discharger; 5, furnace; 6, steam heated air preheater; 7, injection of combustion air (underfire air); and 8, injection of combustion air (overfire air). (Courtesy of Ogden Energy Group, Inc.)

where burning has left some grate surface exposed. The rocking grate was common in U.S. incinerator plants of the 1960s but rapidly declined thereafter.

3. Vibrating, Oscillating, and Impact Grates

The vibrating or oscillating grate is mechanically powered by an eccentric-weight vibration generator or an eccentric-driven connecting rod. The oscillations convey the refuse through the incinerator furnace from one grate section to the next, in the same manner as an oscillating or vibrating conveyor. A similar, but nonuniform, oscillation cycle is used

for the impact stoker or grate. The grate sections are moved either forward or in reverse and then released for spring return against a stop (impact). The grate surfaces are generally of the same type as used in the reciprocating grate elements and indeed, might be considered as a variation of the reciprocating type of grate. Although oscillating and impact grates have been used in fuel-burning furnaces and incinerators for many years, there are fewer of them than the other types of grates thus far described.

Figure 9 shows the oscillating grate system as used to fire biomass fuels (including RDF) that vary in moisture content and heating value. The systems shown uses water-cooled grates for reliability and protection, even when firing the boiler with auxiliary burners. Boiler feedwater is used to cool the grate, thus "recycling" the recovered heat to steam generation. The grate is fabricated of high-temperature cast materials, seated on water-cooling tubes with high-conductivity grout. Siftings fall into the plenum and are carried to the discharge opening by the grate's oscillating motion. Only a small (2- to 4-horsepower), variable-speed drive motor is needed to drive the stoker oscillations. Typically, oscillation cycles are approximately 5 min apart with oscillation periods of 5 to 10 sec and an oscillation amplitude of only about 0.6 cm.

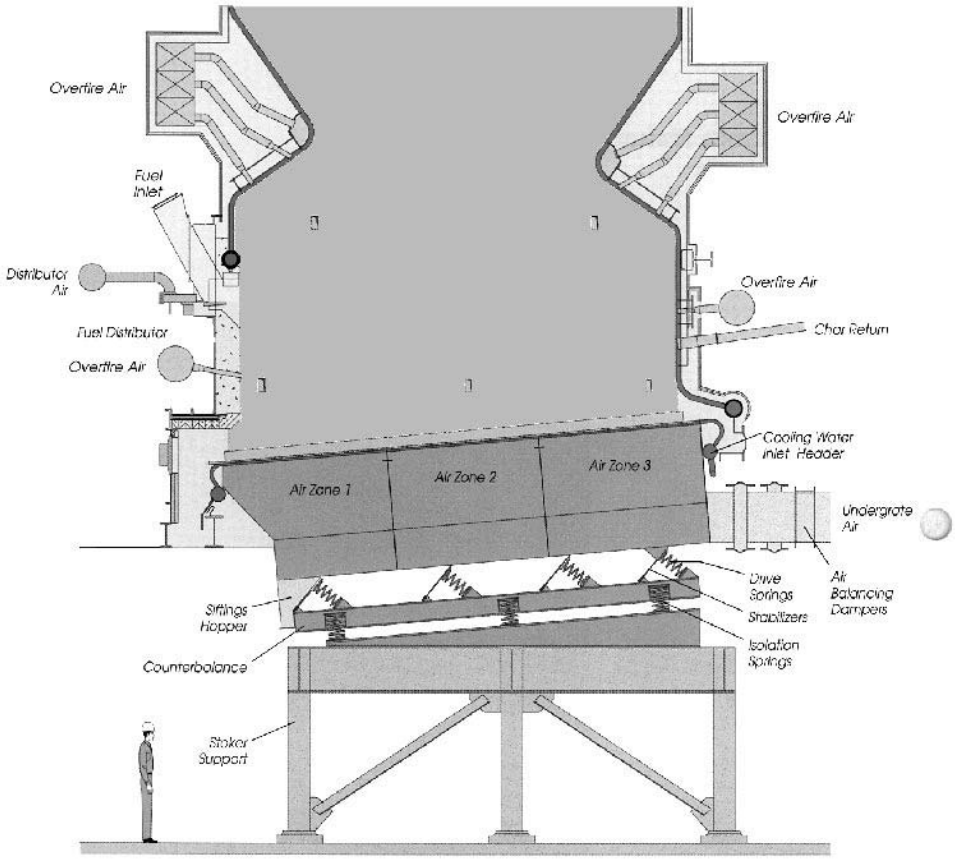


Figure 9 Oscillating grate system. (Courtesy of Babcock Borsig Power, Inc.)

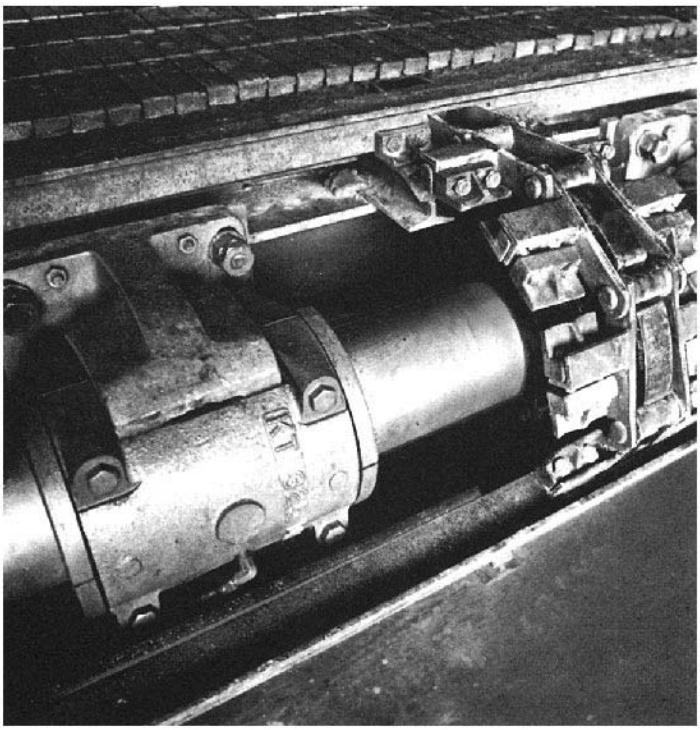
4. Traveling Grate

The traveling grate was the most widely used grate for continuous-flow mass burning incinerator furnaces through the early 1970s. It remains the most common alternative in RDF-fired furnaces. There are many installations in the United States, in Europe, and in Japan. The traveling grate has been in use for many years in coal-fired furnaces and, as in most grate systems, was adapted for use in municipal incinerators. There are two types of traveling grate stokers: the chain grate and the bar grate. Both convey the refuse fuel from the gravity feed chute through the incinerator furnace to the ash residue discharge, much as a conveyor belt.

In RDF applications, grate heat release is approximately two million kcal/m^2-hr, with about 12.8 kcal/hr heat input per meter of grate width over 45% to 50% of the grate width. Typical grate speeds approximate 7.6 m/h.

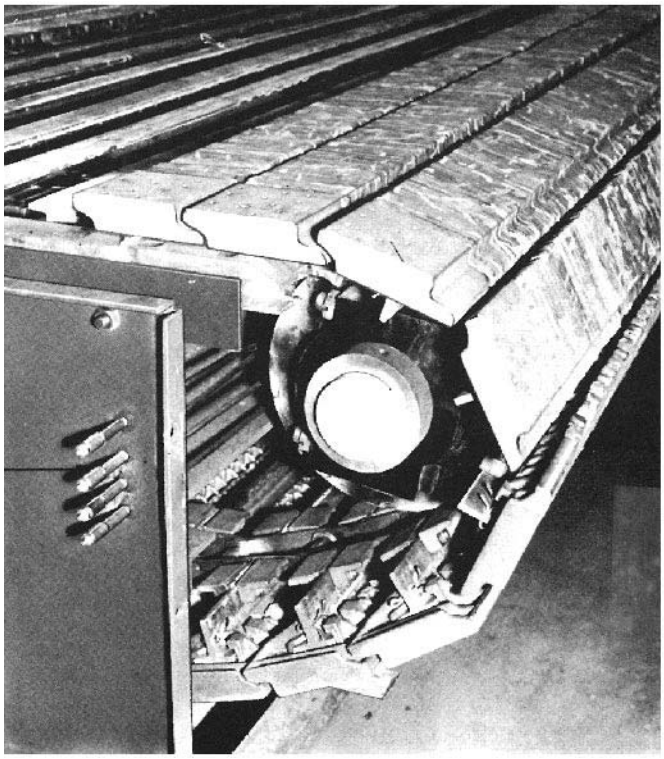
Figure 10(a) shows a partially assembled, spreader feeder-fired traveling grate showing the drive sprocket, skid shoes, and grate racks. As the clips that comprise the exposed grate surface travel around the sprocket ends, they separate to free trapped ash. Figure 10(b) shows the assembled stoker as it rounds the drive shaft. Note that the grease lines penetrate the side wall so that the grate mechanism can be completely lubricated while the unit is in service.

Because the traveling grate stoker does not stoke or mix the fuel bed as it conveys, mass burning incinerator traveling grate stokers are often cascaded in two, three, and even



(a)

Figure 10 (a) Internal features of a traveling grate system near the drive sprocket. (b) Drive sprocket of a traveling grate system. (Courtesy of Babcock Borsig Power, Inc.)



(b)

Figure 10 Continued.

four or more units. With two units in cascade formation, the first portion under the feed chute and continuing through the ignition zone is often called the feeding or drying stoker. The discharge from this first portion of the traveling grate spills and tumbles onto a second unit, thereby mixing, breaking, and redistributing the fuel bed on the second stage. With three or more stages, this spillover and redistribution are repeated. Since the thickness of the refuse fuel bed decreases as the combustion process continues, the linear conveying speed of successive traveling grate units is adjusted to accommodate the rate of combustion and to provide more complete burnout after the combustion rate has subsided (decreased linear speed).

Attempts have been made to install auxiliary mixing devices over the fuel bed on the traveling grate. However, these have not been successful, mainly because of entanglements with scrap wire and other debris contained in the refuse. The best method for stoking or mixing with the traveling grate is to use several grates so that stoking and redistribution are accomplished as the burning refuse is spilled from one section to the succeeding section.

5. Drum Grate

The drum grate, or roller grate (sometimes called the barrel-type grate), was developed by the city of Düsseldorf, West Germany, and subsequently commercialized. The intent of the concept was to reduce the cost of installing multiple traveling grates to obtain better

burnout. Each rotating drum or cylinder represents a minimum length of a traveling grate section, thereby providing a maximum number of tumbling zones in the fuel bed. This rotating grate system consists of six to eight or more rotating grate cylinders, 1.5 m in diameter, mounted on a horizontal axis in close proximity and at a downward inclination of about 30°.

The slow rotation of the drums creates a strong mixing action in the refuse between successive drums, thus loosening and opening bundles of paper or plastic bags. The rotating cylinders extend over the width of the furnace (width of the grate), and each cylinder is equipped with its own variable-speed drive to control the movement of the burning refuse through the incinerator. Thus, the rotating drum grate provides better control of refuse stoking and residence time during combustion than the traveling grate with a consequent improvement in burnout.

F. O'Conner Rotary Combustor (Kiln)

The O'Conner Rotary Combustor is a relatively new combustion concept. The rotating, cylindrical kiln is fabricated of boiler tubes much as a waterwall panel, but it incorporates perforations in the web between tubes. The kiln tubes, which absorb from 25% to 35% of the heat released from the refuse, terminate in a torus-shaped header at the feed and discharge ends of the kiln. A spider of feedwater inlet and outlet piping springs from a rotary joint at the center of the discharge. The kiln discharges into a rectangular waterwall radiant boiler. The waste enters at the high end of the kiln through a choked chute and hydraulic ram and proceeds down the kiln. Below the kiln discharge is a steep, reciprocating burnout grate terminating in a water quench tank and hydraulic ram ash discharger or similar device.

The kiln rides on "tires" and trunnion bearings as a conventional kiln. However, the kiln is surrounded by a segmented windbox. The pressurized segments of the windbox are isolated using flexible metal wiping seals that rub against a plate on the kiln. Air is supplied to the combustion volume from plenums both under the waste (underfire air) and above the fire (overfire air) through the perforations between the boiler tubes comprising the kiln structure.

The rotary combustor design speaks to several of the problems inherent in refractory kilns. It is water-cooled so that rapid heat release does not lead to hot spots and clinker formation. The air supply system allows air to be introduced along the flow path, not just at the feed end. However, the air injection means is relatively ineffective in mixing the gases and in destroying the natural stratification common to kiln devices. Thus, the carbon monoxide concentration in the gases leaving the primary furnace zone and arising from the burnout grates is somewhat greater than is found in many other systems. Secondary air injection in the waterwall secondary chamber is designed to address this situation.

G. Fluid Bed Systems

The general characteristics of fluid bed (FB) incineration systems are presented in Chapter 9 relative to bubbling fluid bed (BFB) applications in burning biological wastewater sludge and in Chapter 11 relative to circulating fluid bed (CFB) applications in burning hazardous wastes and will not be repeated here. These two waste management areas were the dominant applications of fluid bed technology in the United States at the beginning of the 1990s, but several applications for municipal solid waste could be found in Japan and Europe.

In order to provide a feed with relatively homogeneous composition and size, almost all solid wastes fired in BFB or CFB units are preprocessed or, at least, made somewhat more homogeneous through waste separation at the point of generation (e.g., in Japan). Both BFB and CFB furnaces can accept other fuels such as wood chips, coal, or chipped tires. By acquiring these relatively clean, alternate energy sources when the prices are favorable, energy revenues can sometimes be increased significantly with little increase in maintenance and operating cost. BFB applications are discussed in Section XIII of this chapter.

Over 32 plants in Japan (383) make use of a fluidized bed process that, in a sense, is halfway between grate systems and CFB: the "revolving fluidized bed" (RFB). The characteristics of the process favor smaller units (say, 60 to 130 tonne per day). In the RFB, the waste is burned without fine preshredding. Only rough tearing in a twin-screw feed mechanism is applied. Note, however, that items of furniture, whole bicycles, or mattresses, etc., cannot be fed without processing. The units have been operated with high-plastic (high heat content) waste, ordinary refuse, and 79%-moisture-content sewage sludge or night soil (with auxiliary firing). Co-incineration of sludge and refuse is practiced in several facilities (383).

The RFB is fed through the freeboard. The feed falls into a vigorously moving bed with a constriction (the "deflector"), which reduces the cross-sectional area of the furnace to about 40% of the distribution plate plan area. This leads to both vertical and lateral rotation of bed sand and of burning refuse in the volume between the distribution plate and the plane of the constriction. The lateral motion is aided by a peaked conical shape to the distribution plate that directs noncombustible to water-cooled screw conveyor discharge points on the periphery. Bed temperatures are maintained between 700° and 800°C.

Data on NO_x from RFB systems show less than one-half of the concentrations found in grate systems (383). This probably reflects both lower mean and peak temperatures and some in-bed reduction.

In comparison to grate-burning process, FB systems offer intense mixing, long residence time (typically, 4 to 5 sec), excellent residue burnout (typically, less than 1% unburned carbon), lower combustion temperatures (less thermal NO_x, higher boiler efficiency, and less flue gas volume for air pollution control due to reductions in excess air to 40% to 90%), and lowered potential for ash slagging. Note, however, that if slagging occurs, the adverse impact on a fluid bed system is profound. Limestone can be added to the bed of FB units to achieve a nominal reduction in sulfur dioxide (40% to 50% reduction) and some HCl reduction.

VIII. INCINERATOR FURNACE ENCLOSURES

The furnace enclosure provides a controlled environment for the combustion process in the incinerator system. Without the furnace enclosure, the combustion process would be, in effect, "open burning." If one simply installs a metal shield to protect the open burning fire from wind and direct radiation to the atmosphere, we have the conical or "tepee" burner, which was used up until the early 1970s for municipal refuse and wood wastes (Chapter 12). However, the conical unit has the technical limitation that it must be operated with 300% to 600% excess combustion air to prevent catastrophic heat damage to the metal structure and enclosure. At this level of dilution, the quantity of flue gases generated and their flow rate variations are so extreme that air pollution control is untenable. In its time, however, the tepee provided a working example of the most basic concept in furnace enclosure.

Materials for conventional incinerator furnace enclosures (see also, Chapter 5) include

Nonmetals: refractories, e.g., firebrick walls and roofs
Metal: plate, tubes, pipe, etc., fabricated of single metals or clad metals offering a cost-effective combination of cost and corrosion resistance
Refractory-covered metal: castable or firebrick refractory lining or coatings, 3 to 25 cm thick

Either water or air may be used to cool these enclosure materials. Cooling water can be either contained in tubes or pipes or uncontained in the form of a film on the surface of the external metal plate. Air cooling can be employed with forced convection, with forced air jets impinging on the surface, or by radiation and natural convection to the ambient environment. Warmed cooling air can be used as preheated air for combustion or can be ducted for building heat.

A. Refractory Enclosures

1. General

There are at least three types of refractory enclosures: gravity walls with sprung arch roofs, suspended walls and suspended roofs, and refractory linings supported directly by the metal shell.

Gravity walls consist of refractories laid in courses, one above the other, supported on a foundation floor or other support, and are vertical (or almost vertical). The sprung arch used with gravity walls is a portion of a circular arch of refractory shapes. The arch is supported by compression of the side walls through skew-backs retained with structural steel members held together with tie rods.
Suspended refractories are supported on structural steel either directly with clamps attached to each piece of refractory or with intermediate refractory pieces keyed or cast into the refractory roof being supported, with the refractory supporting member held with a metal clamp to the structural steel.
Refractory linings are installed in a circular flue or duct and held like staves in a barrel, or if cast refractory is used, it is supported with metal hooks or dowels fastened to the shell by bolting or welding. Refractory walls can also be cast over pipes or steam tubes, thus protecting the metal tubes against corrosion or flame impingement, and at the same time cooling the refractory surface, with the tubes, in turn, cooled with hot water or steam.

The rotary kiln furnace concept is lined with castable refractory or with large brick shapes called "kiln blocks." It is also possible to use an unlined rotary kiln cooled externally with air or water, or additionally cooled with a water film on the inside of the cylinder. This latter concept has been applied only in industrial incineration.

2. Refractories for Small, Multiple-Chamber Incinerators

The minimum specifications for refractory materials used for lining the exterior walls of multiple-chamber incinerators (127) are the following:

For waste of 2800 to 4500 kcal/kg higher heating value, use
Firebrick: high heat duty, pyrometric cone equivalent (PCE) not less than 32.5
Castable refractory: > 1920 kg/m^3, PCE > 16
For wood, sawdust, and other high-temperature service, use
Firebrick: superduty, PCE not less than 34
Plastic: PCE > 34; density > 2040 kg/m^3

Minimum refractory thickness for lining exterior walls (including arches) of incinerators burning all classes of refuse are the following:

Up to and including 160 kg/hr capacity:
Firebrick: 11 cm
Castable refractory or plastic: 10 cm
Above 160 kg/hr capacity: all refractories, 23 cm

Stacks should be lined with refractory material with a minimum service temperature of 1100°C. In low-capacity units the minimum lining thickness should be 6.5 cm; in units larger than 160 kg/hr, 11 cm.

Doors should be lined with refractory material with a minimum service temperature of 1550°C. Units smaller than 45 kg/hr should have door linings of 5-cm minimum thickness. In the size range of 45 to 160 kg/hr, the linings should be increased to 7.5 cm. In units with capacities from 160 to 450 kg/hr, the doors should be lined with 10 cm of refractory. In units of 450 kg/hr or more, linings should be 15 cm.

The thickness of refractory lining and insulation in the floor of a multiple-chamber incinerator depends primarily on its physical location. Incinerators that are installed on their own concrete foundations outside buildings should have 7.5 cm of firebrick lining backed by a minimum of 3.8 cm of 1100°C insulating material. Incinerators of the semiportable type should have sufficient air space provided beneath the incinerator so that no damage to the pad will result. When incinerators are installed within buildings, it is extremely important that provision be made to prevent damage to floors and walls of the building. Such damage can be prevented by providing air passages beneath the incinerator and adjacent to the building walls to prevent excessive heat from actually reaching the structure. If an air space beneath the incinerator is impractical, then additional insulation should be provided.

For incinerators with capacities up to 225 kg/hr, 11 cm of firebrick and 6.5 cm of insulation should be provided on the floor of the mixing and final combustion chambers. For incinerators with capacities of 225 to 900 kg/hr, 11 cm of firebrick backed by 10 cm of insulation should be provided.

Units in high-temperature service should be provided with an insulating air space of 7.5 to 10 cm between the interior refractory and the exterior steel. This will reduce the temperature of the refractory and extend its life. Adequate openings above and below the incinerator should be furnished for air to enter and exit freely. In some cases forced circulation of the air in this space may be required. Some incinerator designs utilize forced preheated air as secondary combustion air.

The minimum thickness of interior refractory dividing walls generally follows that required for the exterior walls. The bridge wall, with its internal secondary air distribution channels, requires greater thickness. The minimum width of refractory material between

the secondary air channel and the ignition or charging chamber should never be less than 6.5 cm for very small units; 11 cm for units up to 110 kg/hr; and 23 cm for larger units.

3. Refractories for Large Incinerators

The choice of refractory type and the details of installation for large municipal incinerators are still evolving. Table 1 indicates the more common choices for placement in the different regions of the incinerator. In general, suspended construction is preferred, to reduce the initial cost and to reduce maintenance expense.

B. Other Enclosure-Related Design Considerations

1. Air In-Leakage

Refractory walls and roofs can permit air to leak in or furnace gases to leak out depending on the draft conditions in the furnace. "Airtight" metal casings will minimize this problem. Infiltration is particularly common with suspended refractory construction. It can be a benefit in providing air cooling of the wall or roof material, with in-leakage of air adding to that required for combustion. In many installations, however, the in-leakage of air can be excessive to the point that furnace temperatures are reduced, combustion of the furnace gases is quenched, and air pollution control systems are overloaded.

2. Shape Factors

Combustion engineers know that a hot, well-mixed system supplied with sufficient air will achieve complete burnout of the most refractory organic compounds in only a fraction of a second. For conventional fuels, burner designs can be honed with the combined guidance of experiment and theory (the latter greatly aided by the regularity of the system) to coax superior combustion performance over wide ranges of operating conditions. The features of the combustion enclosure in this instance are, therefore, more driven by issues of cost, heat transfer optimisation, and "packaging convenience" than by the combustion process.

In contrast, we know that grate burning inherently is a poor starting point for the realization of complete combustion. The air supply is spatially and temporally irregular as is the air demand. The gasification and heat release processes are in a state of continual upset as the reciprocating grate bars expose new surface and as piles of refuse collapse and fall. This chaos is in stark contrast to the humming regularity of oil, gas, and even pulverized coal flames.

In the incinerator, the physical shape of the furnace enclosure and its appurtenances plays a key role in achieving incineration objectives. The function of the furnace envelope in refuse-fired combustors can be critical; guiding cold gases from the discharge grate area back to the hotter regions where, after mixing, combustion is initiated; guiding hot gases to energy-depleted zones for ignition and drying; guiding oxygen-rich gases to the air-starved pyrolysis zone in the second third of the grate. The furnace shape also serves to funnel and accelerate the fuel-rich gases rising from the gasification regions along the grate to target zones for overfire air jet mixing. The walls constrain the flow to maintain gas velocities high enough to overcome buoyancy-driven stratification and to avoid cold spots and dead zones: wasted combustion volume. Also, the furnace shape, facilitated by skillful placement of (hot) refractory, can provide reradiation to the bed: supplying heat energy for the evaporation of moisture.

The achievement of a very high degree of combustible pollutant control in municipal incineration systems over the period from 1975 to 1985 (including reliable destruction of

Table 1 Suggested Refractory Selection for Incinerators[a]

Incinerator part	Temperature range (°C)	Abrasion	Slagging	Mechanical shock	Spalling	Fly ash adherence	Recommended refractory
Charging gate	20–1425	Severe, very important	Slight	Severe	Severe	None	Superduty
Furnace walls, grate to 1.2 m. above	20–1425	Severe	Severe, very important	Severe	Severe	None	Silicon carbide or superduty
Furnace walls, upper portion	20–1425	Slight	Severe	Moderate	Severe	None	Superduty
Stoking doors	20–1425	Severe, very important	Severe	Severe	Severe	None	Superduty
Furnace ceiling	370–1425	Slight	Moderate	Slight	Severe	Moderate	Superduty
Flue to combustion chamber	650–1425	Slight	Severe, very important	None	Moderate	Moderate	Silicon carbide or superduty
Combustion chamber walls	650–1425	Slight	Moderate	None	Moderate	Moderate	Superduty or 1st quality
Combustion chamber ceiling	650–1425	Slight	Moderate	None	Moderate	Moderate	Superduty or 1st quality
Breeching walls	650–2400	Slight	Slight	None	Moderate	Moderate	Superduty or 1st quality
Breeching ceiling	650–2400	Slight	Slight	None	Moderate	Moderate	Superduty or 1st quality
Subsidence chamber walls	650–870	Slight	Slight	None	Slight	Moderate	Medium duty or 1st quality
Subsidence chamber ceiling	650–870	Slight	Slight	None	Slight	Moderate	Medium duty or 1st quality
Stack	260–540	Slight	None	None	Slight	Slight	Medium duty or 1st quality

[a]From Ref. 129.
[b]Air cooling is often used with subsequent discharge of the warmed air as overfire air.

the precursors of dioxin and furan compounds) was a remarkable technical achievement of the industry. Intensive studies of furnace shape, overfire air injection design, and combustion controls (coupling combustion environment sensors to refuse feed rates and air supply) combined to accept and meet the challenge of dealing with grate-fired systems burning unprocessed, nonhomogeneous waste. Water table (flow table) techniques were used to study the effect of furnace geometry on flow pattern. This design, development, and analysis technology proved to be an important tool in the analysis of the refuse combustion process and is used by most of the major furnace vendors. With this technique, different furnace cross-sections and overfire air injection concepts could be studied at a fraction of the cost of real systems. Changes could be made quickly and problems could be detected promptly.

From the flow table studies and other work, different incinerator system firms have reached somewhat different conclusions about the optimum furnace configuration. Each firm began with a unique, proprietary grate design. This produced a starting point that is particular to the firm. Not surprisingly, from these different starting points, different endpoints emerged.

The three basic concepts in primary furnace combustion chamber geometry are shown in Fig. 11:

The *parallel flow concept*, where gases from the solids feed point (the feed arch) are guided down along the grate over the refuse, rising over the discharge area into the radiant boiler;

The *countercurrent* or *contra flow concept*, where the gases from the discharge area of the grate flow back over the refuse bed, rising over the ignition area into the radiant boiler

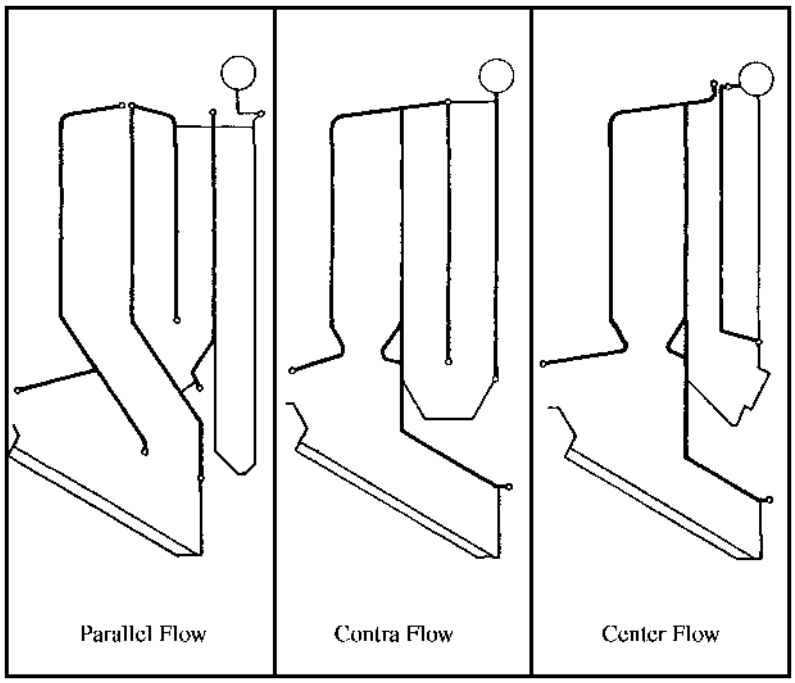


Figure 11 Primary furnace configurations.

The *center flow concept*, where gases from the ignition area flow down the grate in the direction of refuse movement until they meet the gases from the discharge area that are flowing back against the refuse flow direction, rising together over the center of the grate into the radiant boiler.

The heat exchange consequences of these three basic furnace designs are derived from the gas radiation to the bed and the enclosure walls. In this respect, it should be noted that the radiative balance on the top of the bed is an important boundary condition in setting the rate of heat transfer down into the refuse bed and in establishing the temperature profile in the burning mass. Thus, an overbed gas flow that is exceptionally hot or cold has a strong influence on bed burning.

High heat content, relatively dry refuse does not require much heat return to ignite and burn completely. The ignition wave moves rapidly into the mass, and heat release within the bed is more than adequate to sustain combustion. In fact, high heat transfer rates to the incoming refuse can lead to ignition immediately upon entry (perhaps spreading back up the feed chute) and/or may push up the bed temperature to levels where ash softening occurs (with slag buildup on the grate and the side walls). Such increased heat exchange in the entry area is favored by the contra flow design and may be best for low heat content, wet refuse. Conversely, parallel flow designs reduce the heat flux at the entry point; a design that is well suited for dry, high heat content wastes. The center flow system is a good compromise and is optimal for variable waste.

For almost any initial waste characteristic, high heat transfer is not desired in the ash discharge zone where ash cooling is desired. Removal of heat from this area is favored by the contra flow design and, to a degree, by the center flow design.

With parallel flow, the gas flow back into the radiant section impinges on the front wall such that refractory may be necessary to avoid erosive loss and corrosion at the impingement point. With contra and center flow designs, the gas flows uniformly to the radiant furnace and refractory can be minimized (410). The contra flow design also places the front wall of the radiant boiler close to the partition between the refuse bunker and the boiler house. This improves the utilization of plan area of the boiler plant.

In each of these envelope shape concepts, the gases are forced into turbulent whirling and mixing movements by necking and deflections in the combustion chamber made by internal noses, baffles, edges, and deflection walls. Mixing is further stimulated and controlled by the injection of high-velocity secondary air. Water table studies and tests in full-scale incinerators show that all three enclosure concepts can show acceptable and essentially equivalent mixing with proper design and secondary air arrangement (410). However, the parallel flow system shows longer retention time of flue gas flows in the grate area. Also, the high oxygen demand, complex tarry hydrocarbon gases distilled from the entering refuse in the contra flow system can rise as CO-rich streaks into the radiant furnace. To cope with this, mixing must be effected by vigorous secondary air jet attack, where the mixing effectiveness is often facilitated by constricting the flow field with a "nose" (thus increasing the cross-flow velocity differential) at the entry to the radiant furnace.

It is critical that the furnace gases from the various zones of the grate are provided with sufficient air to eliminate reducing gases (CO and H_2) before entering the radiant furnace. Further, the flow field must not result in impingement or scouring of the waterwall construction side-walls. Also, the designer must minimize the pickup and carryover of fly ash. The combination of the exposure of fresh metal surface through erosive processes and

the corrosive effects of reducing gases can be most serious and will lead to unacceptable rates of metal wastage.

In most cases with variable, midrange heating value waste, the center flow design is optimal. The contra flow is quite acceptable, even advantageous if the waste is regularly wet and of low heat content. The parallel flow design should, probably, be reserved for unusual circumstances where layout, reliably dry, hot refuse and other features of the site and waste demand its unusual features (410).

3. Heat Release Rate

The volumetric heat release rate characterizes the combustion intensity and wall temperature level in the furnace enclosure. Although designs vary, most refractory furnaces fall within the range from 130,000 to 225,000 kcal hr^{-1} m^{-3}, with an average of about 180,000 kcal hr^{-1} m^{-3}.

Typical heat release rates per meter of furnace width in waterwall boiler systems approximate 10 million kcal hr^{-1} m^{-1}. The primary furnace volumetric heat release rate approximates 90,000 kcal hr^{-1} m^{-3}. This compares unfavorably with stoker-fired coal

Table 2 Heat Release for Various Fuels and Firing Conditions

Stoker	Fuel	Grate heat release (10^3 kcal hr^{-1} m^{-2})	Volumetric heat release (10^6 kcal hr^{-1} m^{-3})
Single retort (underfeed)	Bituminous coal	540	
Multiple retort (underfeed)	Bituminous coal	810	
Traveling (cross-feed)	Bituminous coal	810	0.26–0.31
	Municipal refuse	810	0.18
Spreader (overfeed)			
on stationary grate	Bituminous coal	950–1080	
	Lignite, bagasse	1220–1630	
on dumping grate	Bituminous coal	1020–1290	
	Lignite, bagasse	1360–1760	
on oscillating grate	Bituminous coal	1500	
	Lignite, bagasse	1760–1900	
on traveling grate	Bituminous coal	1700–1970	
	Lignite, bagasse	2300–2700	
	Pulverized coal:		
N/A	dry bottom	N/A	0.13–0.20
N/A	wet bottom	N/A	0.60–4
	Oil		
N/A	normal pressure	N/A	0.18–1
N/A	increased pressure	N/A	10
N/A	gas turbine	N/A	100
N/A	Gas	N/A	
	Nuclear reactors	N/A	0.18–0.25
N/A	gas cooled	N/A	0.43–0.86
N/A	Pressurized water reactor	N/A	17–160+
N/A	Boiling water reactor	N/A	17–26
N/A	Liquid metal cooled	N/A	170

boilers, which operate at 260,000 to 310,000 kcal hr^{-1} m^{-3}. Comparative heat release rates are shown in Table 2.

4. Secondary Combustion Chambers

Many design specifications require a separate secondary combustion chamber with the incinerator installation. While the primary combustion chamber may be defined as the ignition, volatilization, and burning zone above the incinerator grates, the secondary combustion chamber or zone may be either a separate downstream chamber or an additional furnace volume downstream of the grate area. In either case, the secondary combustion zone provides suitable residence time (usually at least 1 to 2 sec) for completion of the gas phase combustion reactions.

The secondary zone should be located downstream of the point at which additional air is mixed with the furnace gases to supply oxygen for the completion of the combustion. The temperature of the secondary combustion chamber should be maintained above 800° to 900°C to ensure complete oxidation of trace organic pollutants, smoke (carbon and tar particles), hydrocarbon vapors, and combustible particulate and gases (such as carbon monoxide). A tertiary chamber is sometimes added downstream of the secondary chamber in small units to provide additional combustion time, to provide for flue gas cooling and settling of fly ash, or simply to provide a flue gas connection from the secondary chamber to the breeching to the air pollution control device and stack.

5. Slagging and Clinkering

In the design and operation of an incinerator, care should be given to avoiding side-wall, roof, boiler-tube, or grate temperatures where the refuse ash becomes tacky. Under such conditions, slag will build on the walls and roof or massive clinkers can form on the refuse bed. Data or estimates can be made of the temperatures where ash materials become tacky (the "initial deformation" temperature in the ASTM ash fusion temperature test). The grate and the side-walls near the burning refuse bed are likely to operate under reducing conditions, and the initial deformation temperatures under reducing conditions are the

Table 3 Ash Fusion Temperature Ranges of Refuse and Coal[a]

Ash source	Reducing atmosphere (°C)	Oxidizing atmosphere (°C)
Refuse[b]		
initial deformation	1030–1130	1110–1150
softening H = W)	1200–1300	1240–1325
softening (H = 1/2 W)	1210–1310	1255–1345
fluid	1315–1405	1360–1480
Coal[c]		
initial deformation	1060–1100	1105–1245
softening (H = W)	1080–1205	1160–1345
softening (H = 1/2 W)	1195–1215	1240–1355
fluid	1230–1425	1310–1430

[a]From Ref. 130.
[b]From three samples of St. Louis refuse, with magnetic metals removed.
[c]From three samples of Union Electric Company coals.

proper data to use in assessing the problem. Conversely, the slag screen, upper side-walls, and roof are generally in a fully oxidizing gas. Table 3 indicates the effect of temperature and ambient atmosphere on the fusion characteristics of coal and refuse residues.

6. Temperature and Velocity Distribution

The waterwalls and other heat recovery surfaces define the distribution of gas temperature and velocity through the boiler. As discussed in this chapter and elsewhere, both temperature and velocity impact corrosion and erosion losses to boiler tubes. The design conditions through the boiler vary between manufacturers based on their experience, their selection of materials of construction, their tube layout, and so forth. Typical actual gas velocities and temperatures are illustrated below:

Actual gas velocities	m/sec	ft/sec
Primary furnace	3.66	12
Open pass	6.10	20
Convection screen tubes	5.49	18
Superheater	6.10	20
Convection section	6.10	20
Economizer section	7.62	25

Maximum temperature entering superheater:	650°C
Minimum gas temperature leaving economizer	215°C
Desired minimum available air preheat temperature	120°C

IX. ENERGY MARKETS AND ENERGY RECOVERY

As fossil fuel and other energy costs increase, the economic benefits of incorporating energy recovery into an incineration system improve in kind. However, the analyst should carefully consider whether the value of recovered energy does exceed the increased capital and operating expense. And, as important, whether the impact of heat recovery subsystems on the reliability of the waste disposal system seriously erodes achievement of the primary function of the incinerator: cost-effective and reliable waste management. For sludge and solid waste incinerator applications, for example, particular attention should be given to the areas of corrosion, slagging, and other tube-fouling problems. Generally, the problems are considerably less important for liquid or fume incinerator boilers.

Energy markets (a useful application or use for recovered heat) are important to justify incorporating energy recovery into an incinerator design. Energy markets may be characterized in four ways: (1) the size of the market, (2) the energy type, (3) the reliability with which energy will be used (the market stability over the year), and (4) the reliability of revenues.

A. Market Size

The “best markets” for waste-derived energy are large markets. Then, fluctuations in energy recovery from the incinerator (as waste characteristics vary) and/or outright outages from plant shutdowns can be absorbed by other, on-line energy generators. Large markets of this type include electric utilities that serve an effectively infinite market

and are well backed up and major steam users (large steam-intensive manufacturing plants such as paper mills). Smaller users are often concerned about the reliability of energy supply and may demand backup. Ideally, one wishes to sell an energy product that gives the customer the opportunity to avoid capital investment (thus adding value beyond energy cost to the waste-derived energy). If the customer must provide backup steam generation and a "shadow workforce" and/or warm-running to allow quick response to outages, this negates a large fraction of the benefits of waste-to-energy.

B. Market Type

The ideal market is a steam user. This avoids the need to install energy conversion equipment (turbo-generators) and the inefficiency in energy conversion for incineration plants, which often operate with inferior steam conditions (temperature and pressure) compared to a utility generating plant. Unfortunately, it is often very difficult to find steam customers using the quantity of steam that "fits" the incinerator and are located near to the proposed plant. Also, most steam customers present a risk that, prior to the repayment of the incinerator bonds, they may go out of business, cut back operations, or significantly improve energy utilization patterns such that the market (revenue stream) weakens or disappears.

Electrical generation with sale to a local utility firm feeding the electric "grid", has the significant advantage that the market is essentially infinite in extent and assuredly continuing. The primary disadvantage is that there exists a highly efficient "competitor" (the utility) also generating electricity. Energy credits are often limited to the offset per-kilowatt-hour energy cost of fossil fuel. Since the utility price for their fuel is usually low and their heat rate (fuel energy burned per kilowatt-hour generated) is usually superior to that of the incinerator, this means the energy revenue can be minimal. Further, the capital investment in the incinerator energy recovery system may not be recoverable as a "capacity credit" associated with the sale of electricity unless the installed utility generating capacity is marginal (relative to regulatory minimums). Then, the addition of the incinerator generating capacity to the system has worth that can be realized as part of the energy credit.

Wheeling of electrical energy (transmission of electricity from the point of generation to a distant customer over the transmission lines of the local, host utility) is, in concept, a means to sell generated power to a remote utility client that can offer a better price. This strategy is suggested, for example, when the local utility burns coal and the remote utility burns oil. Note, however, that wheeling (1) is provided for a fee and (2) is not a service that a utility must offer under present U.S. energy law. Utilities can (and have) refused to wheel. Wheeling to a remote commercial client (remote from the point of generation) is usually prohibited by the exclusivity terms of the utility franchise. In some circumstances, however, "over-the-fence" sale to commercial clients (e.g., a large industrial complex) is feasible.

C. Market Reliability

The solid waste problem (usually) knows little seasonality. Thus, the ideal energy market is 24 hours per day, 7 days per week, 52 weeks per year. Although this is true for electricity, most steam markets fall short of this goal. Large steam users such as paper mills come the closest. Seven-day industrial operations of lesser size may be acceptable for much of the year. However, "white-collar industry", school or office buildings, and other energy

markets primarily using the steam for space conditioning show strong and unfavorable diurnal and seasonal patterns.

D. Revenue Reliability

The financial lifetime of incineration systems is long. Therefore, energy marketing agreements will extend over many cycles of base energy cost (the cost of the reference fuel often specified in energy contracts and used to scale the unit value of the plant's energy product, such as the cost of No. 2 distillate oil in New York). In some cases, contract terms at fixed prices may be obtained over relatively long times but usually at levels that are significantly lower than those that use more risky "floating rates." On the other hand, if the unit value of energy "floats," the project revenue stream is uncertain. This usually requires some kind of backing for the energy-related revenue stream if bonds (where the payment of principal and interest is based in part on the energy revenues) are used to finance the project.

Also, as noted above for steam sales, the financial viability of the energy customer may weaken or fail in the future such that a needed cash flow stream is cut off.

X. COMBUSTION AIR

For incinerators with grates to support and/or convey the burning refuse through the furnace, "combustion air" usually includes the supply of underfire air, overfire air, and secondary air. Each air supply type serves a special function within the combustion system.

A. Underfire Air

While combustion air for hearth-type systems will be discussed later, underfire air for grate systems is defined as the air supplied under the grate surface through several (typically three or four) independent plenums to provide a proper distribution of air addition along the combustion path. Figure 12 shows an example of a 5-plenum underfire air system for a continuous-feed, reciprocating grate MWC. In the system shown, the plenums are fed from a common header with dampers to partition the air into each windbox. The air passes upward through the grates and beneath the burning refuse. When refuse moisture content is high, the air may be preheated to facilitate drying.

The grate surface meters the primary combustion air, providing a relatively high pressure drop to ensure good distribution of the air over the grate surface. The air flows through small air ports or tuyères in the surface of the individual grate bars with an area approximately 3% of the total grate area.

The flow of underfire air is required to cool the grates (to maintain their structural integrity and to avoid oxidative corrosion of the grate metal). Underfire air is also supplied to furnish oxygen for the gasification and combustion reactions within the bed. In most regions of the bed, the underfire air only serves to dry, pyrolyze, and/or gasify the refuse and remove the volatile components. Completion of the combustion reactions (to CO_2 and water vapor) primarily occurs above the bed and involves oxygen from the overfire air.

It is common practice to design for about 70% of the total air to be underfire air and to operate with about 60% underfire. Thus, the normal underfire air flow rate is slightly above the theoretical requirement for complete combustion of the refuse on the grates. However, poor air distribution vis-a-vis air demand, the high relative rate of the gasification and pyrolysis reactions, and poor gas mixing over the bed require additional air to be

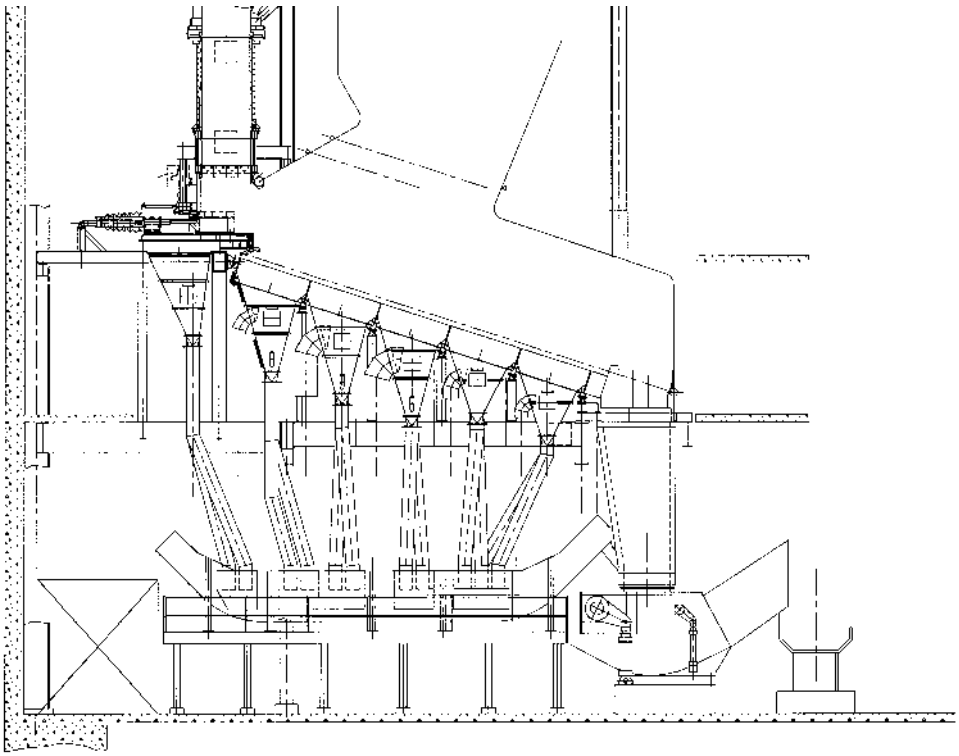


Figure 12 Reciprocating grate MWC showing underfire air supply system. (Courtesy of Von Roll, Inc.)

supplied as overfire or secondary air for combustion, for mixing, and for tempering of the gases (dilution) to maintain temperatures below 980° to 1100°C. Limited quantities of underfire air are required in the last stage of batch incineration process (or near the end of the grate in the continuous process on grates) for oxidation of the remaining fixed carbon in the ash residue in order to provide complete burnout.

B. Overfire Air

Overfire air may be defined as that air admitted above the burning bed of refuse on the grate. It is usually admitted in high-velocity jets directed such as to thoroughly mix the combustible gases rising from the burning refuse with combustion air. In some cases (e.g., above the dump grates in pulverized coal furnaces burning shredded refuse-derived fuel), overgrate air is supplied to provide an "air curtain" at the boiler-tube walls to eliminate the occurrence of reducing conditions that would foster oxidizing–reducing-type tube wastage.

It is common practice to design for about 50% of the total air to be overfire air and to operate with about 40% underfire.

C. Secondary Air

Secondary air, added for temperature control, may be admitted through high-velocity jets in the side walls and roof of the furnace enclosure, either near the upstream end of the

primary furnace or at the transition between the primary and secondary furnaces. Also, secondary air can be added at low velocity through a slot or small openings in the bridge wall separating the primary chamber from the secondary chamber. In the latter case, mixing is dependent more on the shape of the chamber and changes in direction of the main gas stream than on the energy carried by the air jets. The use of such tempering air has diminished greatly with the shift from refractory to waterwall incinerator construction. The cooling effect of the waterwalls is quite sufficient to control gas temperatures, and secondary air is neither needed nor (due to the high cost of adding to the capacity of APC equipment) affordable.

D. Combustion Air Fans

Centrifugal fans with electric motor drives are used to supply combustion air. Since the fans for high-velocity combustion air must operate at higher tip speeds and therefore with considerable noise, the fans should be located where their noise will not be a nuisance. In general, sound-absorbing devices should be considered on these and other high-speed fans.

Low-velocity combustion air can also be admitted through louvers, doors, or other openings as a result of the negative pressure or draft within the furnace chamber. The quantity of combustion air admitted through such openings can be controlled by dampers or by the door opening. This technique, though crude, was useful in small, natural draft incinerator units. As for other secondary air systems, this approach to incinerator air supply has disappeared in modern controlled-air and waterwall heat recovery systems.

Combustion air for suspension burning of shredded and air-classified refuse or other finely divided waste material that does not use grates as the principal site of waste gasification (even when a burnout grate is provided) requires a different combustion air concept than that appropriate for a grate system. In suspension burning within a waterwall furnace or within a refractory furnace, the air that conveys the shredded refuse into the chamber may be half or all of the theoretical air required for combustion; however, it must be sufficient to convey and inject the shredded refuse into the furnace. Often, a portion of the air is supplied through registers that impart some swirl to the injected flow.

Good results have been obtained when air is added tangentially to the furnace chamber to create a cyclonic action, with the burning mass in the center of the rotating cyclone and the air injection surrounding the cyclonic flame. If the suspension burning system includes an auxiliary grate at the bottom of the furnace chamber for completing the burnout of the ash residue, a small amount of underfire air through this grate and an air curtain for side-wall protection are desirable. Although high-speed centrifugal fans in single or multiple stages can be used to supply the air for injection of the shredded refuse for suspension burning, positive displacement blowers can also be used for injection air as well as for high-velocity tangential air jets to induce mixing within the cyclone of flame in the furnace.

E. Air Preheat

In order to cope with high-moisture wastes, underfire air preheat is used to assist in drying the waste. Air preheat may be achieved by directly exchanging heat from the incinerator flue gases to the incoming air or indirectly where the incinerator flue gases generate steam and the steam is used to heat the combustion air. Mass burn units often have the capability to provide air preheat. In the Orient, where waste moisture content is often quite high, air

preheat using direct air preheaters to as high as 300°C is practiced. In RDF systems, preheat from 150° to 175°C is usually available.

1. Direct Air Heaters

The four main problems encountered with direct air preheaters are

1. Low-temperature corrosion, if the incoming air is cold enough to cause the moisture in the flue gas to condense. The HCl and SO_2/SO_3 in the flue gases dissolve in the water to produce strong mineral acids with subsequent corrosion.
2. High-temperature corrosion, if the incoming flue gases are hot enough to oxidize the metal in the preheater.
3. Plugging due to deposition of particulate matter.
4. Mechanical damage due to stresses induced by large temperature differentials. These problems are particularly important when the hot gas temperatures exceed 350° to 400°C. Specialized expansion joints and designs to compensate for differential expansion of the various structures are important solutions to these problems. Due to the importance of this device to continued operations, extra care is needed in vendor selection and in the validation of vendor claims.

There are three common designs for air preheaters: countercurrent, concurrent, and regenerative. In all cases, provision should be made to bleed settled particulate matter from the hot gas plenums.

a. Countercurrent Flow Systems. Countercurrent tubular air preheaters are common and consist of a series of tubes fastened into a stationary tube sheet at the top of the unit and a floating tube sheet at the bottom to allow for expansion. The flue gases pass through the tubes (which can be easily cleaned by brush) with air passing around the outside of the tubes. Baffles are arranged to make the preheater multiple pass for the air flow. Although both horizontal and vertical arrangements are offered, the vertical options are preferable for the dirty gas found in waste burning. The cold air and the hot flue gases enter at opposite ends of the unit to maximize the temperature driving force for heat transfer. This reduces the cost of the unit.

The plate-type unit is constructed of welded envelopes with the air passing through the inside of the envelopes. Gas sweeps on the outside where the width between envelopes is large enough to allow easy access for cleaning of ash deposits. Typical clearances are 25 mm to 35 mm.

b. Concurrent Flow Systems. The design of a concurrent flow air preheater is similar to the countercurrent flow system, but the cold air and hot flue gases enter at the same end. This has the advantage that the potential for condensation is minimized but at the price of increased equipment cost due to the lower overall temperature driving force for heat transfer. Also, the maximum air preheat temperature is limited in the concurrent design.

c. Regenerative Air Preheater. In the regenerative air preheater, heat is transferred from the flue gas to a heat-retaining mass (often of refractory construction) mounted in a rotating wheel. The wheel then rotates past a seal to a zone where the combustion air passes, recovering heat from the heated mass. This type of air preheater is used in some

gas-fired utility boilers but can be problematic if the flue gases contain considerable particulate matter.

2. Air to Steam Coil Air Heaters

An alternative means to avoid condensation and achieve a low level of air preheat is to use a steam coil to warm the combustion air stream. If additional air heating is needed, one can add a direct, gas-to-gas heat exchanger following the steam coil. This avoids the cost of a bypass duct and control system in the direct preheater and provides a use for recovered steam if sale or other beneficial use is not feasible. The primary disadvantage of steam air heaters arises from the low ultimate air temperature as limited by typical refuse boiler steam conditions. However, this limitation is not critical when the steam coil is primarily installed to control condensation. Steam exchangers may be especially economical to preheat overfire air or secondary chamber combustion air in cases where auxiliary fuel is required. All the energy in the air preheat directly offsets purchased fuel energy.

Since the undergrate air is commonly drawn from the dusty environment of the pit, finned tube steam coil air heaters should be designed with generous tube spacing (5 to 6 mm minimum space).

XI. ASH REMOVAL AND HANDLING

A. Overview of Ash Problems

Municipal solid waste includes inert materials that cannot be destroyed in the combustion process. Also, the incineration process is inherently imperfect so that some potentially combustible material is dried, heated, and carbonized but the desired next step (gasification of the char) is not achieved. Further, some material simply "falls between the cracks" (siftings) and leaves the hot combustion environment substantially unburned. These three components comprise bottom ash, the inevitable residue of municipal solid waste incineration operations. Municipal incinerator ash is usually characterized as

Bottom ash: the ash that falls from the grate combined with the s*iftings* that fall through the grate.

Fly ash: the fine ash that becomes airborne in the primary chamber and either settles in the ducts and devices of the incinerator or, ultimately, becomes the inlet loading of particulate matter to the air pollution control system. Also, the fly ash includes refuse constituents that volatilize in the high-temperature zones of the furnace and, subsequently, condense on particulate (often the small-diameter particles that present a large surface area). These may include heavy metals and high-molecular-weight hydrocarbons with a significant health effect.

The presence of ash imposes several technical and economic stresses on the incineration operation and the incineration business:

Since ash is a solid and cannot simply be drained from the incineration system, costly and high-maintenance devices are needed to remove the solids from the combustor and to handle the ash stream.

Ash (especially the smaller particles in the fly ash) is a concentrate of toxic elements such as lead, nickel, and mercury as well as elements that are both carcinogenic and toxic such as cadmium, hexavalent chromium, and arsenic.

Ash constitutes a waste stream of the incinerator, and a place must be found to get rid of it. This generates a continuing operating cost both for transport to its disposal site and for the disposal itself. Potentially, landfill disposal leaves the incinerator firm with a liability for groundwater contamination and other adverse short- and long-term consequences of residue disposal.

Ash hazards (real or imagined) have emerged in many countries as a significant concern among the public and the regulatory agencies. These concerns can be addressed, but they can be an impediment to project implementation.

Ash (especially bottom ash) is not an especially desirable material. It is quite variable in its properties, including both large clinkers and fine dusts; it may include both massive and wire metals and ceramic and stony materials; and it exhibits a variety of colors, mechanical strengths, and other physical and chemical properties. Other than by the extraction of ferrous metal (easy to accomplish with a simple magnetic separator), processing the residue to adjust its properties to meet the demands of the marketplace can be quite costly in comparison to the modest revenue stream that can be expected.

All of these factors can be important in making the environmental assessments, developing the operating strategy, and carrying out the economic analysis concerned with municipal solid waste incineration. Understanding the practical technical alternatives, the legitimate environmental concerns, and the realistic economic factors associated with ash management is an important element of design, operations, and business planning for refuse incineration.

B. Ash Properties

As noted above, ash is variable. Also, the characteristics of incinerator ash are inherently related to the specific sources and character of the waste fed to the incinerator. The physical properties of the ash are closely tied to the characteristics of the incineration process. As a starting point in understanding ash properties, it is useful to review the U.S.- and European-based ash data in the tables that follow.

The major elemental analysis of combined bottom and fly ash is shown in Table 4. The dominant elements are silicon, aluminum, iron, and calcium, much as normal soil (Table 5). From elements present at the "percent level," the material is much like a sandy or clay-like soil except for the high iron content. Handling and disposal of these constituents do not present problems. The iron in U.S. and European refuse residue is primarily present in massive iron and steel shapes (fastenings, iron bars, small appliances, etc.), which can be easily and usually economically separated from the remainder of the residue stream.

However, the heavy metal content of the bottom ash and, especially, the fly ash does present disposal problems to some incinerator operators. Of particular importance has been concern regarding groundwater contamination. As with the sewage sludge ash case, it has been observed that the concentration of many of the heavy metals in fly ash is severalfold

Table 4 Range of Major Elements Analysis of Combined Municipal Solid Waste Bottom and Fly Ash

Element/Compound	Weight percent	Element/Compound	Weight percent
SiO_2	40–50	Na_2O	3–6
Al_2O_3	5–15	SO_3	0.5–1.5
TiO_2	0.75–1.5	P_2O_5	0.5–0.75
Fe_2O_3	12–25	CuO	0.06–0.15
CaO	8–15	PbO	0.04–0.22
MgO	1–2	ZnO	0.12–0.22
K_2O	0.75–1.5	LOI[a]	1–3

[a]LOI = loss on ignition at 750°C.
Source: From (466).

Table 5 Comparison of Ranges of Metal Concentrations in Soil, Refuse Combustibles, Bottom and Fly Ash (mg/kg)

Metal	Common soil	Refuse combustible	Bottom ash	Fly ash
Al min	10,000	3,000	18,000	31,000
max	300,000	25,000	177,000	177,000
As min	1	0	2	3
max	50	15	2,000	750
Ca min	7,000	2,300	4,100	33,000
max	500,000	50,000	96,000	86,000
Cd min	0	0	0	2
max	1	90	170	78,000
Cr min	1	2	10	20
max	1,000	200	2,000	3,000
Cu min	2	20	40	200
max	100	3,400	18,000	5,000
Fe min	7,000	500	400	3,100
max	550,000	45,000	480,000	320,000
Hg min	0	0	0	1
max	0	2	4	100
Ni min	5	1	7	10
max	500	90	600	29,000
Pb min	2	30	30	200
max	200	1,600	44,000	140,000
Zn min	10	40	90	2,000
max	300	8,000	128,000	280,000

Source: From (323).

the concentration in the bottom ash. Golden et al. (323) drew on a data base of nearly 500 documents in preparing a comparison of the levels of metals in municipal solid waste, and the bottom ash and fly ash produced. Descriptive statistics for the data (Table 6) were presented on two bases:

Mean and standard deviation considering all samples as unique no matter how many samples were derived from a single installation

Mean and standard deviation where averages were first calculated for each document/source and then the statistics were calculated such that each document/source was regarded as a single data value

The composition data from Table 6 only hint at what has become the defining characteristic of ash: its content of "heavy metals." The term "heavy metals," although commonly used in the literature, is somewhat of a misnomer since several of the metals of concern are from the "light end" of the metals spectrum: arsenic, selenium, and beryllium. In any event, the presence of toxic and carcinogenic metals, even in trace quantities, raises concern in the regulatory agencies and in the general population and can be a significant problem in finding secondary uses for residue.

Throughout most of the world, the preferred laboratory methodology with which to assess the magnitude of the "heavy metal problem" is the toxicity characteristic leaching procedure, or TCLP. Under this analysis protocol, prepared samples of the material under test are mixed with diluted acid and, after holding the mixture at a set temperature for a specified time, the mixture is filtered and tested for each of a specified list of elements. Under the U.S. EPA guidelines, the material is said to have "passed" the test if the concentrations of the eight specified elements are all less than the "maximum contaminant limit," or MCL. Note that in failing the tests, by U.S. regulation, the material being tested is designated as a hazardous waste with all of the procedural, environmental, political, and economic consequences that arise from the assignment of that characterization.

Table 7 shows TCLP results for combined bottom and fly ash for a Florida incinerator. The vast majority of tests on U.S. residues do pass the TCLP test. Occasionally (usually when someone in the waste generation community has dumped an unusually large amount of a special waste into the refuse stream), the test results indicate that the residue is hazardous (here, marginally, for lead and cadmium) but, almost invariably, retesting results in a "pass."

Some regulators, upon noting the presence of dioxins, furans, and PCBs in some samples of ash, have expressed concern regarding proper handling and disposal. Especially when an electrostatic precipitator (ESP) is used for air pollution control, dioxins and furans can be created in the ESPs and a fraction of the created material adsorbs onto and is captured with the particulate matter. However, very strong bonding to solid matter is a characteristic of all three classes of compounds. Therefore, while the materials can be found in some ashes, these compounds do not leach to any environmentally significant degree from the solid matrix.

Table 8 illustrates several features of the ash metal "problem".

The range of metal concentration for a given element is large; as much as 100-fold. The metal content of the various ashes is strongly dependent on the source of the ash. The finely divided matter (siftings, spray dryer, and baghouse material) is especially "enriched" in heavy metal.

Data on the composition of siftings are quite limited. However, the WASTE program (468) indicated that grate siftings contributed about 3.8% of the total mass flux from a modern mass burn incinerator. Table 9 illustrates the range of concentration of elements found in a one-week study of the siftings from the grates of mass burn and RDF municipal solid waste (MSW) incineration systems.

Table 6 Metal Concentrations in Incinerator Bottom Ash and Fly Ash (323)

Bottom ash (mg/kg)

			All samples		Document averages only		
Metal	No. doc.	No. samp.	Mean	Std. dev.	Mean	Std. dev.	Maximum
Al	8	38	32,000	17,000	31,000	13,000	177,000
As	7	36	300	600	150	350	2,000
Ca	6	23	50,000	28,000	49,000	13,000	96,000
Cd	10	37	20	120	30	30	70
Cr	11	43	3,300	23,000	2,600	7,400	1,800
Cu	10	42	1,700	2,600	1,700	1,100	18,000
Fe	8	37	94,000	111,000	97,000	119,000	480,000
Hg	8	32	1	2	1	1	4
Ni	10	41	180	200	160	140	600
Pb	12	40	6,000	13,000	5,400	10,000	44,000
Zn	13	43	12,000	35,000	12,000	32,000	128,000

Fly ash (mg/kg)

			All samples		Document averages only		
Metal	No. doc.	No. samp.	Mean	Std. dev.	Mean	Std. dev.	Maximum
Al	7	57	96,000	67,000	80,000	45,000	177,000
As	9	68	50	190	60	40	750
Ca	6	56	50,000	31,000	57,000	26,000	86,000
Cd	14	84	2,300	1,000	2,000	6,000	8,300
Cr	13	77	1,000	1,100	900	700	2,900
Cu	11	71	1,000	900	1,000	600	5,000
Fe	9	68	45,000	104,000	55,000	78,000	320,000
Hg	6	15	20	40	20	20	100
Ni	11	63	460	600	360	500	29,000
Pb	13	80	9,300	3,400	13,000	25,000	140,000
Zn	13	72	42,000	126,000	63,000	97,000	280,000

Combined ash (mg/kg)

			All samples		Document averages only		
Metal	No. doc.	No. samp.	Mean	Std. dev.	Mean	Std. dev.	Maximum
Al	6	48	26,000	45,000	34,000	28,000	106,000
As	5	25	2	6	3	3	50
Ca	4	22	41,000	43,000	51,000	31,000	67,000
Cd	8	38	30	100	60	80	70
Cr	9	53	100	160	90	80	1,500
Cu	7	48	3,800	14,000	5,700	10,000	100,000
Fe	6	44	31,000	54,000	34,000	29,000	113,000
Hg	5	24	1	2	4	6	18
Ni	8	21	740	1,800	500	1,100	13,000
Pb	10	64	1,400	2,700	1,900	1,500	8,200
Zn	8	49	2,600	2,700	3,500	2,300	8,000

Table 7 Toxicity Characteristic Leaching Procedure (TCLP) Results for Combined Municipal Solid Waste Bottom and Fly Ash

Parameter	Leachate (mg/l)	Maximum USEPA contaminant limit (MCL)[a] (mg/l)
Arsenic	<0.002	5.0
Barium	2.93	100.0
Cadmium	1.07	1.0
Chromium	0.024	0.5
Lead	5.6	5.0
Mercury	0.006	0.2
Selenium	<0.005	1.0
Silver	<0.01	5.0
Copper	1.2	—
Zinc	120.25	—

[a]Note: 100 times U.S. drinking water standards.
Source: From (466).

Many regulators require the fly-ash dust to be maintained separate from the bottom ash and mandate periodic TCLP testing. In general, if there is a failure, it is the fly-ash fraction that fails TCLP testing. If the TCLP criteria are exceeded, the incinerator operator may be forced to seek a hazardous waste landfill for ash disposal. Due to the inherently lower metal content and larger mass of the bottom ash, combined ash generally passes the TCLP.

Because of the significant economic impact of using a hazardous waste landfill for any or all of the ash, it is highly recommended that the Service Agreement include language that passes the increased ash disposal cost directly to the community generating the waste. This is ultimately fair since it is the contamination of the generator's waste that causes the ash to exceed the TCLP criterion. It is not the fault of the operator of the incinerator. This potential penalty often leads the source community to institute waste rules such as by citing automobile batteries (a major source of lead) as "unacceptable" for

Table 8 Range of Total Metal Concentrations in Various Ash Types

Ash type	No. samples	Cadmium	Copper	Lead	Zinc
Bottom Ash					
Grate	4	<1.0–48.2	420–12,600	300–2,750	903–2,420
Siftings	60	<0.68–67.6	122–21,200	738–103,000	412–46,100
Fly ash					
Boiler tube	7	130–389	534–988	4,280–16,100	11,100–24,300
Spray dryer	5	38.0–59.4	312–880	1,060–1,710	2,830–9,630
Baghouse	56	40–578	142–4,399	1,100–10,340	280–92,356
Combined	54	7.7–120	445–17,355	561–5,100	733–53,800

Source: From (465).

Table 9 Range of Concentration of Elements in Grate Siftings

	Concentration range (mg/kg)	
Element	Mass burn siftings	RDF grate siftings
Ag	—	<0.9
Al	38,000–63,000	36,230–62,300
As	2–65	8–13
Ba	1,349–2,629	150–990
Be	<3.0	<0.9
Bi	—	500–1,170
Ca	—	51,790–92,190
Cd	<5.0–14.6	5.3–12.9
Co	—	28–170
Cr	—	230–460
Cu	2,347–25,215	740–11,530
Fe	—	25,150–36,510
Hg	<0.02–5.39	0.2–2.35
Mg	—	7,660–12,780
Mn	—	490–1,170
Mo	—	40–120
Na	—	31,800–41,600
Ni	169–468	210–1,140
P	—	70–1,560
Pb	5,600–34,000	2,140–20,390
Sb	130–570	6–59
Se	<0.25–8.6	0.3–1.8
Si	—	49,070–99,380
Sn	171–946	450–2,000
Te	—	<2.3
Ti	—	4,390–8,990
V	—	60–170
Zn	2,450–5,334	1,150–6,730

Source: From (468).

disposal in the refuse system. Also, such rules encourage the community to institute programs to recycle and recover mercury from thermometers, hearing aid batteries, and similar sources.

C. Bottom Ash

After complete incineration of the refuse, the ash residue drops into an ash chamber or chute from the end of the grate or kiln. In some instances, a roller is located at the discharge point on the grate to allow the operator to hold back the residue to allow material to burn further or when there is a problem with the ash discharger or ash handling conveyors. Such a roller is illustrated to the right of the last grate element in Fig. 13.

Siftings that have fallen through the grates (which may have been either partially or completely burned) and collected fly ash also may be conveyed to this ash chamber. The

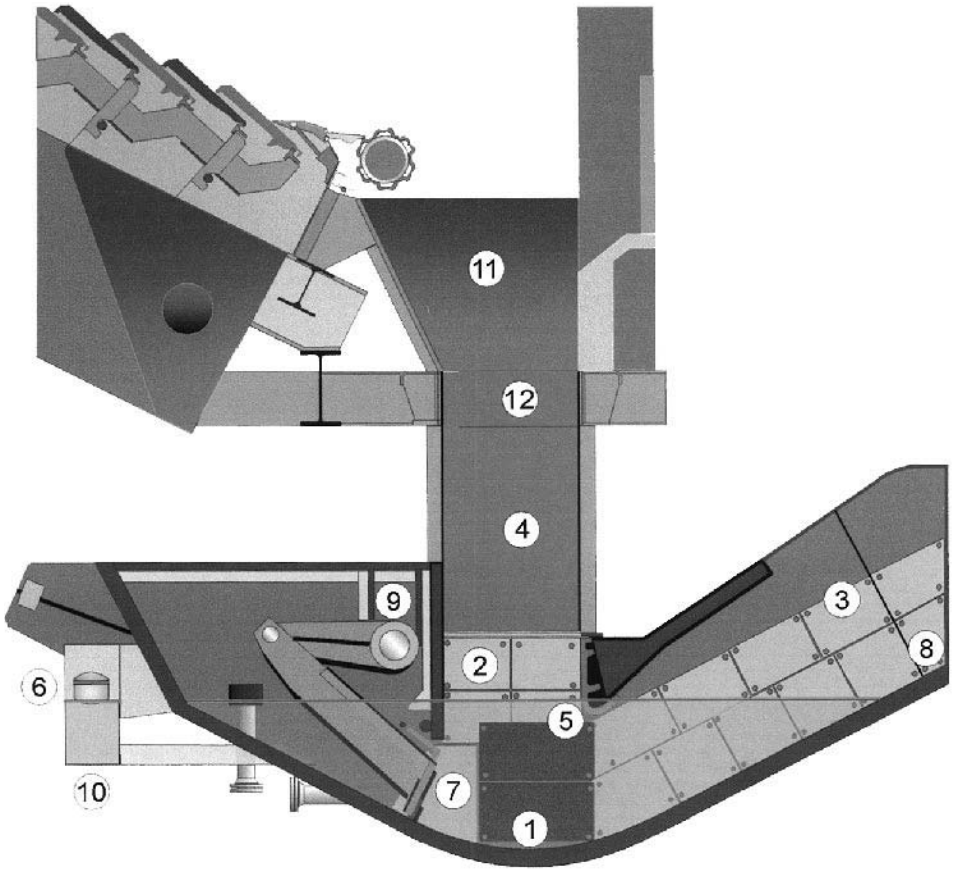


Figure 13 MARTIN® discharger. 1, curved-bottom tub; 2, inlet section; 3, outlet chute; 4, connecting piece; 5, air sealing wall; 6, water level; 7, discharging ram; 8, drop-off edge; 9, driving shaft; 10, float tank with valve; 11, clinker hopper; and 12, intermediate frame. (Courtesy of Ogden Energy Group, Inc.)

ash may be discharged directly into a container or onto suitable conveyors for disposal, or into water for quenching and cooling. The ash residue is then removed from the water with a hydraulic ram, drag conveyor, pusher conveyor, or other means. Rubber-belt conveyors have been used in Europe for some time on water-quenched ash residue, and there are now a few installations in the United States. Alternatively, the ash residue can be handled manually from the ash hopper by discharging into a dump truck or other suitable container and transported to the residue disposal site or serviced to by-product recovery systems.

To prevent in-leakage of air (disrupting the combustion air balance in the furnace) or out-leakage of furnace gases at the point where the gas is removed (impacting air quality in the working environment), a positive air seal is necessary. Dry mechanical seals and seals made by covering the ash receptacle or container have been used to control air leakage. With wet removal of the ash, a wet or hydraulic (water) seal is used or a combination of a wet and mechanical seal is used. The ash residue usually includes abrasive and corrosive materials and miscellaneous slag and metal. Therefore, to avoid malfunctions, the effects of wire, coat hangers, cans, metal hoops, and occasional large and heavy pieces of wood or

metal must be carefully considered in the design of equipment that handles the residue. In order to keep this critical subsystem of the incinerator functioning, designs must incorporate features of ruggedness, flexibility, and resilience. Weak, undersized ash handling systems will cause shutdowns.

Means must be provided for the removal of bottom ash from the primary chamber without significantly changing the furnace draft or allowing large quantities of tramp air to enter the combustion chambers. Such upsets in draft or air supply have a major adverse impact on the combustion process and can lead to overloads in the air flow to the air pollution control device. Also, large quantities of tramp air cool the furnace gases, perhaps to temperatures where combustion reactions stop. This increases CO emissions.

1. Wet Systems

In most plants in the United States, Europe, and Japan, the ash is quenched in a water trough at the discharge end of the grate. Most plants then use a discharge plunger ram to push the ash up an inclined ramp, discharging to an apron or vibrating conveyor. An example of such a ram discharger is shown in Fig. 13. In wet systems, a water seal is maintained to avoid in-leakage of air. The water quenches any burning material and minimizes dusting in subsequent ash handling steps. A large portion of the water drains back from the residue due to compression and the passage up the discharge ramp (the final ash is about 80% to 85% solids). The ash is then carried out of the incinerator building using either a belt or vibrating conveyor. Often a steel vibrating conveyor is preferred to receive the ash as it exits the furnace to minimize wear and cutting problems on a belt conveyor from the impact of oversize noncombustible matter.

Older U.S. incinerator designs and small modular units quench grate residue in a trough filled with water (to provide an air seal). The tank is equipped with a drag chain conveyor to recover the ash. The ash is dragged up an inclined ramp, draining back into the quench tank. Most often, the chute from the grate discharge to the trough is divided into an inverted "Y" leading to two tanks with a pivoted diversion gate so ash can be chuted to one or the other tank. This duplication is justified by the frequent outages in the ash drag chain conveyors and the need to keep the incinerator on-line.

2. Dry Systems

If a dry system is to be used, means are required to ensure that (1) ash is dumped frequently (avoiding excessive buildup) and (2) door opening actions are properly sequenced so that only one door is open at any one time. The inner door seals the furnace against air in-leakage when the outer door is discharging ash directly into a receiving conveyor or container. An alternative design would use a drag chain or apron conveyor to receive the ash from the furnace (using the same, two-door design). The conveyor would discharge into a container.

The space between the doors should be configured as a hopper with sufficient capacity to hold several times the volume of ash expected between the timed dumping cycles. The design of the doors, the grate discharge, and the ash holding hopper should be arranged to ensure that discharging ash or the accumulation of ash in the hopper cannot block complete closing. Gasketing of the doors should be incorporated into the design to improve the air seal.

D. Siftings

Siftings are the fine material that drops through openings in the grate into the air plenums. Screw conveyors or other appropriate materials handling systems are used to move the siftings to the bottom ash discharge point. Data on the quantity of siftings are variable as the quantity generated depends on the characteristics of both the waste and the grate.

E. Fly Ash

Dry fly-ash handling is usually provided using an enclosed screw conveyor. These conveyors are low in cost and efficient to handle the fine dusts collected in electrostatic precipitators and baghouses.

In the simplest configuration, the fly ash is simply combined with the bottom ash. However, environmental regulatory agencies may require separate disposal of bottom ash and fly ash. Usually, the bottom ash is regarded as benign material that can be deposited in any approved landfill while fly ash may require disposal in a "monofill" (a special, leachate-controlled cell in a landfill that is used for a particular waste stream).

Some fly ash will accumulate in hoppers beneath boiler passes. Provision must be made to periodically discharge this material to fly ash or other residue management system. The material is usually a fine material, smaller than sand. The ash collected in the hoppers is dry and can be removed through air lock valves. Data on the quantity of heat recovery system ash are scattered. A study at three German mass burn facilities (469) provided the data in Table 10. Note that at lower feed rates (lower gas velocities in the boiler passes) the fraction of fly ash that settles increases.

F. Materials Recovery from Ash

In a few plants, the bottom ash is processed for ferrous metal recovery. In a few instances, additional processing of the residue yields materials useful as a fill or for road construction.

1. Ferrous Metal Recovery

In the United States, Japan and Europe, the quantity of ferrous metal in incinerator residue ranges from 6% to 9% by weight. At this concentration, if one takes credit for the avoided cost of not having to landfill the ferrous material and with typical low-grade scrap metal prices, recovery of the ferrous metal is, at best, only marginally justified.

The technology of ferrous metal recovery is simple, the capital and operating cost, is low, and the installation has little impact on plant layout or staffing requirements. However, the uncertainty of the ferrous scrap market strongly indicates that no firm revenue stream

Table 10 Fly-Ash Deposition in the Flues of Mass Burn Boilers

Facility	Waste feed rate (mg/hr)	Fly-ash loading (kg/mg of waste)	Percent captured in boiler
A	12	20	7.4
A	10	20	12.5
B	10	30	11
C	10	5	27

Source: From (469).

should be assigned to ferrous recovery. Instead, it is usually prudent to consider ferrous recovery as a cost center, with revenue, if it comes, a welcome benefit. Some client communities desire the environmental benefits of materials recycling and may specify ferrous recovery. In such cases, often the service agreement can be structured as a "pass through" so that the community pays the incremental costs of the ferrous recovery operation and is assigned all (or a portion) of the revenue stream generated from sales of scrap.

Using ballistic and magnetic separation equipment, ferrous metal can be extracted from the overall residue stream for salvage as scrap. Ferrous recovery is generally effected by use of a belt electromagnet. Most often, the magnetic belt is located at a transfer point for the residue conveyor and the recovered ferrous is cast into a chute to a second receiving container. Often, two stages of magnetic separation are required to produce a saleable ferrous product from municipal residue. This may be accomplished using multiple drums or, for belt-type systems, with multiple magnets.

2. Roadbeds and Earthworks

Following processing for ferrous metal removal, the medium ash solids, such as clinker particles, portions of fused glass, or particles of shattered glass that pass the magnet, can sometimes be used as fill material or in surfacing and construction of alleys and secondary streets.

The oversize noncombustible in the ash residue from the incinerator furnace is customarily transported directly to the residue disposal site. In a few instances, oversize noncombustible is passed through crushing or breaker rolls, which flatten larger metal pieces and crush nonmetal pieces.

Incinerator bottom ash can be used in roadbeds and in earthworks (as "clean fill") if it meets applicable environmental quality and use guidelines. The environmental requirements typical in Europe are

- Free of fly ash.
- Stored for at least 6 weeks prior to application.
- Toxicity characteristic leaching procedure or (TCLP) results must comply with standards.
- Loss on ignition (LOI) less than 6%.
- Putrescible material less than 2%.

Typical use constraints include

- Emplacement must be at least 0.5 m above the maximum water table.
- Use in soil or groundwater preservation areas is restricted.
- Measures should be taken to minimize leaching by rainwater (e.g., by use as an underlayment to an asphalt roadway).
- A side and top layer of impervious material must be applied within 6 weeks of emplacement of the ash roadbed.
- The use should focus on larger projects, and the location of the emplacement should be noted in the "as built" final drawings.

To improve the acceptance of the ash as a building material, the size distribution must mesh with the expectations and needs of the user. In the Netherlands, the size distribution shown in Table 11 meets the size requirements. To meet these size requirements, crushing and sieving and magnetic removal of ferrous contaminants are necessary processing steps.

Table 11 Granulometry of Certified Municipal Solid Waste Bottom Ash

Coarse type on sieve	Roadbase material (0/20) unbonded % (m/m)	Roadbase material (0/20) cement bonded % (m/m)	Embankment material (0/40)
45 mm	0	nil	0–10
22.4 mm	0–10	0–10	nil
8 mm	10–40	10–40	nil
2 mm	40–70	40–70	nil
63 μm	92–100	nil	92–100

Source: From (463).

The fine ash that has no salvage value is usually transported by truck to a residue disposal site. Because the fine ash is often enriched with heavy metals, these residues are usually segregated within the landfill in a separate cell (a "monofill"). This minimizes the potential leaching of metals occasioned by percolation through the residue mass of organic acids formed as a normal product of the biological breakdown of refuse within the landfill.

3. Vitrification

The several tables presented above indicate that incinerator residue contains relatively high concentrations of heavy metals and that the leaching of these metals from the residue is, for some regulatory agencies, a matter of concern. Over long times, leaching will occur and, if the residue is not placed in landfills with adequate leachate control and treatment systems, there is a potential for groundwater contamination. In the United States and in some other countries, the legal liability of the groundwater contamination resides with the waste generator (here, the incinerator operator) even though many years may have passed. All of these problems and the general problem of finding acceptable disposal sites for residue have led some jurisdictions to vitrify (melt) the residue to a glass. In the vitrifier, the residue is heated to the fusion point whereupon metals are bound into the matrix of the glass and rendered substantially insoluble. Residue processing by vitrification allows use of the residue as an aggregate or as a "clean fill" without concern regarding environmental contamination impacts.

Vitrification technology has been studied in several countries but is primarily practiced in Japan [see (467) and the Kubota furnace described in Section 3.A in Chapter 9]. In Japan, environmental concerns coupled with extreme cost and siting difficulties for landfills encourage consideration and, in some cases, implementation of vitrification schemes. Vitrification technologies involve use of electric arc furnaces, high-temperature combustion, and other means to raise the residue temperature to above 1500°C. In some instances, lime is added to modify the melting temperature. Under most circumstances, the cost for vitrification equipment and the expense of purchased energy to effect vitrification far exceed the cost of landfill disposal options.

4. Financial Considerations in Residue Processing

Residue is usually not regarded as an incineration by-product of great quality or worth. Its variable properties generally make its use in high-specification products impossible. In most cases, the residue must be transported (another cost) to another location for use.

Although residue represents a large problem to the incinerator, compared to competitive aggregate or fill materials (sand, gravel, etc.), the quantities of residue generated are very small compared with the market. In many cases, crushing and sieving are needed to produce a salable, specification raw material. This further increases the price necessary for a break-even operation. Finally, the cost of sales (sales staff, advertising, applications engineering, etc.) is large in comparison to the quantity of material generated. All of these factors mitigate against the ability to turn residue into a money-making resource. Also, ash processing is a distraction to the principal function of the incinerator and is an improbable and unreliable revenue source.

XII. FLUE GAS CONDITIONING

Flue gas conditioning is defined as the cooling of the flue gas after it has left the combustion zone to permit discharge to mechanical equipment such as dry air pollution control devices and fans or a stack. Conditioning can be effected by water evaporation as an alternative to heat removal in a boiler-type incinerator. Water evaporation conditioning can also be installed as an add-on to boiler systems to lower gas temperatures below those considered safe in a boiler (due to acid gas condensation) in order to improve the removal efficiency of acid gases, mercury, dioxin/furan compounds, and some other pollutants. In general, cooling to 230° to 370°C is necessary if the gas is discharged to mechanical equipment, while cooling to 470° to 590°C is adequate for discharge to a refractory-lined stack.

Both wet and dry methods are used for cooling (or tempering) incinerator flue gas streams. The sections below discuss the technical and economic features of several embodiments of these methods.

A. Cooling by Water Evaporation

In wet methods, water is introduced into the hot gas stream and evaporation occurs. The degree of cooling is controlled by (1) the amount and droplet size of the water added to the gas and (2) the residence time of the gas in the water atmosphere. The quantity of water needed to effect a given reduction in gas temperature is readily calculated using a heat balance on the gas and cooling water as shown in Example 1.

EXAMPLE 1. Determine the amount of water (available at 30°C) needed to cool a hot air stream to 150°C from an initial temperature of 1000°C. Determine the percentage volume change in comparison to the use of a boiler to achieve the same result. Assume operation at a pressure of 1 atm.

Based on the heat capacity correlations given in Section I of Chapter 2, calculate the enthalpy per one mol of air between the two temperatures. For simplicity, use the average molal heat capacity correlations from Fig. 1 of Chapter 2.

$$H_{150} = 6.95(150 - 15) = 938 \text{ kcal/kg mol}$$

$$H_{1000} = 7.55(1000 - 15) = 7437 \text{ kcal kg mol}$$

$$\text{enthalpy change} = 6499 \text{ kcal/kg mol}$$

From steam tables or from the water/steam enthalpy values available from the computer program provided with this book, find the water enthalpy (kcal/kg) at

the two temperatures (liquid water supplied at 30°C and steam leaving the cooler at 150°C).

$$H_{30} = 30.0 \text{ kcal/kg}$$
$$H_{150} = 663.2 \text{ kcal/kg}$$
$$\text{enthalpy change} = 633.2 \text{ kcal/kg}$$

Calculate the water required.

$$\text{water required} = 6499/633.2 = 10.26 \text{ kg } H_2O \text{ per mol of air}$$
$$= 0.57 \text{ kg mols } H_2O$$

Evaluate the volume change.

With a boiler, the volume change of the air is easily determined by the ratio of the absolute temperatures at inlet and outlet:

$$\text{volume ratio} = \frac{[150 + 273.15]}{[1000 + 273.15]} = 33.26\%$$

With water evaporation:

$$\text{initial volume} = nRT/P = (1.0)(0.08206)(1000 + 273.15)/1.0 = 104.47 \text{ m}^3$$
$$\text{final volume} = nRT/P = (1.57)(0.08206)(150 + 273.15)/1.0 = 54.52 \text{ m}^3$$
$$\text{volume ratio} = 54.52(100)/104.47 = 52.18\%$$

Presently, two types of wet cooling are used: the wet bottom method and the dry bottom method.

1. Wet Bottom Methods

The wet bottom method was the most common method used in the 1960s and 1970s but has become unpopular since then due to the costs and problems of the associated wastewater disposal. This approach involved the flow of large quantities of water (much more than was required for cooling the flue gas). The water was supplied by coarse sprays operated at relatively low pressures. The excess water fell to the bottom of the cooling zone and was rejected or recycled. Although not efficient, some removal of particulate occurred by droplet impingement and gravity settling in the spray chamber.

The equipment used in this system consists of several banks of sprays, each with several nozzles with relatively large openings (over 0.5 cm). These spray banks are normally located in the flue leading to the stack or air pollution control equipment. Pumps are not normally required, since line pressure is adequate for satisfactory operation. However, pumps are required if the water is recycled. The bottom of the flue must be maintained watertight to prevent leakage.

The system is generally controlled by measuring the gas temperature downstream of the sprays and modulating water flow, either manually or automatically. Generally, spare spray banks are provided that can be pressed into service quickly in response to sudden temperature increases or plugging of the spray nozzles.

The advantages of this system are that it is relatively simple, reliable, and inexpensive to design and install. The gas is humidified during cooling (approaching saturation conditions), which may be somewhat advantageous for some types of air pollution control equipment (electrostatic precipitators) and disadvantageous for others

(fabric filters). Also, there is a reduction in total gas volume during cooling, as shown in Fig. 14. This figure shows the change in volume of flue gas as a function of inlet gas temperature when the gas is being cooled to 260°C by means of air dilution, water evaporation, and a boiler.

A disadvantage of the wet bottom system is that much more water (greater than 100% excess) is used than is necessary for cooling the gas. The excess water is acidified in use and is contaminated with particulate and dissolved solids. Therefore, it normally requires treatment before it can be discharged from the plant. In some installations the excess water is recycled to the process, and in these cases severe problems of erosion, corrosion, and plugging are encountered in the nozzles, piping, and recirculation pumps. As a result, excessive maintenance costs and equipment down-time are common. Removing suspended solids using clarifiers, hydraulic cyclones, and settling ponds is helpful, but problems with corrosion, plugging, and erosion have not been eliminated. In some plants, the clarifiers and ponds are sources of odor. Also, ponds require considerable land area and may result in groundwater pollution.

Corrosion problems result from the very low pH (less than 2.0) that occurs when recirculation systems are used without alkali addition. There is also a significant accumulation of slightly soluble salts in the recirculated water. These problems can be controlled to some extent by adding chemicals such as lime or soda ash to the contaminated water. However, such systems have significant operating costs and do not completely alleviate corrosion and scale problems.

Another disadvantage of the wet bottom method is that flue gas leaving the spray chamber may carry entrained water droplets or wet particulate matter. These moist particles can cause operating problems with the APC and fan equipment due to fly-ash adherence and accumulation. Also, corrosion of unprotected metal parts downstream or buildup of hardened deposits of solids in the flues and fan housing can occur.

2. Dry Bottom Methods

In the dry bottom method, only enough water is added to cool the gas to a preset temperature and the system is designed and operated to ensure complete evaporation. In this system, a conditioning tower 10 to 30 m high is required and fine, high pressure spray nozzles are used. Booster pumps are necessary to raise the water pressure to assure fine atomization; water pressures from 6 to 36 atm are common in such systems. Alternatively, atomization is effected using compressed air or steam or high-speed rotary atomizers. Control is usually accomplished with a temperature controller measuring the outlet flue gas temperature and modulating the flow of water to the conditioning tower sprays. Since high pressures are required, only a small degree of flow rate modulation by pressure variation is practical. If the flow is too low, the pressure drop across the nozzles will fall, and poor atomization will result; if the flow is too great, the pressure drop across the nozzle will increase and limit flow. As a result, additional spray heads are put into or taken out of service as required to maintain uniform outlet temperatures. Air atomization techniques are preferred to obtain the required turn-down.

Water droplet size is very important in the design of a dry bottom conditioning tower; droplets that are too large will not completely evaporate and, in addition to the problems of water carryover described above, will cause a wet bottom in the conditioning

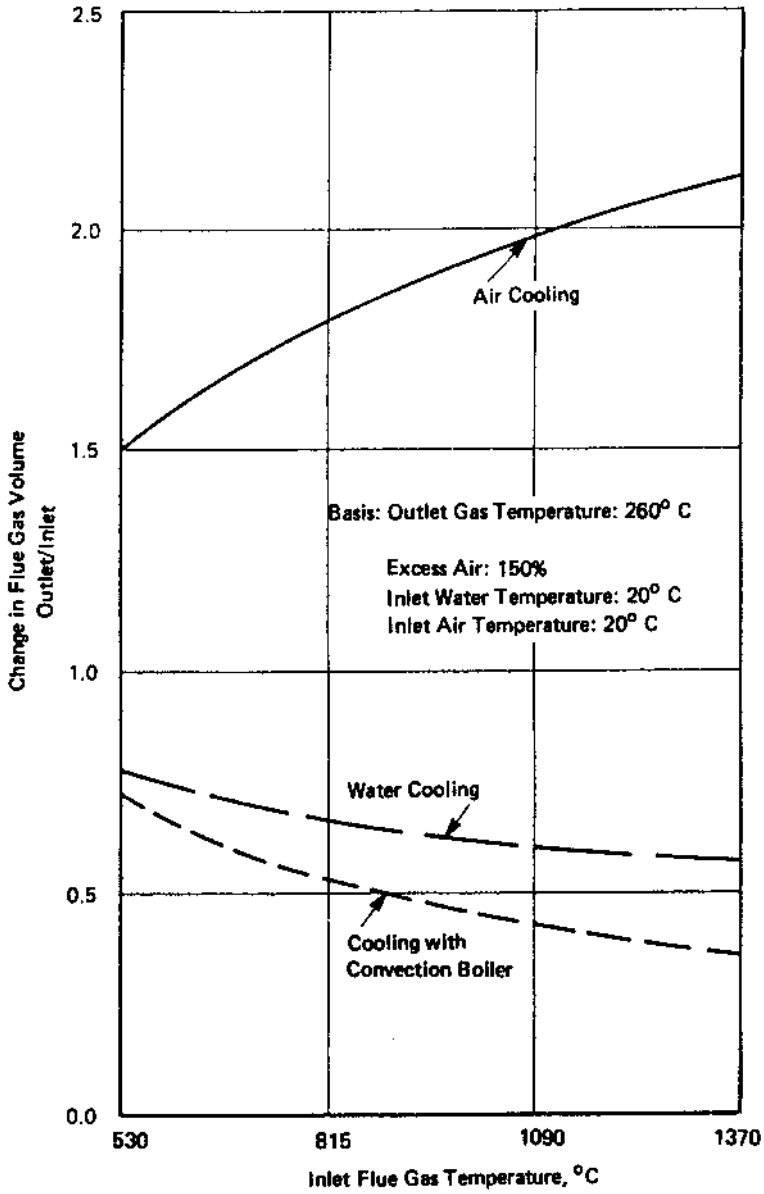


Figure 14 Change in flue-gas volume during cooling to 260°C (to 315°C for boiler). [From (21)].

tower. Droplets that are too fine will lead to high power usage. A balance must be made among droplet size, gas residence time in the tower, and power usage. Equation (1) presents a formula developed by Hardison, of U.O.P. Air Correction Division (131), for estimating the evaporation time of water droplets:

$$t = \frac{r_d}{0.123\ (T - T_d)} \tag{1}$$

where

t = residence time in sec
r_d = droplet radius in microns
T = temperature of gas (°C)
T_d = temperature of droplet (°C)

A second and more complex method of estimating (in a step-wise fashion) the evaporation time of droplets (up to about 600 μm) uses the graph shown in Fig. 15, where

T_a = gas temperature (K)
$\Delta T = T_a - 54$ (°C)
μ = gas viscosity at T_a (g cm^{-1} sec^{-1})
$\beta = 0.071\ (\mu^2 T_a)^{-0.36}$

If the drop temperature varies significantly from 54°C, the evaporation time may be corrected by a factor $(T_a - 54)/(T_a - T_{\text{drop}})$. It is suggested that users of this latter method consult the original paper (132).

Although both of these methods are useful in estimating the residence time required for evaporation, care must be taken in selecting a nozzle that provides uniform-size droplets rather than droplets with a wide size distribution, since the largest droplet will dictate the length of the conditioning tower.

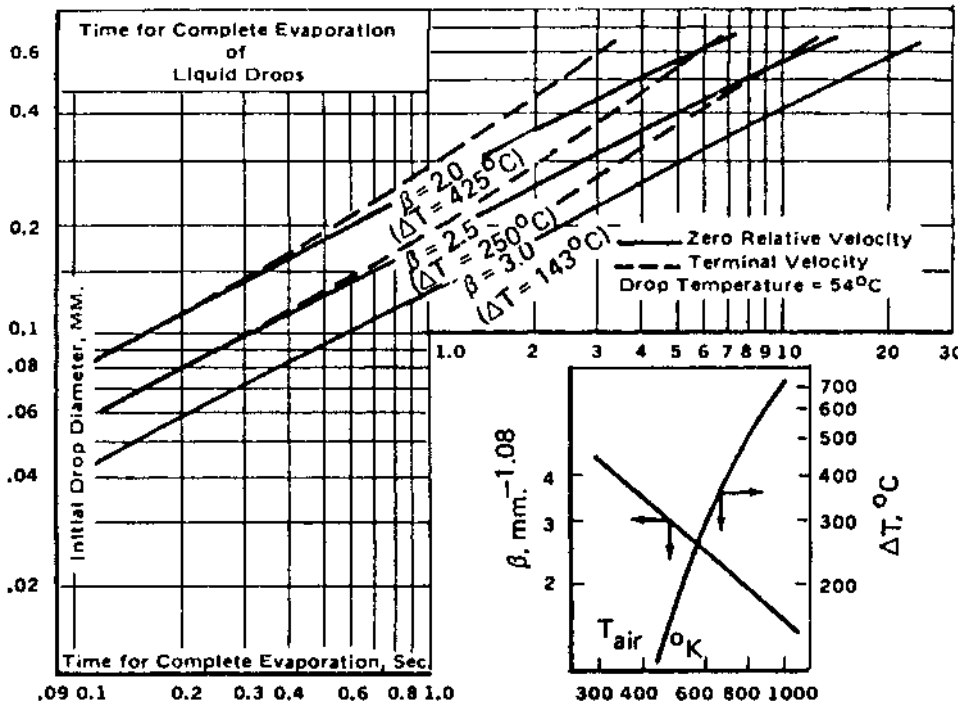


Figure 15 Theoretical evaporation time for water droplets in hot gas streams. [From (132)].

The advantages of the dry bottom system are that it minimizes water consumption, eliminates water pollution problems, produces a "dry" effluent gas (free of entrained water), yet significantly reduces the volume of the flue gas (Fig. 14). The gas is humidified during cooling, which may or may not be desirable. The disadvantages of the system are that it is expensive to design and install, power consumption is high, control is somewhat complex, and the small orifices of the atomizing nozzles make them susceptible to plugging. The nozzle plugging can be minimized by filtration of the water, proper draining of the nozzles when they are not in use, and maintenance of sufficient flow through the nozzles to keep them cool. Generally, the preferred alternative is to use air, steam, or mechanical atomization methods such as those used in the "spray dryer absorber" acid gas control technology.

An installation in New York City used a spray head in which a portion of the water flow was recycled, thus providing additional nozzle cooling. Keeping the nozzles cool and draining them are essential to prevent scale formation in the nozzles due to water hardness; scale is the principal cause of plugging. In order to minimize the risk of outages, the nozzles should be easily accessible and removable during operations, and additional nozzles should be provided for emergency use.

The dry bottom system is more costly than the wet bottom system because of the need for water filtration and the maintenance required for the atomization, pumping, nozzles, and control systems. Proper materials of construction (such as ceramic wear surfaces) are essential for good nozzle life and minimizing corrosion. Power consumption can be minimized by proper nozzle selection.

B. Cooling by Air Dilution

Dilution with air is the simplest and most reliable method for flue gas cooling. Only a damper for air control is necessary for a system with adequate draft. Although air dilution has these advantages, large quantities of air are required for air dilution cooling, increasing the demands placed on the air pollution control equipment and the induced draft fan and stack. The increase in volume caused by air cooling is shown in Fig. 14. Such large increases in volume significantly increase the capital and operating costs of the equipment that follows the point at which dilution takes place. For these reasons, air dilution is no longer used in new incinerator installations.

C. Cooling by Heat Withdrawal

The third method of dry conditioning uses a convection boiler in which heat is removed from the flue gas by the generation of steam. The equipment consists of a convection tube waste heat boiler, an economizer, and all of the auxiliary equipment required, such as boiler feed water pumps, steam drums, and water treatment facilities. In addition, an air or water condenser (the latter served by a nearby natural cooling water source or cooling tower) may be necessary to condense the steam when the steam demand is less than the generation rate. These boilers would have controls similar to conventional boilers and could require an additional full-time operator—a licensed stationary engineer.

The advantages of this system are that heat is recovered and the shrinkage in flue gas is greater than with any other method discussed, as Fig. 14 shows. No water is added to the system during cooling, which may or may not be a benefit. In some cases, the steam generated in the boiler can be used for space heating or process applications (offsetting the burning of fossil fuel) or can be sold to produce income. Alternatively, steam can be used

to generate electricity for internal use or sale. Finally, steam can, in concept, be used in the plant to induce mixing in the incinerator furnace gases (steam jets).

Heat recovery (with 100% energy rejection to an air condenser) followed by a dry baghouse APC system has been found attractive for transportable, short-operating-life hazardous waste incineration systems where the freedom from concern regarding water supply for scrubbers and for wastewater disposal may be an important benefit when coupled with the high collection efficiency of the baghouse.

The disadvantages of heat recovery methods (assuming no attractive energy market exists within economically attractive distances) are that the system is expensive to design and install, the boiler installation is complex to operate and may require an experienced licensed operator, and corrosion and/or erosion problems with the boiler tubes (leading to system outages) may arise if the design is incorrect.

D. Steam Plumes

In the incineration process, water is introduced into the flue gas from the evaporation of refuse moisture and as a result of the combustion process. Water may also be added during conditioning of the gases and by wet scrubbing. As a result, the flue gas leaving the stack can contain significant amounts of water vapor, which will condense, under certain atmospheric conditions, and an opaque stack effluent ("steam plume") will result. Although steam plumes neither cause nor indicate air pollution (often quite the contrary), public reaction is frequently negative and vocal. While these plumes will appear white and not unpleasing in bright sunlight, on cloudy days and at twilight, they may seem dark and "dirty." Under any circumstances, they prominently announce to the "neighbors" that the incinerator is operating.

Formation of a steam plume depends on the discharge temperature and moisture content of the flue gas, the ambient temperature, and the amount of dilution that occurs at the point of flue gas discharge. The processes that occur upon discharge of the stack gases into the ambient are as follows:

- The gases rise from the stack following the flow pattern of a free turbulent nonisothermal jet (sometimes in crossflow due to winds). One characteristic of this flow pattern is that little mixing of the jet fluid with the ambient occurs for a distance of about one stack diameter. As a result, the plume from superheated vapors may "float" above the top of the stack.
- The stack gases then begin to mix with cooler ambient air. As this occurs, the temperature and absolute humidity of the mixed gas fall, about in proportion to the dilution ratio (kg of stack gas per kg of ambient fluid). Thus, the state of the gas mixture, as shown on a temperature–humidity (psychrometric) chart, moves downward and to the left (see Fig. 16). The curve describing the gas state differs from a straight line (between the stack discharge and ambient temperature and humidity point) only as a result of differences in relative specific heat between the flue gas and the ambient air. This effect is often neglected, however, as it acts, in the analysis which follows, to yield a conservative estimate.
- The mixed-gas state thus moves from stack conditions toward cooler and less moist conditions. If, in the course of this change, the mixed-gas conditions cross the saturation curve , a steam plume will form. The gaseous part of the plume then "moves" down the saturation curve while liquid water, in the form of small

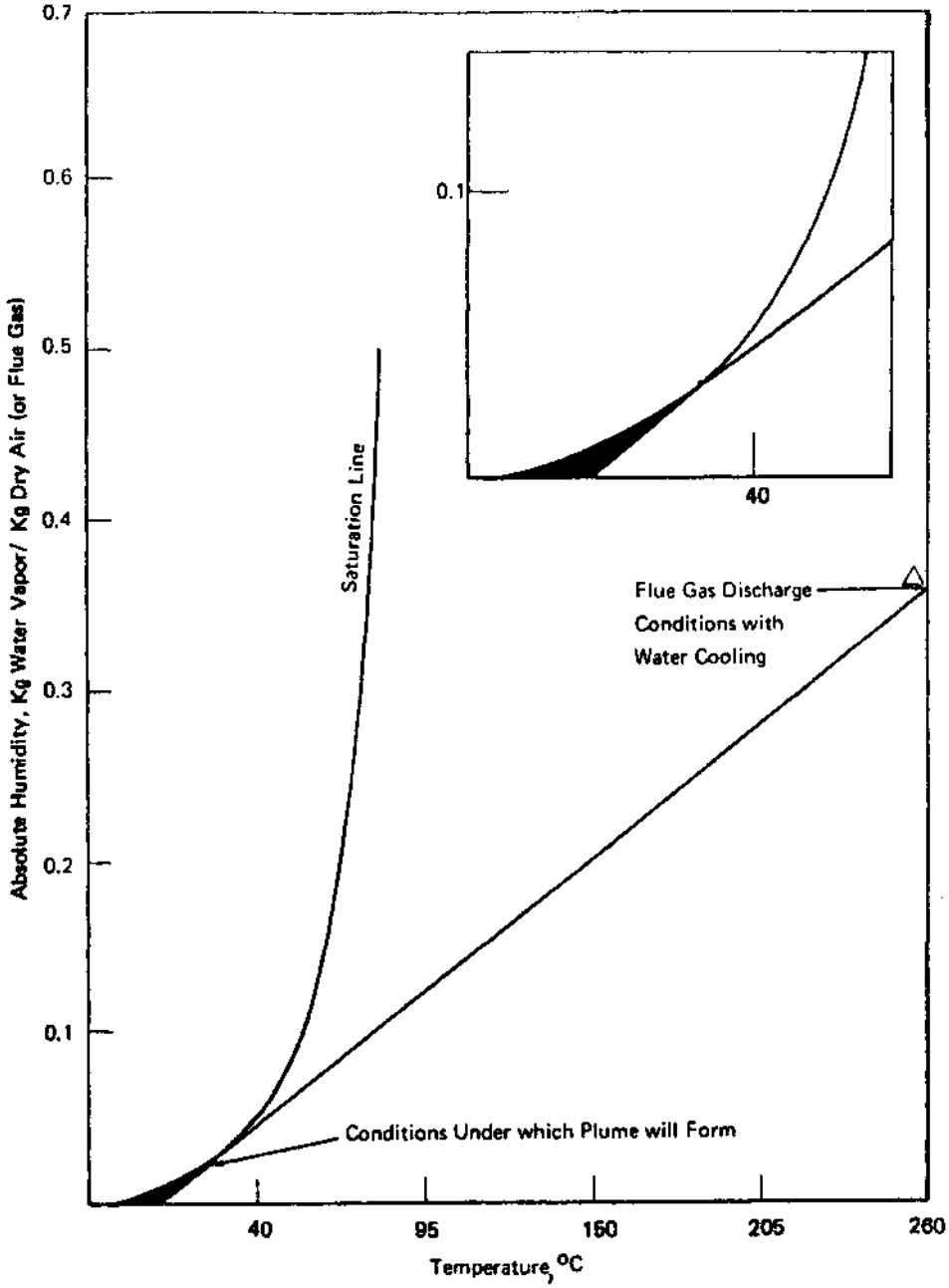


Figure 16 Psychometric chart illustrating steam plume formation. [From (21))].

droplets, is released. The resultant plume opacity is related to the amount of water condensed, the dilution process (which affects cooling rate and droplet number and size distribution), and the ambient temperature and humidity.

As dilution proceeds, the condition of the gaseous part of the plume drops from the saturation curve, and the liquid droplets evaporate. At this point, the plume has "dissipated," and any residual opacity is due to suspended particulate or aerosols. Typically, however, the high dilution at this distance from the stack effectively hides what may have been an intolerable plume opacity caused by high fly-ash loading.

In the case where typical municipal incinerator flue gas is evaporatively cooled from 900 to 260°C, the treated gas will contain approximately 0.36 kg of water vapor per kg of dry air. This moisture includes water formed by refuse combustion in addition to that evaporated in cooling the flue gases. Under these conditions, a line drawn on a psychrometric chart (see Fig. 16) starting at 260°C, 0.36 absolute humidity, and tangent to the saturation line delineates the set of atmospheric conditions under which a steam plume will form. The shaded area on Fig. 16 shows these conditions. For this flue gas, a plume will form any time the ambient temperature falls below 4°C. The plume will also form at higher ambient temperatures, depending on the absolute humidity of the ambient (falling within the shaded area).

If the flue gas is cooled to lower temperatures, say to 90° to 105°C in a wet scrubber, or if the ambient relative humidity is high, plumes will form at higher ambient temperatures. High cross-winds, providing more rapid dilution, may shorten or almost eliminate the plume. Reheating of flue gas, though costly, will reduce the intensity or frequency of plume formation.

Since the costs of reheating will be excessive in regions of frequent low ambient temperature, it is likely that steam plumes (though possibly seasonal) will always be associated with incinerators equipped with wet scrubbers and with plants using evaporative cooling for flue gas conditioning. Steam plumes may be reduced by cooling the flue gases with a secondary scrubber (subcooler) to condense a portion of the water vapor before discharge. A modicum of reheating is still necessary to totally avoid a plume. The heat removal required to condense this water must be compensated for with a cooling tower system or by using very large quantities of subcooling water. With the cooling tower approach, one has only moved the steam plume from the stack to the adjacent cooling tower. The strategy of using very large quantities of water is an approach generally limited to wastewater treatment plants where the water supply (effluent) is abundant and cheap. References (133) and (134) further discuss the steam plume problem.

XIII. ENVIRONMENTAL POLLUTION CONTROL

An incinerator is probably of greatest concern to a municipality because of the fear of the air pollution impact on the contiguous environment. Water pollution from the residue is a secondary issue. However, an incinerator can also create undesirable noise and cause the surrounding area to be unattractive because of litter and other forms of trash that quickly disfigure an incinerator site where good housekeeping is not regarded as a fundamental plant responsibility.

A. Air Pollution

The most noticeable forms of air pollution are fly ash, smoke, odors (from the stack as well as other areas), noxious gases, and dust. All emanate from an incinerator at times.

1. Composition of the Flue Gases

If combustion of the volatile fraction of the refuse is complete, the composition of the flue gas will be principally nitrogen, oxygen, water vapor, and carbon dioxide. There will be small amounts of sulfur oxides, nitrogen oxides, and mineral acids (principally hydrochloric acid, which will result from the combustion of halogenated plastics, particularly polyvinyl chloride). Normally, the concentration of sulfur oxides, nitrogen oxides, and mineral acids will be high enough so that it will trigger the regulatory requirement for air pollution control. If combustion of the volatile is not complete, the flue gases will contain significant amounts of carbon monoxide and other unburned or partly burned organic materials. These emissions are more subtle but can include the polychlorinated dibenzo p-dioxin and dibenzo furan compounds, POMs, and the like. The first easily visible indication of the presence of these materials in high concentrations will be the appearance of black smoke from the incinerator stack, which may be followed by the detection of objectionable odors.

The presence of unburned or partially burned materials is unnecessary and is caused by the poor operation of the incinerator. Their emissions can, in general, be controlled by the proper operation of the incinerator rather than the installation of control devices. Complete combustion can be ensured by operating the incinerator at the proper temperatures (from 750° to 1000°C), by providing sufficient air for combustion, by providing sufficient residence time for the combustion process to occur, and by inducing (by both gas passage configuration and well-designed overfire air jets) sufficient turbulence in the combustion space to mix the combustible gases and aerosols with the necessary air.

Such residence time and some mixing are usually provided for by ducting the flue gases to a secondary combustion chamber or zone. Although it is not essential that such a chamber be provided, it is necessary to provide sufficient volume preceded by vigorous induced mixing in the furnace to ensure that the combustion process is completed. Few single-chamber incinerators meet this need.

2. Particulate Matter

Particulate matter (characterized by flue gas weight loading), generally referred to as fly ash, is generated in and elutriated by the combustion process and must be removed from the effluent gases. The amount of particulate matter generated is somewhat dependent on the design and operation of the incinerator. If the combustion process is not complete, a sooty fly ash will result. The best way to control emissions of carbonaceous particulate is operation at temperatures sufficiently high to ensure complete combustion of these materials.

Studies have been made (21) that indicate a correlation between the amount of fly ash entrained in the effluent gases and the distribution and amount of overfire and underfire air and the type of grate employed. Proper operation will ensure that large amounts of fly ash do not become entrained in the gas stream because of improper air distribution.

No matter how carefully the incinerator is operated, however, particulate matter will be entrained in the effluent gases. The extent to which the particulate matter is removed from the gases depends on the type of emission control equipment used and the way it is

operated and maintained. If abnormal amounts of particulate are being emitted, it may be that the incinerator is being operated improperly. This happens, for example, when combustion is quenched by large amounts of air admitted to the incinerator in an uncontrolled manner, such as occurs in batch-feed incinerators. Also, the emission control equipment may not be operating properly. Problems that could occur in the operation of air pollution control equipment include the plugging of spray nozzles caused by either water hardness or large amounts of solid in recirculated liquid streams, the plugging of cyclones caused by sticky particulate or condensation, failures in the electrical systems of a precipitator, and fabric filter bag failures due to flexing or pinholing from burns (especially from the carryover of still-burning "sparklers").

In a properly designed and operated incinerator, equipped with appropriate air pollution control equipment, the stringent standards established by states and the federal government can be met.

Although the flue gases from incinerators contain a number of pollutants, air pollution control equipment installed on these units are primarily directed at the problem of particulate removal. For this purpose, a number of devices are in use, ranging in particulate removal efficiency from 5% to 15% to above 99%. In light of present and forecast particulate emission standards throughout the world, control efficiencies in excess of 98% are generally required.

The electrostatic precipitator (ESP) and fabric filter are currently receiving the greatest attention for particulate removal from incinerator flue gases. Both systems can be used in conjunction with the spray dryer absorber (fed with lime slurry) for acid gas control. Trends at this writing favor the fabric filter since it has a higher fine-particle control efficiency (important in metal control) and it offers the advantage that the captured filter cake gives a second contact opportunity for acid gas control vis-a-vis the ESP when used with a spray dryer absorber. A summary of expected average control efficiencies of various air pollution control systems is given in Table 12.

3. Smoke

Smoke (characterized by flue gas opacity) may be ash material that is completely burned but is very finely divided. More commonly, smoke is predominantly unburned or partly burned combustible material (tar or soot aerosol). If the smoke is an ash material, control requires the use of very high efficiency emission control equipment. It may be lessened to some extent through improved operation by adjusting the air distribution in the primary furnace.

If the smoke is combustible, it can best be controlled by improved combustion efficiency. Longer residence time, better air distribution, gas mixing, and high operating temperatures will eliminate such pollution.

4. Odor

In addition to odors that emanate from the stack because of poor combustion, there are odors in the pit and in the residue handling area, particularly if water is used for quenching and sluicing the grate siftings. Odors may also emanate from the residue disposal landfill.

The odors from the stack can be best controlled by ensuring complete combustion of the gases. This is done by proper air distribution, elevated temperatures, and proper residence time at these temperatures. Such control is much more effective and less costly than using equipment such as scrubbers for odor removal.

Table 12 Average Control Efficiency of Air Pollution Control (APC) Systems

APC technology	APC system removal efficiency (weight percent)								
	Mineral particulate	Combustible particulate[b]	Carbon monoxide	Nitrogen oxides	Hydrocarbons	Sulfur oxides	Hydrogen chloride	Polynuclear hydrocarbons[c]	Volatile metals[d]
None (flue setting only)[a]	20	2	0	0	0	0	0	10	2
Dry expansion chamber[a]	20	2	0	0	0	0	0	10	0
Wet bottom expansion chamber[a]	33	4	0	7	0	0	10	22	4
Spray chamber[a]	40	5	0	25	0	10	40	40	5
Wetted wall chamber[a]	35	7	0	25	0	10	40	40	7
Wetted, close-spaced baffles[a]	50	10	0	30	0	50	50	85	10
Mechanical cyclones (dry)[a]	70	30	0	0	0	0	0	35	0
Medium-energy scrubber (wet)[a]	90	80	0	65	0	15	95	95	80
Electrostatic precipitator[a]	99	90	0	0	0	0	0	60	90
Fabric filter[a]	99.9	99	0	0	0	0	0	67	99
Carbon adsorption system	N/A	N/A	N/A	N/A	0[e]	N/A	N/A	—	—
Dry absorption system	N/A	N/A	0	0	0	75	80	—	—
Wet–dry absorption system	N/A	N/A	0	0	0	85	95	—	—

[a]From (26).
[b]Assumed <5 microns.
[c]Assumed 2/3 condensed on particulate, 1/3 as vapor.
[d]Assumed <5 microns.
[e]Some removal occurs for higher molecular weight compounds.

Odors in the pit can be controlled by using masking deodorants, minimizing the time the refuse is stored in the pit, planning the withdrawal of material from the pit (a "first-in, first-out" strategy), and periodic clean-out of the pit contents. The deodorants can be applied by using a spray network permanently installed in the pit. However, such a system should be used only in conjunction with a good cleaning program. The crane operator should establish a systematic plan for withdrawing refuse from the pit to ensure that no refuse stays in the pit too long (as by working from one end of the pit to the other). Cleaning should be done once a week by washing the pit down. This can be done without completely emptying the pit by scheduling the washing of only portions of the pit at one time.

Odor control in water systems used for quenching the ash and sluicing the grate siftings can only be accomplished by a very active cleaning program that involves changing the water at least once a week and throughly washing the equipment. Wet ash handling systems are, at best, messy and difficult to keep clean, particularly if burnout is not complete.

5. Dust

Dust is emitted from the pit area when trucks unload and when the crane is operating, from the residue handling area, and from the fly-ash handling area. Dust raised during unloading can be controlled by enclosing the tipping area and by exhausting the tipping floor volume to the combustion air fan intakes. Also, sprays can be used to moisten the refuse in the pit to minimize dust during feeding. Dust in the ash handling area can be controlled by using sprays to moisten the ash and using closed transfer and hopper systems to minimize dust leakage. Some systems of these types are currently being used and have been very effective.

B. Water Pollution

Water is used and immediately discharged from most incinerators. Water is used to wash down the pit and ash handling systems, to quench hot residue and fly ash, to control dust, and to aid in gas quenching and scrubbing. Water rejected from the incinerator will most likely be polluted in one way or another.

The wash water used throughout the plant and the water that drains from the pit and ash handling systems will have high biological and chemical oxygen demands and contain suspended and dissolved solids, both organic and inorganic (135, 136). Since the quantity of this water will be relatively small, it may be discharged into a sanitary sewer or septic system. It should not be discharged to storm drains or streams without treatment.

The water rejected from quenching and scrubbing systems may be quite large in quantity and very hot. It will also be high in suspended and dissolved solids and, unless treated with alkali, will have a low pH. The solids will be both organic and inorganic. The biological and chemical oxygen demand of these waters may also be higher than desirable. In some designs, the scrubbing water is settled to remove suspended solids and recycled; in others, it is discharged after use. Recycling has often proved to be troublesome because of the plugging of lines and spray nozzles with solids and scale.

Discharged water should be sent to a well-designed settling pond to remove solids and permit cooling. If the water is to be discharged to a stream, secondary treatment consisting of pH adjustment and possibly digestion to reduce biological and chemical oxygen demand may be required. The rate of discharge may have to be controlled to prevent the buildup of soluble solids in the stream.

If water is used only for quenching, systems can often be designed to obtain 100% evaporation and thereby eliminate any disposal problem. Wet scrubbers that permit recirculation without plugging are also highly desirable.

C. Noise Pollution

The noise created by the operation of an incinerator can be a disagreeable nuisance. Many large trucks are constantly delivering and removing material from the plant. Also, large fans, pumps, and other equipment often operate 24 hr/day. There are a number of approaches to control truck noise, including the use of proper exhaust mufflers and enforcement of low-noise operating procedures. Also, the noise from the equipment in an incinerator can be controlled by use of enclosures, or silencers, where appropriate (particularly on the large fans).

XIV. INDUCED DRAFT FAN

The induced draft (ID) fan may be regarded as the heart of the system by effecting the necessary gas flow without which the system could not operate. The ID fan draws the flue gas from the furnace, through the heat recovery train and the air pollution control train, and discharges it into the stack. The selection of the ID fan must be based on the maximum gas volumetric flow, the gas temperature, and the estimated pressure drop through the secondary furnace, boiler, air preheater, and the air pollution control train.

Heat and material balances can be used to estimate the design flow and temperature data. Allowance must be made for further cooling through the air pollution control system and the possibility of water vapor pickup if wet scrubbers are used. The estimate of the pressure drop through the complete system requires an analysis of the flow resistance of each component coupled with data based on experience in existing plants.

A. Fan Types

Most induced draft fans are centrifugal fans although axial flow fans are also available. Three basic types of centrifugal fans are commonly designated:

1. Forward-curved blade fans with blades inclined in the direction of wheel rotation
2. Radial blade fans with blades that are radial elements of the wheel
3. Backward-curved blade fans with blades inclined away from the direction of wheel rotation

The most apparent difference between the three fan types lies in the pressure developed at a given rotational speed. Where noise level is not a problem, the forward-curved fan produces the greatest pressure (draft). Also, the volumetric capacity (the relative delivery at a given static pressure of fans of the same wheel diameter) is highest with the forward-curved type. However, experience in the United States suggests that fan noise is often a significant problem.

The particular advantage offered by the radial blade fan is its ability to move fly-ash-laden gases with less risk of blade deposits. Although the induced draft fan will handle cleaned gas, the gas may still carry deposit-forming material. For this reason, the radial fan is often considered the most suitable selection.

B. Inlet and Outlet Connections

The design of the inlet connection between the furnace and air pollution control system and the fan inlet can produce a marked effect on fan operation. Losses that arise from improper inlet connections and duct work not only result in increased inherent pressure losses but also create unbalanced, restricted, or whirling flow into the fan inlet. These effects seriously reduce fan draft and efficiency.

Induced draft fans generally have shaped transition boxes as a feature of design. The inlet duct is connected to the inlet box in a manner to ensure smooth, straight-line flow into the fan inlet. Similarly, the fan outlet should be designed to gradually convert the high outlet velocity pressure to static pressure as it discharges into the stack. Proper design can provide further reduction in operating power and speed for a given fan.

C. Fan Control

Volumetric gas flow and draft must be controlled to maintain balanced draft in the furnace under the varying conditions of waste characteristics and burn rates. Automatic control is very important for this function and is strongly recommended. Control methods generally fall into three classifications:

1. Constant drive and fan speed with auxiliary device (damper) to modify volume flow
2. Constant-speed drive with intermediate device between drive and fan to provide adjustable fan speed
3. Variable-speed drive directly connected to fan, thereby providing capacity control.

1. Damper Control

A sliding power-operated damper may be provided at some convenient point at the fan inlet to throttle volume flow as needed. This method results in relatively heavy pressure losses for a given amount of flow reduction and therefore higher power demand. This method of control provides minimum first cost, maximum operating cost, wide-range regulation, and simplicity of operation.

2. Inlet-Vane Control

This method consists of a series of adjustable-position radial vanes or blades located at the inlet of the fan. The vanes can be adjusted to various positions so that the entering gas is given a change in direction or spin in the direction of fan rotation. This method offers a low first cost and avoids the excess pressure dissipation of damper control, and the power demand is correspondingly reduced compared with damper control. This is the most common method employed on small incineration systems.

For induced draft fans, a louver-type vane control is commonly used at the inlet of the inlet box attached to the fan similar to, but in place of, vane control, which is attached directly to the fan inlet.

3. Hydraulic and Magnetic Drive Control

The hydraulic method combines a constant-speed drive (motor or turbine) with an adjustable-speed power-transmitting device to provide stepless adjustable control of fan speed. The magnetic drive consists of a ring driven by a constant-speed motor, a magnetic element rotating within the ring, and the ring connected to the fan. Both the hydraulic and

magnetic drive methods of control provide a wide-range, low-power consumption option, having an effective response to control demand and with a first cost comparable with variable-speed drives.

4. Variable-Speed Drives

Fan-capacity control by variable-speed motors is not as common in power plant applications as the other applications discussed above, all of which use constant-speed motors. However, variable-speed drives, although expensive, are quite effective in this service.

XV. INCINERATOR STACKS

Several types of stacks or chimneys are used to discharge incinerator flue gases into the ambient atmosphere. The primary engineering design issues include corrosion due to flue gas, flow pressures, thermal stresses, forces due to wind and earthquakes, and weathering conditions.

Stub stacks are usually fabricated of steel and extend a minimum distance upward from the discharge of an induced draft fan. Stacks taller than about 5 diameters and less than 30 m high are often referred to as "short" stacks. These are constructed either of unlined or refractory-lined steel plate or entirely of refractory and structural brick. "Tall" stacks are constructed of the same materials as the short stacks and are used to provide greater draft than that resulting from the shorter stack and to obtain more effective diffusion of the flue gas effluent.

Some metal stacks are made with a double wall with an air space between the metal sheets. This double wall provides an insulating air pocket to prevent condensation on the inside of the stack and thus avoid corrosion of the metal. The draft or negative pressure within a modern incinerator is commonly provided with an induced draft fan. The need for a fan (as opposed to natural draft) is occasioned by the high-pressure drop of modern air pollution control devices, the depressed stack temperatures occurring when wet scrubbers or dry scrubbers are used, and the control advantages realized with mechanical draft systems.

Whenever stack gas temperatures are higher than the ambient, draft will be produced by the buoyancy of the hot gases. The theoretical natural draft may be estimated by

$$P_{ND} = 0.0342 P_a L_s \left(\frac{1}{T_a} - \frac{1}{T_s} \right) \tag{2}$$

where

P_{ND} = theoretical draft (atm)
P_a = barometric (ambient) pressure (atm)
L_s = height of stack above the breeching (m)
T_a = ambient temperature (K)
T_s = stack gas temperature (K)

The value used for T_s should be an average value taking into account heat losses and (for tall stacks) the temperature drop on expansion (Eq. 3) as the atmospheric pressure declines with increasing altitude

$$p = p_0 (1 - 2.244 \times 10^{-5} H)^{5.256} \tag{3}$$

where p is the pressure at an attitude H (m) above sea level and p_0 is the pressure at sea level. As the stack gases pass up the stack, frictional losses reduce the fraction of the theoretical draft available. Frictional losses may be estimated (418) from the following:

$$F_s = \frac{2.94 \times 10^{-5} L_s(\bar{u})^2 \text{ (stack perimeter)}}{T_s \text{ (stack cross-sectional area)}} \tag{4}$$

where

F_s = friction loss (atm)
$\bar{u}$ = mean stack gas velocity (m/sec)

Stack perimeter and area are in m and m^2, respectively.

In addition, some of the draft is lost to the velocity head in the rising gases. This "loss," referred to as the "expansion loss" (F_e) may be estimated (418) by:

$$F_e = \frac{1.764 \times 10^{-4} (\bar{u})^2}{T_s} \tag{5}$$

where F_e is the expansion loss in atm.

Typical natural draft stacks operate with a gas velocity of about 10 m/sec. For forced draft systems, 20 m/sec is more economical and provides a significant plume rise that adds to the dispersion characteristics of the chimney (see Chapter 14).

Given that most incineration plants involve multiple boilers, each chimney shell usually contains multiple flues (liners). Three or four liners can easily be installed in a given shell. If future expansion is envisioned, considerable savings can be realized by making the shell in the initial construction large enough to accommodate the liner serving the new capacity. The multiflue concept allows for several chimney design options:

Circular and noncircular concrete chimneys
Steel stacks
Precast concrete chimneys
Special surface finishes and points
Relief line details
Brick or other insert panels
Provisions for stack sampling, flue gas monitoring
Access for inspection and maintenance
Aviation lighting
Lightning protection

Cast-in-place concrete chimneys: These comprise the majority of chimneys since they provide superior resistance to environmental forces and are flexible as to overall height and diameter. Generally, a cylindrical cross-section is preferred due to savings in forming and structural strength, but architectural features are increasingly important. Departing from cylindrical shapes demands a comprehensive structural analysis looking at static and, particularly, the response to periodic dynamic loads such as from vortex shedding (wind vibration).

Steel stacks: These stacks are limited in height and diameter, but their low cost and short erection schedules make them attractive in some circumstances. Because of the low mass of these stacks, they are more susceptible to wind vibration and interaction with vortices shed from nearby stacks. The principal disadvantage of steel stacks is their size limitation.

This is important if multiple liners are envisioned since substantial clearances are desirable in the shell-liner space (experience has shown that about 1 m is the smallest space required to inspect and maintain the liner).

Precast chimneys: Precast chimneys have several attractive features (reduced installation time, lower purchase price) that arise since most fabrication is done off-site where costs are often lower. These units are cast using molds, and close tolerances can be maintained, thus giving a good fit when the sections are assembled. Codes controlling the design and installation of this kind of chimney are still being refined. However, this alternative can possibly offer a lower cost option (especially for noncircular shapes).

Liners: Clearly, one of the most important issues relating to the selection of liners is corrosion, especially if the gas temperature can go below the dew point of flue gas acids (H_2SO_4, HCl, HF). Most plants are planned for hot operation, and carbon steel and independent brick liners are common. The liners should project above the shell a minimum of one-third of the shell diameter or two-thirds of the liner's diameter to minimize downwash. A skirt should be provided where the liners project through the roof to protect the air space from weather.

Brick liners provide high corrosion resistance but are vulnerable to earthquake forces. In systems where the stack operates under pressure, one must control the escape of gas from the liner with condensation and corrosion of the outer shell. One can pressurize the liner-shell space with a separate fan, but this increases complexity and has a continuing operating cost for power and maintenance. Usually, an acid-proof brick is used with an acid-resistant potassium silicate mortar.

Steel liners are gas-tight and can readily be designed to cope with local earthquake requirements. Generally, a minimum plate thickness of 0.6 cm is used, including a 0.16-cm corrosion allowance. A stainless steel (often, 316L) is used for the top 1.5 diameters (or, at least, below roof level) for corrosion protection, but carbon steel is used for the remainder (418). If the stack is operated below the acid dew point, brick liners or chrome/nickel alloy (solid or clad) is recommended.

Accessories: Numerous accessory features should be incorporated into the stack specification. These include access ladders and working platforms for use in inspections and maintenance and in larger stacks, for stack sampling activity; utilities (especially electrical services, perhaps a jib beam to lift equipment and supplies and lighting); two down-leads (for nonmetal stacks) for lighting protection; and aviation obstruction lights according to the requirements of the relevant aviation agency.

XVI. REFUSE-DERIVED FUEL SYSTEMS

Refuse-derived fuel (RDF) systems are incinerator furnaces where the waste is processed prior to combustion with the objective of significantly reducing its level of heterogeneity. The strategic concept of processing heterogeneous solid waste prior to combustion has several potential virtues:

1. In the course of processing, portions of the waste can be recovered and recycled. Thus, materials recovery can be an inherent partner in on-going or new resource recovery programs.
2. The processing line can be designed to produce a more homogeneous fuel. This should stabilize the combustion process, facilitate more precise combustion control, improve burnout, produce a more stable steaming rate, etc. Since

separation processes can remove stones, glass, and wet material, the mean moisture content of the waste can be reduced and the combustible content enriched, thus increasing the heat recovery potential. Further, one would expect that with better combustion control, excess air levels can be lower, thus reducing the capital cost and many operating expenses for incinerator furnaces, boilers, fans, and air pollution control devices.

3. Improved combustion should reduce air pollution emissions related to unburned or incompletely burned combustibles. Further, because of the materials recovery steps, emissions related to specific waste components (e.g., PVC) can be reduced.
4. Because the processed materials are more regular in physical characteristics (e.g., particle size), materials handling should be easier to automate and should work better.

It was recognized that these benefits would come with some cost: the capital and operating cost increases associated with the processing systems, some increase in the fraction of the incoming waste that was sent to landfill, possibly some minor environmental problems (especially noise and dust from shredder and conveyor operations), and, perhaps, some risk of injury or equipment outage due to explosions. All of these anticipated "costs" and some that were not anticipated have, indeed been experienced—and often at an unanticipated degree of severity and consequence.

In the development and implementation of technology for mass burn facilities, the vendor firms participating in the market generally offer complete "chute-to-stack" systems based on conservative, repeat application of well-proven technological features. Most aspects of the mass burn technology were extensions of combustor concepts developed and proven in burning coal, lignite, and waste fuels such as bagasse. In contrast, many RDF plants incorporate innovative process flowsheets and experiment with untested and unproven items of equipment in the critical RDF processing and handling areas. The extensive body of design data that supported the early mass burn incinerator designs was lacking for RDF systems. Further, the lack of overall system vendors for RDF-based systems reduced the feedback of field experience into process development.

The often-demonstrated characteristic of refuse to profoundly stress, clog, abrade, corrode, and otherwise challenge process and handling equipment made extrapolations from prior experience with other materials uncertain and, quite often, disappointing. Further, the prime RDF processing devices were connected together with materials handling systems where critical design parameters were not well understood and where refuse behavior often was found to be "quite different" from that of reference materials used as the basis for design.

The consequences of these facts and influences was repeated in many if not all plants: long and politically painful startup programs requiring considerable rework of conveyors and processing equipment. This was accompanied by increases in facility capitalization, higher-than-anticipated operations and maintenance costs, and, often, derating of the combustor due to limitations in processing and/or feeding systems. Also, from time to time, many plants experienced explosions, some with lethal consequences, from ignition of combustible vapors released in hammermilling of volatile hydrocarbon (e.g., gasoline) containers.

Despite these challenges and failures, a maturing technology ultimately emerged. By the early 1990s, "package" RDF processing facilities with performance guarantees could

be procured to generate specification RDF. A vendor community offering total RDF-based systems was developing. RDF-only and co-combustion of RDF with other wastes and/or coal were being practiced in several incinerator boiler and utility power plants throughout the United States. The basic technology had become generally "available." The primary concerns limiting implementation of RDF-based projects had shifted from one of high perceived technical risk and problematic operability to the more conventional project development decision criteria: the ordinary issues of cost, permitting, siting, and the like.

A. RDF Processing

The underlying objectives of incineration using RDF (materials recovery and production of a homogeneous fuel) are achieved in the processing line. It is here that materials for recycling are recovered (on "picking belts" by human workers or by automated processes that exploit the physical or chemical characteristics of target refuse components). Before or after the removal of materials, size reduction and size separation take place. In all cases, the RDF facility is heavily involved in materials handling equipment to include a spectrum of loaders, conveyors, hoppers, and feeders. The perverse nature of refuse and its components with conventional materials handling processes has been the major problem with RDF plants.

Table 13 lists several of the common technologies used in the separation of refuse components in the course of RDF preparation. In addition, size-reduction and size-separation equipment are used. These elements of RDF incineration systems are described in Chapter 7. Typical final characteristics of the RDF (532) are shown in Table 14.

B. RDF Combustion Systems

The combustion concepts used in burning RDF fall into two categories: RDF-only combustors and combustors where RDF is burned as a second fuel along with coal, wood waste, or other materials. Since almost all processing concepts include size reduction and the removal of massive metal material, stones, much of the glass, and the very wet

Table 13 Materials Recovery Methods

Method	Component affected
Visual	Aluminum cans
	Corrugated paper
	Newsprint
	Glass containers (by color)
	Plastic containers (by type)
Eddy current magnet	Auminum
Magnetic separation (belt and drum)	Ferrous metal
Air classification	Lights (paper, cardboard)
	Heavies (glass, metal, stone, very wet)
Photodection of color	Glass (green, brown, flint)
X-ray emission by chlorine atoms	Plastic (unchlorinated from PVC)
Trommels and disk screens	Separate by particle size to reject glass and sand and enrich fuel value. Also, separate over-size for recycle to size reduction

Table 14 RDF Quality Impacts of Preprocessing Strategy

Process sequence	RDF yield %	Landfill %	Ash %	Kcal/kg
Without front-end recycling				
Mass burn (no preprocessing)	100	0	23.6	2675
RDF via shred, Fe recovery	93	7	19.9	2860
RDF with classification, etc.	83	17	11.7	3135
	to 70	30	to 8.9	3240
With front-end recycling				
Mass burn (no preprocessing)	100	0	19.6	3060
RDF via shred, Fe recovery	93	7	17.2	3275
RDF with classification, etc.	85	15	9.9	3515
	to 71	29	to 6.6	3605

Source: From (532).

wastes, the remaining fuel is well suited for partial or complete combustion in which the particles of RDF are suspended in gas flows. RDF is poorly suited for grate burning, as it tends to blind the grates and inhibit air flow. Consequently, the types of combustion system used for RDF have focused on the spreader stoker (semisuspension burning) and several embodiments of full suspension firing.

1. Spreader Stoker Firing

The spreader stoker furnace uses a single, flat traveling grate. The grate moves at a slow, constant rate much as a conveyor belt. Air is supplied through the grate from one or more undergrate plenums. The grate elements are designed to develop a relatively high-pressure drop at operating underfire air rates, which results in a uniform air distribution over the entire grate surface. Waste supplied to the furnace is typically shredded such that about 95% passes a 10.2-cm top size. The grate elements are generally fabricated of ductile iron for resistance to mechanical shock.

Wastes are charged to the furnace using several air-swept feeders mounted on the "front face" of the furnace wall. The feeders cast the feed over the fire to land on the grate near the rear wall. The grate moves the waste back toward the front face and discharges ash just below the feeders. All but the very wettest RDF feedstock is dried and ignited in its flight across the furnace through the flow of hot combustion gases rising from the grate. After landing on the grate, the waste continues to burn. For design purposes, it is often assumed that 40% to 60% of the heat release takes place in suspension and the remainder on the grate. The bed depth is maintained between 15 and 30 cm to foster good burnout and to maintain good grate pressure drop (and, as a consequence, good air distribution). Typical grate heat release rate and furnace volumetric heat release rates in several U.S. RDF-based refuse burning applications are summarized in Table 15 based on the total RDF fuel energy input (515). The grate heat release levels are somewhat lower than might be found in, say, a bark-burning furnace.

It is particularly important with spreader stoker burning to get good distribution of fuel. The RDF feeder chutes are swept with a pulsing flow of air (variation in both quantity and pressure at several cycles per minute). The air flow sweeps the bottom of the spout and floats fine, low-density material far into the furnace. Under each spout, a bank of high-

Table 15 RDF Grate and Furnace Heat Release Rates in U.S. Installations

Facility	No. units	TPD per unit	Furnace volume (m^3)	Grate area (m^2)	Typical CO (ppmdv)	Kcal/hr per m^3	Kcal/hr per m^2
Palm Beach (FL)	2	818	929	58.5	55	124,843	1,980,625
MERC (ME)	2	273	201	20.4	90	188,208	1,949,496
Elk River (MN)	1	545	478	37.1	125	132,425	1,709,333
SEMASS (MA)	3	818	1193	55.7	140	84,507	1,808,397
PERC (ME)	2	319	318	27.3	200	150,978	1,758,308
Colombus (OH)	4	455	260	31.8	300	228,357	1,869,582
SPSA (VA)	4	455	500	37.1	400	129,577	1,748,180
Honolulu (HI)	2	809	751	36.8	100	116,906	2,387,707

Source: From (575).

pressure air jets act to "fan" the stream of air-suspended RDF to improve the side-to-side distribution. The pneumatic feeders are described and shown in Section VI above.

Among other issues, poor fuel distribution leads to elevated CO emissions, even to the point where some U.S. RDF boilers burn natural gas or oil through burners mounted just above the firing rate and operating at about 20% excess air to burn out CO. Data on typical CO levels are shown in Table 15. The burner firing rate is adjusted manually or under the control of the CO continuous-emission monitoring system. High CO spikes are also observed when feeder plugging occurs.

Although the RDF preparation step can produce a fuel with considerably greater homogeneity than raw refuse, the benefits of homogeneity require a steady feed rate. Achieving a uniform feed rate has not proven easy. Hangups and blockage occur in almost all systems. This results in irregular feed rates, irregular heat release, and irregular steaming rates. The best performance in feeding has used a "run-around" concept where the mass flow rate of refuse to the boiler exceeds the firing rate. Thus, a substantial quantity of the RDF is recycled.

Overfire air jets are, perhaps, more important for spreader stoker firing than with mass burn units. New units are designed for 50% of the total air supply over the fire with normal operation at 40%. The nature of the firing process gasifies a relatively large fraction of the RDF volatile matter at a high elevation in the furnace. Also, a substantial mass of solid matter is suspended in the flue gases. The high-pressure overfire air jets discharging above the arc of incoming RDF are critical to induce the intense mixing needed to achieve burnout of suspended particles and volatile matter. It has been speculated that the reason that the polychlorinated dioxin/furan emissions of RDF furnaces are observed to exceed those of mass burn systems is due to incompletely burned organic "precursors" that are part of the solids carried out of the primary combustion zone.

Because of the substantial gasification of the refuse while in suspension and the relative homogeneity of the material, the flue gas environment near the side-wall does not show the alternating oxidizing and reducing condition that produces side-wall corrosion in mass burning furnaces. Data at the City of Hamilton, Ontario, RDF furnace (415) showed no significant side-wall attack after four years of operation at overall excess air levels as low as 40%. As a consequence, no refractory cladding appears to be needed. This increases

the heat absorption efficiency of the furnace waterwalls and reduces the boiler investment cost.

2. Suspension Burning

The burning of RDF is suspension has been effected in two ways:

1. In solid fuel boilers using feeding methods that are similar to those used to fire pulverized coal in suspension and in vortex furnaces
2. In fluid bed combustors

In each case, secondary fuels (coal or other waste streams such as wood scraps, sawdust, or agricultural wastes or industrial liquid waste) are often burned at relative heat release rates that range from zero to many times that of the RDF.

a. RDF and RDF-Coal Burning in Suspension-Fired Boilers. Co-burning of refuse and coal is significantly different from burning either fuel alone. With co-burning, the combustion environment must be tailored, to a degree, to the limitations imposed by the poorest fuel. The furnace temperatures will approach that of the dominant (heat release basis) fuel. In retrofit situations, the physical combustor characteristics (height, residence time, heat release patterns, boiler-tube locations, etc.) are inflexible and some compromises will be forced on the operator. Clearly, if either fuel presents failure modes (e.g., low ash fusion temperature or slow combustion), the situation may be such that problems will, necessarily, arise. However, the success to date in refuse–coal co-burning suggests that the problems can be solved, mitigated, or lived with. There will, however, be a greater level of maintenance, increased outage frequency, and many "aggravations" related to plugging, fouling, and the like.

As the particle size of a solid fuel diminishes, behavior in a combustor approaches that of gaseous or liquid fuels. The particles volatilize rapidly. The small char/ash particle that remains has a large surface area, thus facilitating rapid oxidation. To approach this idealized combustion state, coal is pulverized to approximately 200 mesh: only slightly grittier than face powder. In this form, powdered coal may be entrained in an air flow, swept up in an ignitable cloud, and burned to completion in only a few seconds.

In comparison to lump coal that fractures and shatters quite readily, refuse does not pulverize easily. The most important fuel components of refuse are paper and plastic. Both deform and stretch under impact and degrade slowly (and with high energy absorption) in crushing, cutting, or tearing environments. This means that the ultimate particles will be large. The economic practical lower limit on particle-size reduction is approximately 2 cm. Processing costs increase rapidly as the top size decreases below this level.

The top size of the RDF used in suspension burning has varied from as small as 0.95 cm to as much as 6.35 cm. The cost of shredding increases rapidly as the mean particle size decreases. However, larger particles have longer burning time. One should avoid carryover of still-burning RDF because (1) the material can generate clinkers during burnout in the ash hoppers under the boiler passes or, (2) if applicable, still-burning "sparklers" cause pinholes in fabric filters. Therefore, the goal has been to find the largest top size that gives acceptable combustion and minimum carryover of burning material from the primary furnace.

A maximum particle size between 2.5 and 3.8 cm appears optimal. Tests by the Potomac Electric Company with RDF shredded to 95% minus 1 cm appear to have reached

the point where the burnout grate is not necessary. The high cost of processing to this degree makes this strategy unattractive.

In addition to combustion problems associated with mean particle size, a second problem area arises because paper and other refuse components can absorb and/or carry considerable moisture. This contrasts with coal, which can be largely dried in the air-swept pulverizer. The RDF portion that is wet with surface moisture can tolerate several seconds of intense radiant heating before thermal volatilization begins. If the cross-section is thick, the time required for conduction heat transfer and pyrolytic breakdown of the organic matter further delays burnout. This means that the general time frame to achieve full combustion for a significant portion of the refuse fuel will significantly exceed that of coal. The result is a higher carbon loss (unburned carbon heating value in the ash residues) and unfavorable decreases in fly-ash resistivity (important in plants using electrostatic precipitators).

The energy density (kcal/m^3) and specific volumetric air rate (m^3 of air per m^3 of RDF) for RDF and coal are significantly different. Also, the fuel handling tendencies (ease in maintaining a uniform feed rate, potential to hang up or build up on projections, at transfer points, etc.) of coal and RDF are very different. Because of these significant differences and because the coal is usually blown into the boiler directly from the coal grinders (without any buffering hopper where coal and RDF could be blended), it has been found that separate burners for RDF and coal are to be greatly preferred over a mixed-fuel burner concept. Consideration has been given, however, to the use of a burner fabricated of concentric pipes to allow firing of both fuels from the same burner port. In general, the air rate for the refuse burner is kept constant irrespective of the solid feed rate; otherwise, the RDF will begin to settle out, build up, and block the burner piping.

Achieving complete burnout of co-fired RDF with acceptable processing costs requires the installation of a burnout grate at the bottom of the primary furnace. The grate not only helps to achieve substantial burnout (realization of most of the heating value of the waste material), but it also eliminates the problem of fires from the accumulation of combustible waste material in the ash handling system. The burnout grates used successfully to date are simple, flat dump grates although several operators have modified the size and shape of the air holes (increasing the hole area and changing them from circular to slotted).

The grates are supplied with a small amount of air for the combustion of material on the grate. This undergrate air flow has been shown to be necessary to achieve reasonable burnout. The furnace waterwall near the dump grate is exposed to alternating eddies of oxidizing and reducing conditions. These changing gas conditions lead to rapid tube wastage. A simple and effective solution has been to supply a small air flow to the side-wall near the bottom of the boiler (an “air curtain” along the wall) to ensure oxidizing conditions at the wall.

Corrosion is a major concern when contemplating co-burning of refuse with coal in high-temperature, high-pressure boilers. The corrosion process of greatest importance is “high-temperature, chlorine corrosion.” This corrosive process involves attack of the superheater and boiler-tube surfaces in refuse incinerators where the fireside metal temperature exceeds about 425°C. In the co-burning case, one has several factors that appear to mitigate the corrosion problem: significant dilution of chlorine; significant neutralization of hydrochloric acid by alkali in the coal ash; and significant counteraction of the chlorine corrosion reactions by the high concentration of sulfur compounds. The net

result is that there have been no reported cases of severe tube corrosion in refuse–coal co-burning situations.

Opinions vary among operators whether it is preferable to put the RDF in through burners mounted at the top of the burner array or closest to the burnout grate. High entry applies the most intense radiative and convective heat flux to the incoming RDF, thus hastening its final drying and volatilization, but gives the shortest residence time prior to the particles' entering the tube banks. The latter strategy avoids blowout of unburned RDF but, probably, increases the dependency on grate-burning processes.

Refuse constituents (especially bottle glass and other mineral residues such as the high-phosphorous ashes from grasses, food, and brush) generally have a low ash fusion temperature relative to coal. Here, "low" is taken in the context of both the initial deformation temperature of the refuse ash material as it compares to coal ash and the expected high temperature of the coal flame. This can cause problems with slag accumulation, can cause slag falls (with damage to the floor of the boiler passes), and can severely stress the equipment for bottom ash handling.

Most U.S. utilities have operated suspension-fired boilers on mixtures of RDF and coal rather than RDF only. The RDF has been limited to a maximum of about 15% of the total furnace heat release rate. In view of the relative heating value and ash content of coal and RDF, this corresponds to about 30% of the total mass input and ash output. This also reflects the limits permitted by the U.S. EPA concerning the percent of RDF that can be burned before the air pollution emission requirements shift from those of the coal-burning utility industry to that of municipal incineration. Since the latter incur the need for acid gas control, monitoring for dioxin compounds and other pollutants, the 30% mass rate level remains as the maximum average firing rate where there is significant experience.

The vortex ("cyclone-type") combustion technique is an alternative to the suspension burning methods described above. In the vortex furnace, the air–fuel mixture is injected at high velocity at an angle tangential to the inner wall of a large water-cooled burner mounted in one wall of the boiler furnace. The excess air is restricted to achieve high flame temperatures. The ash residues are thrown to the wall, where they accumulate and melt under the intense radiative and convective flux and are tapped from the furnace as a liquid slag. This furnace configuration has been in disfavor in recent years due to its high NO_x emission profile so no new boilers with this burner design are planned. Data are limited, but the results appear promising as an alternative in existing vortex furnace installations.

Regardless of these apparent problems, refuse–coal co-burning in the suspension burning mode has been successfully accomplished in the United States by several utilities and/or large industrial boilers on a long-term (up to 17 years) basis. Most of the boilers firing RDF have practiced "tangential firing" (wherein the fuel is suspended in an air stream and fired from the corners of a square cross-section furnace through burners aimed tangent to an imaginary cylinder concentric with the furnace centerline). However, several boilers have been front-fired: where the air-suspended RDF and coal are fired from an array of burners mounted on one wall of the boiler. The boiler plants co-firing refuse and coal include

Union Electric (St. Louis, MO)	Tangential
Ames Municipal Light Co. (Ames, IO)	Tangential & front
Lakeland Municipal Light Co. (Lakeland, FL)	Front
Madison Gas and Electric (Madison, WI)	Tangential

Rochester Gas and Electric (Rochester, NY)	Tangential
Potomac Electric Plant	Tangential
Northern States Power (several)	Tangential, vortex & front
Eastman Kodak Co. (Rochester, NY)	Tangential

Several of these owner/operators continue to make investments and, importantly, reinvestments in co-burning facilities. Co-burning has not been easy, but the environmental, financial, and/or political benefits appear evident to these owners.

b. Fluid Bed Burning. A fluid bed incinerator/combustor for RDF involves a cylindrical or rectangular chamber containing coarse sand or similar bed material through which a gas is passed to cause the sand to bubble and boil much as a liquid. The fluid bed concept was originally developed as a solids-to-gas contacting device for catalytic operations in the petroleum field. The applicability of the principles of fluidization were soon extended to drying, ore processing, and, ultimately, waste incineration. The development of technology to add boiler surface area removing heat from the bed walls and bayonet tubes removing heat from within the bed itself provided the key to the use of the fluid bed as a general-purpose combustor for solid fuels such as coal, refuse, and wood.

The application of fluid bed technology to refuse burning has been accomplished in several plants in Europe and Japan using "circulating fluid bed" technology. (See Chapter 11 for more details on the combustion concept.) Here, one accepts the slow burning time of the solids and compensates by (1) increasing the flow velocities to transport all of the solids out of the bed and (2) putting a cyclone or other device in the leaving gas flow to capture and recycle (or discharge) the solids. In time, an acceptable level of burnout is achieved.

A second approach to the use of fluid bed technology involves modification of an existing coal furnace (suspension-fired or stoker-fired) to add the distribution plate, high-pressure air supply, sand management, and other features of a bubbling fluid bed. (See Chapter 9 for more details on the basic combustion concept.) RDF, coal, wood, or almost any other feedstock that is compatible with a reasonable overall energy balance can be fed to the bed. A critical requirement is to incorporate features that can adequately handle the segregation and discharge of the noncombustible, "tramp material" fed to the system. Also, it is necessary to effect heat removal from the bed. Heat removal allows control of bed temperatures and avoids ash fusion and bed defluidization. Facilities meeting these requirements are operational in La Crosse, WI, and Tacoma, WA to burn municipal RDF. In addition several other plants use the same process concepts in industrial waste applications.

The La Crosse facility (417) was a reconstruction of a spreader–stoker-fired coal boiler. The fluid bed components were, in essence, a replacement for the stoker and are used to burn RDF and/or hogged wood waste. The Tacoma fluid bed (416) is a separate combustor, rigged external to the boiler and discharging hot combustion gases into two, 25-MW existing boilers (previously, a front-fired pulverized coal system). For Tacoma, the existing boiler became, in effect, a waste heat boiler designed for high-ash fuels. Tacoma burns coal and hogged wood waste as alternatives or together with RDF. Both plants have operated more than 5 years with acceptable on-line availability and economic viability.

RDF for the Tacoma fluid bed system is prepared by shredding to a 1.9 by 10 cm product using a horizontal shaft hammermill. La Crosse begins with a flail mill and disk screening followed by a secondary hammermill shredding. Ferrous metal is removed from both products, and heavies are separated with air classification techniques. The RDF

materials contain between 2% and 10% ash and have about 3000 kcal/kg higher heating value. The preparation plant achieves about a 50% yield of RDF vis-a-vis the received refuse. Some compaction occurs in hauling and handling the RDF, but the material "refluffs" well on handling.

In Tacoma, RDF is dumped in a special area in the feed house: a large, covered, metal building-type structure with four bays for the holding and feeding of the RDF and wood waste. The RDF is moved about, as required, using a large front-end loader. Wood waste is received in large, open-top, semi-trailer truck bodies and, with an automatic, tip-up-type unloader, is emptied into a holding hopper. The wood is then conveyed by belt conveyor to one of several bays in the feed house.

Each bay is provided with a drag conveyor cantilevered over the waste piles. The "bite" of the conveyor into the pile is adjusted by an operator observing the pile and controlling the fuel reclaim operation from a second-story office overlooking the waste piles. The wood and/or RDF is dragged to the back wall of the feed house by the conveyor flights and drops onto a belt conveyor running the length of the building. The conveyor becomes inclined as the end of the building is approached and the feed is elevated to a holding and feeding bin on the roof of the boiler house.

At Tacoma, the wood and RDF are fed from the holding hopper atop the boiler across a vibrating feed table and through a metering feed system (a rotating vane that provides both a metering action and an air lock between the combustor and the feed storage). The material then discharges from four points above the bed. The RDF is regarded as a good fuel of reliable characteristics. The most serious problem in its use is irregular feeding (tends to hang up and then spurt, hang up and spurt, etc.). The compressibility of the RDF leads to packing with the slightest reduction in cross-section of a flow path. The average fuel firing corresponds to:

Fuel	Percent heat release	Mass rate (kg/hr)	Heat rate (1000 kcal/hr)
Coal	50%	13,600	92.5
Wood	35%	34,000	64.8
RDF	15%	12,700	27.7

Each Tacoma fluid bed combustor is equipped with two cyclones to capture and recirculate incompletely burned solids. Each fluid bed includes 471 m^2 of half-submerged bed tubes to remove 58 million kcal/hr of excess heat while evaporating 137,000 kg/hr of water from the fluid bed. In comparison with the concept used in La Crosse (where the bottom of the boiler was cut off and replaced with the fluid bed distribution plate), this results in a higher capital cost and a reduction in the maximum steam production below the original design level. Design steam production is 240,000 kg/hr at 29 bar, 400°C.

The Tacoma bed is about 0.9 to 1.07 m deep (0.61 m slumped depth). Most of the 5555 kcal/kg sub-bituminous coal (10% moisture, 30% volatile matter) burns in the bed at 790° to 815°C. The wood burns on the top of the bed. Refuse and coal fines burn in the freeboard at 870° to 900°C.

Corrosion of the old (>50 years) Tacoma coal boiler has not been a problem, although attack of weldments in the 309–310 stainless steel bed tubes has been observed. Flame spraying of protective materials, the use of extra thick (Schedule 320) tubes for the

submerged portion of the bed tubes, and the addition of fins to the bed tubes to break the bubbles appear to have resolved this problem. Bed erosion problems at La Crosse were resolved by the addition of split pipe shields to the bottom half of the bed tubes.

Some buildup of clinker in the ductwork and in the superheater has occurred despite the cooling of the furnace gases with the bed tubes. It has been suggested that the high alkalinity of the wood ash may act as a low-melting binder for ash. Clinker buildup has been a problem since the massive ash accumulations break off, fall into the bed, and bend or crush the bed tubes.

The fluid bed concept has been successful in both extending the operating life of the existing boilers and providing economic solid waste disposal. Addition of limestone to the fluid bed has been effective in control of HCl and sulfur dioxide. Operating availability has been acceptable.

XVII. INSTRUMENTATION AND CONTROL

Effective instrumentation and controls are key to maintaining plant operation at all times within its design envelope, with desired ash burnout and within environmental regulations. Even if an abundance of labor is available for manual operation and control, it is impossible to provide timely and effective coordination and supervision of the many operating variables without a minimum degree of instrumentation and automatic controls. The degree of automated instrumentation is a decision up to the designer, who must balance the level of operator skill and manpower resources versus the benefits and disadvantages of automation. Incinerators demand steady operation, and quick responses and actions are often required to effectively respond to unexpected process upsets as the waste quantity and characteristics vary. Adjustments must be made to the process variables to meet the plant objectives. The plant operators can readily make some of these adjustments while others are more suited for automation. For some applications within the plant, automated controls will actually do a better job than an operator could do manually.

Monitoring instrumentation that samples the current value of critical process parameters provides plant operators or automated control systems with the information needed to make the necessary adjustments. The plant operating concept can provide for these adjustments to be made manually, but this assumes the continual presence and attention of well-trained, dedicated, and knowledgeable operators. Some form of automatic measurement and control may be provided to take critical process operations out of the hands of the operator and respond directly and instantaneously to plant upsets and operating variations. The sections that follow indicate what is regarded as the appropriate control system, consistent with industry practice for modern MWC systems.

A. Instrumentation and Control System Design Approach

The design effort for plant instrumentation involves several steps leading to a functional system that can effectively and efficiently run the plant. The first step is to prepare a conceptual functional instrumentation specification. This specification should be prepared based on the overall scope of the project once the process flow diagram for the plant has been established and includes an identification of all key systems and equipment to be included in the overall scope of the project. All components within the system as well as the basic control parameters should be identified. Once agreed upon, the conceptual specification should be developed into a design specification that outlines how the scope is

defined in the conceptual instrumentation and control specification and identifies those responsible for each component. This specification includes hardware layouts, process flow diagrams, detailed logic diagrams, and data recording and reporting requirements. More specifically, the design specification

- Identifies systems designed in-house, those systems that will be subcontracted out, and those major systems that will be supplied as a package that includes complete instrumentation (e.g., refuse crane controls, air pollution control equipment).
- Identifies interface requirements and defines scopes.
- Coordinates the use of numbering, symbols, and instrument identification.
- Completes preliminary process flow diagrams, P&IDs, and control descriptions. Consideration must be given as to how the system will be controlled and, also, fail-safe control logic for safety and protection of equipment. The designer must ask what will happen if each piece of equipment fails and develop appropriate interlock and fail-safe logic to protect personnel and equipment.
- Prepares instrument lists and logic diagrams for system interlock, sequencing, control, and alarm systems.
- Prepares data sheets of instrumentation components and functional specifications for procurement.
- Sizes all instruments, control valves, relief valves, and metering devices.
- Prepares supporting documents for instrument installation.
- Reviews instrument equipment vendor's loop and wiring drawings and schematic drawings by packaged unit vendors.
- Prepares instrumentation location and hookup drawings.

B. Process Measurements and Field Instruments

Process measurements obtain necessary data to monitor and control plant operation. These include temperature, pressure, flow, position, level, and flue gas concentrations. The choice of a local readout device or an electronic instrument with transmitted signal and its location should be made with care paid to process considerations and the importance of the parameter, requirements for recording, and the overall control philosophy.

Instruments used to monitor process variables range from relatively simple devices such as thermocouples for temperature measurement and pressure gauges, to position indicators and limit switches, to more complex instruments for flow measurement and flue gas pollutant concentrations. It is important to select the appropriate measurement device for the particular application, purpose, and operating environment. Compatibility with the temperature, humidity, dustiness, and other characteristics of the operating environment is especially important in incinerator applications. Due to the aggressive, corrosive, and abrasive nature of waste, waste dust, and the combustion products of waste, particularly rugged equipment is needed or accuracy will degrade and instrument life will be unacceptably short. Close consultation with manufacturers of the devices is necessary during the design process.

It is equally important to determine the appropriate level of instrumentation and control necessary or desired for a particular application. Process measurements can be displayed at the instrument itself or using a transmitter sending a signal to a local control panel and/or the central control room. Display-only devices are referred to as indication versus transmitting devices that send the measurement signal for use in open- or closed-loop control. An open-loop controller is operated manually from a control station, while a

closed-loop controller controls a variable measurement automatically from a preset set point. The incineration plant will have an abundance of instruments used for indication, open- and closed-loop control, or combinations thereof.

The basic parameters used to operate an MWC include combustion temperature, under- and overfire air damper settings, combustion air flow and temperature, grate speed, furnace draft, steam system parameters (water level, steam temperature, and pressure), and flue gas concentrations of oxygen and regulated pollutants (e.g., CO or SO_2). Indication of these measurements should be provided locally in most cases. However, for critical values and data that are used for subsequent control purposes, data need to be transmitted from the field device to either a local control panel and/or central control room. Then, information can be either used by the operator for control (open-loop control) or transmitted for subsequent automatic control (closed-loop control). Table 16 is a listing of the main operating data and the associated instrumentation typically employed in an incineration plant.

Some process measurements are used both to monitor and to control using either an open or closed control loop. Typically, motorized or pneumatic dampers and valves and motors coupled to such items as pumps, drives, conveyors, and fans are controlled. The combination of the instrument, transmitter, control logic, and device achieves the desired control function. For example, a low reading for the water level in the steam drum may be indicated by a level gauge coupled to a float switch that in turn sends a signal to a valve that increases the feedwater rate until the desired level set point is achieved. Many types of instruments, transmitters, controllers, and recorders are available to the designer for application to an incineration system.

C. Control System Levels

Three levels are involved in the control system. Information and data may also be transmitted or shared between the various control stations as well as control functions themselves facilitated from one or a combination of control stations.

1. **Level 1:** hardwired controls including local controls, controls at motor control centers, and all equipment and protective interlocks. The inter-locks are part of the hardwired controls so that they are active in all modes of control.

Table 16 Principal Operating Data

Parameter	Instrument
Mass of waste	Load cell
Combustion and flue gas temperature	Thermocouple
Damper settings	Position indicator
Combustion air/flue gas flow	Differential pressure gauge/flowmeter
Grate speed	Tachometer
Draft	Draft gauge
Flue gas analysis (O_2, CO, SO_2)	Flue gas analyzer and CEM analyzers
Steam system properties	Thermocouple, pressure gauge, flowmeter, sight level
Tank levels	Level gauge, float
pH	pH meter

2. **Level 2:** local panel level. The packaged equipment control systems include these in some form. Other systems may include local control panels unless the controls for those systems are implemented in the plant control system.

3. **Level 3:** control room. Equipment here can either be computer-based workstations or a master panel with recorders, controllers, switches, and indicating lights.

1. Local Control Stations

Local control stations are

Always located near the equipment
Normally used for maintenance rather than for process control
Sometimes used for simple control by an operator in the field when visual contact with the process or equipment is essential or the necessary adjustments are infrequent or noncritical to the overall operation
Local control stations contain no logic or programming; however, data may be transmitted to local control panels or the central control room as required either for monitoring or use in a control loop. All local control stations should have on/off indicating lights and other indicators of system performance to aid the operator in the field.

Examples include on/off switches for motors so that they can be shut down for maintenance, manual valves and dampers and independent batch operations such as the filling of tanks, and manual preparation of chemicals.

2. Local Control Panels

Local control panels contain programmable controllers, switches, relays, or other control logic receiving signals from field instruments and performing control functions. Two types of local control panels are used:

1. Control panels provided for major systems.
2. Control panels provided with smaller packaged equipment. These panels also generally interface with the central control room or may in some cases be physically located in the central control room.

Major system suppliers (e.g., the air pollution control supplier) provide sophisticated equipment comprising a complete control system. The system includes the complex control logic necessary for automated operation, incorporates necessary safety interlocks, and interfaces with other systems. These panels are generally based on programmable logic controllers (PLC) and can carry out complex control functions. The panels are generally located in the central control room along with panels for other major systems.

Smaller equipment can be provided with PLCs switches or relays. These panels are usually located near the equipment. Examples include a lime slurry preparation system, the refuse crane management system, packaged wastewater treatment plants, continuous-emission monitoring systems (CEMS), ash handling systems, etc. Depending on the application these panels may be controlled.

Locally in the field
From larger control panels
From the central control room

Local control panels may also provide indication or data information to other control panels.

3. Central Control Room

Major data points and controls are monitored, controlled, and recorded in the central control room. Measurements throughout the plant are fed back into the control room and input to a central computer/data logger. Critical measurements such as feed rate, primary and secondary chamber temperature, and O_2, SO_2, and CO concentration are usually continuously displayed while others may be recalled by the operator through the computer. Significant open-loop controls pertaining to the overall process should be controllable from the central control room by the operators. Closed-loop controllers are monitored in the control room and may be manually overridden or the set points adjusted at the discretion of the control room operator. In addition, the computer performs data logging, alarming, as well as storing of historical information.

4. Data Logging

Critical measurements should be recorded to provide an archived record of the status of all plant equipment for subsequent analysis of plant failures or upsets and to verify attainment of performance guarantees under the provisions of the Service Agreement. Further, the data may be submitted to (or periodically accessed by) regulatory authorities to establish that permit requirements are being met. Also, the data base collected in the data logger provides a basis for future design improvements.

Records derived from plant instrumentation may be "hard copy" made by the recording instruments themselves on circular or strip charts, or computer data storage. The latter can provide real-time data trends to guide plant operators and the periodic recall of historical data. Also, the computer data base can be accessed to readily generate reports of overall plant performance. Computers offer the most accurate and efficient means of data collection and data processing. It is strongly recommended, therefore, that a computer data logging system be incorporated into the plant design.

D. General Control Philosophy

The general control concept for an MWC is to operate the plant from a central control room. This optimizes operating efficiency and overall plant safety and minimizes environmental impact. Process controls that require infrequent adjustment or are small, batch-type operations can be operated in the field and manually adjusted as needed. This section provides typical control descriptions and parameters necessary for proper operation of the plant as well as an indication of the type of control recommended.

1. Automated Refuse Weighing

The measurement and recording of the refuse weight are often critical parameters in many Service Agreements. Also, the mass input of wastes is often the measure by which an incinerator operations firm receives payment. From a process analysis standpoint, waste throughput is one of the most basic parameters needed to monitor system performance in terms of combustion capacity.

Refuse is usually weighed through the use of a truck platform scale. The weighing and recording system can be obtained readily from scale vendors. The software can be customized to meet the particular needs of the project even to the degree that the

information collected is directly tied into the accounting and billing systems. When specifying the scale and recording system, the particular needs of the project must be known and the scale must be specified to handle the largest vehicle type that would access the facility. The computerized weighing system, if needed on a project, should include the recording of the following, at a minimum:

Vehicle identification
Vehicle tare weight
Vehicle laden weight
Vehicle load (by difference)
Time
Date
Daily, weekly, monthly, quarterly, and annual summaries

If billing is not needed on a tons-processed basis, a facility scale and scale house may not be necessary, but a system for measuring the feed rate to the incinerator is highly desirable. This typically involves load cells on the refuse cranes that weigh and record each grapple load as it is being charged. This function should be incorporated into the crane specification. The refuse mass measurement system should record and transmit to the central control room at least the following:

Crane identification
Date
Time
Charge weight
Hourly, daily, and weekly summaries

Incorporating a scale and crane recording system is most desirable, so the two measurements of waste quantity can be compared. Variations exist primarily from moisture loss during refuse storage and evaporation. Because the degree to which these mass reductions occur within the MWC facility is uncertain, billing measurements should use the truck scale. Clearly, feed rate measurements used in process analysis, however, should use the crane load cells to more accurately reflect the waste burned. Information from both sources should be transmitted to the central control room for use by operators in monitoring the waste brought to the facility as well as the quantity being charged.

2. Monitoring of Refuse Feed Rate

Refuse feed cranes are generally controlled manually by the operator who guides the bridge and trolley travel to pick up loads and centers the grapple over the feed hopper, raises the grapple and releases it. These control functions should be specified in the crane manufacturer's scope of supply. For plants in excess of 500 tpd, it may also be desirable to have the crane controls included and automatic homing control to bring the grapple from its location in the pit to directly over the feed chute. This saves time and also reduces operator fatigue.

3. Combustion Process Control

Combustion control can be complex, but maximum throughput and compliance with regulations are facilitated by sophisticated control equipment and computerized control. Large-scale mass burn incineration systems typically include vendor proprietary software for automatic combustion controls. For the larger, energy recovery plants, the steaming

rate is used as the central control parameter. Some minimum automatic control is necessary to ensure steady operations and environmental compliance and to protect personnel and equipment. The combustion process itself requires a combination of manually adjusted open-loop controls and automatic controls to maintain steady operations.

a. Manual Controls. The following combustion process parameters and functions can be manually controlled either in the field or through open-loop control from the facility control room.

FIELD-CONTROLLED PARAMETERS

Underfire air plenum damper settings. The underfire air distribution along the grate should not require frequent adjustment. The dampers can be set manually during startup and commissioning of the unit for optimum airflow to the drying, combustion, and burnout zones. Thereafter, damper adjustments may be adjusted periodically as needed to react to changing process conditions.

Overfire air distribution. As with the underfire air distribution, overfire air distribution can be set manually during startup and commissioning of the unit to achieve the appropriate mixing and combustion burnout and then checked periodically. Overfire air distribution should be set by monitoring the CO and O_2 concentrations and combustion temperatures and by visual observation. If possible, the spatial distribution of CO and O_2 should be measured as an indirect measure of the mixing effectiveness of the overfire air jet system. If the capability is built into the design, the direction of the overfire air jets can be modified to more effectively mix the gases rising from the fuel bed.

Steam jet distribution. Although not practiced to a great extent in MWC systems, steam nozzles have been used extensively to provide a means of mixing the combustion gases with minimum mass addition. As for overfire air injection, the optimum steam distribution does not require frequent adjustment. Therefore, manual control valves can be provided to properly adjust the system during startup and commissioning of the MWC system.

Grate speed (and the frequency of the feed ram if incorporated) should have local control stations for field operation and maintenance. However, the control logic for these systems is often integrated and controlled from the central control room during routine operations.

Siftings removal can be continuous or can be initiated from a field control station. Generally, control from the central control room is not necessary. Indication that the system is in use should be displayed in the control room.

Boilers are equipped with a safety valve and a blow-off valve. The latter is set manually at the maximum safe pressure and releases when excess steam is being produced.

OPEN LOOP CONTROLS

Grate speed. Adjustment of grate speed depends on the feed rate and consequent heat release rate of refuse and the quality of the ash product. The waste processing rate, and therefore the grate speed, can be under manual control or can be tied to boiler steaming rate. If the heating value of refuse is found to vary significantly during operations and the situation cannot be controlled by mixing of waste in the pit, grate speed may be left to operator judgment based on observation of the waste and knowledge of the chamber conditions. The control of the feed ram should be made integral with the grate speed controls such that this operation is properly sequenced during a feed cycle.

Underfire air supply. The flow rate of underfire air can be manually controlled by the operator in the control room. This may be accomplished by using a variable-speed fan or by using a damper to control flow. The operator adjusts undergrate air flow in response to observations of the primary combustion air temperature, flue gas oxygen content, and underfire air plenum pressure.

Overfire air supply. The overfire air distribution can be manually set to achieve a discharge velocity that ensures penetration of the air jets across the combustion chamber through adjustment of dampers. The flow rate of overfire air can be manually controlled by the operator in the control room. This may be accomplished with a variable-speed fan or a damper to control flow in consideration of the flue gas oxygen content, CO levels, and furnace exit temperature.

b. Automatic Controls. To maintain steady operation and ensure environmental compliance, automatic control is often preferred. Parameters that benefit from automatic control include the following.

Furnace draft control: The products of combustion, water vapor and excess air within the primary furnace are removed by the induced draft (ID) fan. The ID fan pulls the gases from the furnace through the various downstream components to maintain a constant draft within the furnace at all times to prevent the escape of pollutants (smoke emission into the incinerator building) due to local positive pressures within the system. Closed-loop control of furnace draft is required and can be readily accomplished with a pressure transmitter coupled to the induced draft fan speed or inlet vane damper. As the air flow through the fuel bed changes, induced draft is adjusted automatically to maintain a balanced draft condition in the furnace. The set point for furnace draft can be adjusted manually. The location of the draft gauge on which furnace draft is controlled should be selected to avoid influences such as overfire air or steam jets. To minimize pulling tramp air into the system, the draft should be set at the lowest level that reliably avoids smoking.

Afterburning zone temperature. Pollution control relating to the emission of incomplete products of combustion (CO, dioxins and their precursors, and other hydrocarbon-based pollutants) can be achieved by maintaining temperature and oxygen concentrations within target limits in combination with turbulence in the gas stream and a minimum residence time to allow for molecular-scale mixing. In many countries, temperature and residence time parameters are set by regulation. Often, 1000°C and 2 sec after the flue gases are mixed (the plane just above the overfire air injection nozzles) is set as the baseline for temperature and residence time. If the temperature drops below the mandated level, it is often necessary either to stop feeding waste or to increase the temperature by firing fossil fuel.

An auxiliary fuel burner is often mounted in the furnace walls ahead of the first boiler pass. The burner maintains flue gas temperature during startup and in the event that the flue gas temperature cannot be maintained via air adjustment due to low calorific value of the waste and/or high-moisture content. Thermocouples ahead of the first boiler pass should be used to automatically start the burner when the temperature falls below the set point. Burner startup and flame safety controls should be provided as a package with the burner by the vendor and integrated with the system.

Boiler drum level. If a boiler is incorporated into the process design, water levels within the drum should be automatically controlled using level probes coupled to the feedwater pumps or control valve.

Steam demand. For some steam applications, closed-loop control may be required. This would especially be true when steam is used in a steam turbine or engine to drive pumps or fans. In this case, the flow demand of the device controls a steam valve. The same would also be true for space-heating applications where steam flow would be controlled from a temperature set point. Diversion of unused steam to a condenser or blowdown to atmosphere would be provided.

Back-end temperature. The boiler, air preheater, air pollution control (APC) system, and induced draft fan are sensitive to temperature. In most plants, either a boiler or a water spray system is used to reduce the flue gas temperature to be safe for the back-end equipment. If permitted, a bypass dump stack should be provided for emergency conditions where a failure in boiler-water supply or other malfunction leads to excessive temperatures in the back-end hardware. If the gas temperature exceeds a preset safe level that protects the equipment from damage, the dump stack damper would open automatically. Alternatively, an alarm can be provided to alert the operator to manually engage the damper. The damper release concept should be developed in light of the plausible failure modes affecting the facility to include failure of the water or electricity supply, etc.

System startup (optional). It may be desirable to include an automatic system startup control sequence that uses the auxiliary burner to automatically ramp up the system temperature at a constant rate prior to the feeding of refuse and automatically ramp the system down during shutdown. This can minimize thermal stresses on the system due to rapid thermal expansion and contraction. The startup sequence can be manually controlled, however; operators will need to be careful not to heat the system too rapidly. Likewise when cooling down the unit, the induced draft fan should be controlled to provide a steady but controlled rate of cooling.

Emergency shutdown. Attention should be paid in the design of the control system to include fail-safe and automatic controls to protect personnel and equipment in the event of a significant process upset, malfunction, and water or power failure.

Alarms. Key parameters being measured should also have alarm capability to alert operators to the problem so that the appropriate control measures can be taken. Alarms can be in two tiers, with the first being simply to alert the operator to attend to the problem and the second actually to trigger an automatic sequence to prevent injury to personnel or equipment. Parameters that would need to be alarmed include

Grate drive not functioning (zero-speed switch)
Residue discharger or conveyor not functioning
Zero-speed switches or pressure transmitters on all fans to sense no-flow
Combustion chamber overtemperature
Low boiler-water level
High temperature at air pollution control device inlet
Excessive steam temperature or pressure
Emission limits for CO or SO_2 exceeded, failure of carbon or lime slurry feed system

c. Control Logic. In the early years of waste incineration, the process control strategy was entirely in the hands of the operator. He looked at the waste, the fire, the residue conveyor, and the stack and set the air and grate speed in accord with an unwritten but often effective algorithm developed through personal experience. As incineration evolved from a “fire in a box” for volume reduction to a power plant generating high-temperature,

high-pressure superheated steam, and as the environmental requirements and abatement systems have undergone revolutionary changes from the control of "blackbirds" (large chunks of charred paper ash) using simple wet bottom expansion chambers to complex, multitechnology abatement trains, the process control concepts have also matured.

Control of incineration systems started with a strategy based on visual observations supported with a minimum of indicating instruments leading to manual adjustment of a few basic process variables. In a modern plant, control is centered in a computer that draws information from several real-time sensors testing a variety of system properties and, using a sophisticated system algorithm, exercises direct, automatic control over a suite of seminal process parameters.

Martin GmbH mass burn systems, for example, use flue gas temperature from the second boiler pass, measured by an infrared pyrometer, to control the refuse feeder and the grate. This flue gas temperature is processed in a cascade control loop with the boiler steam flow in order to adjust for the boiler load. A second control loop monitors the O_2 levels in the flue gas to adjust the underfire air rate per underfire air compartment in order to maintain a constant excess rate. The dry scrubber system monitors stack SO_2 and makes real-time adjustments to the lime slurry feed rate to ensure compliance with the SO_2 emission limits.

Another system vendor, Detroit Stoker Company, regulates its stoker-fired boilers by adjusting fuel and combustion air from changes in steam pressure. A change in steam demand initiates a signal from the steam-pressure controller, through the boiler master controller, to increase or decrease both fuel and air simultaneously and in parallel to satisfy the demand. As long as an error in pressure exists (a departure of actual pressure from the set point value), the steam pressure controller will continue to integrate the fuel and air until the pressure has returned to its set point.

A combustion guide, in this case steam flow and air flow, compares pressure error to a calibrated air flow demand to modify the rate of fuel being burned (proportional to steam flow) and initiate any required readjustments to the forced draft damper so that the desired fuel–air ratio is continuously maintained. Furnace draft is regulated separately through the use of a furnace-draft controller and a power operator that positions the uptake damper on the induced draft fan.

4. Air Pollution Control Train

Control of the air pollution control (APC) system will be dependent on the type chosen. However, the basic concepts are similar among systems. Most of the controls would be automatic to ensure that emission limits are being met and would be typically be provided within the APC system vendor's scope. The complexity of the control system and vendor-specific design warrants that the vendor provide a complete system. As with other vendor-supplied systems, clear limits of the scope of supply as well as the interface issues should be well defined.

a. Manual Controls. There are limited functions associated with the APC system that should be controlled manually in the field or through open-loop control from the facility control room. These include the following field-controlled and indicated parameters.

Reagent storage systems. Chemicals used in the APC process (such as lime, activated carbon, and ammonia or urea) will require on-site storage in silos (dry reagents) or tanks (liquids). Delivery and unloading include local operator stations to start and stop these operations. Silos and tanks should be equipped with "high-high" and "low-low" alarms as well as pressure-relief valves if they are enclosed.

Chemical preparation systems. Some chemicals may have to be prepared within the plant in batch operations. These could include preparation of caustic solutions or lime slurry. These batch operations can be supplied with local control panels for operation of mixers, circulating pumps, and pH adjustment. Water addition can be manual or automatic. An alarm should be included to indicate low tank levels to alert operators to make new batches.

Pressure and temperature. Each component of the APC train should be monitored for inlet and outlet temperatures, inlet and outlet draft, as well as draft loss. Measurements are displayed locally on the equipment, transmitted to the APC panel for use in controls, as well as monitored and alarmed from the control room.

Activated carbon injection system. Depending on the emission limits for the plant and the characteristics of the waste stream, combustion performance, etc., an activated carbon injection system may be employed for control of mercury and dioxins. The feed rate of carbon is empirically established based on waste composition as confirmed through the stack testing of the system. Once set, the feed rate should be constant and not require adjustment or control.

b. Automatic Controls. Several areas of the APC process are best controlled automatically to ensure that emissions limitations are being met and to maintain steady operation.

Baghouse inlet temperature control. Proper control of the inlet flue gas temperature is needed to ensure that the baghouse does not experience elevated temperatures which could cause serious damage to the collection bags. A thermocouple at the exit of the water spray tempering system or the spray dryer outlet temperature thermocouple provides a feedback signal to a temperature-indicating controller. The output from the controller is used as a set point for a flow-indicating controller. This controller modulates the cooling water control valve based on a feedback signal from a flow meter. The cascade loop automatically adjusts for changes in water pressure without requiring a change in the outlet temperature.

Acid gas control. The flow rate of lime addition to the system is controlled by a SO_2 monitor in the stack that measures the concentration. The SO_2 monitor is used to control the lime feed pumps or control valve.

Fabric filter cleaning control. The differential pressure across the fabric filter is continuously monitored. Reaching the set point triggers bag cleaning cycles. For pulse-jet systems, compressed air is periodically pulse-injected through individual compartments containing rows of bags. Each compartment is automatically brought off-line during the cleaning process to prevent re-entrainment of dust. The cleaning cycle can be defined by a timer or triggered by the pressure drop increase across the fabric filters. In addition, the pulse may be manually initiated. The sequencing control automatically selects specific compartments for cleaning once the cycle is initiated.

For shaker systems, the cleaning cycle will be set by the maximum pressure drop allowed with extra compartments provided for off-line cleaning. For reverse-air baghouses, the compartment to be cleaned is brought off-line and reverse flow initiated to flex or collapse the filter bags in order to release the cake.

Fabric filter temperature. An automatic bypass damper can be provided to divert hot flue gas and protect the filter bags in the event of excess temperature.

Dust level control. The fabric filter and spray dryer normally have rotary airlock or double dump valve air seals to remove collected particulate. Automatic control is recommended although these devices can be manually controlled. They can be operated on a timed sequence. The timing sequence may be manually adjusted to suit the operating conditions.

A hopper level indicator should be provided to set of an alarm if a rotary or double dump valve fails to operate properly and discharge material. This alarm function can also be used to activate a vibrator to automatically dislodge material or to simply alert the operator.

Continuous-emission monitoring. Many jurisdictions require continuous-emission monitoring (CEM) for pollutants such as CO, O_2, SO_2, NO_x, and dust (opacity). CEM sampling and analysis instruments are highly sensitive and require constant operator attention to perform calibrations and maintenance. Control of the instruments is automatic and should be included under the CEM's vendor scope of supply. To reduce equipment redundancy, these instruments should provide the signals necessary for operator control and monitoring of CO and O_2 as well as for automatic control of acid gases.

Where permit requirements specify a minimum percent removal rate, additional instruments may be required for measurement of the uncontrolled emissions prior to the air pollution control system for automatic calculation of the removal efficiency. The CEM systems should also be provided complete with a data logging and report system (usually PC-based). In addition, instances where emission limits are exceeded should be alarmed to the control room to alert the operations staff.

Emergency shutdown. The APC system should include fail-safe and automatic controls to protect personnel and equipment in the event of a significant process upset, malfunction, or power failure.

Alarms. Alarm capability is needed to alert operators to problems, triggering prompt initiation of control measures. Commonly, alarms are set up in two tiers, with the first alerting the operator to attend to the problem and the second triggering an automatic sequence to prevent injury to personnel or equipment. Parameters that should be alarmed include

Low reagent (lime, carbon, ammonia/urea, etc.) levels.
Water/slurry pumps on/off.
Spray dryer excess temperature (at fabric filter inlet).
Emission exceeds permit limits.
High level in dust collection hoppers.

5. Ash Handling System

The ash handling systems can be manually controlled from either a local control station or the central control room. In any case, indication of the system operating should be observable (perhaps with TV monitors) from the control room.

a. Bottom Ash Collection System. Discharge of bottom ash from the combustion unit has been described under the incinerator section above and would occur automatically from the refuse feed control loop. Siftings removal, however, should be either continuous or manually controlled from the local control station. Indication that the system is functioning should be made to the central control room. If bottom ash and siftings are discharged to a container system, no control is needed. However, if continuous conveyors are used, the following guidelines should be considered.

The bottom ash conveyors should operate continuously to avoid buildup. Bottom ash will be continuously discharged from the combustion unit.

If multiple conveyors are used, they should be coupled together to start in sequence with the conveyor at the discharge end starting and stopping first, followed by the next conveyor upstream. The conveyor at the incinerator discharge should be the last to start in the sequence.
Conveyors should be equipped with zero-speed switches on the drive shaft to indicate malfunctions to the control room.
Drives and motors should be placed at the head (discharge end) of the conveyor.

b. Fly-Ash Collection System. Regulations may mandate separation or allow combination of fly ash and bottom ash. When separate handling is required, fly ash is usually collected and stored in silos. Conveyance of fly ash can involve screw conveyors (up to no more than 30° in incline) or bucket conveyors (for steeper slopes) or can use pneumatic systems to convey the ash to storage silos. The following guidelines should be considered:

The fly-ash conveyors should operate continuously to avoid buildup in the conveyors.
If multiple conveyors are used, they should be coupled together to start in sequence with the conveyor at the discharge end starting and stopping first followed by the next and so forth up to the point where ash is loaded from the collection hoppers.
Conveyors should be equipped with zero-speed switches on the drive shaft to indicate malfunctions to the control room.
Drives and motors should be placed at the head (discharge end) of the conveyor.
Level controls and alarms as well as pressure-relief valves should be provided on storage silos.
Ash conditioning devices and silo discharge mechanisms should have a local control station.
Indication that the system is in use should be provided in the control room.

6. Auxiliaries

Auxiliary systems should be provided with local control stations and/or panels as warranted by the design. Key operating parameters and functions should be indicated and alarmed to the central control room. Examples of auxiliary systems that may be incorporated in the plant include

Fire pumps
Refuse bunker drain pumps
Refuse dewatering device
Refuse bunker motorized delivery doors
Packaged wastewater treatment plant
Feedwater treatment system

E. Portable Instruments

The operating staff should have access to portable instruments to make settings that do not require frequent adjustments or to double-check on electronic measurements. Examples include portable pressure gauges that allow manual settings of individual underfire air

plenums, portable flue gas analyzers to check on a permanently installed devices, and hand-held temperature instruments.

F. Summary

Table 17 summarizes essential measurements and controls described above. While the control room operator has access to all measured variables and can override all control loops, the instruments and controls required by the floor operator are mounted on a local panel or control station as shown in the table. This table is a guideline only and should be reviewed and modified for the particular requirements of a project and the types of equipment and systems employed in the design.

XVIII. OPERATIONS

A comprehensive treatment of the operating problems and challenges of municipal waste incineration would introduce many new topics. Further, the "rightness" or "wrongness" of many of the recommendations would be subject to controversy since the human element, leadership styles, cultural effects, and the like often produce many good and workable answers to the same question. However, there is merit is identifying the major operating problems observed in existing plants as indications to the design engineer that attention is necessary.

A. Mass Burn Incineration

A compilation of such experiences based on a study of the equipment of approximately 30 manufacturers in 52 mass burn incineration plants (384) provides a useful data base. The results of the survey are summarized in Table 18.

Refractory problems were the most common, ranging from the need for minor patching to complete replacement. Minimization of the problem included both attention to avoid charging bulky, metal wastes and replacement of (softer) castable refractory with the more abrasion-resistant, fired brick.

Underfire air ports in modular combustion units were subject to plugging. Enlarging of the orifices and periodic steam purging have been tried to help the problem, but regular maintenance and cleaning are still necessary.

Many plants complain about the limitations of a small tipping floor, which causes congestion during deliveries and does not give room for floor-dumping to inspect incoming waste for auto batteries, hazardous wastes, etc., which local authorities may require. Also, complaints called for the designers to give more attention to the potential traffic flow pattern on the tipping floor.

Warping of dampers and charging doors was also common, especially in starved-air systems and when units are run at higher than design temperatures. Similar problems with charging rams were noted although deficiencies in the hydraulic systems were the prime source of the difficulties.

B. RDF Incineration

An analysis was prepared (533) of operational problems in a three-furnace, 2700-ton-per-day (waste receipt) RDF incineration plant using shred and burn fuel preparation

Table 17 Alternatives in Instrumentation and Control

		Central control room						Local panel/board						Field					
Description	Status	Indica-tion	Record-ing	Closed-loop control	Open-loop control	Alarm	Trip	Indica-tion	Record-ing	Closed-loop control	Open-loop control	Alarm	Trip	Manual control	Indica-tion	Record-ing	Closed-loop control	Open-loop control	Alarm	Trip
Refuse scale	W		X					X	X		X									
Refuse cranes																				
Bridge position											X	X	X							
Trolley position											X	X	X							
Refuse scale											X	X	X							
Position											X	X	X							
Weight	W		X					X	X		X	X								
Primary chamber																				
Grate speed	S	X	X		X	X	X								X			X		
Feed ram	S	X			X	X	X								X			X		
Underfire air flow rate	F/P													X	X					
Overfire air flow rate	F/P													X	X					
Furnace temperature	T	X	X			X	X								X					
Furnace exit temperature	T	X	X			X	X								X					
Forced draft fan	F	X		X		X	X								X					
Furnace draft (pressure)	P	X		X		X	X								X					
Underfire air temperature	T	X	X			X									X					
Underfire air flow	F/P	X			X	X	X								X					
Oxygen monitor	A	X	X		X	X		X				X								
CO monitor	A	X	X		X	X		X				X								
Burner status		X		X		X	X								X					
Boiler																				
Steam pressure	P	X				X	X								X					
Saturated steam temp.	T	X				X	X								X					
Superheated steam temp.	T	X				X	X								X					
Steam flow	F	X	X	X																
Drum level	L	X		X		X	X								X					
Gas temp. at screen tubes	T																			
Temp. at economizer inlet	T	X				X	X								X					
Temp. at economizer outlet	T	X				X	X								X					

Table 17 Alternatives in Instrumentation and Control (Continued)

		Central control room						Local panel/board						Field					
Description	Status	Indication	Recording	Closed-loop control	Open-loop control	Alarm	Trip	Indication	Recording	Closed-loop control	Open-loop control	Alarm	Trip	Manual control	Indication	Recording	Closed-loop control	Open-loop control	Alarm	Trip
Air pollution control																				
Lime reagent storage	L		X			X		X				X						X		
Quench water/slurry flow	F	X	X	X		X		X	X	X		X			X					
Carbon reagent storage	L		X			X		X				X						X		
Carbon feed system	S	X	X	X		X		X	X	X		X			X					
Spray dryer exit temp.	T	X	X	X		X	X	X	X	X		X	X		X					
Spray dryer exit pressure	P	X	X					X	X						X					
Fabric filter cleaning cycle	P	X		X		X	X	X		X		X	X							
Opacity monitor	A	X	X			X		X	X			X								
SO_2 monitor	A	X	X	X		X						X								
Other CEMS	A	X	X			X		X	X			X								
Flue gas flow	F	X	X					X	X											
Bottom ash handling																				
Siftings conveyor		X			X										X			X	X	
Ash discharger	S	X			X	X									X			X	X	
Bottom ash conveyor	S	X			X	X												X	X	
Fly-ash handling																				
Dust hopper level	L					X								X				X	X	
Rotary/double dump valves	S	X				X								X				X	X	
Screw conveyors	S	X				X								X					X	
Ash silo level	L					X													X	
Auxiliaries																				
Storage pit drain pump	F	X				X									X			X	X	
Boiler feedwater treatment	F	X				X		X			X	X								
Boiler feedwater temp.	T	X				X	X													
Wastewater treatment	F	X				X		X			X	X								

Key: F Flow L Level W Weight
T Temperature A Analysis
P Pressure S Speed/frequency

Table Recovery

Problem	Percent with problem	Problem	Percent with problem
Refractory	71%	Underfire air ports	36%
Tipping floor	29%	Charging ram	25%
Fire tubes	25%	Air pollution	23%
Ash conveyor	23%	Not on-line	21%
Controls	19%	Waste supply	19%
Water tubes	17%	Internal ram	18%
Steam demand	13%	I.D. fans	12%
Feed hopper	10%	Quench water	8%
Stack damper	4%	Charging grate	2%
Front end loader	2%		

Source: From (385).

Table 19 RDF Incinerator Plant Availabilities

		1991 Lost time distribution		1992 Lost time distribution		1993 Lost time distribution	
Category	Description	Hours	Subtotals	Hours	Subtotals	Hours	Subtotals
Scheduled	Tube overlays	352.0	1242.8	507.8	1385.3	182.0	904.0
	Weeky maintenance	253.0	52.4%	140.0	65.0%	142.0	58.9%
	Boiler wash	349.8		511.5		443.5	
	Yearly maintenance	315.0		226.0		136.5	
Forced	Feed system[e]	121.7	829.9	40.9	627.9	83.0	603.7
	Grate	248.1	35.5	216.0	29.5%	307.7	39.3%
	Tube leak[e]	369.6		329.5		133.8	
	Misc. trips	84.0		35.5		79.2	
	Bottom ash system[e]	6.5		6.0		0.0	
Equipment/Fuel	Back pressure[e]	93.1	250.1	38.7	112.6	5.8	24.5
	Opacity[e]	32.6	10.6%	16.3	5.3%	8.2	1.6%
	Wet fuel[e]	3.0		12.6		6.6	
	Fuel supply	121.4		45.0		3.9	
Force Majeure	Storms	47.0	47.0	4.0	4.0	2.0	2.0
			2.0%		0.2%		0.1%
	Totals	2369.8		2129.8		1534.2	
	Summary Statistics						
Fuel processing capacity loss[a]			8.30%		5.30%		7.70%
Boiler availability[b]			90.31%		89.57%		90.21%
Feed system availability[c]			97.86%		98.97%		98.28%
Plant availability[d]			87.90%		88.52%		88.48%

[a]Fuel capacity loss based on fuel handling facilities lost hours.
[b]Boiler availability based on scheduled lost hours for Inconel tube re-cladding, quarterly boiler wash and yearly maintenance on electrical equipment plus forced lost hours due to grate failures (esp. link breaks), tube leaks, and bottom ash conveyor problems.
[c]Feed system availability is calculated from combined lost hours of preventive maintenance and feed system problems.
[d]Plant availability includes force majeure in addition to the hours assigned to the boiler and feed systems.
[e]Other: Feed system—jams from stringy material, drag chain failure; tube leaks—especially from sootblower erosion; bottom ash system—clinker; back pressure—forced reduction in feed rate when condenser pressure is too high; opacity—feed reduction when opacity>limit.; wet fuel—jams in feed system.
Source: From (533).

(single-stage shredding to about 15 cm followed by a single, magnetic separation stage removing up to 60% of the ferrous). Each boiler has its own spray drier-absorber and either a 5-stage ESP (boilers 1 and 2) or a 12-compartment baghouse (boiler 3). Urea injection is used for NO_x control. The 380 ton/hr of steam generates 80 MW of electricity using two turbine/generators exhausting to dry, air-cooled condensers. Table 19 summarizes the types of scheduled and forced outages the plant experiences.

9

Incineration Systems for Sludge Wastes

Assisted by the massive construction grant program of the Water Pollution Control Act, a large number of primary and secondary municipal and industrial wastewater treatment plants were brought on-line in the United States between 1970 and 1990. The plants generate large quantities of waste solids (402). These "biosolids" include several waste streams:

"Primary" sludge (produced by gravity settling in the first stage of treatment)
"Biological" ("secondary") sludge produced in the activated sludge process
"Advanced" wastewater treatment sludge from tertiary treatment process
Other treatment plant solids such as the "screenings" recovered by the mechanical removal of large-dimension solids, "grit" recovered by settling sand and other coarse granular solids, and "scum" or "skimmings" recovered as the floatable solids skimmed from clarifiers

At the points of their generation in the treatment plant, these wastes vary in solids content over a very wide range (from 1% to 8% solids). If incineration is to be considered as an affordable process alternative, the sludge must first be dewatered to 20% solids or more. Note that in accordance with common usage, the relative proportions of dry solids and moisture in sludge are referenced in most of the wastewater treatment literature as "percent solids" rather than "percent moisture."

The cooling effect of free water, by greatly slowing the overall combustion rate, is a key process characteristic of these high-moisture sludges. The outer layer of sludge dries and chars on introduction into a hot environment. The ash and char layer insulate the surface, thus reducing the rate of heat transfer to the interior. The high latent heat of evaporation of water in the interior further extends the time required for complete drying and combustion. The net impact of these effects is that the sludge incinerator must either (1) provide effective means to manipulate or abrade the sludge mass to disturb and/or wear off the protective ash/char layer and expose the wet interior to heat or (2) provide an extensive solids residence time.

Sludge is significantly different from municipal solid waste in both chemical and physical properties. In general, mixed wastewater treatment sludge is a relatively homogeneous, pumpable mass that exhibits the rheological properties of a "Bingham plastic." It is characterized by a very high ratio of water to solids. Its chemical makeup is predominantly carbon, hydrogen, and oxygen but includes significant fractions of phosphorous and nitrogen. From a health effects point of view, biological sludge is relatively benign, with the exception of potential problems with pathogenic organisms and/or heavy metals.

A second class of sludge waste is generated in the course of a wide variety of organic chemical synthesis and other processing operations, petroleum product handling and refining, coke manufacture, etc. Although generated in lesser volume than the wastewater sludge on a national basis, the quantities of these sludges and pastes can also be significant. The characteristics of these sludges include (1) medium to low ratio of water to solids, (2) carbon and hydrogen as the dominant elemental constituents, (3) a high room-temperature viscosity (usually temperature-dependent), and (4) health effects that are often adverse from both the raw sludge and its combustion products.

The primary application of the incineration technologies discussed in Chapter 9 is for the management of wastewater treatment plant sludge. The multiple-hearth furnace (MHF) and the fluidized bed (FB) are the incinerator concepts most commonly used to address the unique requirements of this service. Other furnace designs discussed in this chapter were originally developed for domestic or industrial solid wastes and have since been adapted to burn biological sludge. Conversely, the MHF and FB systems can be, and sometimes are, used for the incineration of industrial and/or domestic solid wastes, although with some processing of the solids before feeding. Also, note that modified versions of the FB concept are used for industrial sludge not derived from wastewater treatment (e.g., their application in many refineries to burn API separator sludge and tank bottoms).

Rotary kilns are infrequently used for biological sludge. Kilns see their greatest application for some industrial wastes and for hazardous wastes (including the high heat content sludge) and are discussed in Chapter 11.

Because (most) sludge can be pumped, many of the problems of storing and feeding that are experienced with solid wastes are greatly simplified (although odor can be a severe problem after prolonged storage of biological wastewater treatment sludge). Conversely, the flow characteristics and small ash particle sizes of sludge make the use of a grate-type support during burning unacceptable. For this reason, sludge is burned on a hearth or in suspension.

Table 1 Estimated Incinerator Area Requirements

System	Burning rate (ton/day)	Plant area (m^2)	Specific area (m^2/TPD)
MHF, oxidizing mode	40	1000	25.0
	300	3850	12.8
MHF, pyrolysis mode	12.5	500	40.0
	200	1730	8.7
Fluid bed	20	400	20.0
	120	400	8.3
Fluid bed and dryer	20	510	25.5
	158	1500	9.5

Source: From (396).

The facilities used to burn sludge are relatively large. This reflects the need for redundancy (to provide high reliability in the volume reduction function) and the generally large dimensions of ductwork, scrubbers, conveyors, and other feed systems and bunkers and, of course, the furnaces themselves. Typical floor space requirements for sludge combustion facilities are shown in Table 1. Naturally, the plant area in a particular facility depends on the specific associated equipment, structural and layout interactions with other structures and facilities, etc.

I. MULTIPLE-HEARTH FURNACE (MHF) SYSTEMS

A. Process Characteristics

1. Fully Oxidizing Mode

The multiple-hearth furnace (Fig. 1) operated in the fully oxidizing mode is the most widely used wastewater treatment sludge incinerator in the United States. These units consist of a vertical cylindrical shell containing 4 to 14 firebrick hearths. A hollow cast-

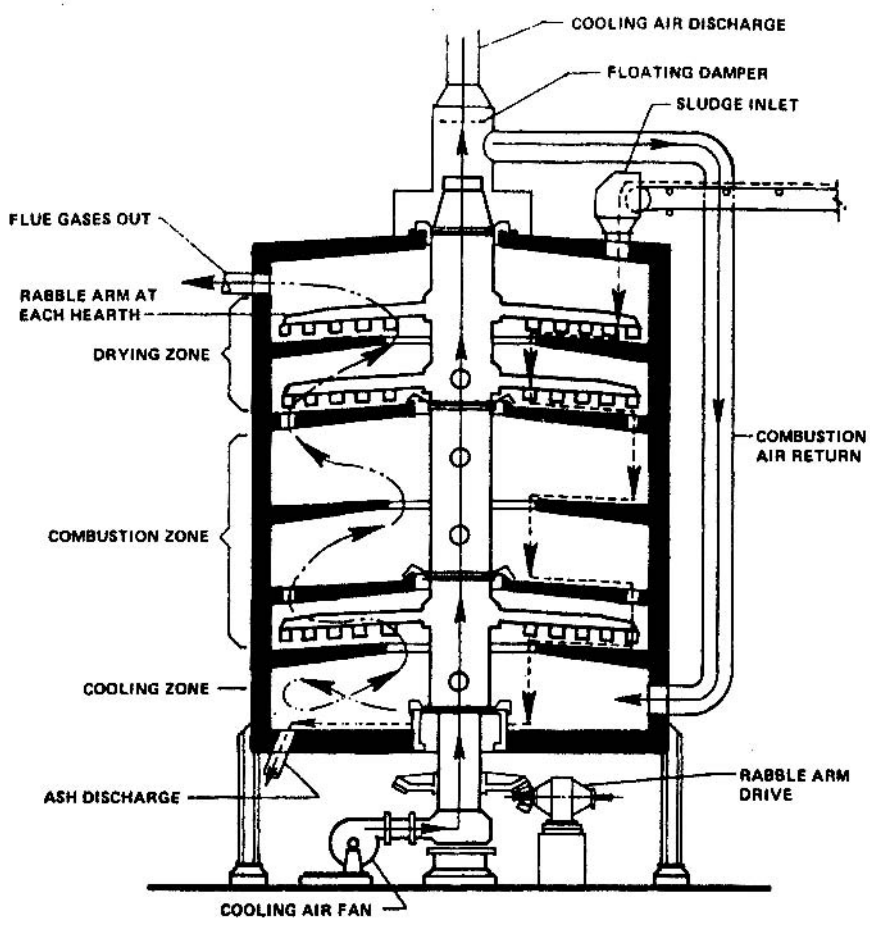


Figure 1 Multiple-hearth sludge incinerator.

iron or steel shaft is mounted in the center of the shell. The center shaft is rotated at 0.5 to 1.5 rpm. Two to four opposed arms are attached to the shaft and are cantilevered out over each hearth. A series of wide, spade-like teeth are mounted on the arms. As the arm rotates, the sludge is plowed or "rabbled" toward the center (on an "in-feed hearth") or toward the outside wall (on an "out-feed hearth").

The center shaft and rabble arms are insulated with refractory and cooled by air forced through a central "cold air tube" by a blower. The air returns via the annular space between the cold air tube and the outer walls: the hot air compartment (Fig. 2). The center shaft is provided with a rotating sand seal on the top and bottom to avoid infiltration of tramp air into the furnace.

Standard units can be purchased in diameters of 1.4 to 8.8 m. The capacity of these furnaces ranges from 100 to 3600 kg/hr of dry sludge. Each hearth has an opening ("drop-

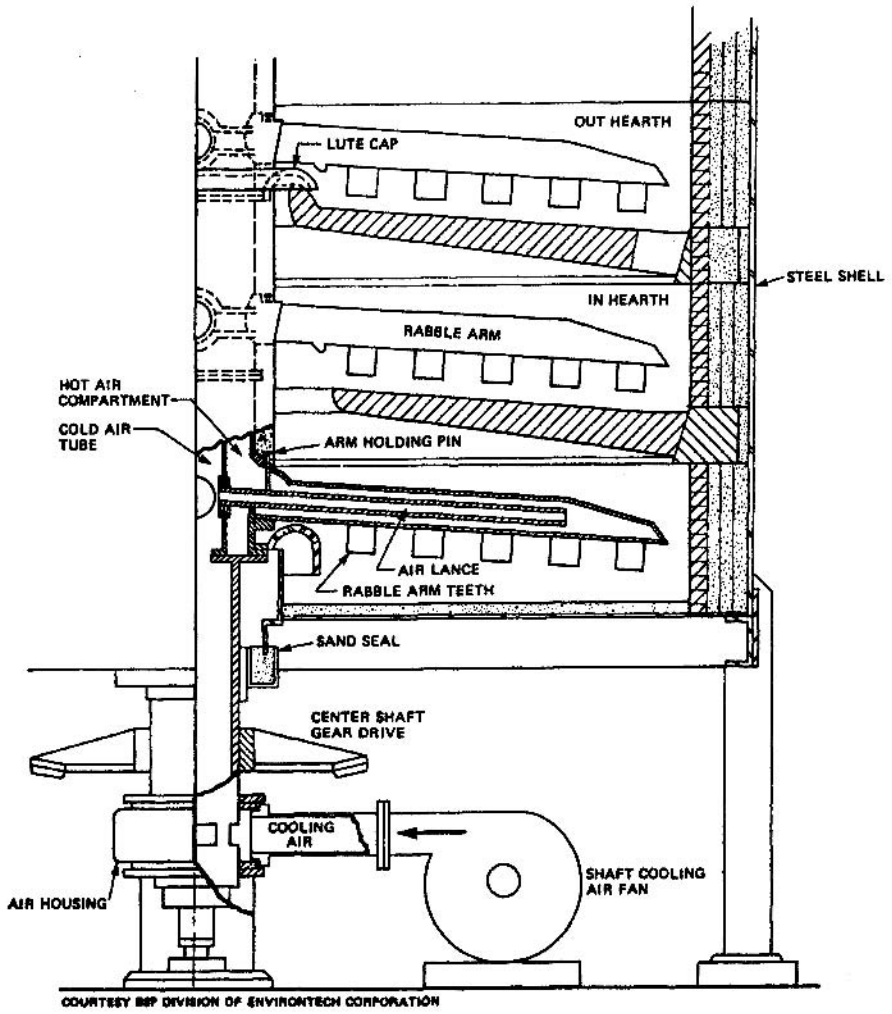


Figure 2 Shaft cooling air arrangement in a multiple-hearth furnace.

Table 2 Typical Dimensions of Multiple-Hearth Incinerators

Furnace O.D. (meters)	Cooling air (m^3/min)	Outhearth area (m^2)	Number of dropholes	Drophole area (m^2)
1.98	20	—	—	—
2.29	25	—	—	—
2.59	30	2.26	24	0.57
3.28	60	3.38	18	0.85
3.89	70	5.59	20	0.93
4.34	85	6.88	24	1.30
5.11	115	9.19	18	2.93
5.71	140	14.05	30	2.30
6.78	200	19.18	30	4.51
7.85	280	28.96	36	5.42

Furnace O.D. (meters)	Inhearth area (m^2)	Drophole area (m^2)	Insulated shaft O.D. (cm)
1.98	—	—	—
2.29	—	—	—
2.59	0.89	0.19	31.8
3.28	1.37	0.22	31.8
3.89	2.18	0.31	48.3
4.34	2.76	0.42	48.3
5.11	3.6	1.03	63.5
5.71	5.19	0.82	71.2
6.78	7.25	1.59	83.8
7.85	9.99	2.21	83.8

Refractory thickness approximately 0.33 meters.

hole") through which the sludge falls from hearth to hearth. The range of common (U.S. practice) furnace dimensions are given in Table 2 to illustrate typical furnace geometry. The drop-hole penetrations alternate in location from a wide clearance around the central shaft (on an "in-feed hearth") to spaced holes at the periphery (an "out-feed hearth"). The sequence is set such that the top hearth is usually fed at the periphery and the bottom hearth discharges at the periphery. The mean residence time of solids in the furnace is variable but approximates 0.75 to 1.25 hours.

The rabbling process acts not only to move the sludge but also to cut, furrow, and open the surface as it passes through the drying, burning or combustion zone, and cooling zone. Observations of the furnace show a significant "freshening" of the luminous diffusion flame rising from the sludge bed on passage of the rabble arm. The flame dies down to a flicker in only a few moments, only to be rekindled with the passage of the next arm. The angle of the rabble teeth on the rabble arms is set both to move the sludge toward the exit opening and to generate ridges, thus increasing the effective exposed area to up to 130% of the plan area. An optimum rabble arm speed is where the width of the level portion in the valley of the furrows is approximately three cm. When rabble speed is too fast, this width will increase. When it is too slow, it will fill in with sludge.

In some instances, the angle of the rabble teeth can be reversed ("back rabbling") to increase residence time and to control the location of the combustion hearth. Back rabbling can approximately double the residence time on the hearth.

Attempts to "move the fire" by changing the rabble arm speed has the secondary effect of either building or stripping the inventory of sludge on the hearths. Excessive sludge inventory can lead to a runaway condition where relatively large quantities of sludge begin to burn at one time. This overloads the air supply and leads to smoking and excessive hydrocarbon emissions. As a generalization, the use of rabbling speed as a day-to-day operating parameter is unwise.

Commonly, each hearth is equipped with two access doors. The doors have fitted cast-iron frames with machined faces to provide a reasonably gastight closure. In circumstances where air inleakage is critical (e.g., starved-air combustion, activated carbon regeneration, or charcoal manufacture), the doors may be gasketed and latched closed.

Several of the intermediate hearths are equipped with burners supplied with natural gas or No. 2 fuel oil. The air for the burners is supplied at a high pressure such that the flame and the excess air are forcibly projected into the overhearth volume. The air supplied through the burners typically supplies the air for sludge combustion. The overall excess air level used in multiple hearth systems varies widely. A good operator working with a feed system that supplies the sludge at a steady rate and consistent moisture content can run the units at 75% to 85% excess air. More typically, one finds the units operated at 100% to 125% excess air. Highly irregular feed conditions and/or indifferent operation leads to excess air levels well over 125%, with consequent excessive fuel and power consumption.

The temperature profile in the countercurrent sludge and flue gas flows depends on the relative magnitude of the following energy terms:

Sludge character and feed rate (moisture content, dry solids heating value, and ash content).

Combustion air quantities and temperature: In some units the warmed air from the hot air compartment (typically 120°–175°C) is used for combustion air. The unused arm cooling air is often blended with the exhaust gas from the scrubber to minimize the persistence of the visible plume. Also, the hearth doors leak some air.

Fuel firing rate: Usually, the burners are provided on the upper and several lower hearths. Also, screenings, grease, and scum are often added to one of the lower hearths.

Heat loss from the outer shell.

In the idealized case, the temperature profile is as shown in Table 3.

Table 3 Idealized Temperature Profile in Multiple-Hearth Furnace Burning Municipal Wastewater Treatment Sludge

	Drying zone	Burning zone	Cooling zone
Sludge	70°C	730°C+	200°C
Flue gases	425°C+	830°C+	175°C+

In theory, the MHF can be operated without generating an odorous off-gas: Little odoriferous matter is distilled until 80% to 90% of the water has been driven off (a sludge solids content of, say, 70%), and, at this point in the furnace, flue gas temperatures are high enough to burn out the odor. In practice, uncompensated variations in sludge moisture and/or heat content, inattentive or untrained operators, inadequate mixing and/or residence time of odorous off-gas, and other factors occur with sufficient frequency to almost ensure that odor will be a problem, at least from time to time. Protection from such problems includes the use of the top hearth as a secondary combustion chamber (with auxiliary fuel firing as needed) or the installation of a separate afterburner chamber.

In the design of MHF units for municipal sludge service, the parameters listed in Table 4 are reported design or operating values for basic parameters.

MHFs may also be used for the incineration of industrial wastes that have a high moisture content. This could include industrial biological wastewater treatment sludge, spent grains, or biomass from fermentation operations and the like. High organic content sludge (e.g., tank bottoms or tarry residues) are more efficiently and completely burned in other incinerator configurations.

MHFs have been tested as a device in which to co-incinerate mixtures of municipal sewage sludge and prepared municipal refuse. Refuse preparation includes shredding and removal of much of the glass and metals (142) (especially wire that tangles in the rabble plows). In this concept, sludge is fed to the top hearth and prepared refuse is fed either to the top or to an intermediate hearth. Several European plants where refuse is fed to the intermediate hearth experienced unacceptable odor emission problems. The problem apparently results from the variability in refuse heat content and consequent swings in the temperature of zones critical to odor destruction. No afterburner was installed. Details on these operations are available (143–147).

Data from the Uzwil co-incineration plant in Switzerland (147) indicate an estimated mean hearth heat release of 57,000 kcal hr^{-1} m^{-2} with a hearth loading of 31.3 to 33.8 kg hr^{-1} m^{-2} and a volumetric heat release of 42,700 kcal hr^{-1} m^{-3}. The exit gas temperature was 880°C. The top two (of 12 original) hearths were removed to provide additional combustion space over the feed hearth.

Table 4 Typical Design Parameters for Multiple-Hearth Incinerators

Parameter	Units	Low	Mean	High
Hearth area burning rate	kg dry solids hr^{-1} m^{-2}	7.2	9.8	16.2
Excess air	percent overall	20	50	80
Cooling air exit temperature	°C	95	150	195
Discharge ash temperature	°C	38	160	400
Off-gas temperature	°C	360	445	740
Sludge properties				
heat content	kcal/kg volatile	5300	5550	7760
volatile content	% of dry solid	43.4	54.2	71.8
Total energy input (fuel plus sludge)	kcal/kg wet sludge (for ~25% solids sludge)	810	1100	1355
	(For ~48% solids sludge)	1595	1730	1922
Volumetric heat release (fuel plus sludge)	kcal hr^{-1} m^{-3}		67,600	

2. Starved-Air (Pyrolysis) Mode

MHFs can be operated with a restricted air supply (starved-air or pyrolysis mode) to give several desirable operating characteristics within a hardware system well proven in conventional, fully oxidizing service. Importantly, the MHF can be configured to permit switching back to the full combustion mode as a process backup.

In conventional MHFs, the system is allowed to operate with full burning. Thus, the gases leaving the furnace are primarily carbon dioxide, water vapor, and the nitrogen and excess oxygen from the air. In the pyrolysis mode, there is a deficiency of air relative to the stoichiometric requirement. In the starved-air mode, perhaps 80% of theoretical air is supplied to the furnace. This releases approximately 80% of the heat of combustion in the sludge. The off-gas contains a mixture of nitrogen, (mostly) low- and high-molecular-weight hydrocarbons, hydrogen, and considerable carbon monoxide. Because of the reducing conditions, one also finds HCN and NH_3 at high concentrations.

The first product of the pyrolysis process is a mixture of carbon and ash. With time, the carbon is gasified by reaction with oxygen, carbon dioxide, and steam according to

$$C + O_2 \rightarrow CO \text{ and/or } CO_2$$

$$C + CO_2 \rightarrow 2CO$$

$$C + H_2O \rightarrow CO + H_2$$

Data from pilot studies (397) presented in Table 5 show the effect of temperature and gas composition on the hearth gasification rate.

The primary beneficial features of the MHF system in the starved-air mode relate to energy conservation. Lower excess air operation (only at 30% to 40% excess) can reduce fuel use. Clinker formation is reduced to a minimum, and refractory maintenance should be reduced due to less severe operating temperatures.

Air emissions (particulate, heavy metals, and organic emissions) are significantly lower in the pyrolysis mode than for MHF systems operating under fully oxidizing conditions (395). Pilot data on pyrolysis zone gas composition from Japan (394) show that from 43% to 87% of the sulfur in the cake remains in the residue. Seventeen percent to 51% of the sulfur was converted into SO_x and between 0% and 7% into H_2S. Fifty-five percent to 87% of the chlorine in the cake remains in the residue, and the remainder converts into HCl. As discussed below, NO_x generation was almost nil at the 60% stoichiometric air mode of the pyrolysis environment.

Table 5 Carbon Gasification Rate for Multiple-Hearth Furnaces Operating in Pyrolysis Mode

Hearth temperature (°C)	Oxygen concentration (%)	CO_2+ steam concentration (%)	Gasification rate (kg/hr m^2)
995	0	42–47	4.21
950	4	25–30	3.28
869	0	42–47	1.47
876	4	25–30	1.47
864	4	25–30	1.22
871	9	16	1.96

Source: From (398).

The oxidation of chromium from the relatively benign trivalent form to the carcinogenic hexavalent form is reduced almost to nil for pyrolysis mode operation. Data from Japanese researchers (393) showed that only 0.08% to 0.09% of the total chromium in the solid residue following pyrolysis mode decomposition was hexavalent in contrast to as much as 34% in the full incineration case. Indeed, the Cr^{+6} content of the ash was lower than that of the inlet sludge. A further benefit was the low solubility of all forms of chromium in the residue.

Data from Concord, California, tests (224) showed an off-gas higher heating value of about 800 kcal per dry standard cubic meter (approximately 5,200 kcal/kg). Tests in Japan (393) showed about 400 to 500 kcal/m^3. The off-gases in the Japanese tests contained about 60% of the fuel value of the original sludge. Thus, in the pyrolysis system, an "afterburner chamber" is required wherein a burner is mounted (to ensure ignition) and additional air (to, perhaps, only 40% excess overall) is added. Since most sludge incinerators are energy-deficient (the sludge fuel energy is insufficient to supply all needed heat), the savings in fuel from operation at this lower level of excess air can be substantial. About 5% of the sludge fuel value can be lost in unburned carbon in the ash unless the lower hearths are operated above the stoichiometric level to ensure burn-out. Data on the composition of pyrolysis mode off-gas are summarized in Table 6.

Some operators have registered concern about the potential for explosions in MHF systems operated in the pyrolysis mode. The expressed opinion is that since the furnace is filled with combustible gases, inadvertent opening of hearth doors will provide the air for an explosive event. To date, such an eventuality has not been realized in the limited operational experience of sludge incineration in the starved-air mode and, also, not in the operational records of the hundreds of MHF furnaces used for activated charcoal manufacture, charcoal regeneration, etc., where the furnace is maintained in a starved-air condition. In general, operator feedback from pyrolysis mode operations suggests that stable conditions could more easily be maintained under pyrolysis than in the oxidizing mode. Further, lower hearth temperatures almost ensure freedom from clinker formation.

B. Process Relationships

1. Retention Time

The retention time of solids in the multiple hearth furnace is proportional to shaft rpm, the number of rabble arms, and the plow angle settings of the rabble teeth. An average of 80

Table 6 Characteristics of MHF Sludge Pyrolysis Off-Gas and Secondary Combustion Chamber Effluent

Pollutant	Volume % in off-gas	Volume % after SCC	Pollutant	ppmdv in off-gas	ppmdv after SCC
H_2	4.27	ND	NO_x	26	94
CO	5.69	ND	NO	25	87
CH_4	0.79	ND	HCl	690	87
C_2H_4	0.5	ND	HCN	524	15
C_2H_6	0.016	ND	NH_3	7125	11
CO_2	8.80	2.95			
N_2, etc.	81.78	97.05			

Source: From (393).

minutes retention time is required for a 20% solids sludge. The mean solids residence time (t) on a hearth is given by

$$t = \frac{r_h}{Ea\omega} \tag{1}$$

where

r_h = hearth radius
E = a factor characterizing the "slip" between the solid material and the movement of the rabble teeth. An efficiency of about 50% is often used for calculations.
a = distance from the center of the furnace to the innermost rabble teeth
ω = angular velocity

2. Heat Transfer

The rate of heat transfer from the furnace walls and the hot flue gases is a complex function of gas temperature, the concentration of radiating gases (e.g., CO_2 and H_2O) and soot and ash particles in the gas (affecting the mean gas emissivity), the relative velocity of gases over the solids, and so forth. Workers in the vendor community (195) suggest the use of an empirical overall heat transfer coefficient (U') given by the following dimensional equation:

$$U' = \frac{T}{100}\,\text{Btu/hr ft}^{2\circ}\text{F} \tag{2}$$

where T is the average gas temperature *in degrees Fahrenheit* and U' is to be used (after conversion of units) with the log mean temperature difference in estimating the heat flux Q as follows:

$$Q = 35.28U'A\Delta T_{\text{lm}} \quad \text{kcal/hr} \tag{3}$$

where A is the area (m^2) and the log mean temperature difference (°C) is given by

$$\Delta T_{\text{lm}} = \frac{(T_{g2} - T_{s1}) - (T_{g1} - T_{s2})}{\log_e\left[\dfrac{(T_{g2} - T_{s1})}{(T_{g1} - T_{s2})}\right]} \tag{4}$$

where the subscripts on temperature refer to gas (g) or solid (s) temperatures at their respective inlet (1) or outlet (2) conditions for the hearth under study.

3. Pyrolysis and Combustion Processes

Pyrolysis reactions of sludge organic matter begin at about 200°C. The reactions are a temperature-dependent chemical reaction with a modest endothermic, then exothermic heat effect and are substantially complete when the temperature reaches about 650°C. Although not rigorous, the degree of pyrolysis effected at a given temperature T may be roughly estimated by

$$\text{fraction pyrolyzed} = 1.0663(1 - e^{\frac{200-T}{162}}) \tag{5}$$

Pyrolysis results in partial gasification of the sludge. Approximately 85% of the sludge combustible is pyrolyzed to a gaseous product. The remaining 15% ends up as a char. The char burns in the solid phase or is subsequently gasified to CO and CO_2. Ultimate burnout

of residual fuel values occurs in the gas phase. A typical rate of gasification of the char for temperatures above about 850°C in the fully oxidizing mode is about 2 kg hr^{-1} m^2.

Data from Japanese MHF pyrolysis experiments showed a two-step process beginning with pyrolytic breakdown of complex organic matter (393). This was followed by gasification of the solid char product by reactions with water vapor, carbon dioxide, and/or oxygen. The pyrolytic step at 800°C brought the overall degradation to 98.17% complete in 7.5 min (linear in $\ln[x - 1]$ versus time, where x is the decimal percent reacted). The slower char gasification process was also linear in the same coordinates: continuing from 98.17% degradation at 7.5 min to 99.75% at 20 min.

The gaseous products of pyrolysis range broadly and include simple, low-molecular-weight hydrocarbons, complex polyaromatics, and a wide variety of partially oxidized alcohols, aldehydes, ketones, and the like. Higher temperatures favor the simpler, low-molecular-weight compounds, and lower temperatures favor the tarry heavy oils.

As the sludge moves through the furnace, the average moisture content drops. However, the onset of combustion comes before the total sludge mass is thoroughly dried. Based on an analysis by Lewis and Lundberg (222), that presumption is in general agreement with observations of operating furnaces where vigorous combustion ensues when the mean moisture content has fallen to 53% (47% solids).

4. Heat and Material Balance Characteristics

The key process feature of the multiple-hearth furnace is the regenerative exchange of heat between the incoming sludge drying on the top hearths and the countercurrent rising flow of gases heated by combustion and ash cooling on the lower hearths. In order to realize this energy economy, the top hearth temperatures must be allowed to fall considerably below levels where combustion takes place (say, as low as from 300° to 350°C). If the incoming sludge contains significant amounts of greases and oils, this may lead to emission of hydrocarbon-rich aerosols from the top hearths.

Regulatory trends in the United States increasingly require those gases in contact with raw sludge to be reheated (say, to 815°C), both to ensure sterilization and deodorization of the off-gas and to burn hydrocarbon vapors. If reheating is a firm requirement, the intrinsic energy efficiency of the multiple hearth is lost. The best-case fuel efficiency in this circumstance matches the multiple hearth with conventional fluid bed units but without the potential for energy recovery that can be achieved in the fluid bed with hot windbox designs.

The overall heat and material balance on a MHF is straightforward. The techniques and results are similar to those presented in Chapter 2. One problem with the furnace, however, is not revealed by such analyses: the sensitivity of the furnace to rapid temperature excursions. The sensitivity arises from the inherent structural design of the hearths, which are very flat, self-supporting refractory arches. Such a structure cannot tolerate the dimensional changes and expansion/contraction stresses associated with a rapid change in temperature. Consequently, relatively large quantities of fuel are used to sustain furnace temperature during no-feed periods, to very slowly bring up the furnace temperature on startup, and to drop the furnace temperature on shutdown.

Perhaps the greatest benefit of the MHF is its energy economy (when environmental regulations permit). Also, the inherent inertia of the system provides a flywheel effect, which allows absorption of feed fluctuations. The problems of the system, aside from the environmental emissions and clinkering problems noted above, result from the complexity and structural sensitivity of the design. The complexity requires considerable operator skill

and, often, results in the simple expedient of turning up the air to wash out the need for fine trim. The structural problem arises due to the flatness of the hearths such that careful control over the rate of temperature rise and fall must be observed to avoid catastrophic hearth failures.

In the starved-air mode, the furnace itself is operated at between 30% and 90% of *theoretical* air. In an external afterburner chamber, sufficient air is added to bring the overall stoichiometry to 25% to 50% *excess* air. Clear advantages in fuel requirements are obvious in comparison to typical operation at 125% excess air and, with indifferent or inattentive operators, up to 200% excess air.

5. Operating Characteristics

Table 7 indicates typical production rates for MHFs burning a variety of sludge feeds. It can be seen that loading rates reflect a balance between the evaporative load and the sludge heat content (roughly scaled by the combustible content). There are significant differences in the observed typical furnace capacity between small and large incineration plants. This difference reflects heat losses, instrumentation and control systems and, to a degree, operator sophistication and training.

Table 8 shows the typical operating labor requirement for MHF installations. The table is based on systems with a high degree of automation. The labor budget includes labor for operation of the furnace, the scrubber, and the ash handling functions.

The multiple hearth is a large furnace with considerable thermal inertia. Thus, it can absorb substantial swings in feed sludge quantity and quality without producing unrecoverable upsets. However, the furnace is complex, with each hearth's processes reflecting the contribution of other hearths' off-gases, burners, and the sludge's own contribution of heat absorption (evaporation) or heat release (combustion/pyrolysis). Because of the interplay of processes from hearth to hearth, the importance of feed stability to achieve fully satisfactory, energy-efficient, and environmentally acceptable system performance cannot be overstated. The staged character of the MHF hearth process means that cycling in feed rate results in the development of several combustion zones in the furnace. This can result in the discharge of still-burning sludge into the residue

Table 7 Typical Hearth Loading Rates for Multiple-Hearth Furnaces

Sludge type (**)	Percent solids	Percent combustibles (dry basis)	Typical wet sludge loading rate ($kg/m^2/hr$) (*)
Primary	30	60	34.3–58.8
Primary + $FeCl_3$	16	47	29.4–49.0
Primary + Low lime	35	45	39.2–58.8
Primary + WAS	16	69	29.4–49.0
Primary + WAS + $FeCl_3$	20	54	31.8–53.9
Primary + WAS + $FeCl_3$	16	53	29.4–49.0
WAS	16	80	29.4–49.0
WAS + $FeCl_3$	16	50	29.4–49.0
Anaerobically digested primary	30	43	34.3–58.8

(*) Lower number is applicable to small plants, higher number to large plants.
(**) WAS = Waste Activated Sludge.
Source: From (223).

Table 8 Labor Requirements for Multiple-Hearth Furnace Installations

No. of furnaces	Labor (man-hours per year)[a]		
	Operation	Maintenance	Total
1	2,920	1,460	4,380
3	8,760	4,380	13,140
5	14,600	7,300	21,900

Note: Assumes fulltime operation (7 days/week, 52 weeks/year) for highly automated process.
[a]Includes operation of the furnace, scrubber, and ash handling units.

conveyors with consequent equipment damage. Further, operator response to the situation where multiple combustion zones have emerged is often to increase the air supply. Increasing air results in greater fuel consumption and cost.

The use of high-pressure piston pumps as a means to feed multiple hearth systems at a steady rate and without introduction of tramp air has shown great success in stabilizing the burning front and improving environmental emissions and fuel economy. With stable feed, the multiple hearth system can be an effective and reliable operating system with few operating problems.

If the combustion-zone temperature becomes excessive relative to the sludge ash fusion point, sintered masses or ash or "clinkers" form that can block dropholes, bind rabble arm movement, and foul or jam the ash conveyor. This problem becomes excessive at temperatures above 1000°C. As noted above, the clinkering problem has been associated with the use of ferric chloride (with lime) as a conditioning aid for sludge dewatering. In the hydrocarbon- and CO/H_2-rich atmosphere within the mass of gasifying solids, ferric oxide formed by dehydration of ferric hydroxide is reduced. The shift in iron oxidation state decreases the ash fusion temperature. High-phosphorus-content sludge also exhibits low ash fusion temperatures.

Problem areas in MHF operation in sludge burning service (beyond the odor problems described above) include high refractory and rabble arm maintenance and the long time required to bring the units into service. Refractory and rabble arm problems arise from rapid temperature excursions (a too-rapid rise to temperature) and high temperatures due to localized overfiring. Ideally, the furnace should be brought to temperature (or cooled down) over a 24- to 30-hr period.

A second class of problems with MHF operation concerns air leaks (350). Since the furnaces are normally operated under draft, air leaks cool the furnace, increase fuel use, and, sometimes with crucial significance, add to the load on the induced draft fan. The four major areas for leaks include the upper shaft sand or water seal, the several furnace doors, the sludge feed, and the emergency bypass damper. The first two leakage points are readily correctable by proper maintenance and operator attention. The latter problems can be serious and are difficult and costly to resolve. The combination of damper and sludge feed leaks at typical furnace draft of 0.75 cm H_2O can lead to infiltration of almost 100 Nm^3/min (350) so remedies will be important contributors to plant efficiency and capacity.

The sludge feed system using a belt conveyor–chute feed is often a problem. Most sludge feed points use counterweighted, flap gates (some use double gates with the goal of having one gate close and seal before the second gate opens). The stickiness of the sludge often keeps the gates from closing fully. This can result in leakage areas of about 650 cm^2. Significant improvement has been observed in plants where the feed system has been converted to high-pressure diaphragm pumps that completely eliminate the leak or to the use of covered screw conveyors and chutes.

The emergency bypass butterfly damper, though made of high-alloy stainless steels, is susceptible to warping. Warping of the damper quickly leads to loss of the ceramic rope caulking, resulting in a leak area of about 350 cm^2. Damper leakage is a difficult problem, and no satisfactory solution for the butterfly damper has emerged. Converting to a sealing stack cap (equipped with a hydraulic opener) of the type used in cupolas has been suggested (350).

In the pyrolysis mode, there is considerably less operating experience than in the fully oxidizing condition. It should be noted that the oxygen-deficient pyrolysis mode requires a reversal of the "normal" response of the operator to temperature rise. In the fully oxidizing mode, temperature can be reduced by increasing the air supply. In the pyrolysis mode, however, adding oxygen *increases* temperature. Operator training was needed to develop this reversed "sense" for pyrolysis mode operation. Hearth-by-hearth temperature control (using air supply as the control means) should be installed for optimum performance. However, data from the Concord, California, plant (224) and from extensive pilot plant studies at Nichols' Research and Engineering, Inc. (225) support the general conclusion that the multiple hearth in the pyrolysis mode is much easier to control than in the oxidizing mode. Further, due to the low hearth temperatures, no clinkering problems were observed.

The ash product from the pyrolysis mode (without special features) is much higher in combustible content than conventional MHF ash. Total combustible ranges from 3% to 30% including up to 20% elemental carbon (224). A portion of the combustible can be gasified by the addition of air to the lower hearths. Char burnout can also be effected by sparging steam into the furnace on the lower hearths. The water–gas reaction gasifies the carbon char (producing CO and hydrogen, which burn in the afterburner) without adding diluent nitrogen, which has an adverse impact on the overall heat balance.

6. General Environmental Considerations

The conventional MHF (with feed to the top hearth and no afterburner) can present problems with air emissions. The inherent regenerative feature of the multiple hearth can lead to excessive distillation of greases in a low-temperature zone with no subsequent means for control. At times, these greases are partially burned, leading to finely divided soot (opacity) and odor emissions. Also, incomplete burning on the top hearth can result in hydrocarbon emissions that exceed regulations. Raw sludge can be carried off by entrainment in the gas flow rising through the drop holes.

If the combustion and char burning hearth temperatures exceed 850° to 1000°C, volatilization of the oxides and chlorides of several toxic and/or carcinogenic metals (especially mercury, lead, arsenic, cadmium, chromium, and nickel) increases markedly. Subsequent cooling of the combustion gases in the upper hearths results in enrichment of the hard-to-collect fine-particle fraction of the particulate matter by these elements. The fine particles present a large fraction of the available surface area (if not the mass fraction) of the particulate matter on which condensation occurs. Since the fine particulate is the

hardest to collect in air pollution control devices, increased emissions of these environmentally important elements result in increased health risk in the area downwind of the incinerator. This topic is considered in greater detail in Chapter 13.

Other than the limited tests in Concord, California, the Nichol's Research and Engineering investigations for the ISIS, and the Japanese testing (393), there are only limited data on the MHF pyrolysis operating configuration. Two full-scale commercial plants (in Alexandria, Virginia, and Cranston, Rhode Island) were designed and constructed to operate in the pyrolysis mode but have not done so. Several incinerators were run in starved-air mode for a short time when high heat content, low moisture sludge was being processed and temperatures became excessive in the fully oxidizing mode. Data indicate that the environmental performance of the multiple hearth when operated in the pyrolysis mode is more stable than in the oxidizing mode. If, for example, feed rates increase suddenly but the air rate is kept constant, furnace heat release does not change. By contrast, in the oxidizing mode, air is available to oxidize the excess combustible associated with increases in feed rate and furnace heat release and temperature will directly track feed-rate pulses.

Due to reduced and more stable heat release, pyrolysis mode hearth loading rates can be higher than for a comparable optimum incineration mode furnace. Wet-weight rate data (397, 399) when processing sludges ranging in solids content from 22% to 35% in a one-meter diameter pilot furnace showed 64 kg/hr-m^2 in the mode producing low-temperature char (HTC). HTC material is similar to charcoal (about 20% carbon, 80% ash), has an average bulk density of 0.26 g/cm^3, and results from processing with a maximum solids temperature of 700°C. When producing high-temperature char (HTC), the processing rate rose to 78 kg/hr-m^2. HTC is a mixture of ash and fixed carbon (about 6.5% carbon, 93.5% ash) and is generated when the solids temperature is allowed to rise to 870°C. When operating to consume all of the carbon, where the average bulk density of the residue reaches 0.53 g/cm^3, the rate falls to 59 kg/hr-m^2. Note that the wet processing rate was almost constant over the range of solids content, whereas the solids processing rate varied significantly.

Due to reduced gas velocities, particulate carryover from pyrolysis operations is reduced almost 50% in comparison to the fully oxidizing mode. Also, minimization of hearth temperatures reduces heavy metal emissions significantly, as predicted from theory. Although data are limited, reducing conditions in the furnace under pyrolysis mode conditions inhibit oxidation of chromium in the sludge from the relatively innocuous Cr^{+3} to the carcinogenic Cr^{+6} valence state form. Significant chromium oxidation (over 30% conversion in some furnaces) has been observed in fully oxidizing multiple hearth systems. Also, fuel nitrogen NO_x generation appears reduced (224) in the pyrolysis operating mode. More data are required to fully characterize and demonstrate the environmental characteristics of the starved-air mode.

II. FLUID BED SYSTEMS

The fluidized bed furnace (FB), as applied in sludge incineration, is an inherently simple combustor. Air at high pressure is forced through a bed of sand. The sand particles become suspended in the rising gas and take on the behavior of a turbulent liquid: bubbling and flowing to maintain especially uniform temperatures throughout the bed volume. Typically, gas temperatures vary less than 5° to 8°C between any one location in the bed and another. The gas velocities under these conditions average between 0.7 and 1.0 m/sec.

The top of the bed is relatively well defined, and the gas rising through the bed includes clearly defined gas bubbles. The hydraulic behavior of the fluidized bed is as though it held an ordinary liquid: solids with a lower density float; the upper surface is well defined and remains horizontal when the bed is tipped; the surface levels equalize when two chambers are interconnected; solids will overflow if the upper surface is higher than a drain point in the sidewall. This is the conventional, "bubbling fluid bed" mode of operation.

Above the fluid bed is a large, cylindrical disengaging space known as the freeboard. The freeboard usually provides about 3 to 4 sec of residence time for final burnout of combustible material. The freeboard operates at or slightly above the bed temperature. The finely divided ash is swept out of the bed and collected in a scrubber or other air pollution control system. Coarse or heavy particles remain in the bed: either decrepitating with time and blowing out or requiring removal through a drain.

At a given time, only a small portion (usually less than 1%) of the bed mass is combustible matter. The large mass of the bed gives it thermal inertia so that the bed can absorb fluctuations in feed characteristics without the problematical upset conditions that affect the MHF. Solids or sludge fed into the bed or into the freeboard are rapidly heated by radiation and intense convection. The rapid heat and mass transfer between bed constituents results in high-temperature uniformity, usually with not more than a few degrees Centigrade differential between any two parts of the bed.

Sludge cake introduced into the hot bed is abraded by the scrubbing action of the sand grains. The sludge particles rapidly dry and then burn, releasing most of their fuel value in the bed. A 5- to 8-cm-diameter plug of sludge discharged into the bed requires 20 to 30 sec to volatilize (343), while more dispersed feeds may gasify within only a few seconds.

The basic FB design concepts and control system logic draw from the petroleum and ore processing industries where the technology originated. The FB system was developed to provide a means to contact finely divided catalysts with high-molecular-weight petroleum feedstocks in a cracking or reforming process. Subsequent development led to a wide range of applications where the objectives included drying of high moisture content solids (e.g., ores), rapid heat and mass transfer to the feed (solid or gas), uniform temperatures, high thermal inertia (insensitivity to minor variations in feed character), and/or relatively short residence times (less than 5 sec).

FBs were introduced for the combustion of sewage sludge in 1962. Although its application in the United States to date has been dwarfed by MHF installations, the energy-efficient "hot windbox design" embodiment of the fluid bed is the system of choice in most new installations. This reflects the greater degree of control available and improved air emissions due to lower, more controllable temperatures (reduced NO_x and heavy metal volatilization) and superior mixing (very low CO and total hydrocarbon emissions). Over 75 furnaces are operating in North America and many more in Europe. The capacities of fluid bed furnaces (in all services) range from 250,000 to 60 million kcal/hr and diameters from slightly over 1 m to 15 m.

FB technology rapidly penetrated the sludge incineration market when fuel was relatively cheap. However, as fuel costs rose steeply in the late 1970s, there were severe cutbacks in the rate of construction of new FB installations, and many existing units were shut down. The energy problem, importantly, derived from two factors. First, the early FBs were simple, plug-flow reactors. Without any regenerative heat feedback, the full price of the heat content corresponding to peak combustion temperatures was paid for with fuel.

Second, the mechanical dewatering equipment in wide use (primarily, the vacuum filter) was not very effective, so the evaporative energy demand was high. This combination made the FB very expensive to operate. The energy efficiency of the MHF, unencumbered with penalties (at that time) for hydrocarbon or carbon monoxide emissions, appeared attractive.

In response to the challenge of burgeoning energy costs, the vendor community developed a new, energy-conserving modification, the "hot windbox fluid bed." Here, the hot off-gas from the freeboard is passed through a shell and tube heat exchanger to preheat the incoming combustion air. Initial designs heated the air to 500°C but, in modern plants, reheat to 850°C is achieved. Recycling heat substantially decreases the net fuel used in the FB.

Beyond the incineration of biological sludge, fluid beds also have been used for a wide variety of wastes including chemical process wastes, petroleum tank bottoms, coffee grounds and tea leaves, sludge from pharmaceutical, pulp and paper, and nylon manufacturing operations, waste plastics, carbon black waste, spent activated carbon, precoat filter cake, and waste oils and solvents. With preshredding and removal of a large fraction of the metal and glass, FBs have also been used to burn dry and wet-processed municipal refuse.

Another embodiment of the fluid bed concept uses higher gas velocities—high enough to continuously sweep the particles from the bed. Downstream, the larger particles are disengaged from the gas stream, passed to a return line, and reinjected into the bed until their combustion is complete. This "circulating fluid bed" design is generally not used for sludge but has found many applications in burning processed solid waste, coal, wood chips, anthracite culm, and other solid fuels and biomass in steam-raising and power generation installations. The circulating bed has also proved useful for the remediation of contaminated soils and other hazardous wastes. These applications are discussed in Chapter 11.

A. Process Characteristics

The conventional "bubbling fluidized bed" sludge incinerator (Fig. 3) is a vertical, cylindrical, refractory-lined vessel with a perforated grid in the lower section supporting a bed of graded sand. The depth of the static, "slumped" bed is usually 0.9 to 1.2 m. Consider the response of such an arrangement, initially at rest, as the flow rate of gas upward through the bed increases:

1. Initially, friction produces a pressure drop across the bed that increases with velocity.
2. At some point the pressure drop has increased until it is equal to the sum of the bed weight per unit cross-sectional area plus the friction of the bed against the walls. Beyond this velocity the bed either lifts and moves as a piston up and out of the chamber (unlikely with loose, granular solids) or the bed expands or fluidizes so the gas can pass without the pressure drop exceeding the bed weight. Pores and channels appear in the early stages of bed expansion.
3. With further increases in gas velocity to about 0.6 to 1.0 m/sec, particle-to-particle spacing increases and the violence of movement fills and eliminates the gross channels. The expanded bed height is, approximately, a linear function of the superficial gas velocity. In conventional biological sludge applications, a bed expansion about 30% to 60% in volume from the slumped bed is typical. Gas

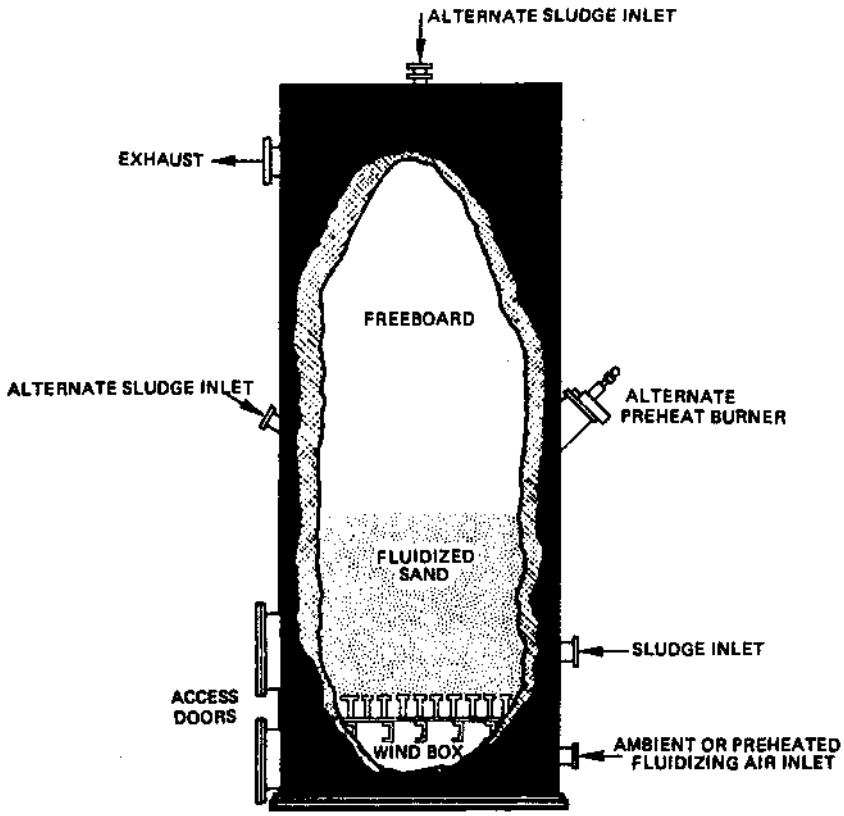


Figure 3 Fluid bed sludge incinerator.

and particles circulate in the bed with some transient streams of extra-high or extra-low particulate concentration but, in general, a high degree of bed uniformity. Bubbles form at the distribution plate and move rapidly through the bed, erupting at the bed surface. Note that it is not necessary to taper the sidewalls to achieve this behavior. Commercial practice includes both flare-then-straight and all-straight wall designs. The beds with higher velocities at the distribution plate (see following paragraph) favor the flared designs to avoid excessive sand loss.

The superficial gas velocity (the gas volumetric flow rate divided by the furnace cross-sectional area) varies with the particle size of the bed material. Conservative design practice suggests velocities at the distribution plate of 0.5 to 1.0 m/sec. Some recent designs, however, are based on velocities as high as 1.3 m/sec. The gas velocity in the freeboard is typically kept lower, averaging about 0.75 m/sec. Heat release rates in the bed range from 900,000 to 1,800,000 kcal/hr/m^3. FB sludge combustors are normally sized at about 500,000 kcal/hr/m^2 of freeboard area. High-velocity FBs achieve over one million kcal/hr/m^2. Overall residence times of the gas at full temperature depend on the volume of the freeboard and ductwork but usually range between 4 and 8 sec. This extended plug-flow zone contributes to excellent burnout of gas phase and solid organic matter. In many

cases, equivalent destruction efficiencies are achieved in fluid beds to rotary kilns operated at 100° to 150°C lower temperatures.

In most instances, the fluid bed is of the "push through" design, where all gas handling is provided by the fluidizing blower. When one or more of the downstream systems (heat recovery, air pollution control, etc.) are such that they must operate under draft, a second induced fan is added ahead of the stack. A balance is struck between the fluidizing blower and the induced draft fan to create a null point (equal to atmospheric pressure) at a target location in the system. Often, the balance point is set just above the bed, thus providing a useful zone where difficult-to-feed materials can be readily charged using a chute or rotary "flinger" without problems with hot furnace gases leaks or excessive cold air in-leakage.

The FB incinerator is well suited to the drying and combustion of a wide variety of wastes. The sand in the bed is in a state of violent recirculating motion that maintains a remarkable uniformity in bed temperature and gas composition. The large mass of the sand, heated to bed temperature, provides a large thermal flywheel effect: protecting against rapid fluctuations in temperature if the feed rate or net heating value changes. For example, a 5-m-diameter freeboard FB reactor, during normal operation, contains about two million Kcal in the bed. As grains of hot sand strike the surface of the incoming sludge, a quantity of water is flashed off. The surface is rapidly dried and abraded so that no insulating layer of ash can develop. Particles of sludge that are sloughed off or abraded into the hot gas stream are ignited and begin to burn almost instantly.

Attention must be given to corrosion of the mild steel shell of the FB reactor when high concentrations of acid gas formers (e.g., sulfides, organic chlorides) are in the feed. Normally, a rubber lining between the steel and acid brick is provided. Alternatively, conditions can be set to ensure that the steel wall temperature is held high enough to prevent condensation. Wall temperatures are maintained at no less than 230° to 260°C where high sulfur concentrations exist and not below 110°C where HCl is present (401).

Other than the bed itself, key equipment includes

- The fluidizing air turbine blower servicing air to the system. In some plants, a boiler is installed following the bed and the blower is powered with a steam turbine drive.
- The freeboard zone wherein combustion is completed. Sometimes overfire air jets assist through stimulation of mixing processes.
- An (optional) heat exchanger. The exchanger preheats fluidizing air countercurrent to the hot gases leaving the furnace.
- An (optional) boiler. The boiler generates hot water or steam from the hot gases leaving the furnace or the heat exchanger.
- The APC equipment. This commonly includes the Venturi and tray scrubber combination (especially in older plants), a dry electrostatic precipitator (used more often in Europe), or a combination of a Venturi scrubber (with or without a tray scrubber) and a wet electrostatic precipitator (ESP).

One of the most useful characteristics of the FB derives from its simple geometry. The cylindrical construction of the FB, the freeboard, and the associated ducting is associated with very robust refractory design and inherent resistance to refractory problems due to temperature excursions. This means that the FB can be shut down for short or long periods of time at the will of the operator. The shutdown (slumped) state loses heat to the surroundings very slowly (usually only 3° to 8°C per hour). Startup is therefore

rapid with only minimal (if any) fuel use to regain operating temperature. This contrasts with the MHF, where fuel firing is required during all standby periods because of the sensitivity of the refractory hearths to uneven and or rapidly changing temperature. Such flexibility is compatible with, say, five-day-per-week or 12-hour-per-day operating schedules except, possibly, at the "wet–dry" interface at the entrance to the scrubber.

It should be noted that the prolonged shutdown of a FB unit can result in severe corrosion problems with dry air pollution control systems. For example, a mild steel, dry ESP would be vulnerable to rapid wastage after the metal temperature passes through the dew point. Isolation and heating of the precipitator after shutdown are conceptually effective to combat this problem but, obviously, present risk. Hazardous waste incinerators in Denmark equipped with mild steel ESPs were successful in avoiding corrosion by washing down the units on shutdown. This problem is not relevant for systems equipped with wet scrubbers.

The ability to shut down the FB from time to time without a significant fuel or maintenance penalty helps to compensate for the limited turndown capability of the furnace. Because of the inherent dynamics of the FB, the gas flow must be within relatively narrow bounds or the bed will collapse. In practice, the units cannot be run at much less than 80% or more than 110% of design capacity. If the shortfall in feed will continue for an extended period, one or more rings of brick can be laid in the furnace to reduce the effective diameter and, in effect, de-rate the furnace. This "turndown" is, clearly, not readily changed but can be useful in those cases where the sludge quantity increases significantly over several years and only one furnace is desired.

Tapered beds facilitate turndown. If operation at low rates is to continue over a long period of time, consideration should be given to changing to a finer grade of bed sand. Increasing the excess air level allows operation at lower feed rates but is often uneconomical. In rectangular beds (more common for circulating-type fluid beds boilers in industrial or power generation service than for sludge incineration), turndown has be achieved by compartmentalizing the windbox and then allowing one compartment of the bed to slump.

1. Fully Oxidizing Mode

Almost all FBs are operated in the oxidizing mode. Excess air levels are maintained at 20% to 40% to minimize fuel costs but ensure complete oxidation of all volatile solids in the sludge cake. The burnout of sludge volatile matter is excellent with, typically, far less than 0.1% unburned matter in the fly ash.

2. Starved-Air (Pyrolysis) Mode

The Hyperion treatment plant in Los Angeles was the first to operate in the starved-air mode. Dewatering is effected using a special, multiple-effect evaporation method (Carver–Greenfield technology) to develop an almost completely dry powder. The dried sludge is then burned in a four-stage, starved-air system. The bed is operated at 30% of theoretical air. Additional air is added in the freeboard to bring the total to 80% of theoretical air. At this point, the sludge volatile matter is fully gasified to include, importantly, the nitrogen compounds in the sludge. The gases then pass to the first of two afterburners, where the air supply is brought to stoichiometric and cooled in a boiler. The final stage is a fully oxidizing afterburner where the total air reaches 135% of theoretical. This design limits NO_x formation from the oxidation of sludge-based nitrogenous matter as well as thermal NO_x.

The operation of a FB unit under substoichiometric conditions is not without precedent. Reducing conditions are used for the processing of iron ores, for iron reduction, and for activated carbon regeneration in fluid beds. With steady sludge flow, the excellent mixing in the fluid bed unit is, indeed, conducive to the attainment of a uniform product gas having the predominant form of unrealized fuel value as hydrogen and carbon monoxide (plus small quantities of low-molecular-weight hydrocarbons). The secondary (afterburner) chamber can involve high turbulence (with air jets and chamber design combining) to ensure complete burnout.

B. Process Relationships (Oxidizing Mode)

1. Heat and Material Balance Characteristics

Combustion occurs largely within the bed. This is important since the heat released in the freeboard is not available to dry the incoming sludge. In most FBs burning sludge, the bed is run between 730° and 840°C. Also, in the general case, the freeboard temperature is, perhaps, 50°C or more higher. This differential is normal, but higher levels should be avoided. Overall excess air levels between 30% and 50% are normal.

For FB sludge incineration at 760°C and 40% excess air, combustion is autogenous (no fuel is required) at an energy parameter (EP) of 425 kg H_2O/million kcal. As the feed sludge becomes dryer and "hotter" (lower EP), the bed temperature will rise. The maximum bed temperature is set by a combination of factors: materials of construction, design features (especially the ability of the distribution plate to accommodate thermal expansion), and the desire to keep the bed cool enough to prevent an approach to the ash fusion temperature of the bed material (rapidly leading to bed defluidization) or excessive volatilization of heavy metals.

Ideally, combustion is completed within the sand bed such that a maximum of energy from sludge combustion is available to dry the incoming sludge. The fraction of the burning that takes place in the freeboard increases as the sludge grease-content increases and when the sludge is dropped through the freeboard space. This starves the bed for drying energy and may lead to overheating (slag formation and adhesion) in the freeboard and outlet flues.

Auxiliary fuels used in sludge incineration operation include light fuel oil (No. 2) and coal. Coal proved especially effective in a West Virginia plant (474). There, a 22% solids at 45% volatile solids mixed primary and secondary sludge was burned using 0.635 cm × zero, 1% sulfur, 15% ash coal (HHV 6,111 kcal/kg) to reach the target bed temperature of 785° to 850°C using 650°C preheated air. The coal was drawn from a silo and fed through a metering screw to two tapered-barrel feed screws along with the sludge. The screws fed the 4.88-m inside-diameter incinerator (6.1-m ID freeboard); no other mixing device was needed. All air permit requirements were met. Freeboard temperatures have averaged only 30°C above the bed temperature (a smaller difference than was observed with oil firing).

Natural gas firing in the bed can be a problem from several standpoints: For good combustion of methane, the bed must be maintained above about 800°C. Also, the discharge of a jet of raw gas tends to overtax the air supply as the gas is swept upward and, often, a significant fraction of the heating value of the gas is released in the freeboard. Thus, when gas is the preferred fuel, it is generally best to consider gas firing of the windbox (to its temperature limits).

Because of the good sludge burnout effected by the FB, boilers can be added without undue risk of fouling. Steam is used in many plants to drive the forced draft fan, the induced draft fan, and/or the feedwater pumps or for general plant hot water, heating, etc. Consideration must be given to reducing the gas velocity in the boiler-tube banks to control erosion. In some plants, boilers are used in addition to the hot windbox design to cool the gases to approximately 260°C prior to an electrostatic precipitator for particulate control.

Boiler-tube surface can also be incorporated into the walls or tube U-bends inserted into the bubbling bed as a means of controlling bed temperature. Clearly, as the level of dewatering increases, the flame temperature will increase until, at some point, there is a risk of defluidization. Also, high bed temperatures (say, >875°C) are undesirable due to the excessive volatilization of heavy metals (especially cadmium, arsenic, lead, etc.). In such circumstances or when burning any fuel with a high flame temperature, one can consider the use of bed tubes to moderate temperatures.

In some circumstances, economic analysis has shown that the economic benefits of reduced or even zero (autogenous combustion) fuel use can be most cost effectively obtained by thermal drying of the sludge prior to incineration (rather than by upgrading dewatering facilities). Such systems use a boiler to recover heat from the fluid bed off-gas. The steam is then passed to an indirect dryer system. Several dryer types are available, but all have the characteristic that the feed sludge to the dryer should be about 60% to 65% solids. At this level of dryness, the rheological characteristics of the sludge are similar to damp sawdust or earth. If the sludge is fed at, say, 30% solids, there is a region in the dryer where the sludge moisture content ranges between 40% and 55% solids. In this range, the sludge may become very sticky and viscous. Then it adheres to the heating surfaces (reducing the heat transfer rate) and greatly increases the shaft power requirement. To resolve this problem, a portion of the dried sludge can be recycled and blended with the freshly dewatered sludge to develop the 60% to 65% solids feedstock.

In broad terms, the heat balance in the fluid bed defines the size of the unit. This is shown in the general capacity data in Tables 9 and 10.

2. Bed Solids and Bed Defluidization

a. Bed Solids. In some systems, the majority of the bed material is purchased, graded sand. The maximum superficial space velocity in the bed (the gas velocity calculated from

Table 9 Nominal Capacity of Bubbling Fluid Bed Incinerators

Reactor diameter (m)	Cold windbox heat release (10^6 kcal/hr)	Hot windbox (*) water evaporation (kg/hr)
3.05	2.420	1,590
4.25	4.760	3,068
5.5	7.890	5,045
6.7	11.590	7,545
7.6	15.195	9,727
8.5	19.075	12,182

*Preheat to 540°C.
Source: From (334).

Table 10 Unit Capacity For Fluid Bed Sludge Incinerators

Sludge percent solids	kg H_2O per m^2/hr*	kcal per m^2/hr*	Heat from sludge (%)	Heat from fuel (%)	Heat from preheated air (%)
Cold windbox					
12	230	530,000	21	79	N/A
20	245	538,400	40	60	N/A
25	264	549,800	72	28	N/A
28	269	552,500	100	0	N/A
Hot windbox					
12	367	671,000	26	54	20
20	382	678,100	49	31	20
25	391	685,100	66	14	20
28	406	692,500	80	0	20

*Based on the cross-sectional area of the construction plate (the bottom of the bed).
Source: From (400).

the open bed diameter and with cognizance of the temperature and static pressure) increases as the mean particle size increases. A common sludge incineration sand uses 10 to 80 mesh alumina or ceramic material. With biological sludges, sand replacement rates vary with the rate of "inherent makeup" from the sludge itself, but a rate of 1% per day is common. If grit is burned along with the sludge, there may be an accumulation of solids in the bed such that solids removal is required from time to time. Most plants include a pneumatic sand makeup system as well as a bed drain.

The slumped bed depth ranges from 0.8 to 1 m deep and undergoes an expansion by 80% to 100% during fluidization. The size of solids that may be fluidized varies from less than 1 μm to 10 cm, with the best (most uniform) operation for particles between 10 and 250 μm. A range of particles is preferred. Mono-disperse (narrow d_p range) beds with large particles are prone to slugging and can have poor top-to-bottom circulation. This results in increased elutriation of incompletely burned solids, higher freeboard burning, and, potentially, greater fuel use.

A particle will remain in the bed as long as the gas flow rate is less than the terminal velocity of the particle as given by

$$U_t = \frac{4g(\rho_p - \rho_g)d_p}{3\rho_g C_x} \tag{6}$$

where

U_t = terminal velocity (the minimum fluidizing velocity)
g = gravitational constant
ρ_p = density of particle
ρ_g = density of the gas (varies with temperature and pressure)
d_p = particle diameter
C_x = drag coefficient (a dimensionless constant that is a function of the particle shape and Reynolds number based on particle dimensions. See Eq. 2 of Chapter 13 and Chapter 13, Section I.A.3.a.).

The lowest operating velocity for sludge incineration beds begins at about $1.2U_t$ but ranges to as much as $2U_t$ to $10U_t$ (343). Conservative sludge bed designs are based on a space velocity (based on freeboard diameter) between 0.8 and 0.9 m/sec, which corresponds to a maximum heat release between 350,000 and 500,000 kcal/h/m^2. Some vendors recommend higher velocities to increase heat release rate (reducing capital cost). As the velocities increase, however, sand losses increase, fluidization may become unstable, and the potential for increased freeboard burning increases.

The materials chosen for the bed sand are selected in view of their resistance to abrasion and melting temperature and, of course, cost. In recent years, some concern has been expressed regarding the potentially adverse health effects on plant personnel of silica-containing sand. Alternatives are readily available, however. Sand replacement rates vary depending on the degree that the inert solids in the feed contribute useful bed material. Typical makeup rates approximate one percent per week.

b. Bed Defluidization. Bed defluidization is a critical failure mode in FBs. The characteristics of the problem are obvious: The bed temperature rises such that the bed sand reaches a condition of incipient fusion. The resulting stickiness of the sand particles leads to agglomeration and, rapidly, to solidification of the bed. Tests of sludge ash residues using differential thermal analysis methods (151) or by placing the residue in combustion boats and holding the mass at progressively higher temperatures in a muffle furnace will help to identify the conditions where clinker formation is likely. Also, the "initial deformation temperature" in the ASTM Ash Fusion Temperature test (with, perhaps, a safety factor of at least 100°C) can be used to anticipate this type of problem.

Although defluidization is driven by a physical phenomena (melting), the cause and control often derive from the chemistry of the ash. The sludge ash components of particular importance in producing low-melting compounds or eutectics include iron, potassium, sodium, phosphorous, and the chloride and sulfate anions. Biological or chemical treatment that fixes phosphorous and potassium compounds in the sludge biosolids can exacerbate ash fusion problems.

For example, some wastewater treatment plants add soluble ferric compounds (e.g., ferric chloride) at the plant headworks for the removal of phosphates according to

$$PO_4^{-3} + Fe^{+3} \rightarrow \underline{FePO_4}$$

As the weight fraction of the ferric phosphate precipitate in the total sludge ash increases, the ash fusion temperature decreases. In some plants, this has caused bed defluidization. The resolution of this problem came through addition of calcium values (as lime) to the sludge such that the total overall iron-to-calcium ratio became at least equal to the proportions given by

$$3Ca^{+2} + \underline{2FePO_4} \rightarrow \underline{Ca_3(PO_4)_2} + 2Fe^{+3}$$

Reaction of the lime with the ferric phosphate occurs in the bed (i.e., the lime could be added as late as the dewatering step). Thus, lime addition need not be made (at substantially higher cost) earlier in the plant in the dilute wastewater.

Another defluidization and slagging problem can occur when high concentrations of alkali metal salts are found in the sludge (226). This occurs, for example, in neutral sulfite semi-chemical (NSSC) waste liquor from paper mills or for petroleum refinery sludge where the salt content in the crude is high. In these circumstances, defluidization problems arise both from eutectics of the alkali metal salts and, also, with silica bed sands, from the

formation of very sticky, viscous, sodium-silicate glasses. For example, the combination of silica, sodium chloride, and water vapor from the bed will react:

$$3SiO_2 + 2NaCl + H_2O \rightarrow Na_2O{\cdot}3SiO_2 + 2HCl$$

Similarly, for potassium chloride:

$$3SiO_2 + 2KCl + H_2O \rightarrow K_2O{\cdot}3SiO_2 + 2HCl$$

Some of the sodium oxide–silica mixtures have melting points as low as 635°C. The ash fusion characteristics of alkali metal salts are discussed further in Chapter 4, and fusion point data are reported in Table 4 of that chapter.

METAL OXIDES FOR DEFLUIDIZATION CONTROL. Metal oxides such as CaO, Fe_2O_3, and Al_2O_3 can convert the low-melting silicate glasses into high-melting compounds (476). These metal oxides can be used to devitrify glasses after a duct or freeboard buildup problem has occurred. For example, the sodium glass noted above reacts with lime as follows:

$$Na_2O{\cdot}3SiO_2 + 3CaO + 3SiO_2 \rightarrow Na_2O{\cdot}3CaO{\cdot}6SiO_2$$

When excess silica is absent, the following reaction occurs:

$$Na_2O{\cdot}3SiO_2 + 2CaO \rightarrow Na_2O{\cdot}2CaO{\cdot}3SiO_2$$

Both of these complex products melt above 1000°C, which is usually considerably above the fluid bed operating temperature. If lime presents problems (e.g., scale in a Venturi scrubber or hygroscopic clumping in a bag filter), finely divided iron oxide or alumina also can neutralize alkali silicate glasses by the reactions

$$Na_2O{\cdot}3SiO_2 + Fe_2O_3 + SiO_2 \rightarrow Na_2O{\cdot}Fe_2O_3{\cdot}4SiO_2$$

$$Na_2O{\cdot}3SiO_2 + Al_2O_3 + 3SiO_2 \rightarrow Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$$

The iron-based product (acmite) has a melting point of 955°C and the aluminum product (albite) a melting point of 1118°C.

Problems with phosphorous eutectics have also been addressed with additives (338). For example, in the presence of calcium chloride, ferric phosphate will react at only 815°C to form calcium phosphate as a solid (s) and release ferric chloride as gas (g) at these temperatures:

$$2FePO_4(s) + 3CaCl_2(s) \rightarrow Ca_3(PO_4)_2(s) + 2FeCl_3(g)$$

The ferric chloride reacts with water vapor to form specular hematite and releases HCl:

$$2FeCl_3(g) + 3H_2O(g) \rightarrow Fe_2O_3(s) + 6HCl(g)$$

The hematite can form scales and layers of red deposits on the dome of the fluidized bed system. Lime can be used to avoid this scaling problem by mixing lime with the feed sludge, converting iron phosphate to iron hydroxide and calcium phosphate in the feed hopper. It has been shown that 2.71 kg of lime (100% soluble CaO basis) are needed per kg of soluble phosphorous. Note that lime values (as soluble calcium) in the sludge act to reduce the requirement for added lime. The reaction proceeds according to

$$2FePO_4(s) + 3Ca(OH)_2(s) \rightarrow Ca_3(PO_4)_2(s) + 2Fe(OH)_3(s)$$

In the fluid bed, at temperatures of 800°C, the hydroxide dehydrates according to

$$2Fe(OH)_3(s) \rightarrow Fe_2O_3(s) + 3H_2O(g)$$

The dehydration occurs in the bed, and therefore gaseous ferric chloride is not formed and the hematite scale does not form.

CLAY (KAOLIN) FOR DEFLUIDIZATION CONTROL. Kaolin clay (a natural mixture of hydrous aluminum silicates) has been used to prevent glassification or bed defluidization before the problem occurs by neutralizing the alkali salts before a low-melting mixture forms. The kaolin, ground very finely and well-mixed with the feed sludge, reacts to form mixed, high-melting sodium–potassium aluminum silicate compounds (226, 337) with a much higher melting point. The reaction sequence is as follows:

First, the kaolin clay dehydrates according to

$$Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O \rightarrow Al_2O_3{\cdot}2SiO_2 + 2H_2O$$

The dehydrated clay neutralizes sodium (or potassium) chloride by forming nepheline (melting point 1526°C) and releasing HCl according to

$$Al_2O_3{\cdot}2SiO_2 + 2NaCl + H_2O \rightarrow Na_2O{\cdot}Al_2O_3{\cdot}2SiO_2 + 2HCl$$

If Na_2SO_4 is present in the bed, it also reacts with the clay to form nepheline but releasing oxygen and SO_2 according to

$$Al_2O_3{\cdot}2SiO_2 + Na_2SO_4 \rightarrow Na_2O{\cdot}Al_2O_3{\cdot}2SiO_2 + SO_2 + \tfrac{1}{2}O_2$$

When using kaolin to neutralize sodium and potassium, the clay is added at a kaolin-to-alkali weight ratio of 5.6 and 3.3, respectively, based on the soluble portion of the alkali metals. In this calculation, one must determine the percent purity of the clay (often about 90%) and, prudently, allow a 25% to 30% safety margin. These rates assume that there is no aluminum and silicon in the sludge. If these elements are present (and they often are), the clay dose can be reduced in proportion. In most cases, silica is present in excess, so for every kilogram of alumina (Al_2O_3) in the dry sludge solids, 258/54 or 4.78 kg less kaolin are needed (476).

BED TEMPERATURE FOR DEFLUIDIZATION CONTROL. An alternative strategy to deal with defluidization is strict temperature control. This approach has been used with the sludges from some petroleum refineries burning API separator sludge, water–oil emulsions from slop-oil recovery, tank cleanings and flotation clarifier sludges from wastewater treatment, low-strength caustic, and other waste liquids. Bed temperatures were maintained at only 720°C and, other than a slow buildup of soft ash on the heat exchanger tubes (hot windbox design), operation has been acceptable. A similar approach for spent NSSC liquor has proven successful by controlling bed temperature and limiting waste chloride content (226).

3. The Distribution Plate

The distribution plate (227) serves several functions, the most important of which is the uniform distribution of the combustion air over the entire bed. The plate includes an array of tuyers (the metal devices that penetrate the distribution plate and pass the combustion air from the windbox to the active bed). The tuyers are fabricated in several designs but have the common characteristic that when the bed is either active or shut down (slumping), the sand does not drain into the windbox. The pressure ratio across the tuyers varies from 10 : 1 to 3 : 1, with the higher ratios providing the greatest degree of uniformity in flow throughout the furnace. Common pressure drop ranges between 0.035 and 0.055 atm.

4. Sludge Feed

Sludge feed systems have been designed to inject the sludge into the bed, to drop the sludge onto the bed from the freeboard dome, or to cast out the sludge over and into the bed from strategically located sidewall locations. In general, feed systems are chosen on the basis of the solids content of the waste stream. Each approach presents certain advantages and disadvantages.

a. Bed Injection. Direct injection into the bed was the dominant approach used in the early days of FB sludge incineration and remains the preference in the United States. From 1960 to 1970, most of the sludge was dewatered using centrifuges or vacuum filters and, at best, was a comparatively liquid 16% to 18% solids. The injectors were, in essence, shallow flight screw extruders that forced the sludge into the bed against a back pressure of 0.1 to 0.2 atm. The high moisture content of the sludge helped to cool the barrel of the injectors, but there was only a modest extension of the injector pipe into the bed in most cases.

In the late 1970s, improved dewatering led to abrasion problems with the screw injectors. Also, the reduced moisture content gave little leeway before an injector that had stopped for even a short period was almost solidified. The same time period saw the development of high-pressure, piston sludge pumps that could handle stiff sludge (over 35% solids). Although these pumps are costly, they are a reliable means to introduce the sludge, feed at a steady and controlled rate, and provide considerable design and layout flexibility.

The injection of sludge at a given point in the sidewall leads to a measure of "focus" of the heat demand for the evaporation of moisture in the bed sector above the injection point. As the feed rate increases, eventually the sector becomes overloaded and a portion of the combustion heat release moves to the freeboard. A useful design basis suggests that for a freeboard temperature of 815°C, there should be one feed point for each 1,130 kg of feed water. For a freeboard working temperature of 925°C, there should be about one feed point for each 2,275 kg of feed water.

b. Freeboard Injection. An alternative feed method used in the early days involved injection of the sludge at the roof of the freeboard dome. The sludge fell against the rising bed gases and into the bed. This approach was low in cost and simple and worked well when the sludge was wet. However, as the sludge moisture dropped, the surface of the sludge "chunk" falling through the freeboard dried enough to flash off greases and oils and to allow a portion of the volatile combustion to occur in the freeboard. Freeboard temperatures rose. This acted to starve the bed of heat. Compensating fuel firing in the bed raised freeboard temperatures even more. Bed defluidization became a continuing threat. Few U.S. plants are operated with feed injection through the freeboard, although this approach is preferred in Europe.

c. Sidewall Chute or Rotary Vane Feeders. When the furnace diameter exceeds 5 to 6 m, one must be increasingly concerned with the effective use of the entire bed volume if conventional design practice is followed and all of the sludge is fed from the wall. The use of long, cantilevered feed points is conceptually feasible but presents structural problems at high bed temperatures and requires uninterrupted cooling for survival.

For very large beds where one wishes to inject at least some portion of the feed sludge deep into the bed and one has a highly dewatered sludge, an alternative feeding strategy can be used involving the use of a "flinger" feeder. The flinger, a device similar to

a mechanical spreader stoker, is then mounted at the balance point just above the top of the expanded bed. These feed devices can easily cast the sludge 3 to 5 m into the center of the bed. This device can also be used to feed other relatively dry materials such as screenings, grit, and other irregular or abrasive material that is not compatible with a pump feed.

With a flinger or with a gravity chute, the fluid bed should be designed with both forced and induced draft fans to define a plane at, say, one meter above the top of the expanded bed that can be held at atmospheric pressure (see below). An opening for a gravity chute or a flinger-type feeder can then be made without undue concern for either blowout of furnace gases or unreasonable in-leakage of cold air.

5. Air Supply and Flow Balance

Air at 0.2 to 0.35 atm is forced into the windbox and passes into the cylindrical furnace through a refractory or refractory-lined "distribution plate" or "constriction plate." The pressure drop across the distribution plate and sand bed is about 0.15 atm, and the remainder of the total static pressure provides for the exhaust gas treatment (scrubber) system. Initially, the sand bed rests on the distribution plate. As the rate of air flow increases, the sand bed expands. The bed growth results in a density high enough that sludge will not float to the top of the bed, yet with insufficient air flow to blow the sand out of the reactor. Typically, the superficial air velocity at the bottom of the bed (based on the bed diameter and windbox temperature) is 0.5 to 1.0 m/sec. The air supply system is usually designed with a 10% to 15% safety factor. More detailed information on fluid bed design and operational characteristics may be found in (148–150, 343).

The general design regarding air supply and flue gas handling can be of two types: the push-through concept and the push-and-pull concept. For push-through, there is only one blower. This fan pushes the air into the system with sufficient static pressure to meet the distribution plate and scrubber pressure drop requirements and to accommodate the duct pressure drop and discharge kinetic energy. With this approach, the static pressure in the ductwork is above atmospheric at all points.

In the push-and-pull concept, the combustion air is provided with one blower and an induced draft fan is provided after the scrubber. With this system, the static pressure in the ductwork can be controlled to meet special needs. These can include a neutral point where the internal static pressure is just balanced with atmospheric pressure (useful at an injection point for solids). Also, since the ductwork is generally all below atmospheric pressure, there is no discharge of dust through small holes, at imperfectly sealed hatches, etc.

6. Combustion Air Preheat

To improve energy economy, recent designs often include a combustion air preheater. If only a modest amount of preheat is required, the energy for preheat can come from steam heating coils (the "warm windbox design"). This approach is useful to achieve preheat levels up to 175°C. Ideally, the steam is supplied from a boiler fitted to the FB.

When higher levels of preheat are required, air from the combustion air blower is passed on the shell side of a stainless steel shell and tube heat exchanger to preheat it prior to introduction to the windbox. Flue gases from the furnace are passed through the tube side. Typically, the tube diameter is about 75 cm and gas velocities range from 30 to 40 m/sec. With this technique, preheat levels of up to 650°C are reliably achievable. The heat exchanger used in this service is of special design and is fabricated of carefully selected materials; often high-nickel alloys such as Alloy 625. The expansion joints on the

tubes must work over a wide temperature range and under moist, abrasive conditions. The heat exchanger is the most vulnerable device in the incineration train and is critical to system availability. This piece of equipment is not the place to save money. Even with sound design, replacement of the expansion joints (the weak link) should be expected at five-year intervals. Complete tube bundle replacement every 10 years is normal.

Preheating the combustion air makes significant demands on the design of the windbox. The plenum, the distribution plate, and the supporting structure are simple for cold windbox FB systems. However, increasing the air temperature demands careful design to provide adequate structural strength and to compensate for the significant thermal expansion. Some vendors use proprietary refractory arch designs to achieve these ends. Others use metal ducts to service the tuyers and run with a relatively cold backside to the distribution plate. Both techniques are satisfactory although they generate different capital and operating cost tradeoff scenarios.

7. The Freeboard

The freeboard is a relatively simple, cylindrical chamber. Functionally, however, the freeboard volume is very important to incinerator performance. Most important, the freeboard provides the residence time for ultimate burnout of the combustible matter (both in the gaseous flow and in the solid particulate). The freeboard provides 4 to 6 sec of residence time in many designs, sufficient for complete burnout of almost all organic material. This accounts for the low carbon monoxide and hydrocarbon pollutant emission from the FB and for the low percent combustible in the fly ash.

The diameter of the freeboard bears a relationship to the constriction plate diameter. However, since more water is evaporated per unit volume of air in a hot windbox unit, the constriction-plate-to-freeboard-area ratios are different for the two configurations. The specifics vary between incinerator manufacturers, but common ratios would be 1.66 for the cold windbox design and 1.86 for the hot windbox.

When the material being burned has an exceptionally high volatile content or the degree of burnout must be exceptionally high (as in hazardous waste incineration applications), it may be desirable to incorporate overfire jets in the freeboard to stimulate mixing and, in some cases, to add additional air. The jets can use steam or air for this purpose. Some designs use two levels of jets. The lower bank uses jets aimed at an angle such as to induce, say, a clockwise flow. The upper bank jets are aimed to induce a counterrotating flow so the net swirl effect is null but vigorous mixing is induced. The mass addition in these jets should be minimized to avoid chilling the combustion gas flow.

C. Operating Characteristics

The FB furnace is stable in operation. Commonly, oxygen instrumentation is used to adjust fuel feed to maintain a relatively constant excess air level and bed temperature. Because of the simple refractory design, furnace maintenance costs are low. Maintenance problems with the heat exchanger used in the hot windbox design have been experienced due to thermal stresses and fouling. In general, these problems can be handled with proper design and operation (especially avoidance of excessive temperatures).

Electrical usage by the fluid bed is high due to the energy used in the high-pressure fluidizing blower. Typical power usage is summarized graphically in Fig. 4.

As sludge burns out in the bed, the finer ash particles are swept from the bed. As a consequence, highly efficient air pollution control devices should be used with these units.

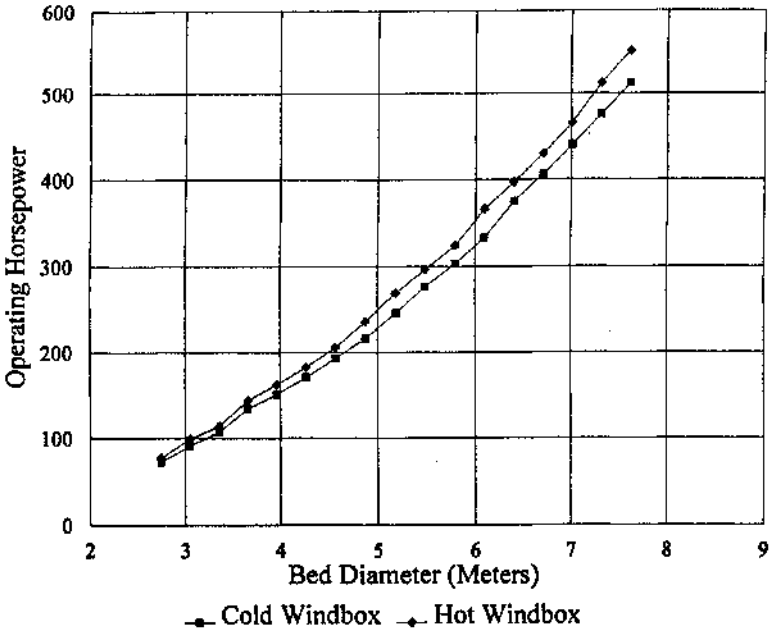


Figure 4 Typical power usage in a fluid bed incinerator.

The coarser particles in the sludge residue accumulate in the bed. On balance, however, there is often a net loss in the sand bed due to abrasion and disintegration such that periodic sand addition is required. Accumulation of bed solids may occur, however, and means for withdrawal of material should be provided. Generally, only a simple downcomer is needed to drain bed solids. Data on the particle-size distribution of the fly ash elutriated from fluid bed incinerators burning domestic wastewater treatment sludge are given in Table 11.

Problem areas with fluid beds for sewage sludge or other liquid or sludge waste disposal center in two areas:

Control of the temperature throughout the bed and flues
Clinker (slag) formation

The former problem is particularly serious if the waste is fed into the freeboard. If continuous or periodic ignition occurs in this area (where mixing is very imperfect), overheating of regions of the flue may occur, causing slag buildup and necessitating shutdown. Problems with bed defluidization are serious and, if not resolved, render continuing operation of the FB problematical. Often, additive approaches have been successful, though at a cost for both the additive and increased residue disposal.

An unexpected problem can occur when firing natural gas through a lance to make up for energy deficiencies. In this instance, the natural gas appears to accelerate rapidly to the surrounding gas velocity, and thereafter mixing stops. Consequently, the gas passes up through the bed and, ultimately, burns in the freeboard: not where the energy release was needed.

Table 11 Particle-Size Distribution of Fluid Bed Sludge Incinerator Fly Ash

Median diameter (μ)	Weight percent in indicated size range						
	Poughkeepsie, NY	Somerset-Raritan Valley, NJ	Liberty, NY	Bayshore, NJ	Northwest Bergen County, NJ		
					Test 1	Test 2	Test 3
1.8	1.5	1.4	1.5	1.5	1.2	1.5	0.8
2.8	2.0	2.0	2.5	2.0	2.0	2.0	2.0
5.4	8.5	6.5	8.5	4.0	6.0	6.4	6.0
11.5	14.0	10.0	16.0	5.0	11.5	13.4	13.0
19.0	16.2	23.7	15.0	16.3	12.2	17.5	12.5
28.0	12.5	23.0	12.2	15.0	8.5	15.3	8.7
31.0	2.5	7.5	3.2	8.0	2.8	4.5	2.8
Residue	42.8	25.9	41.4	48.2	55.8	39.6	54.2
Total	100.0	100.0	100.3	100.0	101.0	102.2	103.0

Source: Courtesy of Dorr-Oliver, Inc. and participating communities.

Published data on the Hyperion plant performance in the starved-air mode have been limited as of this writing. However, it is reported that the performance of the FB portion of the plant has been very satisfactory. It should be noted, however, that the Hyperion FB is fed with dried sludge and, therefore, its behavior may be atypical. At Hyperion, pneumatic feeder problems have been noted with its dry (>95% solids) feed.

D. General Environmental Considerations

Because of the excellent mixing in the bed and the long residence times of gases in the freeboard, emissions of hydrocarbons and carbon monoxide from the FB are small. If excessive emission of hydrocarbons becomes a problem, addition of air jets in the freeboard is often effective in realizing acceptable burnout. Fluid beds have achieved 99.9994% DREs for toluene at a bed temperature of only 700°C due to the excellent mixing and long (8-sec) residence times. Trial burns of various fluid bed incinerators have met or exceeded 99.99% DRE targets for chlorobenzene, aniline, carbon tetrachloride, chloroform, cresol, para-dichlorobenzene, methyl methacrylate, perchloroethylene, phenol 1,1,1-trichloroethane, and other hazardous chemicals (334).

In most plants all of the sludge ash is emitted from the bed suspended in the flue gas. Thus, high-efficiency particulate control systems are necessary. The low bed temperatures of the FB allow the operator to avoid the heavy metal volatilization problem. Although most U.S. systems use the Venturi-tray scrubber system, many European plants, in combination with energy recovery in a boiler, have applied the electrostatic precipitator for particulate removal. Excellent particulate resistivity properties lead to a collection efficiency that meets or exceeds U.S. standards.

Data on the particle size of ash emitted from the furnace (402) indicate the following:

Diameter:	>50μ	>40μ	>30μ	>20μ
Cumulative %:	7–15	10–20	17–30	25–40
Diameter:	>10μ	>5μ	>2μ	
Cumulative %:	50–60	68–73	89–95	

Operation of the starved-air mode fluid bed in a two-stage manner with intermediate heat removal is very beneficial from an environmental viewpoint. As noted above, NO_x and heavy metal enrichment of fines (2) are minimized due to the low bed temperatures and the reducing gas environment. Also, the reducing environment would be expected to minimize chromium oxidation.

III. SLAGGING COMBUSTION SYSTEMS FOR BIOLOGICAL SLUDGE

Concern regarding the leaching of heavy metals from sludge ash has led to the development of several combustion systems wherein the sludge ash is heated beyond the point of fusion. Then, a glassy slag is formed. Leaching tests on the slag show limited to no solvation of metals. The Kubota Corporation of Osaka, Japan, drew on a furnace design developed at the Volkswagonwerks in the 1960s in Wolfsberg, Germany, to offer a "melting furnace" to achieve this functional behavior. Another Japanese firm, Itoh Takuma, uses a reciprocating grate furnace-boiler quite similar to those used for solid waste to achieve a similar endpoint.

A. Kubota System

The primary furnace used by Kubota makes use of a slowly rotating, refractory-lined cylindrical, cuplike chamber with an outlet tap in the center of the floor of the furnace (Fig. 5). The furnace is driven from the periphery. Mounted above the discharge tap is a fixed, relatively flat, refractory-lined, reverse-conical roof equipped with one or more down-firing burners. The feed of predried sludge (>85% solids) moves by gravity through the annulus between the roof and lower chamber into the cavity between the roof and the lower chamber. Movement of the sludge is "encouraged" by the slow rotation of the lower body. In the internal cavity, the burners, supplied with preheated air (about 85% of theoretical air overall), reduce the sludge to a molten slag. A portion of the combustion heat in the sludge solids is released by furnishing excess air (relative to the burner fuel requirements) through the burner ports. The size of the cavity may be adjusted to increase (larger cavity) or decrease (smaller cavity) the processing rate. The primary furnace cavity is maintained slightly substoichiometric. This produces maximum temperatures and minimizes the gas flow, thus reducing particle entrainment.

The molten slag and off-gas from the primary chamber flow down into a secondary combustion chamber. The slag continues to fall to a solidification area or directly into a water quench. Slow cooling favors crystal growth and forms a dense, obsidianlike black glass. Fast cooling in the water quench results in a granular black glass frit with poorer structural characteristics than the slow-cooled product. Addition of secondary air completes the combustion in the tunnel-type secondary chamber or afterburner.

The hot gases from the secondary are used to preheat the combustion air for the primary furnace (using a heat exchanger similar in design to the hot windbox fluid bed) and then are tempered and used in a direct contact tray or rotary dryer to dry the incoming sludge. Off-gas from the dryer is cleansed with an electrostatic precipitator, condenser, and scrubber.

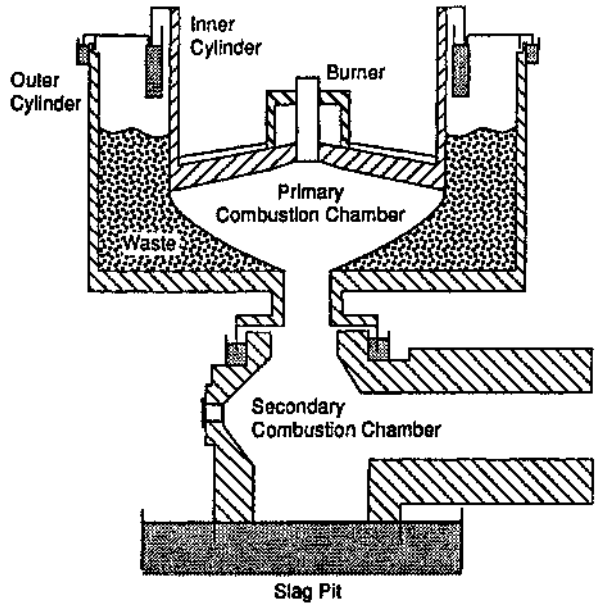


Figure 5 Kubota melting furnace.

The use of fossil fuel is minimized by the low overall excess air of the unit (10% to 30%). Temperatures in the primary furnace are maintained at approximately 1450°C for most sludge to yield acceptable sludge fluidity. Data indicate that acceptable long-term operation is possible. Several plants are now operating in Japan, the United States, and Germany using the Kubota melting process. The first plant came on-line in 1975. The furnace operation is stable, as seen from strip charts of temperature and gas composition.

The operation of the primary chamber substoichiometric greatly limits the formation of fuel-nitrogen NO_x. Net NO_x in the flue gases from several plants averaged 100 to 150 ppm. Although one might expect the high primary furnace temperatures to result in emission of heavy metals, data indicate that the majority of the metals are bound into the fluid slag that blankets the incoming sludge and do not show up as heightened metal emissions in the small particles.

The key environmental characteristic of the Kubota furnace is the ash, which exhibits essentially no leaching (below the detection limits by atomic absorption) for cadmium, chromium +6 and +3, arsenic, mercury, and lead. There was also no detection of PCBs or cyanide ion, although these species appear in the raw sludge. The slag formed has a specific gravity of 2.4 to 2.7 and appears useful as a clean fill or road bed material. Fuel requirements are modest, but the plant is complex, including dryers, several air cleansing systems, and a complex, high-temperature furnace and heat recovery system.

B. Itoh Takuma System

The Itoh Takuma system also requires a dried sludge feed (>85% solids), but the sludge is burned with controlled and limited air on a reciprocating grate. The grate is enclosed in a waterwall boiler with a configuration not unlike a refuse-fired incinerator. Steam raised in

the boiler is used to dry the sludge using an indirect dryer. The temperatures in the bed are high enough to sinter the sludge ash to produce a clinker similar in appearance to coal ash. Although the ash is not a true glass as is the Kubota product, the leaching characteristics are almost as good and the furnace system is of significantly lower cost and simplicity of operation.

10

Incineration Systems for Liquid and Gaseous Wastes

I. LIQUID WASTE INCINERATORS

In many industrial processes, waste liquids are produced for which disposal by incineration is effective, economical, and environmentally sound. Such waste liquids include wastewater contaminated with combustible toxic chemicals, solvents or oils for which purification costs are excessive, and heavy pitches and tars. Not all of these wastes fall into the category of "hazardous wastes," but it is noteworthy that the largest fraction of the U.S. hazardous waste incineration facilities involve liquid waste incinerators.

In many instances, waste liquids are burned as fuels in larger furnaces designed primarily for solids disposal. However, several incinerator designs have been developed for liquid firing alone. These furnaces are comprised of cylindrical chambers with atomized liquid and combustion air introduced axially or tangentially. Also, the fluid bed incinerators described in Chapter 9 may be used for liquid waste incineration.

A. Liquid Storage

Often liquid waste incinerators are operated only a fraction of the work week or day. Thus, tanks are required to hold the waste. The design of such containers and associated piping should include careful consideration of the following.

1. *Corrosive attack.* The liquids to be stored may range widely in chemical composition. The availability of an incineration system in a plant will often result in its use (and misuse) for waste streams perhaps not envisioned during design. The materials of construction of the storage tank, piping, valves, pumps, etc., should be selected with this in mind.

2. *Chemical reactions.* Particularly for incineration facilities serving complex or multiproduct chemical plants or for commercial incineration facilities, a wide variety of wastes may be sent to the incinerator system. In many cases, the exact composition is

unknown and the full range of possible reactions cannot be investigated. Reactions of concern include

Exothermic reactions that liberate enough heat to cause boiling, accelerate corrosion, etc.
Polymerization reactions that could solidify or turn the tank contents into an unpumpable gel
Gas-forming reactions that could cause foaming or otherwise force liquid out of the tank
Precipitation reactions that could produce unacceptably large quantities of solid sludge in the tank
Pyrophoric reactions that could result in spontaneous ignition of the tank contents.

3. *Phase separation.* Often various waste streams are immiscible or contain settlable solids. Upon setting, phase separation or settling can occur such that the incinerator will experience major changes in feed composition over a short time, an undesirable condition. Decanting systems, recirculating pumps, and/or agitation may resolve these problems.

4. *Abrasion.* The presence of solid phase in the wastes can cause rapid abrasion in pumps, valves, and piping.

5. *Freezing and/or viscosity increase.* Many wastes freeze or become viscous at ambient temperatures. In such cases heating of the containers and steam or electrical tracing of piping may be necessary to avoid freezeups or pumping problems.

6. *Vaporization.* Introduction of hot wastes into the storage tank may volatilize low-boiling compounds, sometimes explosively. Proper care in waste dumping and the installation of tank vents (with flame arresters) are appropriate countermeasures.

B. Atomization

Atomization is the process of physically breaking up a liquid into particles. Liquid wastes should be atomized so that the combustion air can quickly surround the surface of the droplets to produce a combustible mixture. Also, fine atomization speeds the rate of vaporization of the waste, a prerequisite for ignition and combustion.

A number of methods are available to effect the atomization of liquid wastes. They vary in their relative capital and operating cost, their maximum capacity (l/min), the proportion of combustion air to be supplied as secondary air, the range of operating rates (turndown) required, and the desired flame shape.

The minimum energy input requirements for atomization are determined by the viscosity of the waste at the atomization point. The kinematic viscosity (absolute viscosity/density) of the liquid is often used to characterize atomizer requirements. In the CGS system, the units of kinematic viscosity are cm^2/sec, or "stokes." For oils and other viscous liquids, the centistoke gives numerical values in the 0 to 100 range. The more common unit is based upon a determination of the kinematic viscosity by measurement of the time t (in seconds) of efflux of a fixed volume of fluid through a

short standard capillary tube. Commercial viscometers are designed to obey the empirical relationship

$$v = a_1 - \frac{a_2}{t} \text{ cm}^2/\text{sec (stokes)} \tag{1a}$$

$$t = \frac{v}{2a_1} + \left[\left(\frac{v}{2a_1}\right)^2 + a_2\right]^{1/2} \tag{1b}$$

For a common viscometer (4):

Viscometer	a_1	a_2
Saybolt Universal (SSU)	0.0022	1.8
Redwood No. 1	0.0026	1.72
Redwood No. 2 (Admirality)	0.027	20
Engler	0.00147	3.74

It is also useful to recognize that, for many liquids, a plot of absolute viscosity versus absolute temperature on log-log paper is, essentially, a straight line.

EXAMPLE 1. Measurements of the kinematic viscosity of a waste oil indicate 200 SSU at 99°C and 400 SSU at 83°C. The specific gravity of the oil in this temperature range is 1.02. To what temperature should the oil be heated to have a kinematic viscosity of 85 SSU, the viscosity recommended for atomization?

From Eq. (1a), the kinematic and absolute viscosities corresponding to the Saybolt Universal determinations are:

	SSU	Centistokes	Centipoises
at 99°C (372°K)	200	43.1	44.0
at 83°C (356°K)	400	87.6	89.3

The objective is to find the temperature where the oil has a viscosity of 85 SSU, which corresponds to $v = 16.58$ or $\mu = 16.91$. Plotting μ versus absolute temperature on log-log paper gives the result 122°C.

The droplet size formed through pneumatic atomization is important as it strongly affects the flame length and heat release patterns in the incinerator. Consequently, several investigators have analyzed the atomization process. Calvert considered the atomization process as one where the bulk flow shattered at a critical value of the Weber number he suggested to be about 12. The Weber number is a dimensionless ratio of momentum to surface tension forces given by

$$N_{\text{We}} = \frac{\rho_g V_r^2 d}{2\sigma} \tag{2}$$

where

ρ_g = density of the gas
V_r = velocity of the gas stream relative to the droplet
d = droplet diameter
σ = surface tension

A discussion by Murty (348) noted the utility of the following upper-limit function (351) to describe the distribution (symmetrical about the axis $y = 0$) of droplet volume in a stream sprayed from a pressure nozzle:

$$\frac{dV}{dy} = \frac{\delta}{\sqrt{\pi}} e^{-\delta^2 y^2} \tag{3}$$

where

V = volume of the fraction of droplets with a diameter x
$y = \ln[ax/(x_m - x)]$ with "a" as found by experiment (352) = 0.8803
x_m = maximum drop diameter (m)
δ = measure of deviation and found by experiment (352) = 0.8739

Given the symmetry about $y = 0$ and the fact that the median-volume diameter (x_{mvd} = the diameter corresponding to 50% of the total droplet volume) corresponds to the value of x at $y = 0$, we thus have

$$x_{\text{mvd}} = \frac{x_m}{1 + a} = \frac{x_m}{1.8803} \tag{4}$$

To find x_{mvd}, we substitute the maximum drop diameter from the following expression (353), giving

$$\frac{x_m}{D} = 57\left[\frac{\rho v D}{\mu}\right]^{-0.48}\left[\frac{\mu v}{\sigma}\right]^{-0.18} \tag{5}$$

where

ρ = density of dispersed liquid (kg/m^3)
μ = absolute viscosity of dispersed liquid (kg/m sec)
σ = surface tension of dispersed liquid (N/m)
v = drop velocity at nozzle exit (m/sec)
D = nozzle orifice diameter (m)

From this correlation, we can estimate the Sauter mean diameter (volume-surface mean diameter) as 85% of x_{mvd}.

1. Low-Pressure Air Atomization

These burners require air at 0.035 to 0.35 atm, usually supplied by blowers. The minimum air pressure requirements (energy cost) are determined by the viscosity of the liquid to be atomized. A heavy pitch with a viscosity (heated) of 80 to 90 SSU requires air over 0.1 atm, whereas aqueous wastes can be atomized at 0.035 atm. Usually, the waste liquid is pumped to a pressure of 0.3 to 1.2 atm. Turndown for these burners range from 3 : 1 up to 6 : 1. The air used for atomization ranges between 2.8 and 7.4 m^3/l, with less air required as the air pressure increases. The resultant flame is comparatively short as, even for a pure fuel oil, about 40% of the stoichiometric air is intimately mixed with the fuel spray as the mixture enters the furnace.

2. High-Pressure Air or Steam Atomization

These burners require air or steam at pressures in excess of 2 atm and often to 10 atm. Atomizing air consumption ranges from 0.6 to 1.6 m^3 air/l of waste as the supply pressure varies over this range. Steam requirements range from 0.25 to 0.5 kg/l with careful

operation (a wasteful operator may use up to 1 kg/ l). Waste heating to reduce viscosity is required only to the extent needed for pumpability.

In general, high-pressure atomizing burners show poor turndown (3 : 1 or 4 : 1) and consume considerable compressor energy or steam (typically, for boilers, about 2% of the steam output). Since only a small fraction of the stoichiometric air or a inert gas (when steam is used) is mixed with the emerging fuel spray, flames from these burners are relatively long.

In burning high-carbon pitches and tars, the addition of steam has been shown to reduce the tendency for soot formation. This apparently results from the enhanced concentration of hydroxyl radicals, which act as vigorous oxidants with the unsaturated carbon radicals, which are precursors to soot.

3. Mechanical Atomization

These burners atomize by forcing the liquid, under high pressure (5 to 20 atm), through a fixed orifice. The result is a conical spray into which combustion air is drawn. In its simplest embodiment, the waste is fed directly to a nozzle. With such an arrangement, turndown is limited to 2.5 to 3.5 : 1, since, for example, a 75% reduction in pressure (atomization energy) is required to reduce the flow rate by 50%. Thus, atomization effectiveness (droplet fineness) drops rapidly as the burner moves off the design flow rate.

The second type of mechanical atomizing nozzle incorporates a return flow such that a much smaller change in atomization pressure is needed to effect a change in flow rate. For these atomizers, turndown can be as great as 10 : 1. The viscosity of fluids atomized mechanically need not be as low as that for low-pressure air atomization: 150 SSU is a typical design value.

The flame from mechanical atomizing burners is usually short, bushy, and of low velocity. The half-angle of the flame can be altered somewhat by changing the atomizing nozzle but, because all the air is provided by secondary means, combustion is not as rapid as with other types of burners, and a larger combustion space is usually required.

Mechanical atomizing burners are usually applied where large peak capacities (40–4000 l/hr) are required and where large turndown ratios are desirable. Its capital cost is higher than for other designs, but subsequent operating costs are low. In waste-burning applications, consideration must be given to the problems of erosion and plugging of small orifices due to solid matter in the waste stream.

4. Rotary Cup Atomization

These burners atomize by the action of a high-speed rotating conical metal cup from the outer edge of which the waste liquid is thrown into a stream of low-pressure air entering the incinerator around the cup. The rotary cup is usually attached to an extension of the low-pressure centrifugal blower shaft, and the waste liquid is delivered to the cup at low pressure through the shaft or at the side of the cup at its inner edges. Hinze and Milborn have extensively studied the atomization process in rotary cup devices (405) and offer several design and process correlations.

Since the rotary cup system has little requirement for fluid pressurization, it is ideal for waste-burning applications where the solids content of the waste is high. Also, the viscosity of the waste need only be reduced to 150 to 330 SSU. Turn-down is about 5 : 1, and burners with capacities from 4 to 1000 l/hr are available.

The flame shape from rotary cup burners is similar to that from mechanical atomizing burners, but with a somewhat increased combustion rate since a portion of the combustion air is supplied with the waste stream.

5. Secondary Atomization

Secondary atomization involves the introduction of a volatile component into a waste stream. When droplets of the mixture are heated as they enter the combustion space, the volatile component flashes. The sudden release of vapor shatters the droplet, thereby improving atomization quality. The enhanced atomization can be especially useful when the waste is unusually viscous or contains solids or when erosion or plugging has somewhat degraded nozzle performance such that atomization has become the limiting factor in achieving or maintaining the target DRE. Note that secondary atomization may already be inherent in a given system due to the normal range of volatilities found in the waste.

This technique was demonstrated in atomization and combustion tests to be effective (322) in improving atomization effectiveness and achieving an enhanced DRE of a test material (No. 2 fuel oil). The dopants used and their boiling points were dichloromethane (39°C), acrylonitrile (79°C), benzene (80°C), isopropanol (82°C), and benzal chloride (205°C). These represented a wide range of volatility relative to the No. 2 oil (210–260°C). It was found that the onset of secondary atomization was not simply related to boiling point in that isopropanol was, by far, the dopant that gave the greatest enhancement to atomization at the lowest concentration in the base "waste." The intensity of secondary atomization was dependent on the dopant concentration. For most dopants, secondary atomization was active only at a concentration above 2%. Isopropanol showed activity at only 0.5%.

Combustor tests were made (322) with isopropanol (high-effect dopant) and benzal chloride (low-effect dopant) under conditions where atomization effectiveness was limiting on DRE. The results showed the following:

	Fraction of waste undestroyed	
Weight fraction in mixture	Isopropanol	Benzal chloride
0.5%	1.8×10^{-3}	2.5×10^{-2}
2.0%	2.5×10^{-5}	1.2×10^{-2}
10.0%	Nondetect	1.7×10^{-3}

C. Ignition Tiles

In order to ensure rapid ignition of the waste-air spray, a refractory block or "ignition tile" is used. The tile usually consists of a conical depression with an opening at the small end of the cone which mates to the atomizing burner. Its objective is to facilitate lighting, maintain ignition under all normal conditions, and confine the air introduced by the burner so that it will be properly mixed with the vaporizing waste. Its design affects the shape of the flame and the quantity of air that can be induced by the burner.

When the heat content of the waste is low or when the combustion chamber temperatures are too low to secure complete combustion, a refractory tunnel extension is

often added to the ignition tile, increasing the intensity of radiation (for waste vaporization). When wastes contain a substantial fusible ash content, special care must be given to the type and design of these tiles to avoid rapid fluxing losses and slag buildup.

D. Combustion Space

The combustor heat release volume requirement (kcal/m^3) depends on the combustibility of the waste and the mean furnace temperature. For difficult-to-burn wastes or low furnace temperatures, more volume is needed than for the reverse. Typical ranges are as follows:

Temperature (°C)	Combustion volume (kcal hr^{-1} m^{-3})
300–800	30,000–130,000
800–1100	130,000–350,000
1100–1400	350,000–500,000
1400–1650+	500,000–900,000

Flue areas should be chosen to balance the desire to minimize the infiltration of tramp air (i.e., keep furnace pressure elevated) and yet avoid pressurization of the furnace, which will inhibit the flow of needed combustion air. For systems operating such that 25% to 50% of the air is to be induced by natural draft, the total air supply approximates 20% excess, and furnace gas temperatures are about 1000°C; approximately 0.25 m^2 per million kcal/hr heat release is a typical design point. If all of the air is supplied by forced draft, one-half this flue area is typical. However, it should be recognized that a large number of variables are involved in such determinations, and a careful analysis of furnace flow dynamics is appropriate prior to setting flue dimensions.

The penetration of the liquid jet into the combustion chamber has been studied extensively. Ingebo (404) showed that the penetration depended on the Weber number [Eq. (2)] and the Reynold's number and on the liquid-to-gas velocity ratio. The maximum penetration distance $x_{\max}$ is related to the maximum droplet diameter $d_{\max}$ by

$$\frac{x_{\max}}{d_{\max}} = 0.08 N_{\mathrm{Re}} N_{\mathrm{We}}^{-0.41} \left(\frac{V_g}{V_L}\right)^{0.29} \tag{7}$$

It should be noted, however, that this relationship does not take into account the combustion process (including the transition, above a critical gas velocity, from a diffusion flame all around the droplet to a "wake flame"). In the wake flame scenario, the flame envelope is stripped from the droplet and combustion occurs in the wake behind the droplet (405).

On the other hand, for volatile fuels, most droplets do not burn individually but rapidly evaporate and thereafter burn in a jet, much as a gas diffusion flame. This was proven in experiments conducted with light distillate (406) and heavy (407) fuel oil.

The combustion time (t_b in sec) for droplets of hydrocarbon liquid of a molecular weight MW_i, a minimum size of 30 μm, and a velocity equal to that of the gas may be computed as follows (153):

$$t_b = \left(\frac{29{,}800}{P_{\mathrm{O2}}}\right) \mathrm{MW}_i T^{-1.75} d_0^2 \tag{8}$$

where

P_{O2} = partial pressure of oxygen in the ambient (atm)
T = furnace temperature (K)
d_0 = the original droplet diameter (cm)

E. Incinerator Types

Incinerators for liquids are typically comprised of simple cylindrical, refractory-lined chambers.

1. Axial or Side-Fired Nonswirling Type

In these units, the burner is mounted either on the axis or in the sidewall, firing along a radius. Such units are simple to design and construct although they are relatively inefficient in the use of combustion volume. For these systems, the lower combustion volume heat release rate parameters are appropriate. In essence, these units simply provide a hot refractory enclosure in which to burn wastes and collect the flue gases for pollution control.

In the design, special care should be given to realizing good turbulence levels to ensure that a large fraction of the combustion volume is utilized. To this end, high-pressure secondary air jets are appropriate. Care should also be given to evaluate the probable flame length (to avoid flame impingement).

2. Vortex Type

To increase the efficiency of utilization of combustion space, swirl burners or tangential entry designs are commonly used. In these systems, one of two designs is commonly used: the axial swirl burner or tangential inlet cyclonic designs. The design concepts for these systems are described in Chapter 6, Section I.B. In designs where there is concern regarding flame stability, a small, side-mounted burner is added and operated as the fuel-supervised burner, leaving the main burner as the mixing burner. This concept provides continuous ignition and flame stability.

II. INCINERATORS FOR GASES (AFTERBURNERS)

The incineration of gaseous streams differs from all other incineration processes in that the processing rate is almost always driven by the generation rate of the waste stream since the convenience and economy of storage available for solid, liquids, and sludge are not available. Furthermore, the characteristics of the gas streams also cannot be readily blended as can the condensed phase wastes. Thus, the incineration system burning gases must adapt to what may be very significant changes in flow rate and heat content (oxygen demand).

The principal performance parameter is the destruction-removal efficiency or "DRE": the percentage of the inlet feed rate of significant waste(s) that persists in the exhaust stream following the combustion system and any associated air pollution control equipment. From a practical standpoint, a second important performance parameter is the energy consumption required to achieve the target DRE. In general, the achievement of the DRE is in fairly straightforward relationship to the working temperature and oxygen concentration within the combustion system (although, of course, mixing efficiency and

other factors play a role). Therefore, it is the energy-efficiency factor that shapes the physical characteristics of the afterburner and, of course, its operating cost and, thus, its practicality as a means to control the offending compound(s).

A. Energy Conservation Impacts on Afterburner Design

Afterburner systems break into two broad categories depending on the heat content of the gas stream to be controlled: fuel-rich fumes and dilute fumes. In processing dilute fumes, where the energy content of the hydrocarbon portion is small, careful attention to energy consumption is critical to maintain economic acceptability. Political interest in energy conservation has coupled with significant increases in the cost of purchased fossil fuels in recent years to emphasize the need to attend to this aspect of system design. Three concepts illustrate this focus: the conventional direct thermal oxidizer; the recuperative thermal oxidizer; and the regenerative thermal oxidizer (Fig. 1). A fourth approach to minimize fuel use involves use of an oxidation catalyst to reduce the gas temperature required to achieve the destruction target. This approach is discussed in Section B.2 below.

The conventional thermal oxidizer is a simple combustion chamber into which atmospheric temperature air and the waste gas are introduced. To the extent that the resulting flame temperature is lower than is desired or forced by regulation or permit, fuel is added.

In the second alternative, the recuperative thermal oxidizer, the hot exhaust from the combustion chamber is passed countercurrent through a heat exchanger to preheat the incoming waste gas. In most cases, the heat exchanger is fabricated from stainless steel and both corrosion (especially when the waste gas contains chlorine compounds) and materials constraints limit the heat recovery to about 60% of the heat originally in the exhaust gases. The recuperative concept may also be combined with a catalytic oxidation system, thus combining the energy-conserving feature of recuperation with the reduced temperature requirement of catalytically enhanced oxidation. The pressure drop experienced across the catalyst and the heat exchanger is related to the level of energy recovery:

Equipment type	Heat recovery (%)	Pressure drop (kPa)
Fixed bed catalyst	0	1.5
Heat exchanger	35	1.0
Heat exchanger	50	2.0
Heat exchanger	70	3.7

In the third alternative, the regenerative thermal oxidizer (an RTO), hot exhaust gases from the combustion chamber are passed through a bed of "cold," refractory material. Over time, the refractory approaches combustion chamber temperature. Meanwhile, before entering the combustion chamber, the incoming waste gas is preheated by passing through a bed of "hot" refractory. Over time, this refractory cools and approaches ambient air temperatures. At an appropriate time, large gas valves are actuated to switch the gas flow so the now-cold, originally hot material is reheated and the now-heated, originally cold material becomes the preheating medium. The energy recovery for this type of system can exceed 90% of the heat originally in the exhaust gases.

The heat sinks in the RTO can be refractory saddles or other types of random packing or they can be structured refractory packing blocks. From time to time, the

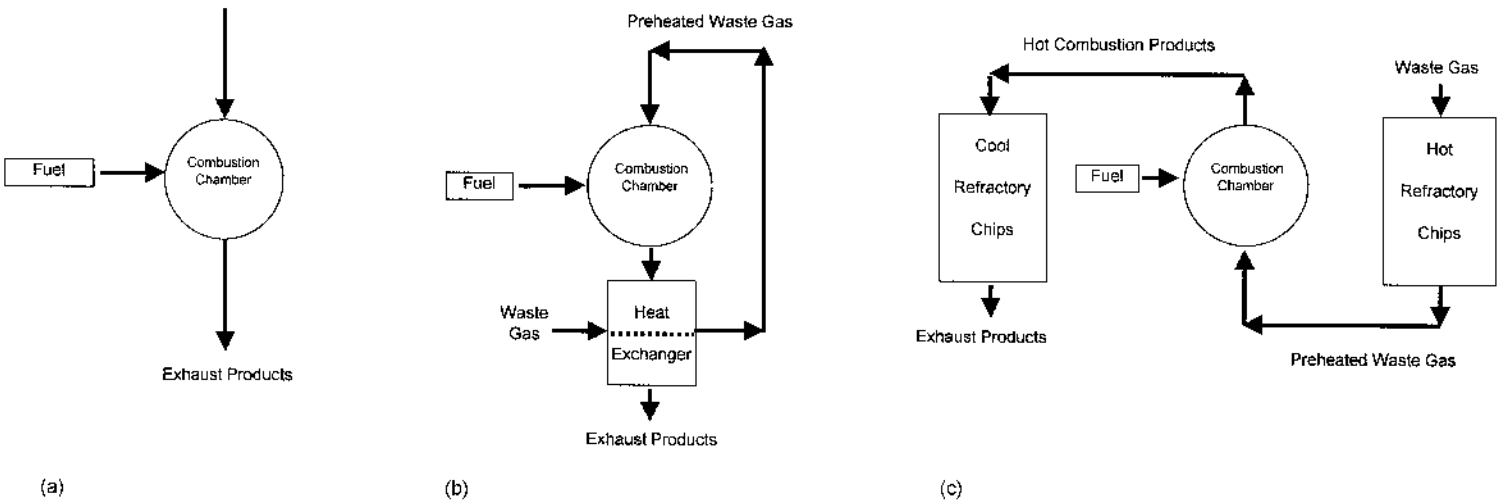


Figure 1 Design strategies for afterburner energy conservation. (a) Conventional thermal oxidizer; (b) recuperative thermal oxidizer; and (c) regenerative thermal oxidizer.

packing can be held at high temperatures for an extended time to burn out ("bake out") accumulated organic particulate matter. The effectiveness of the seal on the gas valves and the disposition of the gases in the internal gas passages in the RTO are important parameters when the DRE requirements for the RTO exceed 95%. Leaking valves obviously lead to the bypassing of unremediated gases from the inlet plenum to the outlet duct. The redirection of the incoming gas in the ducting to the outlet duct within the RTO during switchover also could result in the avoidance of the combustion zone. To avoid this, manufacturers purge the unremediated gas before opening the valve to the outlet duct.

B. Current Afterburner Engineering Technology

A large body of knowledge, both theoretical and empirical, is available to support and guide the design and evaluation of afterburner systems. This knowledge, which concerns the heat transfer, fluid mechanics, and kinematics of combustion phenomena, can be used to determine the design characteristics for optimum performance and thus to develop criteria against which to evaluate existing afterburner systems.

1. Direct Flame Afterburner Technology

Considerable experience exists in the use of direct flame afterburners for the combustion of gaseous and gas-borne combustible pollutants (152,153). Many of these systems consist of little more than a burner in a cylindrical, refractory-lined chamber and are constructed on-site by facilities engineers. Indeed, the designs of many direct flame afterburners now on the market are derived from such "homemade" devices.

a. Combustible Gaseous Pollutant Control. Most applications for afterburners concern the destruction of combustible gaseous emissions and, particularly, volatile organic compounds (VOCs). The concentration of these pollutants is usually too low to permit self-sustaining combustion because they are often intentionally diluted below the lower flammability limit for safety reasons. As a result, external energy must usually be added. Most insurance carriers insist that the gases entering the incinerator be below 25% of the lower explosive limit (LEL) [which can be estimated, for gas mixtures (298) using Eq. (9)]. For the LEL of pure substances, see Appendix D.

$$\mathrm{LEL}_{mix} = \frac{1}{\sum_j^n \dfrac{x_j}{(\sum_i^n x_i) \times \mathrm{LEL}_j}} \tag{9}$$

where

$\mathrm{LEL}_{\mathrm{mix}}$ = lower explosive limit of a mixture of n components
x_i, x_j = volume fraction of combustible components i, j
LEL = lower explosive limit of component j

The energy content equivalent to the lower limit of flammability of most gas–air mixtures is 0.46 kcal/Nm^3; therefore, fuel must be introduced into the gas stream to increase the energy potential and permit subsequent ignition and oxidation of the mixture. Because preheat (sensible energy) in the pollutant stream is equivalent to chemical energy, the flammability energy limit (kcal/Nm^3) decreases as the inlet temperature increases until it is zero at the ignition temperature.

However, operating a system at the limit of flammability (either through sensible or chemical heat input) increases the probability that residual partially burned combustible materials will appear in the effluent. The presence of these materials (carbon monoxide, formaldehyde, methanol, etc.) generally indicates either inadequate mixing or quenching (by dilution air or cooled surfaces). The combustion characteristics of such homogeneous systems are described below.

COMBUSTION KINETICS. In general, the combustion of hydrocarbon vapors is controlled by the mixing processes within the system, rather than by combustion kinetics (154). The classical results of Longwell and Weiss (155), Hottel et al. (11), and Mayer (156) on combustion in well-stirred reactors have clearly demonstrated the extremely high combustion intensities possible (107 to 109 kcal hr^{-1} m^{-3}) when mixing processes are eliminated as rate-controlling steps. These workers also showed that the reactions of hydrocarbons or ketones are very fast relative to that of the carbon monoxide intermediate formed in the course of the oxidation reactions. It is also clear that all combustion reactions proceed by a free-radical mechanism and thus are susceptible to wall quenching and the action of radical stabilizing species such as NO_2 and branch chain hydrocarbons.

Nerheim and Schneider studied the burning rate of carbon monoxide and propane premixed with oxygen, hydrogen, and water vapor in various proportions over ranges of equivalence ratios and pressures (11). Burning rates were determined from metered flow rates and analysis of reactor products. The final relationship presented by these authors is shown in Chapter 2, Eq. (57).

The kinetic mechanism proposed by Nerheim and Schneider which fits the data for CO called for the rate-limiting step shown in Eq. (10a), equilibrium for Eq. (10b), (10c), and (10d), and a three-body chain terminating step.

$$CO + OH = CO_2 + H \tag{10a}$$

$$OH + H_2 = H_2O + H \tag{10b}$$

$$H + O_2 = OH + O \tag{10c}$$

$$O + H_2 = OH + H \tag{10d}$$

The mechanism proposed for propane combustion involved the addition of a very fast reaction of propane to CO and H_2O at the expense of OH, O, and H. The small difference between the two correlations suggests the commanding role of CO combustion in hydrocarbon oxidation reactions.

Combustion kinetics for more complex compounds such as ethers involve more complex steps at lower temperatures. For example, the slow oxidation of diisopropyl ether at temperatures between 360° and 460°C apparently consists of the production and combustion of methyl radicals, the process being facilitated by aldehydes, particularly acetaldehyde (157). As the temperature increases over 450°C, the thermal pyrolysis of the ether becomes of great importance in facilitating the production of radicals.

FLUID DYNAMICS. Through the action of free radicals in combustion processes, intense recirculation patterns near the flame front can be extremely important in augmenting the combustion rate. By such means, free radicals can be returned to the ignition areas. Thus, mixing in hydrocarbon afterburners not only promotes intimate contact of fuel and air but also returns activated species for rapid initiation of the ignition and combustion reactions. Recirculation effects can be viewed by evaluating homogeneous

combustion systems in terms of plug-flow and well-stirred regions. A number of excellent studies by Hottel, Essenhigh, and others illustrate such techniques.

An example of a system that uses recirculation to enhance the burning rate is given by the swirling jet (13). In addition to increasing the combustion intensity, the axial recirculation vortex causes burning gases to travel back toward the burner, thereby piloting the flame and increasing its stability. The appearance of an optimum swirl number for combustion systems suggests the ability of the designer to control the ratio of well-mixed and plug-flow zones to maximize combustion intensity and flame stability (158).

b. Combustible Particulate Pollutant Control. Many industrial processes emit particulate matter. The composition and particle-size distribution of these pollutants vary widely, from the inorganic dusts of the mineral pyroprocessing industry to the high-moisture and volatile matter, low-ash dusts of the grain milling industry and the dry low-ash furnace dusts of the channel black industry. In many cases, the recovery of product values or the relatively large dimensions of the particles suggest the application of conventional particulate control systems (cyclones, precipitators, filters, scrubbers, etc.) rather than destruction. As the particle size drops below 50 μm, however, and as the value of the material to be recovered diminishes (e.g., the aerosols from a drying oven or the soot from a solid waste incinerator), the applicability and desirability of direct flame incineration increase.

The sections below discuss the important combustion parameters that apply to the burning of such particulate materials.

RETENTION TIME. One of the primary considerations in the design of afterburners is the retention time. In principle, retention time is a derived quantity, calculable as the sum of the time for preheat of the particulate and the gas stream and the appropriate combustion time for the particulate or gaseous species under consideration, as influenced by the dynamics of the combustion system. In practice, however, the retention time is often considered to be constant, and consideration is not given to the possibility of reducing it (and thus system cost) through manipulation of the controlling parameters (159). This arises, in part, from the assumption that the system designer cannot greatly alter the times required for the various process steps and from the relative complexity of the analysis and computations required. In fact, the designer does have a measure of control over the combustion time of particles (through temperature and air control), the preheat time for the gas stream, and, to some extent, gas phase combustion rates. (The latter can be modified by utilization of mixing and recirculation principles; recirculation is important for incineration of hydrocarbon vapors, as discussed below.)

The time required to heat the entering gas to the furnace temperature is dependent on the combustion intensity within the system and the incremental temperature rise required. This time (in seconds) may be computed as follows:

$$t = \frac{C^{\circ}_{p,\mathrm{av}} \Delta T}{\dot{q}_v} \tag{11}$$

where

$C^{\circ}_{p,\mathrm{av}}$ = gas heat capacity (kcal m^{-3} $^{\circ}\mathrm{C}^{-1}$) over range of ΔT
ΔT = required temperature rise ($^{\circ}$C)
$\dot{q}$ = combustion intensity (kcal m^{-3} sec^{-1})

In low-pressure gas jet mixers, the combustion intensity can be as low as 0.009 kcal sec^{-1} m^{-3}, but in premixed mechanical burners it ranges above 4.45 kcal sec^{-1} m^{-3} (153). Typical values for premixed high-pressure gas jet, multiple-port burners range from 1.0 to 1.4 kcal sec^{-1} m^{-3}.

Often the difficulty in obtaining high-combustion intensities has been attributed to the limitations of homogeneous combustion reaction kinetics. Evidence to the contrary is provided by studies on well-stirred reactors (11,155,156) in which air and fuel are premixed and fed into the reactors through small holes. The resulting high-velocity (often sonic) jets promote an intense mixing of the fuel/air mixture with the products of combustion. These experiments have clearly shown that the kinetics of oxidation for a large number of fuels are so fast that volumetric heat release rates of 90 to 9000 kcal sec^{-1} m^{-3} are achievable over the 1100° to 1700°C temperature range.

PARTICLE HEATING. The initial step in the combustion of particulate matter is to raise the surface temperature of the particle to levels where oxidation reactions can occur at significant rates. In general, the time required to heat particles of the size range of interest for afterburners to combustion temperatures is small compared to the actual particle burning time. This is shown in the Nusselt number correlation for zero relative gas velocity (i.e., when the particulate is moving at the same velocity as the gas):

$$h_c = \frac{2\lambda}{d} \tag{12}$$

where

h_c = heat transfer coefficient in kcal m^{-2} hr^{-1} $°C^{-1}$
λ = gas thermal conductivity in kcal hr^{-1} m^{-2} $(°C/m)^{-1}$
d = particle diameter (m)

Evaluation of this equation at 700°C for a 50-μm particle, for example, gives an overall heat transfer coefficient of almost 2440 kcal hr^{-1} m^{-3} $°C^{-1}$. Under such high-flux conditions, the particle temperature rises quickly to that of the ambient gas, and combustion ensues under mixed chemical reaction- and diffusion-rate control.

PARTICLE COMBUSTION. The design requirements for the burnout of carbonaceous particles can be determined from a consideration of the rates of oxygen diffusion to the particle surface and the chemical kinetics of carbon burning. The time for burnout for the particles can be shown to be inversely proportional to the oxygen partial pressure, to increase with particle size, and to decrease with increasing temperature (13). The approximate burning time in seconds is given by Eq. (63) in Chapter 2.

The two terms within the large brackets of Eq. (63) in Chapter 2 represent the resistances due to chemical kinetics and diffusion, respectively. At the temperatures found in incinerators, the burning rate is usually limited by chemical kinetics. Some uncertainty exists concerning the kinetics and mechanism of carbon and soot combustion, but this does not influence the general conclusions derived from application of Eq. (63) in Chapter 2.

2. Catalytic Afterburner Technology

The principle underlying the catalytic afterburning of organic gases or vapors derives from the fact that, from the viewpoint of thermodynamics, these substances are unstable in the presence of oxygen, and their equilibrium concentrations are extremely small. With a catalytic afterburner, the combustible materials may be present in any concentration below the flammability limit. The factors that influence the combustion are temperature, pressure,

oxygen concentration, catalyst selected for use, nature of the materials to be burned, and the contact of the material with the catalytic surface.

a. Catalyst Systems. An oxidizing catalyst is used. Metals (platinum, etc.), metal oxides, semiconductors (vanadium pentoxide, etc.), and complex semiconductors (spinels such as copper chromites, manganese cobaltites, cobalt manganite, etc.) are all known to promote oxidation of hydrocarbons. Since the surface catalytic reaction consists of a number of elementary acts such as the breaking and formation of bonds in the reactant molecules and electron transfer between the latter and the solid catalyst, the electronic properties of catalyst surfaces are important. Consequently, the catalytic activities of metals and semiconductors would be expected to differ due to their different electronic properties. However, under conditions of oxidation catalysis, many metals become coated with a layer of oxide, and this might be the reason why the mechanisms of hydrocarbon oxidation on metals and on semiconductors are so similar (160).

Attempts have been made to correlate the activity patterns with the electronic structure of the catalysts (161–163), the d-electron configuration of cations (164), and the heat of formation of oxides (165). Only moderate success has been achieved, and at present a general theory of oxidation catalysis is not available. Consequently, the choice of an active oxidation catalyst is still based upon extensive empirical information or rather coarse approximations.

In catalytic afterburner practice, platinum with alloying metals is prevalent because of its high activity and the lower temperature needed to induce catalytic oxidation when compared with the other catalysts. It is either deposited on nickel alloy ribbons and formed into filterlike mats, or deposited on small, thin ceramic rods for the fabrication of small blocks or bricks. Other possible catalysts include copper chromite and the oxides of vanadium, copper, chromium, manganese, nickel, and cobalt.

Particularly relevant is a great deal of work done in connection with automobile emission control. Since automobile engines have various modes of operation (cold starts, idling, high speed, acceleration, and deceleration), the catalyst system must be effective over a wide range of exhaust temperatures, gas flow rates, and gas compositions. In contrast, the conditions encountered in stationary afterburner systems are much more steady; hence, any catalytic system suitable for automobile emission control should be effective in afterburners.

b. Catalytic Oxidation Kinetics. Basic data on catalytic oxidation of hydrocarbons have been available for many years. Anderson et al. (166) showed that even a fairly refractory hydrocarbon gas like methane can be oxidized completely on a precious metal/alumina catalyst at 400°C or less. In general, the higher-molecular-weight hydrocarbons are more easily oxidized than the lower, and hydrocarbons of a given carbon number increase in reactivity according to the following series:

$$\text{aromatics} < \text{branched paraffins} < \text{normal paraffins} < \text{olefinics} < \text{acetylenics}$$

Some kinetic data are also available in the literature. Work by Caretto and Nobe (167) pays particular attention to the catalytic afterburning of some substances at low concentrations in air. They determined the burning rate of saturated and unsaturated hydrocarbons, aliphatics, aromatics, and carbon monoxide on copper oxide–alumina catalysts. The rate equations were found to be not of integral orders, and the activation energies were in the region of 15 to 27 kcal/mol of combustible substance.

In general, the course of a catalytic reaction can be conveniently considered in five steps as follows:

1. The reactants diffuse from the body of the gas onto the surface of the catalyst.
2. The reactants are adsorbed into the surface.
3. The adsorbed species interact in the surface.
4. The oxidation products are desorbed after the chemical reaction.
5. The desorbed products diffuse into the body of the gas.

Any one of these steps could be the slowest step, whose rate would determine that of the overall catalytic reaction. When the rates of several steps are comparable, they will jointly determine the rate of the overall reaction.

The catalytic afterburner usually operates in the region where diffusion rate is important. Vollheim (168), for instance, found that at temperatures up to 300°C with copper chromoxide as a catalyst and up to 270°C with palladium, the burning rate of propane is determined by the reaction rate on the catalyst surface. At higher temperatures, the effect of diffusion became increasingly noticeable.

In comparison, we may cite that the most commonly encountered hydrocarbons and combustible organic vapors require catalyst surface temperatures in the range of 245° to 400°C to initiate catalytic oxidation. Some alcohols, paint solvents, and light unsaturates may oxidize at substantially lower catalyst surface temperatures, while aromatics from the tar melting processes may require higher initiation temperatures. Hydrogen, on the other hand, will undergo catalytic oxidation at ambient temperatures. Most of the catalytic burners operate between 345° and 540°C, where diffusion rate is important. Theoretical relations between mass diffusion and chemical reaction on the catalyst surface are well developed (169,170).

Laboratory data must be used with caution, because most supporting studies have used granular catalyst support beds and have paid little or no attention to the fluid pressure drop. Industrial catalyst systems for fume abatement, however, have had to design with relatively open structures to minimize the fluid resistance. Since mass transfer is important, it should be expected that the geometry of these open catalyst support structures should greatly influence fluid flow, and hence mass transfer behavior.

The influence of pressure on the reaction rate of catalytic combustion processes has received little attention. This oversight should be remedied because, if reaction rates increase with pressure, capital cost might be reduced by operating the afterburner combustion under moderate pressure.

C. Afterburner Systems

Process exhaust gases containing combustible contaminants released at concentrations within or below the flammable range can, in most cases, be destroyed effectively by either furnace disposal or catalytic combustion. Properly designed, applied, operated, and serviced, either system can produce oxidation and odor reduction efficiencies exceeding 98% on hydrocarbons and organic vapors. The choice of one over the other will usually be based on initial, operating, and service costs and safety rather than on efficiency. With the thermal disposal technique, the residence temperature may vary from 510°C for naphtha vapor to 870°C for methane and somewhat higher for some aromatic hydrocarbons. The operating temperature of the catalytic afterburners is usually about 340° to 540°C. Hein (171), summarizing the economic significance of low operating temperature, showed that

costs for direct flame incineration range from 150% to 600% of the cost of catalytic oxidation, depending on various factors. Furthermore, a catalytic afterburner minimizes the problem of NO_x generation during disposal. Catalytic systems are, in fact, used for the chemical reduction of these oxides (172).

1. Direct Flame Afterburner Systems

a. Types. Furnaces for removing undesirable gases or particulate matter from the exhaust of a chemical or manufacturing process by direct flame incineration are, in general, either similar or identical to those used for generating heat. There are many design variations in conventional furnaces; so are there a variety of incinerator systems. The principal differences between the two types of furnaces are obviously related to the introduction of the effluent feed stream and the construction materials necessary to withstand special erosive or corrosive effects.

Most direct flame afterburners utilize natural gas. Since in many cases gas is employed as the primary fuel in the process to which the afterburner is applied, installation may be relatively simple, and it produces a cleaner exhaust than does burning fuel oil. Gas burner designs are conventional and may be of either the premixed or diffusion type: that is, either the fuel and air are mixed prior to entering the furnace or they are introduced separately. In some cases the (primary) air is premixed with the fuel and additional (secondary) air is introduced into the combustion chamber. The method of fuel–air injection generally defines the type and performance of the afterburner. Typical assemblies include ring, pipe, torch, immersion, tunnel, radiant flame, and static pressure burners.

Atmospheric, or low-pressure, burners generally are of relatively simple design, while high-pressure burner systems require either a source of high-pressure gas and air or special equipment in the burner. Low-pressure systems tend to produce a lower combustion intensity, resulting in larger combustion chambers and, in some cases, lower efficiencies; however, their initial cost may be less when the plant does not have high-pressure gas and air supplies.

The method of introducing the effluent feed stream into the furnace depends on its composition and the type of gas burner; however, since it generally contains a high percentage of air, it is usually fed into the system in essentially the same manner that air is introduced into conventional burners.

Other significant components of the furnace system relate to methods of (1) enhancing the mixing of fuel, air, and waste gas, (2) holding the flame in the desired position within the chamber, (3) preventing the flame from flashing back through the waste gas feed stream to its source, and (4) removing undesirable gases and particulate matter either before entering or after exiting from the furnace.

The furnaces are constructed of high-temperature alloys or lined with refractory materials. Alloys must be selected on the basis of design stress at maximum temperature and on the known corrosive effects of the feed stream and combustion products. Refractories offer the advantages of (1) providing insulation for reducing heat loss, (2) radiating heat back into the chamber gases and particulate, and (3) resisting erosion and corrosion. The application of refractories in furnaces is a well-developed art; thermal shock, shrinkage, spalling, and deformation characteristics have been established for a variety of refractory materials.

When economically justified, heat is recovered from the products of combustion of afterburners, either by the addition of heat exchangers in the exhaust stream or by using a convection (boiler) furnace as the afterburner. The heat exchangers used to recover heat

from the afterburner exhaust are of conventional design and include the many variations of both recuperative and regenerative systems. Among the furnaces modified to be used both as afterburners and as a source of heat for some other purpose are boilers, kilns, and chemical reactors.

b. Design and Performance Characteristics. The effectiveness of afterburners in the removal of the pollutant from the waste gas depends primarily on the temperatures achieved within the afterburner, the mixing, and the residence time. For a given rate of throughput, higher temperatures and longer residence times provide higher levels of removal of the combustible pollutants, but require more fuel and larger combustion chambers, thus leading to higher operating and equipment costs.

In most current systems, operating temperatures are relatively high, and so the time for chemical reaction to take place is short compared to mixing times. Particles larger than 50 to 100 μm may require a relatively long residence time; however, they are generally removed by techniques other than combustion.

Since mixing of the fuel and air and of burned products with the unburned materials is important to most furnaces as well as to afterburners, considerable effort has been expended in increasing combustion intensity and turbulence. Among the methods that are being employed or investigated are insertion of the gases tangentially within the combustor, high-velocity injection of the gases, multiple-ported injection of fuel and air, baffles, recirculation of hot products into the unburned zone, and injectors that introduce swirl. In general, the design of afterburners has not received that attention applied to conventional furnaces, since the economic impact derived by improved design is low compared to that attainable with improvements in, for example, boiler furnace efficiency. In addition, the afterburner cost can be quite small compared to that for the overall equipment and operating costs of the associated chemical or manufacturing process.

Control systems for fume incinerators are generally based on temperature. The temperature is allowed to fall to a preset level as the heat content of the waste gas decreases and, at the set point, auxiliary fuel burning is started. Temperature alone may be an unsatisfactory control variable since there are two combustion situations (on either side of stoichiometric) that result in the same temperature. Since the substoichiometric condition is dangerous, it is prudent to incorporate sensing of flue gas oxygen content into the instrumentation and control system. The system should automatically override the temperature controller when an oxygen deficit is detected.

As with all other processes, the demand to decrease the cost of operating afterburners will continue; however, we also expect that the need to reduce pollution from all sources will require that afterburners be more effective and their use more widespread. These factors will demand that more attention be applied to afterburner design. Obviously, except for when waste heat recovery is employed, the primary performance criteria of direct flame afterburners are considerably different from those for conventional furnaces: that is, the percentage of pollutant removed per unit of fuel is one of the principal objectives for afterburners, while for conventional furnaces it is the usable thermal energy per unit of fuel. These differences should be carefully examined and exploited in the search for improved afterburner systems.

2. Flares

The flare is a special case among direct afterburner systems. Flares are common in refineries and petrochemical plants, in landfill gas disposal applications, and in process

plants where small quantities of combustible gases are generated in an irregular fashion such that a more conventional afterburner cannot cope with the surging flow pattern. Flares are low in cost relative to conventional afterburners and perform satisfactorily for the disposal of nontoxic gases.

A flare is, in essence, an open pipe discharging a burning combustible gas directly into the atmosphere. The unit can be mounted at ground level or elevated. Flares are elevated, most particularly, where the flame, as a potentially dangerous ignition source, must be physically isolated from a process unit. Also, elevation enhances dispersion of the products of combustion and reduces noise, heat, smoke, thermal radiation, and objectionable odors in the working area.

In the 1920s, the primary function of a flare was pressure relief for oil wells and refineries where excess gas was not usable. These early flares were simple lengths of pipe ignited by hoisting a burning rag to the tip. In most modern flares, combustion involves a highly crafted, turbulent diffusion flame. The flare includes proprietary tip designs incorporating features enhancing flame stability, ignition reliability, and noise suppression. The flame retention devices can support a stable flame over a flare gas exit velocity range from 0.5 to 175 m/sec. Capacity is usually limited by the pressure available at the flare gas source. Flare diameter is normally sized such that at maximum firing rate, the gas velocity approximates about 50% of the sonic velocity of the gas.

a. Ignition. All flares include a continuous pilot designed for stability. The preferred pilot ignition system uses a remote, grade-level ignition panel that mixes air and fuel, electrically ignites the gas using high-energy capacitor-discharge igniters and directs the resulting flame to the pilot through a 2- to 3-cm diameter pipe (491). Because the pilot ignition system's integrity is critical to reliable operation, the gas supply must include condensate traps and drain valves, and the service piping between the pilots and the ignition panels must be properly sloped.

The pilot burners are positioned around the outer perimeter of the flare tip. Pilots are commonly monitored using a simple thermocouple with a thermowell and shroud, although other flame detection methods are also used. Ultraviolet or infrared sensors are problematic since they cannot readily differentiate between the flare flame and the pilot flame. The number of pilot burners (typically burning about 2 m^3 of natural gas per hour) depends on the flare tip diameter. Good practice (296) suggests the following:

Flare tip diameter (cm)	No. of burners
2 to 25	1
30 to 60	2
75 to 150	3
>150	4

Flare pilots must ensure reliable ignition of waste gases flowing at high speed (as much as 270 m/sec. To prevent flame-outs, flare pilots must withstand hurricane-force cross-winds and must be easily reignited if flame failure occurs. Thus, simple retention-type nozzles are unacceptable as their design is vulnerable to cross-winds.

b. Control of Smoking. Steam is often injected into flares to improve mixing and as an oxidant to prevent smoking if higher-molecular-weight hydrocarbons are to be burned. Experience shows that if the molecular weight of the hydrocarbons being burned is above

20, smoke is likely (491). Steam-to-gas ratios are increased as the molecular weight of the gas and its degree of unsaturation increase. Typical, the mass ratio of steam to gas is in the range 0.1 to 0.6 with a minimum flow of 150 to 200 kg/hr. For effectiveness, steam at a pressure over 0.7 atm is necessary to ensure that sufficient momentum and mixing energy are introduced. In refinery applications, the average steam-to-gas ratio is 0.25 kg/kg. Chemical plants flaring large quantities of unsaturated hydrocarbons may use a ratio of 0.5 kg/kg.

Although steam injection improves combustion and helps to control soot formation, it comes at a cost in energy and water treatment and increased noise (adding a high-frequency "jet" noise to the crackle and rumble of the flame). If too much steam is used, the effectiveness of steam injection decreases due to excessive cooling. Also, excessive steam can lead to instability with associated flame pulsation and low-frequency noise generation.

Other means to control smoke include the use of air blowers; high-velocity multi-tips that use the kinetic energy of the waste stream for smokeless flaring; and water sprays. With good atomization, water injection flares use a water-to-hydrocarbon mass ratio of 1 : 1. With poor atomization, the quantity of water to control smoke increases to as much as 4 : 1 or even 7 : 1 (491). This contrasts with the use of steam at ratios of 1 : 4.

c. Design Parameters

FLARES FOR INDUSTRIAL APPLICATIONS. U.S. EPA requirements for steam-assisted, elevated flares requires

An exit velocity at the flare tip of less than 18.3 m/sec for 75 kcal/m^3 gas streams and less than 120 m/sec for >250 kcal/m^3 gas streams. Between these extremes, the maximum permitted velocity (V_{max} in m/sec) is given by

$$\log_{10}(V_{max}) = \frac{B_v + 6{,}890}{7{,}580} \tag{13}$$

where B_v is the net heating value in kcal/m^3.

No visible emissions (a 5-min exception is permitted in any two consecutive hours).

Flame present whenever gases are vented. The pilot flame must be continuously monitored.

Net heating value of the flare gas must exceed 75 kcal/m^3 (either the inherent heating value of the gas or the result of blending natural gas or other fuel gas with the vent stream).

A windshield is usually installed around the entire flare tip to prevent flames from licking down the stack or liftoff or blowout of the flame. The windshield for the pilot should be at least one-third the total length of the pilot flame. Care must be given to prevent air penetration within the flare, which could cause an explosion or lead to burnback inside the flare tip and stack.

FLARES FOR LANDFILL GAS AND DIGESTER GAS. Mixtures of methane, carbon dioxide, and nitrogen with small amounts of oxygen (from in-leakage), hydrogen sulfide, and traces of other hydrocarbons are generated by anaerobic biological activity in landfills and in the digestion of wastewater treatment plant sludge. When the quantity of generated gas is small or if an economically attractive energy market is unavailable, a flare is often used to safely effect destruction of the methane and the accompanying odorous species. In this application, three principal types of flares are used: candlestick flares, enclosed flame

flares, and thermal oxidizers. The advantages and disadvantages of the three types (493) are shown in Table 1.

The candlestick flare is distinguished by its exposed flame. Its simple design (no combustion chamber or ignition tube) keeps capital investment low but at the price of poor performance. Indeed, the high-emission profile often makes this design inadequate to meet air pollution regulations. Measured destruction efficiencies range from only 60% to 75%.

Enclosed flame flares consist of a vertical combustion chamber with forced air addition. Ceramic blanket insulation maintains high temperatures in the combustion chamber and lowers the skin temperature. Well-designed units can achieve hydrocarbon destruction rates of up to 99.9% and low (<200 ppm) CO and NO_x (493).

d. Radiation from Flares. Flares are often elevated in order to minimize the intensity of heat radiation in the nearby area. A generally accepted thermal intensity for continuous work is about 1350 kcal/hr per m^2. Equation (14), after Hajek and Ludwig, can be used to establish the minimum distance "L" (m) from the center of the flare flame to the point where the target thermal intensity is to be maintained (297). Estimates of heat radiation from flames are presented in Table 2.

$$L = \sqrt{\frac{\tau f R}{4\pi K}} \tag{14}$$

where

τ = fraction of heat intensity transmitted (assume = 1)
f = fraction of heat radiated (from Table 2 or a typical value of 0.2)
R = net heat release (kcal/hr)
K = allowable thermal intensity (1350 kcal/hr per m^2)

In assessing the importance of radiant heat emission, one must address the issue of deciding what maximum heat intensity is acceptable. Equipment is often allowed to experience a higher intensity than people, and plant workers are often allowed to experience a higher intensity than the general public. Also, the use of protective clothing permits exposure to higher intensities; as much as 4.73 kW/m^2 for several minutes (494,

Table 1 Advantages and Disadvantages of Flare Designs

Flare design type	Advantages	Disadvantages
Candlestick flare	Low initial cost	High emissions Little control, turndown Minimal safety controls Restricted to high heat content fumes
Enclosed flame flare	High destruction rates Low CO and NO_x emissions Safety controls	High initial cost Cannot handle heavier fume streams
Thermal oxidizer	High destruction rates Low CO and NO_x emissions Safety controls Wide range of fume heat content	Higher initial cost Equipment weight

Table 2 Heat Radiation from Various Gaseous Diffusion Flames

Gas	Flare tip diameter (cm)	Fraction of heat radiated (f)
Hydrogen	<2.5	0.10
	4.0	0.11
	8.4	0.16
	20.3	0.15
	40.5	0.17
Butane	<2.5	0.29
	4.0	0.29
	8.4	0.29
	20.3	0.28
	40.5	0.30
Methane	<2.5	0.16
	4.0	0.16
	8.4	0.15
Natural gas	20.3	0.19
	40.5	0.23

Source: From (297).

495). This is sufficient for many situations where short-term action is needed within an industrial area or when the duration of the flaring activity is limited.

The establishment of a design maximum radiant intensity should also recognize that solar radiation adds to the radiative exposure. A correction of 0.47 to 1.10 kW/m^2 to account for solar radiation is, therefore, appropriate. Finally, the general heat stress load carried by the industrial worker should be taken into account. If the general working area is hot and humid, the energy rejection system of the worker may already be heavily burdened and, thus, a reduction in the permissible additional load from radiation should be considered.

e. Flare Destruction Efficiency. Flare destruction efficiency (typically $> 98\%$) is affected by several factors relating to the gas being burned and to the environment. Good performance is favored by wide flammability limits (the range of stoichiometric compositions that will produce a stable flame without a continuous pilot). High heating value gas (high flame temperature with consequently enhanced combustion kinetics and buoyant mixing) is also preferable.

The environmental problems commonly associated with flares include noise (rumbling, steam jet "scream," or crackling noises) and adverse reactions to the luminosity.

3. Catalytic Afterburner Systems

a. Types. In most cases, the chief aim in the design and operation of the catalytic afterburner is to keep the input of additional energy as low as possible. In Fig. 2(a), the sole purpose of the catalytic unit is to purify the polluted air by passing it, if necessary after preheating, over the catalyst into the atmosphere. In Fig. 2(b), the heat content of the

purified air is used to preheat the waste gas not yet purified by means of a heat exchanger. In Fig. 2(c), the heat content still remaining after this stage is utilized as heating energy for the original process emitting the waste gas. This scheme is applicable to the processes where the waste gas carries a large fraction of the total energy consumed. In the cases where the concentration of burnable material is very high, the two-stage afterburner scheme, as shown in Fig. 2(d), will allow the heat exchange to be operated at lower temperatures. Further recovery of the heat content of the waste gases is easily carried out in a subsequent waste-heat boiler. When the concentrations of organic materials in the waste gases are still higher, imbedding cooling surfaces in the catalyst bed is preferable since most of the heat of reaction can be removed close to the point of generation, thus keeping the maximum temperature in the reactor low and avoiding material selection problems.

b. Catalysts. Many substances exhibit catalytic properties, but metals in the platinum family are conventionally used because of their ability to produce the lowest ignition

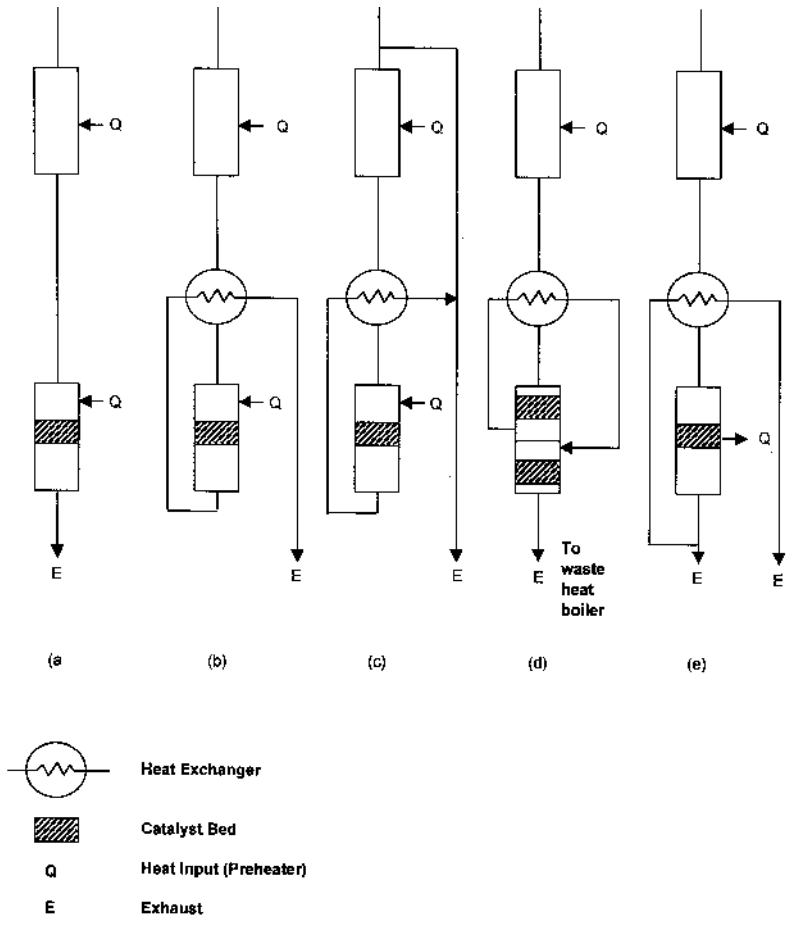


Figure 2 Types of catalytic afterburners: (a) straightforward catalytic afterburning of waste gas; (b) catalytic afterburner coupled with heat exchanger; (c) catalytic afterburner coupled with heat exchanger and hot-air recycling; (d) two-stage afterburners with heat exchanger; (e) catalytic afterburner with cooling surfaces imbedded in the catalyst, coupled with heat exchanger.

temperatures. Others are copper chromite and the oxides of copper, chromium, manganese, nickel, and cobalt.

In industrial use, the active component of the catalyst is usually deposited on a carrier material, as in the following combinations, for example:

Active metal/metallic carrier (e.g., platinum deposited on stainless steel or nickel alloy ribbon)
Active oxide/oxide carrier (e.g., copper/manganese oxide deposited on α-alumina or cobalt oxide on τ-alumina)
Active metal/oxide carrier (e.g., platinum and γ-alumina)

The following are some of the important characteristics of catalysts:

Catalyst composition
Catalyst total surface area
Surface areas of the active components
Pore volume
Pore size distribution
Initial catalytic activity toward selected reaction
Compression strength
Surface area decrease upon use
Change in pore volume/pore size distribution upon use
Change in catalytic activity upon use
Change in catalyst composition upon use

The catalyst will gradually lose activity through fouling and erosion of the catalyst surface, so that occasional cleaning is required, and eventually it must be replaced. Common fouling agents include alumina and silica dusts, iron oxides, and silicones.

If excessively high temperatures are experienced by the catalyst bed, sintering of the catalyst reduces the concentration of catalyst at the surface and/or the available surface area. The temperature range where such degradation occurs is catalyst-specific but often begins above 800° to 980°C.

The susceptibility of catalysts to poisons varies, but the following occurrences are common, especially for platinum-family catalysts:

Metallic vapors such as mercury and zinc deactivate the catalyst.
Phosphorus oxidizes to phosphoric acids, which deposit, on cooling, on the catalyst surface.
Sulfur-containing compounds form sulfate and coat the catalyst surface.
For chlorine-containing compounds, which present no problem under normal operating conditions, temporary high temperatures cause the chlorides formed with the active material to sublime from the carrier.
Compounds containing lead, bismuth, arsenic, antimony, and other heavy metals pass through as aerosols and cover up the effective surface area of the catalyst.
For some catalysts, "reversible poisoning" or inhibition occurs through deactivation after absorption of SO_2 or HCl. This problem can be removed by treatment or, if anticipated, through special catalyst design.

c. Performance Potential. Catalytic oxidation could economically dispose of all combustible fumes that are free of appreciable amounts of unburnable solids, which tend to foul

the catalyst bed. However, the catalytic afterburners are most suited for the removal of the components that will vaporize, because of their greater mass and lack of significant Brownian movement, liquid droplets are not likely to contact the catalytic surface to any appreciable degree. For the catalytic burner to operate effectively, the waste stream must not contain materials that will poison the selected catalytic system.

To achieve destruction efficiencies of 90% to 95%, about 1.5 to 2 liters of catalyst is required per standard cubic meter per minute (exhaust stream plus supplementary fuel combustion products). Since the catalytic reaction rate is much greater than the thermal processes, the mean residence time required to achieve a target degree of volatile organic compound (VOC) destruction is correspondingly smaller. For example, when burning hexane with a 95% destruction target, the calculated catalytic system residence time required at 480°C is only about 25% of that for a thermal oxidizer at 650°F.

Catalytic unit destruction potential is often estimated using the space velocity. Space velocity is defined as the volumetric flow rate of the combined gas stream (emission stream plus supplemental fuel plus combustion air) entering the catalyst bed divided by the volume of the bed. As such, space velocity depends on the type of catalyst used. For many organic pollutants, destruction efficiencies of about 95% can be achieved with precious metal catalysts at space velocities of 30,000 to 40,000 hr^{-1}. Base metal catalysts achieve similar performance at 10,000 to 15,000 hr^{-1} (934). Greater catalyst volumes and/or higher temperatures are required to achieve higher destruction efficiencies.

Catalytic units can be particularly useful for small air flows. Catalytic units for flows as small as 3 m/min may be only a fraction of the cost associated with installing and maintaining ductwork and piping to connect such small sources to existing abatement equipment. Processes emitting large volumes of air where the VOC content is less than 25% of the lower explosive limit and where the VOC content tends to be consistent and predictable are especially well suited to catalytic oxidation because the lower operating temperature requires significantly less fuel and the smaller unit size requires much less startup and cooldown time than thermal oxidation systems.

Catalytic units can often economically achieve destruction objectives for organic compounds but, at the same time, can create other problems. For example, high concentrations of methyl ethyl ketone can be reduced by, say, 98% and thus meet VOC destruction requirements. However, for many catalyst combinations, the oxidation proceeds by a mechanism that generates low concentrations of a highly odorous aldehyde as a product of incomplete combustion that can cause significant odor nuisance problems. The potential for inadvertent operational consequences of this type should be carefully considered in selecting a catalytic unit and in the preparation of purchase specifications for this type of VOC control device.

C. Potential Applications

The emission of combustible pollutants, either gaseous or particulate, is common to a wide variety of chemical and manufacturing processes. The release of these materials may be constant, intermittent, or cyclical in volume, temperature, and degree of contamination. The effluent may consist entirely of compounds of one specific type, although they are usually heterogeneous. In some cases, secondary pollutants, such as sulfur dioxide, nitrogen oxides, and hydrogen chloride, may be emitted following incineration. Under such circumstances, secondary effluent treatment methods such as alkalized wet scrubbers

Table 3 Applications for Incinerators Burning Gaseous Wastes

Industrial dryers	Organic chemical production
Food product ovens	Synthetic rubber manufacturing
Solid waste incineration	Asphalt processing
Coke ovens	Fat rendering
Enamel baking furnaces	Fat frying of foods
Foundry core ovens	Petroleum refining
Paper coating and impregnation equipment	Gasoline distribution
Paint, varnish, and lacquer manufacture/use	Degreasing
Dry cleaning	Resin curing ovens
Coffee roasting	Electrode curing ovens
Grain milling	Sewage sludge drying
Carbon black manufacture	Refuse composting

may be desirable. Table 3 lists processes that are typical sources of organic gases and particulate.

The list is by no means inclusive but suggests the wide variety of sources that can be considered for afterburner-type pollution control. Quantification of the characteristics of the effluent from these processes for afterburner control will be made more difficult by the highly variable concentration due to dilution in the fume collection system. The information regarding composition of these pollutant streams as they relate to afterburners would include consideration of inlet temperature, concentration, toxicity, secondary pollutant formation following combustion, photochemical reactivity, heating value, nuisance value, and the degree to which the species may inhibit or enhance the combustion or catalysis processes.

Catalytic incinerators are inherently higher in capital cost than both direct thermal oxidizers and most recuperative oxidizers. However, because of significantly reduced fuel expense, catalytic systems are usually lower in life cycle cost, although consideration should be given to the continuing capital investment for catalyst replacement that, in many cases, arises biannually. Regenerative thermal oxidizers have high initial capital costs, but fuel use is usually the lowest of any of the afterburner alternatives. Also, they are prone to plugging if the gases passed to the RTO have a significant particulate loading.

III. OPERATIONS AND SAFETY

Thermal oxidizers for liquids and gases are useful means of disposing of combustible organic wastes. However, safe operation of these units is not inherent, and safety considerations must be incorporated into both design features and operating practices. Control systems must ensure personnel, equipment, and environmental safety with minimum supervision under both normal and upset operation conditions.

In liquid- or gas-burning incinerators, the combustion temperature should be slightly above the theoretical flame temperature of the waste stream's lower flammability limit (LFL). If necessary, auxiliary fuel should be burned to maintain this temperature goal. If noncombustible gases or dilute aqueous wastes are to be burned, they should be introduced downstream of the principal flame into a well-developed, high-temperature region.

In some instances, combustible gas analyzers can be used to determine if flammable vapor–air mixtures are outside their flammable limits. National Fire Protection Association (NFPA) documents NFPA - 86 (498) and NFPA - 69 (499) do not require a flammability control system for streams up to 25% of the LFL. However, if flammability is controlled by either addition of dilution air (to keep below the LFL) or natural gas addition (to keep above the upper flammability limit, or UFL), the stream should incorporate such instrumentation. In that case, the maximum operating point is set at 50% of the LFL with an initial alarm at 55% LFL and automatic shutdown at 60%.

For systems burning gaseous wastes, flame and detonation arresters are necessary to quench flashback, prevent sustained combustion, and halt flame propagation. Detonation arresters with automatic shutoff and explosion relief should be installed upstream of the incinerator to isolate flammable mixtures from potential ignition sources (497). The types of devices used include dry flame arresters, liquid flame arresters, and detonation arresters.

Safety interlocks recommended (497) to trigger shutdown and critical alarms of the system are summarized in Table 4. All such interlocks and their supporting instrumentation and control logic should fail in a clearly defined safe position in the event of a power failure. If possible, gaseous waste streams should be bypassed to a vent system with appropriate high temperatures and residence times. The instruments should be kept simple but accurate, responding automatically to system and operator failures as well as significant upset conditions.

Table 4 Safety Interlocks for Incinerators for Waste Liquids and Gases

Interlocks triggering shutdown for incineration system
Power failure or loss of instrumentation air
Failure to recognize flame by flame safety system
High or low fuel-oil or natural gas pressure
Low combustion air pressure
Low atomizing-media (steam, air, mechanical pressure) pressure or flow
High oxidizer chamber temperature
Low quench water or recycle flow
High quench temperature
Low water levels or abnormal steam pressure in any waste heat boiler
Interlocks Triggering Alarms and Eventually Shutdown for Incineration System
Low oxidizer chamber temperature
Low excess oxygen for combustion
High CO, stack particulates, or emitted pollutants (e.g., SO_2, NO_x)
pH of scrubbing liquid out of range
Abnormal waste stream pressures

Source: From (497).

11

Incineration Systems for Hazardous Wastes

Incineration systems for hazardous wastes are significantly different than their counterparts for nonhazardous waste. The differences are not, however, in the basic type of combustion technology or associated air pollution control system but in the waste receiving and feeding systems, the instrumentation and control systems, and the intense design and operational attention paid to the reliable, continuous achievement of performance: the burnout of feed material, the abatement of air emissions, and the secure disposal of residues.

A focus on the reliable achievement of burnout leads to the selection of technologies that are inherently free of means for feed materials to avoid an extended residence time in the combustion environment. Thus, grate-type incinerators (with the potential for losses of unburned feed material to the siftings system) are seldom found. Rotary kilns and other furnaces where combustion occurs on a hearth and fluid bed systems (burning in suspension) are commonly used for solids and sludges. The equipment used for liquids and gaseous wastes (Chapter 10) is nearly identical to that used for nonhazardous wastes except for the waste storage and feeding and for the instrumentation and control systems. Table 1 shows the general applicability of different incineration systems to process various classes of hazardous waste material.

I. GENERAL

The creation of "hazardous waste incinerators" as a separate and distinct class involved several steps:

1. Promulgation of federal regulations that designated as "hazardous" specific chemicals, waste classes, and other forms of matter exhibiting one of several adverse health impacts (e.g., materials that are toxic or carcinogenic). Incinerators that burn such materials are, perforce, hazardous waste incinerators. Prior to such regulatory designation, numerous incinerators burned such materials but not under that name.

Table 1 Hazardous Waste Incinerator Applicability

Waste characteristic	Liquid injection	Rotary kiln	Fixed hearth	Fluidized bed
Solids:				
Granular, homogeneous		X	X	X
Irregular, bulky (pallets, etc.)		X	X	
Low melting point (tars, etc.)	X	X	X	X
Organic compounds with fusible ash		X		
Unprepared, large, bulky material		X		
Gases:				
Organic vapor laden	X	X	X	X
Liquids:				
High organic strength aqueous waste	X	X		X
Organic liquids	X	X		X
Solids/liquids:				
Waste contains halogenated aromatics	X	X		
Aqueous organic sludge		X		X

Source: From (335).

2. Development of a formal national permit system that constrains siting, construction, and operation of such units with numerous requirements unique to this incineration class.

3. Promulgation of federal regulations, guidance documents, and the like that specify the minimum performance requirements of such devices and the protocols with which to confirm achievement of these minimums in structured test and evaluation programs ("trial burns"). The most important measure of incinerator performance in U.S. hazardous waste regulations quantifies the destruction (through combustion) and removal (through settling in chambers or capture in air pollution control devices) of one or more designated compound(s) believed to most stringently test combustor performance. These indicator compounds are called the principal organic hazardous constituents (POHC). The performance measure is expressed as the destruction and removal efficiency (DRE). The DRE is calculated from

$$\text{DRE} = \frac{W_{\text{in}} - W_{\text{out}}}{W_{\text{in}}} \times 100 \tag{1}$$

where

$\text{DRE} =$ destruction and removal efficiency (%)
$W_{\text{in}} =$ mass feed rate of each POHC to the incinerator
$W_{\text{out}} =$ mass emission rate of each POHC to the atmosphere

It should be noted that the DRE is not a global measure of performance but focuses only on the designated POHCs. The protocols are indifferent to the causes of POHC changes across the system. Thus, one must be concerned about the mass of a POHC that may be fed inadvertently to the incinerator as a contaminant in fossil fuels or in other wastes where the POHC may not have been quantified but is, in fact, present. Also, the protocols penalize the system in deciding incinerator performance for POHC that is inadvertently "manufactured" in the course of degrading other waste components or that is stripped from

scrubber water or derived from other fugitive sources even though the particular molecules involved were not part of the feed material. Finally, the protocols are also indifferent as to the fate of the POHC. It is only important that the specific chemistry designated as the POHC has disappeared. For example, a POHC that undergoes a slight degradation such that it is chemically different but still remains a hazardous (or more hazardous) compound is "destroyed" as far as the DRE determination is concerned. It is fair to say in this regard, however, that it is difficult to achieve a 99.99% or higher DRE while only modestly disturbing the molecule. The topic of products of incomplete combustion (PICs) is discussed in more detail in the Air Toxics section of Chapter 13.

In some permits, the "combustion efficiency" is to be monitored and maintained at all times in excess of some set point such as 99.9%. The combustion efficiency is related to the concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) by

$$\text{combustion efficiency } (\%) = \frac{CO_2}{CO_2 + CO} \times 100 \tag{2}$$

4. Development of a data base incorporating empirical and theoretical design principles, operating experience, evaluation and test results, and other technical information used as a basis for design or for predicting performance under differing conditions or with differing feeds. Some of this technology base has been incorporated into federal or state regulations or embodied in less formal (but, not necessarily, less mandatory) "guidance" materials.

5. Development of elaborate, structured requirements for periodic testing and performance monitoring, record keeping and reporting, process control set points and prescribed operating envelopes, and other constraints such that federal and local regulatory officials can oversee the status of such units.

6. Creation of a body of criminal and civil law providing severe fines and penalties for those firms and individuals that operate such units outside the permitted ranges and methodologies.

Clearly, the above items adversely impact the schedule of facility development, construction, and startup; they increase engineering, equipment, and permitting costs; and their inflexible constraints produce a more rigid design process.

A. Receiving and Storage Systems

Most of the operational problems that hazardous waste incinerator facilities experience are related to materials handling. Consequently, considerable attention should be given to the design and materials selections for pumps, piping, control valves, atomizers, and the variety of solid/sludge waste handling systems. The handling systems for solids and sludges are described in Chapter 7. The primary topic here relates to the storage, receipt, and transport of liquid wastes or slurries. Further, the primary focus is on design and operational strategies to minimize variation in feed rate and properties. Incinerators perform best with a steady, uniform feed.

1. Waste Storage System

Liquid waste tank capacities are, generally, less than 40,000 liters at incineration facilities rated less than 2.5 million kcal/hr. At larger plants, individual tank capacities are rarely greater than 100,000 liters. Tanks should be equipped with an agitator and, if appropriate, insulated and heated. The tanks should be equipped with spill/rupture containment

structures (backed with an emergency response plan) to protect against accidental releases. Depending on the liquid waste contained, tank storage may also require flash arrester fill pipes and flame arrester rodding and sampling ports.

Equipment to control emissions of volatile organic chemicals should be installed on hazardous waste storage tanks. In many cases, present laws do not require such controls. However, they are prudent investments in anticipation of more stringent future requirements and as a protection for employees and neighboring establishments. Depending on the material being stored, chilled water tank vent condensers with knock-out drums or carbon canisters can be used. Although ducting of vent gases to the incinerator is conceptually attractive, careful consideration of explosion hazards and the high cost of long pipe runs, etc., make this approach questionable. Nitrogen blanketing (often using leased LN_2 storage and evaporation systems) enhances safety at a nominal cost.

Tanks for liquids whose vapors tend to crystallize at ambient temperatures require steam-heated conservation, pressure, or vacuum relief vents. Mushroom vents with flame arresters are appropriate for low-flash-point solvents subject to ignition from external sources. The flame arrester vents may have to be steam-heated if the material being stored produces vapors that tend to condense (such as naphthalene).

In all cases where common facilities are used and in consideration of the disposition of material from overflow pipes or drains from spill containment areas, material compatibility problems must be considered. Compatibility problems include

Heat generation, fire, and/or explosions
Formation of toxic fumes
Volatilization of toxic or flammable substances
Formation of substances of greater toxicity
Formation of shock- and friction-sensitive compounds
Pressurization in closed vessels
Solubilization of toxic substances
Dispersal of toxic dusts, mists, and particles
Violent polymerization

While empirical data exist describing reactions between pure substances under laboratory conditions, little work has been done with multicomponent wastes containing not only known primary materials but also trace quantities of contaminants and by-products, aged materials that may have undergone partial oxidation, and so forth. General guidelines are shown in Fig. 1.

2. Freezing Liquids

Liquid wastes vary in their consistency from highly aqueous materials to viscous, organic/ashy tars. The transport system must be able to cope with (potentially) frequent interruptions of firing due to waste cutoff or mechanical problems. If the material being pumped has a tendency to exhibit rapid increases in viscosity, this can lead to prolonged outage and hazardous cleanup tasks. Such waste streams include waxy organic compounds that are solids at ambient temperatures, wastes that polymerize if overheated, wastes close to saturation such that crystallization can occur with only minor water loss, etc.

For these wastes and, indeed, for many wastes with problematic materials handling characteristics, a "run-around" system may be preferred. Here, the pumping rate from the (heated) storage tank is several times the firing rate. A recycle line is provided with the recycle takeoff connection made as close to the atomizing nozzle as possible. This strategy

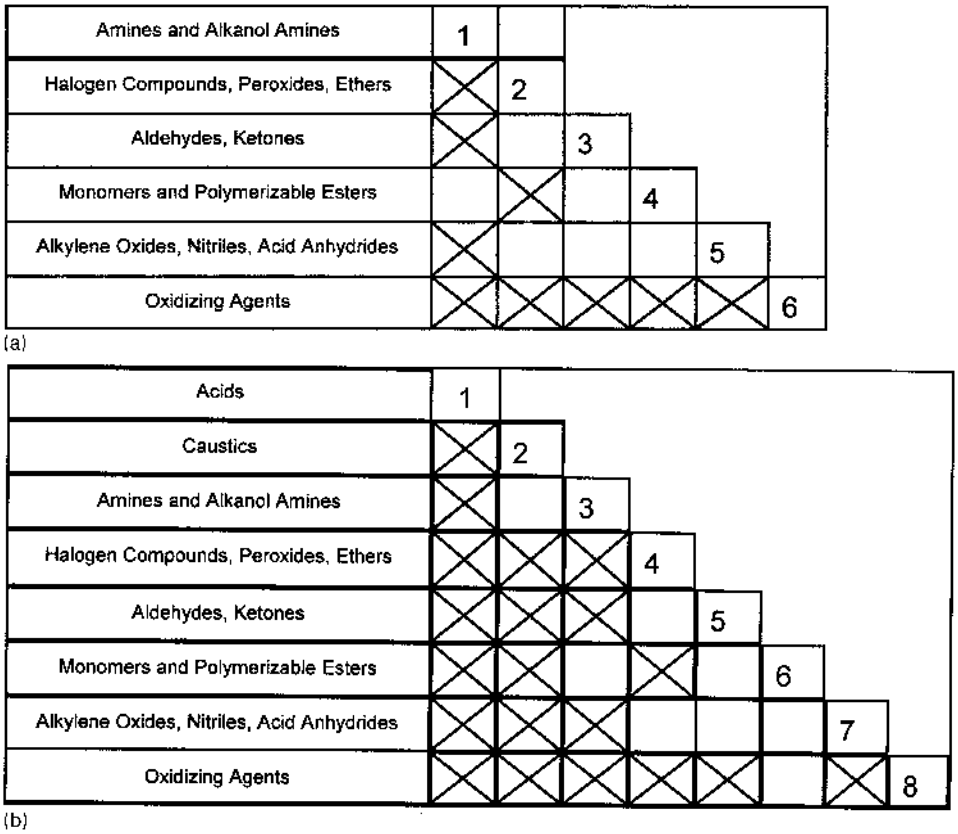


Figure 1 Compatibility matrices for hazardous wastes. (a) Neutralized hazardous wastes. (b) Unneutralized hazardous wastes. (Note: an "X" indicates incompatibility.)

is reported (319) to have satisfactorily resolved problems that preheating, steam tracing, and similar heating methods failed to deal with. Further, provision should be made for rapid purging of lines if prolonged shutdown is forecast and proper sizing (minimum $\frac{3}{4}$-in. IPS pipe) and sloping of the piping such that the lines drain completely and quickly. When in operation, the lines should flow at a minimum of 1 m/sec. A "T" is often preferred to elbows in piping runs to reduce erosion at the turn (the material in the dead end of the "T" acts as a wear surface rather than the elbow wall) and to provide a convenient access point to "rod out" clogged lines.

3. Storage Problems

Stratification is an important problem. When stratification occurs, critical waste characteristics can be expected to change very rapidly: viscosity, heat content, moisture content, and the like. In most cases, such changes precipitate serious system upsets: temperature drop below set points (triggering waste shutdown) or erratic changes in the flue gas oxygen content (that can also trigger automatic shutdown). These problems can often be resolved by use of a "day tank" holding 4 to 8 hours of waste and located between the main storage

tank and the burner. The day tank can be equipped for intense mixing to produce a very uniform and stable feed.

B. Firing Systems

1. Blending

Facilities burning wastes from several outside plants or inside process areas are often required to blend wastes. The blending function is intended to avoid sudden changes in waste heating value, atomization characteristics, and other parameters that would throw the unit into an upset situation. For example, while sustained combustion is possible with wastes as low as 2200 kcal/kg, it is generally preferred to blend to about 4500 kcal/kg. Similarly, although wastes have been burned at as high as 70% chlorine, it is common to blend to concentrations less than 30%. For this purpose, a "day tank" is used where metered quantities of several wastes (confirmed to be entirely compatible with respect to oxidation or reduction reactions, polymerization, gas formation, and other hazard risks) are pumped to a mixed tank for feeding to the incinerator burners.

2. Atomizer Characteristics

Atomizers are critical to successful liquid waste incineration. In order to maintain atomizer performance, they should be designed for removal and change-out when the unit continues to operate. Inspections to observe erosion or corrosion of nozzles should be frequent and thorough. Eroded nozzles will not produce finely divided droplets or a good spray pattern. Instead, a solid liquid stream forms with impingement and, obviously, serious deterioration of combustion performance.

The degree of atomization achieved depends on the kinematic viscosity of the liquid and the concentration and size distribution of solid impurities present. For pumping, the viscosity should be below 10,000 SSU. For atomization, the maximum kinematic viscosity should be below 750 SSU. For some burners, 750 may be too heavy for proper atomization. Often, heating with tank coils or in-line heaters is used to reduce the viscosity although a temperature of 200° to 260°C is usually the limit because of pump limitations and the potential for vaporization, gas evolution, or undesirable chemical reactions (polymerization, corrosive attack of piping and pump materials, etc.). If heating is not feasible, it may be possible to reduce the viscosity by addition of a miscible low-viscosity liquid. Solid impurities interfere with burner operation. Plugging, erosion, and ash buildup are potential problems. If the solids are large relative to the dimensions of the nozzle passages, consideration should be given to filtration to remove the solids. Acceptable combinations of viscosity and solids characteristics for several different atomization methods are summarized in Table 2.

The atomization methods most often used for hazardous waste systems are

Rotary cup atomization
Single-fluid pressure atomization
Two-fluid, low-pressure air atomization
Two-fluid, high-pressure air atomization
Two-fluid, high-pressure steam atomization

The rotary cup atomizer consists of a rapidly rotating open cup mounted on a hollow shaft through which the liquid to be atomized is pumped. As the liquid enters, it spreads in a thin film on the inside of the cup until it is spun off as a droplet from the lip. A carefully

Table 2 Characteristics of Various Atomization Techniques

Atomization type	Maximum kinematic viscosity (SSU)	Maximum solids (mesh size)	Maximum solids concentration
Rotary cup	175 to 300	35 to 100	20%
Single-fluid pressure	150	—	Essentially zero
Internal low pressure ($\leq$ 2 atm)	100	—	Essentially zero
External low pressure (air)	200 to 1500	200[a]	30%[a]
External high pressure (air)	150 to 5000	100 to 200[a]	70%
External high pressure (steam)	150 to 5000	100 to 200[a]	70%

[a]Depends on nozzle inside diameter.
Source: From (335).

adjusted high-velocity jet of primary air is directed axially around the cup to develop a conical, well-shaped flame. This atomization method is solids-tolerant and exhibits a substantial turndown capability (as much as 5:1). Capacities from 1 to 280 cm^3/sec are possible.

Single-fluid pressure atomizers use swirl, imparted by a nozzle with internal vanes, driven by moderate pressures (6.8 to 10 atm). Combustion air is generally added to surround the conical spray of droplets. Capacities range from 40 to 400 l/h. Turndown is limited to 2.5 to 3 : 1 because of the close dependency between the pressure drop and the quality of the atomization process. Some nozzles incorporate a return flow of the liquid to be atomized so that pressure can be maintained at low net flow out of the nozzle. With these designs, turndown up to 10 : 1 can be achieved. The high liquid velocities and close tolerances within these nozzles make them subject to erosion and plugging if the concentration of solids is significant.

Air or steam atomizing is accomplished within the nozzle by impinging the gas and liquid stream inside the nozzle; externally by impinging jets of gas and liquid after they have left the nozzle body; or by sonic means where compressed air creates a high-frequency sound wave that disrupts and atomizes the liquid stream. Since the energy to atomize is not based on high-pressure flow through restricted orifices, little waste pressurization is required and relatively large dimensioned solid matter can be tolerated without plugging.

Preferably, two-fluid atomization (steam or compressed air) should be used instead of pressure atomization. This type of nozzle is far less sensitive to moment-to-moment changes in viscosity and to erosion. Also, the two-fluid nozzles have far better turndown characteristics. Of the two, compressed air atomization is, probably, to be preferred since, in any event, the mass of air added in atomization would be added to the combustion flow. The mass of steam used for atomization is an inert (diluting the oxidizing capacity of the furnace gases) and must be heated to combustion temperatures at some net drain on the furnace heat balance.

Low-pressure atomization uses air from blowers at from 3.5 to 35 kilopascals. Viscous wastes (e.g., at 15 to 18 centistokes) require air above 10 kilopascals, whereas aqueous waste could be readily atomized with only 3.5 kilopascals (335). The waste itself is supplied at from 30 to 120 kilopascals. Turndown ranges from 3 : 1 to 6 : 1 using

atomization air quantities from 2.75 to 7.5 m^3 of air per liter of waste with less air being required as the atomization air pressure increases. Since up to 40% of the combustion air requirement is met by the atomization air, the flame is short.

Higher-pressure atomization uses compressed air or steam at 200 to 1000 kilopascals pressure. The higher pressure results in the use of less atomizing fluid (from 0.6 to 1.6 m^3 of air per liter of waste or 0.25 to 0.5 kg of steam per liter of waste). Turndown is poor (3 to 4 : 1). The limited quantity of air used results in a relatively long flame. However, these burners can burn relatively high-viscosity liquids. Also, steam atomization tends to reduce soot formation.

Another means to achieve high turndown involves the use of several small nozzles rather than just one or two large ones. The smaller nozzles typically have a shorter flame and produce smaller droplets of material. Unfortunately, an increase in the number of nozzles results in an increase in piping and refractory cost. However, the tradeoff may be well worth the cost.

3. Solids Feeding

The feeders for solids are critical. In conjunction with conveyors, the feeders transfer solids at a controlled rate from storage into the process. Four types of feeders are commonly used: rotary, screw, vibrating, and belt as well as several specialty feeders. Table 3 relates feeder types to material characteristics. For hazardous wastes, the screw and belt feeders are most common.

Belt feeders and screw feeders can have problems with dusting, and enclosing the conveyor may be necessary. For belt feeders, accumulation of dust and spillage within the enclosure can ultimately cause the feeder to shut down, thus presenting a hazardous cleanout operation in addition to the consequent incinerator outage. With screw feeders, dust leakage around covers and along shaft seals is common.

Container feeding is sometimes needed; especially when the material in the container presents hazards if exposed to the air or when the material is not readily removable from the container. Batch feeding of large, highly combustible wastes clearly leads to excursions in air demand and overpressure ("puffs") of the primary furnace chamber (see Table 4). Conveyor to air-lock charging or hydraulic drum and pack-feeders are common. In some instances, special close-tolerance high-torque screw feeders are used to force sludges or mixed-media solid/sludge mixtures into the combustion chamber. Clearly, the design features of these specialized screw feeders, including the use of corrosion and abrasion-resistant materials, make them quite costly.

Table 3 Feeders for Bulk Solid Materials

Material characteristics	Feeder type
Fine, free-flowing materials	Bar flight, belt, oscillating or vibrating, rotary vane, screw
Nonabrasive and granular materials, materials with some lumps	Apron, bar flight, belt, oscillating or vibrating, reciprocating, rotary plate, screw
Materials difficult to handle (hot, abrasive, lumpy, stringy)	Apron, bar flight, belt, oscillating or vibrating, reciprocating
Heavy, lumpy, or abrasive materials (e.g., pit-run stone and ore)	Apron, oscillating or vibrating, reciprocating

Table 4 Maximum Container Size as Related to Primary Combustion Chamber Heat Release

Container size		Chamber size	
English units	Metric units	10^6 Btu/hr	10^6 kcal/hr
2 ft^3	0.057 m^3	14	3.53
5 gal	18.93 lit.	5	1.26
30 gal	113.6 lit.	30	7.56
55 gal	208.2 lit	55	13.86

Source: From (317).

4. Containerization

For some wastes (especially pastes or sludge materials in relatively small quantities), a container is used to accumulate, hold, and then fire the waste (particularly for rotary kiln units). Both plastic and fiber drums have been used in this service. Generally, a container is selected that is completely burned in the incinerator (versus, say, steel drums) in order to minimize the quantity of residue requiring handling and disposal. The maximum container size charged to an incinerator must be matched with the capacity of the primary furnace to absorb the peak equivalent heat release that occurs on rupture of the container if it were to contain a volatile, high-heating-value material. Table 4 indicates typical container sizes.

5. Oxidation Strategy

With only a few exceptions, incinerators are intended to burn in the fully oxidizing condition. Pyrolysis processes are slower and produce a complex mixture of products of incomplete combustion (PICs) including soot and/or tarry intermediates that, in general, burn with greater difficulty than the parent molecule. Thus, the designer and operator should give careful attention in the selection of air/fuel settings, maintenance of air registers and combustion monitoring and control instruments, hardware setups to achieve desired flow patterns, inclusion of means to induce mixing, and other steps to ensure that, indeed, the system is oxidizing everywhere.

C. Control Systems

The stringent performance requirements placed on hazardous waste incinerators demand a complex, multiparameter instrumentation and control system. Beyond the conventional need for such equipment as an aid to operation, the operating permit for the facility often requires that several channels of real-time information must be archived to provide a historical data base confirming to the regulatory agencies that the system is indeed being operated at all times within the parameter ranges confirmed as satisfactory in the trial burn. Further, the instrumentation and control system must be designed with interlocks and "fail-safe" set points such that shutdown of the feed (not simply an alarm) and other intrusive, protective actions are initiated automatically if key parameters fall outside the approved operating envelope. Several of the more common parameters are listed in Table 5.

Table 5 Incineration System Parameters Triggering Fail-Safe Controls

	Basis for corrective action		
Parameter	Excess emissions	Worker safety	Equipment protection
High CO in stack gas	X		
Low chamber temperature	X		
High combustion gas flow	X		
Low pH of scrubber water			X
Low scrubber water flow	X		X
Low scrubber pressure drop	X		
Low sump levels	X		X
High chamber pressure		X	
High chamber temperature		X	X
Excessive fan vibration			X
Low burner air pressure	X		
Low burner fuel pressure	X		
Burner flame loss	X	X	X

Source: From (336).

D. Refractory

Chapter 5 presents a general discussion of refractories and refractory properties. The material that follows is focused on the selection of refractories for hazardous waste incineration service where high operating temperatures and the (often) high salt and halogen content of the feedstock can present a special challenge and demand special considerations. In most such facilities, refractory repair and replacement constitute the major maintenance expense and are a common cause of outage. In general, the investment of additional capital to install superior-quality refractory is well repaid.

A survey of operating incineration plants (346) found a clear pattern in the refractories that gave acceptably long service. The results, generalized in their applicability to both liquid injection and rotary kiln facilities, suggest the following for alkali-laden waste and halogenated hydrocarbons:

Operating temperature (°C)	Type of refractory
980–1090	High-fired superduty brick (40%–45% Al_2O_3)
1150–1370	High-purity 60%–70% Al_2O_3 brick
1370–1540	High-purity mullite-bonded 90% Al_2O_3 brick

Several precautions were identified, including the following:

1. Basic brick (magnesite and magnesite-chrome bricks) can often be shown in laboratory tests to show superior results when compared to alumina brick in slab-brick reactions. However, these bricks are relatively porous compared to a high-density, low-porosity alumina brick. Thus, slag penetration and susceptibility to massive material loss due to thermal spalling associated with differential thermal expansion may counter the fluxing advantages.
2. Basic brick is susceptible to hydration on exposure to moisture during operation or improper storage. This can significantly reduce service life.

3. Phosphate-bonded high-alumina bricks may be more susceptible to fluxing than mullite-bonded brick.

4. Although castable or plastic materials are often necessary, calcium aluminate cement-bonded castables and gun mixes have shown poor resistance to most hazardous waste incinerator slags and to chlorides (forming calcium chloride compounds). This particular problem and the generally greater vulnerability of these materials strongly support the use of brick structures in the high-temperature regions of the furnace.

5. In rotary kiln practice, where iron oxide slags were formed from incineration of wastes in steel barrels, a 90% Al_2O_3/10% Cr_2O_3 brick gave excellent performance when system conditions varied between 1260° and 1540°C. This brick has good potential for extremely high temperature areas for both liquid injection and rotary kiln service.

The life of the refractory is generally related to the working temperature and the general service. As a general rule of thumb (369) suggests that the temperature should dictate the alumina content of the lining. At lower temperatures, lower Al_3O_3 content is acceptable. With selection of high-quality refractory appropriate to the service, a working life for rotary kiln of liquid injection incinerators under severe conditions (say, temperatures above 1100°C) of one to two years is to be expected. In very moderate, low-temperature service with little or no abrasion (e.g., in liquid injection service at working temperatures of about 870°C, a working life of up to 10 years is not uncommon.

Alkalis can have a very detrimental effect in their reactions with fire-clay and high-alumina refractories. The alkalis (sodium compounds are often the most prevalent) form glasses with the alumina-silica (40%–55% Al_2O_3) which glaze and seal the refractory. At higher temperatures, the glaze becomes sufficiently fluid to drain from the surface, thus eroding the brick. Also, their penetration significantly changes the thermal expansion characteristics of the brick in the densified, glassy zone. On rapid temperature change, this produces stresses in the brick that result in spalling losses. Higher alumina (70% alumina or greater containing free corundum) also react with sodium compounds to form expansive nepheline phase. This disrupts the brick structure and leads to strength losses.

Halides (especially chlorides and fluorides) are part of another compound group detrimental to refractory. Chlorine reacts with silica and alumina to form volatile chlorides, thus increasing refractory porosity and reducing strength.

E. Air Pollution Control for Hazardous Waste Incinerators

The regulation of air emissions from hazardous waste incinerators initially focused on means to ensure destruction of the toxic organic matter in the feed and on control of acid gases (particularly, HCl). This led to concern over the severity of the combustion environment (monitored through temperature, oxygen concentration, and total flow rate) and, usually, to the addition of Venturi scrubbers with alkali for particulate and acid gas capture. In the mid- and late 1980s, it became clear that the effluent gases could, and often did, include heavy metals. This led to increased regulatory attention on metals emissions and, often, to requirements for "health risk assessments" on the implications of metals emissions. However, in most instances, the Venturi scrubber systems can satisfactorily achieve acceptable emission levels. In large plants in the United States and Europe, the spray dryer with fabric filter combination or the Venturi-wet ESP combination has become accepted. The distribution of APC alternatives in the mid-1980s is shown in Table 6.

At most rotary kiln and many liquid injection systems, the most common APC system is a high-energy Venturi scrubber followed by two sieve trays for additional gas

Table 6 Air Pollution Control systems on Hazardous Waste Incineration Systems (1987)

Air pollution control type	Number	Percent
Quencher	21	23.3
Venturi scrubber	32	35.6
Wet scrubber	7	7.8
Wet ESP	5	5.5
Ionizing wet scrubber	5	5.5
Other, non-specified scrubber	12	13.3
Packed tower absorber	18	20.0
Spray tower absorber	2	2.2
Tray tower absorber	1	1.1
Other absorber	2	2.2
None/unknown	31	34.4
Total systems surveyed	90	

Source: From (336).

absorption and then another sieve tray and an inertial separator or other demister to minimize carryover of droplets. In many situations, a quencher section is provided ahead of the scrubber. The decision to use or not use a quencher may be made according to the following:

A quencher should be used upstream of either packed bed or plate towers unless preceded by a Venturi scrubber.
A quencher is optional with a Venturi scrubber but, by dropping the temperature, often reduces the material costs for the Venturi.
Mist eliminators are an integral part of wet APC systems and should be included after the last scrubber in the APC train.

Because of the highly corrosive nature of many of the products of combustion of hazardous wastes, Hastelloy C and Inconel 625 have found wide acceptance in the quench section. Stainless steels (especially the austenitic 304 stainless) are generally unacceptable due to stress corrosion cracking sensitivity under acid conditions in the presence of chlorides. Unprotected carbon steel degrades rapidly. Carbon graphite or acid-resistant refractories can be used as a lining material for carbon steel construction, but spray nozzles should use the Hastelloy C or Inconel 625 material.

In the scrubber, Hastelloy C or Inconel 625 can be recommended for the scrubber shell and internals. Ceramic, carbon, or plastics can be used for packing material. If the temperature reduction in the quench section is reliable, FRP can be used in the scrubber to gain its features of low cost, easy fabrication, excellent corrosion resistance (to about 95°C) and light weight. To ensure reliable quenching, emergency water service should be provided.

F. Evaluation Tests and POHC Selection

The high degree of regulatory scrutiny applied to hazardous waste incinerators is reflected in an elaborate and detailed testing and evaluation procedure. In the United States, the

heart of the regulatory approval process is the "trial burn." In the tests comprising the trial burn, a waste (either the "real" material or a surrogate of comparable heat content, chlorine content, and content of designated POHCs) is burned at a known and measured rate under defined incinerator conditions (especially temperature and flue gas oxygen content). Elaborate stack sampling programs produce the data needed to determine the DRE for each of the POHCs. Often, the tests are run over a range of operating conditions to give the owner/operator a measure of flexibility in his or her operations. Particularly, achievement of target DREs with several feed rates, heat release rates, and temperatures is desirable.

The selection of the POHC(s) to use in the testing program is critical. The incinerability of the POHC used in the DRE testing is the most important criterion since this sets the "worst-case scenario" for all future operations. No POHC presenting a more difficult incinerability characteristic can be burned without requalification of the unit. However, incinerability is not the only issue. A comprehensive list of pertinent POHC selection characteristics (372) is shown in Table 7.

1. Thermal Behavior

As noted, the single most important characteristic in selecting a POHC is its relative incinerability since this sets the "worst case" of any waste that can be burned in the facility

Table 7 POHC Selection Criteria

Thermal behavior	**Chemical characteristics**
Incinerability ranking	Chemical class/structure
Tendency to form a PIC from waste or fuel	Halogen content
Tendency to generate PICs	**Incinerator design elements**
Effect of combustion atmosphere	Waste-handling systems and firing methods
Physical characteristics	On-site versus off-site
Heating value	Permit conditions desired
Viscosity	Air pollution control equipment
Volatility	Auxiliary fuel and scrubber water as POHC sources
Solubility	**Practical considerations for use of surrogates**
Waste characteristics	Availability
Concentration of native POHCs	Cost
Toxicity of native POHCs	Handling hazards
Physical state/characteristics of waste	Ease of mixing/spiking
Interaction of POHCs with waste streams	
Sampling and analysis considerations	
Chemical and physical properties affecting sampling and analysis	
Requirements for specialized sampling train or analytical method	
Analytical interferences	
Contamination potential	
Recoveries	
Availability of analytical standards	
Quality control	

Source: From (372).

without requalification. Unfortunately, there is not yet consensus in the regulatory or scientific community as to the "best" approach to assessing incinerability. The U.S. EPA has suggested a ranking using heat of combustion. But analysis of DRE data shows this is an imperfect scale. Laboratory decomposition kinetic studies under low oxygen conditions developed by the University of Dayton (373) are promising and correlate well with DRE determinations in the field. The U.S. National Bureau of Standard's flame-mode kinetics method, ranking by autoignition temperature or by the temperature giving 99% or 99.99% reduction under a set of fixed time and oxygen concentration conditions, have also been explored with some success. Appendix G provides a ranked list of the relative incinerability of various organic compounds based on kinetic data and the University of Dayton determinations.

Other issues relating to decomposition behavior include the predominant PICs. In general, a POHC that is formed as a PIC from the incomplete oxidation of constituents present in significant concentrations in the waste stream of interest should not be selected. Also, the sensitivity of combustion to the oxygen concentration or to the flue gas moisture or halogen content may be important. These elements of the POHC selection process are not quantitative, and their relative importance or the mode of their application in decision-making is not a matter of general agreement. Rather, if it is known that one or the other sensitivity exists, it is worth considering, especially in the selection of surrogates.

2. Chemical and Physical Characteristics

The chemical class (aromatic, aliphatic, unsaturated, oxygen, nitrogen and/or halogen containing, etc.) is important. Regulatory agencies prefer to see a diversity of classes studied and to see close structural and elemental parallels between proposed surrogates and the reference chemicals they are to represent. Halogen content matching is key to allowing confirmation of the achievement of acid gas control efficiency standards.

Physical characteristics include volatility, viscosity, solubility, and the like that affect atomization and volatilization characteristics and the blending of the POHC with the main waste stream. If preheating of the waste is needed (e.g., to reduce viscosity), one must be assured that the POHC is not volatilized and flashed off.

3. Incinerator Design Characteristics

If the incinerator is associated with a specific process line, the feedstock is probably well defined and stable. If this is so, the POHC may be easy to identify. If a commercial incineration facility or an industrial facility serving several plants is of interest, the POHC (or surrogate) must be chosen to give sufficient flexibility to permit operation for all reasonable conditions. If the "normal" operation does not require HCl control (e.g., the burning of an HCN off-gas), one must be careful not to select a POHC that due to its halogen content, adds an HCl control requirement or causes corrosion problems during the tests. Also, the potential contribution to the stack emissions of PICs from any auxiliary fuel (especially oil or coal-fired systems) or POHCs stripped from scrubber water (e.g., if treated plant effluent water is used as scrubber water) should be considered.

4. Waste Characteristics and the Use of Surrogates

POHCs that are compatible with the wastes should be selected. If, for example, an aqueous waste is being studied, solubility in water is desirable. If the POHC is strongly adsorbed onto solid surfaces, that may impact recovery of the waste in analysis of the solid product or removal of traces of the waste from particulate in the flue gas stream. The commercial

availability, safety in handling and mixing, and transportability of proposed POHCs should be considered, as should the purity and composition variation of commercial grades of chemicals used as surrogates or to surcharge or "spike" the waste stream being tested.

Waste components that are present in the "normal waste" in high concentrations that also meet the relative incinerability requirements are good candidates. However, in many instances, the constituents present in high concentrations may not present the "worst-case" incinerability characteristics, they may be highly variable in concentration, they may be significant PICs of waste or fuel components, etc. In these circumstances, it may be desirable to select a surrogate POHC not necessarily present in the waste in meaningful concentrations that adequately evaluates the system performance without risking failure due to sampling and analysis problems, etc., and that does not present unreasonable safety or other handling/feeding problems. As long as the chemical, physical, and incinerability measures approximate or are more stringent than the "real waste," many permitting agencies will agree to the substitution.

5. Sampling and Analysis Issues

The sampling and analysis of materials in the raw waste and in the stack gases produce the fundamental data used to judge whether or not the facility meets the key DRE requirement. Thus, it is not wise to select POHCs where the protocols for sampling/analysis are still developmental, where the materials can react or degrade in storage, where analytical standards are unavailable, or where interferences from other compounds one might expect to find in the effluent are serious. A number of POHCs where these kinds of problems often occur have been identified (374).

The key constituent in the waste from the standpoint of toxicity or incinerability may be present in low concentrations. Experience has shown that systems often appear to "fail" the test burn when a POHC is selected such that the concentrations to be measured in the stack gases at the DRE approach the levels of analytical detection. The POHC should be selected such that the inherent concentration in the waste (or that achieved by "spiking") gives a stack concentration at an acceptable DRE that is at least an order of magnitude greater than the analytical detection threshold.

II. ROTARY KILN SYSTEMS

The rotary kiln is an extremely versatile incineration system used to burn solid wastes in a variety of containerized, bulk, granular, and other physical forms. Kilns are also used for slurries, sludges, and pastes. Installation of liquid and/or gaseous waste burners discharging into the kiln or its secondary combustion chamber further enhances the flexibility of the furnace system as the premier "omnivore" among waste management alternatives. These units are operated at temperatures from 800° to 1650°C such that the residues range from dry, free-flowing material to liquid slags. Systems with heat release rates as high as 30 million kcal/hr have been operated, but 15 million kcal/hr is a more common size range. Volumetric heat release rates are generally in the range from 60 to 100 kcal/m^3-sec (342).

A basic rotary kiln is comprised of a cylindrical, refractory-lined steel shell, supported on two or more (but, preferably, only two) trunnions. Kilns in hazardous waste service are typically from 2.1 to 3.7 m inside diameter (ID) and 7.5 to 20 m in length. Typically, the kiln shell is augmented by a heavy steel "tire" at the point of support. The kiln may be driven by a powered trunnion roller, by a gear mounted external to the kiln

(usually near one of the support points), or by a chain driving a large, circumferential sprocket. The kiln is sloped gently (usually, from 0.0 to 0.03 m/m) and rotated slowly (0.5 to 3.0 rpm is the common range). Usually, the rotational rate is less than 2 rpm, but many facilities have the capability to operate between 1 and 5 rpm. The internal surface of the kiln may be smooth or may contain longitudinal plates or ridges (flights) to lift and spill the material, circumferential ridges (dams) to hold back material, and/or a multitude of festooned chains or baffles (internals) designed to improve the contact of the solid with the air or flue gas flowing through the kiln.

A kiln may be operated in the co-current (parallel) or countercurrent mode with respect to the relative direction of gas and solids flow. Generally, co-current flow is used primarily for wastes with higher heats of combustion and relatively low moisture content (autogenous). Countercurrent mode operations are primarily for high-moisture content (>30%) wastes and for waste with a low heat of combustion. Kilns operated in the countercurrent mode maximize heat and mass transfer. They have a distinct "cold end" where the solids are charged. Since the preheating of the solids withdraws heat from the gases, the leaving gases are considerably colder than in the firing zone, where preheated solids and burning fuels combine. Also, since the freshly fed solids are, as yet, unburned, the potential exists for distilling/evaporating organic matter from the waste into an environment with a temperature that is below the combustion threshold. As a consequence, combustion may have to be rekindled through fuel (or "hot" waste) burning in the secondary chamber. Clearly, this situation also emphasizes the importance of achieving good mixing in the secondary.

At its feed end and discharge, the rotating kiln mates to fixed chambers using specialized sliding seals. In-leakage at these seals is common. A number of proprietary seal designs are in use. The gases discharge to a secondary chamber for continued burning and mixing of the gas phase. Also, some means must be provided to withdraw the solid residues from the system. In many industrial pyroprocessing embodiments of the kiln principle, the solids removal system is designed to recover heat from the ash in a "clinker cooler" by preheating a portion of the combustion air.

The rate of movement of material through a kiln may be estimated using several relationships. It should be noted that the character of the waste changes as it progresses down the kiln. Thus, the relationships should, more appropriately, be used for several reasonably uniform zones along the kiln and the total residence time calculated as the sum of the residence time for the several zones.

$$\theta = \frac{0.19 L_T}{NDS} \tag{3}$$

where

θ = the mean residence time (min)
L_T = the length of the kiln (m)
N = the kiln rotational velocity (revolutions per min)
D = the kiln inside diameter (m)
S = the kiln slope (m/m)

Another estimation technique for kiln residence time (339) is based on the consideration of the two types of material motion that occur within a kiln: tumbling or sliding. Tumbling is the preferred action since it induces waste mixing, proper retention, and enhanced combustion. In tumbling, the friction factor (μ) between the material and the

kiln lining is great enough so that material is lifted up with the rotation of the kiln until the angle ψ (the angle between a theoretical line connecting the center of gravity of the material to the axial center and vertical centerline of the kiln) exceeds the angle of repose of the material (β) whereupon the material falls. The cycle is repeated. When the sliding process dominates, one notes that the friction factor between the material and the kiln lining is small and the material often breaks loose and begins to slide before reaching the angle of repose. In general,

Tumbling action occurs when $\beta < \psi$
Sliding action occurs when $\beta \geq \psi$

If the material properties are known (see Table 8), a more accurate design relationship for kiln residence time (θ) for a kiln with a slope of σ degrees is given by

$$\theta = \frac{1.77\beta^{1/2}\Omega}{\sigma N}\frac{L_T}{D} \tag{4}$$

The factor Ω adjusts for the presence of lifters, flights, or dams in the kiln and is 1.0 for a smooth kiln and may be as low as 0.5 with lifters. The effect of dams and other internals on mean retention time has been described by Bayard (141). Typical values of residence time in ashing kilns range from 20 min to over 1 hour. In slagging kilns, solids residence times of 1 to 2 hours are common.

The length to diameter (L/D) ratio of units range from 2 : 1 to 10 : 1, with most being found with a L/D between 2.5 and 4.0. The particularly long kilns are used, most especially with high-moisture wastes, high fixed-carbon content waste, or low heat of combustion waste. The longer kilns have a disadvantage in that the long sweep of gases across the waste leads to high particulate entrainment and carryover. Gas velocities are usually maintained in the 4.5 to 6.5 m/sec range. Kiln internal pressure in the kiln is maintained between 1 and 5 cm of water (draft) to provide some protection against "puffs": pressure surge events that arise when a sudden release occurs (such as rupture of a container of volatile solvent). The ability of a kiln to accommodate the sudden heat release from various containers is illustrated in Table 4.

The rotary kiln system cannot be limited to the kiln alone. The kiln provides a useful and rugged support on which to accept, move, and stoke wastes as they burn. However,

Table 8 Typical Material Characteristics (for Application in Kiln Residence Time Estimation)

Material	Density (gm/cc)	Angle of repose
Ash (dry)	0.56–0.64	45+
Bark, wood waste	0.16–0.48	45
Earth (dry)	1.12–1.28	30–45
Earth (moist)	1.25	30–45
Earth (wet, with clay)	1.60–1.76	45
Fullers earth oil filters	0.56–0.64	35
Hospital waste (bagged)	0.08–0.24	40
Municipal waste	0.16–0.24	35–40
Sand (dry)	1.14–1.76	25–35
Wood chips	0.16–0.48	45+

Source: From (339).

with the exception of the O'Conner Combustor described in Chapter 6 (used primarily for municipal solid wastes), there is no means to introduce air along the kiln length. Thus, the kiln process includes a large measure of "starved-air combustion" and relatively poor mixing in the overbed space. The kiln gases are often highly stratified with oxygen-starved, high-temperature gases along the top of the kiln and relatively cool, oxygen-rich gases near the bed. The solids are usually well burned out however (especially if strongly heated by radiation from a burner and/or if the kiln is operated in the slagging mode). It is the off-gas that needs attention. The secondary chamber incorporates auxiliary burners to ensure achievement of high temperatures and to introduce mixing energy that is critical to meeting the superior DREs demanded of hazardous waste incinerators.

The loading of the kiln as measured by the volumetric holding rate (ϕ) expressed as a percentage of the total kiln volume occupied by the waste is kept below 20%. In ashing kilns, the load usually takes up 7.5% to 15% (10% is typical), while in slagging kilns, 4% to 6% is common. The holding rate is defined (339) in Eq. (5) as

$$\phi = 100\frac{F\theta}{V} \tag{5}$$

where

ϕ = holding rate (%)
F = waste throughput (m^3/min)
θ = residence time (min) of the solid waste
V = kiln volume (m^3)

Based on the relationship between β, μ, and ψ from above, it can be shown that for $\mu = 0.5$ and $\beta = 35^\circ$ (typical values), many waste materials exhibit the following approximate motion characteristics:

For $\phi \geq 6\%$, tumbling action occurs.
For $\phi < 6\%$, sliding action occurs.

For many incineration applications, the burnout of combustible greatly decreases the volumetric holding rate in the discharge end. To avoid sliding behavior, longitudinal refractory ridges are sometimes created by installing brick 4 cm or so greater in depth than the normal kiln block, thus giving a lifting and holding effect. Also, circumferential "dams" are sometimes installed.

A. Sludge Incineration Applications

In operation, sludge is fed to the higher end of the kiln. Kiln loading is usually in the range of 3% to 12% of the cross-sectional area. The time–temperature profile experienced by the sludge depends on the mode of operation: concurrent or countercurrent.

In concurrent flow, a relatively large burner is used in the feed hood to apply heat to the incoming wet feed. By the time a significant portion of the sludge has dried to the point where ignition can take place, the sludge is often too far from the primary burner to effect reliable ignition. A second kiln with an ignition burner would then be appropriate. The high cost of a second kiln, drive, and supports, and the high fuel consumption make this strategy unattractive. Note that with this operating method, the heat release from the burning sludge is unavailable for wet sludge drying.

In countercurrent flow, the burner is mounted at the discharge end of the kiln, firing against the direction of sludge movement. Entering sludge passes down the kiln, into ever-hotter regions: the drying zone, the preheating zone, the ignition and burning zones, and, just before discharge, the ash cooling zone. As the gases pass up the kiln, they are progressively cooled but continue to transfer heat since they are in contact with cooler sludge. Thus, the combustion energy of the sludge and the burner is most efficiently extracted. Unfortunately, it is just this efficiency that creates a problem: low wet-end temperatures and consequent odorous off-gas. In hazardous waste incinerator applications, low cold-end temperatures result in unburned POHC, thus emphasizing the role of the secondary chamber (with heat addition) to complete the combustion process. In these energy-conscious years since the late 1970s, the high fuel costs for odor destruction (using an afterburner) of the typically high gas volumes (corresponding to 200%–300% excess air) in countercurrent sludge burning operations are often unacceptable. Clearly, however, well-dewatered sludges, operations to hold wet-end temperatures as high as possible, and excess air control can minimize this serious disadvantage.

B. Solid Waste Incineration Applications

1. Ashing Kilns

The rotary kiln, operated in the ashing mode (with a "dry", nonmolten residue), is the most common and well-proven system for the incineration of hazardous solid waste. Most of the discussions presented above are directly applicable to the ashing mode operation and will not be repeated here. The ashing mode is most appropriate when the feedstocks are of low heat content as, for example, in the remediation of contaminated soils. Flue gas velocities at the kiln discharge are usually kept to a maximum of 4.5 m/sec and, more commonly, 3 m/sec to minimize the suspension and carryover of particulate matter.

At operating temperatures in the 980°C range, a high-fired, superduty fireclay refractory should be suitable, minimizing reactions and maximizing service life (369). For higher kiln temperatures (1150°–1370°C), 60% to 70% alumina brick is needed to minimize the impact of alkali fluxing and attack by iron oxides. At still higher temperatures (1480°–1600°C), solid solution bonded alumina-chromic oxide compositions have been suggested to cope with the Fe_2O_3 reactions. Note that the freedom from significant iron concentrations in the secondary chamber reduces the necessity of the costly alumina-chromic oxide materials.

2. Slagging Kilns

As the operating temperature in a kiln increases, one reaches a point where the solid residuals fuse to a molten slag. Ideally, one maintains the temperature and residue chemistry such that the viscosity of the slag is correct. "Correct" viscosities are not so high that unwanted buildup occurs nor so low that refractory penetration and rapid wastage occur. Further, one wants the toxic metals in the residue to be firmly bound such that low-cost fill applications for the (cooled) slag exhibit acceptable leaching characteristics and, thus, are environmentally acceptable (vis-a-vis directed disposal in a costly hazardous waste storage landfill). Control of slag composition is usually feasible in industrial kiln operations but much less so in incineration situations. There, the operator seldom knows the slag composition and is unable to influence it. One must, therefore, rely on experience with the wastes being fired.

The slag formed after burnoff of the organic fraction of industrial wastes is primarily made up of inorganic oxides: most commonly silica, alumina, iron oxide(s), and lime. In forming low-leaching slags, one wishes to build strong chains within the slag matrix. Silica, alumina, Fe_2O_3, and other acidic oxides contribute to this characteristic. Basic oxides, including the oxides of the alkali metals (Na_2O, K_2O), and lime (CaO) and sulfide and chloride anions are "chain breakers." They contribute to the sensitivity of the slag to weathering and its tendency to fail leaching tests.

The "replacement indices" in Table 9 are derived from an analysis of the radius, charge, coordination number, and electron configuration of an ion. The index is useful in judging the "fit" of a potential heavy-metal contaminant with a given slag. For example, a slag high in calcium (Ca^{+2}) would be a good host for cadmium or lead ions. Rapid cooling (e.g., quenching of the slag in a water bath) also helps in the incorporation of foreign ions into the slag matrix.

The slagging condition tends to reduce several problems inherent in ashing kilns but at a price. For example, the particulate loading that can become excessive in ashing kilns is reduced as much as 25% to 75% due to the "stickiness" of the molten pool. However, NO_x emissions are considerably increased as the operating point moves above 1450°C, where the thermal NO_x equilibrium is beginning to shift significantly.

a. Slag Fusion Temperature. The concept of a single slag fusion temperature is, generally, inaccurate. More properly, a given mass of slag melts over a range of temperatures beginning with the "eutectic" temperature and finishing at the "liquidus" temperature. Some of the residue (e.g., the metal from shredded drums) may remain unmelted. The melting characteristics of slags are determined using the ASTM ash fusion testing procedures (or their equivalent) as described in Chapter 4. The melting point can be estimated using the relationships presented there. Phase diagrams relating melting points or zones can be developed for the primary slag constituents using triangle graph paper. However, accurate predictions are difficult, in part because the ash chemistry is variable and/or unknown.

A few generalizations (316) are useful. For example, if the alumina concentration exceeds 15%, the melting point usually exceeds the practical limits of rotary kiln

Table 9 Indices of Ionic Requirement

Cation	Index of ionic replacement
Na^{+}	0.06
Ba^{+2}	0.07
Pb^{+2}	0.08
Ca^{+2}	0.09
Cd^{+2}	0.09
Zn^{+2}	0.14
Cu^{+2}	0.14
Ni^{+2}	0.14
Mg^{+2}	0.14
Fe^{+3}	0.22
Al^{+3}	0.35
Si^{+4}	0.48
As^{+5}	0.60

Source: From (316).

incinerators (approximately 1400°C). Similarly, if the silica concentration is less than 25%, melting is difficult. Alkali metal oxides or chlorides present above 5% act as a flux and significantly reduce melting point. Avoidance of excessive molar basicity helps to maintain a fusible slag.

b. Slag Molar Basicity. The molar basicity is calculated as the ratio of the mols of basic oxides (Na_2O, K_2O, CaO, $S^=$, Cl^-, and FeO) to the mols of acidic oxides (SiO_2, P_2O_5, Al_2O_3, Cr_2O_3, TiO_2, Fe_2O_3, and ZnO). A value of 1.0 for the molar basicity is "neutral." Acidic oxides readily incorporate into a silicate polymer network. Note that iron in the slag can act as either a strong base or a weak acid (with consequent changes in the molar basicity) depending on its degree of oxidation. Conversion from one iron oxide to the other can occur when the atmosphere changes from oxidizing to reducing. This can result in a significant change in the fusion temperatures of slags under different environmental conditions (see below). For slags containing Fe_2O_3, it is a reasonable approximation to assume that half of the iron behaves as an acid and the other half as a base. If the iron is present as FeO, assume it all acts as a base.

Increasing slag basicity tends to increase slag liquidus temperature and decreases slag liquid phase viscosity. The more basic the slag, the more basic must be the refractory to contain it since a low-viscosity, basic liquid slag will penetrate and flux (melt and/or weaken) acidic (e.g., high-alumina) refractory. If slag molar basicity is between 0.9 and 1.3, slag fluidity (the reciprocal of viscosity) is likely to be acceptable.

c. Slag Viscosity. A slag with a liquidus temperature of less than 1300°C and a molar basicity between 0.9 and 1.3 is likely to be fluid. A target viscosity of about 25 poise (approximately that of a SAE 70 weight motor oil) is sought. As the viscosity increases, the slag becomes less fluid. Buildup can occur if the viscosity exceeds 200 poise. On the other hand, if the viscosity falls below 10 poise, the refractory brick penetration and erosion rate is accelerated (316).

The presence of suspended solids in the slag increases the apparent slag viscosity. This is seen in Table 10 for a slag with a "true" viscosity of 15 poise.

It is generally found that when slag silica content exceeds 45%, slag fluidity suffers. At very high silica, the viscosity increases rapidly (especially if the alumina content exceeds 10%). Also, magnesia (MgO) at concentrations greater than 8% and chromic oxide at greater than 4% tend to react with alumina and FeO to form insoluble spinel-type precipitates. Then, the behavior illustrated in Table 10 occurs and viscosity increases rapidly (316).

Table 10 Effect of Solids Content on Slag Velocity

Solids volume %	Viscosity (poise)
0	15
10	22
20	33
30	55
40	105
50	250

Source: From (316).

d. Slag Oxidation Potential. In a hearth-burning situation such as a kiln, a reducing environment is created in and near organic material as it pyrolyzes. In combination with the limited penetration of oxygen into the load, it is not surprising, therefore, that the slag remains in a reducing state until residual carbon, metallics, and other oxygen scavengers are fully oxidized. Until this point, much of the iron is present as FeO with its tendency to increase basicity and facilitate melting. As the slag begins to oxidize, its liquidus temperature increases because of the shift to the less basic Fe_3O_4 (magnetite). Also, the magnetite has a low solubility in silicates low in CaO. The reduced fraction melted couples with the suspended solids effect to increase the effective viscosity.

The slagging kiln has been received well by the European hazardous waste establishment. The capture of heavy-metal oxides in the slag matrix is particularly important in Europe since secure landfill availability is limited and high in cost. Despite this unique advantage, however, the high cost for refractory maintenance in the slagging mode is slowly decreasing the attractiveness of this option, and the majority of the new plants operate in the ashing mode.

e. Refractory Life. Perhaps the greatest failing of the slagging mode is the high cost for refractory maintenance. Refractory replacement as frequently as every 3000 to 5000 hours of operation has been noted. This represents a cost in labor and materials and, also, in the out-of-service time.

3. Secondary Chambers

A rotary kiln system *must* be associated with a secondary chamber. Despite the mixing processes induced in the kiln by burners and air jets, kiln systems show a strong stratification in temperature and oxygen concentration. The gases at the top of the kiln are usually hot and oxygen-deficient, while the gas over the discharging solids is relatively cool and oxygen-rich. The secondary chamber is where the gas phase burnout is completed. Typical volumetric heat release rates are from 1 to 1.5 million kcal m^{-3} hr^{-1}, and heat release expressed over the average cross-sectional area is from 125,000 to 300,000 kcal m^{-2} hr^{-1} (409).

Mixing in secondary chambers is a complex function of the relative chamber and kiln diameters, the inlet geometry, and the location of burners. Most secondary chambers are tall "U-tubes" with the gases first rising and then falling. The gas velocities range from 2 to 6 m/s. Residence times (based on mean temperature and the volume from the uppermost burner level to the boiler or scrubber entry) range from 4 to 6 sec. The set-point temperatures depend on the characteristics of the POHCs and range from 1000° to 1400°C. It has been suggested that similarity comparisons between the mixing processes in the secondary chamber for two systems should be characterized by the modified Froude number ($N_{Fr'}$) calculated as

$$N_{Fr'} = \frac{V^2}{gL}\left(\frac{\rho}{\Delta\rho}\right) \tag{7}$$

where V is the gas velocity, L is a characteristic system dimension, and ρ and $\Delta\rho$ reflect the main gas flow temperature and the density differences in the system. The conventional Froude number is developed as the ratio of momentum to gravity forces. However, this modified Froude number is formed as the ratio of momentum to buoyancy forces in the secondary chamber flow field.

Often the top of the secondary combustion chamber is equipped with a thermal relief vent to vent hot flue gases if the temperature exceeds the preset maximum. The relief is *not* used to vent when temperatures are low.

Burners are provided both to ensure attainment of preset temperatures and to stimulate mixing. When possible, high-heat-content gaseous wastes or readily atomizable liquid wastes are used as fuels; fossil fuels are provided as a backup. Since the burners may supply combustion air for kiln off-gas, the burners are selected to operate over a wide range of air-to-fuel ratios (say, from 70% to 200% excess air based on the air demand of the burner fuel). When burning fossil fuels, the burners are trimmed to operate from near zero to 20% excess air. Burners with a 10 : 1 turndown with gas and 5 : 1 with liquid fuels give the flexibility desired to keep costs down and performance always at the highest level.

Entrainment of kiln off-gases in the burner flow may be estimated (389) using

$$\text{entrainment } (\text{m}^3/\text{sec}) = \frac{0.64 L Q_0}{D'} - Q_0 \tag{8}$$

where

L = flame length (m)
Q_o = air and gas injected through the burner at temperature (m^3/sec)
D' = flame diameter in (m)

The region of influence (the "throw") of the flame at a heat release rate of R million kcal/hr may be estimated (389) by

$$\text{throw (m)} = 1.926\ R^{0.625} \text{ (for zero-swirl burners)} \tag{9a}$$

$$\text{throw (m)} = 4.077\ R^{0.307} \text{ (for high-swirl burners)} \tag{9b}$$

and the flame diameter (meters) may be approximated by

$$D(\text{m}) = 0.5735\ R^{0.2275} \text{(for zero-swirl burners with } L/D \text{ of } 1:1) \tag{10}$$

III. CIRCULATING FLUID BED

Circulating fluid bed (CFB) combustors have become popular since the late 1970s. Their first major application was in standard coal combustion applications, but more recently they have been used in hazardous waste incineration applications. To prevent bed defluidization, mean gas temperatures in a CFB are purposely maintained below about 870°C. Nonetheless, burnout of both solid and gaseous phases is achieved due to the uniformity of the temperature and to generally good mixing. Performance levels with conventional hazardous materials to and beyond a 99.99% DRE (380) and with PCBs and dioxins to and beyond a 99.9999% DRE have been achieved (382).

Average gas residence time (based on system dimensions, gas flow rates, and temperatures) are typically about 2 seconds in hazardous waste incineration applications. Solids residence times up to 100 times longer are possible depending on the initial size, composition, and density of the particles. The CFB behaves as a plug-flow reactor. Reactive bed solids (e.g., limestone) can be incorporated to achieve a measure of acid gas control. Data have shown 88% to more than 99% sulfur dioxide and HCl control (381).

A. CFB Hydrodynamics

CFB systems typically operate between 5 and 10 m/sec gas velocities. Thus, unlike the bubbling bed described in Chapter 9 where the solids remain within the bed, the CFB velocities are high enough to result in rapid carryover of solids in the off-gas. Unlike the bubbling bed counterpart, the CFB furnace or "riser" does not have a well-defined bed surface. There is a dense region near the base and a gradient in solids concentration falling (relatively) smoothly from the bottom to the top of the vessel. The turndown achievable with CFB systems can be as much as 3:1 in comparison to the more modest 1.25 : 1 for bubbling beds (341).

A large fraction of the solids passing out of the bed are captured and returned. Large-diameter cyclone separators are commonly used to capture carryover solids. They are fabricated of steel with abrasion-resistant refractory lining. In a few cases (primarily in power plant combustors), waterwall boiler cyclone construction methods are used. Collection efficiency for the coarse solids has been measured at about 99% (370). The collected solids from the cyclone are rejected to the standpipe, and the off-gas flows to the subsequent convection boiler passes or to a secondary combustion chamber.

In some wood waste burning plants, a labyrinth array of uncooled, 310 stainless steel (or equivalent) channels ("U-Beams") is positioned vertically in the horizontal gas duct leaving the riser. Velocities in the separator are kept in the 4 to 5 m/sec range to control erosion. Particulate matter impacts the flat of the channel web and falls down the stagnant zone between the flanges of the channel to a collecting hopper and standpipe return leg below.

In its most common form in fuel-burning applications, the standpipe consists of a gently bubbling fluidized bed. This is quite different from the fine-powder standpipes in fluidized catalytic crackers. To minimize problems in aeration, the standpipe should be constructed as a simple cylinder with a vertical axis. The material in power plant CFBs is often kept fluidized; otherwise a packed bed will quickly form. Gas velocities in these risers are just in excess of the minimum to achieve fluidization. The solids at the bottom of the return leg are fluidized and reinjected just above the grid plate. Few of the CFBs used for hazardous waste use the fluidized standpipe concept. Several configurations of check valves and other solids control systems have been devised to control the return of solids. The simple loop seal (341) is preferred. If desired, a portion of the solids can be drawn off the bottom of the return leg.

At the high velocities in CFB systems, in-bed tubes are not feasible. Heat release in CFB units is often from 60,000 to 70,000 kcal/hr-m^2 of plan area compared with 20,000 to 29,000 kcal/hr-m^2 for a bubbling bed. Membrane "waterwalls" are used for heat removal. CFBs tend to be tall and thin rather than the short and fat conventional bubbling beds. Heat transfer rates to the wall approximate 170 to 215 kcal/hr-$m^2{}^\circ$C. Additional heat removal surface, if required, is often achieved by inserting vertical membrane wall panels ("wing walls") into the riser chamber.

If NO_x is a problem, the NO_x-forming reactions can be minimized by operating with staged combustion. Here, the lower region of the bed is operated with about 50% to 60% stoichiometric air (reducing). The remainder of the combustion air is added as secondary air after most of the fuel nitrogen has been released. In hazardous waste incineration applications, the reduction of NO_x is usually of secondary interest in comparison to achieving the maximum burnout of POHCs. One notes, however, that selective, non-catalytic reduction techniques using urea or ammonia have achieved 40% to 65% control of NO_x without resorting to staged combustion techniques.

Sulfur dioxide emissions from CFB units can be minimized by adding limestone to the feed. If the temperature is not too high (below, say, 900°C), 90% capture has been achieved at Ca/S molar feed ratios of as little as 1.3 to 1.5 to 1 (341).

IV. THERMAL DESORPTION

Thermal desorption (TD) technology was developed to remediate large quantities of soils, sediments, and sludges contaminated with hazardous materials. Often, this requirement is associated with the cleanup of the land in and about refineries, coal gasification plants, motor pools, and other operations involving the handling and storage of petroleum products, waste disposal, or manufacturing facilities that have been shut down, leaving large amounts of soil contaminated with the accumulation of years of spillage, improper land disposal practices, and the like.

TD involves the use of heat to volatilize the contaminants. Depending on the maximum soil temperature reached during passage through the system, TD is classified as either low-temperature (90° to 320°C) or high-temperature (320° to 560°C). Oxidation of the contaminants within the TD reactor is minimized by the low working temperatures. In some cases, an inert carrier gas such as nitrogen is used to sweep the contaminants from the TD reactor followed by recovery or destruction in downstream processes. TD has been extensively applied to the remediation of soils, dealing with contaminants such as volatile organic compounds, semivolatile organic compounds, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and a wide range of fuels and lubricants. Water is normally added to the treated soil for dust control.

TD systems consist of a rotary dryer device (directly or indirectly fired) or a heated screw-type conveyor. The rotary unit mechanically conveys and tumbles the soil, thus exposing a fresh surface and enhancing the volatilization rate. The screw systems use an abrasion-resistant screw heated with circulating hot oil or steam. In some designs, the heat transfer is enhanced by passing heated flue gases over the exposed surface of the solids.

Economic and practical TD can be difficult with

High-moisture soils. High moisture may require dewatering and also expresses a high latent heat load on the system.

Soils with a substantial particle size fraction larger than 5 cm. Large particles may require segregation and either crushing or manual cleaning.

Contaminants that have a low volatility and/or are strongly adsorbed onto the soil particles. In some cases, multiple passes (and increased cost) are required.

Abrasive soils. Abrasive particles may damage the processing units.

High-humic-content soils. Humic materials may lead to a requirement for increased retention time due to the binding of contaminants to the solid.

Clearly, the character of the soil has a pervasive impact on the application of TD technology; therefore, a brief introduction to soil classifications and characteristics is an important foundation to understanding the opportunities and constraints in using TD for soil remediation.

A. Soil Parameters

Soils are commonly classified according to the Unified Soil Classification System (USCS) (502). The basis for the USCS is that coarse-grained soils can be classified according to grain size distributions, whereas the engineering behavior of fine-grained soils is primarily

related to their plasticity. Table 11 describes the major soil divisions, names, and group symbols based on the USCS.

There are four major divisions in the USCS: coarse-grained, fine-grained, organic soils, and peat. Classification is performed using the material that passes through a 75-mm sieve. Material greater than 300-mm equivalent diameter are termed "boulders." Materials between 75 mm and 300 mm are called "cobbles." Coarse-grained soils (e.g., sands and gravels) have more than 50% retained on a 75-mm sieve, whereas fine-grained soils (e.g., clays and silts) have more than 50% passing through a 75-mm sieve. Organic soils and peat are included in the fine-grained fraction without consideration of the grain size range. Their identification is visual.

1. Moisture Effects

The moisture content of contaminated soils may range from 5% to over 30% although, commonly, soil moisture runs from 10% to 20%. Moisture may be adsorbed on the surface of soil particles or chemically bound. Moisture affects the physical properties of soils (especially for the fine-grained soils as discussed below) but, most importantly, impacts the heat balance of TD processes. In most practical cases, the energy required to evaporate moisture to steam and to heat the steam in an afterburner device is the most significant term in the overall TD system energy balance.

The removal of organic matter is assisted by the "steam-stripping" effect coming from the evaporation of moisture from the soil. The water vapor acts in the same way as in conventional steam distillation techniques to remove organic compounds with a low aqueous solubility and a low vapor pressure at TD operating conditions.

2. Coarse-Grained Soils

The division of coarse-grained soils includes gravels, gravelly soils, sands, and sandy soils. These materials are generally free-flowing and not agglomerated. Thus, in TD systems, the grains are exposed to both radiant and convective heat and flowing gases without the buffering effect of a layer of agglomerated soil grains. Compared to highly plastic, fine-grained soils, the coarser soils have relatively good heat transfer characteristics. The degree of difficulty of processing these materials is summarized in Table 12.

3. Fine-Grained Soils

The fine-grained soil division includes silts and clays where moisture content strongly influences their materials handling properties. This sensitivity shows itself in the plasticity of the soil (the soil's ability to deform without shearing) and the cohesiveness of the soil grains. These properties impact the degree of difficulty of screening, crushing, and processing steps where these soils tend to stick to equipment and, when compressed, mold themselves into large particles with unfavorable surface area-to-volume ratios for TD heating processes. The degree of difficulty of processing for these materials is summarized in Table 12.

A particularly difficult aspect of fine-grained soil behavior derives from its tendency to become entrained in a combustion gas flow stream. When dried, the fine particles are readily entrained to the extent of 5% to 30% of the soil feed rate. The degree of entrainment depends on the particle size distribution, the gas velocity, and the type of solids–gas contact.

Entrained particles may not be heated long enough or to a high enough temperature to effect desorption of the contaminant of interest. Thus, the solids captured downstream

Table 11 Unified Soil Conservation Service Soil Classification Chart

Major divisions			Group symbols	Typical names
Coarse-grained soils (More than half of material is larger than No. 200 sieve size.)	**Gravels** (More than half of coarse fraction is larger than No. 4 sieve size.)	**Clean gravels** (Little or no fines)	**GW**	Well-graded gravels, gravel–sand mixtures, little or no fines
			GP	Poorly graded gravels, gravel–sand mix, little or no fines
		Gravels with fines (Appreciable amounts of fines)	**GM**	Silty gravels, gravel, sand and silt mixtures
			GC	Clayey gravels, gravel, sand, and silt mixtures
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size.)	**Clean sands** (Little or no fines)	**SW**	Well-graded sands, gravelly sands, little or no fines
			SP	Poorly graded sands, gravelly sands, little or no fines
		Sands with fines (Appreciable amounts of fines)	**SM**	Silty sands, sand and silt mixtures
			SC	Clayey sands, sand and clay mixtures
Fine-grained soils (More than half of material is smaller than No. 200 sieve size.)		**Silts and clays** (Liquid limit less than 50)	**ML**	Inorganic clays of low to medium plasticity; gravelly, sandy, silty, and lean clays
			CL	Inorganic clays of low to medium plasticity; gravelly, sandy, silty, and lean clays
			OL	Organic silts and organic silty clays of low plasticity
		Silts and clays (Liquid limit more than 50)	**MH**	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
			CH	Inorganic silts of high plasticity, fat clays
			OH	Organic clays of medium to high plasticity, organic silts
Highly organic soils			**Pt**	Peat and other highly organic soils

Source: From (502).

Table 12 Soil Processing Difficulty and Pretreatment Requirements

Soil division	Groups	Processing difficulty	Pretreatment needs
Coarse-grained soils			
	SW/SP	Low	None
	SM/SC	Low to medium	Possible screening
	GW/GP	Medium	Screening
	GM/GC	Medium to high	Screening, some crushing
	Cobbles+	High	Crushing
Fine-grained and organic soils			
	Pt	Low[a]	[b]
	ML	Low[a]	[b]
	OL	Low to medium[a]	[b]
	OH	Low to medium[a]	[b]
	MH	Medium[a]	[b]
	CL	Medium to high[a]	[b]
	CH	High[a]	[b]

[a]Based on relative cohesive properties of soils in a plastic state and dry crushing strength if the soils are brittle, dry solids.
[b]May require moisture reduction to modify plasticity characteristics.

of the TD device may have to be recycled. Also, heavy metals in the entrained solids may be volatilized in an afterburner, thus exascerbating the air pollution control challenges. Finally, and often most problematically, the shear quantity of entrained material can overwhelm downstream equipment through heavy settlement in gas passages, slagging afterburners, buildup on impacted surfaces (heat transfer surfaces, dampers, etc.), abrasion and erosion in equipment, exceeding design limits for scrubber sludge handling, etc.

B. Thermal Desorption Systems

1. Rotary Dryers

The most widely used TD concept makes use of a rotary dryer operated in either co-current or countercurrent modes. A rotary dryer differs from a rotary kiln incinerator in that the dryer is constructed of carbon (for low-temperature TD) or alloy steel (for high-temperature TD) but without a refractory lining. The absence of the refractory (with a very substantial thermal mass) results in a comparatively quick startup. The dryers rotate with a peripheral speed of about 40 m/sec. They are sloped at about 1° to 2° downward from the feed end to move the soil through the unit. The fill fraction for the dryers is 6% to 14% of the internal cross-sectional area. This latter variable sets the inventory of soil in the unit and, therefore, the solid's residence time.

A rotary dryer incorporates "flights" or "lifters" welded to the inside wall that lift the soil and then sift it into the hot combustion gas stream, thus enhancing the degree of contact between the soil and heat source. Lifters are spaced between 18 and 24 cm around the circumference of the dryer. Generally, lifters extend from the wall 8% to 12% of the dryer's diameter. The lifters are offset every 1 to 2 m along the length of the dryer to spread out the gas–solids contact. For free-flowing materials, a radial lifter with a 90° lip is used. For sticky materials, a flat radial lifter with no lip is used. Lifters can be fabricated with other angles to match the needs of the process. If the soil properties change significantly as

drying proceeds, it may be appropriate to change the lifter design along the length of the dryer.

In most systems, the dryer is direct-fired by a burner discharging into the dryer shell. However, some systems are indirectly fired: Hot combustion gases are generated in a furnace structure surrounding a rotating dryer shell. Heat is transferred by conduction through the shell to the load. Typical residence times for the soil in indirectly fired systems range from 1 to 2 hours. Although the indirectly fired dryer is less efficient in transferring heat from the fuel to the soil, the off-gas is much more concentrated with consequently reduced afterburner fuel expense. Also, since the gas velocities within the indirectly fired dryer are significantly lower than in the direct-fired units, the amount of soil entrainment and carryover is substantially reduced.

The processing of the soil takes place in two zones: the drying zone and the contaminant volatilization zone. Residence time is set by the rotational speed, the angle of inclination, and the arrangement of internal lifters. The residence time varies depending on the type of unit and the volatility of the contaminants. For example, volatile solvents on a relatively dry soil might be satisfactorily treated in a direct-fired dryer in 6 to 10 minutes, whereas PCBs on a moist soil in an indirectly heated dryer might require 90 minutes or more. There is a strong time–temperature relationship: higher gas temperature reduces the required residence time and increases unit capacity but at the cost of increased fuel consumption.

a. Co-Current Dryers. Co-current dryers include low-temperature, carbon steel units operating with a soil discharge temperature from 150° to 425°C to high-temperature, alloy steel units operating with soil discharge temperatures up to 650°C. In general, the leaving gas temperature in a co-current design system is from 10° to 40° above the soil discharge temperature.

The main advantages of the co-current dryer is that the exiting gas temperature is greater than the leaving solids temperatures. Therefore, the solids captured in the cyclone and/or other air pollution control systems are well cleared of their volatile organic matter and are less likely to be contaminated. The main disadvantage is that the cocurrent system is less efficient at heat transfer in comparison to the countercurrent dryer. The exit gas temperature is higher and has a higher mass flow rate per unit of comparable soil processed; therefore, the fuel consumption is greater and the APC system is larger (more costly).

b. Countercurrent Dryers. The most obvious advantages of the countercurrent design are the energy economy and the achievement of higher throughput in a given piece of equipment. The off-gas from countercurrent dryers is much cooler than in the co-current design and, most often, can be sent to a cyclone and fabric filter without use of dilution air or water addition for cooling. Thus, the size of the downstream APC equipment is minimized. The main disadvantage is that because the gases sweep over solids at the colder end of the dryer, the fines captured in the cyclone and fabric filter may not be decontaminated and thus require recycle. Also, heavy organic compounds stripped from the incoming feed and present in cooler gases may condense in the filter fabric, blinding the bags, increasing pressure drop, and decreasing capacity.

2. Heated Screws

Heated-screw TD units typically use hot oil or steam inside a screw to heat the screw that then heats, mixes, and conveys the feed through an enclosed shell or trough. Hot-oil

systems are limited to a treated soil temperature of 275°C by the temperature limitations of the oil. Typical residence times within the screw system are 1 to 2 hours. Clearly, this is a disadvantage brought about by the low heat transfer efficiency in comparison to the rotary dryer. This leads to high remediation costs. The primary advantage is the low gas flow rates leading to a concentrated contaminant. Also, since there is no direct contact between the contaminant and combustion gases, permitting of the units is sometimes easier.

3. Off-Gas Treatment

For direct-fired rotary dryer systems, a cyclone is usually used to capture the majority of the elutriated particulate matter. The cyclone is followed by an afterburner to destroy the organic matter. If there is no need for acid gas control (the organic matter is dilute or not halogenated), an evaporative cooler and baghouse complete the process train. If HCl or other acid gas is generated in quantities requiring acid gas control, a Venturi scrubber with caustic addition can be used. In short-term remediation situations, however, a wet scrubber system can present significant problems in wastewater treatment and disposal.

Indirect dryers and heated screws can produce an off-gas with high enough concentrations of the contaminant organic matter to allow use of a condenser to cool and collect the material. An afterburner is an appropriate cleanup stage with care given to avoid propagation of a flame back into the condenser or dryer/screw unit.

C. Operating Parameters

1. Temperature

The temperature of the heating fluid (combustion products or heated oil) at its inlet and outlet and the maximum temperature achieved by the soil are key parameters. The temperature drop in the heating fluid scales the quantity of material required to achieve a unit of capacity. Thus, for a given piece of equipment, the higher the inlet temperature, the higher the throughput or, for a given throughput, the lesser the gas volume requiring APC on the back end.

The temperature achieved by the soils controls both the degree of decontamination and the breadth of contaminants that can be removed. The soil temperatures achieved for various technologies are summarized in Table 13. The target temperature is mandated by the vapor characteristics of the contaminant. Due to strong adsorption energies in some cases, the temperature required to achieve acceptable remediation may considerably exceed the normal boiling point.

Table 13 Soil Temperatures for Various Technologies

Technology	Soil temperature (°C)
Rotary dryer—direct-fired	150–585
Rotary dryer—indirectly fired	120–620
Heated screws	200–280

Source: From (503).

Total heat transfer rates can be estimated (442) for commercial dryers with a flight count per circle of 2.4 to 3 times the diameter and with shell peripheral speeds of 18 to 23 m/min according to:

$$Q_t = 0.0674LDG^{0.67}\Delta t_m \tag{11}$$

where

Q_t = total heat transferred (kcal/hr)
L = dryer length (m)
D = dryer diameter (m)
G = gas mass velocity (kg/hr/m^2 of dryer cross-section)
Δt_m = log mean of the drying gas wet-bulb temperature depression at the inlet end and exit end of the dryer shell (°C)

Because the impact of adsorption energy, steam-stripping effects, and the effect of the lifters on heat and mass transfer are difficult to assess from a first-principles approach, pilot testing is recommended.

2. Residence Time

The effect of residence time parallels in importance that of solids temperature in determining the treatment effectiveness of a TD unit. In general, operation at a higher temperature allows a shorter residence time.

Because the action of the lifters strongly influences the materials transport characteristics of the dryer, the conventional residence time correlations used with rotary kilns are usually not applicable to estimating behavior in dryer systems. Instead, empirical relationships for the particular soil characteristics and lifter designs are best obtained through testing. The time of passage in rotary dryers can be estimated using the relationships developed by Friedman and Marshall (505):

$$\text{residence time (min)} = \frac{0.23L}{SN^{0.9}D} \pm 1.97\frac{BLG}{F} \quad \text{with} \quad B = 5(D_p)^{-0.5} \tag{12}$$

where

L = dryer length (m)
S = dryer slope (m/m)
N = rotation speed (rpm)
D = dryer diameter (m)
G = air mass velocity (kg/hour/m^2)
F = feed rate to dryer (kg dry feed/hour/m^2 of dryer cross-section)
Sign = plus for countercurrent flow and minus for co-current flow
D_p = weight average particle size of material handled (microns)

3. Sweep Gas

Sweep gas acts to sweep the vaporized contaminant from the TD unit. In direct-fired units, the sweep gas is the combustion products. In indirectly fired units, the sweep gas can be steam or nitrogen. Steam is typically employed in systems with an afterburner but may also be used with systems using a condenser for product recovery. Nitrogen prevents combustion of the contaminants in the treatment unit. The nitrogen is often recycled with only a small blowdown stream to bleed off accumulated oxygen.

D. Remediation Performance

When properly applied, TD systems have achieved substantial removal of organic contaminants with considerably smaller flue gas emissions than a corresponding incineration system. Rotary dryer systems have, for example, reduced halogenated VOCs and polynuclear aromatic hydrocarbons (PAHs) to 0.1 mg/kg, and 1 mg/kg, respectively, for individual PAHs and 10 mg/kg for total PAHs (504). However, failure to meet treatment objectives has been experienced, especially when pilot-scale testing was not carried out to properly set system operating parameters and to set realistic performance objectives.

V. PLASMA TECHNOLOGY

Plasma technology involves the development of a sustained electrical arc, created by passing an electrical current through a gas. The gas presents a high electrical resistivity to the current and generates significant heat. At 2000°C, the gas molecules dissociate into the atomic state. That is, O_2 breaks down into two highly energetic oxygen atoms; CO_2 into an atom of carbon and two oxygen atoms. At 3000°C, the gas molecules become ionized as electrons are stripped away. The ionized gas (or "plasma") is electrically conducting and can be confined by electromagnetic fields. Surprisingly, due to the strong interactions between the plasma components, the viscosity of the plasma is more like that of a liquid than a gas. If desired, higher temperatures (say, to 20,000°C or more) can be achieved by increasing the electrical current.

A plasma torch is, therefore, simply a method for producing heat. Plasma technology has been considered for waste management applications to treat, remediate, or recycle hazardous waste. In particular, attention has focused on (1) processing radioactive wastes where radio nuclides can be trapped in the slags, (2) processing PCBs, waste military nerve gases, and medical wastes where the severe operating conditions give assurance of complete destruction of highly toxic organic compounds, and (3) processing contaminated soils where the minimal off-gas quantity offers, in concept, potential for lower back-end flue gas treatment expense. Because of its high cost, the use of plasma methods for more benign wastes has not received great attention.

In principle, the plasma environment can process almost any waste to produce a glassy, nonleachable vitrified residue and, compared with full oxidation in an incinerator, minimal quantities of gaseous products. The organic fraction of the feed is completely destroyed. Organic molecules break down to benign species such as carbon monoxide, hydrogen, carbon dioxide, and/or water vapor depending on operating conditions. Halogens will also be found in the gaseous effluent stream, often appearing in the off-gases as the element rather than as the more easily captured acid: a challenge in the selection of materials of construction for the downstream equipment. Metallic waste components melt, sink to the bottom of the liquid pool of condensed phase products, and can be drawn off as a potentially recyclable scrap metal stream. Inorganic fractions of the waste may form a molten slag layer on top of any metallic layer. The overall volume reduction depends on the proportions of organic matter, ash, and metallic components in the feed waste.

Plasma torches have been used for decades in many industrial applications: surface plasma spray coating, metallurgical processing, and materials synthesis. A nontransferred mode plasma torch consists of a closely spaced pair of water-cooled electrodes within which an electric arc discharge is magnetically rotated at extremely high speeds. A process

gas is injected into the space (usually only a few mm) between the electrodes. The combination of high arc rotation speeds and high gas flow rates provides an excellent heat transfer between arc and gas. The gas then exits the torch as a superheated gas flow that can be directed into a furnace or other process reactor to accomplish a heating function. Due to the physical dimensional constraints of many of the nontransferred mode systems, their feed is limited to liquids or gases.

Alternatively, the arc can be struck between the torch electrode and the melt (transferred mode). In this instance, a substantial fraction of the heat passes into the melt. This mode has the advantage that larger masses of material can be heated to the fusion point with lesser pretreatment.

Plasma treatment systems consist of several components besides the plasma producing unit: a waste feed system, a processing chamber, a solid residue removal and handling system, an off-gas cleanup and handling system, and operational controls and monitors. These supporting components, though similar to counterparts in conventional combustion systems, often have a number of special requirements or unusual features that relate to the coupling of the component to an extremely high temperature system handling materials that may present a significant health risk.

Waste feed systems often require engineering development to enable the addition of solids, liquids, sludge, or other wastes with a minimum of pretreatment or handling. Also, for hazardous wastes, leaks and other fugitive emission of the unremediated waste material must be minimized or eliminated. Feed shut-off capabilities are important if the operating conditions stray from the envelope defined by the operating permit.

Since the unit operates at high temperatures, water cooling is often required for the survival of the treatment vessel. There are risks, therefore, that leaks in the water-cooling jacket may lead to steam explosions and injury to personnel and equipment destruction. The treatment vessel needs to eliminate, to the extent possible, fugitive emissions.

The off-gas cleanup needs to treat the hot, dusty, and potentially combustible gas mixtures generated in the plasma environment. This may include an afterburner, acid gas treatment, and particulate control systems. Also, if the fraction of the waste containing inorganic material is large, the management of the molten residue is critical to on-line availability of the unit. Freezing of the slag discharge ports and/or buildup within the plasma chamber is unacceptable. Volatile metals will be vaporized within the plasma chamber and carried out of the unit with the gas stream. Subsequent condensation as a finely divided fume produces a particulate control challenge.

In many instances where the plasma operates under pyrolytic conditions with a reducing atmosphere, air or oxygen is added to the off-gas, leaving the plasma treatment zone to provide an afterburner function. The ensuing combustion has the advantage of eliminating the CO and carbon emissions (as CO_2) but increases the volume of flue gas to be treated and, also, creates the potential for dioxin formation.

In development hardware, plasma units have achieved or exceeded a DRE of 99.99% to include tests showing 99.9999% DRE for PCB materials. Performance in this DRE range is a reflection of the extremely high working temperature of plasma systems such that simple thermal dissociation, rather than kinetically controlled oxidation processes is taking place. As of the turn of the century, DRE performance and equipment reliability had not been demonstrated in continuously operating commercial units working within a competitive environment where cost is an issue. The electrical energy consumption of this technology is very high and the processing rate is relatively low in relation to the capital

investment. Published cost estimates for waste treatment using plasma technology are uncertain and, often, are based on estimates drawn from limited data and incorporate critical assumptions regarding energy efficiency, maintenance expense, on-line availability, and so forth that have not been substantiated by experience.

Research and advanced development of plasma technology for waste processing application are widespread. However, there are at present no commercial applications where breadth of applicability to the typical mix of wastes delivered for treatment has been demonstrated, where on-line availability and maintainability have been proven, and where cost effectiveness has been shown in a realistic competitive environment.

12

Other Incineration Systems for Solid Wastes

The solids of concern in this chapter include "trash" (waste usually containing a large fraction of paper and cardboard), relatively dry food waste, waste wood, agricultural residues (bagasse, corn cobs) and brush, organic containing bulky wastes (automobile bodies, rail cars), etc. Many of these solids include substantial amounts of noncombustible (wire, steel banding, drums, nails, as well as "ash"). "Standard" or reference waste compositions and incinerator classifications have been developed by the Incinerator Institute of America (Tables 1 and 2) for the specification of on-site incinerator systems.

Although not discussed in depth, the materials handling problems of waste feeding, entanglement during passage through the burning zone, and ash removal are critical; the effect of poor design in these areas has a greater impact on efficient and reliable operation than on combustion performance. These potential problems, as well as the risk of explosion of containerized volatile combustible, etc., are abetted by the difficulty in identifying and/or removing "troublesome" materials prior to feeding.

Of the several incinerator designs described herein, only the systems operating with a controlled air supply system are potentially compatible with modern air pollution control systems and, thus, are constructable in the stringent regulatory environment of the "first world." However, some of the equipment described here illustrate features that were important benchmarks in the evolution of incinerator design. Also, the descriptions may provide useful design guidelines where low first cost, simplicity, and brute effectiveness are, for the present, of primary importance.

I. MULTIPLE CHAMBER (HEARTH OR FIXED GRATE)

Multiple-chamber incinerators are among the most simple. They usually consist of a rectangular, refractory-lined furnace chamber with a hearth floor or simple fixed grate. In small trash burning units (50–250 kg/hr), combustion air is supplied by natural draft. Large units, handling several tons per hour of bulky wastes, are often equipped with forced draft. For even minimally acceptable burnout of smoke, a secondary chamber is necessary.

Table 1 Classification of Incinerators

Class I:	Portable, packaged, completely assembled direct-fed incinerators, having not over 0.14 m^3 storage capacity, or 11 kg/h burning rate, suitable for Type 2 waste.
Class IA:	Portable, packaged, or job assembled, direct-fed incinerators 0.14 m^3 to 0.42 m^3 primary chamber volume; or a burning rate of 11 kg/h up to, but not including, 45 kg/h of Type 0, Type 1, or Type 2 waste; or a burning rate of 11 kg/h up to, but not including, 35 kg/h of Type 3 waste.
Class II:	Flue-fed, single-chamber incinerators with more than 0.19 m^2 burning area, for Type 2 waste. This type of incinerator is served by one vertical flue functioning both as a chute for charging waste and to carry the products of combustion to atmosphere. This type of incinerator has been installed in apartment houses or multiple dwellings.
Class IIA:	Chute-fed multiple chamber incinerators, for apartment buildings with more than 0.19 m^3 burning area, suitable for Type 1 or Type 2 waste. (Not recommended for industrial installations.) This type of incinerator is served by a vertical chute for charging wastes from two or more floors above the incinerator and a separate flue for carrying the products of combustion to atmosphere.
Class III:	Direct-fed incinerators with a burning rate of 45 kg/h and over, suitable for Type 0, Type 1 or Type 2 waste.
Class IV:	Direct-fed incinerators with a burning rate of 35 kg/h or over, suitable.
Class V:	Municipal incinerators suitable for Type 0, Type 1, Type 2, or Type 3 wastes, or a combination of all four wastes, and are rated in tons per hour or tons per 24 h.
Class VI:	Crematory and pathological incinerators, suitable for Type 4 wastes.
Class VII:	Incinerators designed for specific byproduct wastes, Types 5 or 6.

Source: From (137).

Auxiliary burners are often needed to maintain secondary chamber temperatures above 650° to 700°C during startup or shutdown.

The design of large units, suitable for the combustion of 1000 to 2500 kg/hr of tree stumps, demolition waste, sofas, chairs, mattresses, etc. (heat of combustion approximately 4000 kcal/kg) can be based on the following (117):

Furnace floor hearth area corresponds to 75 kg hr^{-1} m^{-2} (300,000 kcal hr^{-1} m^{-2}).
Furnace height 3.75 m (to ensure clearance during charging).
Furnace length 6 to 8 m.
Furnace width 2.5 to 5 m.
Secondary chamber volume 65% of furnace.

Forced air supply corresponds to 150% excess, supplied 25% through 7-cm-diameter floor ports at 30 m/sec; 75% through 8-cm-diameter sidewall ports. Sidewall port nozzle velocity is selected to give 10 m/sec at furnace midplane. Assume 500 m/min inflow velocity through charging door clearances.

Area of flue ("flame port") between furnace and secondary is designed to flow at 500 m/min for 175% excess air at the mean firing rate; 650 m/min between secondary chamber and outlet breeching to the simple, scrubber-type air pollution control system.

Such furnaces have been constructed and tested (117,118,121) and found satisfactory in this service for an operating cycle of 7 hours of charging at 25-min intervals and a burndown through the next 17 hours. Similar designs can be developed for car bodies, drum cleaning, and other bulky waste incineration, although consideration should be given

Table 2 Classification of Wastes[a]

Classification of wastes	Principal components	Approximate composition (% by weight)	Moisture content (%)	Incombustible solids (%)	kcal/kg of refuse as fired	kcal of auxiliary fuel per kg of waste to be included in combustion calculations	Recommended minimum kcal/hr burner input per pound waste
Trash,[b] type 0	Highly combustible waste, paper, wood, cardboard, cartons, including up to 10% treated papers, plastic or rubber scraps; commercial and industrial sources	Trash, 100	10	5	4700	0	0
Rubbish,[b] type 1	Combustible waste, paper, cartons, rags, wood scraps, combustible floor sweepings; domestic, commercial, and industrial sources	Rubbish, 80 Garbage, 20	25	10	3600	0	0
Refuse,[b] type 2	Rubbish and garbage; residential sources	Rubbish, 50 Garbage, 50	50	7	2400	0	800
Garbage,[b] type 3	Animal and vegetable wastes, restaurants, hotels, markets, institutional, commercial, and club sources	Garbage, 65 Rubbish, 35	70	5	1400	800	1700
Animal solids and organic wastes, type 4	Carcasses, organs, solid organic wastes, hospital, laboratory, abattoirs, animal pounds, and similar sources	Animal and human tissue, 100	85	5	550	1670	4500 (2800 primary) (1700 secondary)
Gaseous, liquid or semiliquid wastes, type 5	Industrial process wastes	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey
Semisolid and solid wastes, type 6	Combustibles requiring hearth, retort, or grate burning equipment	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey

[a]From Ref. 137.

[b]The figures on moisture content, ash, and kcal as fired have been determined by analysis of many samples. They are recommended for use in computing heat release, burning rate, velocity, and other details of incinerator designs. Any design based on these calculations can accommodate minor variations.

to the heat release rate relative to the above. Auxiliary burners may be added to the furnace to hold temperatures at or above 550°C to ensure acceptably high burning rates. The heat input requirements may be estimated using the basic heat and material balances, heat loss, and infiltration estimates presented above.

For commercial or light industrial waste disposal in the capacity range from 20 to 1000 kg/hr, a well-established design rational has been developed. The design, based on an extensive empirical investigation undertaken by the Air Pollution Control District of Los Angeles County over the years 1949 to 1956, has been reduced to a series of nomographs, tables, and graphs relating construction parameters to burning rate [Refs. (138,139) and reported in Ref. (127)].

The Los Angeles designs were meant to be applied to wastes with a higher heating value from 2400 to 3600 kcal/kg (typically paper, rags, foliage, some garbage, etc.). The unit designs are predicated upon the use of natural draft to draw in air under the fire (about 10%), over the fire (about 70%), and into the secondary (mixing) chamber (about 20%). Typically, the total air ranges from 100% to 300% excess.

The Los Angeles design methods are applied in two configurations: the retort and the in-line. The retort style derives its name from the return flow of flue gases through the secondary combustion chambers, which sit in a side-by-side arrangement with the ignition (primary) chamber. The in-line style places the ignition (furnace), mixing, and combustion (secondary combustion) chambers in a line. The retort design has the advantages of compactness and structural economy and is more efficient than the in-line design at capacities to 350 kg/hr. Above 450 kg/hr, the in-line design is superior.

II. MULTIPLE CHAMBER (MOVING GRATE)

These units are similar in design and operation to the older refractory-lined municipal incinerators described above. Because of the refractory construction, the units usually are operated at 200% excess air or greater to avoid slag accumulation and refractory degradation. Their general capacity range of 50 to 300 tons/day per furnace restricts their economical use to the larger industrial complexes.

In many cases such units are equipped with burners for waste oils, pitches, solvents, etc., as well as cage dryers for drying wastewater treatment plant sludge prior to incineration. Some plants have provisions for feeding drums to be fire-cleaned. The smaller units are useful for medical wastes.

Since the waste-supporting surfaces of most moving grate systems are perforated or designed with clearances to admit underfire air, care must be taken to control the nature of the feed to minimize the occurrence of serious undergrate fires. For example, drums of flammable solvents, tars, and other thermoplastic materials that flow when heated should not be charged. Steam or fog-type water spray fire control systems and/or, more commonly, a water-sluiced siftings removal system should be considered if the probability of such occurrences is high or if incinerator outages are critical to maintaining overall plant facility operation.

III. MODULAR STARVED AIR

In the 1960s, a number of manufacturers, recognizing the increasing emphasis on smoke abatement, began producing incinerators that limited (or starved) the combustion air supplied to the primary chamber to about 80% of theoretical and the overall combustion

air to about 120% excess. This holds flue gas temperatures high and minimizes the need and/or fuel consumption for afterburner devices.

The starved-air units consist of a cylindrical or elliptical cross-section primary chamber incorporating underfire air supply through the transfer rams that propel the waste and the residue along the hearth-type floor (Fig. 1). Overfire air is also supplied in the primary chamber. The low total air supply minimizes the carryover of particulate. The lower chamber temperature (700°–750°C), achieved by restraining the air supply to less than theoretical, minimizes fusion of glass (clinker formation) but with some sacrifice in the quality of burnout of the residue. All combustion air is provided by forced draft fans. In many such incinerators, the proportion of underfire to overfire air is regulated from a thermocouple in the exhaust flue (higher exit temperatures increase overfire air and decrease underfire air).

The gases leaving the primary chamber contain a substantial concentration of carbon monoxide, hydrogen, light hydrocarbons, etc. The gases are passed to a secondary chamber (Fig. 2) where the remaining combustion air is added. A pilot flame ensures ignition. Most units incorporate a gas or oil burner in the secondary or afterburner chamber for use during startup, during shutdown, and when refuse heat content is insufficient to achieve regulatory minimum operating temperatures. The burner is energized whenever the gas temperature falls below the set point temperature. In some configurations, the afterburner is mounted in the refractory-lined stack.

Starved-air incinerators are available in capacities from 100 to 3000 kg/hr. In the larger units, one or more air-cooled rams can be incorporated into the design of the primary chamber to push and gently mix the waste in the unit. Also, the larger units incorporate hydraulic ram feeders (with air-lock covers and guillotine dampers at the furnace entrance), quench tanks, and drag conveyors to provide for continuous ash removal as shown in Fig. 3.

If properly operated and maintained and equipped with appropriate air pollution control devices, these units can readily meet most federal, state, and local air pollution codes when fed with typical office and plant trash (principally paper, cardboard, and wood). The residence time of solids is relatively long (often more than 4–6 hours) such that modest proportions of relatively wet materials (such as sewage sludges) can be mixed with the refuse and burned. These furnaces are generally not well suited to burn dense wastes such as sawdust or 100% sludge or pastes such that air flow within the refuse bed is greatly restricted.

IV. OPEN PIT TYPE

The disposal of scrap wood, pallets, brush, and other readily combustible, bulky, low-ash wastes is often a problem. Open burning is prohibited in many communities and, because of its slowness and inefficiency, is costly (labor costs) and presents safety hazards.

Monroe (140) developed a simple refractory-lined pit incinerator that has shown utility in these applications. His concept uses perforated pipes in the floor of a rectangular in-ground or above-ground pit to supply forced underfire air. Jet nozzles, directed such as to “bounce” off a sidewall onto the fire, are mounted along one side of the pit. For benign materials (such as brush, stumps, etc.), regulatory agencies have been tolerant of these devices. For dangerous but diluted explosive or strongly oxidizing or reducing wastes (such as papers or boxboard contaminated with benzoyl peroxide or dynamite), the open safety features of burning in such an open pit has also led to regulatory tolerance.

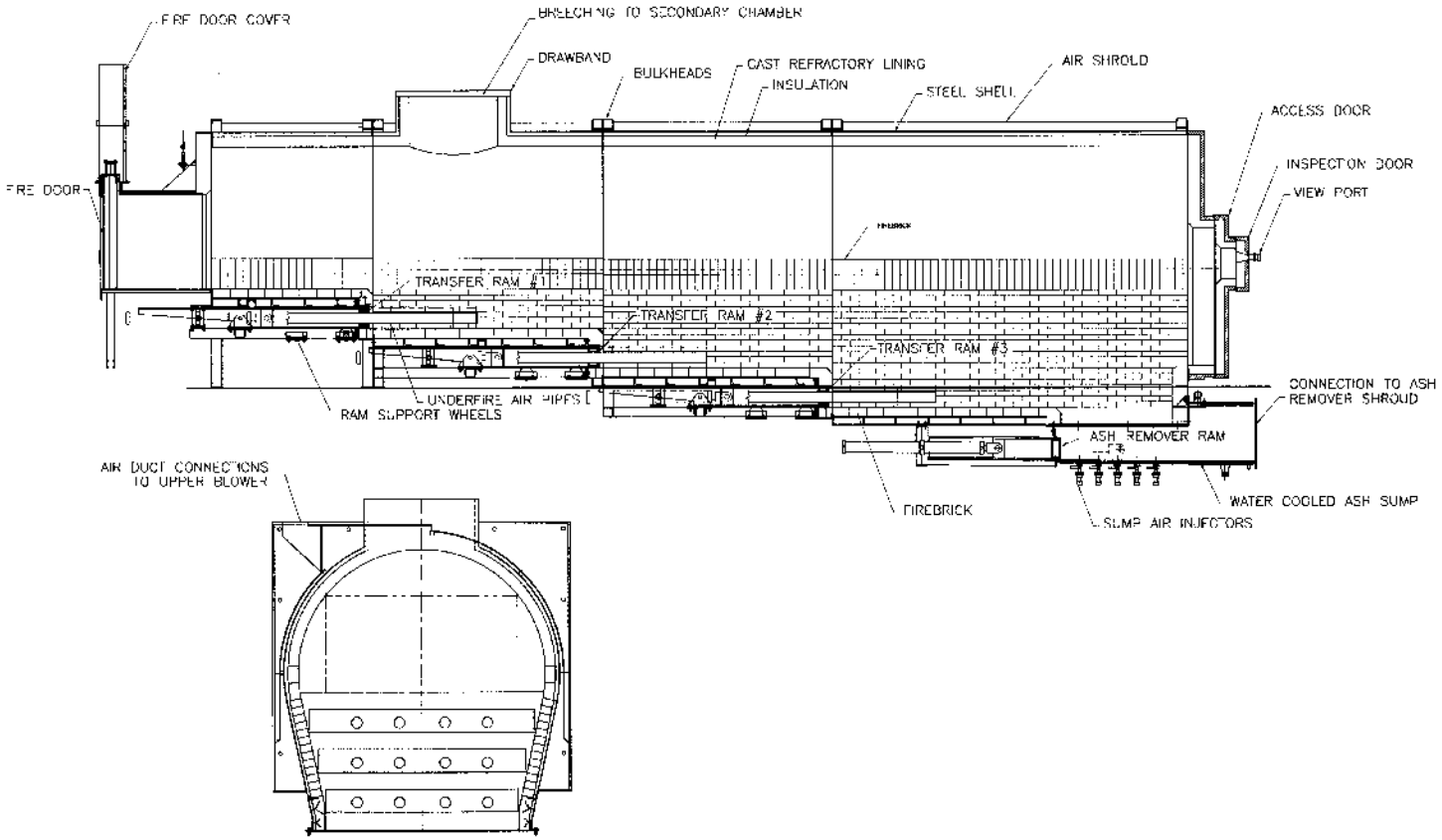


Figure 1 Lower chamber sectional view (typical). (Courtesy of Consutech Systems, LLC.)

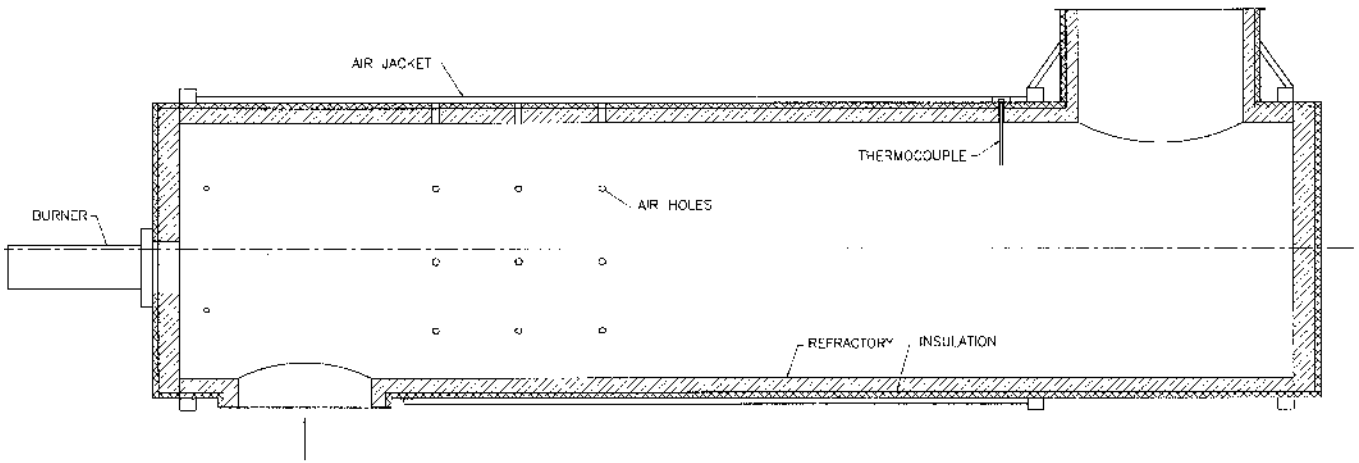


Figure 2 Upper chamber section (typical single chamber). (Courtesy of Consutech Systems, LLC.)

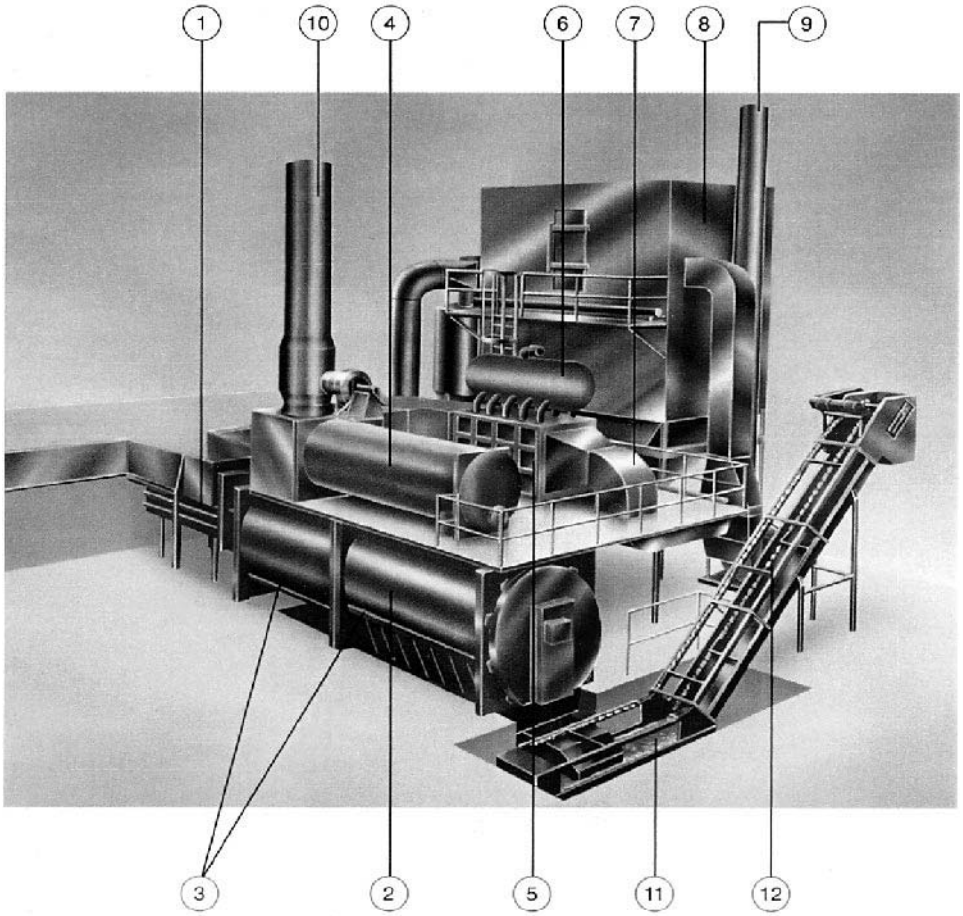


Figure 3 The Consumat® modular system. 1) Automatic feed system, 2) primary chamber, 3) transfer rams, 4) secondary chamber, 5) steam generator, 6) steam separator, 7) energy duct, 8) emissions control system, 9) exhaust stack, 10) emergency bypass, 11) wet ash sump, and 12) ash conveyer. (Courtesy of Consutech Systems, LLC.)

Similar incinerator designs have been used for the disposal of heavy pitch and tar residues, but with variable success and generally great concern on the part of air pollution regulatory agencies. This is particularly true when the waste includes toxic organic components (since the degree of combustion completeness is most uncertain) or includes toxic/carcinogenic ash constituents (e.g., heavy metals) since air pollution control is essentially impossible.

V. CONICAL (TEPEE) TYPE

The conical or tepee incinerator, as its name implies, is a large, perforated metal cone. Waste (usually brush and other low-density or bulky wood waste) is charged to the unit on

a batch basis. Air is typically supplied by natural draft, but, in some units, a refractory-lined floor is installed with holes for forced underfire air. Excess air levels, by design of the sidewall perforations, exceed 400% to 600% to maintain the structural integrity of the steel shell and to minimize oxidative metal wastage. Such units are little more than a "bonfire in a box" and offer few advantages when stringent air pollution regulations must be met. They have enjoyed some utility in large-scale land clearing or lumbering operations.

VI. GASIFICATION PROCESSES FOR MSW

The strong concern of many environmental action groups and of the regulatory community has put the spotlight on air emissions from municipal waste combustion (MWCs). This has fostered vigorous opposition to proposed plants and led to the adoption of increasingly stringent emission requirements. One response in this adversarial environment is to upgrade the processes and enhance the control technology for "conventional" mass burn and RDF-type MWC systems. An alternative approach is to develop altogether new thermal processing technologies that are inherently low in emissions yet still have the target of accepting the wide range of feedstocks comprising municipal solid waste (MSW). One such class of new, environmentally benign technologies is those based on the gasification of refuse coupled with intensive cleanup of the product gas.

In its simplest embodiment, gasification occurs by the simple heating of organic material to temperatures of the order of 400° to 600°C whereupon complex molecules break into shorter chain species that are gases under the extant conditions. This is pyrolysis-type gasification. The products of pyrolysis include low-molecular-weight gaseous compounds such as methane, ethane, ethylene, and the like; medium-molecular-weight compounds that may be gases at high temperatures but that would condense to liquids at normal ambient temperatures; and high-molecular-weight carbonaceous char and viscous sludge material. The chemistry of the products ranges from pure hydrocarbons to myriad compounds with oxygen, sulfur, nitrogen, and halogen atoms.

The heat for the pyrolysis reaches the organic molecules as pure heat transfer arriving as radiation, conduction from physical contact with hot surfaces, or the mingling of the material with hot gases. Alternatively, the material can be ignited and burned with an insufficiency of air. The heat release by partial oxidation acts to dry and bring portions of the material to pyrolysis temperatures while consuming a fraction. Clearly, the partial combustion approach is simple, but some of the heat content of the original organic material is lost in the combustion process and the product gas includes the diluent nitrogen brought in with the combustion air.

A second strategy used to effect gasification exposes the organic material to hot steam that heats the material inducing pyrolysis plus acts as an oxidant that, through the water–gas and water–gas shift reactions, yields a gaseous fuel product with minimum char residual and without addition of nitrogen. The reactions include:

Water–gas reaction: $C + H_2O \rightleftharpoons CO + H_2$

Water–gas shift: $CO + H_2O \rightleftharpoons CO_2 + H_2$

Gasification processes applied to MSW are often (but not exclusively) fed waste previously subjected to recycling and refined to an RDF. The organic fraction is heated with limited or no air to yield a gaseous product stream with a substantial heat content. This intermediate product gas can then be cleaned of metals and other particulate matter and of HCl, HF, ammonia, hydrogen sulfide, and other gaseous contaminants. Then the gas can be used as a chemical feedstock or can be burned in a gas engine or gas turbine to

generate electricity. The gas cleanup effort need only deal with the relatively small quantity of product gas stream from the gasification reactor. This contrasts with the scale of cleanup for conventional incinerator flue gases that have been greatly expanded in volume by the addition of almost twice the theoretical quantity of combustion air and associated high dilution with nitrogen and excess oxygen. As a consequence, the equipment and operating cost for environmental emissions control can be substantially lower.

Further, the ultimate combustion process and energy conversion take place with relatively high-quality, clean fuels comprised, importantly, of CO and hydrogen rather than a flue gas derived from MSW and thus bearing corrosive particulate, acid gases, and moisture. Combustion of a "clean gas" allows use of high-efficiency technology for energy conversion (high kWh/kcal) and produces very low emission rates of dioxins, acid gases, and other problematic pollutants.

Gasification is an old technology, with roots in charcoal making, in the reduction of iron and other metal ores, in the manufacture of city gas, and the like. MSW gasification is a more recent application of the technology and, as we enter the new millennium, is still in the advanced developmental stage with only a few plants worldwide based on this technology that have continuous operating experience under commercial conditions. Thus, it is reasonable to expect that process or equipment deficiencies or difficulties will appear in the technologies still under development. Those with knowledge of the technical evolution within the conventional waste-to-energy industry are familiar with the development history of Purox, Landgard, Torrax, Black-Clawson, Melt-Zit, Ecologenics, and many other concepts, which struggled to achieve technical and commercial feasibility but, ultimately, were not successful. In the aggressive working environment of waste management service, with its uncompromising demand for reasonable cost, high reliability, and operational flexibility, such failures can cause significant, costly, and politically painful problems.

A study (559) of emerging gasification technologies identified three that appeared near commercialization: TPS Termiska AB, a process developed by Battelle Laboratories, and a process by Thermoselect Inc. All involve gasification of MSW (Termiska and Battelle with an RDF feed stream and Thermoselect with raw, unprocessed MSW) followed by fuel gas cleanup and gas combustion for the generation of electricity. The descriptions of the processes given below are intended to highlight the technical features and characteristics of these three examples of MSW gasification.

It would be premature to suggest that gasification technology is the thermal processing strategy of the future or even that it will be a strong competitor. Solid waste is a very difficult fuel and waste management a stern and critical taskmaster. However, in both niche market sectors and the broader market, these gasification technologies or others may well emerge as viable alternatives alongside the mass burning, RDF, and fluidized bed technologies that currently dominate the market.

The penetration of the thermal processing market by advanced technologies is paced by their environmental, economic, and performance acceptability. From an environmental viewpoint, the gasification technologies appear to represent a sound response to the regulatory challenges of the U.S. EPA and the equally restrictive regulations within the European community. Economics has always been a critical and probably pacing factor affecting the penetration of thermal processing technology, and economic viability as well as performance acceptability (which most importantly focuses on on-line availability and safety) will only be confidently known when commercial operation over an extended duration is achieved.

A. General

MSW handling is one of the major challenges to successful implementation of any MSW system. Today's mass burn systems employ combined manual/automatic equipment systems, which rely to a large extent on gravity feed and a mass of MSW as a pressure seal. Equipment includes a pit, a crane and bucket, a chute that provides a seal, and a feeder/stoker. The material in the chute provides a plug to prevent the hot gases from escaping to the atmosphere. This simple strategy is preferred over valves or lock hoppers because it results in continuous MSW feeding. Some batch feed systems use an arrangement of lock hoppers that periodically admit MSW to the combustion process. Such arrangements are usually found in small combustion systems. Many of the three technologies described are in this size range, and they use such lock-hopper feeding systems.

Since heat transfer to the feed waste is a basic step in gasification, almost all gasification technologies require processing of raw MSW to an RDF (see Chapter 7). The more uniform and highly subdivided character of RDF increases the rate of gasification processes and assists in achieving a high conversion efficiency.

Two of the three processes to be presented use fluid bed technology (see also Chapter 9, Sect. II). A classical bubbling fluid bed combustor involves a cylindrical or rectangular chamber containing coarse sand or similar bed material through which gas is passed at a rate that causes the sand bed to expand and move in a turbulent, roiling motion. If the gas velocity is further increased, a fraction of the particles will be blown out of the bed. One can then interpose a medium-to-low-efficiency particulate collector such that the larger particles will be captured and returned to the bed for continued processing. Often, an array of vertically oriented steel channels is mounted in the duct leaving the freeboard. These channels (known as "U-beams") intercept the coarser solids. The U-beams are followed by a somewhat more efficient particulate capture system; say, a cyclone collecting 100% of particles with greater than a 30-micron aerodynamic diameter. This embodiment of the suspended combustion concept is called a circulating fluid bed.

As discussed in Chapter 9, the advantages of the fluid bed environment include the uniformity of chemical and temperature environment brought about by the mixing effects and thermal inertia of the dynamic motion of the sand and the effectiveness of the circulating sand to both carry heat to incoming material to dry and abrade feed particles. The abrasion removes the ash layer that protects the unreacted core material and reduces the particle size to facilitate combustion.

A detailed heat and mass balance is essential to assess the energy conversion efficiency and to identify the liquid, solid, and gaseous side streams that require either additional treatment or disposal. Product gas can be characterized by its relative heat content class:

Low-heat-content gas	950 to 2,800 kcal/Nm^3	100 to 300 Btu/sft^3
Medium-heat-content gas	2,800 to 5,700 kcal/Nm^3	300 to 600 Btu/sft^3
High-heat-content gas	>5,700 kcal/Nm^3	>600 Btu/sft^3

Typically, the methanation reactions are important in lower-temperature systems, while the reforming reactions are more prominent in high-temperature systems. The reactions that predominate in the gasifier strongly depend on temperature (establishing gas phase equilibria and reaction rates) and the attack of the solid phase material by oxygen, water vapor, or a combination of the two. The means used to control the input of the

oxidant is important, as are the reliability and state of development of the instrumentation and control system and its effectiveness in achieving maximum gasification efficiency and avoiding upsets.

The basic objective of gasification-based processes is to convert a heterogeneous solid fuel with handling and pollutant-emissions problems into a combustible gas containing the maximum remaining heating value. In a way, this is an extension of the RDF preparation to produce a high-form-value, gaseous fuel. In many cases, the combustible gas is burned in a gas engine or turbine combustor to generate electricity. Where warranted, heat recovery from the exhaust of the engine or turbine can be passed to a boiler to produce steam and the steam, in turn, converted to a second quantity of electricity using a conventional steam turbine/generator.

B. Gasification of an RDF by Partial Combustion

1. Introduction

TPS Termiska Processer (Thermal Processes), or TPS, is a Swedish company located near Nyköping working in energy and environmental process research and technology development. The TPS gasifier is comprised of a bubbling fluid bed into which RDF or RDF pellets are fed. Addition of secondary air partway up the furnace transforms the bed's aerodynamic balance such that smaller, lighter particles are blown from the bed: a circulating bed. Heavy, still-burning "chunks" remain in the dense bubbling fluid bed until they are consumed. Ground dolomitic lime is added in a second bed to catalyze breakdown of high-molecular-weight hydrocarbons into lighter products. The product gas may be cleaned to generate a fuel gas suitable for use in a gas engine or turbine or can be burned directly in a boiler or process furnace. The flowsheet is shown in Fig. 4.

In 1992, Ansaldo Aerimpianti SpA of Italy installed a commercial two-bed unit in Grève-in-Chianti, Italy. The Grève units have a combined heat release capacity of 25.8×10^6 kcal/hr when burning 100% pelletized RDF fuel. The beds have also processed biomass (coarsely shredded wood or agricultural wastes). Fuel gas generated at the plant is either burned in a boiler to generate electricity or used as a fuel in an adjacent lime kiln operation.

2. Process Description

a. General. In the TSP feed bed, the RDF feed rate is set such that the air rate is lower than the theoretical oxygen quantity needed for full oxidation of the feed material. Under these conditions, the product gas and solids leaving the bed contain unreleased fuel value. The TSP initial bed is run as a circulating bed so that (1) large "chunks" stay in the bed until through combustion, pyrolysis, and attrition they are finally blown out and (2) medium-sized char particles are returned to the bed to give additional time for oxidation. The heating value of the gases, the bed temperature, and the yield of char increase as the air setting decreases relative to the theoretical oxygen demand. This is the *gasification mode* of operation.

As the temperature of a fluidized bed increases, the system can approach the state of bed defluidization: The bed temperature approaches the fusion point and the sand becomes sticky. Operation in the gasification mode has the advantage that the operating temperature for satisfactory gasification is considerably below that where RDF ash fusion is likely.

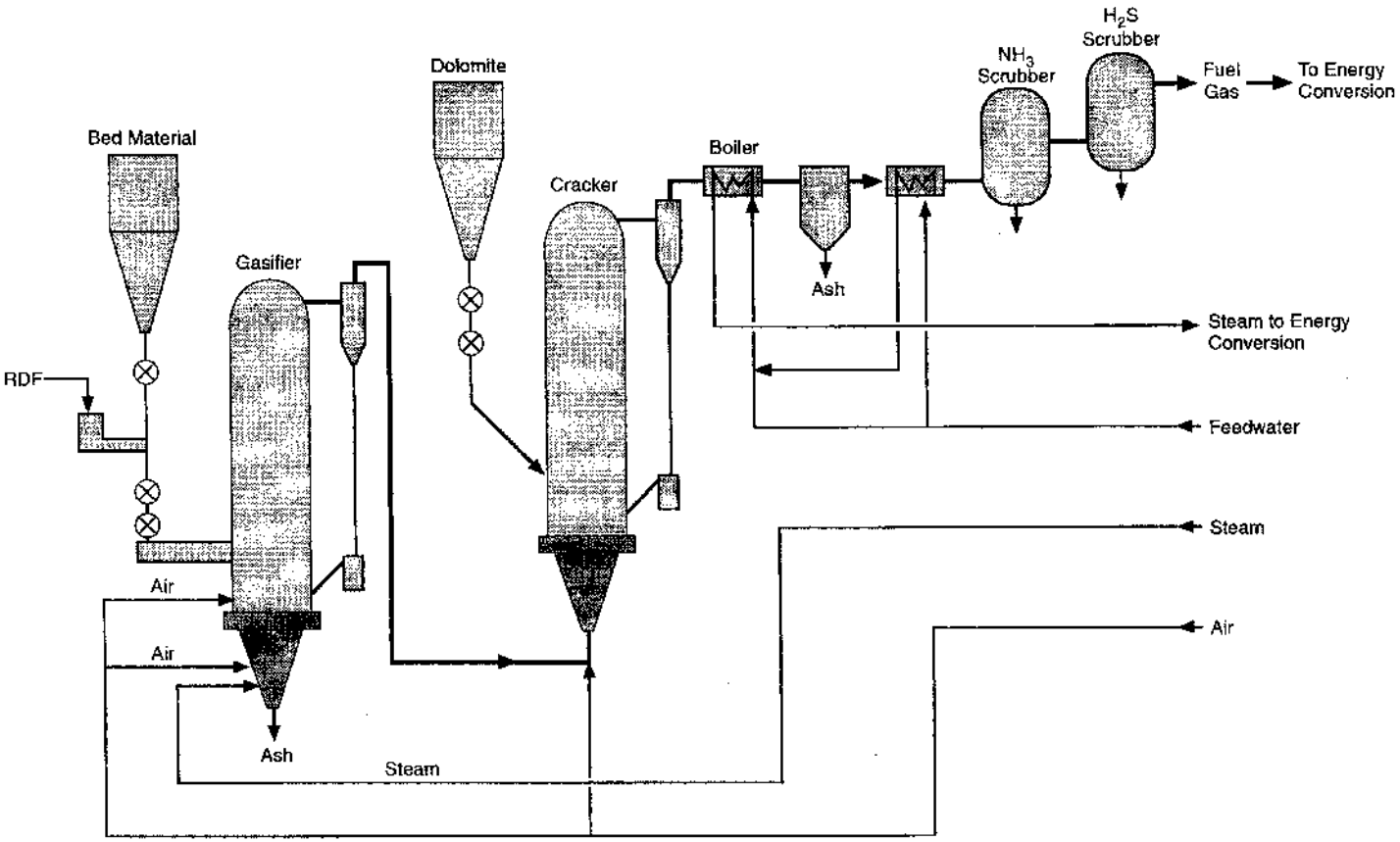


Figure 4 4a TPS termiska processor AB—process flowsheet.

Under these conditions (750° to 900°C), most organic refuse components and biomass materials (e.g., wood) break down into volatile components. The remainder is found as a solid char. The cyclone or other device in the leaving gas captures and returns the solids such that an acceptable level of carbon burnout is achieved.

The feasibility of the CFB as a gasifier is greatly enhanced by the large fraction of the organic material present as "volatile matter." This quality of the RDF is reported in a proximate analysis and reflects the fraction of the waste that is distilled off upon heating. This favorable circumstance is not the case for most coals where the dominant product with bed heating would be fixed carbon. If the volatile fraction of the RDF is low and char yield is high, often steam is added to the fluidizing medium to enhance gasification of the carbon char via the water–gas reaction.

The volatilized organic matter can appear in the off-gas in various forms. For convenience, one can categorize them as basic *synthesis gas* (carbon monoxide and hydrogen), low-to-medium-molecular-weight *hydrocarbons* (say, those with boiling points at or below 100°C), and high-molecular-weight hydrocarbons sometimes called *tar*. The combination of heating values of these gases and tarry compounds constitutes the fuel value of the resulting gas. Another potentially useful energy form found in the CFB off-gas is the sensible heat (enthalpy) associated with gas temperature.

The overall heat balance of the bed and off-gas suggests a relationship between gas temperature (and its enthalpy), waste moisture content, and the fuel gas heating value. As any of the three quantities increases, it is at the sacrifice of the others. For example, if the moisture content of the waste increases, either the gas temperature or the heating value (or both to some lesser extent) must fall. Note also that the off-gas is diluted with the nitrogen brought in with the combustion air. Shifting to the use of oxygen-enriched air or pure oxygen could, therefore, act to increase off-gas heat content (at the price of increased operating cost).

The tarry material in the off-gas from a gasifier such as this normally presents a problem. If the gas is cooled and scrubbed of the tars using a water scrubber, both the enthalpy of the gases and the fuel value of the tars are substantially lost. If a boiler is installed between the CFB and the scrubber, the sensible heat will be captured for a time but the tars will condense on the tubes, quickly fouling the heat transfer surface. If the off-gas is burned without removing the tars, it is often found that combustion of the tarry compounds is less complete than that of the lower-molecular-weight hydrocarbons and synthesis gas components. This may lead to soot formation. Once soot has formed, relatively severe combustion conditions (temperature and residence time) may be required for adequate burnout. Finally, the tars are both quite odorous and believed by some to be potentially carcinogenic.

Because of these problems, TSP added a second CFB and cyclone following the CFB gasifier. The second bed is fed with crushed dolomite (a naturally occurring mixed calcium and magnesium carbonate), which acts as a catalyst at about 900°C to crack the tars to lower-molecular-weight hydrocarbons. A small fraction of the cracking products remains in the form of heavier molecules such as benzene, toluene, and naphthalene. Only an unimportant portion of the heating value of the tarry organic compounds is lost in the dolomite gas cleaning/reforming processes. In the course of catalyzing the cracking reactions, the dolomite also scavenges the flue gases for acidic components such as hydrochloric acid (HCl) and sulfur oxides (SO_2 and SO_3). The product gas from the second bed can be sent through a boiler for recovery of sensible heat and clean, relatively soot-free combustion.

b. The TPS Circulating System

RDF PREPARATION. The RDF fed to the TPS fluid bed is produced through horizontal shaft hammermill or shear shredder-type primary shredding; secondary hammermill shredding; magnetic separation; air classification; and disc screening of the fines for removal of glass and grit. Grève and the TPS pilot plant used pelletized RDF in their initial operation. If this is, in fact, a requirement, pelletization would require an additional processing step in RDF preparation. TPS believes that although pelletization was used to increase the density for economic hauling, the actual RDF pellets fed to the gasifiers degrade to a "fluff state" as a consequence of the normal mechanical abuse in the handling system. It is common to incorporate some kind of intermediate RDF storage as a buffer between RDF preparation and the combustion facility. At the Grève facility, four 80-ton steel silos were used.

The RDF feed specifications for the Grève system are

Pelletized with average dimensions of:	
Diameter	10–15 mm
Length	50–150 mm
Bulk density	500–700 kg/m^3
Net calorific value	4104 kcal/kg
Moisture (typical)	6.5%
Volatile matter	71.1%
Fixed carbon	11.4%
Sulfur	0.5%
Chlorine	0.4%–0.6%
Total noncombustibles	11.0%

RDF RECLAIMING AND FEEDING. RDF is reclaimed from storage, moved to a small feed hopper, and then fed to the gasifier. The Grève plant recovers the RDF (or biomass) from its storage silos using a twin-screw reclaimer that "digs" the waste from the silos and deposits it into a bucket conveyor. From the bucket elevator, the RDF is moved by a screw conveyor that runs the length of the building, discharging into the feed hopper. RDF fuel is augured from the hopper with a twin-screw reclaimer, passed through a rotary valve, and chuted into the gasifier.

FLUID BED GASIFIER. The heart of the TPS process is the fluid bed gasifier: a cylindrical, bubbling bed system, operating at about atmospheric pressure at the top of the bed. Feed is distributed across the lower "dense bed" and begins to volatilize. The temperature in this zone is approximately 700°–800°C. Residence time in the dense bed (for larger particles) can be quite long. As the particles are reduced, they are lifted up and out of the dense, bubbling bed zone. Steam can be added to the dense bed if required to facilitate gasification of carbon in wastes with a high fixed carbon content.

Above the dense bed zone, secondary air is injected. The combination of heat release (temperature increase and density reduction) and greater mass flow increases the upward gas velocity and facilitates carbon oxidation. The temperature increases to about 850°–900°C in the upper reaches of the bubbling bed zone described by TPS as the "fast bed." In beds firing fuels with a limited moisture content, it is necessary to add steam to the fluidizing gas flow. Water acts as an oxidizer to gasify carbon (to CO and hydrogen).

The gases leaving the bed pass through a duct incorporating U-beam particulate interception. The gas then passes to a large-diameter, refractory-lined cyclone where additional particulate recovery occurs. The solid streams from the U-beam and cyclone

hoppers accumulate in a vertical pipe where they form an air seal or plug. At the very bottom of the accumulation pipe, a small amount of nitrogen is introduced to fluidize the lower mass of solids. Then, by gravity, the fluidized solids flow from the pipe and are reintroduced into the dense-phase, bubbling fluidized bed. Oxygen-free gas is used as the fluidizing medium to avoid the high temperatures that would be obtained if air (with oxygen) was used to move the still-hot, ignitable char solids.

The off-gas from the cyclone is, then, a fuel gas comprised of a mixture of synthesis gas, hydrocarbons, and tars with some residual particulate matter all diluted with the nitrogen from the air used in the process. The typical composition and heating value of gas derived from RDF in the TPS pilot facility and gas composition data from the Grève facility are shown in Table 3.

For industrial combustors that already incorporate air pollution control systems (e.g., rotary cement or lightweight aggregate kilns or process furnaces), the gasification reactors' product gas can be used directly as a medium-heat-content fuel gas. The product gas can be the only fuel used or it can be the base firing fuel with supplemental fossil fuel to trim the operation for load-following. The fuel can also be used in an industrial or utility boiler for steam or power production. An air pollution control train may be required to remove HCl, HF, SO_2, Hg, and other heavy metals, particulate, etc., depending on the chemistry of the RDF and regulatory requirements.

Alternatively, the fluid bed off-gas can be cleaned before being burned to the degree required for combustion in a gas engine or gas turbine for the direct generation of electricity. Without the dolomite cracker circulating bed and associated cyclone appended to the gasifier, this would result in the loss of the sensible heat of the fuel gas. With the cracker, almost all of the tar is converted into lower-molecular-weight compounds and a small amount of benzene, toluene, and naphthalene. Nitrogen-containing compounds and hydrogen cyanide decompose into either nitrogen gas or ammonia. Also, carbon-containing dust is gasified by the residual oxidizing gases (e.g., H_2O and CO_2) at the higher temperatures of the cracker bed. Following the cracker, a heat recovery boiler surface

Table 3 Typical Off-Gas Composition at Grève

	Volume percent		
Component	Grève data	Typical data[a]	Percent of heating value[a]
CO_2	15.65	10	None
$N_2 + Ar$	45.83	40	None
CO	8.79	22	34.9
H_2	8.61	14	22.5
Methane	6.51	4	12.8
C_xH_y	4.88	2	29.7
H_2S	48.61 (ppm)	0.02	0.06
H_2O	9.48	8	None
Other	0.14	—	N/A
Total	100.00	—	1800 kcal/Nm^3 202 Btu/sft^3

[a]For typical off-gases at tar cracker discharge.
Source: From (559).

brings the temperature down to about 200°C, where a fabric filter system removes particulate matter. The particulate consists mainly of calcined dolomite and fine soot and is of a nonabrasive nature. At this point, the gas is suitable for use in fuel-sensitive combustors.

Optimum electrical generation is found in the combined cycle mode where the exhaust gases from a gas engine or gas turbine are passed through a boiler to generate steam providing additional (about one-third more) power generation.

AIR POLLUTION CONTROL. In addition to the acid gas control achieved through the dolomitic lime addition, the combustion train is normally equipped with fabric filters for particulate capture. Demonstrated sulfur oxides removal is over 70%. Carbon injection can be provided for mercury control although the Grève data suggest that acceptable mercury emissions may be achievable without this feature. TPS offers a wet scrubber system when there is a need for enhanced ammonia, tar, acid gas (H_2S, HCl), and condensible vapor removal. At this point, the fuel gas is of a quality that can be burned in a boiler to generate steam (without further cleanup) or it can be cleaned to be used as fuel in a gas engine or turbine combustor for the generation of electricity.

TYPICAL PLANT CONFIGURATIONS AND PERFORMANCE. TPS provides its fluid bed equipment in two styles: (1) as a fuel generator to fire a boiler or a process furnace; or (2) a fuel gas generator feeding a gas engine or turbine. Combined cycle design of the latter alternatives offers optimum energy conversion.

3. Environmental Aspects

a. Air Emissions. Data are available from stack tests of the Grève system. Data from tests made when the plant was burning RDF are shown in Table 4. Heavy-metal data from Grève are shown in Table 5. The complete TPS system (including tar cracker, baghouse filters, and scrubbers) appears able to meet all European and U.S. emission standards.

b. Wastewater Emissions. Other than boiler and cooling tower blowdown streams, there are no major wastewater streams from the TPS process. Wastewater is produced in the scrubber systems. Pilot test data suggest that these streams can be treated in a biological system or in activated carbon filters.

c. Residue Characteristics. Data on the leaching characteristics of TPS process residues are not available.

Table 4 Air Emission Data for the Grève-in-Chianti Plant

Pollutant	Measured emission rates (11% O_2)	Gréve regulatory limits (11% O_2)
CO	2.5–5 mg/Nm^3	50 mg/Nm^3
Particulate	3–7 mg/Nm^3	10 mg/Nm^3
HCl	0.5–2 mg/Nm^3	30 mg/Nm^3
HF + HBr	<0.1 mg/Nm^3	2 mg/Nm^3
SO_2	5–15 mg/Nm^3	100 mg/Nm^3
Heavy metals	2.2 mg/Nm^3	(see below)
NO_x	200–300 mg/Nm^3	300 mg/Nm^3
PCB	163.0 ng/Nm^3	0.1 mg/Nm^3
PCDD + PCDF	13.1 ng/Nm^3	2860 ng/Nm^3

Source: From (559).

Table 5 Heavy-Metals Emission Data for the Grève-in-Chianti Plant

Metal	Measured value (mg/Nm^3)	Italian regulatory limit (mg/Nm^3)
Lead (Pb)	max 0.005	3
Cadmium (Cd)	<0.0004	0.1
Mercury (Hg)	0.008–0.05	0.1

Source: From (559).

4. Product Gas and Residue

Because of the high dilution with nitrogen (from the air), it is unlikely that one would refine the TPS gasifier product as a syngas feedstock but would, rather, burn it as a process heating fuel or in a boiler or gas turbine for power generation. Cleaning the gas prior to combustion is an option due to the high cost of particulate and acid gas control on the larger-volume burned gases. However, cooling and cleaning the fluid bed off-gas result in the loss of up to 25% of the net heat content defined as the combination of sensible heat and fuel energy in the gas and particulate carbon. Losses of this magnitude suggest the merits of limiting gas cleanup to cyclone removal of particulate using a multicyclone to reduce slagging in the boiler. Gas characteristics were described previously.

C. Gasification of an RDF by Pyrolysis and Steam Reforming (Battelle)

1. Introduction

Battelle is a research and development and consulting firm headquartered in Columbus, Ohio. In the course of product and process development activities for clients, the firm works in a number of technical areas involving solid waste, combustion, and MSW technology.

The Battelle High Throughput Gasification System (BHTGS) is an indirectly heated, two-stage process that uses circulating fluidized bed (CFB) reactors. In the first reactor, refuse-derived fuel (RDF) or other biomass feedstock is gasified to a medium-heating-value gas (4550 to 5350 $kcal/Nm^3$) using steam without oxygen as the fluidizing medium. Char, formed in the gasification reactor, is burned with preheated air in a second CFB combustor. A circulating hot sand phase transfers heat between the separate reactors. The process is shown schematically in Fig. 5.

Battelle's tests with the process research units (PRUs) during the mid-1980s demonstrated the technical feasibility of the gasification process and provided the basis for generating a detailed process conceptual design in 15- and 25-cm gasifiers at rates from 0.22 to 9.1 tons/day dry RDF, respectively. Data from these units showed that extremely high throughput rates per unit area of reactor (>19.5 $tons/h\text{-}m^2$) could be achieved. A wide range of feed materials, including RDF, was tested in the system.

Testing of a highly prepared RDF was conducted in 1989 in a 25-cm ID, 6.9-m-high gasifier and a 100-cm-diameter, 3.5-m-high combustor. Throughput was 650 kg/d (560,561). The PRU has logged over 10,000 operating hours on a variety of feedstocks; the longest continuous operating run was approximately 100 hours at 9.1 tons/day of dry RDF. A 200-kW gas turbine has been installed on the PRU and operated with wood for about 60 hours as an integrated gasifier/turbine system. A 25-megawatt demonstration is

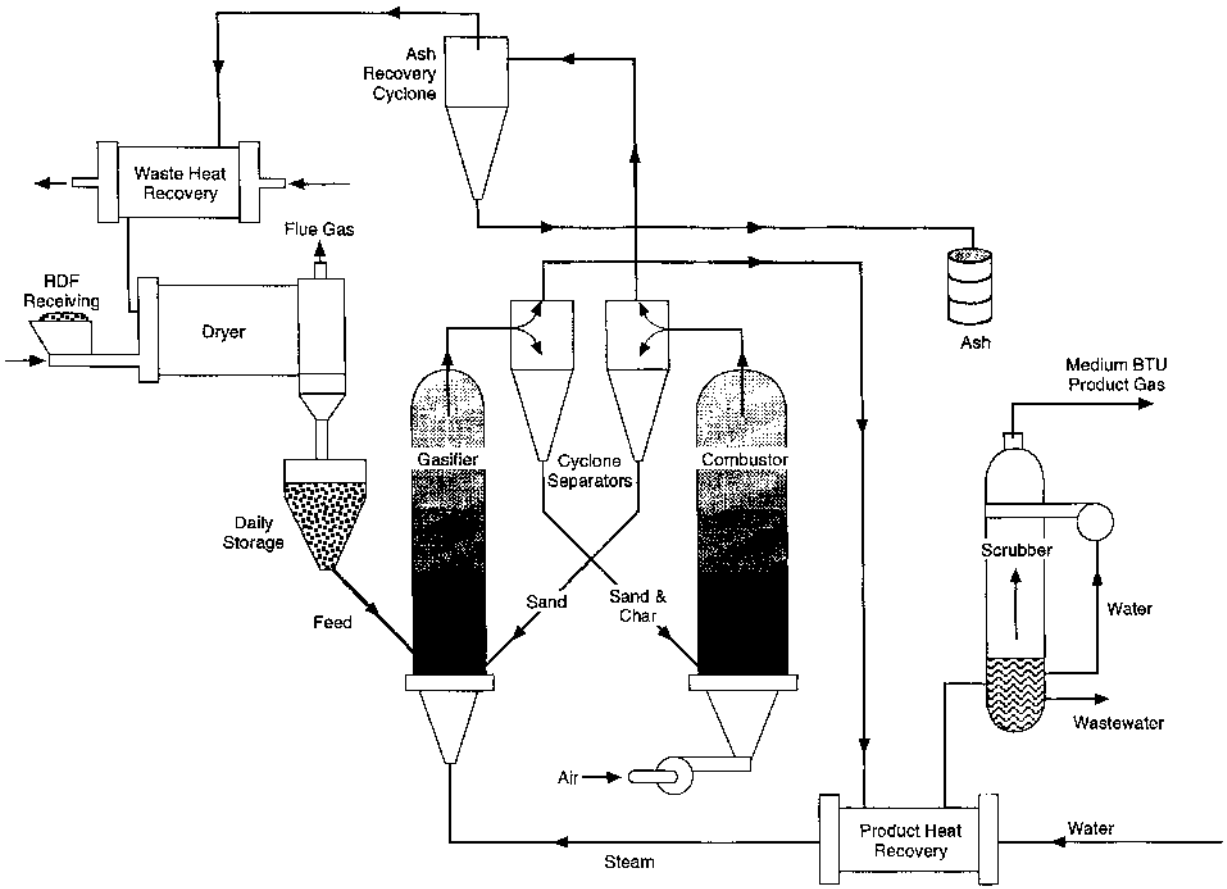


Figure 5 BHTGS process flowsheet.

under way at Burlington Electric's McNeil Generating Station in Burlington, Vermont, using whole tree wood chips.

2. Process Description

a. General. The Battelle biomass gasification process uses a CFB gasifier to achieve a high processing rate of biomass material to produce a medium-heat-content product gas without the need for an oxygen plant. The process schematic in Fig. 5 shows the two reactors and their integration into the overall gasification process. This process uses two physically separate reactors:

- A gasification reactor, fluidized with steam, in which the biomass is converted into a medium-heating-level gas and residual char
- A combustion reactor that burns the small amount of char produced by the gasification reactions (typically 20% of the feed material) to provide a stream of hot sand that circulates between the gasifier and the combustion reactor

Heat transfer between the reactors is accomplished by the circulating sand.

The Battelle process provides a cooled, clean, 4450 to 5350 $\mathrm{kcal/Nm^3}$ product gas; ash; and treated wastewater. The medium-heating-value gas generated can readily be used in conventional natural-gas-fired combustion equipment. Steam boilers, gas turbines, industrial heat treating furnaces, and process heaters are examples of potential users of the gas. Waste heat in the flue gas from the combustor can be used to preheat incoming air to 400°C and then dry the incoming feedstock. These unit operations are not required, but they increase product yield and overall energy efficiency by recycling low-grade waste heat to meet process requirements. The condensed, organic phase scrubbed from the product gas is decanted to separate the organic phase from the water in which it is insoluble and injected into the combustor.

Table 6 shows the chemical similarity of wood and RDF. Wood has been successfully tested and a commercial plant is in operation. The analysis shown is typical for "fluff" RDF produced from MSW collected in the Baltimore, Maryland, region. This same RDF was used during the Battelle PRU tests. The chemical similarity of the two materials suggests that RDF might behave in a similar manner to wood in the Battelle process. The PRU tests conducted in 1989 verified this expectation and demonstrated the potential of the process for providing an economical alternative to current spreader stoker or full combustion fluid bed RDF-based MSW systems.

b. The Battelle Dual Bed System. As shown in Fig. 5, steam, as the fluidizing gas, enters the gasifier at a level below the RDF feed entry port and an L-valve sand recycle entry. Sand, heated in the combustor bed, enters the gasification reactor at 975°C and brings the gasifier working temperature to approximately 800°C. The sand, char, and product gas from the gasifier are directed through the cyclone mounted atop the bed. The cyclone disengages the sand and char and directs their flow to the combustor bed. The product gas passes through an additional cyclone, product heat recovery, and a scrubber.

The combustor, a bubbling fluidized bed with a refractory lining, is designed to minimize heat losses. The bed operates at 975°C. Cool sand from the gasifier bed cyclone enters the combustor bed through a closed chute line. This line enters through the top of the combustor and extends downward into the fluidized bed. The sand is returned to the gasifier bed from the combustor cyclone through an L-valve. The L-valve provides the necessary seal between the combustor and gasifier environments. Exhaust gases from the

Table 6 Comparison of Wood and RDF Analyses

	% Dry basis	
Description	Wood	RDF
Proximate analysis		
Volatile matter	83.89	77.76
Fixed carbon	15.78	11.23
Ash	0.33	11.09
Total	100.00	100.00
Ultimate analysis		
C	52.37	47.31
H	6.04	6.16
O	41.30	45.71
N	0.02	0.68
S	0.25	0.14
Cl	0.02	—
Total	100.00	100.00
Heating value, MJ/kg (Btu/lb) (dry)	9.22 (8739)	8.53 (8082)

Source: From (559).

combustor pass through a cyclone separator, which discharges the fine, separated particles directly back into the fluidized bed. The flue gases then are further cleaned and cooled by a waste-heat recovery system and RDF dryer before being exhausted to the atmosphere.

3. Environmental Aspects

a. Air Emissions. Low by-product generation results in simple environmental systems. During the limited test program with RDF, lower concentrations of condensed organic materials were generated than in tests with wood. Battelle indicates that a much more extensive evaluation is necessary to confirm and quantify these results.

The BHTGS includes a wet scrubber in the process loop. Battelle suggests that this scrubber will significantly reduce the particulate matter concentration in the fuel gas stream, simplifying the end use of the gas for power plant fuel applications. It is uncertain, however, whether the quality of gas after a simple wet scrubber will be sufficient for use in gas engines and, particularly, gas turbines without secondary gas cleanup. Possible pollutants include mercury and other heavy metals present as vapor or finely divided particulate matter.

Chlorine and its compounds were not measured during the RDF testing. However, subsequent Battelle data indicate that organic chlorine compounds in the waste stream are converted completely to HCl in the gasifier and do not reform as chlorinated organic materials such as dioxins and furans. Some of the HCl reacts with alkaline ash components, but there is a small residual concentration of HCl present in the product gas, most of which is removed by the scrubber.

b. Waste water Emissions. Wastewater from the scrubber contains a mixture of hydrocarbons that are relatively insoluble in water, thus greatly simplifying projected wastewater cleanup requirements.

c. Residue Characteristics. Inorganic compounds, including most of the heavy metals, exit the BHTGS as part of the ash stream. Although sufficient RDF operating data have not been developed to provide complete mass-balance results for all inorganic species, Battelle's experience with other forms of biomass suggests that inorganic compounds tend to be removed from the combustor as fine, fly-ash material.

Glass and aluminum, like other low-melting-point species, have the potential for causing operating difficulties if they become part of the high-temperature sand circulating circuit. The BHTGS, because of its CFB (entrained flow through the reactors), removes larger tramp material, such as glass and aluminum, from the bottom of the reactor.

4. Product Gas

The results of BHTGS testing with RDF are the end product data shown in Tables 7 and 8. Although these data indicate the potential of the process, more information taken over a wider range of waste and system conditions are needed to fully assess the commercial characteristics of the process.

D. Gasification of Raw MSW by Pyrolysis

1. Introduction

Thermoselect SA is a privately held Swiss company created to commercialize the Thermoselect process, for which over 31 patents have been issued. In January 1995 the German utility Badenwerke AG joined the company as a 25% owner. The Thermoselect system processes commingled MSW and "selected" industrial waste and converts them

Table 7 End Product Data

Gasifier operating temperature	660°–840°C
Percent RDF carbon gasified	41–69%
Product gas heating value	4825–5565 kcal/Nm^3
Product gas yield	0.43–0.75 Nm^3 per kg MAF basis RDF
Heating value of gas produced	2035–3655 kcal per kg MAF basis RDF

Source: From (559).

Table 8 Product Gas Composition

Component	Volume percent
H_2	15.7
CO_2	11.1
CO	43.9
CH_4	16.3
C_2H_4	11.2

Source: From (559).

into products: a cleaned fuel or synthesis gas, vitrified solid granules, elemental sulfur, and dry sodium salts. If the full system of recovery features is selected by a client, no liquid effluents are discharged into the environment. Process water is treated and recycled. The process is intended to minimize both the formation and emission of particulate matter, nitrogen oxides, and other pollutants.

Gasification is achieved at a high temperature. The products of gasification are then held at high temperatures for more than 4 seconds—a relatively long residence time. Data indicate that this combination of time and temperature destroys the complex organic compounds produced in the gasification process and yields a product gas that, substantially, has reached chemical equilibrium. The raw gas is cleaned in a train of air pollution control/gas purification systems to remove HCl and HF, hydrogen sulfide, particulate, and volatile heavy metals. The ultimate process air emissions result solely from the combustion of clean gas during the production of heat in boilers or gas engines or turbines for the generation of electric power (primarily NO_x and traces of CO).

The Thermoselect demonstration plant is located at Fondotoce, Italy, near Lago Maggiore in the southern foothills of the Alps. Its testing facility consists of one process line with a nominal capacity of 4 tons per hour that is housed in a low-level building with two relatively short stacks.

2. Process Description

Figure 6 is a schematic of the Thermoselect® gasification system. Table 9 presents the physical and process characteristics as it has evolved from subscale to thin standard plant. The various stages of this process are described in the following subsections.

a. Compaction. An industrial scrap-metal compactor is used to pack commingled waste to less than 10% of its original volume, thereby removing the air contained in the original loose material. The raw waste is dropped by grapple from the waste pit into the housing of the compactor, which presses the loose material against a heavy metal gate to a density of $1,250\ \text{kg/m}^3$. As the process calls for feed, the gate opens, and the compactor moves the plug of waste though an unheated transition section into the degassing channel.

b. Degassing and Pyrolysis. The degassing channel containing the extruded plug of compacted material is externally heated to 600°C with a portion of the process generated gas. The reactor gas is burned with forced air in a rectangular annulus surrounding the channel. As the compacted waste plug heats, volatile components from the pyrolyzing waste vaporize and flow to the next stage. The heated vapors include steam from the free water carried in with the solid waste. As the waste plug is pushed down the degassing channel, it receives radiant heat from the next stage. The temperature in this area is 800°C. The transition point between the degassing channel and the next stage is called the "high-temperature chamber" (HTC). During the degassing stage, the conditions and ingredients of the water–gas reaction are present ($C + H_2O \rightleftarrows CO + H_2$). Hydrogen and carbon monoxide thus move with the vaporized organic matter from the degassing channel into the upper section of the HTC, which is maintained at 1200°C.

At this point, the waste plug is much smaller because it has lost volatile components (water and organic matter). The nonvolatile organic portion has been carbonized to a high degree. The inorganic portion of the waste has remained virtually unaffected and is part of the carbon matrix. Upon reaching the transition point with the HTC, the carbon matrix breaks apart and falls into the lower section of the HTC. The travel time through the degassing channel is normally less than 2 hours.

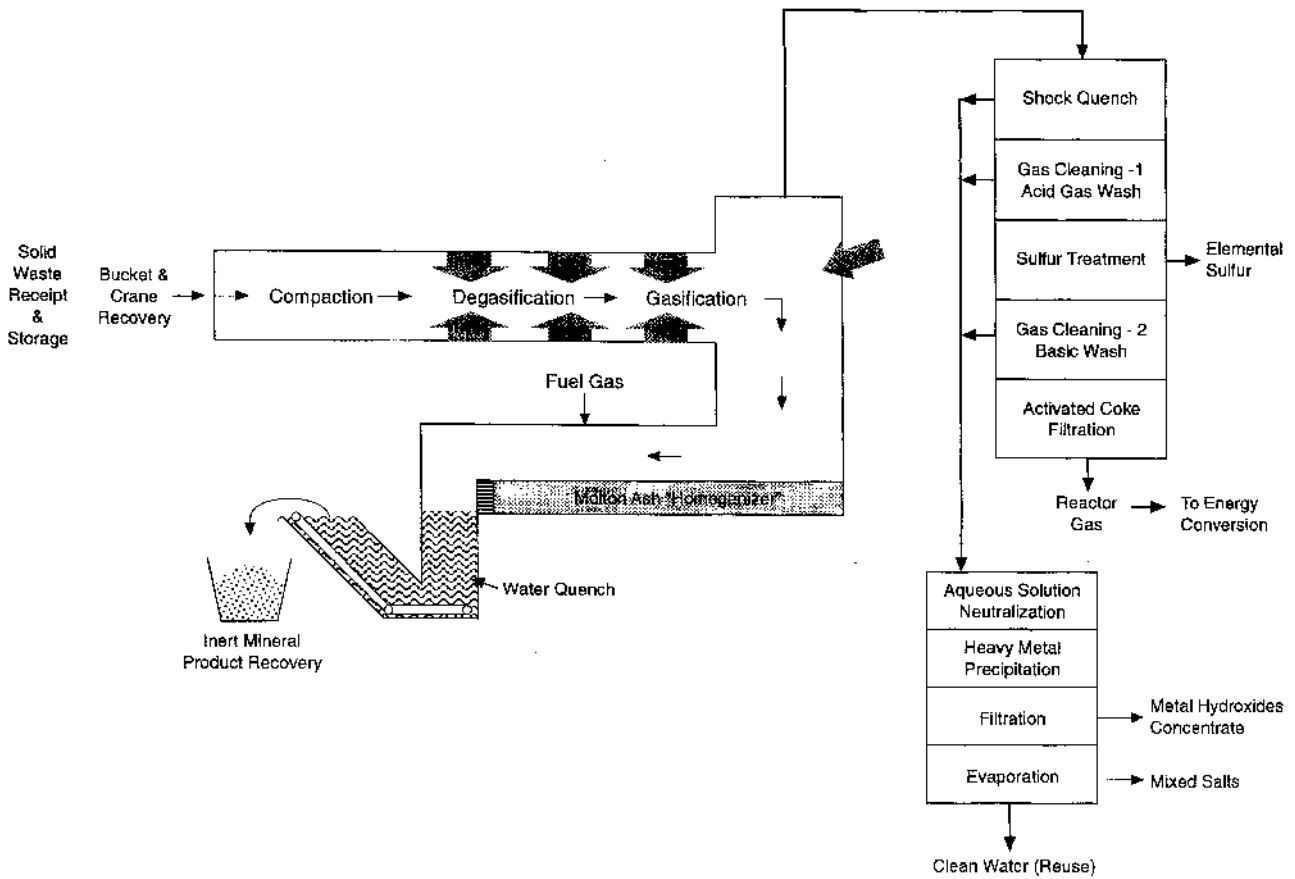


Figure 6 Thermoselect process flowsheet.

c. High-Temperature Gasification. The matrix of carbon and inorganic material fills the lower section of the HTC, where oxygen is introduced. The vigorous reaction of oxygen with the hot carbon produces a local temperature of 2000°C. This controlled exothermic reaction provides the heat necessary to melt the inorganic fractions—composed primarily of glass products and various metals contained in the carbon matrix. In effect, this lower section performs as a smelter. The inorganic molten mass of mineral and liquid metals flows from the lower HTC into the homogenization stage, where it is prepared for removal from the process.

In the lower section of the HTC, the equilibrium reaction ($C + O_2 \rightarrow CO_2$) between carbon and oxygen produces carbon dioxide (CO_2). By shifting the equilibrium in the presence of CO_2($C + CO_2 \rightarrow 2\ CO$), a high-volume percentage of the energy carrier (CO) is formed. Both these gases (the CO and a reduced volume of CO_2), flow to the upper section of the HTC and join the other gaseous products received from the degassing channel of the process.

Table 9 Characteristics of Thermoselect Process Hardware

Category		Units	Subscale work #1	Subscale work #2	Fondotoce facility	Standard plant
Line	Capacity	Mg/h	1.00	—	3.8	10.00
	Factor capacity[a]	—	—	—	4.20	2.38
Press (compactor)	Maximum capacity	Mg/h	1.50	—	6.00	16.00
	Capacity	kg/cycle	80.00	—	280.00	600.00
	Cycles	1/h	12.50	—	15.00	16.67
Degassing channel	Length	m	20.00	13.00	13.00	14.00
	Height	m	0.25	0.25	0.35	0.50
	Width	m	0.90	0.90	1.50	1.80
	Section area	m^2	0.23	0.23	0.53	0.90
	Surface factor[a]	—	—	—	2.33	1.71
	Volume	m^3	4.50	2.93	6.83	12.60
	Capacity	Mg	7.20	4.68	10.92	20.16
	Residence time	h	7.20	4.68	2.60	2.02
High-temperature chamber	Diameter lower section	m	2.10	—	2.10	2.60
	Height solid bed	m	0.90	—	1.60	3.20
	Volume lower section	m^3	3.12	—	5.54	16.99
	Capacity lower section	Mg	6.23	—	11.08	33.97
	Capacity factor[a]	—	—	—	1.78	3.07
	Energy input	MW	—	—	proportional	proportional
	Residence time, top section	second	~2	—	>2.5	>2.5
Homogenization chamber	Length×width[a] factor	—	—	—	~2.5	~2.5

[a]Scale-up factor from Subscale #1 to Fondotoce demonstration plant and from Fondotoce plant to standard plant.
Source: From (559).

In the upper chamber of the HTC, the addition of oxygen maintains the temperature at 1200°C. This upper chamber is the collection point for all process gases. The temperature provided in this section through a proprietary oxygen introduction technique, combined with a residence period approaching 4 seconds and turbulence, is adequate to destroy the most complex organic compounds. The resultant hot gases at 1200°C exit the HTC and are immediately water-quenched in a spray chamber to below 70°C.

d. Homogenization Chamber. The metal and mineral flow from the lower HTC and enter the homogenization chamber where additional oxygen is introduced to react with any remaining carbon particles in the mineral/metal melt flow. As the remaining carbon is depleted, additional heat is required to maintain the melt. Natural gas burners provide this heat at 23 kg/ton of waste or 31.15 m^3/ton. The combined molten metal and mineral melt streams are quenched in a water bath. As the flow enters the water bath, the vitrified mineral stream cools and forms a granulate. The metal mix freezes, forming metal alloy pellets. The resultant mix of granulate and metal pellets is recovered using a drag chain conveyor. As shown in Table 10, the vitrified mineral granulate meets U.S. EPA Toxicity Characteristics Leaching Procedure (TCLP) standards. The developers believe that the low leachability of the solids may make possible the use of this glass-like mineral product for

Raw material components for making clinker brick
A cement substitute analogous to the use of anthracite fly ash
A concrete additive
A filler for bituminous mixtures
A filler and antifrost layer in underground engineering
Mineral fiber and heat insulation fibers
Decorative blocks for the building industry

The redox processes occurring above 1800°C reduce the metal oxides and cause typical alloy-forming metals such as nickel, chromium, and copper to pass into an iron-rich metal melt. Since this melt has a very low concentration of high-vapor-pressure

Table 10 Vitreous Mineral Product: Elution Testing

Analysis	Result	Unit	EPA regulatory limit
Ignition	>200	°F	<140
Corrosivity	6.9	pH	<2, >12.5
As cyanide	<0.10	mg/kg	variable
As sulfide	<0.50	mg/kg	variable
Arsenic, TCLP	<0.40	mg/l	5.0
Barium, TCLP	0.07	mg/l	100.0
Cadmium, TCLP	<0.01	mg/l	1.0
Chromium, TCLP	0.04	mg/l	5.0
Copper, TCLP	0.11	mg/l	100.0
Lead, TCLP	<0.10	mg/l	5.0
Mercury, TCLP	<0.0025	mg/l	0.2
Selenium, TCLP	<1.0	mg/l	1.0
Silver, TCLP	0.03	mg/l	5.0
Zinc, TCLP	0.22	mg/l	500.0

Source: From (559).

components such as mercury, zinc, cadmium, lead, and arsenic, the developers believe that it can be used directly for metallurgical purposes.

Because of the severe duty imposed on the homogenizer section, it must be replaced periodically. The developer includes a "spare" homogenizer in the basic plant capitalization to ensure that an exchange with a spare section can be performed with minimum line outage. The replacement period is believed to be 6 months, and Thermoselect has stated that cooling and removal of the spent unit, positioning of the refreshed unit, and restart can be accomplished over a weekend.

e. Gas Cooling and Gas Separation from Process Water. The hot gases contained in the upper section of the HTC exit are rapidly water-quenched to below 70°C. The reactor gases and sulfur-bearing gases (hydrogen sulfide in the reducing environment of the furnace) are separated from the quench water and passed through successive scrubbers: an acid wash at ~ 60°C, treatment for desulfurization; and an alkaline wash at 40°C. They are chilled to 5°C to remove water vapor and are then passed through a coke filter and warmed to ambient temperature before use.

The high-volume water quench of the hot process gases quickly lowers the temperature of the gases; the water serves as a sink for particulate matter including heavy metals and water-soluble acid gases such as Cl_2 and F_2, which form HCl and HF, respectively.

The sulfur-removal system converts hydrogen sulfide (H_2S) to sulfur using a ferric iron complex via a well-proven, proprietary process. The resultant ferrous iron complex, proportionately formed, is regenerated in an adjoining stage using oxygen from air. The sulfur is precipitated as the element. The removal of elemental sulfur (S), compared with the removal of sulfur as gypsum ($CaSO_4$) common to most control processes based on the use of lime, reduces the mass of sulfur solids end product by a factor of more than four. Further, the developer believes that the quality of the sulfur is suitable for sale.

f. Process By-Products. The processing-water solutions generated from the gas-cleaning sections are subject to conventional chemical material separation processes. After precipitation and removal of the heavy-metal hydroxides as a solid concentrate and other insoluble portions of the process water, the combined streams are passed through a reverse-osmosis membrane, removing much of the remaining salts (primarily sodium chloride). This step is followed by evaporation of the water to concentrate and remove soluble residuals. The clean, distilled water is returned for use in the process-water loops and cooling towers. Since the process recovers the water contained in the original waste input, excess water is recovered as part of the process; it is pumped to hybrid cooling towers and evaporated. No process water need be diverted to a sewer.

The following by-products are collected in addition to the product gas, vitrified mineral product, and metal alloy pellets:

Industrial-grade sodium chloride (salt)
Elemental sulfur
Concentrate containing heavy-metal hydroxides

The metal and vitrified mineral granulates collected from the homogenization chamber can be density separated when in molten form, but they are more easily handled in granulate and metal-pellet form. These pellets can then be separated by a magnet into vitrified mineral product and metal alloy pellets. The metal pellets consist of iron alloy ($>90\%$), with considerable amounts of copper (3 to 5%), nickel (0.6%), chromium (0.3%),

tin (0.4%), and phosphorus (0.1%). The developer believes the concentrations of heavy metals that find their way into these by-products are at acceptable levels.

The residual aqueous solution from the wastewater purification system flows to a distillation tower to concentrate the residual sodium salt and recover high-quality water for recycle to the process. Thermoselect claims the concentrate contains only minimal amounts of contaminants.

3. Environmental Aspects

a. Air Emissions. An extensive testing program was conducted between June and September 1994 by 10 institutions from Germany, Switzerland, and Italy. Some of the participants were:

RWTÜ-Essen
Badenwerke AG-Karlsruhe
TÜ Energy & Environment GMBH
Filderstadt and Steiger Environmental Technology AG-Lista

Emission data from the gases exhausted when heating the degasification channel (Table 11) indicate emissions are well below the U.S. EPA requirements for new MWCs.

Further, test results indicate less than 0.1% free oxygen in the product synthesis or fuel gas and only minute traces of organic compounds. No chlorinated aromatic hydrocarbons, other than PCDD and PCDF, were detected. No aromatic amines, carbonyl sulfide, carbon sulfide, or phosgene could be detected. The data indicate that this system will comply with U.S. environmental regulations.

Table 11 Comparison of Air Emissions

Component	Units	U.S. EPA[a]	Thermoselect[b]
HCl	ppm(v)	25 (or 95% removal)	0.5
SO_2	ppm(v)	30 (or 80% removal)	2.0
NO_x	ppm(v)		<80.0[c]
First year		180	
Subsequent years		150	
CO	ppm(v)	[d]	30.0
Dust	mg/Nm^3	24.0	9.0
Cd and Tl	mg/Nm^3	0.020	<0.01
Hg	mg/Nm^3	0.08 (or 85% removal)	0.03
Pb[e]	mg/Nm^3	0.20	0.01
PCDD & PCDF			
Total	ng/Nm^3	13.0	
TEQ	ng/Nm^3	0.20	0.02

[a]Final U.S. EPA standards. NSPS for New MWCs: *Federal Register*, December 19, 1995, 40 CFR Part 60.
[b]Represents average daily values.
[c]This value is dependent on the method used to convert synthesis gas into an energy form.
[d]Depends on EPA interpretation of combustor class.
[e]Pb plus all remaining heavy metals: $<0.07\,mg/Nm^3$.
$\sum$: Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Sn.
Source: From (559).

Table 12 Average Reactor Gas Composition

Component	Volume percent
Carbon monoxide (CO)	34–39
Hydrogen (H_2)	32–35
Carbon dioxide (CO_2)	22–27
Nitrogen (N_2)	3–4
Methane (CH_4)	<0.1
Other	<0.6

Source: From (559).

b. Wastewater Emissions. The developers believe that the system has no wastewater.

c. Residue Characteristics. The developers believe that the system has no solid residues and that all of the solids produced by the process can be sold or disposed at no net cost for use rather than disposal. The validity of these assumptions is yet to be tested in long-term commercial practice.

4. Product Gas and Residue

When a waste feed containing 50% organic matter, 25% organic matter, 25% water at 2480 kcal/kg is processed, a 1980 kcal/Nm^3 reactor gas with the average composition shown in Table 12 results.

These values appear close to those predicted by the assumption of thermodynamic equilibrium at 1200°C, which is reasonable given the high temperature (fast reactions) and long (4 sec) retention time. The small amounts of methane, as well as larger proportions of CO, are indicative of the substantially complete decomposition of higher-molecular-weight substances.

The cleaned reactor gas is an energy source for the production of electricity using a gas engine or gas turbine (as a combined cycle, if a large facility is involved) or as a fuel to a steam boiler for use as either process steam or for the generation of electricity via a conventional Rankine cycle. The developer includes the energy conversion plant as part of the scope of supply. In concept, the reactor gas can also be a chemical feedstock for methanol or other chemical manufacturing use.

As shown in Table 11, air emissions on burning the gas are significantly below the U.S. EPA New Source Performance Standards for large MSW combustors.

13

Air Pollution Aspects of Incineration Processes

Air pollutant emissions have become the focus of public concern and regulatory scrutiny regarding incineration facilities. The fraction of total facility capital cost for system components functionally directed at compliance with air emission limitations is, for many plants, more than 35% of the total investment. In many instances, the award of air pollution permits is the pacing and controlling event in the implementation of incineration facilities. Because of these realities, those wishing to construct and operate incineration systems should explore and understand the relationships between the quantity and characteristics of air pollutant emissions and

The specific chemical and physical characteristics of the wastes to be burned
The design features of the combustor
The operating conditions in the combustor
The control effected by the air pollution control device(s)

With this knowledge, the analyst can institute controls on the types or relative firing rate of the wastes to be burned and/or configure the hardware designs and the operating regimens to ensure that no adverse air quality impacts detract from the benefits of incineration as a useful tool in waste management.

I. AIR POLLUTANTS FROM COMBUSTION PROCESSES

In the combustion of fuels and wastes, air contaminants are generated that have significance to the design engineer or system analyst in three areas:

1. Obtaining permits from regulatory agencies for installation and/or operation of the system
2. Establishing the specifications for air pollution control systems
3. Establishing the basic design, suggesting modifications to existing designs, or interpreting problems in emission minimization or control

Many air pollutants are emitted from combustion processes. The most basic is inorganic particulate matter. The total suspended particulate (TSP) is, predominantly, relatively inert "ash": a mixture of benign compounds primarily composed of silicon, aluminum, calcium, iron aluminum, and oxygen. However, this portion of combustor emissions also includes the "heavy metals" of lead, mercury, cadmium, arsenic, and other elements that may have significant toxic, carcinogenic, and other health effects.

Finally, the inorganic TSP includes an important portion of the small particle size material denoted as "$PM_{2.5}$." $PM_{2.5}$ is the respirable fraction under 2.5 microns in mass mean diameter and has been shown to have an important role in both the onset and aggravation of asthma and other respiratory diseases. Data on fine particulate matter show sulfates and nitrates to be the most abundant species in atmospheric aerosols, with sulfates being the predominant contributor to $PM_{2.5}$ (507). A substantial fraction of the total atmospheric $PM_{2.5}$ is formed outside the stack from SO_x and NO_x precursors (secondary $PM_{2.5}$). However, because of the health concerns regarding $PM_{2.5}$, one might expect more stringent increasing limits to be placed on acid gas and NO_x emissions, even if baghouse and wet electrostatic precipitator controls effectively capture the primary $PM_{2.5}$ in the exhaust gases.

A second category of emission includes the combustible solids, liquids, and gases. A portion of these combustibles can be a fraction of the raw waste originally fed to the unit. Beyond this, a complex mixture of products of incomplete combustion (PICs) is usually found. These include carbonaceous soot and char; carbon monoxide; "hydrocarbons"; and representatives of many classes of carbon–hydrogen–oxygen–nitrogen–halogen compounds such as benzene-soluble organic matter (BSO), polycyclic organic matter (POM) (e.g., benzo-(α)-pyrene), and a variety of polyhalogenated hydrocarbons (PHH), including the isomers and congeners comprising the families of polychlorinated and polybrominated dibenzo-furans (PCDF, PBDF), p-dibenzo dioxins (PCDD, PBDD), and biphenyls (PCB, PBB).

Some of the organic and/or inorganic compounds emitted from incinerators exhibit (or are suspected to exhibit) significant adverse health effects. Some of the compounds react in the atmosphere (especially under the influence of ultraviolet radiation) to generate ozone and a spectrum of eye-irritating oxygenated reaction products. With the great strides in sampling and analysis technology in recent years, the emission of these compounds can be quantified, regulated, and used as a basis for fines and penalties and, of vital importance, continuation of permission to operate.

For several pollutants the emission level is directly related to fuel chemistry. These include the sulfur oxides, the halogens and hydrogen halides, trace elements, and radioactive elements. Others, such as the nitrogen oxides, show emission levels related to both fuel chemistry and the combustion process. Inert particulate emissions are related to the fraction of "ash" in the feed and the fluid flow and other physical processes that can elutriate and convey the material from the combustion zone. Net pollutant emissions of pollutants such as the PICs arise partly from the waste chemistry (contributing "building blocks"), partly from failures in the combustion process (generating the PICs), and partly from successes in the combustion process (destroying a portion of the PICs).

The sections that follow yield more detailed insights into the mechanisms by which these pollutants arise. This knowledge provides guidance from which the waste characteristics and the incinerator design features and operating conditions can be used to quantitatively estimate uncontrolled emission rates for many of the important pollutants. Such calculations and the physical principles that may underlie them also provide the

designer and operator (both have a role in most cases) with tools to minimize the emission rates.

Beyond the engineering utility of emission estimation relationships, the regulatory process in the United States and worldwide now demands detailed consideration of air emissions in the permitting and public participation phases of project development. The preparation of permit applications and the hearings that are increasingly a part of the permit approval process usually predate the availability of hard emission data. When the proposed combustor is of a new design or the waste is unique, the engineer is faced with a need to generate credible emission estimates without a facility/waste-specific data base on which to draw. The emission estimates, however, are often critical to securing a permit to construct and as a basis for environmental impact evaluations, health risk assessments, and other analyses where data from the operating facility are not yet available.

The emission estimation methodologies described ahead attempt to predict the actual concentrations of pollutants in the exhaust of combustion systems and in the discharge after air pollution control. As such, a factor of safety must be applied to provide a reasonable level for "not to exceed" permit limits. This is appropriate (1) in recognition of the uncertainties in the estimation methods, (2) to provide some margin for expected variability in the feed and/or system characteristics, and (3) in those situations where the permit limits will be passed on to incinerator system vendors (who will be asked to guarantee permit compliance), to associate the emission requirements with a reasonable and fair level of commercial risk.

A. Particulate Matter

1. General

This section deals with inorganic particulate matter, which, for the purposes of this discussion, is differentiated from the total particulate (the sum of inorganic particulate plus the soot, tar, and other organic-based substances comprising combustible particulate matter). This is an acknowledgment of the inherent refractory nature of inorganic particulate (emission rates cannot be reduced by better combustion) and, to clearly establish its primary source: the ash content of the fuel or waste that is burned. In principle, inorganic particulate can also arise from mechanical degradation of refractory or from oxidation and flaking of fireside metal surfaces. However, the great majority of the emission results from the carryover of mineral matter introduced with the fuel or waste. In unusual conditions, where combustion air is drawn from an area with a high dust loading, a portion of the emission could be associated with the air supply.

Important particulate characteristics include size, size distribution, shape, density, stickiness, corrosivity, reactivity, and toxicity. Of these, particle size distribution (PSD) has the most important impact on air pollution control. PSD can be expressed as a particle count and as a mass distribution. Most commonly, the greatest mass is associated with the larger particles, but the greater number of particles, visual impact (opacity due to light scattering), surface area, and difficulty in capture are found with the smaller particles.

The Gaussian or "normal" distribution function is often used to describe many data populations. However, the log normal distribution function (see Chapter 2) is usually superior to characterize particles from industrial sources. In this case, a plot of the log of the particle size against frequency produces a straight line on log-probability paper. As an example, consider the particle size distribution data shown in Table 1.

Table 1 Particle Size Distribution Data

Column 1	Column 2	Column 3	Column 4
Size range (microns)	Mass (mg)	Mass fraction in size range	Cumulative % less than top size
0–2	4.5	0.0049	0.5
2–5	197.8	0.2150	22.0
5–9	395.6	0.4300	65.0
9–15	257.6	0.2800	93.0
15–25	59.8	0.0650	99.5
>25	4.6	0.0050	100.0

Summing the mass in column 2, the mass fraction (column 3) is calculated and then the cumulative mass weights generate column 4. If one then plots the upper limit of the size range against the cumulative percent less than top size on log-probability paper, a straight line is generated (confirming the assumption of a log normal distribution) with a value of particle diameter at cumulative percentages of 15.9%, 50%, and 84.1% ($d_{15.9}$ at one standard deviation below the geometric mean, d_{gm} at the geometric mean, and $d_{84.1}$ at one standard deviation above the geometric mean, respectively) of 4.6, 7.4, and 12.0 microns. The geometric standard deviation σ_g is given by

$$\sigma_g = d_{84.1}/d_{\text{gm}} = 12.0/7.4 = 1.62$$

$$\sigma_g = d_{\text{gm}}/d_{15.9} = 7.4/4.6 = 1.61$$

with an average value for σ_g of 1.615.

Therefore, this graphical analysis shows a geometric mean diameter (equal to the mass median diameter, or MMD) for the particle size distribution of 7.4 microns and a geometric standard deviation of 1.615 microns.

Particle size determinations are commonly made in two ways: by direct measurement using an electron microscope of particulate matter captured on a filter or by use of a cascade impactor. With the impactor device, a sample of gas and particles is drawn through a series of stages consisting of slots or holes and impaction plates. Each successive stage has narrower slots and closer plates so that increasingly smaller particles are captured. Following an appropriate sampling period, the mass of particles on each plate is measured to determine the size distribution. Since the capture of particles is directly related to the balance of drag and inertial forces acting on a particle in a flow field, the characteristic dimension being determined is the aerodynamic diameter, a property that combines factors of shape, density, and physical dimension. This may differ somewhat from the physical diameter measured with the microscope. The aerodynamic diameter can be thought of as the diameter of a water droplet (unit density) having the same aerodynamic properties as the actual particle.

2. Gaseous and Liquid Wastes and Fuels

A desktop assessment of the fraction of the inorganic matter in a fuel that appears in the flue gas is often difficult because of the complexity of the processes involved. Thus, empirical estimation methods are necessary unless the system design is such that

essentially all introduced solids must leave via the flue gas stream. This is often true for systems burning gaseous or liquid waste. For many conventional gaseous and liquid fuels, combustion systems often do not include air pollution control for particulate matter. When burning liquid or gaseous waste streams, however, sampling or estimation of inorganic content is an appropriate step during the design phase to ensure that no control system is needed. Then consideration can be given to either pretreatment of the waste to remove the solid matter or installation of a flue gas particulate air pollution control device.

EXAMPLE 1. A liquid waste stream is to be incinerated. In preparing the permit, the analyst wonders about the need for air pollution control. It is known that 95% of the inorganic suspended solids can be removed by centrifuging the liquid before incineration. The applicable particulate emission code sets an upper limit of 300 mg/m^3, corrected to 20°C, 1 atm, and a (dry) flue gas CO_2 content of 12% (by volume). Evaluate the situation.

Component	Waste composition (weight percent)
n-Hexane (C_6H_{14})	46.0
Ethanol (C_2H_5OH)	23.0
Water (H_2O)	28.7
Suspended mineral solids	2.3
Total	100.0

Basis: 100 kg of waste

Component	kg	Moles	Moles C	Moles H_2	Moles O_2	Moles stoichiometric O_2 required
C_6H_{14}	46.0	0.535	3.209	3.744	0.0	5.081
C_2H_5OH	23.0	0.5	1.0	1.5	0.25	1.5
H_2O	28.7	1.594	0.0	1.594	0.797	0.0
Total	100.0	2.629	4.209	6.838	1.047	6.581

In the dry flue gases at test conditions of 12% CO_2,

$$12.00 = \frac{(\text{mols } CO_2)(100.0)}{\text{mols } CO_2 + \text{mols } O_2 \text{ in excess air} + \text{mols } N_2 \text{ in stoichiometric and excess air}}$$

For X mols O_2 in the flue gases,

$$12.00 = \frac{(4.209)(100.0)}{4.209 + X + (79/21)(6.681 + X)}$$

$$X = 1.283 \text{ moles } O_2 \text{ (equivalent to 19.5\% excess air)}$$

The dry flue gas contains

CO_2	4.209 mol	or	12.0%
O_2	1.283 mol	or	36.6%
N_2	29.584 mol	or	84.4%
Total	35.076 mol	or	100%

At code conditions, the dry flue gas will have a volume of

$$(35.076)(22.4)(293/273) = 843\,\mathrm{m}^3$$

For the worst-case assumption that all of the mineral particulate appears in the flue gas, the gases will contain 2300×10^3 mg of solids for a corrected particulate loading of $2730\,\mathrm{mg/m}^3$. This is considerably in excess of the code. Ninety-five percent suspended solids removal will reduce the loading of mineral particulate to $136.5\,\mathrm{mg/m}^3$, or about 60% of the code. The decision is thus clear: either waste pretreatment *or* air pollution control will be required, with the selection of the optimum to be based on several considerations:

- A comprehensive economic analysis (including capital and operating costs, the relative disposal costs of centrifuged solids or ash, etc.)
- Judgments as to changes in waste composition and treatability in the future that may change the ability to achieve compliance through pretreatment
- Judgments as to the willingness of the permitting agency to approve a permit where compliance depends on unmonitored operating practices

3. Sludge

The sludge considered in this section refers to biological wastewater treatment plant biosolids. The emission characteristics when burning high-organic sludge (such as the tarry material found as distillation bottoms, API separator sludge, or petroleum tank bottoms) are expected to compare favorably to the emission behavior of liquid wastes albeit with adjustment for higher ash content.

Biosolids are generated through settling (primary treatment) and activated sludge (secondary treatment) or other process steps for the conversion of soluble pollutants into biomass (biota). Because of the nature of the wastewater collection and treatment process, biological sludge ash is primarily comprised of finely divided inorganic material that can be suspended in fast-moving flue gases with relative ease. The emission rate of inorganic particulate is strongly tied to the type of incineration system and to its operating characteristics.

a. Multiple Hearth Furnace (MHF). The relationships between the uncontrolled pollutant emissions and MHF design and operating conditions are complex. The carryover of particulate, the formation of carbon monoxide and other combustible pollutants, the emission patterns of the key toxic metals, and so forth change in a nonlinear manner and in response to different system variables. Therefore, a substantial data base that includes both emission and system variables is needed to characterize system behavior. Also, the data must be both ahead of and following the air pollution control device (the uncontrolled and the controlled emission rate) such that insightful system-emission relationships may be developed.

The emission correlations given here for particulate and in the sections that follow for other pollutants were based on analysis of 154 sets of multiple hearth furnace process and emissions data comprised of 55 sets of uncontrolled emission data, 99 sets of controlled emission data, with 45 sets of matched inlet–outlet data for the same unit and sludge (Refs. 229–255). The analysis produced correlations between design and operating configuration and emissions/control efficiency. The results supported the formulation of generation/control algorithms for 17 pollutants: total suspended particulate

(TSP), NO_x, SO_2, SO_3, CO, total hydrocarbons (THC), PCDD, PCDF, and the elements As, Be, Cu, Ni, Cd, Pb, Hg, Cr, and Zn.

As with most "real-world" data sets, the data vary in an unknown way with the sophistication of the testing firms and in completeness relative to the need for a comprehensive set of design, operating, and emissions information. While often frustratingly incomplete or clearly including either inaccuracies or assumptions (rather than hard data), the data base supports what appear to be reasonable and useful correlations.

In general, the analysis was conducted by devising possible process variable-emission relationships and then testing the statistical significance of correlations using the coefficient of determination (r^2) for the least-squares fit of the data for differing functional relationships. The scatter inherent in such a group of data from different testing firms, furnaces, etc., regularly led to low r^2 values (say, 0.3 to 0.7) so graphical visualization of the degree of fit supplemented the purely mathematical test.

The TSP emissions (percent of ash fed to the furnace which is carried over) showed their strongest correlation to the dry, standard cubic meters per minute of furnace flue gas (DSCM) per kilogram of ash fed to the furnace. For most plants, 2% to 3% of the ash in the feed sludge is carried over, although, at high excess air rates, the emissions can reach 5% or 6%. The suggested linear functional relationship (based on consideration of 19 data points, $r^2 = 0.46$) is

$$\text{percent of ash in feed that is emitted} = -0.2382 + 0.4955\ (\text{DSCM})$$

The correlation is plausible based on the speculation that the primary mechanism for particulate emission is elutriation of fines in the sludge by the flue gas flow.

b. Fluid Bed. The fluid bed furnace is unique in that, except for the solids drained from the bed (a mixture of sludge ash and bed material), all of the sludge ash is blown from the bed. Thus, the dust mass rate (kg/hr) entering the collector is approximately equal to the total feed rate of sludge ash to the furnace plus the time-averaged bed sand makeup rate less the settlement in the ductwork. The latter is negligible (steady state) except in the case where a boiler is installed when there may be some drawoff of solids from a hopper in the boiler.

4. Solid Wastes and Fuels

Unlike liquid or gaseous fuels, which may contain little inorganic matter, almost all solid wastes and fuels have a substantial ash content. Since these latter fuels are seldom susceptible to pretreatment to reduce emissions, the designer must give careful attention to design features and operating practices to minimize the uncontrolled emission rate. Even with such precautions, it is likely that emission control will be required.

a. Suspension Burning. The maximum inorganic particulate emission rate corresponds to the situation where all noncombustible solids are swept from the combustion chamber. This is largely the case for burners fired with pulverized coal, shredded and air-separated municipal refuse, sawdust, rice hulls, and other *suspension firing* systems. In such systems, a portion of the fly ash may settle in the bottom of the primary furnace or in following chambers or boiler sections. The degree to which settlement reduces emission rate depends on the flue gas properties, on the characteristic dimensions and weight of the fly-ash particles (settling rate), and on the velocity of the gas stream relative to the chamber dimensions (transit time).

An approach to estimating the potential for fallout makes use of Stokes' law (and its various extensions into the "transition" regime for larger particles), although the result will tend to *overestimate* the fallout rate. The complications tending to lower the measured settling efficiency below the calculated value are

Nonsphericity of particles.
Particle re-entrainment due to turbulence. This can be minimized by use of baffles (creating low-turbulence zones) or, if appropriate, a wet, water-sluiced chamber floor.
Nonuniformity of particle density: the coarser particles tend to be lower in density.
Particle–particle interactions ("hindered settling").
Fallout of the very coarse particles prior to the chamber under analysis, leaving a less easily settled dust in the gas stream.

In general, settling velocities for *homogeneous spherical particles* can be calculated from the relation

$$u_t = \left[\frac{4d(\rho_s - \rho_a)g}{3\rho_a C_x}\right]^{1/2} \tag{1}$$

where

u_t = Terminal settling velocity (m/sec)
d = Particle diameter (m)
ρ_s = Density of particle (kg/m^3)
ρ_a = Density of gas (kg/m^3)
g = Gravitational constant (m/sec^2)
C_x = Drag coefficient (dimensionless)

In the streamline flow region (small particles), the drag coefficient is inversely proportional to the dimensionless Reynold's number N_{Re}:

$$C_x = \frac{24}{N_{\mathrm{Re}}} = \frac{24\mu}{du_t\rho_a} \tag{2}$$

where μ = viscosity of gas, in kg/m sec^{-1}, and

$$N_{\mathrm{Re}} = \text{Reynolds' number} = \frac{(du_t\rho_a)}{\mu} \tag{3}$$

In the streamline flow region, combining (1) and (2) leads to Stokes' law:

$$u_t = \frac{d(\rho_s - \rho_a)g}{18\mu} \tag{4}$$

For practical purposes, the streamline flow region stops at about $N_{\mathrm{Re}} = 0.5$ to 1.0. Thus, for 200°C gases and particulate densities of 2.5 g/cm^3 (2500 kg/m^3), Eq. (2), and thus Stokes' law, is valid only up to diameters of about 90 μm. Above this region, we must use relationships other than Eq. (2) to characterize the dependence of C_x on N_{Re}. For larger particles, the relation of Schiller and Naumann (32) indicates

$$C_x = \frac{24}{N_{\mathrm{Re}}}[1 + 0.15N_{\mathrm{Re}}^{0.687}] \tag{5}$$

This relation is valid for $0.5 < N_{\mathrm{Re}} < 800$.

Table 2 Calculated Settling Velocities in Hot Air (Spherical Particles)[a]

Diameter (μm)	Settling velocity (m/sec)			
	(Density = 2.0 g/cm^3)		(Density = 3.0 g/cm^3)	
	at 200°C	at 800°C	at 200°C	at 800°C
30	0.03	0.03	0.06	0.03
40	0.06	0.03	0.09	0.06
50	0.12	0.06	0.15	0.09
60	0.15	0.09	0.24	0.12
70	0.21	0.12	0.34	0.18
80	0.27	0.15	0.43*	0.24
90	0.37*	0.21	0.49	0.30
100	0.43	0.24*	0.55	0.37*
200	1.13	0.85	1.55	1.22
300	1.92	1.65	2.56	2.29
400	2.68	2.50	3.54	3.41
500	3.38	3.35	4.45	4.54
600	4.08	4.21	5.33	5.64
700	4.75	5.03	6.16	6.71
800	5.36	5.85	6.98	7.74
900	6.00	6.64	7.89	8.75
1000	6.58	7.41	8.50	9.72

[a]The asterisk denotes the largest particle for which Stokes' Law was used; Schiller–Naumann extension (32) was used for all larger particles.

Unlike the combination of Eqs. (1) and (2), the combination of Eqs. (1) and (5) no longer gives an explicit relation for u_t but requires a trial-and-error solution. As an example, application of these relations to particles of density 2.0 and 3.0 g/cm^3 in hot air at two temperatures leads to the settling velocities shown in Table 2. Note that for large particles, the effect of temperature is not very great.

For a chamber 9 m high with a mean gas residence time of 5 sec (similar to the settling chamber originally installed at the Hamilton Avenue incinerator in New York City for operation at 300% excess air), all particles falling faster than about 1.8 m/sec (or bigger than about 250 μm in diameter from Table 1) should reach the bottom of the chamber during the 5-sec transit time. Particles falling at a slower rate should be deposited in proportion to the ratio of their settling velocities to the critical velocity (1.8 m/sec for this chamber). The performance for a nominal size distribution (21) would be as shown in Table 3.

Such a "perfect" chamber would remove about 41% of the incoming particulate weight. In practice, due to the factors mentioned above, a typical efficiency for a dry settling chamber is only 15% (33). In Installation No. 1 as described by Walker and Schmitz (34), the efficiency of such a chamber is estimated at 21%. Operation with wet floors to prevent re-entrainment increases the efficiency. For example, at Hamilton Avenue, the efficiency was measured at about 35% and 31% at another installation. A second test at the latter plant gave only a 21% efficiency. Baffling can also raise the collection efficiency by increasing the probability of a particle's encountering a solid surface.

Table 3 Calculated Performance of a Settling Chamber (Nominal Dust Size and Density (21); 9 m High, 5-sec Residence Time)

Diameter (μm)	Weight (kg) of particles per 100 kg of total dust entering	Removal efficiency (%)[a]	Weight (kg) of particles remaining	Weight (kg) of particles per 100 kg of total dust remaining
<1	9	0	9	15
1–2	5	0	5	9
2–5	7	0	7	12
5–10	6	0	6	10
10–15	5	0	5	8
15–20	3	0	3	5
20–30	5	1	5	8
30–40	3	3	3	5
40–50	4	5	4	7
50–100	8	15	7	12
100–200	8	50	4	7
200–300	5	90	1	2
>300	32	100	0	0
Total	100		59	100

[a]Removal efficiency = 100 − 59 = 41%. Based on settling velocities given in Table 2.

The theoretical performance of other settling chambers can be calculated as above with the aid of the settling velocities given in Table 2. Thus, for example, a shorter drop (say a 4.5-m height with the same residence time at 200°C) would, in theory, remove all particles larger than 150 μm and have a total removal efficiency of about 47% (compared with the 41% for the chamber twice as high). The efficiency of these devices is low, but so is their pressure drop—typically below 0.3 mm Hg. The major portions of this pressure loss occur at the inlet and a lesser amount at the outlet of the chamber, as a result of expansion and contraction losses.

b. Mass Burning. In mass burning, the fuel or waste is moved through the combustion chamber on a grate. The introduction of a portion of the combustion air through the grate provides a mechanism whereby some of the ash can be fluidized and carried off with the flue gases. This mechanism is favored by fuels or wastes with a high percentage of fine (i.e., suspendable) ash, by high underfire air velocities, or by other factors that induce a high gas velocity through and over the bed. Secondary inducements to emission include agitation of the bed and the volatilization of metallic salts. Grate systems designed with large air passages (such that a substantial fraction of the fine ash is dropped out) tend to reduce the emission rate.

ASH CONTENT. Ash particles may be entrained when the velocity of the gases through the fuel bed exceeds the terminal velocity of the particles as calculated using Stokes' law [Eq. (4)]. Undergrate air velocities in municipal incinerators typically vary from a minimum of 0.05 $sm^3\ sec^{-1}\ m^{-2}$ of grate area to 0.5 $sm^3\ sec^{-1}\ m^{-2}$. Based on the terminal velocity of ash particles (Table 2), it is therefore expected that particles up to 70 μm will be entrained at the lowest velocities and up to 400 μm at the highest at a mean temperature of 1100°C. This postulated mechanism of particulate entrainment is supported by the observed range of particle sizes of fly ash, the increases in particulate emission with

increases in refuse ash content, observed increases in particulate emission with undergrate air velocity, and the similarity in the chemical analyses of fly ash and that of the ash of the principal constituents of refuse.

Evaluation of the particle size distribution of fly ash (21) shows 70 wt% of the particles are smaller than 250 μm. This is consistent with the calculations of terminal velocities. The data available, however, are insufficient to test the expectation that the maximum particle size of the fly ash emitted increases with undergrate air velocity.

The dependence of the particulate emission factors on the ash content of refuse is most striking. The high ash content of German refuse collected during the winter in the mid-1960s (when most furnaces for domestic heating were coal-fired) accounts for their high emission rates. The correlation of furnace emission factors with ash content of refuse is demonstrated by the data abstracted in Table 4 from articles by Eberhardt and Mayer (35) and by Nowak (36). The refuse ash content and furnace emission rates in January are greater than the corresponding values in August by factors exceeding 4 and 6, respectively. The percentage of the refuse ash carried over would be smaller if the value were based on the fine particle fraction of the ash in place of the total ash content, but the percentage of the fine ash carried over would, of course, be larger. It is interesting to note that values reported for the particulate emission for a chain grate stoker burning coal corresponds to a little over 20% of the ash content of the coal, a value not very different from the range found for refuse.

Additional evidence of the effect of ash content on particulate is provided by the Public Health Service (PHS) studies on an experimental incinerator (37). Tests were conducted first with a synthetic refuse consisting of newspaper, cardboard, wood, and potatoes and then repeated with a high-ash paper substituted for the newspaper. The ash contents have been estimated here to be 2.0 wt% for a 25% moisture synthetic refuse and 7.5 wt% for the case in which high-ash paper is substituted for the refuse. These estimates were obtained from the percentages of the different components reported by the PHS and

Table 4 Seasonal Variation in Refuse Ash Content and Furnace Emission

Month	Refuse ash content (%)	Refuse heating value (kcal/kg)	Furnace emission rate (g/Nm^3)[a]	Refuse ash emitted (%)
January	44.5	1200	15	14
February	38	1311	12.8	15
March	30.5	1422	9.3	13
April	27	1467	7	13
May	22	1533	5.3	12
June	18	1650	4	13
July	12.5	1667	2.3	10
August	10.5	1583	1.9	10
September	14.5	1578	2.7	10
October	26	1444	5.7	11
November	35.5	1350	10	13
December	43	1289	13.7	14

[a]Grams of particulate per normal (volume of a gas at standard conditions of temperature and pressure) cubic meter.

Source: From Refs. 35 and 36.

Table 5 Effect of Ash on Emission Rates

Refuse ash content (%)	Underfire air (% of total)	Emission rate kg/tonne	Refuse ash emitted (%)
2.0	15	0.57–2.19	2.74–11
2.0	60	1.55–4.46	7.75–22
7.5	15	0.74–1.86	1.0–2.5
7.5	60	6.61–15.83	8.8–21

Source: From Ref. 37.

from the ultimate composition of typical refuse components reported by Kaiser et al. (38–40). The results, summarized in Table 5, show that, for large percentages of underfire air, the percentage of the refuse ash carried over in the combustion gases is approximately the same for the two different fuels and ranges from 8% to 22% with a maximum value a little greater than that found in European practice. However, at low underfire air rates, the percentage of the fly ash carried over is much smaller, and better agreement is found between the absolute emission rates for low- and high-ash-content fuels than between the corresponding percentages of ash carried over.

These findings show that the ash content of the refuse is a major factor in determining emission rates and that the percentage of the ash carried over ranges mostly between 10% and 20% of the total. The actual percentage carried over for a particular incinerator will, of course, depend on other factors, such as the underfire air rate. Consideration of the particle terminal velocities indicates that the above conclusions apply only to fine particle ash (finer than 400 μm).

The above conclusion, that approximately 10% to 20% of the fine ash content of refuse is carried over, may be tested by application to a municipal refuse composition. A ton of typical 1960's U.S. refuse, as received, contained about 54 kg of fine ash (calculated by excluding the metal and glass components of total ash) and thus would be expected to yield a furnace emission of 5.5 to 11 kg/ton. This is in fair agreement with the uncontrolled emission factors of U.S. incinerators of that period. In addition, the composition of the fly ash may be calculated from the ash composition of the refuse constituents, with the assumption that no selective entrainment occurs.

The composition of fly ash so estimated is compared in Table 6 with analyses of the combustible-free fly ash collected in three New York City incinerators (40) and the average analysis of 25 slag samples obtained from nine incinerators in New York, New Jersey, and Connecticut (39). The agreement between the data on fly-ash composition and the values computed from the ash of a typical refuse is satisfactory, with the major differences being the higher values of iron, aluminum, and sulfur oxide found in the ash collected in the New York City incinerators. Oxidation of most of the aluminum foil and part of the iron refuse is the possible explanation for the high percentage of aluminum and iron oxides in the fly ash. The high sulfur content may be attributed to calcium sulfate in wallboard or plaster. From these results, the ash entrainment mechanism seems to be the dominant one in municipal incinerators.

The upper limit given above for the size of particles that could be entrained corresponds to the diameter of a spherical particle. Much larger, thin, flat plates can be entrained; for example, charred paper bits, known as "blackbirds." Unfortunately, most

Table 6 Composition (Weight Percent) of Inorganic Components of Fly Ash

Component	Computed for typical refuse	NYC incinerators[a]		Average analysis of 25 slag samples[b]
		73rd St., Manhattan	So. Shore, Long Island	
SiO_2	53.0	46.4	55.5	44.73
Al_2O_2	6.2	28.2	20.5	17.44
Fe_2O_3	2.6	7.1	6.0	9.26
CaO	14.8	10.6	7.8	10.52
MgO	9.3	2.9	1.9	2.1
Na_2O	4.3	3.0	7.0	8.14
K_2O	3.5	2.3	—	—
TiO_2	4.2	3.1	—	—
SO_3	0.1	2.7	2.3	3.69
P_2O_5	1.5	—	—	1.52
ZnO	0.4	—	—	1.54
BaO	0.1	—	—	—
	100.0			

[a]From Ref. 40.
[b]From Ref. 39.

sampling technicians do not collect these large elements, and no quantitative measure of their rate of emission is available.

UNDERFIRE AIR RATE. A systematic study of the effects of underfire air, secondary air, excess air, charging rate, stoking interval, and fuel moisture content on the emission rate from an experimental incinerator by the PHS led to the conclusion that the velocity of the underfire air was the variable that most strongly influenced particulate emission rate. The data on 25% and 50% moisture fuel were correlated (37) by

$$W = 4.35V^{0.543} \tag{6}$$

where W is the emission factor expressed in units of kg of particulate per metric ton of refuse burned, and V is the underfire air rate (in $sm^3\,sec^{-1}\,m^{-2}$ of grate area). The range of undergrate velocities studied ranged from 0.01 to $0.5\,sm^3\,sec^{-1}\,m^{-2}$ of grate area. Subsequent field evaluation by the PHS (41) of emission rates indicated that the effect of underfire air rate was less pronounced than that predicted by the above equation and suggested that, for the two municipal incinerators tested, the effect was small for undergrate velocities below 0.18 to $0.2\,sm^3\,sec^{-1}\,m^{-2}$ of grate area but significant above that rate.

Walker and Schmitz (34), however, correlated their test results on three municipal incinerators with the relationships developed by the PHS on the experimental incinerator. The results showed general agreement with the predicted slope but scattered ±20%. This is not surprising in view of probable differences in refuse composition, furnace size, and other variables. Although the data demonstrating the increase of particulate emission with

underfire air are limited, supporting evidence for the trend observed is provided by numerous observations of the effect in the literature (42–45).

Additional data supporting the conclusions derived in the literature are those on Plant No. 76 (21). The tests of this furnace showed that the emission increased 59% as the *underfire* air rate was increased from 50% to 100% of stoichiometric, but that decreasing the overall excess air from 50% to 20% resulted in a 44% increase in emission. The anomalous behavior at 20% excess may be attributed to very poor burning characteristic and extensive hand stoking required at the low excess air limit.

Although reduction in the underfire air rate can reduce the emission from the furnace, there is usually (41, 43) an attendant reduction in burning rate. An economic analysis of the trade-off between furnace capacity and air pollution control equipment costs is necessary to optimize the underfire air rate. There is, of course, a minimum underfire air requirement necessary to protect the grate.

INCINERATOR SIZE. Larger incinerator units seem to have slightly higher emission rates, but the effect of size on emission factors has not been quantitatively established. Part of the increase is due to the higher burning rates and, hence, higher underfire air rates associated with large units. However, if emission on large and small units is compared at equal underfire air velocities, a residual effect of size is found. Possibly the higher emission rates for the larger size are a consequence of the higher natural convection currents encountered in large units (see page 243, ff.).

BURNING RATE. For reasons similar to those presented in the preceding paragraph, it is expected that higher emission factors will be encountered at higher burning rates. Rehm (46) cites that reductions in rate of burning to 75% of rated capacity have shown as much as a 30% reduction in furnace emission from that at full capacity; however, insufficient data are available for a quantitative relationship to be established.

GRATE TYPE. Stoking has been observed to increase particulate emission rates. This is particularly evident from the tests on Plant No. 76 (21) and the PHS field tests (41) on the effect of underfire air rate, where the stoking required at the lowest air rates led to a significant increase in emission. Walker and Schmitz (34), however, report results that suggest that the effect of grate design on emission is secondary to the effect of underfire air rate or ash content. The results of their tests on the emission from furnaces operated with a two-section traveling grate, a rocking grate, and a reciprocating grate led them to conclude that the differences in emission factors were primarily due to the differences in underfire air velocities used in the different units.

In order to assess the effect of grate type on emission factors, data on the different types of units were compiled (21). The emission rates from reciprocating grate stokers were seen to be significantly higher than those from other grate types. It is probable that higher rates in the reciprocating grate units are due to a combination of greater stoking, higher underfire air rates, and larger furnace sizes than in the other units. Another factor is the difference in grate openings, which can result in large differences in the amount of fine ash that can sift through the grate; lower emission rates would be expected from grates (e.g., rocking grates) that have large amounts of fine ash sifting through the grate.

COMBUSTION CHAMBER DESIGN. Practically the only data in this area are provided by the studies in Los Angeles County. From these data it can be concluded (43) that the emission from small units can be reduced substantially by use of multichambers and a low arch. The emission in these tests was primarily particles under 5 μm in size, and there is uncertainty concerning the applicability of the results to large municipal incinerators. The

need for a prolonged residence time and/or a secondary combustion chamber for soot burnout in large units will depend mainly on mixing in the primary chamber, which, if effective, should limit the formation of carbonaceous emissions.

VOLATILIZATION OF METALLIC SALTS. Although a major fraction of fly ash from municipal incinerators seems to have been entrained from the fuel bed or formed by cracking of pyrolysis products (soot), trends in the emission rate from small incinerators cannot be explained solely by an entrainment mechanism (43, 47). For example, the sizes of the particulate in the stack discharge data reported by Rose and Crabaugh (43) are mostly in the 0- to 5-μm range. Based on the physical shape as determined from microscopic examination, and on chemical analyses of the noncombustible, Rose and Crabaugh concluded that particles were formed by volatilization and recondensation of metallic salts. This finding, however, is inconsistent with the data on large units for which particles of 0 to 5 μm usually constitute a small fraction of the total uncontrolled emission. In municipal incinerators, the oxidation of the metals is known to be significant, but the volatilization of the salts formed is only of importance for trace constituents; the majority of the oxides are mechanically entrained from the bed.

Although data are insufficient, it would not be surprising to find that volatilization mechanisms are important in municipal waste and other incineration systems relative to the emission of some metals. Here, the metals (especially as chlorides, which, of the compounds of the common anions, often exhibit the lowest boiling points) may volatilize from the bed where temperatures often exceed 1000°C. The chlorine effect is shown in Table 7. Subsequent heterogeneous condensation (generally onto the small particles, which present a large surface area) would produce an enrichment of the fine particles with the volatile metals. Such behavior is seen in coal furnaces (295, 299) and in incinerators (see Section II below of this chapter).

Table 7 Boiling Points of Selected Inorganic Compounds

Compound	Boiling point (°C)
$AlBr_3$	255
NH_4Br	396
NH_4Cl	338
$SbCl_3$	220
$AsCl_3$	130
$BeBr_2$	520
$BeCl_2$	482
$BiCl_3$	447
$CaCl_2$	960
$CdCl_2$	960
$FeCl_3$	316
$PbCl_2$	951
$HgCl_4$	383
$SnCl_2$	623
$ZnCl_2$	732

c. Rotary Kilns. The entrainment of particulate matter from rotary kilns burning hazardous waste and, especially, those used for thermal desorption in soil remediation is a significant operational issue because of its impact on downstream air pollution control and fly-ash handling equipment. For that reason, an accurate estimation method for carryover is highly desirable to proper design.

The amount of particulate carryover is the result of the interplay of a number of factors acting in complex ways (508, 509):

The type of kiln (co-current versus countercurrent)
The characteristics of the processes waste or soil (especially the fraction of the silts and clays)
Mode of oxidation (oxidative versus pyrolytic, which affects gas volume)
Gas velocity through the kiln
The use (or absence) of flights or lifters and internal or terminal dams
The kiln rotational rate
The percent of the kiln cross-section obscured by the material being processed
Wall roughness and the presence of crevices, cracks, and imperfections
Feed and exit design features that impact gas–solid contact opportunities
Solids feed rate

The primary mechanisms responsible for the entrainment of particulate are edge entrainment, surface entrainment, and kiln design entrainment (508).

1. Edge entrainment is due to the cascading of particulate from the upper edge of the bed into the open gas flow path within the kiln and is the principal mechanism of particulate pickup. Edge entrainment arises in three ways:

    a. Friction entrainment, where the feed material is lifted by contact with the rotating kiln wall. When the mass breaks and falls, particles are caught up in the gas flow.
    b. Adhesion/suspension, where sticky material (tars, sludges, wet clayey soils) ride up with the kiln wall, ultimately fall, and are entrained.
    c. Mechanical, where crevices in the refractory surface, cracks between bricks, or lifters mechanically hold quantities of solids that, ultimately, spill into the gas stream as the kiln wall rotates.

2. Surface entrainment is particularly significant for very fine clays and silts where, at high gas velocities, the fines at the surface are scoured, released from the bed, and become airborne. Fortunately, the natural bed movement leads to segregation that brings the larger particles to the top. Thus, unless the size consist of the feed is largely fines, this mechanism is usually not the most significant.
3. Kiln design summarizes a number of factors that can increase or cause entrainment. These include the means of feed entry and product spillover, the path of infiltration air, the direction of burners and other high-velocity gas jets, and the like.

A functional relationship to estimate particulate entrainment in a rotary kiln was treated by Knodorov and Li (509):

$$w = K_2(DF\omega s^{-1}\theta^{1/2})^{1/2}\frac{u_g^4\mu_g^{3/2}\rho_g}{\rho_{\text{feed}}^{3/2}D^{3/4}d_s^3 nf(C_f)} \tag{7}$$

where

w = Entrainment rate (kg/sec)
K_2 = Proportionality constant varying with the roughness between the kiln wall and the feed solids
D = Inside diameter of the kiln (m)
F = Solid feed rate (kg/sec)
ω = Kiln rotational rate (radians/sec)
s = Kiln slope (m/meter)
θ = Dynamic angle of repose of the solid (radians)
u_g = Gas velocity (m/sec)
μ_g = Gas viscosity (Newton sec/m^2)
ρ_g = Gas density (kg/m^3)
ρ_{feed} = Solid density (kg/m^3)
d_s = Diameter of the feed particles (m)
n = Solid particle size distribution parameter
$f(C_f)$ = Modification parameter related to the concentration of entrainable fines in the feed

Equation (7) is difficult to apply quantitatively as it includes a number of unspecified constants and parameters, but the form of the equation is most useful to illustrate the effect of the critical operational parameters on entrainment rate.

B. Combustible Solids, Liquids, and Gases

Complete combustion is a basic objective of almost all combustion systems. In most real systems, however, the full attainment of this goal is either impossible or impractical. Thus, some unburned combustible will always be present in the effluent gases. In the 1970s and afterward, one saw the confluence of several forces in the environmental area that focused attention on incompletely burned species:

The emission characteristics and control technologies for the "basic pollutants" (particulate, NO_x, SO_2, and CO) were relatively well understood. Air-quality criteria (denoting the relationship between the long-term average concentration of the pollutant and human health effects) had been set. The academic and the regulatory communities were seeking new areas of endeavor.

Analytical equipment and sampling and analysis techniques were rapidly evolving such that one could identify the specific chemistry of complex organic species in flue gases. The combustor is an incredibly prolific "chemistry set" when it comes to producing a spectrum of products: a broad range of polynuclear, oxygenated, halogenated, and otherwise medically significant species. The concentrations were small, but the classes of compounds (POMs, halogenated organic compounds, etc.) were provocative.

Methodologies were emerging, in consort with worldwide interest in hazardous wastes, for the evaluation of the health risk associated with exposure to subacute levels of pollutants. Further, the public was looking at "risk" as a new scale against which to evaluate projects. Unfortunately, the conservatism of health risk evaluation methodology, the conservatism inherent in the development of most dose-response data, and the (very low) level of risk that the public appeared willing to accept as "acceptable" combined in a very severe screening process.

From these factors has come increasing awareness and concern by regulatory authorities throughout the world over the health implications of combustible emissions. This concern emphasizes the importance of careful design and operations to minimize both generation and survival of these pollutants.

1. Pollutant Characterization

The incomplete combustion of carbon-containing fuels or waste materials forms a spectrum of different chemical species. The simplest, carbon itself, can contribute importantly to the opacity of the effluent. This is due both to the refractive index and color of the particles and to the typically small particle size. Small particles have a greater light scattering power for a given mass loading than coarse particles. Carbonaceous soot can be amorphous in character but is more often graphitic. This is unfortunate since graphitic carbon is more difficult to oxidize than the amorphous material.

A second class of pollutants includes the carbon–hydrogen compounds. The chemical nature of these compounds ranges from methane, ethane, acetylene, and other simple straight and branch-chained aliphatic compounds to complex saturated and unsaturated ring compounds. The health significance of these pollutants varies greatly. The sub-class of complex aromatic compounds (polynuclear organic matter, or "POM") includes compounds such as the carcinogenic benz-α-pyrene.

The third class of pollutants includes the carbon–hydrogen–oxygen compounds. These also range from simple compounds such as carbon monoxide and formaldehyde to complex organic acids, esters, alcohols, ethers, aldehydes, ketones, and so forth. These compounds are often associated with "odorous" emissions and show very low minimum detection concentration limits. In particular, aldehydes that are formed as PICs are often major contributors to the "burnt" smell.

The fourth class of pollutants includes the carbon–hydrogen–nitrogen compounds. These include the PICs formed from combustion of amines, N-ring compounds, many proteins, and other chemical species. Some also incorporate oxygen in the molecule. These compounds are especially significant due to their participation in the formation of "fuel nitrogen NO_x" and their contribution to odor.

The fifth class of pollutants includes the carbon–hydrogen–oxygen–halogen compounds. These include the chlorinated solvents, fluorinated and chlorinated polymers, and many other environmentally significant PIC-derived chemical compounds. Importantly, this class includes the several congeners and isomers of polychlorinated dibenzo p-dioxin, dibenzo furan, and biphenyl compounds. The chlorinated solvents and polymers contribute to the formation of the halogen acids (HF, HCl, HBr, and HI) that, under U.S. law, often trigger a requirement for "acid gas control." Members of the polychlorinated dioxins, furans, and biphenyls are under intense scrutiny by the regulatory community and the general public worldwide. Carcinogenicity and other significant health effects are often associated with these materials.

The incompletely burned or PIC pollutants are associated with almost every criterion of air quality:

Some are solid particulate or aerosols and contribute to atmospheric haze and solids fallout.

Some are photochemically reactive and thus participate in the reactions leading to smog.

Some are recognized as injurious to plants (e.g., ethylene) and animal life respiration (e.g., carbon monoxide) or are known to cause cancer in humans (e.g., benz-α-pyrene) or to promote adverse health effects in animals similar to that of pesticides (e.g., halogenated biphenyls).

Because of the health-related impact of these pollutants, their control assumes an importance out of proportion to the weight emitted.

2. Mechanisms of Formation

By definition, the appearance of combustible material in the effluent of an incineration system reflects a partial failure of the combustion process. As described earlier, this indicates one or more of the following:

Inadequate residence time to complete combustion reactions.

Inadequate temperature levels to speed combustion reactions to completion.

Inadequate oxygen in intimate admixture with fuel gases to allow oxidation to proceed to completion. This often may be characterized by a lack of adequate mixing of the flow or an insufficient air supply.

These deficiencies affect both the formation and the persistence of combustible pollutants. In burning solids, the formation of hydrocarbon pyrolysis products, carbon monoxide, carbon char, and similar species is an inherent part of the gasification stage of the process. Thus, the appearance of these materials in the flue gas reflects flow bypassing, quenching (by contact with cool surfaces or admixture with cold gases), or thermal cracking (dehydrogenation of carbon–hydrogen compounds at elevated temperatures); all with a subsequent time, temperature, and composition history that prevents burnout.

It should be recognized that even the more complex ring compounds can be formed from the combustion of chemically simple fuels. Thus, polycyclic organic matter is found in the effluent from boilers burning natural gas. It is not known at this time whether such pollutants arise from, for example, the hydrogenation of soot (which has a complex, six-membered ring structure) or from trace hydrocarbons in the fuel.

3. Concepts for Control

The most direct and effective approach to the control of combustible pollutants is through enhancement of the combustion process throughout the combustor. In U.S. regulatory language, this control strategy is called “good combustion practice.” Much of the material throughout this book relates to various design features and operating techniques to effect complete combustion.

An effective but often costly approach to combustible pollutant control involves the addition of an afterburner zone or a separate afterburner chamber to the basic combustor. Here, the designer concludes that the assured achievement of some minimum temperature (the afterburner set point) will provide an acceptable level of control. The system is then equipped with burners to provide the needed temperature increment. Often the flow

patterns and velocity of the flue gas stream and/or the injected burner or secondary air jets are arranged to break up stratified flows and/or foster mixing. Gas temperature sensing and burner control instrumentation is installed to monitor the state of the gases leaving the combustion space and to trigger fuel use when the temperature falls below the set point. Also, the combustion space is designed to afford some increment of residence time that experience or judgment suggests is adequate for the mixing and combustion processes.

A measure of combustible pollutant control is often effected by several types of back-end air pollution control systems. Obviously, there is a reduction in combustible particulate matter by cyclones, fabric filters, and other particulate control devices. In addition, wet and dry scrubbers and carbon absorption units reduce combustible pollutants. The reduction of temperature coupled with particle capture is a key element of both wet and dry scrubbers. If the temperature drop results in condensation of aerosols or in increased condensation of high-molecular-weight compounds on existing particle surfaces, removal occurs. This is an important control mechanism for the dioxin, furan, and POM pollutants. These control devices and techniques are discussed later in this chapter in the section on air pollution control systems.

C. Gaseous Pollutants Related to Fuel Chemistry

A third group of pollutants is generated by release and/or reaction of elements in the fuel. Common and important among these are sulfur oxides and hydrogen chloride.

1. Sulfur Oxides

Many waste streams and fossil fuels contain sulfur. The sulfur can be present in any or all of its many oxidation states from S^{-2} to S^{+6}. Of particular interest from an air pollution standpoint is the sulfur appearing as organic or inorganic (pyritic) sulfur, free sulfur, or sulfur appearing in organic or inorganic acid forms. In each of these cases, the sulfur can be expected to appear in the fuel gases as sulfur dioxide or trioxide. A portion of the sulfur that exists as inorganic sulfates in fuels or in waste materials such as gypsum-filled wallboard (calcium sulfate) may be released by reduction reactions, especially in the high-temperature environment on the grate in mass burning incinerators.

Depending on the chemical composition (alkalinity) of the mineral ash residues, a portion of the sulfur oxides may be lost from the flue gas by gas–solid reactions. Also, some sulfur may remain with the ash. Typically, however, these losses are relatively small, and in excess of 95% of the sulfur (other than that appearing as inorganic sulfates in the fuel or waste) will be found in the fuel gases from suspension-fired combustors (48). About 70% is released in mass burning systems (49), based on analogy with coal-burning plants.

Since waste changes with time, the SO_2 concentration in the exit gases should be expected to change. Table 8 shows the frequency of observation of 30-minute average SO_2 concentrations for several concentration ranges over a 6-month testing program conducted in Germany in 1995.

The proportioning of sulfur between the dioxide or the trioxide forms depends on the chemistry of sulfur in the fuel, on the time sequence of temperature and composition of the flue gases, and on the presence or absence of catalytic ash material. Although cold-end chemical equilibrium considerations and excess oxygen concentrations favor oxidation to the trioxide, reaction rates are slow, and generally only 2% to 4% of the sulfur appears as the trioxide. Higher proportions of trioxide result from the burning of organic sulfonates,

Table 8 Frequency of Observation of SO_2 in Mass Burn APC Inlet Duct

Concentration range (mg/Nm^3 SO_2 at 11% O_2)	Number of times 30-min average was in noted range	Concentration range (mg/Nm^3 SO_2 at 11% O_2)	Number of times 30-min. average was in noted range
0–50	100	400–450	25
50–100	380	450–500	20
100–150	425	500–550	20
150–200	275	550–600	20
200–250	175	600–650	15
250–300	75	650–700	10
300–350	60	700–750	5
350–400	60	750–800	0

Source: From (514).

some heavy-metal sulfates (which dissociate to SO_3 and an oxide), or the "burning" of wastes such as discarded automobile batteries, which contain free sulfuric acid. The equilibrium relationship between the sulfur oxides (259) for partial pressures in atmospheres and temperature in °K is given by

$$SO_2 + 0.5O_2 \rightleftarrows SO_3$$

$$K_p = \frac{p_{SO3}}{p_{SO2} p_{O2}^{1/2}} \text{ atm}^{-1/2} \tag{8}$$

$$\log_{10} K_p = \frac{5186.5}{T} + 0.611 \log_{10} T - 6.7497 \tag{9}$$

Sulfur oxides have importance as a pollutant due to their health effects (especially in combination with respirable particulate matter) and their corrosive effects on natural and manmade materials. In the combustion system, sulfur trioxide reacts with water vapor to form sulfuric acid, which has a dew point considerably above that for pure water. To prevent serious corrosion from sulfuric acid (e.g., in the stack), combustion system cold-end temperatures should be limited to a value safely above the sulfuric acid dew point. Pierce (390) presented the data in Table 9 for the percent SO_x as SO_3.

In an analysis of 35 sets of gas analyses from multiple hearth furnaces burning domestic sewage sludge, Niessen (218) showed a fairly regular partitioning of sulfur oxides between SO_2 and SO_3 (98.46% SO_2, 1.54% SO_3). The reported uncontrolled SO_2

Table 9 Percent Conversion of SO_2 to SO_3 in Fossil Fuel Combustors

	Percent sulfur in fuel					
Fuel	0.5	1.0	2.0	3.0	4.0	5.0
Oil–5% excess air	2%	3%	3%	4%	5%	6%
Oil–11% excess air	6%	7%	8%	10%	12%	14%
Coal–25% excess air	3%–7%	7%–14%	14%–28%	20%–40%	27%–54%	33%–66%

concentration (corrected to 7% O_2) ranged from 6.98 ppmdv to 1081.47 ppmdv, with an average of 577.6 ppmdv and a standard deviation of 353.4 ppmdv.

2. The Halogens and Their Acids (Chlorine, Hydrogen Chloride, etc.)

The halogens are important constituents of waste. Some of the organic compounds of the halogens are toxic, carcinogenic, or otherwise of concern regarding their health effects. Further, the acid gases formed during combustion are strong acids that can attack metals (e.g., in boilers) and can be highly corrosive in their water solutions in scrubbers. Chlorine and hydrochloric acid are generally the most important members of this family.

Chlorine appears in waste streams both in inorganic salts (e.g., sodium chloride) and in organic compounds. In the combustion of many industrial wastes and, importantly, in municipal solid wastes, a substantial quantity of organic matter containing chlorine may be charged to the furnace. In the combustion environment (usually containing hydrogen in considerable excess relative to the chlorine) the organic chlorine is converted, almost quantitatively, to hydrogen chloride (hydrochloric acid). In mass burning incinerators, about 35% to 40% of the stoichiometric HCl generated through combustion is absorbed by alkaline constituents of the ash (Na_2O, CaO, etc.).

The importance of hydrogen chloride emissions from combustion sources depends on the quantity in the fuel but is usually small. Of importance to system designers, however, is the high solubility of hydrogen chloride in scrubber water (or in the condensed "dew" on cold-end surfaces in boilers). Acid attack and chloride corrosion of ferrous metal surfaces are well demonstrated. A further problem is the stress corrosion cracking phenomenon associated with the austenitic stainless steels (304 stainless and, to a degree, 316 stainless, for example) in the presence of chloride ion under acidic conditions.

As for SO_2 , HCl concentration in the exit gases will change with time. Table 10 shows the frequency of observation of 30-minute average HCl concentrations for several concentration ranges over a 6-month testing program conducted in Germany in 1995. The variability is significant since, in many plants, the SO_2 concentration is used as the control variable for all acid gas control (e.g., the lime slurry feed rate to a semi-dry scrubber). Since there is no reason to expect the SO_2 variation to be tracked by other acid gases such as HCl, there may be times when the HCl is overcontrolled and other times when HCl is undercontrolled.

Table 10 Frequency of Observation of HCl in Mass Burn APC Inlet Duct

Concentration range (mg/Nm^3 HCl at 11% O_2)	Number of times 30-min average was in noted range	Concentration range (mg/Nm^3 HCl at 11% O_2)	Number of times 30-min. average was in noted range
0–100	0	800–900	375
100–200	0	900–1000	200
200–300	0	1000–1100	75
300–400	5	1100–1200	30
400–500	5	1200–1300	20
500–600	60	1300–1400	15
600–700	340	1400–1500	0
700–800	600	1500–1600	0

Source: From (574).

Stress corrosion cracking is characterized by the formation and rapid propagation of cracks in areas under stress (including both mechanical stresses and "locked-in" thermal stresses from welding operations). There is little material removal in such a corrosion process, but the resulting mechanical or structural failure can be quite rapid and catastrophic (e.g., the disintegration of high-speed fan blades). The presence of HCl or other combinations of chlorides and acidic conditions requires special consideration to the selection of materials of construction. Often, extra-low carbon stainless steels (e.g., 316-ELC) or costly high nickel–chromium steels such as the Hastelloy or Inconel alloys are necessary to deal with this problem. Sources of organic chlorine in wastes are shown in Table 11.

In the incineration environment, the halogen acids (HX) and the free elements (X_2) are in dynamic equilibrium with water vapor and oxygen (the Deacon reaction) according to

$$2HX + 0.5O_2 \rightleftarrows H_2O + X_2$$

While the reaction is usually negligible for fluorine and hydrofluoric acid, the conversion can be significant under some conditions for the chlorine, bromine, and iodine. For the equilibrium constant given by

$$K_p = \frac{p_{H_2O} p_{X_2}}{p_{HX}^2 p_{O_2}^{1/2}} \text{ atm}^{-1/2} \tag{10}$$

the temperature dependence of K_p [for partial pressure in atm and temperature (T) in °K] is given by

$$\text{Chlorine } \ln K_p = -8.244 + 1.512 \times 10^{-4} T + 7087/T \tag{11}$$

$$\text{Bromine } \ln K_p = -18.72 - 1.016 \times 10^{-3} T + 20{,}400/T \tag{12}$$

$$\text{Iodine } \ln K_p = -25.35 - 1.980 \times 10^{-4} T + 35{,}410/T \tag{13}$$

D. Nitrogen Oxides

Nitric oxide (NO) is produced from its elements at the high temperatures attained in furnaces and incinerators. At lower temperatures, NO formation is limited by equilibrium (which favors dissociation to the elements) and kinetics. Although only a small portion of the NO further oxidizes to nitrogen dioxide (NO_2) within the furnace, oxidation does take place slowly after leaving the stack at the temperatures and high oxygen concentrations of the ambient atmosphere. The air-quality impact of the nitrogen oxides (referred to

Table 11 Organic Chlorine Content of Plastic Materials

Compound	Chlorine (Wt.%)	Uses
Polyvinyl chloride	59.0[a]	Bottles, film, furniture
Polyvinylidene chloride	73.2[a]	Film
Methylene chloride	82.6	Solvent
Chloroform	88.2	Anesthetic
DDT	50.0	Insecticide
Chlordane	59.0	Insecticide

[a]Pure resin.

collectively as NO_x and reported as NO_2) arises from their participation in atmospheric chemical reactions. These reactions, especially those stimulated by solar ultraviolet light (a photochemical reaction), produce ozone and a variety of oxygenated compounds that account for the visibility reduction and eye irritation associated with smog.

In combustion systems, nitrogen oxides arise through fixation of nitrogen from the combustion air with oxygen (thermal generation). Also, NO_x is formed by oxidation of nitrogen entering the system bound in the fuel (fuel nitrogen generation). At very high temperatures, the dominant source of NO_x is thermal generation, but, at lower temperatures, fuel nitrogen mechanisms dominate. The keys to the distribution among these mechanisms are the equilibrium and kinetic relationships that control the process.

1. Thermal Generation

The fixation of nitrogen with oxygen occurs by the following overall chain reaction mechanism according to Zel'dovitch (50):

$$O_2 + M \rightleftarrows 2O + M \tag{14a}$$

$$O + N_2 \rightleftarrows NO + N \tag{14b}$$

$$N + O_2 \rightleftarrows NO + O \tag{14c}$$

and, in fuel-rich flames, by the additional reaction

$$OH + N \rightleftarrows NO + H \tag{14d}$$

The chain-initiating step [Eq. (14a)] involves the collision of oxygen molecules with other molecules in the gas (represented by M) to form oxygen radicals. Combining the mechanism equations [Eqs. (14a–14c)] and correcting for the presence of excess air result in Eq. (15) after Bowman (520) for the *net* generation rate of NO_x (noting that, by convention, the molecular weight of the NO_x is taken to be that of NO_2):

$$\frac{d(f_{NO_x})}{dt} = 1.45 \times 10^{17} T^{-1/2} \exp\left(\frac{-69{,}460}{T}\right)\left[\frac{P}{RT}\right]^{1/2} (f_{N_2})(f_{O_2})^{1/2} \text{ sec}^{-1} \tag{15}$$

where (f_{NO_x}), (f_{N_2}), and (f_{O_2}) are mol fractions and T is in °K.

Equilibrium considerations lead to the following relationship for the overall reaction

$N_2O_2 \rightleftarrows 2NO$:

$$K_p = \frac{(NO)^2}{(N_2)(O_2)} = 21.9 \exp\left(\frac{-43{,}400}{RT}\right) \tag{16}$$

The rate of formation of NO is significant only at temperatures in excess of 1000°C, due to kinetic limitations, and doubles for every 40°C increase in flame temperature. Thus, NO_x emissions are encouraged by high flame temperatures (e.g., by air preheat) and high excess air. NO_x can be reduced by

Water or steam injection or flue gas recirculation (to lower flame temperature)
Operation at low excess air (to reduce oxygen concentrations)
Staged combustion where the fuel is partially burned, heat is withdrawn through boiler surfaces, and then the rest of the required air for combustion is added (the overall effect is to lower the peak temperatures attained after the combustion gases contain a net excess of oxygen)

Selection of burner designs ("low-NO_x burners") that reduce the intensity (volumetric burning rate) of combustion, produce relatively long diffusion flames, or encourage either two-stage combustion or low-temperature gas recirculation

2. Fuel Nitrogen Generation

Studies by the U.S. EPA and other researchers worldwide have suggested an important contribution of fuel nitrogen sources to NO_x emissions from combustion systems. The California Air Resources Board has concluded (228) that fuel nitrogen accounts for 75% to 80% of the total NO_x from refuse incineration plants. The mechanism by which the fuel nitrogen is converted into nitrogen oxides was not specified, however, and the data base supporting the conclusion was limited. Laboratory experiments have typically shown that 15% to 100% of the fuel nitrogen can be converted with the higher conversion efficiencies obtained when the fuel nitrogen content is low (<0.5%) or when the combustor is operated lean (52).

Laboratory data clearly show that the NO_x concentrations arising by the fuel nitrogen route can be several times the equilibrium thermal NO_x levels. With time, at furnace temperatures where reactions are fast, the gas phase concentration can be expected to shift toward the equilibrium level to the extent limited by the reaction rate. Thus, if one compares the time variation of observed NO_x concentration in two, isothermal scenarios: scenario no. 1 with 100% thermal NO_x and scenario no. 2 with 100% fuel nitrogen NO_x, one might expect to see behavior as indicated schematically in Fig. 1. Here, the scenario no. 1 thermal NO_x rises slowly toward the equilibrium value under kinetic control. However, in scenario no. 2, the fuel nitrogen NO_x rises rapidly, exceeding the equilibrium level and then trending downward with time, approaching the equilibrium value from above. Note that along a real reaction path where the temperature eventually falls (e.g., in a boiler), the reaction will ultimately "freeze" and the final NO_x in the stack gas could be "anywhere."

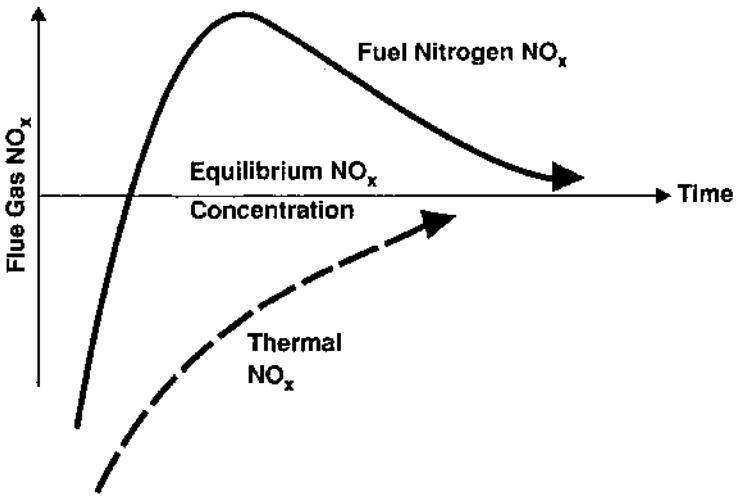


Figure 1 Thermal and fuel nitrogen routes to NO_x in combustion flue gases.

One might speculate that the nitrogenous compounds in municipal solid waste (grass clippings, protein material in food waste, etc.) generate NO_x via the fuel nitrogen mechanism. Hahn, reviewing daily NO_x data from a Connecticut plant, observed (257) that the concentration of NO_x in the stack gases from a mass burn incinerator burning municipal solid wastes appeared to increase and decrease throughout the year in proportion to the seasonal variation in "yard wastes" concentrations in the waste. However, a statistical analysis by Rigo et al. (516) of a comprehensive collection of NO_x data from mass burn MSW incinerators and a phenomenological analysis of the combustion process convincingly suggest that fuel nitrogen is, in fact, of limited importance in MSW incinerator NO_x emissions. In the analysis, mass burn combustion was characterized as a staged process starting with gasification under air-limited conditions on the grate followed by completion of combustion in the overfire space after oxygen addition and mixing from the overfire air system. Along this combustion path, most of the fuel-bound nitrogen in the waste is released in the gasification stage as elemental nitrogen. Subsequent completion of the oxidation process over the bed can produce some NO_x via the thermal NO_x route but to no greater extent than from air-supplied nitrogen. Other workers (290) evaluating similar data from several facilities do not observe the trend. As reported by Chen et al. (517) and referenced by Seeker et al. (518) for the staged combustion of fossil fuel, unstaged combustion led to between 900 and 1400 ppm NO_x but staged combustion produced 200 to 350 ppm NO_x. Similar full-scale tests by Habelt (519) converted only a small percentage of the nitrogen in coal to NO_x.

3. Emission Estimation

Because of the complexity of NO_x generation and destruction within a combustor, emission estimation without data as a confirmation is uncertain. In many circumstances, however, an estimate is required if, for nothing else, to provide a rough starting point from which to assess the importance of this pollutant. The techniques described below provide such a rough estimate. The uncertainty of the results, however, is significantly greater than for the emission estimates of the other gaseous pollutants.

a. Fuel Nitrogen. A kinetic evaluation by Soete, reported by Bowman [Eq. (17)], can be solved iteratively to estimate the fraction Y of fuel nitrogen N_f converted to NO. For $[N_f]_o$ equal to the NO concentration for 100% conversion of N_f to NO and $[O_2]$ the oxygen concentration (g mol/cm^3) and temperature T in degrees K, the following obtains:

$$Y = \left[\frac{2}{1/Y - \{[2.5 \times 10^3[N_f]_o]/[T \exp(-3150/T)[O_2]]\}}\right] - 1 \tag{17}$$

The Soete relationship was developed using laboratory burners with several nitrogen-containing fuels. Comparison of Soete predictions evaluated at adiabatic flame temperature conditions with the concentration of NO_x measured in the stack of grate-type solid waste incinerators suggests that the Soete relationship used in this fashion predicts about four times the measured value at the stack. The demonstrated importance of fuel nitrogen in increasing NO_x emissions can be of particular importance for industrial waste incineration. Organic liquid wastes may contain solvents (e.g., pyridine, amines, or other chemicals) with a substantial "fuel nitrogen" content.

b. Fossil Fuels. Because nitric oxide emissions are determined by flame temperature, it has been observed (54) for a variety of fuels that the heating value of the fuel provides a better correlating parameter than the mass of fuel. Data are therefore usually converted to

units of kg of NO_x (expressed as NO_2) per million kcal. The median emission rate for the small-scale PHS tests (43) is 1 kg NO_x per 3.27×10^6 kcal heat release, or 0.31 kg NO_x per 10^6 kcal. Correlations of NO_x formation that have been proposed by PHS for coal, gas, and oil (54) are

$$\text{kg NO}_x/\text{hr} = \left(\frac{\text{kcal/hr}}{3.24 \times 10^6}\right)^{1.18} \quad \text{for gas} \tag{18a}$$

$$\text{kg NO}_x/\text{hr} = \left(\frac{\text{kcal/hr}}{2.18 \times 10^6}\right)^{1.18} \quad \text{for oil} \tag{18b}$$

$$\text{kg NO}_x/\text{hr} = \left(\frac{\text{kcal/hr}}{1.87 \times 10^6}\right)^{1.18} \quad \text{for coal} \tag{18c}$$

If the emission rate of 1 kg NO_x per 3.27×10^6 kcal associated with the 2.7 tonne/day PHS municipal refuse test incinerator (0.28×10^6 kcal/hr with 2470 kcal/kg refuse) and the corresponding NO_x emission rate (0.0857 kg/hr) are cast into the same functional form as Eqs. (18), the resulting constant term within the brackets is 2.26×10^6. However, it must be recognized that this correlation provides only rough estimates, since factors such as furnace heat loss and excess air, which are known to influence NO_x production, are not taken into account. That the data for the three fossil fuels are correlated best with an exponent on firing rate greater than unity is a consequence of the increase in the mean emission factor with increases in furnace size.

c. Incineration Sources

REFUSE INCINERATORS. The PHS (54) obtained a comparable correlation for refuse combustion in small units with an exponent of 1.14 in place of 1.18. In the absence of sufficient data to obtain a reliable estimate of the exponent for municipal-scale refuse incinerators, the value of 1.18 is recommended to extrapolate data from one size to another. A summary of NO_x emission data from U.S. municipal waste combustors (258) is shown in Table 12.

Emission factors for the combustion of wastes other than municipal refuse can be approximated by analogy with the combustion processes for gas, oil, coal, and (mass burning) refuse. If waste analysis indicates a fuel nitrogen content greater than, say, 0.2%,

Table 12 Summary of NO_x Emission Data from Municipal Waste Combustors [258]

		No_x emissions (ppm at 7% O_2)	
Combustor type	No. units	Average	Range
Mass burn, refractory wall	8	155	59–240
Mass burn, waterwall	24	240	154–370
Refuse derived fuel	5	270	195–345
Modular, excess air	8	140	105–280
Modular, starved air	5	215	86–280
All types	51	210	59–370

and/or operation will be at a relatively high excess air level (as is often the case for waste combustion), consideration should be given to increasing the estimate above the emission rate calculated using Eqs. (18). An estimate of the maximum NO_x emission can be made using the equilibrium relationship in Eq. (16) (evaluated at the adiabatic flame temperature). Experience shows, however, that such a technique produces unrealistically high estimates, as do the estimates made with the Soete relationship [Eq. (17)]. It may be useful, however, to use the equilibrium and Soete relationships to judge the shape of the emission factor curve as a means to extrapolate or interpolate field data. An example of such an analysis for a high-moisture waste with a 1.41% nitrogen content (dry basis) is shown in Fig. 2.

LIQUID INJECTION INCINERATORS. For the special case of a liquid injection vortex-type incinerator, Kiang (208) developed a dimensional relationship for the formation of NO:

$$\log_e[Y] = 2.9 - 1.027S - 0.4665 \log_e[\text{percent } O_2] - \frac{158.2452}{T} \tag{19}$$

where

Y is percent of fuel nitrogen converted to NO (as a percent).
S is the mean residence time (sec)
Percent O_2 is the dry percent oxygen (as a percent)
T is the temperature (°F)

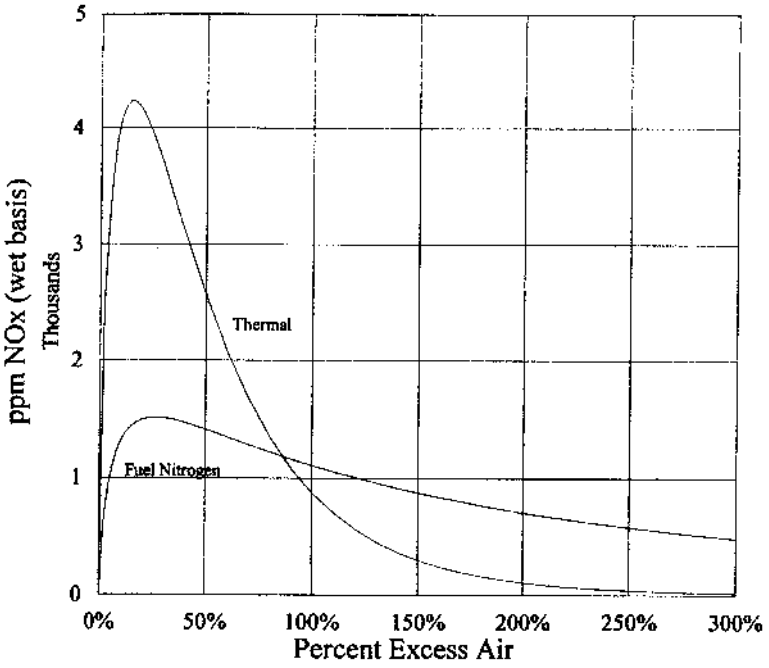


Figure 2 Thermal and fuel nitrogen NO_x generation.

Kiang found that the formation of NO_x was not related to the specific nature of the nitrogen in the waste chemistry (−NO, −CN, $-NH_2$, etc.) nor to the partial pressure of water vapor in the incinerator flue gases.

SLUDGE INCINERATORS. In an analysis of over 55 data sets for multiple hearth sludge incinerators, Niessen (218) was unable to develop a statistically significant correlation for the NO_x emission rate as a function of incineration characteristics. As is often the case, no information on sludge nitrogen content (contributing to fuel nitrogen NO_x) was available to match the NO_x data. The average NO_x concentration for the entire data base was 283.6 ppmdv (corrected to 7% O_2). The standard deviation of the NO_x data was 165.2 ppmdv. A study of NO_x emissions by Goldberg et al. (354) showed that most of the NO_x was derived from the 2% nitrogen found in the sludge solids. Their findings showed the following:

High excess air increased NO_x.

Lowest NO_x was achieved when all of the combustion air was supplied from the center shaft Warm Air Return ducting. Use of ambient air introduced above the burning zone increased NO_x.

Maintaining low NO_x emissions required a high degree of process stability. This includes stable feed rate, feed characteristics, and hearth temperatures. Operators need to avoid overcorrection when minor process upsets require intervention.

Increasing afterburner temperatures increased NO_x.

Increasing cake solids (lower fuel firing) reduced NO_x on a mass per dry ton basis.

Increased scrubber water flow (volume per volume of gas) decreased NO_x.

Prior to experimentation, the furnace NO_x levels were approximately 240 ppmdv. After efforts in the areas noted, the NO_x for four furnaces varied from 67 to 101 ppmdv.

II. AIR TOXICS

The name "air toxics" has been applied to a spectrum of organic and inorganic compounds found in stack emissions. The U.S. EPA defines air toxics as pollutants known or suspected of causing serious health concerns such as cancer or birth defects. The EPA's list of air toxics as of the year 2000 is shown in Table 13.

The health effects triggering inclusion in the air toxics list are summarized in Table 14. In many (if not most) cases, the concentration of these compounds in the stack gases is small: they are "micropollutants." Thus, after dispersion and dilution of the stack gases by the atmosphere, the resulting average ambient air concentrations and associated inferred health risk consequences are often acceptable. However, since these pollutants are directly related to human health effects, they receive focused attention by both regulatory agencies and the general public.

The incineration of wastes is, not unexpectedly, viewed as an important potential source of air toxics emissions. This results from the fact that, being fired with diverse wastes, contamination by trace metals (some of them toxic) is certainly possible, if not probable. Further, "wastes" may include a variety of toxic organic compounds targeted for disposal or toxics formed as by-products of industrial preparation reactions. Finally, due to moment-to-moment variation of the feed and other parameters, the incineration environment degrades from time to time, thus allowing a "puff" of toxic material to escape. The combination of these possibilities leads to intense scrutiny of incineration regarding air toxics.

Table 13 Air Toxics

Acetaldehyde	Ethylene oxide
Acrolein	Formaldehyde
Acrylonitrile	Hexachlorobenzene
Arsenic compounds	Hydrazine
Benzene	Lead compounds
Beryllium compounds	Manganese compounds
1,3-Butadiene	Mercury compounds
Cadmium compounds	Methylene chloride
Carbon tetrachloride	Nickel compounds
Chloroform	Polychlorinated biphenyls (PCBs)
Chromium compounds	Polycyclic organic matter
Coke oven emissions	Quinoline
Dioxin/furans[a]	1,1,2,2-Tetrachloroethane
Ethylene dibromide	Perchloroethylene
Propylene dichloride	Trichloroethylene
1,3-Dichloropropene	Vinyl chloride
Ethylene dichloride	Diesel particulate matter[a]

[a]Health effect results not yet available.
Source: U.S. EPA (2000).

The simplest approach to estimating metal emission rates is to assume that the relative proportions of the metal in the emitted particulate matter are the same as those of the metal in the total inorganic fraction of the feed. There are several potential weaknesses in this approach:

Some metals are trapped in relatively massive bottom ash and are never emitted to any significant degree. The chromium in large pieces of stainless steel is an example of this.

Some metals are emitted strongly relative to their concentration in the ash. Mercury and its compounds are examples. Because of the high volatility of mercury, almost 100% of this metal is emitted from the furnace. Other metals show lesser but often significant degrees of emission enhancement. Barton et al. (359) ranked several key metals by their "volatility temperature": the temperature where the

Table 14 Health Effect Classifications

Health effect class	Characteristic impact
Toxic	Kills cells or the organism by poisonous nature. Often a threshold dose (mg/kg of body weight) characterizes the onset of impacts.
Carcinogenic	Causes cancer. Often the dose-response function is characterized as a log-log correlation between dosage and the probability of observing cancerous cells.
Mutagenic	Causes mutation of cells.
Teratogenic	Causes changes in cells during pre-natal development. May lead to birth defects or deformity.

sum of the vapor pressures of all species containing the metal present at equilibrium and weighted by their relative concentrations is 10^{-6} atm.

Metal	Volatility temperature (°C)	Metal	Volatility temperature (°C)
Mercury	16	Antimony	660
Arsenic	32	Barium	849
Thallium	138	Silver	904
Cadmium	216	Beryllium	1216
Lead	627	Chromium	1610

In a few instances, the balance between these and other factors influencing emissions has been studied and estimates can be made of the partitioning of feed metals between bottom ash and fly-ash emissions. This is the case for sewage sludge incinerators. Estimation methods are presented below for this source category. Care must be shown, however, that overly simplistic approaches to estimation are not applied without consideration of the potential errors.

A. Metal Emission Rates

1. General Factors Affecting Heavy-Metal Emission Rates

The controlled (post-APC) emission rate of heavy metals (relative to the metal content of the feed waste) for incinerators reflects the interaction of several waste and system parameters:

Waste metal content
Operating temperature
Waste chloride content
Flow patterns leading to solids drop-out ahead of APC
APC control efficiency as a function of particle size

The quantity of each metal in the feed is the basic scalar of emissions. Metals in waste arise from several sources including the waste sources, industrial process conditions, consumer preferences, and so forth. Data in Chapter 4 suggest the metals content for a wide range of waste types. The metals content in wastes often varies from day to day.

The temperature of the combustion environment has an impact on metal emissions:

1. At elevated temperatures, many heavy-metal compounds decompose and/or vaporize (Table 15). The higher the temperature, the larger the fraction of the specific metal that is vaporized. This temperature effect is particularly important for mercury, cadmium, arsenic, and (to a lesser degree) lead. Reviewing the boiling points of the oxides of toxic metals in a given waste may be of some value in anticipating volatilization behavior, but, especially for hazardous waste incineration, the chlorides and/or bromides may be equally or more important. Table 16 illustrates these patterns.

For specific metals and compounds, environmentally important vapor pressure functions (P in atm and T in °K) are given as follows:

Table 15 Volatility Temperatures for Various Metals Showing Chlorine Effects

Metal	Volatility temperature[a] (°C) at 0% chlorine	Principal vapor species	Volatility temperature[a] (°C) at 10% chlorine	Principal vapor species
Chromium	1613	CrO_2/CrO_3	1610	CrO_2/CrO_3
Nickel	1210	$Ni(OH)_2$	693	$NiCl_2$
Beryllium	1054	$Be(OH)_2$	1054	$Be(OH)_2$
Silver	904	Ag	627	AgCl
Barium	849	$Ba(OH)_2$	904	$BaCl_2$
Thallium	721	Tl_2O_3	138	TlOH
Antimony	660	Sb_2O_3	660	Sb_2O_2
Lead	627	Pb	−15	$PbCl_4$
Selenium	318	SeO_2	318	SeO_2
Cadmium	214	Cd	214	Cd
Arsenic	32	As_2O_3	32	As_2O_3
Mercury	14	Hg	14	Hg

[a]Volatility temperature is defined as the temperature at which the compound's vapor pressure is 1×10^{-6} atm.
Source: From (510).

Lead (447)

$$\log_{10} P = -10130/T + 8.28 - 0.985(\log_{10} T)$$

Lead oxide (447)

$$\log_{10} P = -10598/T + 6.012$$

Table 17 presents the temperature–vapor pressure relationship for several metals and compounds of interest.

2. As temperatures drop, a fraction of the metals condenses. Heterogeneous nucleation (condensation on existing particulate) rather than homogeneous nucleation is the dominant mechanism. This favors deposition on the small particles that present a surface area disproportionately greater than their mass fraction. This "fine particle enrichment" phenomenon is particularly important from an emission standpoint since the collection efficiency of most APC systems decreases as the particle size decreases. Thus, the net emission rate of volatile metals usually increases as the combustion temperature increases.

2. Municipal Waste Combustors

a. General. Data that indicate the range of uncontrolled emission rates of metals from municipal waste combustors (MWCs) are limited. Other than for the special case of mercury (discussed below), these pollutants are captured in a fabric filter or electrostatic precipitator particulate collection system such that stack emissions are well below regulatory limits. Also (again, except for mercury), regulations address only the ultimate emission level or concentration and do not specify a required collection efficiency. Thus, there is little incentive to collect inlet concentration data.

Studies attempting to close a material balance on heavy metals around MSW furnaces show wide variations. Some of the variation reflects the difficulty in obtaining

Table 16 Boiling Points of Selected Inorganic Compounds

Compound	Boiling point (°C)	
$AsCl_3$	130	
As_2O_3	460	
BCl_3	12	
BaO	2000	
$BeCl_2$	520	
$BiCl_3$	447	
Cd	767	
$CdCl_2$	960	
CdO	900–1000	(decomposes)
CrO_2Cl_2	117	(sublimes)
CuCl	1366	
$CuCl_2$	993	(decomposes to CuCl)
$FeCl_2$	>670	
$FeCl_3$	315	
$GaCl_3$	201	
Ga_2O	>500	(sublimes)
$GeCl_4$	83.1	
$PbCl_2$	950	
Hg	357	
$HgCl_2$	304	
HgCl	302	
$NiCl_2$	973	
P_2O_5	250	(sublimes)
$SbCl_3$	602	
SeO_2	317	
$SnCl_2$	623	
$SnCl_4$	114	
TlCl	720	
Tl_2O	1457	(decomposes and sublimes)
ZnO	>1800	
$ZnCl_2$	732	

representative samples; some variation is due to the different process conditions in the incinerators; and, undoubtedly, some is due to differences in the characteristics of the waste itself. The following table indicates the reported observed range in the reported fraction of metal in the waste that appears as the "uncontrolled emission rate" (ahead of air pollution control) for three mass burn systems (468, 521, 522).

Fraction of metal in waste appearing in furnace flue gases

	Element					
	Cd	Cr	Fe	Hg	Pb	Zn
Low value	37.3	2.2	0.4	93.5	5.5	13.6
High value	96.3	7.0	1.0	—	42.0	58.0

Table 17 Vapor Pressure of Selected Metals and Their Compounds

Formula	Name	Temperature (°C for the indicated temperature in Pascals)					
		1 Pa	10 Pa	100 Pa	1 kPa	10 kPa	100 kPa
AgCl	Silver (I) chloride	670	769	873	1052	1264	1561
$AsCl_3$	Arsenic (III) chloride	—	—	—	21	63	129
$BeCl_2$	Beryllium chloride	196	237	284	339	402	487
$CdCl_2$	Cadmium chloride	412	471	541	634	768	959
CuCl	Copper (I) chloride	—	459	543	675	914	1477
$FeCl_2$	Ferrous chloride	—	—	—	685	821	1025
$HgCl_2$	Mercuric chloride	64	94	131	175	229	304
$NiCl_2$	Nickel (II) chloride	534	392	662	747	852	985
Pb	Lead	705	815	956	1139	1387	1754
PbO	Lead oxide	724	816	928	1065	1241	1471
$PbCl_2$	Lead (II) chloride	—	—	541	637	765	949
P_2O_5	Phorphorous pentoxide	285	328	378	434	501	591
SeO_2	Selenium oxide	125	154	188	228	275	315
Sn	Tin	1224	1384	1582	1834	2065	2620
$SnCl_2$	Stannic Chloride	—	253	308	381	479	622
Zn	Zinc	337	397	477	579	717	912
$ZnCl_2$	Zinc chloride	305	356	419	497	596	726

Source: From (434).

b. Mercury. In MWC furnace gases, the concentration and emission chemistry for mercury and its compounds are variable. Because of the high volatility of elemental mercury (boiling point 357°C) and the fact that all of its compounds decompose at relatively low temperatures, almost all of the mercury in the feed waste appears in the furnace gases. Mercury pollutant control efficiency data must be taken using simultaneous inlet and outlet determinations since ratios of "controlled emissions measured in the morning" to "uncontrolled emissions measured in the afternoon" are of uncertain validity. Citations of "negative collection efficiencies" in the literature are symptomatic of this effect.

The chemistry of the mercury in the flue gases also has an effect on the accuracy of mercury emission data: elemental mercury (Hg or Hg_2), mercuric or mercurous chloride ($HgCl_2$ or HgCl), mercuric or mercurous sulfide (HgS or Hg_2S), etc. The chemistry-related effects result from the impact of physical form (gas or solid) and/or reactions in the sampling train on reported mercury quantities. Therefore, data sets under analysis need to be annotated with the specific sampling/analysis methodology used, and, if the methodology differs, one must take care that apparent trends or other conclusions are valid.

Also, there are many effects of process variables on mercury control effectiveness. Temperature in the control device is very important. However, other variables such as the inlet mercury concentration and the presence of reactive chemicals such as hypochlorite ions in scrubbing solutions may also influence reported collection efficiency.

Another process impact relates to the tendency of some processes (e.g., RDF-fired furnaces) to produce a flue gas with a high concentration of charred particles or soot. The strong adsorption characteristics of carbon for mercury and its compounds lead to low apparent mercury concentrations in the flue gas. Since the starting mercury concentration

is reduced, the percent mercury control effected by some back-end air pollution control systems (as discussed in Chapter 14, activated carbon injection is often used) may appear low.

The consequence of these complexities is that data on mercury emissions and control effectiveness are often inconsistent. Data from several sources may not conveniently "group," and process trends (e.g., control effectiveness as a function of temperature) are not easily visualized by simple data plots. It may not be appropriate to aggregate data for several plants (which may have different mercury chemistries in the waste and in the flue gases) to determine the potential control effectiveness of a particular technology. In general, the uncontrolled mercury emissions in MWCs appear to be slowly decreasing as battery manufacturers (a major source of mercury in MSW) have shifted to new electrochemical concepts. Also, many of the medical uses of mercury, including both medicinals and equipment (e.g., blood-pressure devices and thermometers), have declined.

3. Hazardous Waste Incinerators

The emission of metals from hazardous waste incinerators is highly variable. This reflects the wide range of wastes that are fired in such devices. The general guidelines for evaluating metal volatilization given above suggest, however, that metal emissions from these units (when the elements are present in the waste) should be relatively high: high temperature operation coupled with the presence of organic chlorine compounds. Studies were conducted in a laboratory swirl flame incinerator (523) generating high-temperature, turbulent combustion conditions (similar to a liquid injection incinerator). The ratio of Cr^{+6} to total chromium of the chromium compounds in the flue gases, in the absence of sulfur or chlorine, was about 2% independent of the valence of chromium fed (Cr^{+3} or Cr^{+6} forms). The Cr^{+6} to total Cr ratio generally followed the trends of equilibrium predictions. The addition of chlorine compounds (to 6700 ppm) increased the fraction of Cr^{+6} in the small particles from approximately 30% to 70% and the ratio increased to about 8%. The addition of sulfur (no chlorine present) sharply diminished Cr^{+6} emission. At 7900 ppm sulfur, the Cr^{+6} percentage approached the detection limit. Although not tested experimentally, equilibrium calculations predict that relatively small quantities of sulfur can counteract the Cr^{+6} enhancing effects of chlorine.

4. Fluid Bed Sewage Sludge Incinerators

As an example of the implications of simplistic approaches to emission estimation, a permit document for a fluid bed incinerator in an eastern U.S. seaboard state used the concentration of selected elements in the raw sludge as the basis for emission estimation. Sludge data were used in combination with "conservative" emission control efficiencies (expressed as a percent of metal in the feed sludge). The control efficiencies used for the calculations were those recommended by the federal EPA based on measurements on incinerators with relatively inefficient particulate collectors. However, the air pollution train in the proposed facility included a highly efficient dry electrostatic precipitator with a guaranteed outlet loading of 32 mg per dry standard cubic meter corrected to 7% O_2 (mg/dscm). The sludge data, permit control efficiencies, and consequent emission rates are summarized in Table 18.

Consideration of these results shows the unrealistic results that can occur by application of simplistic emission estimation assumptions to this new, high-particulate control efficiency situation. The calculated metal emissions indicate that the heavy-metal content of the particulate is 416 of the 955 g/hr emitted: over 43%! It is reasonable to

Table 18 Sludge Metal Content, APC Control Efficiency and Calculated Emission Rates (Fluid Bed Furnace) (Basis: 9,400 lb/hr dry sludge feed rate)

Element	Dry sludge mg/kg (dry)	Gross emission rate (mg/hr)	Percent of all sludge metal	Typical control efficiency (%)	Net emission rate (mg/hr)	% of emitted metals
As	2.02	8,631	0.15	96.00	345	0.08
Be	0.02	85	0.00	98.00	2	0.00
Cd	16.05	68,577	1.19	90.00	6,858	1.65
Cr	566.70	2,421,355	41.86	96.00	96,854	23.24
Pb	695.00	2,969,545	51.33	90.00	296,955	71.24
Ni	74.09	316,566	5.47	95.00	15,828	3.80
Total		5,784,760	100.00		416,842	100.0

The total particulate emission rate is estimated to be 954.8 grams/hr based on a permitted flue gas concentration of 32 mg/dscm and an estimated flue gas flow rate of 496 scm/min.

expect, however, that the bulk of "real particulate" is comprised of benign elements: calcium, aluminum, silicon, oxygen, etc. Therefore, new estimation approaches are needed based on more realistic measures of the "metals" content of particulate.

The quantity of each metal in the feed sludge is the basic scalar of emissions. Metals in sludge arise from several sources including industrial discharges (especially plating wastes), corrosion of plumbing materials, street runoff (especially deposited lead compounds from lead-containing paints and use of "regular" gasoline), and other domestic and industrial activities. The metals content varies from day to day, reflecting a diversity of meteorological and other factors.

As noted, the temperature of the combustion environment has an impact on metal emissions. Fluid bed operating temperatures are selected to minimize fuel use and, also, to mitigate the volatilization process (815°–850°C). Correlations of furnace temperature with emission rate (218, 219) show little increase in volatile metal emissions below 870°C. Sludge chloride content increases the sensitivity of lead and cadmium emissions to bed temperature (217). This may be due to the high volatility of the metal chlorides ($PbCl_2$ and $CdCl_2$) at combustion temperatures. Chloride ion concentration in sewage sludge varies widely but is usually below 0.5% (dry basis). However, when the sludge is conditioned with lime and ferric chloride to aid in dewatering, the chloride ion concentration can approach 7% to 9%. At these concentrations, sludge kiln emission data at 870°C showed a 30% to 600% increase in lead and cadmium volatilization, respectively (217), over emissions when burning raw, unconditioned sludge.

An inherent feature of most fluid bed sludge incinerators is that 100% of the ash content is carried off in the flue gases leaving the bed. In most instances where sludge incinerator emission estimation is necessary, it is desirable to have a technique that calculates the emissions based on the metal content of the raw sludge (which is the type of metals data most available for treatment plants). Where possible (when sludge feed rate and metals analysis are given in association with emission data), sludge heavy-metal rates are used as "inlet" values to calculate efficiency. Otherwise, a direct analysis of the "inlet loading" particulate catch can be used.

It should be noted that in passing through the equipment train between the fluid bed and the APC system, a fraction of the particulate may settle out. This material is drawn off

from ash hoppers located in the ductwork, beneath boilers, etc. Consequently, the inlet loading to the APC system may not close a material balance on total ash or any specific element based on input from the feed sludge. However, the error induced by these (usually unquantified) withdrawals from intermediate system discharge points makes the stack emission estimate conservative.

The most effective method to reduce metal emissions is through installation of highly efficient APC systems. The analysis of fluid bed emission data shown below determined the net metal emissions to be expected with high-efficiency trains and explored the possible improvement achievable with several APC systems that are cascaded to achieve the target stack emission rate.

b. Emission Data. Table 19 presents a summary of U.S. data on the emissions of the key metals from incineration of sewage sludge in fluid bed incinerators. Restriction of the data base to fluid beds is necessary since multiple hearth systems involve a considerably different process and expose the sludge to hearth temperatures much higher than for modern fluid beds (218).

The data from the test at 925°C (Data Numbers 23 and 24) and the data reported in Ref. (210) (Data Numbers 16, 17, and 18) were omitted from this data analysis. These high-temperature tests reflect a most atypical operating condition. One observes a considerable metal emission increase at these temperature levels. While the effects of elevated temperatures are interesting and clearly indicate that such conditions should be avoided, the 925°C data distort the average calculated from the remainder of the data. Thus, the conclusions and observations in this analysis are applicable only to fluid beds run at temperatures below about 870°C.

The data in Ref. (210) (as noted in the footnotes to Table 19) are also not included, as they used analytical methods of questionable accuracy. The data in Table 19 include "inlet data" that correspond either to the sludge ash analysis (i.e., assuming 100% carryover to the APC), noted with an asterisk, or to direct determinations of inlet particulate chemistry. "Outlet" data reflect analysis of particulate sampled from the stack. When a wet electrostatic precipitator (WESP) followed the Venturi, the reported outlet loading is for the WESP and the corresponding WESP inlet is the Venturi outlet.

ARSENIC CONTROL. Arsenic concentrations in the ash are lower in the Venturi outlet relative to the inlet but increase for the V + WESP case. This suggests that the volatilization process has moved the arsenic to the very finest particulate fraction. This also shows in the level of Venturi control of arsenic: considerably below the overall particulate control level.

BERYLLIUM CONTROL. Data indicate that beryllium may be concentrated in the relatively coarse particulate. This may reflect the characteristics of the source (metal turnings or grinding dust or relatively coarse beryllium-containing minerals with soil origins rather than finely divided precipitates of soluble beryllium compounds).

There is no observable enrichment process. This is not unexpected in view of the highly refractory character of beryllium oxide, chloride, etc. Consequently, with the high-particulate collection efficiency of V + WESP combination, stack emissions of beryllium are often reported as "zero" or "less than the detection limit." Collection efficiency for beryllium is thus equal to or better than the overall TSP control efficiency.

CADMIUM CONTROL. Data clearly show that the cadmium is concentrated in the finer particulate. A substantial average enrichment factor is shown for the Venturi and a still-higher factor for the V + WESP. The enrichment process shifts cadmium from a

Table 19 Fluidized Bed Metals Emission Rates

No.	Ref.	Run No.	Units	Data Type	As	Be	Cd	Cr	Pb	Ni	Total Particulate	Particulate Control (%)		
												Venturi	V + WESP	WESP
1	209	7-D	mg/hr	V-I	3,410	900	3,210	59,100	46,500	24,700	413,000,000			
2	209	7-D	mg/hr	V-O	0.0	0.1	2.5	16.0	23.2	12.3	14,300	99.997%		
3	209	9-D	mg/hr	V-I	5,650	652	4,230	62,100	60,000	34,300	484,000,000			
4	209	9-D	mg/hr	V-O	0.0	0-0	1.5	11.5	3.8	6.6	23,700	99.995%		
5	209	10-D	mg/hr	V-I	1,600	303	2,230	26,400	26,400	17,400	178,000,000			
6	209	10-D	mg/hr	V-O	0.0	0.0	0.6	7.3	1.9	4.0	16,600	99.991%		
7	209	5-D	mg/hr	V-O	0.00	0.08	3.08	7.63	9.89	8.64	34,300			
8	209	5-A	mg/hr	E-O	0.0	0.0	0.1	1.0	0.0	0.0	2,770		99.999%	86.903%
9	209	5-B	mg/hr	E-O	0.0	0.0	0.2	2.2	0.0	0.5	4,900		99.999%	76.832%
10	209	7-D	mg/hr	V-O	0.00	0.08	2.46	16.00	23.20	12.30	14,300			
11	209	7-A	mg/hr	E-O	2.1	0.0	0.4	1.9	0.1	1.9	670		100.000%	96.832%
12	209	7-B	mg/hr	E-O	0.0	0.0	0.6	2.2	0.6	2.2	1,660		100.000%	92.151%
13	209	9-D	mg/hr	V-O	0.00	0.00	1.46	11.50	3.78	6.57	23,700			
14	209	9-A	mg/hr	E-O	0.00	0.00	0.73	3.42	0.00	5.95	12,100		99.997%	42.790%
15	209	9-B	mg/hr	E-O	3.82	0.00	10.00	9.59	0.42	2.36	7,500		99.998%	64.539%
16	210(1)	Composite	%	V-I*	<Detection	N/A	0.08%	0.22%	0.59%	0.06%	100.00%			
17	210(1)	Composite	ug/m^3	V-O	<Detection	N/A	7.00	14.00	114.00	<Detection	9,400			
18	210(1)	Composite	%	V-O	<Detection	N/A	0.13%	0.28%	2.26%	0.00%	100.00%			
19	211	1300 Deg.F	mg/hr	V-I*	71	N/A	732	8,488	42,074	5,488	32,739,100			
20	211	1300 Deg.F	mg/hr	V-O	0.43	N/A	1	7.3	28	0	31,093	99.905%		
21	211	1500 Deg.F	mg/hr	V-I*	49	N/A	849	6,364	44,546	4,242	33,496,000			
22	211	1500 Deg.F	mg/hr	V-O	2.2	N/A	32.5	7	112	0	55,120	99.835%		
23	211(1)	1700 Deg. F	mg/hr	V-I*	64	N/A	945	7,089	47,261	4,726	41,352,500			
24	211(1)	1700 Deg.F	mg/hr	V-O	7.4	N/A	382	47	3704	0	75,616			
25	212	Site 3	mg/hr	V-I*	23,983	637	6,277	266,056	325,076	1,144,792	343,812,273			
26	212	Site 3	mg/hr	V-O	22.6	<Detection	199.0	650.0	346.0	5760.0	N/A			
27	213	Site G	mg/hr	V-I*	N/A	N/A	2,720	176,000	68,000	24,000	52,960,000			
28	213	Site G	mg/hr	V-I	N/A	N/A	369	204,838	111,652	42,716	123,100,000			
29	213	Site G	mg/hr	V-I*	N/A	N/A	1,581	103,044	34,875	14,694	40,734,000			
30	213	Site G	mg/hr	V-O	N/A	N/A	0.15	72.85	44.65	17.35	50,000	99.931%		

31	213	Site J	mg/hr	V-I*	N/A	N/A	26,190	134,442	633,798	190,314	401,580,000			
32	213	Site J	mg/hr	V-I	N/A	N/A	916	2,581	31,968	3,463	16,650,000			
33	213	Site J	mg/hr	V-I*	N/A	N/A	14,740	113,900	493,120	143,380	318,920,000			
34	213	Site J	mg/hr	V-O	N/A	N/A	3.58	9.85	120.20	13.92	49,000	99.980%		
35	214	Hyperion	mg/hr	B-I*	54,091	N/A	114,545	865,455	448,636	432,727	N/A			
36	214	Hyperion	ug/m3	B-O	0.002	0.03	0.18	3.56	0.61	2.24	N/A			
37	215	Trial 1	mg/hr	V-I	118,271	31,133	111,503	2,049,181	1,612,814	855,306	14,311,782,000			
38	215	Trial 1	mg/hr	V-O	0.00	3.38	84.60	553.28	803.70	426.38	497,448	99.997%		
39	215	Trial 1	mg/hr	E-O	73.27	0.00	14.97	66.96	3.15	66.18	23,634		100.000%	97.193%
40	215	Trial 1	mg/hr	E-O	0.00	0.00	22.06	77.99	19.70	75.63	58,297		100.000%	93.076%
41	215	Trial 2	mg/hr	V-I	197,686	22,730	147,920	2,170,925	2,098,429	1,199,373	16,905,218,400			
42	215	Trial 2	mg/hr	V-O	0.00	0.00	51.66	401.23	132.59	229.03	828,282	99.995%		
43	215	Trial 2	mg/hr	E-O	0.00	0.00	25.37	119.02	0.00	207.80	422,435		99.997%	49.826%
44	215	Trial 2	mg/hr	E-O	133.66	0.00	351.22	335.61	14.63	82.93	261,.461		99.998%	68.946%
45	215	Trial 3	mg/hr	V-O	0.00	1.91	107.02	267.54	345.89	393.67	1,200,108			
46	215	Trial 3	mg/hr	E-O	0.00	0.00	4.18	33.43	0.00	0.00	96,953		99.999%	88.485%
47	215	Trial 3	mg/hr	E-O	0.00	0.00	6.69	77.73	0.00	16.72	169,667		99.999%	79.848%
48	216	Site 3-1	mg/hr	V-I	25,000	700	6,700	280,000	350,000	1,210,000	293,598,165			
49	216	Site 3-1	mg/hr	V-O	31	0	240	748	467	7,406	411,000	99.860%		
50	216	Site 3-2	mg/hr	V-I	25,000	700	6,700	280,000	350,000	1,210,000	371,999,768			
51	216	Site 3-2	mg/hr	V-O	26.1	0	237	940	519	6,182	444,000	99.881%		
52	216	Site 3-3	mg/hr	V-I	25,000	700	6,700	280,000	350,000	1,210,000	456,520,000			
53	216	Site 3-3	mg/hr	V-O	23.7	0	339	475	363	4,239	307,000	99.933%		
											Average	99.942%	99.999%	78.118%
											Std. Deviation	0.057%	0.001%	17.419%
											No. Data Points	12	12	12

Notes:

V-I*, Venturi Inlet (Based on Sludge Analysis)

V-I, Venturi inlet (Based on Particulate Analysis)

V-O, Venturi Outlet (for Wet ESP runs, this is the inlet)

B-I*, Baghouse Inlet (Based on Sludge Analysis)

B-I, Baghouse Outlet

E-O, Wet ESP Outlet (associated V-O is the inlet)

(1) Elemental analyses for Reference 210 were developed using X-Ray fluorescence methods which is significantly less accurate than the chemical digestion and Atomic Absorption methods used elsewhere. Thus, these data were not used in analysis of metals etc.

(2) The data for bed operation at 1700 deg. F. were deleted in the analysis.

relatively unimportant constituent in the total sludge ash to a much more significant constituent in the net emitted ash. Overall, cadmium collection efficiencies are significantly lower than the overall particulate control.

CHROMIUM CONTROL. Data for the several sludge sources comprising the data base show the high relative importance of chromium as a constituent in sludge ash.

Again, probably due to the refractory character of chromium compounds, little enrichment is seen for the Venturi. An enrichment factor of almost two-fold is observed for the V + WESP, but this may be due in part to the depletion of lead values by the Venturi, thus enriching the apparent chromium content by significantly reducing the total metals. Overall chromium control levels are close to those for total particulate.

LEAD CONTROL. Although lead is often considered as "volatile," the data show a "negative" enrichment factor for the Venturi discharge and still further lead depletion in the Venturi discharge. This strongly suggests that the lead is heavily concentrated in relatively coarse particulate. Overall collection efficiency for lead is very high: generally at or above the total particulate control level.

NICKEL CONTROL. Nickel appears as a significant fraction of total metals. Enrichment phenomena do not appear significant, and collection efficiency is only slightly below total particulate control levels.

c. Enrichment Factors. The data in Table 19 often show significant enrichment of the metal content of emitted particulate relative to the ash. The degree of enrichment is variable among the test data for any one metal and between metals. Quantification of the enrichment phenomena provides a means to develop estimates of elemental emission rates based on initial sludge chemistry and the (guaranteed) total particulate stack emission rate. For such calculations, the enrichment factor (EF) employed should be conservative.

EFs developed from the data in Table 19 were analyzed by assuming that they followed a log normal distribution. Factors were calculated as the ratio of the concentration of metal in the emitted ash to the concentration in the total sludge ash. The 90th-percentile EF was then determined. The results of this analysis (including the coefficient of determination: "r-squared") for the assumed log normal distribution are shown in Table 20.

The 90th-percentile EF is significantly greater than the average. The r^2 values suggest that the assumption of a log normal distribution is acceptable. It is likely that the

Table 20 90th Percentile Enrichment Factor (EF) in Fluid Bed Furnaces for Bed Temperatures $< 875°C$

	Feed to Venturi outlet		Feed to WESP outlet		Venturi outlet to WESP outlet	
Element	EF	r^2	EF	r^2	EF	r^2
As	30.8	0.86	N/A	N/A	N/A	N/A
Be	5.6	0.88	N/A	N/A	N/A	N/A
Cd	98.3	0.87	167.5	0.86	13.2	0.89
Cr	8.1	0.94	18.9	0.89	3.4	0.87
Pb	6.2	0.70	4.5	0.90	0.5	0.87
Ni	15.8	0.91	67.4	0.93	4.0	0.89

Table 21 General Enrichment Factors (EF) in Fluid Bed Furnaces for Bed Temperatures < 875°C

	Percentile enrichment factor					
Element	50%	80%	90%	95%	r^2	No. data sets
As	2.9	13.7	30.8	60.2	0.86	5
Be	2.0	4.0	5.6	7.5	0.88	3
Cd	12.4	58.5	130.5	253.9	0.92	24
Cr	3.4	8.6	13.9	20.6	0.96	24
Pb	1.5	3.5	5.4	7.8	0.83	18
Ni	5.6	17.0	30.4	49.0	0.97	20

high EF values in the data base are associated with beds operating at the high end of the temperature range. Therefore, the 90th-percentile levels probably represent a conservative "worst case."

Based on the assumption that the enrichment process results from volatilization and condensation phenomena that shift the more volatile metals to fine particulate, one might speculate that a correlation exists between the EF data and penetration (1 − efficiency). The presumption would be that the EF should increase as the penetration decreases. However, there is no statistically significant relationship between EF and penetration. This leads to the conclusion that at the efficiency levels studied in these tests, there is no discernible effect of further increases in control efficiency on emitted metals concentration.

The EF data are reevaluated without respect to the type of APC device to determine percentile EF values suitable for all state-of-the-art control devices. The results are shown in Table 21.

d. Emission Rate Estimation Methodology. The enrichment factors in Table 21 provide the means to estimate the net emission rates of key metals from fluid bed incineration of sludge. Table 22 shows the emission calculation procedure for the sludge described in Table 18 when burned in a system equipped with a high-efficiency dry ESP control train.

The total particulate emission rate is estimated in Table 18 to be 954.8 g/hr based on a permitted flue gas concentration of 32 mg/dscm and an estimated flue gas flow rate of

Table 22 Estimation Methodology for Metal Emissions from Fluid Bed Furnaces at Bed Temperatures < 875°C (Basis: Combustion of 9,400 lb/hr sludge solids, 27.935% Ash)

Element	% of all sludge metals	% of sludge ash	Emission factor (90th percentile)	% of emitted ash	% of all emitted metals	Net emission rate mg/sec	% Control
As	0.15	0.00072	30.8	0.02225	0.39	0.0590	97.5
Be	0.00	0.00001	5.6	0.00004	0.00	0.0001	99.5
Cd	1.19	0.00575	130.5	0.74996	13.04	1.9891	89.5
Cr	41.86	0.20286	13.9	2.82143	49.07	7.4832	98.9
Pb	51.33	0.24879	5.4	1.35034	23.48	3.5815	88.6
Ni	5.47	0.02652	30.4	0.80614	14.02	2.1381	97.6
	100.00				100.00	15.2510	

496 dscm/min. Using the results above, the metals comprise 0.48% of the sludge but 5.75% of the emitted particulate.

5. Multiple Hearth Sewage Sludge Incinerators

a. Furnace Emission Characteristics. The heavy-metal emission characteristics for multiple hearth furnaces (MHF) are somewhat different than those for fluid beds. As a staged combustion system, the MHF system exhibits the fine particle enrichment process, but the key temperature is the combustion hearth temperature rather than the gas exit temperature. The metallic emissions of MHF systems were studied by Niessen (218) based on data from 95 emission tests (including 55 tests ahead of the APC device and 95 at the stack). These data often showed a sensitivity to the combustion hearth temperature. Especially for the elements known to exhibit volatilization (arsenic, cadmium, zinc, and lead), uncontrolled emissions calculated as a fraction of the element fed to the incinerator increased as the burning hearth temperature increased. The more refractory compounds of beryllium, copper, chromium, and nickel showed lesser volatilization behavior. The relative temperature sensitivity shown in the data was fully in line with expectations.

Niessen determined the enrichment factor between the metal concentration in the inorganic component of the feed sludge and the metal concentration in the particulate at the entrance to the APC system. The EFs range from near unity for beryllium, copper, etc., to over 10-fold for arsenic and cadmium at elevated combustion hearth temperatures (T_{comb}). For the special case of mercury, it is reasonable to assume that 100% of the feed metal is emitted.

ARSENIC. Above 760°C, arsenic showed a strong but somewhat irregular combustion hearth temperature sensitivity. The enrichment factor (EF_{As}) for 12 data points ($r^2 = 0.44$) is

$$\text{EF}_{\text{As}} = \frac{T_{\text{comb}} - 694.2}{210} \tag{20}$$

CADMIUM. Above 760°C, cadmium also showed a strong combustion hearth temperature sensitivity, possibly due to the high vapor pressure of cadmium chloride. The enrichment factor (EF_{Cd}) for 16 data points shows considerable scatter ($r^2 = 0.32$). The correlation is described by

$$\text{EF}_{\text{Cd}} = \frac{T_{\text{comb}} - 689.7}{67.8} \tag{21}$$

LEAD. Paralleling experience in municipal solid waste incineration, lead does not show the strong temperature sensitivity seen for arsenic and cadmium. The more modest enrichment factor (EF_{Pb}) from 17 data points ($r^2 = 0.67$) is

$$\text{EF}_{\text{Pb}} = \exp\left(\frac{T_{\text{comb}} - 721.4}{94.95}\right) \tag{22}$$

ZINC. Zinc emission data were irregular in character in attempted correlations with T_{comb}. Little enrichment was observed below 860°C, and a modest enrichment above that. For temperatures above 860°C, the following relationship roughly parallels the data:

$$\text{EF}_{\text{Zn}}(T_{\text{comb}} > 860^\circ\text{C}) = 0.0288 T_{\text{comb}} - 23.69 \tag{23}$$

CHROMIUM, COPPER, NICKEL, AND BERYLLIUM. Emission data for these metals showed no significant sensitivity to temperature. However, the data show a relatively

Table 23 Multiple Hearth Furnace Enrichment Factors

Element	Enrichment factor	No. data points	Std. deviation (% of average)
Chromium	1.28	16	34.65
Copper	0.94	10	41.65
Nickel	1.11	19	59.56
Beryllium	0.62	14	74.30

consistent enrichment/depletion factor compared to the metal content in the original sludge ash. The factors are shown in Table 23.

One might speculate that the lack of a temperature sensitivity for copper and nickel and the fact that the values are close to unity reflect a mix of particle sizes of the compounds of these elements in the ash slightly more finely divided than that of "typical" sludge ash. Conversely, the quite low beryllium factor suggests that the beryllium is in the coarser solids that are not elutriated from the ash. These generalities are reasonable in that (1) the chromium and copper are most likely precipitates or scoured insoluble deposits and (2) the beryllium probably enters the sewage as a constituent of beryl or other sand/soil derived beryllium-bearing mineral.

b. Air Pollution Control Metal Capture. Niessen (218) analyzed 45 sets of paired inlet–outlet metal concentration data from multiple hearth units burning domestic sewage sludge. The data indicate that the collection efficiency for some metals differs in comparison to the overall TSP collection efficiency. Inlet–outlet data pairs for TSP and for the individual metals showed similar trends to the uncontrolled emissions: sensitivity to the combustion hearth temperature for some elements and a lack of strong sensitivity for others.

Consistent with theory, one presumes that volatilization processes can lead to enhanced emission rates in the hot zone with subsequent condensation on the smaller, hard-to-collect particles in the cooler regions of the system. Thus, high hearth temperatures not only increase emission but also decrease collection efficiency.

MERCURY. For mercury, an average collection efficiency of 76% was observed relative to the inlet loading for the APC train of a Venturi plus an impingement tray wet scrubber.

ARSENIC. As for the emission correlation, sensitivity of the scrubber efficiency to T_{comb} was observed. For 20 data points ($r^2 = 0.39$), the relative efficiency (RE_{As}) is given by

$$RE_{As} = 13.9 - 0.00825T_{comb} - 5077/T_{comb}$$

CADMIUM. Cadmium collection efficiency clearly shows degradation reflecting T_{comb} effects, but there is considerable scatter (for 20 data points, $r^2 = 0.22$). The RE_{Cd} is given by:

$$RE_{Cd} = 1.82 - 0.00118T_{comb}$$

OTHER METALS. The collection factors for other metals of interest are shown in Table 24. The emission rates of these elements can be estimated using the enrichment factor multiplied by the natural sludge ash concentration of the respective elements.

Table 24 Multiple Hearth Furnace Average Collection Efficiency

Element	Collection efficiency	No. data points	Std. deviation (% of average)
Chromium	73.3%	9	38.65
Copper	90.9%	13	26.16
Nickel	59.5%	12	86.93
Beryllium	100.0% (est.)	3	N/A
Zinc	97.7%	13	7.84
Lead	87.8%	21	16.14

B. Emissions of Organic Compounds

1. General

A priori estimation of the emission rates of the spectrum of organic compounds formed by combustion sources on a quantitative, speciated basis is not possible at this time. The time variation in the composition of the feed material and in the combustion process itself and the uncertain efficiency of air pollution control devices for organic compounds produce a scenario too complex to fathom. We know that compounds are both destroyed and created in the system so, unlike the case for elements, "mass balance" approaches to emission estimation for organic compounds are unproductive.

In the special case of a hazardous waste incinerator where relatively large concentrations of specific compounds of concern are found in the feed (the principal organic hazardous constituents, or "POHCs"), one is able to track the overall degradation and removal process. One can measure and report a value for the destruction and removal efficiency (DRE). Note, however, that selecting a compound to monitor the POHC, which is likely to be formed from degradation of other waste components, can present a problem to system acceptance testing: you may totally destroy the actual molecules of POHC present in the waste but fail the test because new molecules of POHC are formed.

An alternative strategy to evaluate the importance of the emissions of individual compounds is to (1) examine the expected total nonmethane hydrocarbon (THC) emissions from the system, (2) calculate the consequent annual average ground-level concentrations (GLCs) and, then, (3) ask the question, "Are there *any* compounds that could conceivably be present as a constituent of the THC which would be significant on a health risk basis at the calculated exposure concentrations?" If excellent combustion conditions (low THC) and effective flue gas dispersion (dilution of the already small concentrations in the stack gases) take place, the GLCs will be very low relative to accepted continuous exposure concentrations, and one may conclude that the probable health risk is negligibly small.

EXAMPLE 2. For a proposed incinerator, the stack gas generation rate calculated from the design burning rate is shown to be 4.82 m^3/sec (at 395°K). For an average flue gas molecular weight of 30, this corresponds to 155,000 tons/year of flue gases. From an analysis of comparable incinerators, the nonmethane hydrocarbon (NMHC) emissions have been estimated as "less than one tonne per year." Thus, for a hypothetical organic compound with a molecular weight of 30, the approximate volume and weight fractions of NMHC in the stack gases are 7.1 ppmv and 6.4 ppmw, respectively. Dispersion analyses

conducted as part of the environmental assessment effort show that an emission rate of 1.0 g/sec results in an annual average GLC of 2.16 micrograms/m^3. What is the estimated GLC of NMHC? Is there a significant health risk from several compounds found in incinerator effluents such as phosgene, chlorobenzene, dicyclopentadiene, ethylene dibromide, and vinyl chloride?

Based on the dispersion analysis, the dilution ratio of NMHC between the concentration in the stack gases and the annual average GLC is given by

$$\text{dilution} = \frac{\dfrac{1}{4.82}}{2.16 \times 10^{-6}} = 96{,}050 \ldots \text{say } 10^5$$

Consequently, one concludes that for a NMHC present in the stack gases at 7.1 ppm, the annual average GLC is 7.1×10^{-5} ppm.

Second, one must consider the likely concentration of any one organic compound in the stack gases. A review of mass spectrographic data screening NMHC data indicates that for mixed waste systems (*not* an industrial waste situation where there are high concentrations of environmentally significant compounds), one finds no single compounds present in large concentrations. Rather, one sees a broad spectrum of organic chemistry. It is not unreasonable, therefore, to suggest that the absolute maximum annual average fraction of *any one compound* in the NMHC is less than 1% of the NMHC. Indeed, it is more likely that the "correct value" for any one compound is orders of magnitude smaller.

That is not to say that there are no episodic "puffs" of specific compounds in measurable concentrations. For example, one might expect a short-term excursion following the rupture of, say, a 5-liter can of a "pure compound" of potential concern or during a momentary upset of the combustion process. However, the public health impact of these short-term excursions does not appear significant nor has the regulatory community viewed it as significant. On an "annual average concentration" basis, the significance of the short-term phenomena is very greatly diminished.

If one accepts the 1% maximum, however, as a "very worst-case scenario," the combination of low total and fractional concentration as THC and excellent dispersion, the annual average maximum exposure to any compound for the scenario described above is 0.7 millionths of a ppm (7×10^{-7} ppm by volume) for a compound with a reference molecular weight of 30. For compounds with a higher molecular weight, the concentration is reduced proportionately.

For example, calculations for the several environmentally significant organic compounds summarized in Table 25 suggest "safety factors" relative to assumed acceptable continuous-exposure concentration limits of from 50-fold to over one million to one.

Table 25 Indicated Safety Factors for Environmentally Significant Compounds

Compound	Mol. wt.	Max. conc. (ppm)	Acceptable conc. (ppm)	Safety factor
Phosgene	99	1.8×10^{-7} ppm	0.1	500,000
Chlorobenzene	112	1.6×10^{-7} ppm	0.02	125,000
Dicyclopentadiene	132	1.4×10^{-7} ppm	2×10^{-4}	1,460
Ethylene dibromide	185	1.0×10^{-7} ppm	5×10^{-6}	50
Vinyl chloride	62	2.9×10^{-7} ppm	5	17×10^6

These calculations and a review of health effect data for numerous other compounds that possibly may be found in the stack gases support the conclusion that health impacts from trace organic compounds in the incinerator stack are expected to be negligible.

2. Emissions of Specific Compounds

a. General. For an arbitrary mixed waste and a real incinerator/combustor system, it is not possible quantitatively and with accuracy to estimate the emission rate of incompletely burned POHCs from a first-principles analysis. Incinerators are intended and designed to effect 100% destruction. Their inability to do so (to some minor degree) generally is the consequence of a combination of subtle and unanticipated "failures" in mixing, in kinetics, and in other factors. Quantifying these design or operational problems is simply too complex and uncertain.

A second class of organic pollutant emissions arises from synthesis in the combustor. These pollutants are of several types:

- Fragments of feed organic material (e.g., an ethylene residue arising from the quenching of dehydrogenation steps in ethane oxidation)
- Partially oxygenated fragments (e.g., the formaldehyde or CO formed in the combustion of almost any organic material)
- Compounds synthesized from specific precursor chemicals (e.g., the formation of polychlorinated dibenzo-p-dioxin from dimerization of polychlorinated chlorophenols)
- Compounds synthesized by the "combustor chemistry set" from molecular fragments (such as "de-novo" synthesis of chlorinated methanes when burning mixtures of chlorinated organic compounds)
- De-novo synthesis catalyzed by solids in the combustor flow field (boiler deposits, captured particulate in dry APC devices, particles reacting "on the fly")

Clearly, quantitative estimation of emissions generated through these routes is even more outside the range of present-day capability than is the estimation of the unburned fraction of feed POHCs. Consequently, in most cases, emission estimates for specific compounds must be based on the results of tests run in similar facilities and with similar wastes. Such data almost invariably show very small quantities of any one species. Further, the vast majority of the mass comprising the emissions is benign or relatively benign compounds. Table 26 presents volatile organic emissions data from U.S. EPA studies of industrial boilers and incinerators burning hazardous waste. The data are presented to indicate the range of chemistry and, in most cases, the very low concentrations involved.

b. Polychlorinated Dibenzo-p-Dioxins. The several congeners and isomers comprising the polychlorinated dibenzo-p-dioxin (PCDD) and polychlorinated dibenzo-furan (PCDF) compounds are a special case in the assessment of organic compound emissions. Many researchers had considered the adverse health effects following exposure to these two classes of compounds to be particularly significant. Thus, when relatively high concentrations of PCDDs and PCDFs were detected in the fly ash from municipal refuse incinerators in the late 1970s, a worldwide effort was triggered to assess the magnitude of the health effects, to determine how much was being emitted, to find out the chemical mechanisms by which they were being formed, to develop control technologies, and so forth. Literally tens of millions of U.S. dollars were spent on tests, studies, and developments for this special set of compounds over the following 15 years (328). Important outcomes of the dioxin

Table 26 Volatile PICs Present in Stack Gases from Boilers and Incinerators Burning Hazardous Waste (ng/liter)

Compound	No. boilers	No. incinerators	Conc. in boilers	Conc. in incinerators
Chloroform	5	5	4.2–1900	1–1330
Tetrachloroethylene	5	3	0.3–760	0.1–2.5
Chloromethane	4	—	4.6–410	N/A
Methylene chloride	4	2	83–2000	2–27
Benzene	3	6	9.4–270	12–670
1,1,1-Trichloroethane	3	3	5.9–270	0.1–1.5
1,2-Dichloroethane	3	—	1.3–1200	N/A
Toluene	—	2	N/A	2–75
Bromodichloromethane	—	4	N/A	3–32
Bromoform	—	3	N/A	0.2–24
Naphthalene	—	3	N/A	5–100
Chlorobenzene	—	3	N/A	1–10
Hexachlorobenzene	—	2	N/A	0.05–7
o-Nitrophenol	—	2	N/A	25–50
Phenol	—	2	N/A	4–22
Bromochloromethane	—	1	N/A	14
Carbon disulfide	—	1	N/A	32
Methylene bromide	—	1	N/A	18
2,4,6-Trichlorophenol	—	1	N/A	110
Bromoethane	—	1	N/A	1
Chloromethane	—	1	N/A	3
Pyrene	—	1	N/A	1
Fluoranthene	—	1	N/A	1
Dichlorobenzene	—	1	N/A	2–4
Trichlorobenzene	—	1	N/A	7
Methyl ethyl ketone	—	1	N/A	3
Diethyl phthalate	—	1	N/A	7
o-Chlorophenol	—	1	N/A	2–22
Pentachlorophenol	—	1	N/A	6
2,4 Dimethyl phenol	—	1	N/A	1–21

programs were the "popularization" and politization of health effects as a factor in facility acceptance, siting evaluations, permit approvals, etc.

The health response to a chemical can be described in terms of several acute effects:

Toxicity (a "poisoning" effect lethal to cell tissue)
Carcinogenicity (the stimulation of cancerous growth)
Mutagenicity (the stimulation of mutations in cell structure or function)
Teratogenicity (the stimulation of adverse changes in fetal tissue)

Also, there can be a spectrum of nonacute effects ranging from observable but nonlethal disabilities to subtle changes in the biochemical reactions within the organism that have no recognizable adverse health consequence. In all but laboratory situations, human exposure to dioxin has been below the acute toxic level. Although elevated industrial exposures have produced chloracne (a severe skin eruption) and aesthenia (numbing of the tactile

response), there do not appear to be clear-cut life-threatening toxic responses in human beings for exposures even orders of magnitude above the exposures resulting from refuse combustion.

Carcinogenicity and mutagenicity effects are also questionable in human beings, especially for the low-concentration exposures from refuse combustion. Some spontaneous abortions were associated with the massive human exposures in the Seveso incident in Italy (involving the rupture of a process reactor containing a reacting mass of chlorinated phenolic chemicals that also contained dioxin compounds that had formed as side reactions). In Seveso, however, the role of dioxin per se was clouded by the concurrent release of *very* large quantities of a spectrum of chlorinated phenolic compounds that have their own adverse health effects.

PCDD toxicity assessments must take cognizance of the fact that there are 75 discrete chemical compounds comprising the PCDD family: from two (the dichloro-PCDD compounds) to eight (the octachloro-PCDD compounds) chlorine atoms (congeners) dispersed in differing spatial relationships (isomers) among the eight sites in the base dioxin molecule. Also, one must consider the several polychlorinated dibenzo-furan (PCDF) species that usually occur along with the PCDDs and appear to have the same genesis. The PCDFs include 135 different compounds. To most investigators the "dioxin problem" is the combined health effect due to both PCDDs and PCDFs.

Each of the 210 dioxin/furan compounds produces a different toxic response in a given receptor organism. There are also significant differences in the toxic response between receptor organisms. For example, the dose at which one-half of a population of guinea pigs are killed (the lethal dose for 50%, or LD/50) for the most toxic PCDD compound (2,3,7,8 tetrachloro dibenzo-p-dioxin) is 0.6 μg/kg. The LD/50 is ten thousand times greater (5051 μg/kg) for the hamster, a rodent species not greatly unlike the guinea pig. One must decide whether the target species of concern (e.g., humans) is more like guinea pigs or hamsters. If one simply seizes on the "worst case," one can end up with a too conservative result. If one picks the "best case," one is challenged by project adversaries who see a "white wash."

The U.S. EPA and many other health groups worldwide apply a "relative toxicity factor" to the mass emission of each compound or group of compounds in the PCDD/PCDF family to provide a weighted estimate of the health significance where the distribution of compounds among the 210 PCDD/PCDF compounds differs. The factor normalizes the health effect of a given dose of a compound to that of 2,3,7,8 tetrachloro dibenzo-p-dioxin (2,3,7,8 TCDD), the most toxic of all the 210 PCDD/PCDF compounds. Laboratory animal dose-response data were used to determine the factors. Two sets of factors are used in the United States for "dioxin risk assessments." These include the U.S. EPA factors (developed by the EPA Cancer Advisory Group, or "CAG") and the Eadon factors used by the New York State Department of Health (NYDOH). European countries vary: some have their own numbers and some have adopted the U.S. EPA values. The toxicity equivalence factors from several sources are presented in Table 27.

Numerous theories have been proposed to account for PCDD/PCDF emissions, but no consensus has been reached. The four principal classes of the theories (330, 331, 333, 524–526] are

Table 27 Toxicity Equivalency Factors (TEFs) for Specific PCDD and PCDF Congeners

Positions chlorinated	Equivalency factor (TEF_i)				
Dioxins	International (470)	Eadon	USEPA (471)	BGA (472)	Nordic (473)
2,3,7,8 Tetra CDD	1.0	1	1	1	1
1,2,3,7,8 Penta CDD	0.5	1	0.2	0.1	0.5
1,2,3,4,7,8 Hexa CDD	0.1	0.03	0.04	0.1	0.1
1,2,3,6,7,8 Hexa CDD	0.1	0.03	0.04	0.1	0.1
1,2,3,7,8,9 Hexa CDD	0.1	0.03	0.04	0.1	0.1
1,2,3,4,6,7,8 Hepta CDD	0.01	0	0	0.01	0.01
1,2,3,4,6,7,8,9 Octa CDD	0.001	0	0	0.001	0.001
Furans					
2,3,7,8 Tetra CDF	0.1	0.33	0.1	0.1	0.1
1,2,3,7,8 Penta CDF	0.01	0.33	0.1	0.1	0.01
2,3,4,7,8 Penta CDF	0.5	0.33	0.1	0.1	0.5
1,2,3,4,7,8 Hexa CDF	0.1	0.01	0.01	0.1	0.1
1,2,3,4,8,9 Hexa CDF	0.1	0.01	0.01	0.1	0.1
1,2,3,6,7,8 Hexa CDF	0.1	0.01	0.01	0.1	0.1
2,3,4,6,7,8 Hexa CDF	0.1	0.01	0.01	0.1	0.1
1,2,3,4,5,6,7 Hepta CDF	0.01	0	0.001	0.01	0.01
1,2,3,4,7,8,9 Hepta CDF	0.01	0	0.001	0.01	0.01
1,2,3,4,6,7,8,9 Octa CDF	0.001	0	0	0.001	0.001
Other PCDD/PCDF	0	0	0–0.01	0.001–0.01	0

$TE = \sum_{i=1,n}(X_i \cdot \mathrm{TEF}_i)$

where TE = toxic equivalent, X_i = concentration of congener "i" and $\mathrm{TEF_i}$ = toxic equivalency factor.

Note: when only homologue test data are available, the most conservative (largest) equivalency factor should be applied.

1. CDD/CDF compounds are present in the waste and survive passage through the combustion environment undestroyed
2. CDD/CDF compounds are formed in the course of gas phase reactions involving chlorinated precursors such as chlorobenzenes, chlorophenols, or polychlorinated biphenyls.
3. CDD/CDF compounds are formed in the course of heterogeneous gas–solid reactions involving surface reactions of gas phase precursors and fly ash.
4. CDD/CDF compounds are formed at relatively low temperatures (250–600°C) in solid phase reactions on the surface of fly ash involving metal chlorides or chlorine in the flue gas and fly-ash carbon (de-novo synthesis).

The "survival" theory has been weakened by several detailed analyses of waste that suggest that not all wastes contain CDD/CDF compounds even though they are found in almost all effluents. Further, the oxidation rate of these species at relatively modest temperatures (say, over 600°C) makes them unlikely to escape destruction (329, 330, 528).

In-furnace reactions could generate the precursor compounds and the reactions forming the CDD/CDF compounds are known and not unreasonable: especially those involving well-configured precursors (e.g., chlorophenols, chlorobenzenes, PCBs) where

the number of steps and the complexity of steps between precursor and CAD/CDFs are limited (527, 331, 332). However, although this route is plausible, the low concentrations of the precursors make it difficult to conclude that this is the dominant source of the CDD/CDF compounds.

Bench-scale experiments by several investigators have provided convincing evidence that CDD/CDF compounds can be created downstream of the furnace (330, 333). These experiments show a catalytically assisted reaction on the surface of fly ash with maximum tetra- to octa-PCDD and PCDF formation near 300°C. PCDF also shows a lower peak generation rate near 450°C (525). As the temperature falls below 250°C, the reaction rate falls quickly to near zero. The precursor materials involved are simple: carbon char and inorganic chlorides. Interestingly, most researchers do not show a correlation of CDD/CDF generation with the HCl concentration in the flue gases. Further, there has been no conclusive scientific evidence that specific solid-waste components (such as polyvinyl chloride plastics) are responsible for any significant fraction of the total CDD/CDF (529, 530). Much of the data (e.g., 358) show that at temperatures between 200° and 300°C, generally more than 80% of the mass of the compounds are in the gaseous emissions rather than adsorbed on the emitted particulate.

The hypothesis for CDD/CDF generation by catalytic formation on the surface of particulate is consistent with most of the reported data and broad trends in data for mass burning and RDF-fired systems. Data from the Quebec City mass burn incinerator (366) reveal a strong correlation between the mass of CDD/CDF generated per tonne of refuse fed and the ash carryover expressed as the mass of uncontrolled ash per mass of refuse fed ($r^2 = 0.874$). These results suggest that the most appropriate control technology for these compounds involves insightful use of overfire air mixing and similar means to effect substantially complete burnout of the precursor organic compounds. Low CO levels appear as an indirect but generally reliable indication that effective burnout is, indeed, being achieved.

Based on this generation hypothesis, it is clear that CDD/CDF can be minimized through operation of the MWC such as to (1) minimize formation, carryover, and persistence of carbonaceous particulate and (2) minimize the residence time of any carbonaceous particulate in the critical 300–450°C reaction zone. The specific design and operational strategies to accomplish these objectives include

- Mix solid waste prior to firing to minimize irregularities in heat release, moisture content, and oxygen demand. This will avoid cold areas on the grates where char formation occurs and poor combustion conditions to burn out what char does form.
- Effect good mixing in the overfire space using both overfire air jets and furnace configuration to ensure achievement of high and uniform temperatures (>950°C), extended residence time at temperature (1 to 2 sec), and uniform and adequate oxygen concentrations (>3% O_2) to facilitate combustion of soot and char particles before the flue gases enter the boiler passes and begin to cool (528).
- Minimize the residence time of particulate in the boiler passes in the temperature range where CDD/CDF compounds form. Generally, this parameter is not practical as a control concept due to the high cost and limited flexibility available for the boiler design.
- Minimize the residence time of particulate in the post-boiler gas conditioning and air pollution control equipment in the temperature range where CDD/CDF com-

pounds form. In tests on an electrostatic precipitator (ESP) operating in the range of 150° to 300°C, the CDD/CDF concentration in the gases leaving the ESP was found to be as much as 200 times the inlet concentrations (531). Further, the ratio of increase across the ESP increased as the working temperature increased. In other plants (presumably, where the carbonaceous char was well burned out, temperatures were low, and the ESP efficiency was high), small decreases have been measured. In general, when using an ESP, operation at the lowest practical temperature is critical.

Consider use of semi-dry scrubber to accomplish acid gas reduction but, importantly, to reduce the gas temperature to below the CDD/CDF formation reaction zone. The semi-dry scrubber effluent temperature (the inlet temperature to the particulate control device) is of the order of 145°C such that CDD/CDF reactions are greatly slowed. Also, as discussed in Chapter 14, injection of activated carbon (for mercury capture) is also effective to adsorb CDD/CDF compounds.

14

Air Pollution Control for Incineration Systems

The previous chapters give the analyst several tools to estimate the uncontrolled emission rate of pollutants: the mass loading of particulate matter or the concentration of gaseous pollutants at the inlet of air pollution control (APC) devices. When available, data from physically comparable facilities that are burning comparable wastes under comparable operating conditions can also be used (subject only to the thoughtful determination that, indeed, the situation is comparable).

In most cases, the target outlet loading is well defined by local, state, or federal regulations. Thus, the selection of an air pollution control device appears relatively straightforward: review the available art to determine the optimum technology to reduce the pollutant loading from the known or conservatively estimated inlet level to (or below) the outlet loading specified by regulation. This approach to selecting a technology selection often leads to different selections at different times or in different places.

For example, a simple wetted baffle gave acceptable performance and was well priced for APC on U.S. municipal incinerators in the early 1960s. Then the only regulated pollutant was particulate matter and the regulations were not very stringent. In the 1970s, a few plants installed high-energy scrubbers or cyclones, but the dominant move was to the dry electrostatic precipitator (ESPs) that controlled particulate to the more stringent New Source Performance Standards arising from the Clean Air Act of 1970. The economics of the ESP were helped greatly by the emergence of the gas-tight waterwall boiler design that limited excess air (flue gas volume). In fact, the initial movement of incinerator construction to waterwall designs in the 1970–1973 time period was primarily driven by the need to reduce flue gas volume, not to recover energy. In the 1980s, regulations in many states added requirements for the control of acid gas emissions (primarily targeted on hydrochloric acid). Coupled with still more stringent particulate standards, the semi-dry absorber or "dry scrubber" (described below under "Absorbers") followed by a fabric filter moved to the leadership position. Thus, the "right technology" is ever-changing and is set by the combination of local and federal regulations that control emission rate.

The process of selecting an optimal APC technology is complex. Defining the meaning of "optimum" requires consideration of several technical, economic, and other criteria. The criteria include

- Pollutant removal efficiency (relative to all regulated pollutants and giving attention to the potential generation of new pollutants in the course of abating others)
- Capital investment to include
  - Basic APC device and installation, etc.
  - Fans, pumps, and piping
  - Foundations and structural support
  - Ductwork to incinerator and to fan and stack
  - Insulation
  - Instrumentation and control systems
  - Electrical supply, motor control centers, etc.
  - Water supply, sewer, and portion of treatment system
  - Working capital in spare parts
  - Allowance for device replacement (useful life)
- Operating cost to include
  - Operating labor
  - Special costs for training in operations and maintenance
  - Operating parts and supplies
  - Absorbents, reagents, and similar consumables
  - Fuel
  - Electricity
    - Fan power
    - Pump power
    - Device power (especially for electrostatic precipitator but also for shakers, air compressors, etc.)
  - Water
  - Maintenance labor
  - Maintenance parts and supplies
  - Wastewater treatment and disposal
  - Ash treatment and disposal
  - Contract maintenance expenses (e.g., for instrumentation maintenance)
- Impact on incinerator availability (reliability) and capacity
- Operability and maintainability (including consideration of compatibility with general plant operating and maintenance labor skills, maintenance facilities, and tools)
- Compatibility with layout limitations
- Compatibility with other regulations (noise, odor, illumination, visible plume, icing of adjacent roadways, or electrical wires)

The detailed design and selection of APC systems is a major technical area in itself. Presenting such information is beyond the scope and objectives of this book. However,

several topics unique to incineration applications of air pollution control merit attention. The topics divide the problem of selecting an APC technology three ways: by *control* device, by *pollutant*, and by *source* (incinerator) type.

I. EQUIPMENT OPTIONS FOR INCINERATOR AIR POLLUTION CONTROL

A. Settling Chambers

A settling chamber is a distinct chamber or zone where the gas velocity is reduced to permit gravity settling of particulate to occur. The controlling physical relationship (Stoke's law) is described in Chapter 13. The capture of particulate by settling is sensitive to re-entrainment so settling chambers are often designed with a wet bottom wherein a sluice of water is used to both trap and convey solids. Clearly, settling chambers are not highly efficient and their applicability in modern plants is nil as a means to meet emission regulations. They were, however, the standard in the U.S. municipal incinerator industry in the 1950s and 1960s.

The settling process is, however, always operative in an incinerator system and merits consideration by the designer. Any duct or chamber in an incinerator will act as a settling chamber to some degree. Unless provision is made to draw off the settled particulate, the material that settles in the duct or at the bottom of a chamber will accumulate and partially block the flow passage. In some cases, the settled material will sinter or fuse, thus limiting the ease with which it may be removed. The increased velocity due to the blockage will eventually limit further deposition. However, the flow reduction will increase the pressure drop in the flow system, will reduce the mean residence time in the system, and may introduce undesirable flow irregularities. For that reason, many flow passages, boiler passes, etc., are equipped with cone bottoms and double dump valves (described below under "Cyclones") or the like to facilitate regular removal of settled solids.

The settling chamber concept is also applied as a means to remove larger bits of gasborne solids. For example, incinerators that burn solid wastes can expect periodic release of relatively large pieces of material that is still burning or smoldering: a "sparkler." If such a glowing or burning particle is introduced to a fabric filter APC device, one of the bags may be perforated or a fire may be started. Therefore, a knockout chamber (a simple, flow-reversing down/up leg in the ductwork) is often incorporated in the flow system.

B. Cyclones and Inertial Collectors

"Cyclone" denotes the most common member of a family of particulate control devices that depend on inertial forces to remove relatively large, massive particulate materials from a gas stream. The removal efficiency of a cyclone is related to the angular velocity achieved in the vortical flow zone within the cyclone separator. As the rotational velocity within the device increases, progressively smaller particles reach the collection area at the outer wall and are captured. The inlet ducting is often tailored (a tangential, helical, or involute entry) and/or internal vanes are used to facilitate the vortical acceleration and deceleration in order to minimize pressure losses.

Cyclone collection efficiency increases directly as a strong function of the aerodynamic particle size and density. The efficiency is often characterized by the "d_{p50} cut size," which denotes the particle diameter where 50% is collected and 50% escapes.

Lapple (256) uses empirical data to correlate the cut size to the number of turns of the vortex within the cyclone (N_e) and a combination of particle, gas, and hardware characteristics. Lapple's correlations are

$$N_e \cong \frac{1}{H}\left(L_b + \frac{L_c}{2}\right) \tag{1}$$

$$d_{p50} = \left(\frac{9\mu_g W}{2\pi N_e \rho_p V_g}\right)^{1/2} \tag{2}$$

where

H = Height of the inlet duct to the cyclone
L_b = Length of the cylindrical portion of the cyclone
L_c = Length of the conical portion of the cyclone
μ_g = Gas viscosity
W = Width of the inlet duct
π = Constant (3.14159)
ρ_p = Density of the particle
V_g = Gas velocity in the inlet duct

A more typical and accurate efficiency correlation by Leith and Licht (266) relates the collection efficiency η to the particle diameter d_p in an exponential function of the form

$$\eta = 1 - \exp[-2(C\Psi)^{\frac{1}{2n}+2}] \tag{3a}$$

where for a cyclone of outside diameter D and for a gas temperature of T°K:

$$n = 1 - \frac{D^{0.14}}{2.5}\left(\frac{T}{283}\right)^{0.3} \tag{3b}$$

The constant d in Eq. (3d) is the diameter of the conical section at k, the farthest distance that the vortex extends below the gas exit duct (diameter D_e) that projects a distance S down into the cyclone's cylindrical section. D_d is the diameter of the dust exit duct at the bottom of the cyclone. The constant Ψ is a modified inertial impaction parameter as given in Eq. (3f).

$$k = 2.3 D_e \left(\frac{D^2}{WH}\right)^{1/2} \tag{3c}$$

$$d = D - (D - D_d)(S + k - L_b)/L_c \tag{3d}$$

$$C = \frac{\pi D^2}{WH}\left[2\left(1 - \left(\frac{D_e}{D}\right)^2\right)\left(\frac{S}{D} - \frac{H}{2D}\right) + \frac{1}{3}\left(\frac{S + k - L_b}{D}\right)\left(1 + \frac{d}{D} + \left(\frac{d}{D}\right)^2\right) + \frac{L_b}{D} - \left(\frac{D_e}{D}\right)^2 \frac{k}{D} - \frac{S}{D}\right] \tag{3e}$$

$$\Psi = \frac{\rho_p d_p^2 V_g}{18\mu_g D}(n + 1) \tag{3f}$$

The pressure drop across the collector is related to the efficiency with which static pressure energy is used to accelerate the gas to the peak rotational velocity and then is recovered as

the gas decelerates and then exits the device. Studies by Shepherd and Lapple (267) showed empirically that the pressure drop (expressed as the number of inlet gas velocity heads) depends inversely on the square of the exit diameter with a proportionality that depends on the inlet configuration. The inlet gas velocity head is calculated as $0.5\rho_g V_g^2$, and their relations showed

$$\Delta P = \frac{1}{2}\rho_g V_g^2 K\left(\frac{HW}{D_e^2}\right) \tag{4}$$

where ΔP is given in pascals (newtons/m^2), the gas density in kg/m^3, and the inlet gas velocity in m/sec. The dimensionless constant K is 16 for a tangential inlet and 7.5 for a cyclone equipped with an inlet vane. Inlet velocities for cyclones range from 6 to 25 m/sec, although common velocities range from 15 to 18 m/sec. At velocities greater than 25 m/sec, scouring of the cyclone by the particles will increase.

Cyclones are fabricated of carbon steel for softer particulate (e.g., wood sawdust or sander dust). Most fly-ash materials are very abrasive, and the collection cone of an ordinary carbon steel cyclone would rapidly erode and perforate. Therefore, hardened, abrasion-resistant cast iron or similar materials are used for the cones in fly-ash applications. For high-temperature applications where low efficiency is acceptable, (e.g., removal of the bulk of the coarse particulate from the flue gas leaving a fluid bed sludge incinerator), a refractory lining is cast in a large-diameter steel casing.

For higher gas flow rates combined with high efficiency (requiring a number of small cyclones in parallel), a rectangular array of several cyclones is mounted in a tube sheet fed from a common plenum and discharging to a common ash hopper. This array is known as a multiple cyclone or "multiclone collector." The performance is comparable to that of any of the individual cyclones in the array.

If not done properly, the discharge of dust from a cyclone can significantly reduce collection efficiency. Specifically, the dust must be withdrawn without allowing outside air to leak into the low-pressure regime in the cone. Even a small in-leakage flow will resuspend the dust. This sensitivity to leakage can be exploited in reverse: drawing off about 15% of the total gas flow through the hopper increases collection efficiency as much as 40% to 50% (264).

A double dump valve is normally used to discharge the ash and control in-leakage. With such a device, two dust valves are positioned one above the other. The upper valve opens first and dust falls from the hopper into the space between the valves. Then the top valve closes. Now, the lower valve opens and the dust is discharged. In low-cost dust valve designs, the valves are actuated by the weight of the dust. Unless the counterweights are carefully balanced and the pivot bearings regularly and properly lubricated, these valves can, and do, leak air. Better designs use compressed air cylinders to give positive opening and closing action for the double dump valve mechanisms.

Cyclones are sometimes installed ahead of an electrostatic precipitator (ESP) or fabric filter (FF) as a means to reduce the inlet loading and reduce the cost of the senior collector. A lower inlet loading means that the ESP can be downsized to achieve a given outlet load (fewer fields or lower specific collection area). Given the relative cost of the two collector types, the total capital investment is reduced at constant stack particulate loading. For the FF system, the savings come in the frequency of bag shaking (triggered by the buildup to a given cake thickness). Lower inlet loading means longer between shaking events, which means longer bag life. A contrary perspective reflects concern about the common development of a strongly adherent and/or impenetrable cake if the coarse

particles are removed. This has caused problems in cleaning the ESP plates or the FF bags in some installations.

C. Wet Scrubbers

Wet scrubbers include a broad class of APC devices that often have a dual function: removal of particulate matter and absorption of one or more gaseous pollutants. The gas cooling and humidification taking place in a wet scrubber may be important (and, sometimes, undesirable) side effects. The focus of design depends on the regulatory and flue gas contamination scenario. Although wet scrubbers can be effective for particulate and gas removal, their operation introduces a process waste (an aqueous discharge) needing either a sewer or a receiving stream. This new effluent may require monitoring and/or treatment and almost certainly will require a permit. These disadvantages often encourage the use of dry collectors as the preferred alternative.

For particulate removal, all wet scrubbers use the same basic principle: they create a wet surface (most often, a dispersion of droplets) to act as a "target" for particles, and they accelerate the gas to develop a velocity differential between the target and the particle-laden gas. The particulate is then captured by three mechanisms:

1. Impaction—where the particle directly impacts the wet surface or droplet
2. Interception—where the particle comes close enough to the wet surface or droplet to be captured
3. Diffusion—where the particle is driven by Brownian motion and impacts the wet surface or droplet and is captured

The collection efficiency of all three collection mechanisms is enhanced by increases in the concentration of target droplets, the velocity differential between particle and droplet, and the inertial characteristics (mass) of the particles. The pressure drop across the device is related to the efficiency with which static pressure is converted into velocity head and then recovered after particle collection is effected. The specific contour of the Venturi scrubber is aimed at optimizing this energy conversion process. It is not surprising, therefore, that Venturi designs are able to show the highest collection performance at a given pressure drop.

Wet scrubbers targeted on particulate collection fall into five groups:

1. Venturi scrubbers
2. Mechanically aided scrubbers
3. Pump-aided scrubbers
4. Wetted-filter scrubbers
5. Tray or sieve scrubbers

In modern incineration applications with stringent particulate limits, the Venturi and tray/sieve scrubbers are, by far, the most common, and they are the foci of this brief presentation. In most applications, a "quencher" is installed upstream of the wet scrubber to cool and humidify the combustion gases before entering the scrubber proper. This is particularly important when the scrubbing liquid incorporates dissolved or suspended solids. Without a pre-quench with relatively clean water, the contact of hot (especially $> 250^{\circ}C$), dry gas with the liquid leads to flashing of the water and formation of an aerosol of fine particulate that is hard to collect in the downstream zones of the scrubber.

1. Venturi Scrubbers

The Venturi is the most common scrubber concept used in incineration applications. This dominant position reflects the high particulate control efficiency that is achievable over the range of particles between 0.5 and 5 microns in diameter, the acceptable gas–liquid contact to achieve acid gas absorption (see below), and the mechanical "openness" of the Venturi and its flow system. Also, since the Venturi can be designed with an adjustable throat dimension, collection efficiency can be maintained over a range of gas flow rates. The benefit of "openness" of the liquid and gaseous flow passages relates to the lack of high-pressure nozzles, high liquid rates, small-diameter perforations, and the like, and can be important with flows that include accumulated solids.

The Venturi scrubber has three zones: the *convergent zone*, where the gas is accelerated in a smoothly converging duct to its maximum velocity; the *throat zone*, where the liquid is introduced using a spray or, more simply, by overflowing a weir; and the *divergent zone*, where the gas is decelerated in a smoothly diverging duct to or near its original velocity. In the throat region, the large differential between the gas and liquid velocity acts, if necessary, to shatter the liquid flow into myriad small target droplets. The throat is the location where the velocity differential is greatest and, thus, where the majority of the particle–droplet collisions occur. The discharge from the Venturi (carrying a substantial flow of abrasive, particle-laden liquid water moving at high speed) is often directed through a right-angle turn. At the turn, the water is allowed to pool in this "flooded elbow" to slow and provide a sump for the excess fluid.

The key parameters influencing collection efficiency in a Venturi scrubber are the pressure drop (a scale of the throat velocity and, thus, the gas-to-droplet velocity differential) and the liquid-to-gas ratio (a scale of the concentration of droplets). The liquid-to-gas ratio is commonly between 0.7 and 2.7 l/m^3 and the throat velocity between 0.5 and 1.2 m/sec. The estimated pressure drop across the Venturi scrubber has been correlated by Hesketh (268) as

$$\Delta P \cong 2.584 \times 10^{-3} V_g^2 \rho_g A_{\text{throat}}^{0.133} (L/G)^{0.78} \tag{5}$$

where

ΔP = Venturi pressure drop (cm H_2O) from inlet duct to the outlet duct
V_g = Gas velocity at throat (m/sec)
ρ_g = Gas density (kg/m^3 at throat)
A_{throat} = Venturi throat area (cm^2)
L/G = Liquid-to-gas ratio (l/m^3)

Calvert (269) suggests an estimation methodology for application to individual particles of diameter d_p microns. By application of the methodology to a mass-averaged particle diameter representing each of several particle size ranges that are known mass fractions of the total dust loading, the methodology can be extended to estimate the overall particulate abatement efficiency where the size distribution is known.

The Calvert methodology begins with the characterization of several APC design and operational parameters starting with application of his correlation for pressure drop

(ΔP) in cm H_2O as it relates to the throat velocity (V_t) in m/sec and the liquid-to-gas ratio (L/G) in l/min per m^3/min. The Calvert pressure drop is calculated as

$$\Delta P = 0.01022 V_t^2 \left(\frac{L}{G}\right) \tag{6}$$

The physical properties of the gas and liquid are dependent on the actual physical situation involved, but the following estimation algorithms may be useful for air and (pure) water:

Mean free path (m) for air at a throat temperature T_{throat} (°K):

$$\lambda = 6.7 \times 10^{-8} \left(\frac{1033.24}{1033.24 - \Delta P}\right) \sqrt{\frac{273.1}{T_{\text{throat}}}} \tag{7}$$

Viscosity (kg/m-sec) for air:

$$\mu_g = 2.23 \times 10^{-5} \sqrt{\frac{T_{\text{throat}}}{294.1}} \tag{8}$$

Water viscosity (poise) for a liquid temperature of T_w (°C):

$$\mu_w = [2.1482(T_w - 8.435 + \sqrt{8078.4 + (T_w - 8.435)^2}) - 120] \times 10^{-4} \tag{9}$$

Calvert adjusts the estimated collection efficiency with an empirical correction factor to account for the effect of particle wetability and other effects. His dimensionless coefficient (γ) varies from 0.1 to a suggested and conservative value of 0.25 for hydrophobic (hard to wet—such as an oil aerosol) particles to 0.4 to 0.5 for hydrophilic (easy to wet—such as for soluble compounds, acids, or fly ash with SO_2 and SO_3) particles. The factor increases at L/G ratios below about 0.2 l/m^3 and approaches 0.5 for large scrubbers.

The first step is the calculation of the term A as given by

$$A = 1.257 + 0.4 \exp\left(\frac{-1.1 d_p}{2.0\lambda \times 10^6}\right) \tag{10}$$

Then the term C is calculated as given by

$$C = 1 + \frac{2A\lambda \times 10^6}{d_p} \tag{11}$$

The mean droplet size (m) of the scrubbing fluid is then calculated from

$$d_d = \left[\frac{18.5}{V_{\text{throat}}} \sqrt{\frac{\sigma_w}{\rho_w}} + 2.82 \left(\frac{\mu_w^2}{\sigma_w \rho_w}\right)^{0.255} \left(\frac{L}{G}\right)^{1.5}\right] \times 10^{-3} \tag{12}$$

Then the inertia parameter Ψ is calculated from

$$\Psi = \frac{C \rho_p V_{\text{throat}} d_p^2}{9 d_d \mu_g \times 10^{12}} \tag{13}$$

and the parameter F from

$$F = \left(\frac{1}{\Psi}\right)\left[-0.7 - \Psi\gamma + 1.4 \log_e\left(\frac{\Psi\gamma + 0.7}{0.7}\right) + \frac{0.49}{\Psi\gamma + 0.7}\right] \tag{14}$$

Finally, the fractional collection efficiency η is calculated from

$$\eta = 1 - \exp[0.036364\left(\frac{L}{G}\right)V_{\text{throat}}\rho_w d_d\left(\frac{1}{\mu_g}\right)F] \tag{15}$$

Example 1 Gas saturated at 60°C is to be cleaned. The inlet dust (particle-specific gravity of 1.8), which has been described as "somewhat hydrophobic," is to be passed through a Venturi scrubber with water recycle. The design throat velocity is 15 m/sec, and the liquid-to-gas ratio is 2.0 l/m^3. If the inlet dust loading is 300 mg/Nm^3 at standard conditions, and the particle size distribution is as shown in the table below, will the discharge meet the regulation of 100 mg/Nm^3 in the stack gases?

Particle size range (μ)	Percent of total wt.	Mean diameter (μ)
0–0.5	10.0	0.23
0.5–1	15.0	0.75
1–2	20.0	1.5
2–5	30.0	3.0
5–20	15.0	13.0
> 20	10.0	30.0
	Total 100.0	

We shall assume that the wetability coefficient is 0.15 and calculate according to the Calvert correlation that the pressure drop is 4.6 cm of water corresponding to the gas velocity at the throat of 15 m/sec. At the indicated temperature, the mean free path of gas molecules is 6.093×10^{-8} m and the gas viscosity is 2.373×10^{-5} kg/msec. The viscosity, density, and surface tension of pure water at the wet bulb temperature of 60°C (assuming no influence of the captured dust or other dissolved matter—shaky assumptions) are 0.02 poise, 1,000 kg/m^3, and 72 dyne/cm, respectively. Then, applying the Calvert methodology:

Particle size range (μ)	Percent of total wt.	Fractional collection efficiency (%)	Percent penetration
0–0.5	10.0	0.213	9.979
0.5–1	15.0	11.316	13.303
1–2	20.0	78.522	4.296
2–5	30.0	100.000	0.000
5–20	15.0	100.000	0.000
> 20	10.0	100.000	0.000
	Total 100.0		Total 27.577

For the first range, the intermediate quantities are

$$A = 1.30718$$
$$C = 1.69266$$
$$d_d = 3.96 \times 10^{-4} \text{ m}$$
$$\Psi = 0.014296$$
$$F = -1.1704 \times 10^{-7}$$

The overall collection efficiency = 100.000 − 27.577 = 72.423%.

Stack particulate loading $= 0.27577 \times 300 = 83.73 \text{mg/Nm}^3$, and the unit should pass. The factor of safety, however, is inadequate. Consider increasing the pressure drop.

2. Tray/Sieve Scrubbers

Tray scrubbers are, typically, cylindrical structures within which are mounted one or more horizontal platforms (trays). The trays are perforated and include a weir to establish a working water depth and a drain pipe leading to the next-lower tray (a "downcomer"). Scrubbing fluid is pumped to the top tray and pools to a depth set by the weir. Gas passes up through the perforations, providing good contact between the countercurrent liquid and gaseous flows. This is the "sieve tray" tower form of this type of contactor and is in common use for mass transfer (e.g., absorber) operations. When particulate removal is of importance, an impingement baffle is incorporated as a "target" over the perforations.

The tray tower (usually with two to four trays) is often used in conjunction with Venturi scrubbers on sewage sludge incinerators and in other applications where one or more of the following functions are sought:

Collection of carryover droplets from a Venturi
Incremental particulate control (these units are usually inadequate to meet stringent modern particulate standards)
Acid gas control (by addition of caustic soda alkali to the scrubbing fluid)
Cooling of the flue gases (subcooling) as described in the next section

The collection efficiency (η) for hydrophilic particles of aerodynamic diameter d_p microns by water on sieve plates has been correlated (270) by the expression

$$\eta = 1 - \exp(-40 \cdot \rho_{\text{foam}} \Psi_{\text{hole}}) \tag{16}$$

where ρ_{foam} is the density of the foam on the tray (g/cm^3) and Ψ is the inertial parameter evaluated for conditions in the sieve holes. Specifically, V_{hole} is the velocity through the sieve hole (cm/sec), μ_g the gas viscosity (poises), and d_h the hole diameter (cm):

$$\Psi_{\text{hole}} = \frac{V_{\text{hole}} d_p^2}{9 \mu_g d_h} \tag{17}$$

The effect of the impingement target on particulate control is not reliably provided by theory or supported with well-documented empirical relationships.

3. Subcooling and Plume Reduction

In some instances, subcooling of the exhaust gases after a wet scrubber is desired. The reasons for this additional process step include (1) humidity reduction to avoid dense plumes that might obscure an adjacent highway, foster ice buildup on utility wiring or buildings in the winter, or simply call attention to the incinerator operation (visible, dense plumes) or (2) pollutant reduction where lower gas temperatures increase the condensation and deposition of pollutants such as mercury and its compounds, dioxin/furan compounds, etc. In most instances, subcooling is limited to installations near wastewater treatment plants where large quantities of low-cost effluent can be made available. The practice is quite common for wastewater treatment sludge incinerators in the United States. In those instances, the impingement tray scrubber is generally used as the subcooler.

In instances where plume reduction is needed but the water resources are insufficient to use subcooling methods, reheat of the plume may be employed. Clearly, there may be

significant energy costs for plume reheat. However, constraints on the quantity or cost of water and/or permit limitations on the maximum temperature of discharge water may require this approach.

Analysis of a plume suppression process is straightforward. In this discussion, reference will be made to Fig. 1: a psychometric (humidity–temperature) chart. One begins in the furnace after the last boiler (heat withdrawal) pass when the temperature and humidity of the gases are at point "A." On entering the scrubber, the gases are humidified. Assuming that the scrubber water is recirculated, the scrubber water and the leaving gas temperature will approach the wet bulb condition of the flue gases at point "B," moving along the adiabatic saturation curve A–B. One notes that in passing through the scrubber, the temperature drops and the humidity increases.

If the meteorological conditions in the surroundings are those at point "C," the plume gases, as they discharge from the stack and mix with the ambient air, will (approximately) start to move along through the sequence of temperature–humidity states defined by the straight line B–C. As long as the hypothetical mixed-gas state is to the left of the saturation curve, moisture will condense and a visible plume will form. The gas state remains on the saturation curve, and the liquid moisture appears as a fog of small, light-scattering droplets.

In order to resolve this circumstance, two alternatives present themselves. The first approach is to reheat the gases (at approximately constant humidity) from point "B" to point "D" such that the mixing line after plume discharge is just tangent to the saturation

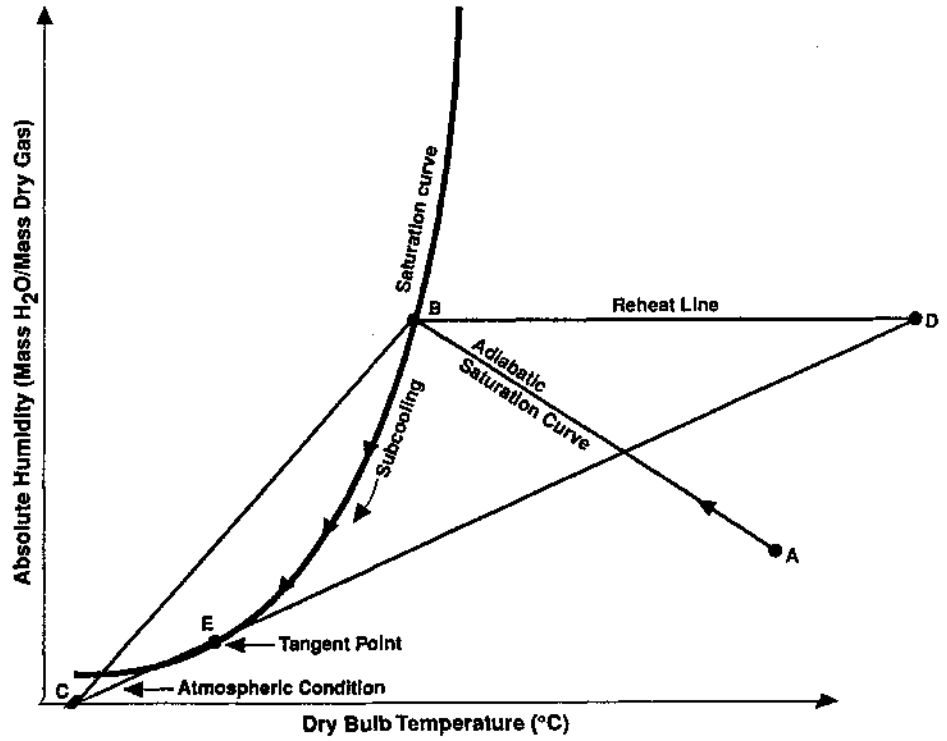


Figure 1 Flue gas psychometric chart for plume reduction.

curve at point "E." The second approach is to use additional gas–water contact with fresh cool water such as to subcool the flue gases: moving the flue gas state down the saturation curve to point "E." The analysis of either scenario involves relatively simple heat and material balances but can be laborious. A utility computer program may be appropriate if the calculations must be made frequently. The following analytical expressions for the dew point temperature, the saturation curve, and the saturation humidity (271) may be useful in the design of such programs.

Dew point temperature (T°_{dp}C) as a function of the partial pressure of water vapor ($p_{\mathrm{H_2O}}$ atm):

Let $\xi = \log_e(14.7p_{\mathrm{H_2O}})$. Then

$$T_{\mathrm{dp}} = 68.45 + 18.441\xi + 1.288\xi^2 + 0.09486\xi^3 + 0.6702(14.7p_{\mathrm{H_2O}})^{0.1984} \quad (18)$$

Saturation water vapor pressure (P_{sat} atm) as a function of liquid water temperature (T°_{sat}K):

Let

$$\varphi = -5800.221T_{\mathrm{sat}}^{-1} - 5.51626 - 0.04864024T_{\mathrm{sat}} + 4.17928766 \times 10^{-5}T_{\mathrm{sat}}^2 - 1.44520926 \times 10^{-8}T_{\mathrm{sat}}^3 + 6.5459673\log_e(T_{\mathrm{sat}})$$

then

$$P_{\mathrm{sat}} = \frac{\exp(\varphi)}{101.325} \quad (19)$$

Saturation humidity (h_{sat} kg H_2O per kg dry air) as a function of the saturation vapor pressure (P_{sat} atm):

$$h_{\mathrm{sat}} = \frac{0.62198P_{\mathrm{sat}}}{1.0 - P_{\mathrm{sat}}} \quad (20)$$

Wet bulb properties relationship for air with an initial humidity h_0 at T_0 (°F), the wet bulb temperature T_{wb} and the associated wet bulb humidity h_{wb} are related by

$$h_0 = \frac{h_{\mathrm{wb}}(1093 - 0.556T_{\mathrm{wb}}) - 0.240(T_0 - T_{\mathrm{wb}})}{1093 + 0.444T_0 - T_{\mathrm{wb}}} \quad (21)$$

The state of an air–water vapor mixture is completely defined by the pressure, temperature, and humidity and, for an air–water vapor mixture, Dalton's rule states

$$p_{\mathrm{air}} + p_{\mathrm{water}} = p_{\mathrm{total}}$$

The relative saturation is defined as the ratio of the partial pressure of water vapor in the gas mixture of interest to that present if the air were saturated:

$$\text{relative saturation} = \frac{p_{\mathrm{water}}}{p_{\text{water at saturation}}} \quad (22)$$

The relative humidity is the relative saturation expressed as a percentage.

4. Mist Elimination

In the course of passing through a scrubber, the flue gases carry off a significant amount of liquid water in the form of small droplets. These droplets incorporate both dissolved and insoluble particulate matter. The capture and return of these droplets to the scrubber liquid system is often critical to the achievement of the "R(emoval)" element of efficiency needed to meet the DRE for hazardous waste incinerators and, also, in meeting the particulate removal goal. This function is accomplished in the mist elimination equipment that follows the scrubber prior to the stack.

The factors contributing to selection of a proper mist elimination system (349) include

The droplet particle size distribution
The acceptable pressure drop
The susceptibility of the separator to plugging by solids (if present)
The liquid handling capability of the separator
Whether the separator can be integrated into existing equipment or must be in a standalone vessel
The available materials of construction as constrained by process features
Cost for the mist eliminator and appurtenances

Droplets formed through mechanical action (bubbling, boiling, shear of liquids from the surface of trays or heat exchanger) are usually coarse, ranging from 6 to 800 μm in diameter. Pressure atomization spray nozzles almost always generate droplets larger than 50–200 μm, while two-phase (air or steam) atomization can generate mists with particles of 10 μm or less. Chemical reactions (e.g., the formation of sulfuric acid mist from the reaction of SO_3 with moisture) can generate droplets most of which are less than 1 μm.

Most mist eliminators use a type of impingement concept to collect the droplets. These include baffles, chevrons, wire meshes, or fiber beds. These devices capture droplets by several mechanisms: inertial impaction, direct interception, and diffusion. A dimensionless group, the Separation Number (N_s), can be calculated for each mechanism. Comparing N_s for the three collection mechanisms gives a relative measure of the importance of each mechanism in effecting mist elimination for a given application. A higher N_s corresponds to a higher collection efficiency.

a. Inertial Impaction. Inertial impaction collects those particles where the momentum is sufficiently high to break through the streamlines and impact the target surface. The Separation Number for inertial impaction is given by

$$N_{si} = \frac{C' \rho_l d_p^2 V}{18 \mu d_b} \tag{23}$$

where

ρ_l = Liquid density
μ = Gas viscosity
d_p, d_b = Characteristic dimension (e.g., diameter) of particle/baffle
V = Gas velocity
C' = Cunningham correction factor [see Eq. (29) below]

b. Direct Interception. Direct interception involves passage of a particle close enough to the baffle target that the distance from the particle centerline to the target is less than one-

half of the particle diameter. Thus, the particle touches the target and can be collected. The Separation Number for direct impaction is given by

$$N_{sd} = \frac{d_p}{d_b} \tag{24}$$

c. Diffusion. Diffusion acts to collect still-smaller particles (typically below 1.0 μm) that exhibit random, Brownian motion. These particles can be driven to impact the target even if the gas velocity is zero. The Separation Number for diffusion is given by

$$N_{sb} = \frac{D_v}{V d_b} \tag{25}$$

where D_v is the particle diffusion coefficient given by

$$D_v = \frac{kTC'}{3\pi\mu d_p}$$

where

k = Boltzmann's constant
T = Absolute temperature
C' = Cunningham correction factor
μ = Gas viscosity
d_p = Particle diameter

d. Demister Alternatives

BAFFLE TYPES. The baffle-type demister (e.g., the vane or chevron-shaped devices; Fig. 2) are common in relatively low-duty applications. The chevron demister systems are formed from sheet metal and they impose a surface in the path of the droplet leaving the scrubber that requires a "zig-zag" motion of the gas. The droplet impacts the surface and drains off.

This class of demister is acceptable where removal goals are limited to droplets larger than 40 μm (special designs can get as low as 15 μm) and where low-pressure drop (typically 10–15 mm H_2O) is important. The spacing between the baffles ranges from 5 to 75 mm, with a total depth in the flow direction of 150 to 300 mm. The design velocity (V) is dictated by

$$V = K\left(\frac{\rho_l - \rho_g}{\rho_l}\right)^{1/2} \tag{26}$$

where K is the empirical Souders–Brown coefficient ranging from 0.09 to 0.3 m/sec and the density of liquid and gas (ρ_l and ρ_g, respectively) are in consistent units. Higher gas velocities can be tolerated if the unit is run with the gas flow horizontal (facilitating drainoff of liquid), where the efficiency of droplet separation (η) is approximated by

$$\eta = 1 - \exp\left(\frac{-V_t m W \theta}{57.3 V_g b \tan\theta}\right) \tag{27}$$

where

V_t = Terminal settling velocity = $g d_p^2[\rho_l - \rho_G]/[18\mu_g]$ (cm/sec)
m = Number of rows of baffles or bends

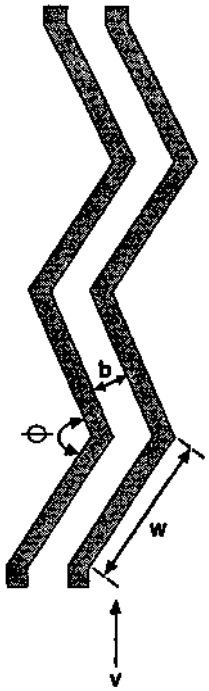


Figure 2 Vane or chevron-shaped mist eliminator (sectional view).

W = Width of a vane's baffle (cm)
θ = Angle between baffles in a vane-type eliminator (degrees)
V_g = Superficial gas velocity (cm/sec)
b = Spacing between baffles in the same row (cm)

The pressure drop through the device is given by

$$\Delta P = \frac{\Sigma 1.02 \times 10^{-3} C_D \rho_g V_a^2 A_p}{2A_t} \tag{28}$$

where

ΔP = Pressure drop (cm water) summed over number of rows of baffles present
C_D = Drag coefficient (a function based on the angle of incidence between the separator and the gas flow)

Angle (degrees)	C_D function of angle α (degrees)
0–8	0.0575(α)
8–15	0.46−0.008714(α–8)
15–47	0.4+0.01531(α–15)
47–70	0.89+0.007955(α–47)

$V_a = V_G/\cos\theta$ (note that the angle of incidence θ for the second and successive rows of baffles is twice the angle of incidence for the first row)
ρ_g = Gas density (g/cm^3)
A_p = Total projected area of a row of baffles in direction of gas flow
A_t = Cross-sectional area of the duct

WIRE-MESH TYPES. The knitted-wire-mesh mist eliminator is by far the most common system used in the chemical process industries. The material is fabricated from wires of from 0.1- to 0.28-mm diameter and the overall pad has a void fraction from 95% to 99%. The pad thickness varies from 10 to 30 cm. Collection efficiency approaches 100% for particles larger than 3 μm. Turndown of wire-mesh pads is about 30%. Below a Souders–Brown vapor load velocity of 0.036 m/sec, collection efficiency may decline significantly.

Pressure drop in mist eliminators is usually less than 25 mm H_2O. When particularly high efficiency is desired, two pads are run in series with the first pad (of fine wires) run above its flooding velocity (where some liquid holdup occurs) and the second (of coarser wires) operates below flooding and acts to collect the large, coalesced droplets blown off the first unit. When buildup of dissolved or suspended solids in the liquid is a problem, the pads can be irrigated with spray wash systems. Spraying should be directed toward the leading edge of the pad. Spraying the trailing edge causes more liquid holdup on the pad and decreases vapor load capacity. A typical washing rate is 120 l/min per m^2 of mesh.

FIBER-BED TYPES. Fiber-bed mist eliminators use very small diameter fibers (< 2.0 μm) to capture very small droplets. The surface area of a fiber-bed unit can be 3 to 150 times that of a wire-mesh unit for equal gas volumes. Units designed around the impaction mode of collection use face velocities of 60–180 m/min. If diffusion capture is the design approach, only 3–12 m/min can be used. The capital cost of these devices is high relative to the baffle or wire-mesh demisters. Also, the pressure drop (100–300 mm H_2O) is high.

OTHER TYPES. Some demisters use vanes, tangential inlets, and/or rotating elements to impart a cyclonic spin to the flow. The inertial forces carry the droplets to the periphery of the chamber, where they coalesce and drain into the liquid sump. In other applications (especially when the solids content of the droplets is high), a Venturi scrubber or wet electrostatic precipitator is used for demisting.

D. Electrostatic Precipitators

1. Dry Electrostatic Precipitator Systems

The electrostatic precipitator (ESP) uses electrical forces to move particulate matter in a flowing gas stream to a collecting surface. The particles are electrically charged by passage through a corona: a region characterized by a luminous blue glow within the ESP containing a high concentration of gaseous ions. Both positive and negative ions or electrons can be generated in a corona, but, for industrial gas cleaning operations, the negative corona is most commonly used. The charging process is most effective with large particles since they sweep a proportionally larger cross-sectional area and accumulate more electrons as they pass through the corona region. The converse can reduce ESP efficiency: inadequate particle charging with high concentrations of submicron particles leading to "space-charge quenching" (high voltages with low currents).

Since the particles form a continuous layer on the collection plates, all of the ion current must flow through the dust layer. This current creates an electrical field in the dust

layer that can become large enough to cause local electrical breakdown, injecting new ions (of the wrong polarity) into the space between the discharge electrodes and the collection plates. This reduces the charge on the particles and may cause sparking. This breakdown condition is called "back corona" and leads to a reduction in collection efficiency.

The electrical field that drives the charged particles is created by applying a high DC voltage (40–75 kilovolts DC) with a negative polarity between the corona-generating electrode and either flat or concentric cylindrical collecting plates. Normally, ESPs operate at the maximum voltage as sensed by the rate of sparkover between the high-tension electrodes. Depending on the gas and dust conditions, the corona current densities range from 0.1 to 1 milliamp/m^2.

An optimum sparking rate of 90 to 100 sparks/minute per section of ESP is common. Conventional automatic control devices for ESPs continuously ramp up the voltage until sparking ensues and then back off and start increasing again. Setting a unit to avoid sparking generally means that the maximum efficiency potential of the ESP is not being achieved. One must also be careful that misalignment of electrodes, condensation (especially with SO_3-containing gases), and/or dust accumulation in and about the high-voltage penetrations of the ESP shell do not adversely impact the sparkover rate.

Many older ESPs are fabricated using the "plate-wire" design where the high-voltage corona-generating electrodes are long wires (plain or barbed), supported at the top from insulators and kept straight and in tension with a weight at the bottom. The wires hang between a bank of flat, parallel, collecting plates. More recent designs use discharge electrodes that are mast-like structures (rigid frames), where electrode strips, often fitted with barbs or other "points," are supported between sections of frame tubing attached to a structural carrier both front and rear and supported by insulators. A third electrode design, the rigid electrode type, has a top-supported electrode hanging the full height of the ESP from a frame attached to insulators. Fewer ESPs are fabricated using the "flat plate" design (patented by United McGill Corporation), where the high-voltage discharge electrodes are plates. In this design, the corona-generating electrodes (needles or hanging wires) are mounted at the leading and, occasionally, also at the trailing edge of the "discharge plate."

The collection surface is the total plate area used for particulate collection: a series of steel plates formed into a curtain and supported from the top. The plates are spaced in rows across the width, typically on 300- to 400-cm centers. Note that when we calculate the surface area for collection, the curtain assembly is treated as a plane and includes both sides of the plates. Since breakdown of the electric field by sparkover significantly degrades collection, the alignment of the collection surface and the discharge electrodes must be maintained within tight tolerances. For that reason, some manufacturers add stiffener bars to the collection plates to maintain straightness.

In either design, the particles build up as a cake on the collection plates and for dry ESPs are removed periodically by rapping the plates with pneumatic, electrical, or mechanical hammers. In normal operation, dust buildup of 6 to 25 mm is allowed before rapping is initiated (542). The rapping mechanisms apply a minimum acceleration of 100 "g's" to the collection surface as measured at the farthest point from the rapper impact. Rappers are also applied to the inlet flow smoothing distribution plates and to the discharge electrodes. The rapping frequency and duration are usually adjustable and vary from a few minutes to several hours depending on the type and quantity of dust and the rapping technique. Sticky and high-resistivity fly ash is more difficult to clean than dry, low-resistivity ash.

Some re-entrainment occurs upon rapping. This is especially so for dusts that strongly hold a charge (high resistivity) where the individual particles tend to repel one

another, thus forming a soft, easily broken up cake. Stack gas opacity monitors in a power plant often show discrete spikes (say, from a baseline of 5% to 10% or 15% depending on the intensity of the rapping) that coincide with the onset of rapping. The percent of collected particulate that is re-entrained has been measured at approximately 12% in plate-wire ESPs and up to 15% in flat plate ESPs operating with high transit velocities (> 1.5 m/sec). The re-entrainment ratio is zero for tubular ESPs. Re-entrainment falls to zero in a wet ESP and is significantly reduced if the fly ash is sticky. Very fine particle size material tends to form a dust cake that does not break up as easily on rapping; this reduces the re-entrainment ratio. The loss in efficiency due to the re-entrainment process encourages a reduced frequency of rapping. A strategy of infrequent rapping is not achievable when high-particulate inlet loading accelerates the buildup of cake or when high-resistivity ash characteristics impair collection (see below).

In a multistage ESP, the rapping frequency and intensity in the second and subsequent stages can be significantly lower than the first stage (which carries the greatest particulate removal burden). These changes in rapping strategy improve collection efficiency by reducing re-entrainment. For this reason, some dust control situations call for insertion of an upstream, low-pressure-drop cyclone to "skim off" a large portion of the mass of particulate. Then, the ESP can focus on cleanup of the remainder. This strategy is very appropriate when ESPs are used for particulate control on kilns practicing thermal desorption on silty clay soils where the carryover of solids can be extreme.

Ash falls from the collection plates into pyramidal hoppers supported from the lower grid. Hopper side angles should be at least 60° from the horizontal to facilitate flow of ash through a dump valve that ensures a continuous gas seal. Hopper heaters and vibrators are suggested to initiate ash flow since hopper dumping is intermittent.

The sequence of particle charging and collection is usually repeated several times within a single precipitator. These collection zones or "fields" are separately energized (often at different voltages). In general, the overall ESP efficiency increases as the number of fields is increased. In municipal incinerators, one finds from two to five field ESPs with, in general, newer units having the larger number of fields.

a. Theory and Design Principles. In theory, a particle moving in an electric field is accelerated in proportion to the magnitude of the charge and the field intensity and slowed by the Stoke's law drag forces. For very small particles (less than about 0.5 micron in diameter), a correction to the drag force relationship is needed (the Cunningham slip correction factor). This is because the basic formulation of Stoke's law presupposes a continuum of gas-particle interaction. However, as the particle becomes small relative to the mean free path of the gas (λ), this is no longer the case. The dimensionless Cunningham factor C' (269), which is the ratio of the actual settling velocity for fine particles to that predicted by Stokes law, adjusts for this change in the character of the gas-particle collisions:

$$C' = 1.0 + \frac{2\theta\lambda}{D_p} \tag{29}$$

where

$$\lambda = \text{Mean free path of the gas molecules (m)}$$
$$= \frac{1}{\sqrt{2\pi n d_m^2}} \tag{30}$$

Table 1 Values of the Cunningham Correction Factor for Air

	Values of C' at temperature of:		
Particle diameter (μm)	21 °C	100 °C	260 °C
0.1	2.88	3.61	5.14
0.25	1.682	1.952	2.528
0.5	1.325	1.446	1.711
1.0	1.16	1.217	1.338
2.5	1.064	1.087	1.133
5.0	1.032	1.043	1.067
10.0	1.016	1.022	1.033

n = Gas molecular density (molecules per m^3)
d_m = Gas molecule diameter (m)
D_p = Particle diameter (m)
$\theta = 1.257 + 0.4\exp(-1.1D_p/2\lambda)$ (dimensionless)

Values of the Cunningham factor for air are presented in Table 1.

The limiting or terminal velocity of the particle in this scenario (usually denoted w) is called the migration or drift velocity and is given by

$$w = \frac{E_c E_0 D_p C'}{4\pi\mu_g} \tag{31}$$

where

E_c = Charging field strength (electrostatic volts/cm)
E_0 = Collecting field strength (electrostatic volts/cm)
D_p = Particle diameter (cm)
C' = Cunningham correction factor
π = Constant (3.14159...)
μ_g = Gas viscosity (g/cm-sec)

Based on work by Anderson (272) and Deutsch (274), an empirical relationship (the "Deutsch–Anderson equation") was derived:

$$\eta = 1 - \exp(-\frac{A_0}{Q}w) \tag{32}$$

where

η = Collection efficiency
A_0 = Collection area (m^2)
Q = Gas volume flow rate (m^3/sec)
w = Migration velocity (m/sec)

Equation (32) does not include corrections for the various types of re-entrainment nor does it consider particle size or particle charging effects. However, the Deutsch–Anderson equation is a useful and effective predictive tool if an "effective migration velocity w_e," an empirical proportionality constant (the "precipitation rate parameter"), is

used rather than the theoretically defined migration velocity. The effective migration velocity is back-calculated from efficiency measurements.

The most important design variable to size an ESP is the specific collection area (SCA). The units of SCA are square meters (of collection surface) per actual cubic meters of gas flow. In English units, SCA is commonly reported in $ft^2/1000$ acfm. Note that the SCA is equal to the parameter group A/Q in the Deutsch–Anderson equation.

The collection efficiency of an ESP is related to the several factors discussed above. These factors result in a significant variation in the collection efficiency with particle size for a given ESP device. In particular, the ESP is less efficient for smaller particles (< 2 microns) than for larger ones. This contrasts with the fabric filter systems that show a high and relatively uniform collection efficiency for small particles. A comparison study (353) of 8 ESPs and 5 baghouse sources showed the baghouse provided an almost constant collection efficiency of about 99.95% capture for particles ranging in diameter from 0.5 to 10 microns. The ESP collection efficiency varied significantly, dropping from 99.8% for a particle diameter of 20 microns to a low of only about 97% at 1 micron.

In practice, it is often observed that the effective migration velocity changes as the efficiency of collection changes. An empirical modification of the Deutsch–Anderson equation for use in ESP sizing above 95% efficiency was developed by Matts and Ohnfelt (536). They used an equivalent and constant reference migration velocity (w_{eMO}) determined from data taken in the 90%–95% efficiency range rather than the w_e from Deutsch–Anderson, which shows variation. Their relationship is

$$\eta = 1 - \exp\left[-\left(\frac{A}{Q}\right)w_{eMO}\right]^k \tag{33}$$

or

$$SCA = \frac{A}{Q} = \frac{[-\ln(1-\eta)]^{\frac{1}{k}}}{w_{eMO}} \tag{34}$$

where k is a constant, usually between 0.4 and 1.0. Based on statistical analysis of data presented by Davis (537), it was shown (440) that $k = 0.6$ gives the best predictions for fly ash and $k = 1.0$ for other industrial dust control applications. Below 95%, the Deutsch–Anderson relationship describes the data best, and in between 95% and 99%, an average of the results with the two equations should be used. Above 99%, Matts–Ohnfelt is preferred.

For incinerator fly ash, values of w_e, showing their apparent variation with efficiency, have been found as given in Table 2. The indicated changes in w_e as performance targets are raised suggest the need for additional ESP plate area to achieve the higher collection efficiencies than would be estimated assuming the w_e is based on the 95% efficiency data.

The flow field entering an ESP must be slowed and smoothed in order to evenly distribute the gas over the face of the bank of collecting plates. The force tending to divert the charged particles to the collection plates is relatively weak and eddies or other flow disturbances will both inhibit collection and can act to re-entrain material that is already collected. Most commonly, turning vanes are used (if appropriate) to minimize the effect of upstream duct turns, and one or more perforated diffuser plates are mounted at the entrance to the ESP. The diffuser plates use round holes 5 to 7 cm in diameter with an open area of between 50% and 65% of the total.

Flow uniformity can be assessed quantitatively by measuring the velocity profile of the flow field across the face of the ESP. Indications of poor distribution can sometimes be

Table 2 Precipitation Rate Parameters (cm/sec) for Municipal Refuse Incineration

	90%	95%	99%	99.5%	99.9%
Plate-wire ESP systems					
Operation at 120 °C, no back corona	—	15.3	11.4	10.6	9.4
With back corona	—	6.2	4.2	3.7	2.9
Flat plate (United McGill type)					
Operation at 120 °C, no back corona	—	25.2	16.9	21.1	18.3
Tubular					
15 micron mass median diameter, no back corona, 1.5% sneakage, single section, no re-entrainment on rapping	40.8	39	—	—	—

Source: From (537).

obtained by observations of patterns of buildup in ducts and on the collecting and/or flow distribution plates. Good gas flow variation should approximate a Gaussian (normal) distribution with a standard deviation of approximately 1.25. The "flatter" the flow profile, the better. The Industrial Gas Cleaning Institute recommends that 85% of the local velocities be within ±25% of the mean and that no single velocity vary more than ±40%. The consequences of poor distribution can be profound. Excessive re-entrainment can often be detected by an abnormal size distribution in the exit dust (a favoring of the larger particles that are preferentially re-entrained).

b. Operational Features. The pressure drop through the ESP is usually not high and indeed is often lower than the associated collection system and ductwork. Typical ranges of pressure drop across the several ESP components are presented in Table 3. The largest pressure drop is associated with the enlargement loss at the inlet transition. Gas velocity through the ESP varies between designs, but the maximum acceptable is about 1.5 m/sec for plate-wire ESPs and 1 m/second for flat-plate ESPs and when resistivity is low and re-entrainment minimization is critical.

Efficiency reduction also results from the bypassing of the collection zone. This includes gas flow through the hoppers and over the top of the collection plates. This

Table 3 Typical ESP Pressure Drop

	Typical pressure drop (Pascals)	
Component	Low range	High range
Diffuser	2.5	22.4
Inlet transition	17.4	34.8
Outlet transition	1.7	3.7
Baffles	0.15	30.6
Collection plates	0.07	2.0
Total	22.4	94.6

Source: From (537).

"sneakage" (the fraction of the gas flow that bypasses the collection zone) is minimized through the use of baffles. Measured sneakage in plate-wire ESPs approximates about 7% and 10% in flat-plate ESPs.

The electrical resistance characteristics of the collected dust layer (the resistivity, usually expressed in units of ohm-cm) is an important system property. Dust resistivity values can be classified into three groups:

Low resistivity	10^4 to 10^7 ohm-cm
Normal resistivity	10^7 to 10^{10} ohm-cm
High resistivity	above 10^{10} ohm-cm

Ideally, the resistivity is in the range 10^6 to 10^{10} ohm-cm. The resistivity of the cake varies widely among different dusts. A set of data for municipal incinerator plants (371), for example, showed peak resistivities of 2×10^8 to 1.2×10^{11} ohm-cm at 12% H_2O. The peaks occurred at from 123° to 154°C.

Carbon, alkali metal salts, and adsorbed sulfur trioxide or moisture reduce resistivity. Inorganic clays and minerals such as alumina increase it. Resistivity is also a (concave downward) function of temperature and decreases as the moisture content of the flue gases increases. Resistivity prediction models based on dust chemistry have been developed by Bickelhaupt (262, 263). The material used (total dust or collected dust), the location of measurement (laboratory or in-situ), and the testing method affect the values determined for resistivity.

A dust resistivity that is too high or too low can produce undesirable results:

Low-resistivity cake ($< 10^{+8}$ ohm-cm) will bleed off the charge on the particles such that the attractive forces weaken and re-entrainment can begin to occur.

High-resistivity cake ($> 2 \times 10^{+11}$ ohm-cm) will firmly hold its charge such that, as the cake builds, the voltage drop across the dust layer increases, thus impairing collection efficiency. In severe cases, the electric field in the layer is large enough to cause local electrical breakdown (back corona), thus reducing efficiency.

Several factors affect the collection efficiency of an ESP system. These include

Collection plate area per unit gas flow rate (specific collection area—SCA)
Gas velocity through the collector
Size distribution and electrical properties (resistivity) of the particles
Number, width, and length of gas passages
Electrical field strength and degree of high-tension sectionalization
Particle in-field residence time
Gas temperatures and humidity (effects on resistivity)
Re-entrainment or disturbance of the flow field in the ESP due to flow eddies arising from air inflow past the dust valves on the hoppers, sinking flow along cold surfaces where the enclosure insulation has been removed, or air in-leakage around poorly sealed man ways and other access doors

It is possible to attain the desired control efficiency by altering the design specifications for each of the above parameters. Further, several positive characteristics of an ESP are important when considering their use in controlling incinerator emissions. These include

High overall collection efficiency and reliability
Relatively low power requirements

Ability to accommodate flue gas temperatures in the range of 120 to 320°C with the lower limit dictated by the gas dew point
Minimal change in collection efficiency over a wide range of particle size
Minimal fire hazard potential

In applications with municipal solid waste, the potential design and operating problems include

Variations in flue gas temperature and fly-ash resistivity
Condensation of corrosive flue gas constituents
Variation in incinerator processing and emission rate
Deviations between design and actual gas flow rates
Low collection area or excessive velocity (low specific collection area—SCA)

The major adverse effect of these problems is to lower the collection efficiency. The relationship between efficiency and the specific collection area (SCA in ft/sec) is shown in Fig. 3 (204) based on design and performance data from over 10 municipal refuse incinerator plants. Corrosion problems can be alleviated through construction to avoid air leakage into the ESP and insulation and external heating of the unit to avoid cold spots where condensation can occur. Corrosion is normally not a problem as long as the flue gas temperature remains above 130°C. Also, at high flue gas temperatures, fly-ash resistivity is more predictable and particulate collection efficiency is enhanced.

2. Wet Electrostatic Precipitator Systems

In wet electrostatic precipitators (WESP), the dust is removed by continuous or periodic irrigation of the collection plates by water sprays or a water film. Both flat-plate and tubular designs are found in practice. Since the dust is wetted, re-entrainment is not a problem. Often, water sprays are used upstream of the WESP to bring the gases to the saturation point. Unevaporated water from preconditioning can either be treated separately

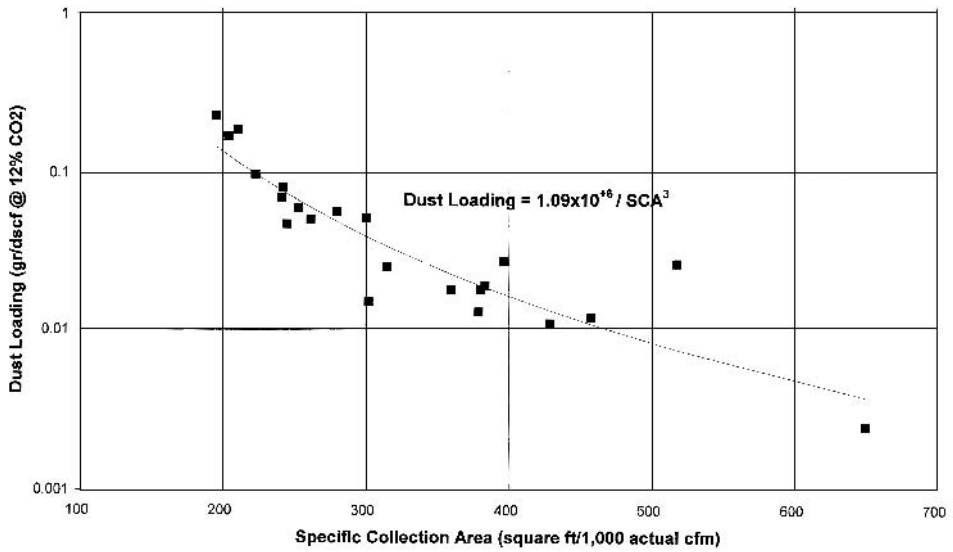


Figure 3 ESP control efficiency (outlet dust loading) correlation for Waterwall mass burn facilities.

from the primary WESP wastewater treatment system or be passed forward for use as the plate irrigation water in the WESP itself.

WESP applications may or may not have a requirement for significant wastewater treatment handling depending on the quantity of water used to irrigate the collection plates and transport the collected dust. Some systems use very little water and produce a sludge-like residue. Others use a clarifier and solids concentrator (often a vacuum filter), sometimes with pH adjustment and with flocculation aids.

WESPs used in sewage sludge service operate at much lower discharge electrode voltages (1000 to 6000 volts dc) and are usually located after a conventional Venturi-impingement tray scrubbers system. The primary target for the WESP is the submicron particulate matter with particular focus on heavy metals and soot.

E. Fabric Filter (Baghouse)

Filtration is a very effective means to remove fine particulate from a gas stream. Removal efficiency remains high in comparison to most other control technologies for submicron particulate. This is the particulate fraction of special significance in the emissions of respirable particulate ($PM_{2.5}$ and PM_{10}) and of many carcinogenic and toxic organic aerosols and heavy metals. It is not surprising, therefore, that the use of filtration-based devices in incineration applications has grown significantly as regulations have become more and more stringent.

Filtration devices are of two types: cloth or fabric filters and in-depth or bed filters. Fabric filters are generally found as an array of long, cylindrical bags mounted in a structure (a "baghouse"). Bed filters can be of several types but in incineration applications are most often a deep, packed bed (a "gravel bed" filter).

The key characteristics of fabrics for use in gas filtration include

Temperature—a maximum continuous service temperature higher than the normal working temperature. Peaks in temperature and their duration must be considered if the temperatures do not reliably hold at or below the norm.

Corrosiveness—Some gas constituents are aggressive and will attack the fabric. The inherent resistance to such attack is specific: gas to fiber.

Hydrolysis—Flue gas humidity can affect the strength and dimensional stability of the fabrics.

Cost—obvious in importance but evaluated in the light of air-to-cloth ratio (affecting the number of bags), unit cost per bag, loss during installation (important with some bags that are sensitive to mishandling), and expected service life (replacement cost).

Several basic fiber properties are summarized in Table 4.

The three most important criteria of performance for filtration devices are collection efficiency, pressure drop, and useful life. The collection efficiency is inherently high and includes contributions from the fabric itself but, more importantly, from filtration by the cake of collected dust. Thus, pressure drop and efficiency vary throughout the cleaning cycle. The low point in both pressure drop and efficiency occurs immediately after cleaning of the bag. The high points are just prior to cleaning when the thickness of the accumulated dust cake is at a maximum. The cost for fan power (directly related to pressure drop) is the principal operating cost element for a fabric filter. The useful life is important as it affects bag replacement cost. There are tradeoffs possible between the first

Table 4 Fabric Filter Characteristics

Fabric	Maximum working temp. (°C)	Resistance to: Abrasion	Flex	Mineral acid	Organic acid	Alkali	Fluoride	Solvent
Acrylic	80	G	—	G	G	F	—	G
Cotton	85	G	VG	P	G	G	P	E
Fiberglass	260	P, G	F	VG	E	P, F	P	E
Modacrylic (Dynel)	80	F	—	VG	VG	G	—	G
Nomex (nylon)	205	E	E	F	F	VG	G	E
Nylon (polyamide)	105	E	—	P	F	VG	—	E
Polyester	135	E	—	G	G	G	—	E
Polypropylene	95	E	—	E	E	E	P	G
Teflon	260	F, G	F	E	E	E	P, F	E
Wool	100	F, G	VG	F	F	P, F	—	G

cost of the bags and bag life, which, unfortunately, are difficult to assess a priori and are often specific to a particular application and its unique dust and gas characteristics.

The pressure drop and collection efficiency of a fabric filter are difficult to estimate from first principles. Since the collection medium is predominately the cake itself, theoretical relationships involving the collision and capture of particles on a matrix of bag fibers are interesting but substantially impotent. Theory can, however, indicate the expected dependency of the several variables as a guide to data analysis and correlation. Extensive discussions of filtration theory can be found in several references (274, 275, and especially 276). For the purposes of this volume, the theory is summarized with a focus on sharing a basic understanding of the form and general behavior of key parameters.

The pressure drop across a filter fabric and its cake may be estimated (277) by

$$\begin{aligned} \Delta P &= \Delta P_0 + \Delta P_p \\ &= \frac{(\zeta_0 + \bar{\alpha} m) V_f \mu_g}{g_c} \end{aligned} \tag{35}$$

where

ΔP = Total pressure drop (cm H_2O)
ΔP_0 = Pressure drop across the fabric (cm H_2O)
ΔP_p = Pressure drop across the cake (cm H_2O)
ζ_0 = Pressure loss coefficient for clean cloth (a function of fabric and the weave) (m^{-1})
$\bar{\alpha}$ = Average specific resistance of cake (a function of particle size distribution, void volume, particle density) (m/kg)
m = Dust cake mass (kg/m^2)
V_f = Filtering (superficial) gas velocity (cm/sec)
μ_g = Gas viscosity (kg/m-sec)
g_c = Constant 9.8 (m-kg/sec^2-kg)

Typical values for the parameters in the units noted would be 7×10^7 for ζ_0 and 3×10^{10} for $\bar{\alpha}$ (when V_f is in the range 1 to 10 cm/sec). Note that the numerical value for V_f that corresponds to a ΔP_0 of 1.27 cm H_2O is reported as the "permeability" of the fabric. The rate of increase of pressure drop with cake accumulation of a log normally distributed, polydisperse dust is predicted by the Kozeny–Carman relationship (277):

$$\frac{d(\Delta P)_p}{dm} = \frac{180 \mu_g V_f (1 - \varepsilon_p)}{g_c \rho_p D_{PS}^2 C' \varepsilon_p^3} \tag{36}$$

where

ε_p = Dust cake porosity (void volume of cake divided by the total cake volume) (dimensionless)
C' = Cunningham correction factor [see Electrostatic Precipitators, Eq. (29)]
ρ_p = Particle density (kg/m^3)
D_{PS} = Specific surface or Sauter diameter (m) related to the mass median diameter (D_{MMD}) and the geometric standard deviation of the particle size distribution σ_g by the relationship (278)

$$D_{PS} = \frac{D_{MMD}}{10^{1.1513} \log_e^2[\sigma_g]} \tag{37}$$

Unfortunately, this elegant development predicts the pressure drop conservatively high (by a factor of 2 or more).

The face velocity V_f is often called the "air-to-cloth ratio" and abbreviated in text as A/C. A/C is defined as the volumetric gas flow rate divided by the total filtration area. Therefore, this important parameter has the net dimensions of a velocity (length/time) and, thus, varies between English and metric units by the factor

$$A/C_{\text{metric}}\ (\text{m/min}) = AC_{\text{English}}\ (\text{ft/min}) \times 0.3048 \tag{38}$$

The installed cloth area depends on the A/C ratio based on the collection area in active use at any point in time. Because of maintenance, cleaning, or other outages, the area installed must be larger than the minimum area calculated from the gas flow rate and the target A/C ratio. The factor multiplying the collection area to derive the installed area is given in Table 5.

Particle collection by a fabric filter arises as a combination of five classical mechanisms involving interactions between a particle moving in a gas stream and a filter fiber:

1. Gravity—where the larger particles settle out of the gas stream (negligible for most finely divided particulate)
2. Direct interception—where the particle, following a streamline and in streamline flow, directly collides with the fiber.
3. Inertial impaction—where the particle track diverges from the streamlines due to inertial forces and impacts the fiber (primarily for particles >5 μm)
4. Diffusion—where the smaller particles, say, within a factor of 10 to 100 times the diameter of gas molecules, are driven by random molecular collisions (Brownian motion) to collide with the fiber (dominant for submicron particles)

Table 5 Factors Relating Gross and Net Fabric Filter Collection Area

Net cloth area (m^2)		
From	To	Factor = gross/net area
1	370	2.00
371	1,115	1.50
1,116	2,230	1.25
2,231	3,344	1.17
3,345	4,459	1.125
4,460	5,574	1.11
5,575	6,689	1.10
6,690	7,804	1.09
7,805	8,919	1.08
8,920	10,033	1.07
10,034	12,263	1.06
12,264	16.722	1.05

Source: From (539).

5. Electrostatic attraction—where the particle and/or the fiber are electrically charged such that electrostatic forces increase the tendency for the particle to migrate to and impact the fiber

Each of these mechanisms can be formulated in a capture efficiency relationship and combined to yield an overall efficiency. Lee and Liu (280) formulated such a combined expression:

$$\eta = \left(\frac{1-\alpha}{K}\right)\frac{R^2}{1+R} + 2.6\left(\frac{1-\alpha}{K}\right)^{1/3} N_{Pe}^{-2/3} \tag{39}$$

where

α = Filter solidarity (the fraction of total filter volume actually occupied by fibers). α is typically 0.1 or less for fibrous filters but 0.2 to 0.3 for fabric filters.
K = Constant about equal to 3.0, but some researchers (281) report other values.
R = Ratio of particle diameter d_p to filter fiber diameter d_f.
V_f = Face velocity.
k = Boltzmann's constant.
T = Absolute temperature.
C' = Cunningham correction factor.
μ_g = Gas viscosity.
N_{Pe} = Peclet number (dimensionless) given by

$$N_{Pe} = \frac{3\pi\mu_g d_p d_f V_f}{kTC'} \tag{40}$$

This equation adequately predicts the functional dependencies of collection efficiency on particle diameter and face velocity for fibrous mat filters. Note, however, that empirical adjustment of the constants is required for quantitative "prediction."

The predictive capability fails, however, for fabric filters. For example, the relationship predicts that collection efficiency should increase as the face velocity and/or the particle diameter increases. However, Leith and First (282) show this is not to be for reverse-air or pulse-jet fabric filters. For these types, efficiency decreases as face velocity increases, and there is practically no dependence of efficiency on particle diameter.

These clear inadequacies led Leith and First and other researchers to incorporate into the theory two "failure mechanisms" of fabric filters: *particle penetration* through "pinholes" or other noncollecting gas passageways and *seepage*, wherein collected particulate matter migrates through the cake and fabric and ultimately is released. Pinhole penetration appears to be the dominant mechanism for penetration for reverse-air/shake-deflate fabric filtration. Seepage appears dominant for pulse-jet fabric filtration.

The inability of theory to predict pressure drop or efficiency performance indicates the difficulty inherent in analyzing the behavior of filtration systems from first principles alone. Nonetheless, theoretical analysis was seen to be useful in suggesting approaches to correlate data and, when necessary, to extrapolate or interpolate to new operating points when limited data are available. Clearly, the latter use involves risk. However, such risks may be reasonable when the alternative is baseless linear extrapolation or the like.

1. Baghouse Classifications

As the dust cake builds and the pressure drop across the fabric filter increases, at some point, the bags must be cleaned. In most equipment, a timer is used to control the cleaning cycle although a pressure-drop monitor can also be used. Normally, the pressure-drop limits are set between 1.2 and 5 kPa. The methodology used to clean the bags differentiates the three basic classes of fabric filter: (1) mechanical shaking, which flexes the fabric to break up and dislodge the dust cake; (2) reversal of the air flow; and (3) pulse-jet cleaning, which both flexes the fabric and reverses the flow to remove the dust. Selection of the cleaning method is based on the type of fabric used, the pollutant collected, and industry experience. The cleaning methods are compared in Table 6.

a. Mechanical Shaking. Shaker-type baghouses are the oldest form of fabric filter. In this class, the bags are cleaned by the simple expedient of shaking the bag (generally, in the horizontal plane and from the top) via linkage to a mechanical (a motor driving an eccentric), electrical, or pneumatically actuated shaking mechanism. The flow of dirty gas enters the bags from an air plenum at the bottom of the baghouse and the cake builds on the inside of the bag. In operation, the baghouse is normally divided into compartments such that at least one compartment can be dampered out of service while the bags are cleaned. After a short delay following isolation of the compartment, shaking is initiated. The motion is simple harmonic or sinusoidal and is vigorous with an amplitude of from a few millimeters to 3 to 12 cm and a frequency of several cycles per second. The duration of shaking is between 10 and 100 cycles (30 seconds to a few minutes). Typically, these devices are designed for A/C ratios of 0.6 to 1.8 $m^3/min/m^2$ (548).

Mechanical shaking is reliable and often has the lowest capital cost of the three alternatives, although a penalty is associated with the overcapacity to allow for the retirement of one compartment during cleaning. Also, the violent action of shaking, in general, produces more fabric wear and shorter bag life than the other cleaning strategies. Typically, the units are designed with heavier and more durable woven cloth bags operating

Table 6 Comparison of Bag Cleaning Methods

	Cleaning Method			
Parameter	Shaker	Reverse flow	Pulse jet (individual bags)	Pulse jet (compartmented bags)
Cleaning	Off-line	Off-line	On-line	Off-line
Cleaning time	High	High	Low	Low
Cleaning uniformity	Average	Good	Average	Good
Bag attrition	Average	Low	Average	Low
Equipment ruggedness	Average	Good	Good	Good
Fabric type[a]	Woven	Woven	Felt/woven[a]	Felt/woven[a]
Filter velocity	Average	Average	High	High
Power cost	Low	Low to medium	High to medium	Medium
Dust loading	Average	Average	Very high	High
Max. temperature[b]	High	High	Medium	Medium
Collection efficiency	Good	Good	Good[c]	Good[c]

[a] With suitable backing, woven fabrics can perform similar to felted.
[b] Fabric limited.
[c] For a properly operated system with moderate to low pressures, the collection efficiency may rival other methods.
Source: From (538–540).

at a low face velocity (from 0.6 to 1.2 m/min) to yield the longest bag life. Bags are usually 15 to 45 cm in diameter and up to 12 m in length.

b. Reverse Air-Flow. In reverse-air cleaned systems, the flow of dirty gas enters the bags from an air plenum at the bottom of the baghouse and the cake builds on the inside of the bag. When the pressure drop reaches the set point, flow through the compartment to be cleaned is stopped. Then, a gentle, reverse flow of filtered, warm gas is initiated, back-flushing and collapsing the bags (concave inward) within one compartment at a time. The reverse-air flow itself, about at the same volumetric rate as the dirty gas, operates for about 10 to 30 seconds. The total cleaning cycle, including valve opening and closing and dust settling, extends over 1 to 2 minutes. The gas used is usually taken from the outlet of the fan, downstream of the baghouse. Cold outside air generally cannot be used because of potential problems with condensation. Typically, these devices are designed for A/C ratios of 0.3 to 0.9 $m^3/min/m^2$ (548).

Note that this reverse flow adds to the net total volumetric flow rate through the baghouse, thus increasing capital cost (more bags at a given A/C ratio). Usually, a "cage" fabricated of metal wire is mounted inside the bag to provide internal support to avoid collapse and/or to support the bag during cleaning and operation. Woven filter media are generally used at a low face velocity (from 0.6 to 1.2 m/min).

The gentle cleaning process extends bag life. This is particularly important for fiberglass bags where the relatively vigorous manipulation of the fabric with a mechanical shaker significantly increases the rate of fiber breakage and, eventually, bag failure.

C. Pulse-Jet Cleaning. In pulse-jet cleaning, a solenoid valve is electronically opened and a short, high-pressure burst of compressed air is discharged into the open end of a row of the cylindrical bags. Air at about 700 kPa is commonly used although newer designs

allow use of air at from 70 to 350 kPa. The burst of air has a duration of about 0.1 sec. Often, a Venturi nozzle is used to inspire additional air from the exhaust plenum. The large total volume of air rushes down the bag as a shock wave that is reflected from the closed bottom. The pulsing flexion in the bag dislodges the dust cake from the outside of the bags in a very short period of time: generally less than one half-second. Thus, no significant filtration capacity must be provided to provide reserve capacity for the cleaning cycle. There is no need to shut down a compartment. As with the reverse air, an internal metal cage is often used to support the bag, which is normally closed at the bottom and open at the top. Typically, these devices are designed for A/C ratios of 1.5 to 4.6 $m^3/min/m^2$ (548).

The capacity of the pulse-jet systems is inherently high both because of the efficiency in cleaning but also because high face velocities (typically from 1.5 to 3 m/min) are used. Both felted and bulk-knitted filtration fabric can be used. Bags are usually 10 to 15 cm in diameter and from 2.5 to 3 m in length.

2. Bag Life

Bag life is not easy to predict from theory or laboratory measurements. The common laboratory tests for fabrics (e.g., the MIT flex test, elongation to break, tear strength, and the Mullen burst test) fail to correlate with field data. An increase in the percentage of bag failures per year with the A/C ratio (276) is qualitatively correct in that the shortest bag life corresponds to the highest A/C ratio. However, the data range from 0.1% to about 10% per year (a 100-fold variation) at an A/C of 4.

Overall bag life in service is highly variable, depending on the type of bag, cleaning method and frequency, pollutant characteristics, and other factors. A two-year life is a typical average.

3. Operational Characteristics

A fabric filter yields an almost constant collection efficiency over a range of inlet loadings. Therefore, the performance of a baghouse differs from an ESP or wet scrubber, where the collection efficiency is a design feature that varies as the design or operating conditions vary. After the cake character has developed (after several loading and cleaning cycles), collection efficiencies above 99% should be expected. There will be some improvement in efficiency for new bags (where pinholes have not developed), at low A/C ratio, and where cleaning frequency is minimized (since the cake itself is the primary dust collection medium).

The pressure drop across the baghouse is an important guide to the operating condition and an indicator of problems. High pressures arise from excessive gas volumes, mudding or other blinding of the filtering fabric, hopper overload that blocks the bags or an inoperative cleaning mechanism. Low pressures indicate fan or motor problems, broken or unclamped bags, plugged inlet ducting or a closed damper, and/or leakage between sections of the baghouse.

A broken or unclamped bag leads to an immediate jump in the opacity of the cleaned gas. Therefore, an opacity meter is a valuable device to signal the onset of this catastrophic failure mode. Less severe, however, is the progressive breakdown of the bags as a consequence of repeated flexing and other mechanical or chemical abuse. This leads to the gradual development of pinholes that slowly increase the outlet loading of particulate as the operating life of the bag is extended.

Power costs for mechanical shaking approximate 6.5×10^{-5} kW per hour of operation per m^2 of cloth area. For a pulse-jet system, compressed air use is about 120 sm^3 per hour of operation per 1000 sm^3/min of gas cleaned (541).

4. Baghouse Applications for Incineration Systems

Increasing regulatory concern regarding emissions of heavy metals (often as a fume or condensed onto very fine particulate), respirable particulate (PM_{10}), and, generally, a rachetting down of permitted total particulate loading has greatly increased the use of fabric filters for incineration systems. This is particularly true for the municipal incineration in combination with spray dryer absorbers. In incinerator applications, as in the dominant fraction of industrial-source fabric filter applications, the pulse-jet concept is preferred. Generally, the baghouses are outside collection type (dirty gas flows from outside the bag) with short, small-diameter bags (12–15 cm) that are less than 7 m long and fabricated of felted fabrics. These units are usually operated at 1.2 to 1.8 m/min A/C ratio in general industrial service, but municipal incinerator units are designed at A/C ratios as low as 0.6 m/min.

This contrasts to the coal-burning utility industry, which very strongly favors the reverse-air/shake-deflate type of low-flow baghouse with low cleaning energy. These units use large bags (say, 25 cm in diameter), 10 to 12 m long. The bags are operated as inside collectors (dirty flue gases passing inside the bag) and at an A/C ratio between 0.6 to 0.9 or less. Woven fiberglass with a Teflon B finish is preferred in U.S. practice.

Because of the potential for plugging, the temperature of the dirty gas must be a minimum of 25° to 50°C above the stream dew point. If the dew point is crossed, moisture can condense and cause corrosion, "mudding up" (high-pressure drop as wet, pasty cake closes off air flow through the filtration media), bag rupture, and the need to shut down the baghouse and have the bags removed and cleaned. This problem can be even more problematic if acidic gases are present and vulnerable bag materials (organic fabrics) are present. The lower the dew point, the greater the precaution that must be taken to prevent condensation. In a suction-type fabric filter, where the baghouse operates below atmospheric pressure, ambient air infiltration can occur, lowering the temperature below the design level. Therefore, for this type of baghouse and with moist air being processed, the structure walls and hoppers should be insulated and great attention must be paid to ensuring an airtight closure.

F. Absorbers

Absorption is a process for the removal of one or more components from a gas mixture. Absorption is often thought of as involving contact of a gas with a liquid (as in a wet scrubber). However, the principles are applicable in completely dry systems (e.g., the absorption of acid gases by injected lime dust) or "semi-dry" systems (e.g., the absorption of acid gases on lime slurry, where the slurry is injected in quantities and with particle sizes such that complete evaporation of the slurry water occurs).

The particulate abatement technologies described previously use a variety of physical principles to effect capture of individual particles. In absorbers, the mechanism by which pollutants are captured involves a mass transfer flux driven by molecular and eddy diffusion from a region of high concentration to one of low concentration. Capture can involve a reversible (equilibrium) association of pollutant (usually present with a large quantity of diluting carrier gas that does not absorb) with an absorbing material. This

equilibrium can be described by a plot of the mol fraction of the pollutant in the liquid (x_A) against the partial pressure of pollutant in the vapor in equilibrium with the liquid (p_A). If Henry's law applies,

$$p_A = Hx_A \tag{41}$$

where H is the Henry's law constant and is related to the bonding between the solute and the solvent molecules. Generally, H increases with increasing temperature and with the difference between the pollutant and solvent molecules (ionic/nonionic, polar/nonpolar, etc.).

The Henry's law type of pollutant–solvent interaction is typical of gas solubilities in water as, for example, the solution of SO_2 in a water scrubber. In this instance, the chemical reactions (formation of sulfurous acid) are reversible and rapid compared to the rate of diffusion through the liquid. If, however, caustic soda is added to the scrubbing liquid, the reactions are substantially instantaneous and irreversible. Here, if the SO_2 concentrations are high or if the caustic is dilute, the absorption rate may become limited by the rate of diffusion of caustic to the gas–liquid interface.

Contact between the liquid and gas in wet scrubber absorbers can be of three basic types:

1. Countercurrent—where the strongest absorbing liquid is in contact with the weakest pollutant concentrations in the gas, and vice versa. This is a common configuration with weak absorbents and is embodied by a vertical column with liquid feed at the top and gas introduced at the bottom. Note that if trays are inserted into the column, the behavior across any tray is crossflow, but tray-to-tray is countercurrent.
2. Concurrent—where the strongest absorbing liquid is in contact with the strongest pollutant concentrations in the gas, and vice versa. This principle is embodied in the Venturi scrubber and in the dry and semi-dry scrubbers used for acid gas control in municipal incinerators. The concurrent approach is acceptable when the absorption reaction is substantially complete (i.e., acid gases absorbed in strong alkaline reagents).
3. Crossflow—where one stream flows perpendicular to the other stream. This principle is used in spray chambers where the gas travels horizontally while spray drops fall vertically, the tray scrubbers noted above and in some packed tower systems.

1. Wet Packed Towers for Removal of Pollutant Gases

One of the more common absorber devices for the removal of acidic gases is the packed tower. Here, a vertical, cylindrical column is erected. A given depth (Z) of the column is filled with a packing material that is chemically inert and designed to give a minimum of pressure drop and a maximum of gas–liquid contact area. In accord with good practice, the size of the packing is not more than 1/20th of the column diameter. The column is operated at between 50% and 75% of the flooding rate. Flooding rate is defined as the gas volumetric flow rate that, for the tower diameter and packing, would inhibit the flow of liquid down through the tower to the degree that flow would, substantially, be blocked. Several correlations are available to estimate the flooding rate (283).

The column height is then given by

$$Z = N_{OG} H_{OG} \tag{42}$$

where

Z = Packing height (m)
N_{OG} = Number of overall transfer units
H_{OG} = Height of an overall transfer unit (m)

The number of transfer units can be obtained experimentally or calculated as shown below. The height of a transfer unit is also obtained experimentally (usually reported as a function of gas rate with liquid rate as a parameter for a specific packing and solvent–solute pair), but typical values for H_{OG} for a variety of plastic packing are as follows:

Chemical system	H_{OG} (m)
$HCl–H_2O$	0.18–0.33
HCl–NaOH	0.15–0.21
Cl_2–NaOH	0.24–0.36
$NH_3–H_2SO_4$	0.09–0.15
$NH_3–H_2O$	0.09–0.21
SO_2–NaOH	0.21–0.60
$HF–H_2O$	0.12–0.21

For many incineration instances, the pollutant is dilute. If Henry's law applies, the number of transfer units is given by

$$N_{OG} = \frac{\log_e \left[\dfrac{(p_{A1} - Hx_2)}{(p_{A2} - Hx_2)} \left(1 - \frac{1}{A}\right) + \frac{1}{A} \right]}{1 - \frac{1}{A}} \tag{43}$$

where

p_{A1} = Partial pressure of pollutant in the inlet gas (atm)
p_{A2} = Partial pressure of pollutant in the outlet gas (atm)
H = Henry's law constant (atm/mol fraction)
x_2 = Concentration (mol fraction) of pollutant in inlet liquid
L = Liquid rate ($kg\,sec^{-1}\,m^{-2}$)
G = Gas rate ($kg\,sec^{-1}\,m^{-2}$)
$A = L/HG$

The evaluation of other absorbers and solvent–solute pairs, estimation of mass transfer coefficients, equilibrium points, operating lines and the like are beyond the scope of this book. The interested reader is directed to several texts from the chemical engineering and air pollution control literature (269, 274, 275).

2. Dry Absorbent Contactors for Acid Gas Pollutant Control

The highest removal efficiency for gaseous pollutants is often achieved using a wet scrubber with appropriate chemical addition such that the equilibrium partial pressure of the target pollutant is very low. An example would be HCl scrubbed with a caustic soda solution. However, although the wet contactors are efficient, they produce a waste-water requiring treatment and disposal, they present not insolvable but problematic

corrosion problems, they generate a visible plume (unless special and costly countermeasures are taken), and they often present numerous operation and maintenance problems with plugging, solids buildup, and the like. The dry absorbent systems avoid many of these problems and, although they present their own deficiencies, they find use in some incineration applications. This is particularly the case for acid gas abatement.

Dry sorbent injection involves the injection of solid, alkaline material into the flue gases of an incinerator to effect gas–solid reactions in the (short) time available prior to discharge to the stack. Technology based on this approach dates to the 1960s when significant efforts were made in the United States and Europe to use dry limestone injection for SO_2 control. Conceptually, this was seen as the most economical and practical approach for SO_2 control in coal-fired electrical generating plants. To facilitate uniform dispersion of the sorbent, a Venturi section is generally incorporated into the ducting such that the gas velocity is about doubled at the throat. Multiple injection nozzles are used.

The effectiveness of dry sorbent injection is limited. Reaction times are relatively short. Plugging of the pore structure of the alkali by reaction products reduces reagent utilization such that large quantities of reagent relative to the theoretical minimum requirement for acid gas neutralization (the stoichiometric ratio Φ) are required. In most circumstances, the reagent requirement is more than five times the SO_2 plus HCl rate. Also, data show that the most effective control for HCl (the acid gas of predominant interest for refuse incinerators) is achieved in the cooler regions of the furnace. SO_2 is absorbed more completely in the higher-temperature furnace zones, where HCl is absorbed to a very limited degree.

These facts led several municipal refuse incinerator plants (especially in Europe) to add a separate contact chamber with reagent (usually hydrated lime) injection after the boiler. The reactor significantly increased the residence time for HCl absorption reactions in the lowest-temperature zone in the system. Although the reagent consumption was still high, the low cost of limestone or hydrated lime as the absorbing reagent made this alternative worthy of consideration when the HCl removal target is 80% or less and the SO_2 removal target is 50%. Sodium bicarbonate can achieve 90% HCl control with an Φ of 2.0 but at a substantially higher reagent unit cost and with potential regulatory problems associated with disposal of the residue with its content of soluble sodium salts.

In considering the application of dry sorbent injection for acid gas control, the substantial increase in the particulate loading should be considered. This is particularly important when an ESP is used for particulate control. Increasing the particulate load to the degree needed to effect 90% HCl control or better can require almost a doubling of collection area over that required to achieve emission goals without solids addition.

The combination of dry injection with a fabric filter has a special advantage: the alkaline absorbent is deposited with the particulate in the cake on the filtering medium. Thereafter, the filter cake acts as an alkaline absorbent and continues to remove acid gases. This increases the utilization of reagent. Note, however, that the degree of improvement is not extraordinary; perhaps decreasing to an Φ of 4 : 1 due, apparently, to "clogging" of the absorbing surface and pore structure by reaction products.

3. Dry Absorbent Contactors for Volatile Pollutant Control

There is a class of pollutant that is partly or largely in the gas phase at "normal" dry particulate control temperatures (say, 150–300°C). Lowering the temperature ahead of the particulate control device may assist by condensing a larger fraction of the pollutant onto

the surface of the extant particulate matter. This is, in fact, effective and adds to the attractiveness of wet and semi-dry collectors. However, some enhanced removal in an all-dry system is possible if a material is added to the flue gases that selectively adsorbs or captures the volatile. This is the case for the addition of activated carbon and sodium sulfide (Na_2S) to the flue gases of municipal incinerators.

Activated carbon has been shown to be effective in removing a fraction of mercury and to scavenge high-molecular-weight compounds including PNHs and polychlorinated dibenzo p-dioxin and polychlorinated dibenzo-furan compounds. The mechanism is assumed to be adsorption onto the carbon surface. These pollutants are of particular significance for municipal waste combustors. Thus, trapping an incremental quantity of the pollutants using an additive that is subsequently captured by the particulate control system is attractive. Other than a relatively simple bin and injection device, the cost of adding this control is minimal.

Sodium sulfide (Na_2S) can be injected as a solution at a point where the local gas temperature is high enough for rapid and complete evaporation to facilitate capture of mercury vapor after reaction to form the solid sulfide. The mercuric sulfide is subsequently removed by the particulate control device.

4. Semi-Dry Absorbent Contactors for Gaseous Pollutant Control

As noted above, alkaline reagents show their highest utilization (low Φ) for a given level of control if the temperatures are low and if reaction time is long. These two process features led to the development, testing, and implementation of the spray dryer absorber, fabric filter control concept for application to resource recovery systems. In this technology, a large chamber is added following the boiler when the temperature has been reduced to, say, 230°C. At the top of the chamber, a water slurry of hydrated lime is injected through a spray dryer atomizer. The gas temperature and water quantities are kept in balance such that evaporation is rapid and complete in, say, two seconds or less. A conservative margin is added to the mean residence time to assure a dry particulate as input to the bag-house or ESP. Conservative specifications call for 18 seconds in a downflow configuration and 8 seconds in an upflow reactor (365).

In most facilities, pebble lime (CaO) is received in truck-load quantities and stored in a carbon steel silo. The total storage capacity depends on local supply availability and reliability but is often a minimum of 14 days. The silo has a 60°, conical hopper with a knife gate, rotary feeder, weight feeder, and level probe. A vent with a fabric dust collector should be provided. The lime is handled pneumatically for which a blower per silo plus one common spare should be provided. Carbon steel piping with long radius elbows conveys the lime from the truck discharge point and from the silo to the lime slurry preparation system.

The lime is slaked to $Ca(OH)_2$ using a minimum of two slakers, each designed for 100% capacity. Each slaker should have a grit screen and a volumetric capacity such as to operate six to eight hours on a single batch. Heat generation on slaking is 15,250 kcal/kg mol CaO. A dedicated slurry pump should be provided for each slurry tank with one common spare. Dilution water is added to the slurry in accord with the needs for exhaust temperature control for the spray dryer system.

Mechanical rotary atomizers have been used to produce a mist of finely divided droplets. The rotary atomizers typically consist of a 3600-rpm motor coupled to a step-up gearbox to give an atomizer wheel speed between 10,000 and 20,000 rpm. Slurry is

introduced into the center of the wheel and extends over the rotating surface as a thin film. Centrifugal forces accelerate the slurry at the rim of the wheel where shear forces disintegrate the film into 30- to 100-μm-diameter particles.

Two-fluid nozzles are also used to form the fine droplets. In these systems, 4.75- to 6.1-atm compressed air provides the energy for disintegration of the slurry. Since the spray pattern from the two-fluid nozzles is narrower than that of the mechanical atomizers, the subsequent evaporation chamber can be designed with a smaller diameter.

In comparing the two atomization methods, one sees

The rotary atomizers produce a smaller droplet size and a narrower size distribution than do the two-fluid nozzles. This improves collection efficiency.

The high speed and sophistication of the mechanical devices require a well-trained maintenance staff with special tools and equipment. The two-fluid nozzle can be maintained with common tools.

The rotary atomizer has higher maintenance and capital costs but reduces reagent cost through its higher collection efficiency.

For large systems ($> 2800\ m^3/min$) the capital, maintenance, and power costs for the two techniques are about equal.

Gas flow turndown is much lower on a rotary atomizer (2.5 : 1) versus a two-fluid nozzle (20 : 1), but reagent flow turndown is much higher on a rotary atomizer (20 : 1) versus a two-fluid nozzle (356).

The atomization characteristics of rotary and nozzle atomizers and the general characteristics of the two atomizer classes are summarized in Tables 7 and 8.

The water evaporation has two effects: cooling of the flue gases from about 300°C to about 150°C and the generation of a distributed field of acid absorbent particles [a mixture of CaO and $Ca(OH)_2$]. Following the spray dryer chamber, the gas can be passed to an ESP

Table 7 Typical Droplet/Particle Size and Atomizer Operations (for Low-Viscosity, Newtonian Liquids)

Rotary atomizer	
Wheel peripheral velocity (m/sec)	Mean particle size (microns)
>180	20–30
150–180	30–75
125–150	75–150
75–125	150–275
Pressure nozzle	
Pressure (atm)	
>100	15–30
50–100	30–50
25–50	50–150
15–25	150–350
Two-fluid nozzle	
Air-to-liquid mass ratio	
>5 : 1	5–20
2.5 : 1 to 5 : 1	20–30
1.5 : 1 to 2.5 : 1	30–50
0.5 : 1 to 1.5 : 1	50–200

Source: From (549).

Table 8 Features of Spray Dryer Atomizers

Rotary atomizer	Pressure nozzle
Easy control of particle size	Less easy control of particle size
Large flow areas	Small flow areas
Single atomizer for low and high capacities	Nozzle duplication for high capacities
Handles slurries and crystalline feedstocks	Fine feed filtering required
Particle size virtually independent of feed rate	Narrow operating feed rate range
Capacity independent of feed pressure	Capacity proportional to square root of pressure
Large particles dried only in large-diameter drying chambers	Large particles dried in small-diameter drying chambers
Unit cost with pump comparable	Unit cost with pump comparable
Low-pressure feed system	High-pressure feed system
Fine–medium-size particles, individual, mean size up to 200 microns	Coarse, free-flowing particles, individual, mean size up to 350 microns
Deposit tendencies on wall at wheel level	Less tendency to deposit on walls

Source: From (549).

or, more conventionally, a fabric filter. The ESP effects removal of the solid reactants (and other flue gas particulate). The fabric filter option accomplishes particulate removal but also provides another opportunity for acid gas contact as the acid gases pass through the dust cake. About 15% to 20% of the removal occurs on the filter cake (357). The second contact opportunity not only increases reagent utilization and the ultimate removal efficiency but also provides "reserve alkalinity" to respond to "spikes" in acid gas concentration. An air-to-cloth ratio of 3 : 1 or less is a reasonable design point to provide low gas velocities and high solids residence time. The spray dryer absorber–fabric filter combination has achieved above 95% HCl removal and above 80% SO_2 removal while accomplishing general particulate control to levels well below regulatory requirements.

G. Specialized Abatement Technology

1. NO_x Control

a. Waste (Fuel Nitrogen) Control. As described in Chapter 13, NO_x formation from fuel nitrogen sources can be important. Indeed, the NO_x concentrations via this mechanism can even exceed equilibrium levels. Consequently, one should consider the possibility of reducing the concentration of fuel nitrogen in the wastes being burned.

b. Combustion Zone Control. An alternative strategy involves control of the combustion environment to maintain a reducing condition (starved-air combustion or pyrolysis) or low-oxygen condition such that the fuel nitrogen is released (as molecular nitrogen) before entering a zone with a significant oxygen concentration. This is the technique (staged combustion) used in conventional "low-NO_x burners" and, to a degree, one underlying feature of flue gas recirculation. It is also inherent in the operating strategy of the starved-air type of "modular combustion unit" used for municipal and industrial refuse. Further, in conventional mass burn incinerators, the combustion zone where most of the waste gasification occurs is distinctly reducing in nature. It is speculated that much of the fuel nitrogen contained in biomass waste material (e.g., grass clippings) is released in this zone

of the furnace, thus reducing the direct relationship between feed nitrogen content and flue gas NO_x emissions.

Flue gas recirculation is another method that involves recirculation of cooled furnace gases to the combustion zone. These gases both reduce temperature (minimizing thermal NO_x) and reduce the mean oxygen concentration (affecting both fuel nitrogen and thermal NO_x) generation. This technique has produced about 50% of the NO_x as does conventional mass burn technology but involves increased capital cost and a loss of considerable flexibility in the combustor design and operation.

Refuse and sludge incineration in both bubbling and circulating fluid bed incinerators has also shown low NO_x emissions (about 20% to 50% of that from a mass burn). This probably reflects both low excess air operation (typically about 40% to 80% excess air) and the withdrawal of sufficient heat in the waterwall/bed tube systems to minimize thermal NO_x formation mechanisms.

NO_x minimization in the incineration of sewage sludge (typically, high in fuel nitrogen) at the Hyperion wastewater plant in Los Angeles is based on a staged fluidized bed system. The bed is fed predried sludge in an oxygen deficient zone to release the fuel nitrogen. Then, after some heat removal using a boiler, the remainder of the air for combustion is added. Similar starved-air incineration has been practiced in multiple hearth furnaces. There, combustion is completed upon air addition in an afterburner chamber.

C. Reduction Technologies

SELECTIVE, NONCATALYTIC REDUCTION (SNCR). Thermal DeNOx is the proprietary process concept developed and commercialized by the Exxon Corporation (324). Here, ammonia at about a mol ratio to NO_x of between 2 : 1 and 3 : 1 is injected into the furnace gases in the temperature zone from 760° to 1100°C although temperatures above 925°C are preferred. Although the original applications used an injection grid within the flue gas stream, more recent installations inject the ammonia from wall injectors. Several banks of injectors are installed to be sure that ammonia addition can always be made in the correct temperature zone as operating conditions (especially boiler load) vary. In the target temperature range, the ammonia combines with NO (the dominant oxide comprising NO_x) to form water vapor and elemental nitrogen. The principal reactions are

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$
$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

At lower temperatures, the reactions are too slow and unreacted ammonia (known as "ammonia slip") is emitted. This failure mode is costly and causes a new pollution problem in its own right. The major ammonium products formed are ammonium sulfate $[(NH_4)_2SO_4]$ and ammonium bisulfate (NH_4HSO_4). Ammonium sulfate is a dry, fine particulate (1 to 3 microns in diameter) that may contribute to plume formation. The bisulfate is a highly acidic and sticky compound that, when deposited on downstream equipment such as air heaters, contributes to fouling and corrosion.

With injection at temperatures above 1100°C, the ammonia itself oxidizes to NO_x (thus defeating the objective) according to the reaction

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$$

NO_x reduction between 40% and 65% is readily achievable. The process is thus dependent on good combustion control and operational stability to avoid large temperature fluctuations.

In the initial development of the process, anhydrous ammonia was the principal reductant used. Concern regarding the safety of compressed gases onsite has led to development of embodiments of the process using aqueous ammonia. Although the tankage required is much larger and the shipping costs for the reagent are high (ammonia ships as a 28%-by-weight solution), the safety issue has made the aqua ammonia approach preferred.

A second SNCR technology (NO_x–OUT) of similar effectiveness is based on the use of urea (injected as a 5 weight percent concentration aqueous solution prepared by dilution from a 50% stock solution). The process development was sponsored by the Electric Power Research Institute (EPRI) in the United States and subsequently commercialized and patented by Fuel Tech (326). The overall chemical reaction is

$$2CO(NH_2)_2 + 4NO + O_2 \rightarrow 4N_2 + 2CO_2 + 4H_2O$$

The urea-based system nominally operates in the same temperature range and via the same chemical reactions as the ammonia-based technology. However, with use of proprietary additives, the temperature "window" for the process can be widened to span from 650° to 1100°C. At temperatures above 1100°C, oxidation of the ammonia to form new NO_x begins. It too uses several banks of injectors. The urea-based technology has the advantages that its reagent can be stored safely as a solid and that its liquid injection systems are highly effective in achieving good distribution and mixing of the reagent with the flue gases.

SELECTIVE, CATALYTIC REDUCTION (SCR). Selective catalytic reduction (SCR) involves ammonia reduction over a catalyst bed (375). In most cases, titanium oxide and vanadium oxide catalysts are used. Most reactor beds use ceramic honeycomb monoliths with square cell geometry, ranging in cell density of between 1.4 and 60 cells per cm^2. This type of reactor, with its high surface area per unit volume yet low pressure drop, offers distinct technical advantages over other catalyst supporting materials such as random packing (rings or pellets) (550). Increasing the cell density increases catalytic activity and improves mass transfer to the catalyst surface but at the price of an increasing tendency to plug and increased pressure drop per unit volume of gas treated.

To avoid plugging and catalyst poisoning, the bed is sited after the particulate control device. Since SCR operates with optimum performance at temperatures from 360° to 450°C (depending on the type of catalyst) but can operate over the range from 230° to 500°C, this requires reheat (equivalent to as much as 8% of the heat released in the furnace).

The two major reactions occurring of the SCR catalyst are

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$
$$4NH_3 + 2NO_2 + O_2 \rightarrow 3N_2 + 6H_2O$$

The chief advantage of SCR (325) is the achievement of about the same or better control levels as SNCR (commercial systems achieve 80% removal of NO in power plants with essentially no NH_3 slip) but at a 1 : 1 ammonia-to-NO ratio (about one-half the ammonia consumption). Control levels as high as 90% NO removal have been reported but at 40 ppm NH_3 slip. Disadvantages include the energy penalty for reheat and the first cost and replacement cost of the catalyst. It has been reported (375) that replacement of the catalyst can cost as much as 50% of the original total capital cost of the SCR unit.

The use of SCR has an advantage to the SNCR in that incinerator plant data indicate that dioxins and furans are oxidized to a significant degree on the titanium, titanium–tungsten–vanadium, and platinum SCR catalysts (551).

d. Wet Scrubber Control. Nitrogen dioxide (NO_2) can be easily scrubbed with caustic solutions. However, nitric oxide (NO) cannot. Since most combustion systems contain mixtures of the two oxides but favor the formation of NO, achieving high levels of NO_x removal requires a combination of an oxidation step, converting the NO to NO_2 followed by adsorption in an alkaline medium. Although NO oxidizes to NO_2 in the presence of excess oxygen, the oxidation rate at low temperatures and low NO concentrations makes gas phase oxidation strategies impractical.

Oxidants such as ClO_2 react rapidly with NO in the gas phase. Oxidation in the liquid phase is slower, however, because the rate of absorption of NO is slow. The reactions with ClO_2 are

$$2NO + ClO_2 + H_2O \rightarrow NO_2 + HCl + HNO_3$$

Stoichiometric chlorine dioxide has been shown to eliminate about 95% of the NO in less than 2 sec (545). There are problems, however, due to the reactive and hazardous nature of the chlorine dioxide. Other combinations result in some NO removal if NO_2 concentrations are high or if oxidants such as SO_2 are present. However, in most cases, direct scrubbing is an ineffective or problematic approach to remove NO.

An exception is the NO_x scrubber (546) that uses surface active, alkali media in a packed tower design with exceptionally large mass transfer surface. For total NO_x concentrations in excess of 2000 ppmdv, a $NO_2 : NO$ mol ratio of 2 : 1 or greater and an $O_2 : NO_x$ mol ratio greater than 5 : 1, between 90% and 99% NO_x removal can be achieved. Several liquid phase oxidants such as H_2O_2, $KMnO_4$, or NaOCl can be used. The latter, scrubbing at a pH of about 9 (547), is the most cost-effective. The optimum pH increases with contact time (546).

2. Mercury Control

Mercury, as an elemental pollutant, appears in MWC and other incinerator flue gases in trace quantities because of the presence of mercury compounds in the waste fed to the unit. It is not, as with dioxins and the like, "formed" within the system. Due to its variable source characteristics, the mercury concentration in waste as well as the mercury emission chemistry is quite variable. Therefore, control efficiency determinations must be made based on simultaneous inlet–outlet sampling and using sampling and analytical methods that capture all mercury forms. The ratio of the controlled emissions measured at one time to the uncontrolled emission measured at another time is of uncertain meaning and utility. Citations of "negative collection efficiencies" in the literature are symptomatic of this problem.

The mercury data are strongly influenced by the nature of the mercury chemistry in the emission: elemental mercury (Hg or Hg_2), mercuric or mercurous chloride ($HgCl_2$ or HgCl), mercuric or mercurous sulfide (HgS or Hg_2S), etc. These chemistry-related effects result from the interactions between the physical form (gas or solid) and/or chemical reactions in the sampling train on the reported mercury concentration and, thus, the reported capture efficiency. Such problems are being resolved as the sampling and analysis protocols continue to receive attention. The consequence of this continuing development,

however, is that data sets may not be comparable if the sampling/analysis methodology differs.

Finally, many process variables affect both mercury emission character and mercury control effectiveness. Temperature is very important. Thermochemical calculations indicate that mercury compounds convert to elemental mercury in the high-temperature regions of the combustor. As the gas cools, some of the mercury is converted to ionic forms, with mercuric (+2) being the preferred valence state. In the presence of HCl, this often leads to the presence of mercuric chloride ($HgCl_2$).

Other process variables include the inlet mercury chemistry and concentration and the presence of adsorptive surface on particulate. One finds, for example, that RDF-type MWC systems with fly ash having a high carbon content effect some intrinsic mercury control. Also, reactive chemicals (e.g., OCl^- ion) in wet scrubber solutions may influence collection efficiency. Thus, the analyst must carefully research all of the potentially important variables in assessing data from different source types and control system characteristics on the apparent control effectiveness or lack thereof.

The consequence of these complexities is that data on control effectiveness are often inconsistent. Data from several sources do not conveniently "group" nor are process trends (e.g., control effectiveness as a function of temperature) easily visualized by simple data plots. It may not be appropriate to aggregate data for several plants (that may have different mercury chemistries in the waste and/or in the flue gases) in determining the potential control effectiveness of a particular technology (327).

The control technologies applicable to mercury involve four strategies:

1. Cooling of the flue gases such that condensation and absorption onto fly ash occurs. Removal is effected in the particulate control device.
2. Wet scrubbing, a combination of substantial gas cooling coupled with particulate control.
3. Addition of chemicals to the flue gases that react with mercury vapor to produce a solid reaction product. Removal is effected in the particulate control device.
4. Addition of materials to the flue gases that adsorb mercury vapor and the vapor of mercury compounds, thus trapping them. Removal is effected in the particulate control device.

a. Cooling. The first approach (cooling) is effected to a degree by the "dry scrubber" technology (dropping the temperature to about 130°C). Further, the high particle concentration following the dry scrubber provides a large surface area for condensation and adsorption of mercury and its compounds. Data (554) indicate that between 15% and 46% mercury removal can be associated with the cooling and particulate removal of the dry scrubber system itself (no carbon injection). Although the mercury is ultimately captured in the particulate control device that follows, one could ascribe to the dry scrubber the enhancement in collection achieved by the temperature reduction. However, removal efficiency is considerably enhanced at the much lower temperatures (say, 60°C) achieved in wet scrubber systems.

b. Wet Scrubber. The mechanism through which a wet scrubber contributes to the achievement of acceptable mercury control is hard to confidently identify. Somewhat less than 40% control is generally achieved by either a baghouse or ESP collector simply through the collection of particulate (solid phase mercury compounds and some surface adsorption of vapor). The wet scrubber does not achieve the levels of particulate collection

of either of these devices. The impact of the wet scrubber is on the gas phase mercury chemistry: elemental mercury and mercury compounds in the vapor state. The mercury compounds are removed by enhanced condensation at the much lower working temperatures of wet scrubbers (typically less than 65°C) vis-a-vis ESP or baghouse systems. The elemental mercury, however, with water or alkaline scrubbing, would still not be expected to be removed to a significant degree since only about 20% of the total mercury appears as elemental mercury vapor. If active chlorine is added to the scrubbing water (e.g., as sodium hypochlorite), one might expect that the mercury would be converted to the chloride and, then, is scrubbable. This may be an exploitable characteristic of wet scrubbing control.

The data base for assessment of this technology is cloudy. The majority of the available data are on European and Japanese plants where wet scrubbers have been added following ESP or baghouse particulate control systems. Interpretation of European data is difficult due to differences in their sampling and analysis protocols. Also, due to mercury adsorption on carbonaceous fly ash, the incremental contribution from the scrubber in the overall mercury reduction is unclear.

Wet scrubbers are an expensive approach (in capital) and, through the need for wastewater treatment, increased fan power, and, perhaps, the needs for reheat, the operating cost is very high. Some plants have used additives such as trimercapto-s-triazine (TMT) to stabilize condensed mercury compounds to minimize revolatilization of mercury (555). The reagent cost is relatively low for both mercury and acid gases, but the other operating expenses are not. As to the expected control level, assuming that the concept involves both a wet scrubber and either a baghouse or ESP but without carbon addition, one would expect total control levels no more than the 60% to 70% range.

C. Formation of Solid Reaction Products. Reacting mercury vapors to generate a solid reaction product has been effected in Sweden, in Germany, and in trials in British Columbia (555). The plants inject a solution of sodium sulfide (often, about 10 to 15 weight percent by weight Na_2S) upstream of a spray dryer absorber in gases at temperatures between 130° and 250°C. The reactions are not totally clear but appear to be

$$Hg_{gas} + Na_2S \cdot H_2O \rightarrow HgS_{solid} + NaOH$$

$$HgCl_{2gas} + Na_2S \cdot H_2O \rightarrow HgS_{solid} + NaCl \cdot H_2O$$

The sulfide is then removed in the particulate control device. Capital costs and reagent costs are low. However, the explosive and toxic nature of the hydrogen sulfide gas that is released in small but significant amounts when the sodium sulfide is dissolved in water presents an operational hazard. There may be some proprietary features to the sodium sulfide addition.

The performance of the sodium sulfide system appears to be somewhat less than that of activated carbon at a comparable cost (512). It is reported that Na_2S feed rates vary from 0.05 to 0.5 kg/ton of MSW depending on the amount of mercury in the flue gas, the level of control required, and the level of carbon present in the fly ash. Tests at the Burnaby facility in British Columbia (454) showed that injection of sulfide increased mercury removal about 30% beyond that removed by simple humidification and gas cooling in the semi-dry scrubber. This compares well with the 35% incremental control observed at the Stanislaus plant in California (513).

d. Carbon Adsorption. This process technology involves injection of activated carbon into the flue gases followed by physical and chemical adsorption of vapor phase mercury and its compounds onto the carbon. “Doping” of the carbon with chemicals (such as

sulfides) that create strong chemical bonds to elemental mercury may enhance capture. In combination with the removal of solid phase mercury compounds in the particulate control device, high overall control efficiencies are realized.

Of the several technologies for mercury control, there is more experience with injection of dry activated carbon than with alternatives where the carbon is added to the lime slurry tank and injected into the flue gas stream through the spray dryer absorber (SDA) system. The captured mercury compounds are ultimately found in association with the fly ash. Capital costs are relatively low and, due to the low dosage rates (about 60 mg/m^3 of flue gas), the chemical costs are medium to low (in absolute dollar terms). In concept, activated carbon addition can be made either ahead of or after a spray dryer and before either a fabric filter or an electrostatic precipitator. Most facilities inject the carbon ahead of the spray dryer, just after the economizer section of the boiler, and in association with a fabric filter dust collector.

Mercury collection efficiency with carbon injection is related to the injection rate (kg of carbon per ton of refuse burned), to the initial mercury concentration, and to temperature. Higher carbon addition rates and lower temperatures favor high removal efficiency. With spray dryer systems (where temperatures are below 150°C), collection is better than the electrostatic precipitator (ESP) systems, which typically operate above 230°C.

Carbon is injected in the dry state using a pneumatic injection system. The carbon is stored in bulk in a simple silo and reclaimed by gravity through a weigh-feeder, swept up in an eductor, and blown to injection orifices between the economizer outlet and the SDA. With injection at the rate of about 0.4 kg per ton of refuse being burned, control efficiencies of between 85% and 95% appear to be reliably achievable in most plants.

As the carbon unit rate decreases, one sees a drop in collection efficiency as illustrated in tests run at the Stanislaus County, California, facility. The data from the Stanislaus tests (554) were correlated with an r^2 of 0.777 by

$$\ln(\mathrm{Hg_{out}}) = 5.66 - 0.2652(\Lambda)^{0.5} + 0.000724(\mathrm{Hg_{in}}) \tag{44}$$

where $\mathrm{Hg_{out}}$ and $\mathrm{Hg_{in}}$ are the outlet and inlet mercury concentrations, respectively, in units of μgm/dscm and Λ is the carbon concentration in the flue gas in mg/dscm. The tests showed no statistically significant effect of carbon injection location (economizer outlet or spray dryer inlet); no effect of carbon type (wood-based, coal-based, and lignite-based carbon were tried); and no significant effect of ammonia concentration (present as "ammonia slip" from the NO_x control system).

For an inlet mercury concentration of 150 μgm/dscm, Λs of 25, 50, and 100 μgm/dscm would, using this predictive equation, yield an outlet mercury concentration of 85, 49, and 22.5 μgm/dscm, respectively, corresponding to removal efficiencies of 43%, 67%, and 85%, respectively.

In concept, activated carbon addition can be made either ahead of or after a spray dryer and before either a fabric filter or an electrostatic precipitator. Although one might speculate that there should be a temperature effect (higher collection efficiency at lower temperatures), it is not visible in the data. A modest effect of control technology type shows in the data. Some data for ESPs appear slightly lower than for the fabric filter-equipped plants, but the data base is limited and scatters badly.

The carbon can be injected dry ("dry" injection) or added with the lime to the slurry tank feeding a spray dryer acid gas control system ("wet" injection). Data for the spray dryer/ESP plants in Essex and Camden County, New Jersey, showed that dry carbon injection achieved better mercury reduction than wet injection (553); mercury reduction of

greater than 95% was demonstrated at dry carbon rates above 200 mg/dscm, whereas with wet injection, control was limited to between 80% and 90%. These data contrast with dry and wet injection data at the Stanislaus plant in California that showed little difference. Sorbalime©, a proprietary premix of lime, carbon, and sulfur designed for addition using the wet technique, has shown performance equal to that for dry addition.

Facilities serving a large (say, 2350 tpd) MWC plant with carbon addition include a storage silo capable of storing 2 to 2.5 times the capacity of the standard carbon delivery truck serving to the site with a freeboard of 4 m. Eighteen thousand kg is a common road tanker truck for this service, and pneumatic transfer is commonly used to move the carbon from the truck to the silo. A bin vent filter is mounted atop the silo. Note that it is good practice to include blowout panels on the silo to protect against dust explosions.

The carbon is then fed through a weigh-feeder and entrained by an air eductor. For a large plant, a positive displacement blower is used to provide the eductor air flow of about 4.5 sm^3/min at 80 kPa gauge. Piping for the carbon should be a minimum of schedule 40 carbon steel with ceramic backed, 60-cm centerline radius sweep elbows to minimize erosive metal losses on turns.

The dosage rate of carbon is established by a series of tests to determine the optimal injection rate that comfortably meets permit requirements. Plotting the injection rate against the target requirements (a given percent removal or a stack concentration) provides the set point in kg of carbon per hour for use in normal plant operation. The adequacy of the set point is normally confirmed through periodic retesting.

3. Control of Dioxins and Other Hydrocarbon Pollutants

Although back-end APC approaches to limiting organic compound emissions including CDD/CDF are possible, the fact that a number of simple, low-temperature chemical reactions are, most likely, the dominant source of the compounds emphasizes the importance of destroying organic precursors before the compounds leave the furnace: a "control" concept called "good combustion practice," or GCP. Analysis of refuse incinerators shows six major areas of design that impact the achievement of substantially complete oxidation of hydrocarbon species (328):

1. Temperature at the fully mixed location (usually defined as the plane just above the highest overfire air jet inlet) a minimum of 1000°C
2. Amount and distribution of combustion air (to ensure availability of oxygen)
3. Mixing
4. Particulate matter (PM) carryover (to minimize the amount of graphitic carbon reaching the temperature zones in the boiler and APC systems where dioxin formation occurs)
5. Downstream temperature
6. Stability of waste feed rate (to keep temperatures stable and high)

Reaction time is indirectly addressed by the temperature, combustion air, mixing, and PM carryover components. With good mixing, the destruction of the CDD/CDF precursors in the gas phase is rapid at relatively modest temperatures (say, 600°C); far less time is required than the 1- or 2-sec residence time often set as a minimum. Reactions of organic compounds and char associated with PM, however, are much slower and may be controlled by diffusion of oxygen into the particle rather than oxidation kinetics. For these more refractory precursors, the higher target temperature and longer times are appropriate. Note, however, that only the volume of the furnace zones that are well mixed, where temperatures

exceed the target levels and where the oxygen concentration is everywhere greater than zero, should be included in assessing whether sufficient time and temperature are available.

The achievement of these target conditions in the combustion environment requires a well-designed and operated overfire air system in combination with prudent use of underfire air controls to avoid excessive particulate carryover. Blending of the incoming waste to minimize areas on the grate with wet waste is also important. Achievement of good mixing must extend over the practical operating range of the unit. Problems can arise at low load when an overfire air flow rate that is tied in the process control computer to the overall refuse burning rate is turned down. Then, penetration of the fuel-rich gases from the grate by the crossflow air jet may become inadequate. Also, high firing rates can lead to greatly increased air rates with the potential for quenching of combustion, disruption of mixing patterns, and increased PM carryover (328). The examination of data on dioxins and other organic emissions clearly shows that trace organic emissions can be controlled using design and operating measures targeted on ensuring good overall combustion.

Although GCP must be regarded as the primary and most effective strategy for dioxin reduction, data indicate that various elements of the back-end APC systems also impact dioxin emissions. Most importantly, as discussed in Chapter 13, the use of an ESP for particulate control without a spray dryer absorber system that cools the gases after they leave the economizer holds the captured fly ash for extended periods of time at a temperature where CDD/CDFs form by oxychlorination of residual carbon in the fly ash. Thus, unless the carbon residual is very small (probably less than 2% loss on ignition for the fly ash), the mass emission rate of CDD/CDF compounds may actually increase across the ESP despite the removal of the CDD/CDF material associated with the particulate matter.

When the ESP is run "cold" or a baghouse collector is installed after a spray dryer absorber, significant CDD/CDF reductions are normally achieved. The reduction is usually better with the baghouses due to the passage of the flue gas through the filter cake such that the condensed submicron CDD/CDF is captured and additional material is adsorbed on fly ash and sorbent particles. Both the ESP and baghouse alternatives following a spray dryer are made still more effective in CDD/CDF reduction when carbon injection is practiced using either the dry method, the wet method, or the wet method using carbon-enhanced lime-based sorbent in place of lime (558). For example, during three tests in which 360 mg/dscm of dry activated carbon was injected into the flue gases upstream of an ESP-equipped system, stack concentrations of total CDD/CDF dropped from 46.8 ng/dscm to an average of 5.6 ng/dscm. Tests in Europe showed similar effectiveness (558). Although no data are available at the present, some improvement should be expected from carbon injection for the emissions of other high-molecular-weight organic compounds (e.g., PAHs).

4. Dry Sorbent Injection Technology

Dry sorbent injection (DSI, or "dry-dry scrubbing") has been seen by many in the field as a means for existing facilities to effect significant reductions in the emission of acid gases and minor reductions in condensible organic emissions with a modest capital and operating cost investment and minor layout impact. The process concept involved in dry injection is simple: injection of dry, powdered limestone, hydrated lime, or sodium-base alkali (carbonate or bicarbonate) into the flue gas with subsequent collection using the particulate control device. The alkaline additive absorbs HCl, HF, SO_2, and other acid gases. The particulate matter increases the surface area available for condensation of high-

molecular-weight organic matter such as the dioxin and furan compounds and polynuclear hydrocarbons.

However, the actual processes involved in dry injection are complex. Parameters that affect the degree of removal include the temperature at the point of injection, the chemical form of the additive, the temperature at the back end of the flue gas train, and the concentrations of acid gases and hydrocarbons to be removed. The temperature effect produces the three subgroups in dry injection technology: high-temperature furnace injection; moderate-temperature duct injection; and low-temperature duct injection (HTFI, MTDI, and LTDI, respectively). Calcium-based alkali injection is the baseline of the technology. Sodium alkalis remove acid gases quite adequately. However, the calcium alkalis are preferred due to the lack of field data for sodium-based systems, the high solubility of the sodium chloride/sulfite/sulfate reaction products (causing some problems in disposal), and the high relative cost of the sodium chemicals.

HTFI has been used with both conventional and fluid bed combustors (340). When the operating temperatures exceed 760° to 1100°C and with sufficient residence time, limestone will calcine to lime and is a preferred and lower-cost alkali. In conventional refuse incinerators, lime or limestone can be injected into the furnace using the existing overfire air system (or with dedicated injectors). In general, HTFI is focused on SO_2 control since the equilibrium for the HCl removal reaction is not favorable at high temperatures. The overall effectiveness for SO_2 reduction is between 40% and 60% with efficiency increasing as the back-end flue gas temperature decreases.

MTDI and LTDI injection usually involve hydrated lime [$Ca(OH)_2$]. MTDI involves injection in the temperature range from 200° to 315°C and LTDI at about 150°C. Reaction is rapid and, with one to two seconds of residence time ahead of the particulate control device, removal is adequate. Injection means can involve a simple lance, but, in most plants, injection is made at a Venturi constriction located after the economizer and ahead of the particulate control system. Removal of both SO_2 and HCl is effected. The best removal corresponds to the lower-temperature operations and to those where a fabric filter is used for particulate control (thus giving an opportunity for gas–solid reaction both in suspension and as the solids accumulate in the filter cake). Overall collection effectiveness for the fabric filter embodiment ranges from 40% to 50% for SO_2, while from 80% to 90% control is achieved for HCl.

Some control effectiveness has been claimed for the medium- and low-temperature dry sorbent injection technology with respect to dioxin/furan compounds. The claims are based on a process concept involving the availability of additional surface area for condensation of these and other low-vapor-pressure compounds in combination with a presumed benefit of removing HCl from the gas phase. The data are too limited to conclusively show the advantages, however.

II. CONTROL STRATEGIES FOR INCINERATOR AIR POLLUTION CONTROL

A. Air Pollution Control through Process Optimization

As discussed in Chapter 13, the air pollutants generated in incineration systems include mineral and combustible particulate, sulfur oxides, nitrogen oxides, hydrogen halides, incompletely burned “total hydrocarbons” (actually, a diverse mixture of compounds of carbon, hydrogen, oxygen, nitrogen, halogens, etc.), and carbon monoxide. Some pollutants are fragments of original waste components. Others are entirely new species,

created in the chemistry laboratory that is the combustion environment. The relationships between the design and operating parameters of the incinerator/waste system and the emission rates of pollutants are complex but, at least, broadly understandable. This understanding should provide the basis for the first level of "air pollution control." The general relationships available include

Waste control

Exclusion of certain wastes (e.g., auto batteries as a source of lead, mercury batteries as a source of mercury compounds, gypsum wallboard as a source of sulfur oxides)

Feed rate (affecting the mean residence time in the system and the average flow velocities that induce turbulent mixing)

Air supply

Underfire air flow affects particulate loading through elutriation and, perhaps, heavy-metal emissions through excessive bed temperatures.

Overfire air flow affects combustible pollutants through stimulation of vigorous mixing to ensure that the oxygen concentration is maintained everywhere greater than zero but nowhere in so much oversupply as to cool and quench combustion.

Excess air affects the generation of nitrogen oxides and the oxidation rate of combustibles.

Temperature control

Gas temperature strongly impacts combustion rate (kinetics). Of particular importance are the temperatures in failure zones: near walls, cooled surfaces, tramp air in-leakage points, etc., where local temperatures can be very low relative to the mean temperatures measured in the center of outlet ducts and where combustion is "quenched."

High temperatures can lead to volatilization of several metal compounds and, ultimately, increased heavy-metal emissions.

Low temperatures in the back end of units equipped with boilers and scrubbers can lead to condensation of volatilized metal and heavy organic compounds.

It is easy to focus entirely on "back-end" treatment for APC. And yet, there is great power in using these causality relationships and others summarized in Chapter 13 to find design and/or operating levers to significantly reduce the demands on the back end.

B. Control Selections for Incinerator Types

As noted in the introduction to Chapter 13, the designation of a particular item of hardware as the "optimal" APC system is not a simple task nor is the "answer" static and universally valid. Rather, the characteristics of one's particular waste (present and forecast) establishes a preferred incinerator concept. Then, the combination of waste characteristics and the selected incinerator hardware fixes (within limits) the uncontrolled emission rate of the several possible air pollutants. One then looks at the uncontrolled emissions and the extant (and forecast) emission regulations at the federal, state, and local levels. Beyond these relatively firm factors, one must also consider the policies and practices, the financial resources, the personnel skills, and the performance flexibility needs of the ultimate

owning organization. At that point, the "best" APC technology and most of the key design and operating features should fairly spring from the list of candidates.

1. Municipal Refuse Incinerators

In the early days of municipal waste incineration in the United States, the regulatory focus was entirely on particulate. The emission standards of that time could be met with simple wetted baffle "scrubbers." Passage of the Clean Air Act in 1970 tightened the particulate code substantially. In combination with the shift to waterwall construction (minimum air in-leakage and tolerance of high gas temperatures), these regulations introduced the dry ESP as the accepted control device. Interestingly, the requirement for ESPs to meet particulate codes was the driving force for the initial introduction of heat recovery features to U.S. municipal incinerator practice: one could not afford to install an ESP at the high excess air levels commonly used with (leaky) incinerators of all-refractory construction. By 1970, the ESP had already become dominant for European facilities.

In the mid to late 1970s, the regulatory spotlight in the United States shifted to the polychlorinated dioxin/furan compounds. The proper control technology for these materials focuses on upgrading the combustion environment. Burn out the precursors and there will be little or no dioxin. The data on emission factors suggest that combustion control, by itself, is an effective solution and that the dioxin problem is now well in hand.

In parallel with the dioxin/furan controls, the requirements for back-end treatment underwent a major change: extending the control requirement to include "acid gases": most importantly, HCl and SO_2. The solution to the requirement for acid gas control was the combination of the semi-dry absorber with lime slurry addition followed by a fabric filter. This system also cooled the gases and, thus, further reduced dioxin/furan and mercury emissions. The excellent fine-particle control effected by the fabric filter also significantly reduced emissions of heavy metals.

In the early 1990s, attention moved to mercury and to the nitrogen oxides. Mercury can be controlled to an acceptable degree through injection of activated carbon ahead of the fabric filter. As discussed above, operational hazards with the sulfide make the carbon option preferable. Activated carbon injection has also shown effectiveness in reducing dioxin/furan and other high-molecular-weight hydrocarbons (PNH, PCBs) to levels below those achieved by combustion control. Modern plants also address nitrogen oxides control to the 50% to 65% level using ammonia or urea solution injection into the flue gases in the superheater region (selective, noncatalytic reduction, or SNCR technology).

Therefore, at the present, "optimum" control for municipal waste combustors involves high-quality combustion controls and mixing systems, urea/ammonia and carbon injection, semi-dry spray dryer absorbers, and a fabric filter (plus a tall stack that effects dispersion and avoids building downwash). The direction of U.S. regulatory agencies is difficult to predict. However, one might speculate that greater control will be required for metals and, perhaps, for nitrogen oxides. This could lead to the use of a dry followed by a wet electrostatic precipitator (replacing the fabric filter) with reheat ahead of catalytic, ammonia-based NO_x reduction. Some plants with this APC flowsheet are already operating in Europe.

Typical design parameters for ESP, fabric filters, and a backup wet scrubber for application to MWC systems are shown in Table 9. In these instances, it is assumed that a spray dryer-type acid gas control system precedes the dust collector. For the ESP, rigid-frame and rigid-electrode types predominate. Pressurized, heated insulator compartment ventilation is important to minimize the effects of flue gas corrosiveness and the stickiness

Table 9 Design Parameters for MWC Air Pollution Control Devices

Electrostatic precipitator design parameters		
Particulate loading (mg/am^3)		1,150–20,600
Required efficiency (%)		98–99.9
Number of fields		3–4
SCA ($m^2/1000\,acm^3$)		120–170
Average secondary voltage (kV)		35–55
Average secondary current (mA/m^3)		1–1.75
Gas velocity (m/sec)		0.91–1.07
	Particulate	Acid gas control
Flue gas temperature (°C)	165–230	110–150
Flue gas moisture (% volume)	8–16	12–20
Ash resistivity (ohm-cm)	10^8–10^9	10^8–10^9

Fabric filter design parameters		
	Reverse air	Pulse jet
Operating temperature (°C)	110–232	
Type of fabric	Woven fiberglass or Ryton felt	
Fabric coating	10% Teflon B or acid resistant	
Fabric weight (g/m^2)	320	540 or 740
Bag diameter (cm)	20	15
Net air-to-cloth ratio	1.5–2.0 : 1	3.5–4.0 : 1
Minimum compartments	6	4
Overall pressure drop (kPa)	1–1.5	2–2.5
Estimated bag life (years)	3–4	1.5–2

Wet scrubber design parameters		
	Venturi stage	Absorber stage
Gas velocity (m/sec)	27–46	1.8–3
Pressure drop (kPa)	10–17.5	1–2
L/G (l/min per am^3/min)	1.33–2.66	2.66–5.33
Scrubbing medium	Water	Caustic
Solution pH	< 1–2	6.5–9
Materials of construction	Hastelloy, Inconel	FRP-lined C Steel

Source: From (552).

of the fly ash. Fabric filters generally use fiberglass bags, often with Teflon B coatings and thin-film polytetrafluoroethylene membranes to enhance collection of very fine particles. The wet scrubber, sometimes used as part of a two-stage flue gas cleaning system downstream of an ESP, effects a particulate removal polishing function and acid gas removal as an alternative to the spray dryer technique. The low back-end temperature of the scrubber achieves higher SO_2 and HCl removal efficiencies than the spray dryer and, in conjunction with carbon addition, better mercury, metals, and dioxin removal. The absorber can be a packed tower, a tray tower, or a radial spray tower.

2. Biological Wastewater Treatment Sludge Incinerators

Until 1992, air pollution emission limits for sludge incinerators in the United States focused on the control of particulate matter. The relatively lenient particulate emission standards called out in U.S. law were substantially endorsed without change by all of the states. The federal emission limitation of 1.3 pounds of particulate per dry (English) ton of sludge burned can be readily met using a Venturi- and/or tray-type wet scrubber with an overall pressure drop of the order of 0.1 atm. Often, the combination of Venturi and tray tower was used to effect particulate control and, with substantial once-through water flow to the tray section, to subcool the flue gases to condense excess water and effect plume suppression.

In the late 1980s and early 1990s, one began to see a shift in the APC concepts selected for U.S. sludge incinerator upgrades and for new facilities. Specifically, one notes an increase in the use of a wet electrostatic precipitator downstream of a Venturi and impingement tray scrubber. This increment in control substantially reduces total particulate emissions, but the particular objective sought in this control increment was a reduction in the emission of heavy metals and high-molecular-weight hydrocarbon aerosols. The performance with respect to metals control of this coupled APC system is illustrated in Table 10.

For multiple hearth furnaces, stringent total hydrocarbon regulations promulgated in late 1992 led to the installation of separate afterburners (typically operated at 700° to 850°C). An alternative design involved rework of the system to move the sludge feed point to the second hearth and to add burners and simple refractory baffles to the top hearth. The latter concept is known as a "Zeroth Hearth Afterburner." In general, none of the fluid bed incinerators required modification or augmentation to achieve the total hydrocarbon requirements.

3. Hazardous Waste Incinerators

The regulation of air emissions from hazardous waste incinerators initially focused on means to ensure destruction of the toxic organic matter in the feed and on control of acid gases (particularly HCl). This led to concern over the severity of the combustion environment (monitored through temperature, oxygen concentration, and total flow rate) and, usually, to the addition of Venturi scrubbers with alkali for particulate and acid gas capture. In the mid and late 1980s, it became clear that the effluent gases could and often did include heavy metals. This led to increased regulatory attention being paid to metals

Table 10 Metals Control Efficiency of Venturi and Venturi Plus Wet Electrostatic Precipitators in Fluid Bed Sewage Sludge Service

Venturi scrubber (only)				Venturi+wet electrostatic precipitator		
Element	Data sets	Average	Minimum	Data sets	Average	Minimum
Arsenic	13	99.576%	95.510%	12	99.975%	99.892%
Beryllium	13	99.995%	99.987%	12	100.000%	100.000%
Cadmium	17	98.829%	94.940%	12	99.943%	99.690%
Chromium	16	99.909%	99.664%	12	99.994%	99.981%
Lead	16	99.931%	99.749%	12	99.999%	99.999%
Nickel	17	99.863%	99.388%	12	99.992%	99.977%

Table 11 Air Pollution Control Systems on Hazardous Waste Incineration Systems (1987)

Air pollution control type	Number	Percent
Quencher	21	23.3
Venturi scrubber	32	35.6
Wet scrubber	7	7.8
Wet ESP	5	5.5
Ionizing wet scrubber	5	5.5
Other, non-specified scrubber	12	13.3
Packed tower absorber	18	20.0
Spray tower absorber	2	2.2
Tray tower absorber	1	1.1
Other absorber	2	2.2
None/unknown	31	34.4
Total systems surveyed	90	

Source: From (336).

emissions and, often, to requirements for health risk assessments on the implications of metals emissions. However, in most instances, the Venturi scrubber systems can satisfactorily achieve acceptable emission levels. In large plants in the United States and in Europe, the spray dryer with fabric filter combination or the Venturi–wet ESP combinations have become accepted. The distribution of APC alternatives in the mid-1980s is shown in Table 11.

Only in the rare case where an entirely gaseous organic waste or an organic liquid without dissolved or suspended solids is being burned will no follow-up control be required to meet emission regulations. The presence of chlorine or other halogens generally requires a scrubbing or absorption step. Suspended ash will require particulate control. In some specialized cases, such as the combustion of nitrates or nitric acid wastes, NO_x control is necessary. However, in most cases, NO_x control is not a requirement, thus allowing both the combustion conditions and the APC device to focus on the environmentally more significant particulate matter, dioxins, heavy metals, and other hazardous emissions.

The most commonly used APC systems on hazardous waste incinerators involves a water quench followed by a high-energy Venturi scrubber. Although this approach is effective for most particulate matter, the high-pressure drop (3 to 40 kPa) contributes significantly to the operating cost of the incineration facility. A spray dryer absorber or packed tower absorber may be added for acid gas removal and a demister to capture any carryover droplets. If metal aerosols are important, an ionizing wet scrubber or wet ESP may be preferred. If high-molecular-weight organic matter and, especially, dioxin/furan compounds are involved, activated carbon injection may be appropriate. Typical design parameters for APC on hazardous waste incinerators are summarized in Table 12.

C. Continuous-Emission Monitoring

Regulatory agencies have been increasingly demanding continuous-emission monitoring (CEM) of pollutant emissions. In the 1980s, the primary pollutants monitored included particulate (opacity), SO_2, NO_x and CO_2 but by the early 1990s, CEM use was extended to

Table 12 Typical Design Parameters for APC Hazardous Waste Incinerators

Equipment	Design parameters
Particulate	
ESPs	SCA = 1.31 to 1.64 m^2/m^3/min
	w_e = 6 cm/sec
Fabric filters	Pulse-jet A/C = 0.9 to 1.22 m/min
	Reverse-air A/C = 0.46 to 0.61 m/min
Venturi scrubbers	ΔP = 10 to 20 kPa
	L/G = 1 to 2 l/min per m^3/min
Acid gases	
Packed towers	Superficial velocity = 1.8 to 3 m/sec
	Packing depth 1.8 to 3 m
	L/G = 2.7 to 5.3 gal/min per 1000 acfm
	Caustic scrubbing medium, target pH = 6.5
	Stoichiometric ratio = 1.05
Spray dryers	Low temperature
	Retention time 15–20 sec
	Outlet temperature = 121° to 160°C
	High temperature
	Retention time 15–20 sec
	Outlet temperature = 176° to 232°C
	Stoichiometric lime ratio = 2 to 4

Source: From (440).

include HCl, CO, ammonia, and total hydrocarbons (THC). The most common CEM technologies are summarized in Table 13. The output from CEM systems is used to confirm continuing compliance with air emission regulations and also as input to process control.

D. Air Pollution Control to Achieve Air-Quality Objectives

1. General

The ultimate objective of APC efforts is to achieve or improve air quality. Thus, it is often useful to have tools with which stack emission characteristics can be translated into a quantitative assessment of the impact on the ground-level concentration (GLC) of pollutants. This is the art and science of "dispersion modeling."

Dispersion modeling involves the science of meteorology (really micrometeorology) combined with consideration of the many and complex interactions between plume, atmosphere, and flow field of the real world: local meteorological patterns and their variation moment to moment, day to day, and year to year; the role of hills and valleys and other topographic features as well as tall buildings that affect the impaction of plumes; eddy flow about buildings, clusters of buildings, and the stack itself that can disturb plume dispersion; photochemical reactions that generate or destroy pollutants; deposition and washout by rain that removes pollutants from the atmosphere; and so on. The objectives of this book are inconsistent with a comprehensive treatment of these matters. However, we

Table 13 Continuous-Emission Monitoring Technologies

Parameter	CEM technology
Particulate matter (opacity)	Transmissometer, beta ray absorption
Sulfur dioxide (SO_2)	Ultraviolet absorption, IR pulsed fluorescence
Nitrogen oxides (NO_x)	Chemiluminescence, ultraviolet spectroscopy, IR
Hydrogen chloride (HCl)	IR with gas filter
Carbon monoxide (CO)	IR
Carbon dioxide (CO_2)	IR
Oxygen (O_2)	Electrochemical cell
Total hydrocarbons (THC)	Flame ionization detection
Other organic air toxics	Chromatography
Ammonia (NH_3)	Same as NO_x[a]

[a] Ammonia is converted to NO_x in one of two split streams; both are analyzed for NO_x and ammonia determined by difference.

present a simplified treatment that allows a preliminary screening of air-quality impacts as a starting point in assessments.

The discharge of flue gases from a stack begins the process of dispersion and dilution. The overall momentum flux of the discharge establishes the ability of the plume to retain its integrity in conflict with the atmosphere's tendency to dilute and disperse the flow. The velocity of the discharge adds an effective stack height beyond the physical stack. Further increases in effective stack height can arise due to the effects of the temperature and mean molecular weight of the stack discharge relative to the ambient (positive or negative buoyancy effects).

The atmospheric conditions at the time and point of discharge also impact dispersion in many ways. The wind speed is clearly important (consider, for example, the discharge from the stack as a jet in crossflow). Another atmospheric property, the atmospheric stability (Table 14), is also important. Further, the heating of the atmosphere through contact with the ground is known to be different in urban areas from rural areas (the "heat island" effect of the urban areas heats the atmosphere more strongly).

One recognizes that whereas the stack conditions may remain relatively constant with time, atmospheric parameters change constantly. Thus, the validity of any one calculation holds for only a snapshot in time. The hourly, monthly, annual, and other

Table 14 Atmospheric Stability Classifications

Classification	Definition	Typical weather conditions
A	Strong instability	Sunny, sun $\geq 60^\circ$ above horizon, light winds
B	Moderate instability	Sunny, sun 35° to 60° above horizon, light winds
C	Slight instability	Partly sunny, sun 15° to 35° above horizon, light to moderate winds
D	Neutral stability	Cloudy skies (day or night), winds at any speed or clear skies, moderate to strong winds
E	Slight stability	Night, mostly cloudy, light winds
F	Moderate stability	Night, partly cloudy or clear, light winds

averaged ground-level pollutant concentrations are, then, a statistically weighted combination of many calculated ground-level concentration profiles. Structured arrays of the meteorological statistics used in such averaging computations are generally available as computer files from weather services and/or governmental agencies. In the United States, for example, the National Oceanographic and Atmospheric Administration (NOAA) is the source of such information.

2. Simplified Dispersion Calculations

The mathematical evaluation of plume dispersion continues to undergo development. The force driving this technological evolution is the movement of many environmental regulatory agencies toward a health impact and, thus, a ground-level concentration (GLC) basis for decision-making. Because of the heightened regulatory focus on GLC impacts (not just stack concentration) when judging the acceptability of incineration projects, it is useful to have tools available with which to make preliminary evaluations. The methodology presented here is relatively simple. However, it provides both a means to screen GLC patterns from incineration sources as well as an introduction to the discipline of dispersion modeling.

a. Gaussian Dispersion. In the dispersion situations of interest, the relevant atmospheric layer is that nearest to the ground (the troposphere). There, velocity gradients, thermal and induced "mechanical" turbulence, and flow field complexity are the greatest. The transfer of momentum in the atmosphere is related to the stability of the atmosphere and to turbulence effects. As wind speed increases, the effluent from a continuous source is diluted by a greater volume of air. The turbulence-driven spreading of material in the direction normal to the mean wind direction is an important feature of the dispersion process.

The estimation of GLC has evolved from the early work of Sutton (318). A spectrum of sophisticated analysis techniques has developed from that beginning. Most, however, are enhancements of a basic diffusion equation incorporating standard deviations of Gaussian distributions: σ_y for the distribution of material in the plume perpendicular to the wind direction in the horizontal and σ_z for the vertical distribution of material in the plume. Numerical values for these parameters (expressed as a functional relationship for ease in computer analysis) have been developed as a function of the downwind distance x for several standard characterizations of atmospheric stability: from class A (the most unstable) to class F (the most stable).

Table 14 describes the nature of these atmospheric conditions and Table 15 presents the coefficients for the equations describing the standard deviation distributions as a function of distance from the source. In Table 15, the curves for the Gaussian distributions correspond to the following analytic approximations (368):

$$\sigma_z = \frac{Lx}{[1 + (x/a)]^q} \tag{45}$$

$$\sigma_y = \frac{Kx}{[1 + (x/a)]^p} \tag{46}$$

We are interested in the GLCs developed from a stack discharging at an effective total stack height H. The effective height is the sum of the physical stack height (h_s) and an increment due to velocity and buoyancy effects: the plume rise. The general plume

Table 15 Function Coefficients describing Dispersion Standard Deviations σ_y and σ_z

Stability class	a (km)	L (m/km)	q	K (m/km)	p
A	0.927	102.0	−1.918	250.0	0.189
B	0.370	96.2	−0.101	202.0	0.162
C	0.283	72.2	0.102	134.0	0.134
D	0.707	47.5	0.465	78.7	0.135
E	1.07	33.5	0.624	56.6	0.137
F	1.17	22.0	0.700	37.0	0.134

Source: From (368).

dispersion relationship relates the concentration χ to the downwind, lateral, and vertical distance (x, y, and z, respectively) as follows:

$$\chi(x,\ y,\ z;\ H) = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} \tag{47}$$

where

χ = Concentration (kg/m^3)
Q = Emission rate (kg/sec)
u = Wind speed (m/sec)
$\sigma_y,\ \sigma_z,\ H,\ x,\ y$, and z (m)

The units of χ are in kg/m^3 at 20°C. For gases of molecular weight m_0, multiply χ by $10^6 \times 24/m_0$ to convert to parts per million (by volume).

When the concentration is to be calculated along the centerline of the plume ($y = 0$) and at ground level ($z = 0$), Eq. (47) simplifies to

$$\chi(x,\ 0,\ 0;\ H) = \frac{Q}{\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \tag{48}$$

The horizontal and vertical dispersion coefficients (σ_y and σ_z, respectively) are representative of an average sampling time of about 10 minutes and for the case where there is unrestricted vertical diffusion (see below). It is often useful to carry out all of the calculations in dispersion modeling using a unit emission rate (e.g., $Q = 1$ kg/sec). Then, since all of the concentration results scale linearly with Q, only a simple ratio scaling is necessary to produce specific numerical GLC results for a variety of pollutants, each with its own stack emission rates.

b. Averaging Time and Mixing Height Effects. The movement of the atmosphere is not a smooth, isothermal, laminar flow. Instead, the flow field is comprised of eddies of various sizes, rising and falling air streams due to buoyancy effects, and is subject to frequent major and minor changes in direction. As a consequence, the GLC of a pollutant varies with time. As the wind swings through the compass points, the GLC will go to zero for the

upwind receptors. Further, inversion layers may trap pollutants emitted near the ground. This latter situation is characterized by the "mixing height" L.

At a height $2.15\sigma_z$ above the plume centerline, the concentration is one-tenth the plume centerline concentration at the same distance from the source. When this boundary reaches the stable layer height L, the dispersion process becomes significantly restricted. To compensate for this effect, allow σ_z to increase to a value of $L/2.15$ or $0.47L$. At this distance (x_L), the plume is assumed to have a Gaussian distribution in the vertical direction. Assume that by the time the plume travels twice that far (to a distance $2x_L$), the plume has become uniformly distributed (concentration is no longer a function of elevation). For $x > 2x_L$, the concentration at any height between the ground and L is given by Eq. (49a) and the GLC by (49b): for any z from 0 to L and for $x > 2x_L$, where x_L is where $\sigma_z = 0.47L$:

$$\chi(x,\ y,\ z;\ H) = \frac{Q}{\sqrt{2\pi}\sigma_y L u} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_y}\right)^2\right] \tag{49a}$$

$$\chi(x,\ 0,\ 0;\ H) = \frac{Q}{\pi\sigma_y\sigma_z u} \tag{49b}$$

As noted above, the calculations using Eqs. (47) and (48) assume a relatively constant wind direction and speed and are "10-minute averages." That is, a rapid-response instrument would show a fluctuating GLC that, if averaged over 10 minutes, would be approximated by the calculated result. If the averaging time is different, the average GLC would change: to a higher value for shorter-term averaging and to a lower value for longer-term averaging. The effect of averaging time is important since health effect criteria are often presented in the context of some given exposure scenario: a one-hour average, daily average, annual average, etc. Multipliers of the 10-minute result to convert the result to that for different averaging times are presented in Table 16. The calculated 3-minute averaging time concentration is often used to represent "instantaneous" values.

c. Effective Stack Height Considerations. The behavior of the plume from an incinerator stack as a ground source or as an elevated source is often not intuitively obvious. For example, if severe building downwash occurs, the emissions from a stack can be swept into

Table 16 Multiplier Factors for Different Averaging Times (Ratio of Calculated Concentration to 3-Minute Average)

Sampling time	Ratio
3 minutes	1.00
15 minutes	0.82
1 hour	0.61
3 hours	0.51
24 hours	0.36
10 minutes to about 2 hours	$\chi_s = \chi_k \left(\frac{t_k}{t_s}\right)^p$

Where χ_s and χ_k are the concentrations at the desired sampling and for the shorter (probably about 10 minutes) sampling time and p is between 0.17 and 0.2. *Source*: From (292).

the eddy downwind of a building and, afterwards, disperse as though a ground source. The decision as to the dispersion category depends on the stack diameter, height, and discharge temperature and velocity; the wind speed and direction; and the location, size, and geometry of nearby buildings. Clearly, the complexity of the interaction among these several parameters underlines the approximate nature of "rules of thumb" regarding the resulting behavior. However, the structured methodology given below [developed by Briggs in (293)] provides a useful and generally conservative approach to making a judgment in this matter.

If an effluent is discharged at a low velocity into a strong wind, the plume can be drawn down into the low-pressure region in the downwind wake of the stack. The significance of the stack downwash phenomena is tested by analysis of the results from Eq. (50), where D is the inside stack diameter (m), v_s is the discharge velocity (m/sec), u is the wind velocity. The calculations should be made over a range of values, say, from 1.0 to 10 m/sec. The physical stack height above the ground (m) is designated h_s.

$$h' = h_s + 2\left(\frac{v_s}{u} - 1.5\right)D \tag{50}$$

If the effluent is emitted from a stack on or near a building, a second downwash effect (the building downwash) can also limit dispersion. Let $\mathscr{L}_b$ equal the lesser of the building height h_b or the building width perpendicular to the wind direction, w_b. If h' is less than $h_b + 1.5\mathscr{L}_b$ and the point of emission is on the roof, anywhere within $\mathscr{L}_b/4$ of the building, or within $3\mathscr{L}_b$ directly downwind of the building, the plume can be considered to be within the region of building influence. If this is not the case, set $h'' = h'$ and go on to consider buoyancy effects as described in Section d below. If the plume is within the region of building influence, there are four possibilities:

1. If h' is less than $h_b + 0.5\mathscr{L}_b$, part or all of the effluent is likely to circulate within the aerodynamic "cavity" that forms in the lee of the building. The downwind cavity usually begins at the upwind edge of a flat roof (or the ridge line of a pitched roof unless the crest of the roof is parallel to the wind direction). It grows to a height of about $h_b + 0.5\mathscr{L}_b$ and a width a little greater than w_b. It extends over all lee sides of the building and downwind 2 to 3.5 times $\mathscr{L}_b$. Thus, effluents so captured may affect persons on the ground. If building ventilation units draw from the lee side of the building, the building inhabitants could be directly affected also.

The mean concentration (χ) in the cavity region may be estimated using Eq. (51), where Q is defined as the emission rate of the pollutant of interest in kg/sec:

$$\chi = \frac{KQ}{u\mathscr{L}_b^2} \tag{51}$$

Generate the parameter H', calculated as $(h' - h_b)/\mathscr{L}_b$, and if $H' > 0.35$, K is generally 1.0 or less throughout the cavity. However, if $H' < 0.35$, K is typically 1.5 up to as high as 3.0 except on the side of the building where the effluent is emitted, where K can range up to 100.

The pollutant concentration along the downwashed plume can be roughly approximated by

$$\chi = \frac{4Q}{us^2} \tag{52}$$

where s is the distance from the source measured along the axis.

2. If $h' > h_b$, compute $h'' = 2h' - (h_b + 1.5\mathscr{L}_b)$.
   If $h' < h_b$, compute $h'' = h' - 1.5\mathscr{L}_b$.

3. If h'' is greater than $\mathscr{L}_b/2$, the plume remains an elevated source and only buoyancy considerations need further attention.

4. If h'' is less than $\mathscr{L}_b/2$, the plume behaves as a ground source with an initial cross-sectional area $A = \mathscr{L}_b^2$.

The above rules reduce to a simple form for a squat building ($h_b < w_b$). Then if $h' \geq 2.5h_b$, the plume escapes the building influence and $h'' = h'$; if $h' \leq 1.5h_b$, the plume downwashes into the building cavity, becoming a ground source with an area $A = h_b^2$; for in-between values of h', the plume remains elevated where $h'' = 2h' - 2.5h_b$. Note that the simplified relationship between stack and building height is identical to the "2.5 times building height" rule used by most U.S. regulatory authorities in defining a "Good Engineering Practice" (GEP) stack design. The GEP stack is supposedly free of building downwash effects.

d. Buoyancy Effects. If the analysis so far indicates an elevated plume, one should evaluate the effect of plume buoyancy. Buoyancy effects are important if the density of the plume differs from that of the ambient by more than 1%. If the effluent molecular weight is within 2% of that of air and its temperature is within 2.8°C of ambient, buoyancy can be neglected. Then, set H (the effective source height for use in dispersion modeling) equal to h'' and proceed to the modeling calculations described previously.

If this simplifying situation does not obtain, calculate the parameter Δ according to

$$\Delta = \Delta_T + \Delta_m + \Delta_w \tag{53}$$

where Δ_T is the temperature contribution to the relative density difference, Δ_m is the molecular weight contribution, and Δ_w is the liquid water contribution.

Δ_T is calculated from $\Delta_T = -(c_{\text{pe}}/c_{\text{pa}})(\Delta_T/T)$, where c_{pe} is the mass-weighted mean specific heat at constant pressure of the incinerator effluent and c_{pa} is the same for the ambient air ($c_{\text{pa}} = 0.24\,\text{cal/gm°C}$), ΔT is the temperature difference (°C) between the stack gas and the ambient, and T is the ambient absolute temperature (°K).

$\Delta_m = (1 - 28.9/m_0)$, where m_0 is the mass-weighted mean molecular weight of the effluent gases.

$\Delta_w = 8Q_W/M_0$, where Q_W is the estimated mass flux of liquid water in the effluent and M_0 is the mass flux of the total effluent stream. Except for incinerators equipped with a wet scrubber with a poor demister, this effect is usually negligible.

If Δ is positive, the plume is denser than air (negatively buoyant) and may sink to the ground near the source. If Δ is negative, the plume is buoyant and may rise.

NEGATIVE BUOYANCY (POSITIVE Δ). Here, the plume is heavier than air and may fall to the ground rather close to the source if

$$u < 0.22C\sqrt{g\Delta D} \tag{54}$$

where g is the gravitational acceleration of $9.8\,\text{m/sec}^2$ and C is given by

Condition	Urban site	Rural site
Day, $u < 3.5$ m/sec	3	5
Day, $u > 3.5$ m/sec	5	10
Night, $u > 3.5$ m/sec	7	15
Night, $u < 3.5$ m/sec	10	35

If $u > 3.5$ m/sec, set $H = h''$ and conduct the dispersion calculations assuming an elevated plume. If $u < 3.5$ m/sec, however, the plume falls and behaves as a ground source with an initial cross-sectional area $A = 0.2h_s^2$ at a distance roughly equal to

$$x = \frac{4.5h_s u}{\sqrt{g\Delta D}} \text{ (m)} \tag{55}$$

The exception to this rule is the rural source at night when $u < 3.5$ m/sec. In this case, the fall distance is limited to approximately $100|F|^{1/4}$, where F is defined below. In this particular case, treat the plume as above only if $(h_s - 100|F|^{1/4}) < 0.2h_s$, whereas if $(h_s - 100|F|^{1/4}) > 0.2h_s$ but less than $0.5\mathscr{L}_b$, in association with a building, treat it as a ground source with $A = \mathscr{L}_b^2$. If neither of these conditions holds, treat it as an elevated source with $H = h_s - 100|F|^{1/4}$.

Note than even in a windless state, the plume does not reach the ground with no dilution at all. The plume does mix with the air as it falls. To avoid a singularity in the calculations, consider an "effective minimum wind speed" equal to $|F/h_s|^{1/3}$. If this speed is greater than the right-hand side of Eq. (51), the density effect may be neglected and H set equal to h'' followed by elevated plume dispersion modeling. Low-wind situations are important for nonbuoyant plumes. Their frequency can be judged using the following (predominantly at night):

Terrain type	Frequency of $u < 1$ m/sec
Flat	2% to 5%
Rolling	5% to 10%
Hilly	10% to 20%
Mountain region	20% to 30%
Mountain, sheltered	30% to 40%

For the frequency of winds less than 1 m/sec, multiply the above by u^2 (where u is the upper limit in m/sec).

POSITIVE BUOYANCY (NEGATIVE Δ). Here, the plume is lighter than air and the plume gains an effective stack height increment.

First, calculate a value for the parameter F given by

$$F = -2.6\Delta M_0 \tag{56}$$

where M_0 is the mass flux of effluent (kg/sec). During the day or at night when the wind speed u is greater than 3.5 m/sec, the effective source height of a buoyant plume is approximated by

$$H = h'' + 21F^{2/3}/u \tag{57}$$

During the night when u is less than 3.5 m/sec, the effective source height is estimated by

$$H = h'' + 19F^{1/3}/u \tag{58}$$

e. Dispersion Analysis for Odor Sources. Dispersion modeling of odor problems differs considerably from that for more conventional pollutants. Most importantly, the criterion of success is not a mathematically definable event but the lack thereof (no complaints). A complaint can arise when an individual (1) perceives an odor for a long enough time period

to recognize the sensation and (2) concludes that the odor is unwanted (not necessarily "bad"). Odor is often an important factor for sludge management facilities.

The sensory responses involved in respect to odor involve four measures: odor intensity, detectability, character, and hedonic tone. Intensity is the strength of the perceived odor sensation. That differs from both the concentration of the odorant compound and the number of dilutions needed to render the contaminated air "odor-free".

Odor intensity (I) is related to concentration (C) by Eq. (59), where k is a constant and n an exponent that are unique to the odorant compound:

$$I\,(\text{perceived}) = kC^n \tag{59}$$

This relationship (Stevens' law) is an important concept in controlling odor using dilution. For most odorants, n ranges from about 0.2 to 0.8. Note that if $n = 0.2$, a tenfold dilution decreases the perceived intensity by only a factor of 1.6, whereas if $n = 0.8$, the same dilution reduces the perceived intensity by a factor of 6.3. High n compounds include ammonia and aldehydes, and low n compounds include H_2S, butyl acetate, and many amines. Exponents for Stevens' law are given in Table 17.

A scale of intensity has been developed:

0	None	2	Faint	4	Strong
1	Very faint	3	Easily recognized	5	Very strong

In quantitative intensity studies, the magnitude of intensity is determined anchored to a reference (a ratio scale). Often 1-butanol is used as the reference standard. This can cause problems when the odor character of the odorant of interest is significantly different from the standard.

Odor detectability relates to the minimum concentration that produces an olfactory response. Odor perception varies among individuals. Therefore, the concentration that just results in perception of an odor is statistically distributed. The concentration where 50% of

Table 17 Exponents for Stevens' Law

Compound	Exponent
Acetaldehyde	0.26
Allylamine	0.58
Benzene	0.55
Butyl mercaptan	0.29
Chloroform	0.58
Cyclohexane	0.66
Ethyl mercaptan	0.25
Ethanol	0.54
Heptane	0.43
Methyl mercaptan	0.34
Nitrobenzene	0.74
Octane	0.36
Propyl mercaptan	0.33
Styrene	0.48
Toluene	0.53

Source: From (556, 557).

a group just perceive odor is known as the "threshold odor level," or TOL. The TOL is a published "property" of many organic compounds. Note, however, that at the TOL, one-half of the people are still complaining! We must go somewhat below that before the telephone stops ringing. The TOL differs from the recognition threshold: the concentration where the specific compound can be identified.

Odor character identifies an odor and differentiates it from other odors of equal intensity. Over the years, a taxonomy of odor characterization descriptors has developed that supports relatively precise specification of how an odor is perceived. Odor character sometimes changes with concentration.

Odor thresholds and characteristics for several selected odorous compounds are given in Table 18.

Hedonic tone is the property of pleasantness or unpleasantness applied to an odor that relates to the response of a particular exposed individual. Note that this definition differs from "acceptable/unacceptable" since these descriptors include the expectations of the individual in a specific situation. Thus, a lilac odor might be acceptable for a flower arrangement but unacceptable as an emission from a cosmetics firm... but pleasant in either situation. Hedonic tone is an objective measure but is still based on the experience and emotional expectations of the affected individual. Thus, animal manures might be unpleasant to many but pleasant to the dairy farmer. As with character, the hedonic tone for some compounds changes with concentration and may change by adaption of the receptor individual.

Another factor important to the air pollution characterization of odor events related to odor transmission and perception is the duration of the odorous experience. Since the

Table 18 Odor Characteristics of Industrial Odorous Compounds

Compound	Detection threshold (ppmv)	Recognition threshold (ppmv)	Odor descriptors
Acetaldehyde	0.067	0.21	Pungent, fruity
Allyl mercaptan	0.0001	0.0015	Disagreeable, garlic
Ammonia	17	37	Pungent, irritating
n-Butyl amine	0.080	1.8	Sour ammonia
Chlorine	0.080	0.31	Pungent, suffocating
Dibutyl amine	0.016	—	Fishy
Dimethyl amine	0.34	—	Putrid, fishy
Dimethyl sulfide	0.001	0.001	Decayed cabbage
Diphenyl sulfide	0.0001	0.0021	Unpleasant
Ethyl amine	0.27	1.7	Ammoniacal
Ethyl mercaptan	0.0003	0.001	Decayed cabbage
Hydrogen sulfide	0.0005	0.0047	Rotten eggs
Phenyl mercaptan	0.0003	0.0015	Putrid, garlic
Pyridine	0.66	0.74	Pungent, irritating
Skatole	0.001	0.05	Fecal, nauseating
Sulfur dioxide	2.7	4.4	Pungent, irritating
Trimethyl amine	0.0004	—	Putrid, fishy

Source: From (543, 544).

eddy transport mechanism from a source to the receptor involves fluctuations in the degree of dilution achieved, one must carefully distinguish between dilution to where the long-term average concentration is below the TOL (or other goal) and the condition where the instantaneous concentration never exceeds the TOL. Clearly, to achieve the "no complaint" objective, we must dilute to some fraction of the TOL on the average such that no peaks of significant duration or intensity exceed the TOL. Practitioners often use a rule of thumb of 15- to 30-fold less than the TOL as the complaint extinguishment point based on the "instantaneous" concentration (the 3-minute average). Clearly, economic considerations often lead to target objectives that are less aggressive.

The "odor emission rate" is often characterized in "odor units." This measure of odor requires determination of the number of dilutions required to achieve 50% perception, 50% no-perception of odor using a panel of "average" human beings. Samples of the stack gases are diluted until this objective is achieved. Thus, a report that a 1000-ft^3/min stack discharge (corrected to 20°C) has an odor emission of 35,000 odor units means that 35-fold dilution is required of the total gas flow to reach the 50% perception level. The numbers of stack gas dilutions achieved between the point of stack discharge and a receptor may be calculated using Eq. (60):

$$number\ of\ dilutions = \frac{Qm_0}{24M_0\chi} \tag{60}$$

where the variables are as dimensioned and defined above.

15

Approaches to Incinerator Selection and Design

How do you design an incinerator? We wish the answer were straightforward, the underlying principles uncluttered with contradictions and free of the need to apply judgments. This chapter, however, only scratches the surface of the challenge of system design in an attempt to structure, if not guide, the design process.

The selection of a waste management system requires consideration of many factors (technical, economic, political, etc.). The decisions are rightly the responsibility of the ultimate owner or owner/operator of the system, but often the engineer is an active participant. Often, cost factors dominate in these decisions although less quantitative issues such as permitting uncertainty, the impacts of mandated recycling, and community acceptance are increasingly important. Further, the flexibility of the system to cope with both changing waste character and tightening regulatory requirements is critical to long-term viability.

Capital, operating, and maintenance costs are basic and important criteria. For incineration systems, one must be sure that the capital cost includes provision for spare parts, extra-rugged construction, and other features that protect continued operability. Also, operating cost should include consideration of extraordinary training expenses, higher-than-normal operator wage scales (to ensure a sophistication of operator compatible with sophisticated equipment), and other reasonable and prudent investments to keep costly and critical equipment operable and at their peak of performance. Further, maintenance costs should recognize the more aggressive working environment of incineration systems and allow for specialist services such as contract maintenance of instrumentation and control systems, regular refractory repair, and so forth.

Once the basic decision to pursue incineration has been made, however, the steps of implementation include the following:

I. CHARACTERIZE THE WASTE

Using the methods and cautions described previously, obtain the best practical characterization of the quantity, composition, and critical characteristics of the waste. Keep in mind

future growth and the impact of changes in technology, regulations, and economics on operating requirements.

II. LAY OUT THE SYSTEM IN BLOCKS

Too often, incineration facilities are developed in pieces with insufficient attention given to the mating of interfaces between various elements. Remember the concept of *system*. This is particularly important with materials handling facilities.

III. ESTABLISH PERFORMANCE OBJECTIVES

Review present and soon-to-be-enacted (or enforced) regulatory requirements for effluent quality. Evaluate the needs for volume reduction and residue burnout or detoxification.

IV. DEVELOP HEAT AND MATERIAL BALANCES

Using the techniques developed early in this book, determine the flows of material and energy in the waste, combustion air, and flue gases. Consider probable materials of construction and establish reasonable limits on temperatures. Explore the impact of variations from the "average" waste feed composition and quantity. In practice, these off-average characteristics will better characterize the day-to-day operating conditions. Use analytical tools and techniques to the greatest reasonable extent. Pencils are ever so much cheaper than concrete and steel.

V. DEVELOP INCINERATOR ENVELOPE

Establish the overall size of the system using heat release rates per unit area and per unit volume, etc. Use burning rate, flame length and shape, kinetic expressions, and other analysis tools to establish the basic incinerator envelope. The final shape will depend on judgment as well as on these calculations. Draw on the literature and the personal experience of others. Use the techniques described in earlier chapters to confirm the degree to which the experiences of others are, in truth, comparable to your situation and which are not. Learn from others while, perhaps, not copying them.

Interact with engineers, vendors, operators, and designers of other combustion systems with similar operating goals or physical arrangements. Attempt to find the balance between costly overconservatism and the unfortunate fact that few of the answers you want are tractable to definitive analysis and computation. Particularly, talk to system operators. Too frequently, designers speak only to each other and the valuable insights of direct personal experience go unheard or, worse, unasked for.

VI. EVALUATE INCINERATOR DYNAMICS

Apply the jet and burner evaluation methodology, buoyancy calculations, empirical relationships, and conventional furnace draft and pressure-drop evaluation tools to grasp, however inadequately, the dynamics of the system.

VII. DEVELOP THE DESIGNS OF AUXILIARY EQUIPMENT

Decide the sizes and requirements of burners, fans, grates, materials handling systems, pumps, air compressors, air pollution control systems, and the many other auxiliary equipment comprising the system. The cardinal rule in final design is to prepare for *when* "it" happens, not to speculate about *if* "it" will happen—it will.

VIII. DEVELOP INCINERATOR ECONOMICS

As presented in Chapter 1, incineration is often the highest-cost approach to waste management. Consequently, an understanding of the economics of incineration is an

Table 1 Elements of Capital Cost for Incineration Systems

I. Incineration system
  A. Waste conveyance
    1. Open or compaction vehicles, commercial containers
    2. Special design containers
    3. Piping, ducting, conveyors
  B. Waste storage and handling at incinerator
    1. Waste receipt and weighing
    2. Pit and crane, floor dump and front-end loader
    3. Holding tanks, pumps, piping
  C. Incinerator
    1. Outer shell
    2. Refractory
    3. Incinerator internals (grates, catalyst)
    4. Burners
    5. Fans and ducting (forced and induced draft)
    6. Flue gas conditioning (water systems, boiler systems)
    7. Air pollution control
    8. Stacks
    9. Residue handling
    10. Automatic control and indicating instrumentation
    11. Worker sanitary, locker, and office space
II. Auxiliary systems
  A. Buildings, roadways, parking areas
  B. Special maintenance facilities
  C. Steam, electrical, water fuel, and compressed air supply
  D. Secondary pollution control
    1. Residue disposal (landfill, etc.)
    2. Scrubber wastewater treatment
III. Nonequipment expenses
  A. Engineering fees
  B. Land costs
  C. Permits
  D. Interest during construction
  E. Spare parts inventory (working capital)
  F. Investments in operator training
  G. Start-up expenses
  H. Technology fees to engineers, vendors

important part of engineering and management decision-making. Unfortunately, providing definitive guides to economic analysis is as difficult as for the counterpart in design.

A. General

It would be a gross simplification, in most cases, to suggest that incineration system capital costs could be reduced to a simple table or nomograph. Usually, the designs are highly customized, reflecting unique waste handling, ducting, local regulatory requirements, degree of automatic control, enclosure aesthetics, etc., which greatly affect the final *system* cost, even if the basic incinerator itself is of predictable cost. Similarly, operating costs reflect staffing practices, localized labor and utility costs, localized unit values for by-product materials or energy, etc.

Consequently, the following sections emphasize the elements of cost analysis as applied to incineration rather than simplified general numbers. The experienced engineer will recognize this not as an evasion but as an explicit recognition of the dangers of oversimplification.

1. Capital Investment

For many prospective incinerator owners, the initial capital investment is *the* crucial issue. This is particularly true for industry, where the return on invested capital is often the prime measure of business performance. Table 1 shows the major elements of capital expenditure. Note that both purchased equipment and installation cost should be evaluated: the latter can be over 200% of the equipment cost alone.

Table 2 Primary Sizing Parameters for Selected Control Devices and Auxiliaries

Equipment	Primary sizing parameters
	Control devices
Fabric filter	Bag surface area
Electrostatic precipitator	Collection-plate surface area
Wet scrubber	Gas velocity, pressure drop, gas volume flow
Carbon adsorber	Carbon weight, gas velocity, gas volume flow
Gas adsorber	Carbon height, diameter
Thermal/catalytic incinerator	Combustion chamber volume
Refrigerated condenser	Heat exchanger area (or gas flow and percent heat recovery)
Flare	Cooling load (or gas volume flow, inlet–outlet temperatures)
	Auxiliaries
Ductwork	Length, diameter (or weight)
Fan	Wheel diameter, static pressure
Pump	Head, liquid flow
Stack	Height, diameter
Screw conveyor	Length, diameter
Cyclone	Gas volumetric flow (or inlet area)
Spray chamber, quencher	Gas volumetric flow (or length, diameter)
Plant buildings	Floor area

Source: From (490).

Table 3 Scale Exponents (n) For Particulate Control Devices

Equipment	Size range	Scale exponent (n)
Electrostatic precipitator (ESP)		
General ESP	0.5–2 m^3/sec	0.68
Plate-wire, flat-plate, tubular, wet	300–1,400 m^2	0.63
Plate-wire, flat-plate, tubular, wet	1,400–28,000 m^2	0.84
Fabric filters		
Dust collector, cloth	0.0001–0.5 m^3/sec	0.70
Reverse-jet cloth filter	100–225 m^3/min	0.45
Reverse-jet cloth filter	225–450 m^3/min	0.78
Wet scrubbers		
Impingement, 1 stage	25–2,200 m^3/min	0.57
Impingement, 2 stage	25–2,200 m^3/min	0.59
Impingement, 3 stage	25–2,200 m^3/min	0.61
Mesh pad, for mist eliminator	0.6–3.0 m	1.66
Particulate scrubber	N/A	0.60
Venturi, scrubber	N/A	0.60
Venturi, scrubber	540–1,670 m^3/min	0.61
Venturi, scrubber	56–3,400 m^3/min	0.45
Water spray scrubber, heavy-duty	170–425 m^3/min	0.61
Water spray scrubber, heavy-duty	425–850 m^3/min	0.90
Water spray scrubber, light-duty	85–700 m^3/min	0.80
Dry dynamic scrubbers		
Horizontal crossflow scrubber	23–2,300 m^3/min	0.72

Source: From (490).

Table 4 Scale Exponents (n) for Gas Control Devices

Equipment	Size range	Scale exponent (n)
Carbon adsorbers		
Activated carbon adsorbers	113–4,500 kg	0.36
Activated carbon adsorbers	9,000–91,000 kg	0.92
Fixed-bed, regenerable, packaged	160–6,350 kg	0.85
Fixed-bed, generable, custom	6,350–100,000 kg	0.86
Modular or canister	50–3,000 kg	0.97
Flares		
Elevated	1,100–91,000 kg/hr	0.59
Ground-level	1,100–91,000 kg/hr	0.39
Incinerators		
Catalytic, mild steel	1.5–7.5 MMkcal/hr[a]	0.75
Direct flame, mild steel	2.5–35 MMkcal/hr	0.39
Hearth, mild steel	0.4–25 MMkcal/hr	0.64
Rotary kiln, mild steel	0.25–28 MMkcal/hr	0.48
Thermal, 0% heat exchanger efficiency	140–1,400 m^3/min	0.36
Thermal, 35% heat exchanger efficiency	140–1,400 m^3/min	0.38
Thermal, 50% heat exchanger efficiency	140–1,400 m^3/min	0.39
Thermal, 70% heat exchanger efficiency	140–1,400 m^3/min	0.41

[a] MM = one million.
Source: From (490).

Table 5 Scale Exponents (n) for Auxiliary Equipment

Equipment	Size range	Scale exponent (n)
Cyclones		
Single-element	42–280	0.58
Multiclone	0.0000–0.33 m^3/min	0.61
Heavy-duty	57–200	0.61
Heavy-duty	200–850	0.89
Light-duty	57–85	0.37
Light-duty	85–425	0.98
Ductwork		
Dampers (back flow)	25–90-cm diameter	0.94
Fiber-reinforced plastic (FRP)	0.6–1.5 m	1.00
Polyvinyl chloride (PVC)	15–30-cm diameter	1.05
Polyvinyl chloride (PVC)	35–60-cm diameter	1.98
Mild steel (0.3175-cm wall thickness)	17–600-cm diameter	1.04
Stainless (0.3175-cm wall thickness)	15–760-cm diameter	1.02
Fans		
Centrifugal	28–283 m^3/min	0.44
Centrifugal	566–2000 m^3/min	1.17
Motors, electric	7–100 hp	0.86
Rotary air locks	20–50 cm diameter	0.67
Screw conveyors		
10-cm diameter	N/A	0.90
30-cm diameter	N/A	0.83
50-cm diameter	N/A	0.73
Screw conveyors (23-cm fixed diameter)	2.7–60 m	0.78
Spray chamber, quencher		
Spray chamber (carbon steel)	2–6 m^3/min	0.41
Quencher (carbon steel)	0.3–7 m^3/min	0.62
Stacks		
Brick lining, 4.5-m diameter	60–180 m	0.95
Brick lining, 6.0-m diameter	60–180 m	0.98
Brick lining, 9.0-m diameter	60–180 m	1.03
Brick lining, 12.0-m diameter	60–180 m	1.04
Carbon steel, 60-cm diameter	N/A	1.00
Carbon steel, 90-cm diameter	N/A	1.00
Carbon steel, 120-cm diameter	N/A	1.00
Steel lining, 4.5-m diameter	60–180 m	0.81
Steel lining, 6.0-m diameter	60–180 m	0.85
Steel lining, 9.0-m diameter	60–180 m	0.88
Steel lining, 12.0-m diameter	60–180 m	0.89

Source: From (490).

In developing estimates of capital investment, analysts often find themselves with limited cost data and, then, often for equipment or other facilities different in size from those of interest. In such circumstances, scaling "laws" are often used to adjust the cost (C_0) from the size where costs are available (S_0) to the cost (C_i) for the size of interest (S_i). The scaling relationship used is of the form

$$C_i = C_0 \left(\frac{S_i}{S_0} \right)^n \tag{1}$$

where n is the scaling exponent characteristic of the type of equipment. Although a scaling exponent of 0.6 is often assumed as typical, a detailed examination of cost data shows that the exponent varies quite widely. Table 2 indicates the size characterizing variable that should be used to scale the cost. Tables 3, 4, and 5 (490) present the scaling exponents for several particulate control devices, gas control devices, and air pollution control auxiliaries, respectively.

2. Operating Costs

Although capital investment is an important aspect, the actual *total unit cost*, allowing for the cost of capital but including all operating costs, is a more incisive measure of economic impact. For example, contract hauling typically requires little or no owner investment but may represent an unacceptably high unit cost for disposal and/or a long-term liability of considerable worth. Similarly, high-energy scrubbers are lower in capital cost than electrostatic precipitators but, at equivalent efficiency, consume so much power that their cost per unit of gas cleaned is much higher. Typical elements of operating cost for incineration systems are shown in Table 6.

Table 7 provides estimates of the direct labor required for various incineration plant equipment. One must add employee benefits ranging from 22% to 45% of the cost of direct

Table 6 Elements of Operating Cost for Incineration Systems

I.	Fixed costs (credits)
	A. Repayment of debt capital
	B. Payment of interest on outstanding capital
	C. Tax credits for depreciation
II.	Semivariable costs
	A. Labor (including supervision) with overheads
	B. Insurance
	C. Operating supplies
	D. Maintenance and maintenance supplies
III.	Variable costs (credits)
	A. Steam usage (or credits)
	B. Electricity
	C. Water supply and sewerage fees
	D. Oil or natural gas fuels
	E. Compressed air
	F. Chemicals (catalysts, water treatment)
	G. Byproduct credits
	H. Disposal fees

Table 7 Estimated Direct Labor for Incinerator Operations (Adjusted to 1998 for Labor Productivity)

Equipment	No. operators per unit or per shift	Equipment	No. operators per unit or per shift
Auxiliary facilities		Heat exchangers	0.05
Boilers	0.6	Mixers	0.2
Cooling towers	0.6	Pumps	0.0
Boiler-water treatment	0.3	Clarifier/thickener	0.1
Electric substations	0.0	Cyclones	0.0
Wastewater treatment	1.3	Bag filter	0.1
Conveyors	0.1	Electrostatic precipitator	0.1
Crushers, mills	0.3–0.6	Screens	0.03
Fans, compressors	0.03		

Source: From (496).

labor plus 10% to 35% of the cost of labor for supervision. Maintenance costs range from 2% to 10% of capital cost, with the higher percentages applicable to high-temperature processes and processes involving the handling of solids. Insurance and taxes (for private-sector operations) average 3% to 5% of capital investment. Operating supplies average 1% to 3% of capital, and plant overhead is 1% to 5% of capital.

3. Project Comparisons

As a preferred method of analysis, a plant total operating cost and investment schedule should be developed over the projected facility lifetime. Replacement investments for short-lived equipment (such as landfill bulldozers) or major overhauls should be included. Application of present worth factors, year by year, to the net annual costs and investments produces a "total venture cost." The total venture cost represents the amount of cash needed at the project's start that would totally provide for the project's financial needs. The discount rate used is that by which the prospective owner values capital or can obtain capital. By this means true net cost comparisons can be made, on an equitable basis, between high-capital, low-operating-cost projects and those that are low-capital, high-operating-cost.

IX. BUILD AND OPERATE

In many cases, fortunately, nature is kind: reasonable engineering designs will function, though perhaps not to expectations. At times, plants built using the most detailed analysis and care result in problems that
continue throughout the facility's lifetime. Incineration involves some risk. Such is the lot of workers in the complex but fascinating field of industrial and municipal waste combustion.

Appendix A

Symbols: A Partial List

Symbol	Definition	Unit
A	The "frequency factor" or pre-exponential constant in the Arrhenius kinetics expression	varies
A_e	Cross-sectional area of body of cyclone combustion chamber	m^2
A_t	Tangential inlet area of cyclone combustion chamber	m^2
a	Constant a, a_1, a_2, etc.	—
B	Mass transfer driving force	—
C_x	Drag coefficient	—
c	Concentration: c_0, initial or at nozzle; $\bar{c}_m$, mean at jet centerline; $\bar{c}$, on radius of jet	mol/m^3
c_p	Specific heat: c_p^0, at zero pressure; $c_{p,av}^0$ average at zero pressure between given limits of temperature	$kcal\,kg^{-1}\,{}^\circ C^{-1}$
D	Combustion chamber diameter	m
D_s	Stack diameter	m
d	Diameter: d_0, nozzle or initial; d_c, combustion chamber; d_e, exit throat; d_0', effective nozzle diameter	m
E	Energy (enthalpy) change on reaction	cal/mol
ΔE	Activation energy (enthalpy)	cal/mol
F	Force: F_B, buoyant force; F_D, drag force	newtons
F_e	Expansion draft loss in a stack	atm
F_s	Friction draft loss in a stack	atm
f_a	Mole fraction of component a in a mixture	—
f_s	Mole fraction of nozzle gas in a stoichiometric mixture	—
$\dot{G}_0$	Nozzle flux of linear momentum in a swirling jet	$kg\,m^2\,sec^{-2}$

(*continued*)

Symbol	Definition	Unit
g	Acceleration of gravity	m/sec^2
H	Enthalpy (total)	kcal
ΔH	Heat (enthalpy) of reaction	kcal/kg mol
ΔH_c	Heat (enthalpy) of combustion	kcal/kg
ΔH_v	Heat (enthalpy) of vaporization	kcal/kg
H_s	Enthalpy at reference temperature (here, the temperature of the liquid at the surface of a burning pool	kcal/kg
h	Enthalpy per mole	kcal/kg mol
Δh	Sensible heat	kcal
h_c	Heat transfer coefficient by convection	$kcal\,hr^{-1}\,m^{-2}\,{}^{\circ}C^{-1}$
HHV	Higher heating value (water condensed)	kcal/kg mol
J	Entrainment coefficient of a jet ($\bar{v}_m/\bar{u}_m$)	—
K	Time constant for chemical reaction	sec^{-1}
K_d	Diffusional rate constant (soot oxidation)	$g\,cm^{-2}\,sec^{-1}$
K_p	Equilibrium constant (pressure)	varies
K_s	Kinetic rate constant (soot oxidation)	$g\,cm^{-2}\,sec^{-1}$
k	Constant	varies
L	Flame length	m
$\dot{L}_0$	Nozzle flux of angular momentum in a swirling jet	$kg\,m^2\,sec^{-2}$
L_j	Jet penetration distance	m
L_T	Furnace length	m
L_s	Height of a stack above the breeching	m
l	Distance along curved path of a deflected jet	m
LHV	Lower heating value (water uncondensed)	kcal/kg mol
M	Momentum ratio for jet in crossflow	—
$M^0_{c_{P,av}}$	Average molar heat capacity at zero pressure between given limits of temperature	$kcal\,kg\,mol^{-1}\,{}^{\circ}C^{-1}$
M_0	Molecular weight of nozzle gas	kg/kg mol
M_a	Molecular weight of air	kg/kg mol
M_r	Recirculating mass flow relative to nozzle flow	—
m	Surface density	g/cm^2
$\dot{m}$	Mass flow rate: ($\dot{m}_x$), at a distance x in a jet; ($\dot{m}_0$), at the nozzle; ($\dot{m}_r$), recirculating	kg/sec
$\dot{m}''$	Mass burning rate per unit area	$g\,cm^{-2}\,sec^{-1}$
MW	Molecular weight	kg/mol
N	Number of nozzles in a linear array	—
N_f	Nitrogen in fuel	mol
N_{Re}	Reynolds number ($du\sigma/u$)	—
N_s	Swirl number for axial swirl burners	—
N_{SC}	Swirl number for cyclone chambers	—
n	Number of kilogram moles	kg mol
P	Pressure: (ΔP), differential; (ΔP_i), across inlet; (ΔP_{cc}), across combustion chamber; (P_{ND}), natural draft; (P_0), barometric (ambient) pressure	$kg\,m^{-2}$, atm

Symbol	Definition	Unit
p	Partial pressure	atm
Q_T	Volume flow of overfire air	m^3/min
Q_v	Heat release rate per unit volume	$kcal\,m^{-3}\,sec^{-1}$
q	Rate of consumption per unit geometric external surface area	$g\,cm^{-2}\,sec^{-1}$
R, R'	Universal gas constant	varies (see Table 2-1)
r	Radius: (r_d), droplet radius	m
r, r'	Chemical reaction rate	varies
S	Slope of a kiln	m/m
s	Spacing between jet centers in a linear array	m
T	Temperature: (T_0), initial or at nozzle; (T_a), ambient; (T_F), adiabatic flame; (T_R), reference; (T_M), mixture; (T_d), droplet	°C, °K
t	Time: residence time; (t_b), particle burnout time	sec
u	Velocity: (u_0), at nozzle or initial; ($\bar{u}_m$), time averaged mean on jet centerline; ($\bar{u}_0$), time averaged mean at nozzle; (u'), r.m.s. fluctuating component in axial direction; ($\bar{u}_1$), mean crossflow; ($\bar{u}_e$), average at exit; (u_f), final; (u_t), terminal	m/sec
V	Volume	m^3
V	Volume flow rate	m^3/sec
v	Velocity: (v'), r.m.s. fluctuating component in radial velocity in a jet; ($\bar{v}_m$), mean radial velocity into jet	m/sec
W	Radiative emissive power: (W_B), of a black body	$kcal\,m^{-2}\,hr^{-1}$
w	Velocity tangent to a circle centered on the axis of a swirling jet; (w'), r.m.s. fluctuating component in tangential direction; (w_{in}), tangential inlet velocity to cyclone combustor	m/sec
x	A variable, defined as used but often a distance in the x direction; (x^+), distance to end of zone of establishment in a jet; (x_p), impingement point of a deduced jet	varies
Y	Conversion ratio for fuel nitrogen into NO	—
y	A variable, defined as used but often a distance in the y direction; (y^+), distance to end of a zone of establishment in a jet; (y_0), width of a slot jet	varies
Z	Length of a linear jet array	m

Greek Symbols

Symbol	Definition	Unit
α	Thermal diffusivity	m^2/sec
α_0	Jet deflection angle (initial)	degrees or radians
β	Burnedness, the relative degree of completeness of combustion	—
γ	Exponential function $(1/\zeta)\exp(-\zeta)$; (γ_1), exponential integral	—
Δ	A prefix denoting change or difference in a quantity	varies
δ	Angle of attack between jet and crossflow vector	degrees or radians
ε	Emissivity for radiative heat transfer	—
ξ	Nondimensional temperature $\Delta E/RT$	—
θ	Kilograms of oxidant per kilogram of fuel for a stoichiometric mixture	—
θ_m	Moles of reactant per mole of product in a stoichiometric mixture	—
λ	Thermal conductivity	$kcal\,m^{-2}\,sec^{-1}\,(^\circ C/m)^{-1}$
μ	Viscosity: (μ_0), initial	$g\,cm^{-1}\,sec^{-1}$, $kg\,m^{-1}\,sec^{-1}$
ν	Kinematic viscosity	cm^2/sec
ξ	Pressure loss coefficient	—
π	Constant (3.14159 . . .)	—
ρ	Density: (ρ_0), initial or at nozzle; (ρ_a), ambient; (ρ_l), liquid; (ρ_f), at flame temperature; (ρ_{iso}), isothermal case; (ρ_s), of particles; (ρ_c), of char; (ρ_v), of virgin material	kg/m^3
σ	Stephan-Boltzmann constant	$kcal\,m^{-2}\,hr^{-1}\,(K)^{-4}$
Φ	Mixture ratio (mass air/mass fuel) $= 1/\theta$	—
φ	Jet half-angle; (φ_0), without swirl; (φ_s), with swirl	radians
Ω	Dilution ratio of a jet $(\bar{c}/\bar{c}_0)$	—
ω	Parameter in recirculating jet flow	—

Appendix B

Conversion Factors

Quantity	Unit A	× Factor =	Unit B
Length	angstrom	1×10^{-10}	meter
	foot	0.3048	meter
	foot	0.3333	yard
	inch	2.54	centimeter
	meter	100	centimeter
	meter	3.2808	foot
	meter	1.0936	yard
	micrometer	1×10^{-6}	meter
Area	acre	4046.9	square meter
	hectare	1×10^{4}	square meter
	square centimeter	0.155	square inch
	square inch	6.4516	square centimeter
	square foot	929.03	square centimeter
	square foot	0.0929	square meter
	square meter	10.7639	square foot
	square yard	9	square foot
Volume	barrel (oil)	42	gallon
	barrel (oil)	159.983	liter
	cubic foot	2.8317×10^{4}	cubic centimeter
	cubic foot	7.481	gallon
	cubic foot	0.028317	cubic meter
	cubic meter	1×10^{6}	cubic centimeter
	cubic yard	0.7646	cubic meter
	gallon (U.S.)	0.8327	gallon (British)
	gallon	3.7853	liter
	gallon (water)	8.337	pound
	liter	0.03532	cubic foot
	liter	0.001	cubic meter
	liter	0.26418	gallon

(*continued*)

Quantity	Unit A	× Factor =	Unit B
	liter	1.0567	quart
Mass	grain	0.0648	gram
	grain	1.4286×10^{-4}	pound
	kilogram	1000	gram
	kilogram	2.2046	pound
	kilogram	0.001	tonne
	microgram	1×10^{-6}	gram
	pound	453.59	gram
	pound	0.4536	kilogram
	ton	1000	kilogram
	ton	2204.62	pound
	ton (short)	2000	pound
	ton (long)	2240	pound
Time	day	1440	minute
	day	8.64×10^{4}	second
	minute	60	second
	year	8760	hour
Velocity	centimeter/second	1.9685	foot/minute
	foot/minute	0.00508	meter/second
	foot/second	0.3048	meter/second
	meter/minute	0.0547	foot/second
	meter/second	3.281	foot/second
	mile/hour	0.447	meter/second
Flow	cubic centimeters/second	0.002119	cubic feet/minute
	cubic feet/minute	0.1247	gallon/second
	cubic feet/minute	0.4720	liter/second
	cubic feet/second	4.72×10^{-4}	cubic meter/second
	cubic meter/second	35.31	cubic feet/second
	cubic meter/second	2118.6	cubic feet/minute
	cubic meter/minute	16.667	liter/second
	gallon/minute	0.06308	liter/second
Pressure	atmosphere	14.696	pound/square inch
	atmosphere	29.921	inch of mercury
	atmosphere	101.325	kilopascal (kPa)
	atmosphere	760	millimeter of mercury
	atmosphere	1033.2	gram/square centimeter
	atmosphere	33.899	foot of water
	bar	100.0	kilopascal (kPa)
	inch of water	1.8683	millimeter of mercury
	inch of water	0.002458	atmosphere
	foot of water	2.986	kilopascal (kPa)
	millimeter of mercury	0.1333	kilopascal (kPa)
	pound/square inch	0.06805	atmosphere
	pound/square inch	6.895	kilopascal (kPa)
Energy	Btu	0.25198	kilocalorie
	horsepower/hour	641.186	kilocalorie
	joule	2.389×10^{-4}	kilocalorie

Quantity	Unit A	×	Factor	=	Unit B
	kilocalorie		3.9685		Btu
	kilocalorie		1000		calorie
	kilocalorie		0.0015593		horsepower/hour
	kilocalorie		0.0011628		kilowatt/hour
	megajoule		238.846		kilocalorie
	megajoule		947.817		Btu
	watt hour		3.412		Btu
Temperature	$^5/_9(^\circ F - 32)$				$^\circ C$
	$^9/_5(^\circ C) + 32$				$^\circ F$
	$^\circ C + 273.18$				$^\circ K$
	$^\circ F + 460$				$^\circ R$
Heat capacity	Btu/pound °F		1.0		calorie/gram °C
Heat content	Btu/pound		0.5556		calorie/gram
	Btu/pound		0.5556		kilocalorie/kilogram
	kilocalorie/kilogram		1.8		Btu/pound
	kilocalorie/kilogram		4.187		kilojoule/kilogram
	joule/gram		0.4301		Btu/pound
Thermal conductivity	Btu/second square foot °F/inch		1.2404		calorie/second square centimeter °C/centimeter
	Btu/second square foot °F/foot		1.487		kilocalorie/hour square meter °C/meter
Viscosity	gram (weight) second/square centimeter		980.665		poise
	poise		0.01		centipoise
Miscellaneous					
Particulate loading in a gas	grain/cubic foot		2.29×10^6		microgram/cubic meter
Stephan–Boltzmann constant	0.173×10^{-8} Btu/hour square foot $^\circ F^4$				
	4.92×10^{-8} kilo calorie/hour square meter $^\circ K^4$				
Gravitational constant	32.2 feet/second/second				
	980.7 centimeters/second/second				
Density					
	gram/cubic centimeter		62.428		pounds/cubic foot
	pound/cubic yard		0.5933		kilogram/cubic meter

Appendix C

Periodic Table of Elements

Periodic Table of Elements

Substance	Symbol	Atomic weight	Atomic number	Substance	Symbol	Atomic weight	Atomic number
Actininum	Ac	227	89	Neodymium	Nd	144.24	60
Aluminum	Al	26.98	13	Neon	Ne	20.1797	10
Americium	Am	243	95	Neptunium	Np	237	93
Antimony	Sb	121.76	51	Nickel	Ni	58.69	28
Argon	A	39.948	18	Niobium	Nb	92.91	41
Arsenic	As	74.92	33	Nitrogen	N	14.0067	7
Astatine	At	210	85	Osmium	Os	190.2	76
Barium	Ba	137.33	56	Oxygen	O	16.0000	8
Beryllium	Be	9.01	4	Palladium	Pd	106.42	46
Bismuth	Bi	208.98	83	Phosphorus	P	30.974	15
Boron	B	10.81	5	Platinum	Pt	195.078	78
Bromine	Br	79.904	35	Plutonium	Pu	244	94
Cadmium	Cd	112.41	48	Polonium	Po	209	84
Calcium	Ca	40.08	20	Potassium	K	39.098	19
Carbon	C	12.010	6	Praseodymium	Pr	140.908	59
Cerium	Ce	140.12	58	Promethium	Pm	145	61
Cesium	Cs	132.91	55	Protactinium	Pa	231	91
Chlorine	Cl	35.455	17	Radium	Ra	226.05	88
Chromium	Cr	51.996	24	Radon	Rn	222	86
Cobalt	Co	58.933	27	Rhenium	Re	186.207	75
Copper	Cu	63.546	29	Rhodium	Rh	102.91	45
Curium	Cm	247	96	Rubidium	Rb	85.47	37
Dysprosium	Dy	162.5	66	Ruthenium	Ru	101.07	44
Erbium	Er	167.26	68	Samarium	Sm	150.56	62
Europium	Eu	152.0	63	Scandium	Sc	44.96	21

(*continued*)

Substance	Symbol	Atomic weight	Atomic number	Substance	Symbol	Atomic weight	Atomic number
Fluorine	F	19.00	9	Selenium	Se	78.96	34
Francium	Fr	223	87	Silicon	Si	28.086	14
Gadolinium	Gd	157.25	64	Silver	Ag	107.868	47
Gallium	Ga	69.72	31	Sodium	Na	22.990	11
Germanium	Ge	72.61	32	Strontium	Sr	87.62	38
Gold	Au	196.967	79	Sulfur	S	32.066	16
Hafnium	Hf	178.49	72	Tantalum	Ta	180.95	73
Helium	He	4.003	32	Technetium	Tc	98	43
Holmium	Ho	164.93	67	Tellurium	Te	127.60	52
Hydrogen	H	1.0080	1	Terbium	Tb	158.925	65
Indium	In	114.82	49	Thallium	Tl	104.38	81
Iodine	I	126.904	53	Thorium	Th	232.038	90
Iridium	Ir	192.217	77	Thulium	Tm	168.93	69
Iron	Fe	55.85	26	Tin	Sn	118.71	50
Krypton	Kr	83.8	36	Titanium	Ti	47.867	22
Lanthanum	La	138.91	57	Tungsten	W	183.84	74
Lead	Pb	207.21	82	Uranium	U	238.03	92
Lithium	Li	6.941	3	Vanadium	V	50.94	23
Lutetium	Lu	174.97	71	Xenon	Xe	131.3	54
Magnesium	Mg	24.305	12	Ytterbium	Yb	173.04	70
Manganese	Mn	54.94	25	Yttrium	Y	88.91	39
Mercury	Hg	200.59	80	Zinc	Zn	65.39	30
Molybdenum	Mo	95.94	42	Zirconium	Zr	91.22	40

Appendix D

Combustion Properties of Coal, Oil, Natural Gas, and Other Materials

Often in waste incineration, conventional fossil fuels are burned. The data in Tables 1 to 7 will then be useful to carry out the relevant energy and material balances.

Heat of Combustion Data (Table 8) is presented for a variety of chemical substances and materials in common use in industry and/or commonly appearing in waste streams. Note that the values presented are for the *lower heating value* (water as a gas). See also the several tables in the text (especially Tables 24, 27, and 28 in Chapter 4).

Inflammability limits and ignition temperatures in Table 9 are useful in evaluating hazards in transporting or storing materials.

Table 1 Classification of Coals by Rank[a] (ASTM D 388)

Class	Group	Fixed carbon limits, % (dry, mineral-matter-free-basis)		Volatile matter limits, % (dry, mineral-matter-free-basis)		Calorific value limits, kcal/kg (moist,[b] mineral-matter-free basis)		Agglomerating character
		Equal or greater than	Less than	Greater than	Equal or less than	Equal or greater than	Less than	
I. Anthracite	1. Meta-anthracite	98	—	—	2	—	—	Nonagglomerating
	2. Anthracite	92	98	2	8	—	—	
	3. Semianthracite[c]	86	92	8	14	—	—	
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22	—	—	Commonly agglomerating[e]
	2. Medium volatile bituminous coal	69	78	22	31	—	—	
	3. High volatile A bituminous coal	—	69	31	—	7778[d]	—	
	4. High volatile B bituminous coal	—	—	—	—	7222[d]	7778	
	5. High volatile C bituminous coal	—	—	—	—	6389	7222	
						5833[e]	5833	Agglomerating
III. Subbituminous	1. Subbituminous A coal	—	—	—	—	5833	6389	Nonagglomerating
	2. Subbituminous B coal	—	—	—	—	5278	5833	
	3. Subbituminous C coal	—	—	—	—	4611	5278	
IV. Lignite	1. Lignite A	—	—	—	—	3500	4611	
	2. Lignite B	—	—	—	—	—	3500	

[a] This classification does not include a few coals, principally nonbanded varieties, which have unusual physical and chemical properties and which come within the limits of fixed carbon or calorific value of the high-volatile bituminous and subbituminous ranks. All of these coals either contain less than 48% dry, mineral-matter-free fixed carbon or have more than 8610 moist, mineral-matter-free kcal/kg (higher heating value).

[b] Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal. Higher heating value.

[c] If agglomerating, classify in low-volatile group of the bituminous class.

[d] Coals having 69% or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of calorific value.

[e] It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and there are notable exceptions in high volatile C bituminous group.

Table 2 Selected U.S. and International Coals Arranged in Order of ASTM Classification[a]

	Coal rank				Coal analysis, bed moisture basis					
No.	Class	Group	State	County	M	VM	FC	A	S	kcal
1	I	1	Pa.	Schuylkill	4.5	1.7	84.1	9.7	0.77	7081
2	I	2	Pa.	Lackawanna	2.5	6.2	79.4	11.9	0.60	7181
3	I	3	Va.	Montgomery	2.0	10.6	67.2	20.2	0.62	6625
4	II	1	W. Va.	McDowell	1.0	16.6	77.3	5.1	0.74	8175
5	II	1	Pa.	Cambria	1.3	17.5	70.9	10.3	1.68	7667
6	II	2	Pa.	Somerset	1.5	20.8	67.5	10.2	1.68	7622
7	II	2	Pa.	Indiana	1.5	23.4	64.9	10.2	2.20	7667
8	II	3	Pa.	Westmoreland	1.5	30.7	56.6	11.2	1.82	7403
9	II	3	Ky.	Pike	2.5	36.7	57.5	3.3	0.70	8044
10	II	3	Ohio	Belmont	3.6	40.0	47.3	9.1	4.00	7139
11	II	4	Ill.	Williamson	5.8	36.2	46.3	11.7	2.70	6617
12	II	4	Utah	Emery	5.2	38.2	50.2	6.4	0.90	7000
13	II	5	Ill.	Vermilion	12.2	38.8	40.0	9.0	3.20	6300
14	III	1	Mont.	Musselshell	14.1	32.2	46.7	7.0	0.43	6189
15	III	2	Wyo.	Sheridan	25.0	30.5	40.8	3.7	0.30	5192
16	III	3	Wyo.	Campbell	31.0	31.4	32.8	4.8	0.55	4622
17	IV	1	N.D.	Mercer	37.0	26.6	32.3	4.2	0.40	4130
	Coal rank				Coal analysis, bed moisture basis					
No.	Class	Group	State	Country	M	VM	FC	A	S	kcal
18	II	4	N/A	Australia	6.9	24.8	44.3	24.0	0.4	5367
19	II	4	N/A	China	17.1	30.9	47.2	4.7	0.5	5967
20	II	3	N/A	France	0.8	36.1	55.0	8.1	0.8	7302
21	II	3	N/A	S. Africa	4.3	35.3	50.3	10.1	0.7	6761
22	II	4	N/A	Indonesia	23.9	45.6	28.8	1.8	0.2	5467
23	I	3	N/A	Korea	0.5	7.5	68.6	23.5	2.1	5246
24	III	2	N/A	Spain	1.8	45.3	14.2	38.7	7.5	3388

[a] For definition of rank classification according to ASTM requirements, see Table B-1. Data on coal (bed moisture basis): M = equilibrium moisture; %; VM = volatile matter, %; FC = fixed carbon, %; A = ash, %; S = sulfur, %; kcal = kcal/kg, high heating value.

Table 3 Coal Analysis, Dry, Ash-Free Basis (%)

Coals Table 2 No.	Volatile matter	Fixed carbon	C	H_2	O_2	N_2	kcal/kg[a]
1	2.0	98.0	93.9	2.1	2.3	0.3	8250
2	7.3	92.7	93.5	2.6	2.3	0.9	8389
3	13.6	86.4	90.7	4.2	3.3	1.0	1514
4	17.7	82.3	90.4	4.8	2.7	1.3	8706
5	19.8	80.2	89.4	4.8	2.4	1.5	8675
6	23.5	76.5	88.6	4.8	3.1	1.6	8633
7	26.5	73.5	87.6	5.2	3.3	1.4	8683
8	35.2	64.8	85.0	5.4	5.8	1.7	8481
9	39.0	61.0	85.5	5.5	6.7	1.6	8539
10	45.8	54.2	80.9	5.7	7.4	1.4	8183
11	43.8	56.2	80.5	5.5	9.1	1.6	8017
12	43.2	56.8	79.8	5.6	11.8	1.7	7922
13	49.3	50.7	79.2	5.7	9.5	1.5	8000
14	40.8	59.2	80.9	5.1	12.2	1.3	7839
15	42.8	57.2	75.9	5.1	17.0	1.6	7278
16	49.0	51.0	74.0	5.6	18.6	0.9	7206
17	45.3	54.7	72.7	4.9	20.8	0.9	6850
18	35.9	64.1	81.9	5.1	10.8	1.8	7767
19	39.6	60.4	80.2	4.9	13.2	1.1	7634
20	39.7	60.3	81.9	5.3	10.3	1.5	8018
21	41.2	58.8	81.4	5.3	10.6	1.9	7898
22	61.3	38.7	76.1	5.6	16.9	1.2	7355
23	9.8	90.2	90.1	1.2	5.8	0.3	6901
24	76.1	23.9	62.2	4.6	19.1	1.5	5693

[a] Higher heating value.

Table 4 ASTM Standard Specifications for Fuel Oils[a]

No. 1: A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel.
No. 2: A distillate oil for general purpose domestic heating for use in burners not requiring No. 1 fuel oil.
No. 4: Preheating not usually required for handling or burning.

Grade of fuel oil[b]	Flash Point, °F (°C) Min	Pour Point,[e] °F (°C) Max	Water and sediment (% by volume) Max	Carbon residue on 10% bottoms, % Max	Ash (% by weight) Max	Distillation temperatures, °F (°C)		
						10% Point	90% Point	
						Max	Min	Max
No. 1	100 or legal (38)	0	trace	0.15	—	420 (215)	—	550 (288)
No. 2	100 or legal (38)	20[c] (−7)	0.10	0.35	—	[d]	540[c] (282)	640 (338)
No. 4	130 or legal (55)	20 (−7)	0.50	—	0.10	—	—	—
No. 5 (light)	130 or legal (55)	—	1.00	—	0.10	—	—	—
No. 5 (heavy)	130 or legal (55)	—	1.00	—	0.10	—	—	—
No. 6	150 (65)	—	2.00[g]	—	—	—	—	—

No. 5: (Light). Preheating may be required depending on climate and equipment.
No. 5: (Heavy). Preheating may be required for burning and, in cold climates, may be required for handling.
No. 6: Preheating required for burning and handling.

(*continued*)

Table 4 ASTM Standard Specifications for Fuel Oils (Continued)

Saybolt viscosity (sec)				Kinematic viscosity (centistokes)					
Universal at 100°F (38°C)		Furol at 122°F (50°C)		At 100°F (38°C)		At 122°F (50°C)		Gravity (deg API)	Copper strip corrosion
Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
—	—	—	—	1.4	2.2	—	—	35	No. 3
(32.6)[f]	(37.93)	—	—	2.0[c]	3.6	—	—	30	—
45	125	—	—	(5.8)	(26.4)	—	—	—	—
150	300	—	—	(32)	(65)	—	—	—	—
350	750	(23)	(40)	(75)	(162)	(42)	(81)	—	—
(900)	(9000)	45	300	—	—	(92)	(638)	—	—

[a] Source ASTM D 396. Recognizing the necessity for low-sulfur fuel oils used in connection with heat treatment, nonferrous metal, glass, and ceramic furnaces, and other special uses, a sulfur requirement may be specified in accordance with the following: No. 1 Grade: 0.5% max sulfur; No. 2 Grade: 0.7%; No. 4 Grade: no limit; No. 5 Grade: no limit; No. 6 Grade: no limit. Other sulfur limits may be specified only by mutual agreement between the purchaser and the seller.

[b] It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

[c] Lower or higher pour points may be specified whenever required by conditions of storage or use.

[d] The 10% distillation temperature point may be specified at 440°F (226°C) maximum for use in other than atomizing burners.

[e] When pour point less than 0°F is specified, the minimum viscosity shall be 1.8 cs (32.0 sec, Saybolt Universal) and the minimum 90% point shall be waived.

[f] Viscosity values in parentheses are for information only and not necessarily limiting.

[g] The amount of water by distillation plus the sediment by extraction shall not exceed 2.00%. The amount of sediment by extraction shall not exceed 0.50%. A deduction in quantity shall be made for all water and sediment in excess of 1.0%.

Table 5 Selected Analysis of Fuel Oils

Grade of fuel oil	No. 1	No. 2	No. 4	No. 5	No. 6
Weight, percent					
Sulfur	0.1	0.3	0.8	1.0	2.3
Hydrogen	13.8	12.5	—	—	9.7
Carbon	86.1	87.2	—	—	85.6
Nitrogen	—	0.02	—	—	
Oxygen	Nil	Nil	—	—	2.0
Ash	Nil	Nil	0.03	0.03	0.12
Gravity[a]					
Deg API	42	32	20	19	—
Specific gravity	0.815	0.865	0.934	0.940	—
Pour point					
°F	−35	−5	+20	+30	—
°C	−37.2	−20.5	−6.7	−1.1	—
Viscosity					
Centistokes @ 100°F (38°C)	1.8	2.4	27.5	130	—
SUS @ 100°F (38°C)	—	34	130	—	—
SSF @ 122°F (50°C)	—	—	—	30	—
Water, sediment, vol %	Nil	Nil	0.2	0.3	0.74
Heating value, kcal/kg					
(higher heating value)	11,006	10,794	10,478	10,422	10,167[b]

[a] American Petroleum Institute (API) gravity refers to a hydrometer scale with the following relation to specific gravity: degrees API = {141.5/[sp gr @ (15.5/15.5°C)]} − 131.5 where sp gr @ 15.5/15.5°C represents the ratio of oil density at 15.5°C (60°F) to that of water at 15.5°C.

[b] Bomb calorimeter determination.

Table 6 Range of Analyses of Fuel Oils

Grade of fuel oil	No. 1	No. 2	No. 4	No. 5	No. 6
Weight, percent					
Sulfur	0.01–0.5	0.05–1.0	0.2–2.0	0.5–3.0	0.7–3.5
Hydrogen	13.3–14.1	11.8–13.9	(10.6–13.0)[a]	(10.5–12.0)[a]	(9.5–12.0)[a]
Carbon	85.9–86.7	86.1–88.2	(86.5–89.2)[a]	(86.5–89.2)[a]	(86.5–90.2)[a]
Nitrogen	Nil–0.1	Nil–0.1	—	—	—
Oxygen	—	—	—	—	—
Ash	—	—	0–0.1	0–0.1	0.01–0.5
Gravity					
Deg API	40–44	28–40	15–30	14–22	7–22
Specific gravity	0.825–0.806	0.887–0.825	0.966–0.876	0.972–0.922	1.022–0.922
Pour point					
°F	0 to −50	0 to −40	−10 to +50	−10 to +80	+15 to +85
°C	−18 to −46	−18 to −40	−28 to +10	−28 to +27	−9 to +29
Viscosity					
Centistokes @ 38°C (100°F)	1.4–2.2	1.9–3.0	10.5–65	65–200	260–750
SUS @ 38°C (100°F)	—	32–38	60–300	—	—
SSF @ 50°C (112°F)	—	—	—	20–40	45–300
Water, sediment, vol %	—	0–0.1	tr to 1.0	0.05–1.0	0.05–2.0
Heating value, kcal/kgm (higher heating value, calculated)	10,928–11,033	10,650–10,972	10,156–10,778	10,056–10,567	9,672–10,550

[a] Estimated.

Table 7 Selected Samples of Natural Gas from United States Fields

	Source of gas				
Analyses	PA	So. CA	OH	LA	OK
Constituents, vol %					
H_2 Hydrogen	—	—	1.82	—	—
CH_4 Methane	83.40	84.00	93.33	90.00	84.10
C_2H_4 Ethylene	—	—	0.25	—	—
C_2H_6 Ethane	15.80	14.80	—	5.00	6.70
CO Carbon monoxide	—	—	0.45	—	—
CO_2 Carbon dioxide	—	0.70	0.22	—	0.80
N_2 Nitrogen	0.80	0.50	3.40	5.00	8.40
O_2 Oxygen	—	—	0.35	—	—
H_2S Hydrogen sulfide	—	—	0.18	—	—
Ultimate, wt %					
S Sulfur	—	—	0.34	—	—
H_2 Hydrogen	23.53	23.30	23.20	22.68	20.85
C Carbon	75.25	74.72	69.12	69.26	64.84
N_2 Nitrogen	1.22	0.76	5.76	8.06	12.90
O_2 Oxygen	—	1.22	1.58	—	1.41
Specific gravity (rel to air)	0.636	0.636	0.567	0.600	0.630
Higher heat value					
kcal/m^3 @ 15.6°C, 1 atm	10,045	9930	8577	8915	8666
kcal/kg of fuel	12,872	12,724	12,260	12,124	11,200

Table 8 Heat of Combustion for Selected Materials

I. Organic Compounds[a]

Name	Formula	Physical state	Lower heat of combustion[b]
Acetaldehyde	CH_3CHO	Liquid	279.0
Acetic acid	CH_3CO_2H	Liquid	209.4
Acetone	$(CH_3)_2CO$	Liquid	426.8
Acetylene	CHCH	Gas	312.0
Aniline	$C_6H_5NH_2$	Liquid	811.7
Benzaldehyde	C_6H_5CHO	Liquid	841.3
Benzene	C_6H_6	Liquid	782.3
n-Butyl alcohol	C_4H_9OH	Liquid	638.6
Carbon disulfide	CS_2	Liquid	246.6
Carbon tetrachloride	CCl_4	Liquid	37.3
Chloroform	$CHCl_3$	Liquid	89.2
Cresol (av. o, m, p)	$CH_3C_6H_4OH$	Liquid	881.9
Ethane	C_2H_6	Gas	368.4
Ethyl acetate	$CH_3CO_2C_2H_5$	Liquid	536.9
Ethyl alcohol	C_2H_5OH	Liquid	327.6
Ethylene (ethene)	CH_2CH_2	Gas	331.6
Glycerol (glycerin)	$(CH_2OH)_2$	Liquid	397.0

(*continued*)

Table 8 Heat of Combustion for Selected Materials (continued)

Name	Formula	Physical state	Lower heat of combustion[b]
n-Heptane	C_7H_{16}	Liquid	1149.9
n-Hexane	C_6H_{14}	Liquid	989.8
iso-Butyl alcohol	$(CH_3)_2CH_2CH_2OH$	Liquid	638.2
iso-Propyl alcohol	$(CH_3)_2CHOH$	Liquid	474.8
Methane	CH_4	Gas	210.8
Methyl alcohol	CH_3OH	Liquid	170.9
Methylene chloride	CH_2Cl_2	Gas	106.8
Methyl ethyl ketone	$CH_3COC_2H_5$	Liquid	582.3
n-Octane	C_8H_{18}	Liquid	1302.7
Phenol	C_6H_5OH	Solid	732.2
Phthalic acid	$C_6H_4(CO_2H)_2$	Solid	771.0
Propane	C_3H_8	Gas	526.3
n-Propyl alcohol	C_3H_7OH	Liquid	480.5
Propylene	CH_3CHCH_2	Gas	490.2
Starch	$(C_6H_{10}O_5)_x$ per kg	Solid	4178.8
Toluene	$CH_3C_6H_5$	Liquid	934.2
Urea	$(NH_2)_2CO$	Solid	151.6
Xylene (av. o, m, p)	$(CH_3)_2C_6H_4$	Liquid	1089.7

II. Various Substances

Name	Lower heat of combustion[c]
Asphalt	9.53
Bagasse (12% H_2O)	4.05
Bamboo (10% H_2O)	4.11
Charcoal (4% H_2O)	7.26
Coal (see Tables 1, 2 and 3 in Appendix D)	
Fats (animal)	9.50
Gases (see Tables 7 and 8.I in Appendix D)	
Iron (to Fe_2O_3)	1.58
Magnesium (to MgO)	4.73
Oil, fuel (see Tables 4, 5 and 6 in Appendix D)	
Oil, cotton seed	9.50
Paraffin	10.34
Pitch	8.40
Sulfur (rhombic)	2.20
Wood, oak (13% H_2O)	3.99
Wood, pine (12% H_2O)	4.42

[a] *Source*: Kharasch, U.S. Bureau of Standards, *Journal of Research*, *2*:359 (1929).

[b] Kilocalories per gram molecular weight at 1 atm, 20°C; carbon dioxide, water vapor, and nitrogen (if present) as gases.

[c] Kilocalories per gram at 1 atm, 20°C; carbon dioxide, water vapor, and nitrogen (if present) as gases.

Table 9 Flammability Limits and Ignition Temperatures of Various Substances

Chemical	Flammability limit (volume %)[a]			Ignition temperature (°C)	
	State[b]	Lower	Upper	in air	in O_2
Acetic acid	g	5.40	—	—	—
Acetone	g	2.15	13.00	538	—
Acetylene	g	2.50	80.00	335	—
Acrolein	g	2.60	31.00	300	—
Acrylic acid	g	3.10	—	438	—
Acrylonitrile	g	3.05	17.00	481	—
Ammonia	g	15.50	27.00	—	—
Amyl alcohol	g	1.4	10.00	353	—
Benzene	g	1.40	8.00	740	662
n-Butane	g	1.60	6.50	430	—
Butyl alcohol	g	1.70	9.00	367	—
Butylene	g	1.65	9.95	443	—
Carbon, fixed (anthracite coal)	s	—	—	448–601	—
Carbon, fixed (bituminous coal)	s	—	—	407	—
Carbon, fixed (semibituminous) coal)	s	—	—	465	—
Carbon disulfide	g	1.25	50.00	120	—
Carbon monoxide	g	12.50	74.20	651	637–658
Charcoal	s	—	—	650	—
Decane	g	0.67	2.60	260	—
Dichlorobenzene	g	1.50	—	648	—
1,1-Dichloroethylene	g	5.60	11.40	460	—
Dodecane	g	0.60	—	203	—
Ethane	g	3.30	10.60	510	520–630
Ethyl acetate	g	2.18	11.50	486	—
Ethyl acetoacetate	g	1.30	—	427	—
Ethyl alcohol	g	3.28	19.00	426	—
Ethylene	g	3.02	34.00	543	500–519
Ethylene glycol	g	3.20	—	413	—
Ethylene oxide	g	3.00	80.00	429	—
Gasoline	g	1.30	6.00	257	—
n-Heptane	g	1.00	6.00	233	—
n-Hexane	g	1.25	6.90	247	—
Hydrocyanic acid	g	5.60	40.00	538	—
Hydrogen	g	4.10	74.20	580	580–590
Hydrogen sulfide	g	4.30	45.50	290	—
Isoprene	g	1.30	—	220	—
Kerosene	l	—	—	254–293	—
Maleic anyhdride	g	3.00	—	482	—
Methyl ethyl ketone	g	1.81	11.50	516	—
Methyl alcohol	g	6.00	36.50	470	—
Methyl i-butyl ketone	g	1.10	7.95	457	—
Methyl n-butyl ketone	g	1.22	8.00	450	—
Methyl vinyl ketone	g	1.90	—	504	—
Mineral spirits	g	0.77	—	246	—

(*continued*)

Table 9 Flammability Limits and Ignition Temperatures of Various Substances (continued)

Chemical	Flammability limit (volume %)[a]			Ignition temperature (°C)	
	State[b]	Lower	Upper	in air	in O_2
Methane	g	4.80	13.50	537	556–700
n-Octane	g	0.84	3.20	232	—
n-Pentane	g	1.40	8.00	309	—
Petroleum ether	g	1.40	5.90	246	—
Phenol	g	1.40	—	715	—
Phthalic anhydride	g	1.30	9.20	584	—
Propane	g	2.30	7.30	468	—
Propyl acetate	g	1.77	8.00	450	—
Propyl alcohol	g	2.15	13.50	433	—
Propylene	g	2.00	11.10	497	—
Sulfur	s	—	—	243	—
Toluene	g	1.27	7.00	552	—
Vinyl acetate	g	2.00	—	427	—
Vinyl chloride	g	4.00	22.00	519	—
Xylene	g	1.00	6.00	496	—

Source: From (488).
[a] At 20°C, 1.0 atm in air.
[b] g = gas, l = liquid, s = solid.

Table 10 Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL) (Volume Percent)

Compound	LEL	UEL	Compound	LEL	UEL
Methane	5.00	15.0	p-Xylene	1.10	6.6
Ethane	3.00	12.5	Cumene	0.88	6.5
Propane	2.10	9.5	Cyclopropane	2.40	10.6
n-Butane	1.90	8.5	Cyclohexane	1.30	8.0
n-Pentane	1.40	8.0	Cycloheptane	1.10	6.7
n-Hexane	1.10	7.5	Methyl alcohol	6.0	36.0
n-Heptane	1.05	6.7	Ethyl alcohol	3.30	19.0
n-Octane	1.00	6.5	n-Propyl alcohol	2.20	13.7
n-Decane	0.80	5.4	n-Butyl alcohol	1.40	11.2
n-Dodecane	0.60	—	n-Amyl alcohol	1.20	9.0
n-Tetradecane	0.50	—	Dimethyl ether	3.40	27.0
Ethylene	2.70	36.0	Diethyl ether	1.90	36.0
Propylene	2.00	11.1	Formaldehyde	7.00	73.0
Butene-1	1.60	10.0	Acetaldehyde	4.00	60.0
cis-Butene-2	1.70	9.0	Propionaldehyde	2.60	17.0
Isobutylene	1.80	9.6	Acetone	2.50	12.8
3-Methyl-butene-1	1.50	9.1	Methyl ethyl ketone	1.40	11.4
Acetylene	2.50	100.0	Methyl propyl ketone	1.50	8.2
Methylacetylene	2.10	12.5	Diethyl ketone	1.60	—
Benzene	1.30	7.0	Methyl butyl ketone	1.00	8.0
Toluene	1.20	7.1	Methylene chloride	13.00	23.0
Ethylbenzene	1.00	6.7	Acetonitrile	3.00	16.0
Xylene (o-, m-)	1.10	6.4	Carbon monoxide	12.50	74.0

Source: From (434).

Appendix E

Pyrometric Cone Equivalent

Pyrometric cone equivalent (PCE) is defined as "the number of that standard cone whose tip would touch the supporting plaque simultaneously with that of a cone of the material being investigated, when tested in accordance with the Standard Method of Test for Pyrometric Cone Equivalent (PCE) of refractory materials (ASTM Designation C 24) of the American Society for Testing Materials" (June 1955).

The temperatures given in Table 1 apply only to the small (1 1/8-in.) PCE cones when heated in an oxidizing atmosphere at the prescribed rate of 150°C per hour.

The PCE test is not to be regarded as an accurate measurement of temperature, but rather as "a comparison of thermal behavior in terms of standard cones." While the test does not provide an index of the behavior of a refractory in service, it is useful in evaluating the relative refractoriness of fireclay and some classes of high-alumina refractory materials. It is not applicable to basic and some other refractories.

Table 1 Pyrometric Cone Equivalent (PCE): Cone Temperatures (to the nearest 5°)[a]

	End points			End points	
Cone no.	°F	°C	Cone no.	°F	°C
12	2440	1335	29	3020	1660
12–13	2450	1345	29–31	3040	1670
13	2460	1350	31	3060	1685
13–14	2505	1375	31–31 1/2	3075	1690
14	2550	1400	31 1/2	3090	1700
14–15	2580	1415	31 1/2–32	3105	1710
15	2605	1430	32	3125	1715
15–16	2660	1460	32–32 1/2	3130	1720
16	2715	1490	32 1/2	3135	1725
16–17	2735	1500	32 1/2–33	3150	1735
17	2755	1510	33	3170	1745
17–18	2765	1515	33–34	3185	1755
18	2770	1520	34	3205	1765
18–19	2790	1530	34–35	3225	1775
19	2805	1540	35	3245	1785
19–20	2825	1555	35–36	3260	1795
20	2845	1565	36	3280	1805
20–23	2885	1585	36–37	3295	1810
23	2920	1605	37	3310	1820
23–26	2935	1615	38	3360	1850*
26	2950	1620	39	3390	1865*
26–27	2965	1630	40	3425	1885*
27	2985	1640	41	3580	1970*
27–29	3000	1650	42	3660	2015*

[a] (*) Based on the work of Fairchild and Peters, Characteristics of Pyrometric Cones, *J. Am. Cer. Soc.*, *9*:700 (1926). Cone Numbers 39 through 42 were heated at a rate of 600°C/hr.

Appendix F

Spreadsheet Templates for Use in Heat and Material Balance Calculations

The 3.5″ diskette enclosed with this volume contains seven spreadsheet files, a three-file group that installs an executable program with associated support files, and a text file:

Ex2-10.xls	Moisture.xls
Met-H&M.xls	Equil.xls
Eng-H&M.xls	EqSample.xls
Hcomb.xls	Appendix.txt

STEAM subdirectory including: Setup.arv, Setupmn.arv, and Setup.exe (which loads the executable program STEAM.exe), Read me.txt and Steam.ico.

The spreadsheet files were prepared for use on a personal computer (using Microsoft Windows 3.1 or above) using Excel Office 97. The ".txt" file is an ASCII file of this appendix. The spreadsheet files can usually be translated and imported into Corel's Quattro Pro, Lotus 1-2-3, and, perhaps, other spreadsheet executive programs for use in the analysis of combustion situations. The graphical analysis incorporated into the heat and material balance spreadsheet files (flue gas heat content versus gas temperature) will have to be reconfigured in all but the Excel case. However, no guarantee of the success of such conversions is made or implied.

It is strongly recommended that users make working copies of the files on another floppy disk or on the hard disk of the computer to be used. Thus, the risk of inadvertently corrupting the archive version of the files in the course of making changes and so forth is minimized. The diskette is not write-protected; if the file is corrupted, a replacement charge (plus postage and handling) will be required by contacting Marcel Dekker, Inc.

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A. Heat and Material Balance Spreadsheets

The Ex2-10.xls, Met-H&M.xls, and Eng-H&M.xls spreadsheets are (1) a completed metric heat and material balance corresponding to the problem in Example 10 of Chapter 2 from the text; and (2) two analysis templates (one in metric and one in English units, respectively) of the same computational strategy as the example that can be used as an analysis tool for the rapid and accurate preparation of other heat and material balances. The speed, accuracy, and flexibility of the spreadsheet approach to these basic calculations for thermal systems are commanding. In the original files supplied with this book, the spreadsheet cells are not "protected," so the template can be modified or extended by the user with relative ease.

The following description of the use of the spreadsheet is made relative to the Ex2-10.xls sample problem shown in Fig. F-1.

1. Input

Up to 10 feeds can be accommodated in the spreadsheet as presented. The user can add provision for more by adding rows to the feed list and copying the formatting and equation cells from an existing blank feed input row into the space. The user can set variables such as the percent excess air, the percent of total heat input constituting "radiation losses," the ambient (or preheat) temperature and absolute humidity of the combustion air. The heat and material balance can be printed as a table. Also, the spreadsheet is set up (using Excel) to generate a graph showing the gas heat content as a function of gas temperature.

With a color monitor and in Excel Office 97, the values to be input show in red. These include

The **ambient temperature in °C** (°**F**) (cell C2).
The **temperature in °C** (°**F**) of the combustion air (cell C3).
The **percent excess air** (cell C4).
The **ambient pressure in atmospheres** (cell C5).
The **absolute humidity** of the ambient air (cell G2).
The **melting point °C** (°**F**) of any ash material (cell G3).
The **heat of fusion in kcal/kg (Btu/lb) of any ash** material (cell G4).
The percentage of total heat input lost as "**radiation losses**" (cell G5).

Heat & Material Balance

Ambient Temperature	15.50	Degrees C.	Ambient Humidity	0.0080	kg H_2O/Kg dry air
Air Preheat Temperature	300.00	Degrees C.	Ash Melting Temperature	800	Degrees C.
Percent Excess Air	10.00%		Ash Fusion Latent Heat	85.0	kcal/kg
Ambient Pressure	1.00	Atm.	Percent Furnace Heat Loss	5.00%	

BASIS: 100.00 kilograms

Feed	Feed Name	As-Fired Kg	% C	% H_2	% O_2	% N_2	% S	% Cl_2	%Ash	% Moisture	DRY BASIS Total %	If both HHV and LHV are input, the HHV is Used: Input HHV	Input LHV	Used HHV Kcal per Dry Kilogram	Estimated dry HHV (See Chap.4) by Chang Kcal per Kilogram	by Boie Kcal per Kilogram	by DuLong Kcal per Kilogram
			DRY BASIS ANALYSIS									kcal per dry kilogram					
1	Benzene	70.00	92.26%	7.74%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	10,078.3	-	10,078.3	9,952.1	9,608.6	10,006.0
2	Carbon	8.20	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	8,076.7	-	8,076.7	8,561.1	8,320.0	7,831.0
3	Ash	9.30	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	100.00%	-	-	-	0.0	0.0	0.0
4	Moisture	12.50	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	-	-	-	8,561.1	0.0	0.0
5	N/A	0.00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	-	-	-	8,561.1	0.0	0.0
6	N/A	0.00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	-	-	-	8,561.1	0.0	0.0
7	N/A	0.00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	-	-	-	8,561.1	0.0	0.0
8	N/A	0.00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	-	-	-	8,561.1	0.0	0.0
9	N/A	0.00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	-	-	-	8,561.1	0.0	0.0
10	N/A	0.00	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	-	-	-	8,561.1	0.0	0.0
	Total	100.00															
	Total Mass (Kg		72.78	5.42	0.00	0.00	0.00	0.00	9.30	12.50	100.00	771,709.9	-	771,709.9	766,851.1	740,822.9	764,635.4
	Total Kg Mols		6.06	2.69	0.00	0.00	0.00	0.00	9.30	0.69		Total Btu Input	Total Btu Input	Total kcal	------- Estimated Total Heat Input ------- Total kcal		

Line	Component	As-Fired kg	Atoms or Mols (a)	Product of Combustion	Mols O_2 Required	Mols Formed in Stoichiometric Combustion (d) CO_2	H_2O	SO_2	HCl	N_2	O_2	Total (d)
1	Carbon - C	72.78	6.060	CO2	6.060	6.060						6.060
2	Hydrogen - H2	5.42	2.688	H2O	1.344		2.688					2.688
3	Sulfur - S	0.00	0.000	SO2	0.000			0.000				0.000
4	Oxygen - O2	0.00	0.000	---	(0.000)							0.000
5	Nitrogen - N2	0.00	0.000	N2						0.000		0.000
6	Moisture - H2O	12.50	0.694	H2O			0.694					0.694
7	Ash	9.30	N/A	---								0.000
8	Chlorine - Cl2	0.00	0.00	HCl					0.000			0.000
	Total	100.00	9.442		7.404	6.060	3.382	0.000	0.000	0.000	0.000	9.442
9	Mols N2 in Stoichiometric Air (c)									27.853		27.853
	Excess Air Level =		10.00%									
10	Mols N2 in Excess Air									2.785		2.785
11	Mols O2 in Excess Air										0.740	0.740
	Ambient Humidity = HUM =		0.008	kg H2O/kg dry air								
12	Mols Moisture in Combustion Air (d)						0.497					0.497
13	Total Mols in Flue Gas					6.060	3.879	0.000	0.000	30.638	0.740	41.317
14	Volume (Mol) Percent in Wet Flue Gases					14.67%	9.39%	0.00%	0.00%	74.15%	1.79%	100.00%
15	Orsat (dry) Flue Gas Analysis (Mols)					6.060		0.000	0.000	30.638	0.740	37.438
16	A. With selective SO2 testing -- Vol %					16.19%	N/A	0.00%	N/A	81.84%	1.98%	100.00%
17	B. With alkaline CO2 testing only -- Vol %					16.19%	N/A	N/A	N/A	81.84%	1.98%	100.00%
18	C. With SO2 loss in testing -- Vol %					16.19%	N/A	N/A	N/A	81.84%	1.98%	100.00%
19	Hydrochloric Acid - concentration in ppm (wet basis)				0.00	ppm						

COMBUSTION AIR
1,846.2 cubic meters (moist)
at: **300.0** Deg. C
and **1.00** Atm.

PREHEATED COMBUSTION AIR
1,846.2 cubic meters (moist)
at: **300.0** Deg. C
and **1.00** Atm.

NOTES:

(a) The symbol in the Component column shows whether these are kg mols or kg atoms
(b) Throughout this analysis, dry combustion air is assumed to contain 21.0% oxygen, 79.0% nitrogen
(c) Calculated as follows: (HUM/18.016)[(Mol N2 in air)(28.016) + (1+% excess air)(Mols O2 for stoichiometric)(32.)]
Note that the weight of oxygen is adjusted to be the oxygen in the total combustion air, not only the excess oxygen.
(d) Subsequent energy calculations assume that the HCl concentration is negligable.

CALCULATED FLAME TEMPERATURE **2094.0 Degrees C**
Assumptions: **3801.2 Degrees F**
Total Heat Input **850,930** Kcal
Air Preheat Temperature **300.00** Degrees C
Heat Losses At **5.00%** Percent

FLUE GAS VOLUMETRIC FLOW RATES:
Equal to:
8,020.5 cubic meters wet basis at:
Flame Temperature Pressure
2094.0 Deg. C 1.00 Atm.

1,010.2 cubic meters wet basis at:
ArbitraryTemperature Pressure
25.00 Deg. C **1.00** Atm.

915.4 cubic meters dry basis at:
ArbitraryTemperature Pressure
25.00 Deg. C **1.00** Atm.

Figure F.1

The **kilograms (pounds) of each feed** on an as-fired basis (cells C10 through C19). This can correspond to a reference quantity such as 100 kg (100 lb) or to a unit time (e.g., the mass rate per hour of incinerator operation).

The **percent carbon, hydrogen, oxygen, nitrogen, sulfur, chlorine, and ash in each feed stream** on a dry basis (the range of cells D10 through J19). Note that the carbon should be that oxidizing to CO_2; the hydrogen that forming HCl or H_2O; the oxygen that is available to become CO_2, H_2O, or SO_2; the S that will oxidize to SO_2; and the Cl that forms HCl. This would exclude, for example, the carbon and oxygen in inorganic carbonates, the sulfur and oxygen in inorganic sulfates, and the chlorine in inorganic chlorides. The mass of the elements not participating in the basic combustion oxidation reactions or in the formation of HCl should be lumped into the "ash" quantity.

The **percent moisture in each feed stream** (the range of cells K10 through K19).

The **higher heating value (HHV) of each feed in kcal/kg (Btu/lb)** dry basis (cells M10 through M19) **or the lower heating value (LHV) of each feed in kcal/kg (Btu/lb)** dry basis (cells N10 through N19). The spreadsheet actually uses the HHV in its calculations and, if the LHV is entered, the HHV is calculated based on the hydrogen content of the feed stream. If both HHV and LHV are entered, the HHV that is entered will be used in the calculations.

2. Methodology

Metric-H&M.xls and English-H&M.xls carry out a conventional material balance based on the input data and the conventional assumptions regarding the fate of the elements in the feeds as described in the text (C to CO_2, H_2 to H_2O, nitrogen in the feeds to N_2, S to SO_2, and Cl to HCl). The heat balance first calculates the net heat content of the flue gases as being equal to the total of the weighted higher heat content of the feed streams, discounted by the heat of evaporation of the moisture and supplemented by the heat content of any air preheat and heat losses estimated (based on input from the user) as a percentage of the total heat input. This is done in the calculation block in cells B107 to F116. The total sensible heat of the flue gas is set equal to the integral of the sum of the weighted heat capacities of the flue gas constituents (a cubic equation in the gas temperature). The cubic equation is solved analytically to yield the flame temperature.

3. Output

The spreadsheets produce a number of useful quantities including the flue gas leaving temperature (cells E57 in °C and E58 in °F), volumetric wet basis flow rates of preheated combustion air (cell N37), and the wet basis flow rate of the flue gases leaving the furnace (cell K51). Calculator blocks are provided to calculate the wet or dry basis volumetric flows at any arbitrary temperature. These are illustrated in the sample output, Fig. F-1, for the metric spreadsheet. The graph of flue gas heat content is shown in the text as Fig. 4 of Chapter 2.

4. Extended Applications of the Basic Spreadsheet

The basic spreadsheet can be used as is or be extended and modified to analyze more complex situations. For example, to evaluate the fuel requirement for an afterburner, one of the feeds could be called "Fuel" (say, oil or natural gas) with an appropriate chemistry and

heat content. Then, one could play "what-if" with the feed rate of "Fuel" until the temperature equaled the target set point.

A second analysis might split the "Ash" into two portions: the residue that leaves at a temperature set by the analyst and a second portion (call it "fly ash") that leaves at the gas temperature. One would have to add a new line in the flue gas sensible heat content calculation (cells B107–F116) to reduce the heat content by the amount of heat lost from the flue gas to the residue fraction and change the flue gas ash contribution to the heat content correlation by adjusting the quantity in cell P70 to equal the fly-ash mass (not the total ash mass).

Another analysis might be looking at a multichamber system with an afterburner in the second chamber. Then, use one spreadsheet as the primary chamber and carry the flue gas quantity and composition and its heat content over to a second spreadsheet and then add the afterburner "Fuel" as a new feed for the second sheet.

There are numerous ways in which the basic spreadsheets can be assembled and combined to analyze more complex furnace situations. The basic computations are straightforward; if one is careful to keep to the basic flow path, the results can be most useful and helpful.

B. Heat of Combustion Calculator: HCOMB.xls

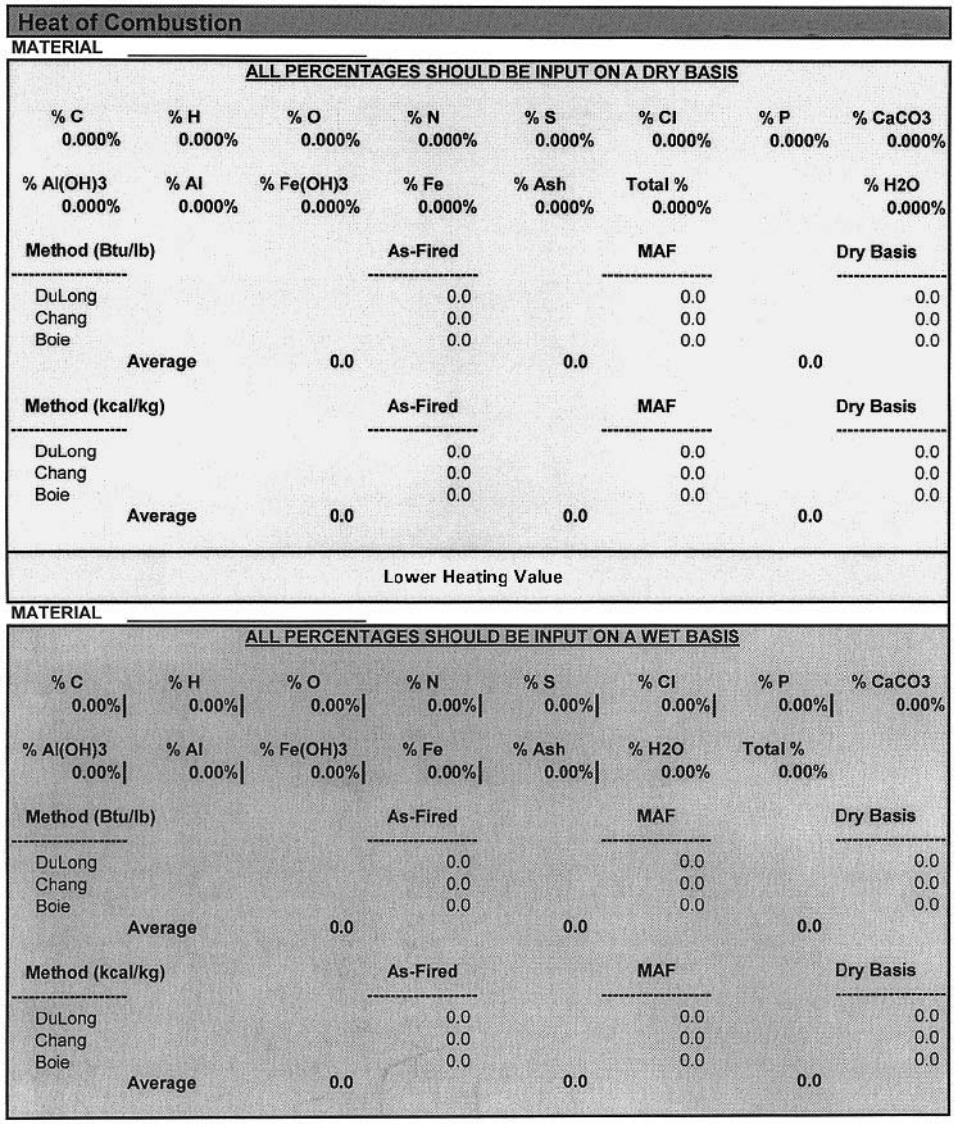
HCOMB.xls is a simple but useful pair of spreadsheets for a comparative estimation of the heat of combustion via the Chang, Boie, and DuLong equations (see Chapter 4). One of the spreadsheets generates the higher heating value (HHV) and the other the lower heating value (LHV).

Values for the percentage of the constituent elements on a **dry basis can be substituted in the upper screen** (cell Range A1–H20) or on a **wet basis in the lower screen** (cell Range A21–H40). A printout of the HHV spreadsheet is shown as Fig. F-2.

The spreadsheet calculator is used by entering the dry or wet basis waste chemistry into either the Lower Heating Value sheet or the Higher Heating Value sheet. The estimated heat content for each of the three estimation formulas in both English and metric units is presented on a dry basis, on a moisture and ashfree (MAF) basis, and on a wet (as-fired) basis. The average of the three is calculated.

C. Moisture Correction in Refuse Analyses: Moisture.xls

Published data on the moisture content of various solid waste constituents are widely available. However, when using these data it is important to note that the moisture content of waste components varies significantly between the "as-discarded" and the "as-fired" bases. This is because fresh waste at the moment of generation (as-discarded waste) exhibits different properties than it does after interacting with other wastes in the waste storage, collection, and disposal process (as-fired waste). Specifically, as they are mixed together, waste components often absorb or lose water. For example, most food wastes have a naturally high moisture content. When the food waste is mixed with dry waste components such as paper or cardboard, the food waste loses moisture as water is transferred from the food and absorbed by the paper. Therefore, when the mass of food waste in a sample of mixed waste is measured, the indicated mass will be less than the original mass of food waste when it had "typical food waste properties" and the quantity of paper will be greater than paper with "typical paper properties." The effects of moisture



Heat of Combustion

MATERIAL

ALL PERCENTAGES SHOULD BE INPUT ON A DRY BASIS

% C	% H	% O	% N	% S	% Cl	% P	% CaCO3
0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%

% Al(OH)3	% Al	% Fe(OH)3	% Fe	% Ash	Total %	% H2O
0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%

Method (Btu/lb)	As-Fired	MAF	Dry Basis
DuLong	0.0	0.0	0.0
Chang	0.0	0.0	0.0
Boie	0.0	0.0	0.0
Average	0.0	0.0	0.0

Method (kcal/kg)	As-Fired	MAF	Dry Basis
DuLong	0.0	0.0	0.0
Chang	0.0	0.0	0.0
Boie	0.0	0.0	0.0
Average	0.0	0.0	0.0

Lower Heating Value

MATERIAL

ALL PERCENTAGES SHOULD BE INPUT ON A WET BASIS

% C	% H	% O	% N	% S	% Cl	% P	% CaCO3
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

% Al(OH)3	% Al	% Fe(OH)3	% Fe	% Ash	% H2O	Total %
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Method (Btu/lb)	As-Fired	MAF	Dry Basis
DuLong	0.0	0.0	0.0
Chang	0.0	0.0	0.0
Boie	0.0	0.0	0.0
Average	0.0	0.0	0.0

Method (kcal/kg)	As-Fired	MAF	Dry Basis
DuLong	0.0	0.0	0.0
Chang	0.0	0.0	0.0
Boie	0.0	0.0	0.0
Average	0.0	0.0	0.0

Figure F.2

redistribution are of special importance when considering data on waste with a high fraction of high-moisture waste components.

Thus, when using waste composition data it is important to establish whether the values reported are on a *as-discarded basis* (meaning the condition prior to mixing with the other components in the refuse) or on an *as-fired basis* (meaning the modified properties after the components are mixed with other components in the refuse and where moisture has had the opportunity to be either gained or lost). Data collected from mixed refuse sampling would normally be on an as-fired basis, whereas data typically found in textbooks is presented on an as-discarded basis. If one is using textbook information (e.g.,

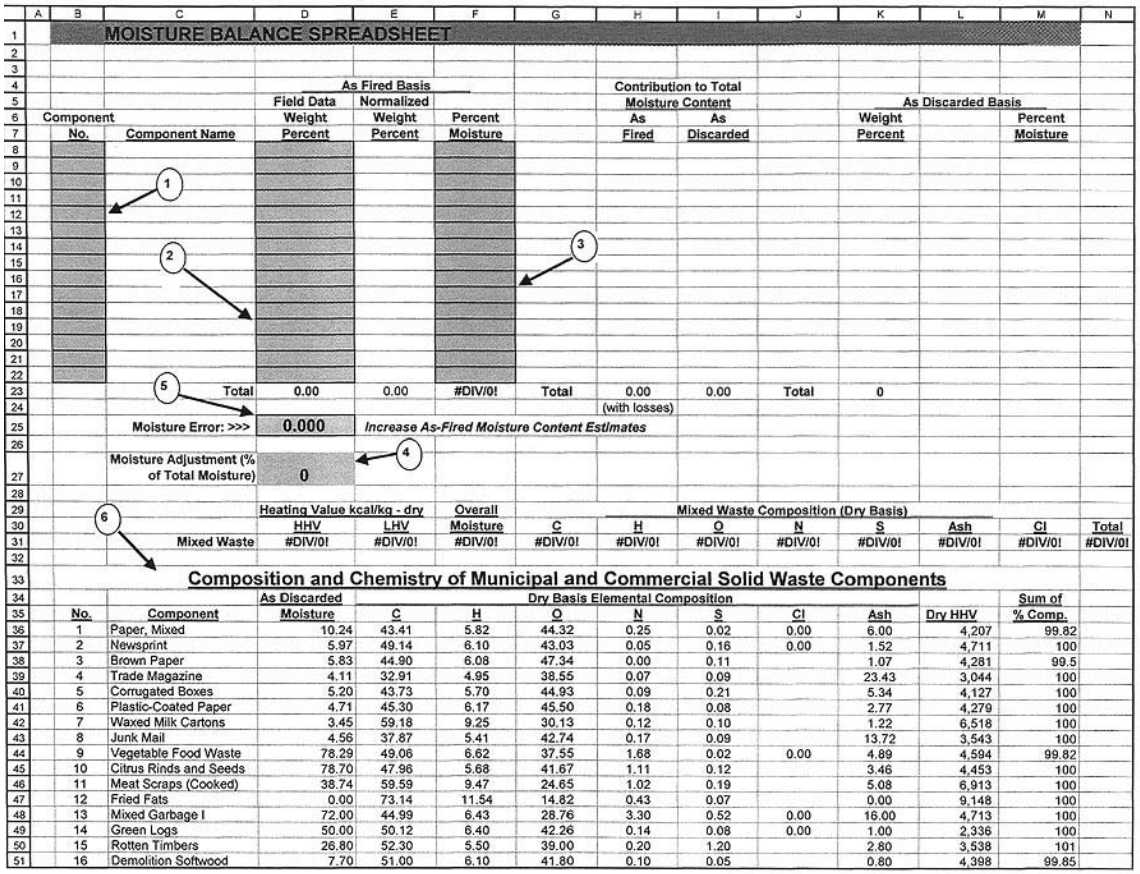
the wet basis carbon, hydrogen and other elemental composition, and the heat content) on an as-discarded basis to establish the fuel chemistry and energy content of a waste stream based on compositional weight data on an as-fired basis, appropriate adjustment of the composition data must be made to correct the composition to that prior to the moisture exchange. Further, one must at least consider the possibility that water either has evaporated from the waste (perhaps as it lays in the sun during the sampling process) or has been added to the waste (by rainfall, for example).

A computational approach to putting the waste back to its premixed state involves the use of a moisture balance applied to the reported waste distribution between various categories and the moisture content for the same categories in the as-discarded waste (e.g., as are tabulated in Chapter 4). This methodology is applied in the calculator that is provided in the Excel file Moisture.xls. With this spreadsheet, the engineer can take waste composition data (in whatever categories are convenient and adequate for waste characterization) and develop an estimate of the waste chemical makeup and calorific value. These data can then be used in the material and energy balances spreadsheets described previously.

The working area of Waste Balance is shown in Fig. F-3. Input data are required in the orange-colored blocks (marked as No. 1, 2, 3, and 4 in the figure). Calculated results are displayed in black or blue. The calculator is used as follows:

1. A field sampling program has produced a waste analysis that includes the weight percent of each of a maximum of 15 components. The analyst first reviews the standard component list noted as Item 6 in Fig. F-3 (cells C36 through C74) and tries to match each of the components from the field test data to standard components. For each of these field components, enter the Component Number (from Column B, cells B36–B74) into the cells noted as Item 1 in Fig. F-3 (cells B8–B22). Neither the order in which they are entered nor the total number of components cited is important.
2. If the components from the field test do not reasonably match those in the table, new names, moisture contents, chemistry, etc., can be entered into the table in cells B75 through L85. Be sure to use "as-discarded" data for the table.
3. Enter the field test weight percent of each component into the cells noted as Item 2 in Fig. F-3 (cells D8–D22). Don't worry if the total does not exactly equal 100%. The data will be normalized in cells E8–E22.
4. Enter your best estimate of the *actual* percent moisture in the component as it is found in the mixed waste. Enter as a percent (not a decimal) for each component in the cells noted as Item 3 in Fig. F-3 (cells F8–F22). Ideally, the moisture data used will be based on laboratory analysis of the materials collected in the field tests, but engineering estimates may be the only option. The weighted average moisture content of the overall mixed waste will be displayed in cell F23.
5. If you believe that the overall waste has lost X percent of its moisture due, say, to sitting out in the sun on a dry day during the testing program or has gained Y percent of its original moisture due, say, to sitting out in the rain during the sampling effort, enter the percent moisture loss as a negative number or the percent gain as a positive number in cell D27. Enter as a percent, not as a decimal.

The spreadsheet will display the calculated composition of the waste on an as-discarded basis in cells K8–K22. The percent moisture of the as-discarded component is



MOISTURE BALANCE SPREADSHEET

Component No.	Component Name	As Fired Basis: Field Data Weight Percent	As Fired Basis: Normalized Weight Percent	As Fired Basis: Percent Moisture	Contribution to Total Moisture Content: As Fired	Contribution to Total Moisture Content: As Discarded	As Discarded Basis: Weight Percent	As Discarded Basis: Percent Moisture
	Total	0.00	0.00	#DIV/0!	Total	0.00 (with losses)	0.00	Total 0

Moisture Error: >>> 0.000 *Increase As-Fired Moisture Content Estimates*

Moisture Adjustment (% of Total Moisture) 0

	Heating Value kcal/kg - dry: HHV	LHV	Overall Moisture	C	Mixed Waste Composition (Dry Basis): H	O	N	S	Ash	Cl	Total
Mixed Waste	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

Composition and Chemistry of Municipal and Commercial Solid Waste Components

No.	Component	As Discarded Moisture	Dry Basis Elemental Composition: C	H	O	N	S	Cl	Ash	Dry HHV	Sum of % Comp.
1	Paper, Mixed	10.24	43.41	5.82	44.32	0.25	0.02	0.00	6.00	4,207	99.82
2	Newsprint	5.97	49.14	6.10	43.03	0.05	0.16	0.00	1.52	4,711	100
3	Brown Paper	5.83	44.90	6.08	47.34	0.00	0.11		1.07	4,281	99.5
4	Trade Magazine	4.11	32.91	4.95	38.55	0.07	0.09		23.43	3,044	100
5	Corrugated Boxes	5.20	43.73	5.70	44.93	0.09	0.21		5.34	4,127	100
6	Plastic-Coated Paper	4.71	45.30	6.17	45.50	0.18	0.08		2.77	4,279	100
7	Waxed Milk Cartons	3.45	59.18	9.25	30.13	0.12	0.10		1.22	6,518	100
8	Junk Mail	4.56	37.87	5.41	42.74	0.17	0.09		13.72	3,543	100
9	Vegetable Food Waste	78.29	49.06	6.62	37.55	1.68	0.02	0.00	4.89	4,594	99.82
10	Citrus Rinds and Seeds	78.70	47.96	5.68	41.67	1.11	0.12		3.46	4,453	100
11	Meat Scraps (Cooked)	38.74	59.59	9.47	24.65	1.02	0.19		5.08	6,913	100
12	Fried Fats	0.00	73.14	11.54	14.82	0.43	0.07		0.00	9,148	100
13	Mixed Garbage I	72.00	44.99	6.43	28.76	3.30	0.52	0.00	16.00	4,713	100
14	Green Logs	50.00	50.12	6.40	42.26	0.14	0.08	0.00	1.00	2,336	100
15	Rotten Timbers	26.80	52.30	5.50	39.00	0.20	1.20		2.80	3,538	101
16	Demolition Softwood	7.70	51.00	6.10	41.80	0.10	0.05		0.80	4,398	99.85

Figure F.3

displayed in cells M8–M22. The projected higher heating value (see Chapter 3 for a discussion of this property), lower heating value, moisture content, and chemical composition (dry basis) of the mixed waste are displayed in cells D31–M31.

In all likelihood, the field data (or engineering estimates) for percent moisture from the field test will not indicate a perfect fit with the moisture based on the typical, as-discarded moisture content. A compensation for the error can be made by repeated manual adjustment of the as-fired percent moisture data (cells F8–F22) using engineering judgment until the moisture balance closes. Closure of the moisture balance means that the total moisture calculated for the as-fired field waste composition minus (or plus) the estimated moisture loss (or gain) in Kg H_2O/10,000 kg waste, as displayed in cell H23, equals the total moisture calculated for the as-discarded waste composition as displayed in cell I23. To aid in closure of the successive approximation process, the moisture error is displayed in the yellow cell noted as Item 4 in Fig. F-3 (cell D25), and guidance as to which direction to adjust to bring the error to zero is given in cells D25–G25.

The judgment involved in the adjustment of the assumed moisture content values is not based on an exact science. The basic principle involved is that "wet" wastes (such as food waste and, to a lesser extent, lawn and yard wastes) can be expected to give up moisture, and "absorbent" wastes (such as paper and textiles) will take up moisture relative to their as-discarded moisture levels. Ash and dirt can also take on moisture. Wastes such as plastic and metal and glass generally neither give up nor gain moisture.

D. Equilibrium Constant Estimation: Equil.xls

Chemical equilibria (see Chapter 2) describe the quantitative relationships between the relative concentrations of the reactants and the products of chemical reactions. The numerical value of the equilibrium constant is calculated from the enthalpy of formation (ΔH_{298}) and the free energy of formation (ΔF_{298}) at 298°K of the reactants and products. The temperature dependence of the equilibrium constant arises from the relative heat capacities of the reactants and products and the numbers of molecules of each (the stoichiometric coefficients) in the balanced chemical equation.

For ease in describing the use of the spreadsheet, a sample problem is worked out in the Excel file EqSample.xls and shown in Fig. F-4. The problem is to determine the K_p for the water gas shift reaction (where CO reacts with H_2O to form H_2 and CO_2) at a temperature of 1000°C. As in the Heat and Material Balance spreadsheets, the data to be entered are presented in red and calculated results in black or blue.

We enter the stoichiometric coefficients of CO, H_2O, H_2, and CO_2 in cells E5–E8 and the names in cells F5–F8. Then, from standard handbooks such as *Perry's Chemical Engineer's Handbook* (442) or the *Handbook of Chemistry and Physics* (434), we look up the enthalpy of formation and the free energy of formation of each of the reactants and products and enter them in cells H5–H8. The next step is to enter the coefficients of the analytical heat capacity functions for each of the reactants and products. The heat capacities must be of the form

$$C_p = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 \frac{1}{T} \tag{1}$$

Constants a_0 through a_4 are inserted in cells C113 through G13 for the first component, in cells C114 through G14 for the second, and so forth. It is unimportant if one or more of the coefficients are zero, but no other temperature dependencies can be accommodated.

	A	B	C	D	E	F	G	H	I	J
1	**Equilibrium Constant**									
2										
3					Stoichiometric				**cal/per gram mol . . .**	
4	**General Equilibrium Spreadsheet**				Coefficient	Component	Component	Type	**del H-298**	**del F-298**
5				a=	**0**	**A**	--	Reactant #1	**0.00**	**0.00**
6	**aA + bB ---> cC + dD**			b=	**0**	**B**	--	Reactant #2	**0.00**	**0.00**
7				c=	**0**	**C**	--	Product #1	**0.00**	**0.00**
8				d=	**0**	**D**	--	Product #2	**0.00**	**0.00**
9										
10	**HEAT CAPACITY COEFFICIENTS OF:**									
11		**Stoich.**								
12	**Component**	**Coefficient**	**Constant**	**T**	**T^2**	**T^3**	**1/T**			
13	--	**0**	**0.00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**			
14	--	**0**	**0.00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**			
15	--	**0**	**0.00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**			
16	--	**0**	**0.00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**	**0.0000E+00**			
17										
18		**At A Temperature of**		**1000.0**	Deg. C or	1831.7	Deg. F or			
19		**The Equilibrium**		1273.2	Deg. K	2291.7	Deg. R			
20		**Constant is given by:**								
21										
22		**Ln(Kp) =**	0							
23				**dimensions of Kp, 1/Kp**						
24		**Kp=**	1.0000	atmospheres raised to the		0	power			
25		**1/Kp=**	1.0000	atmospheres raised to the		0	power			
26										
27										

Figure F.4

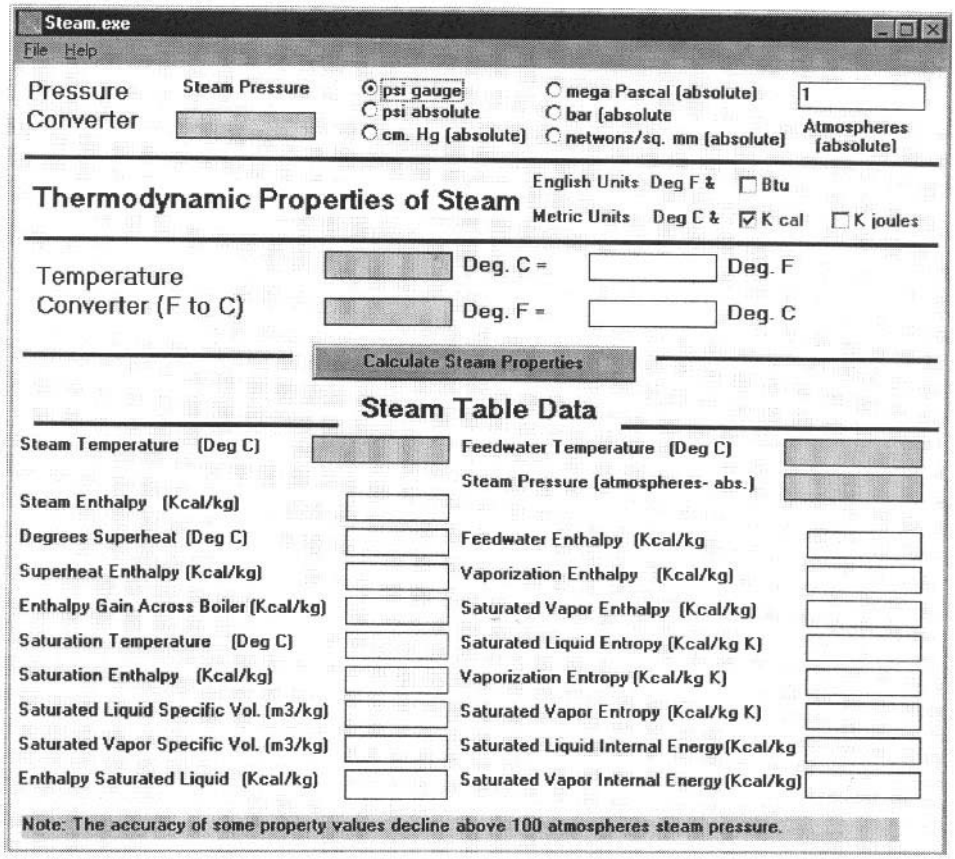


Figure F.5

The temperature where the K_p is desired (here, 1000°C) is entered in cell D18, and the equilibrium constant K_p is read from cell C24. Table 2 in Chapter 2 may be useful to find the constants for the heat capacity functional relationships. Also, *Perry's Chemical Engineer's Handbook* (442) and other standard texts often include these functions.

E. Steam.exe Program

The Steam program is a Visual Basic executable program that calculates the range of steam properties shown in Fig. F-5 for an input steam temperature and pressure and feedwater temperature. The program requires several supporting dynamic link libraries (.dll files). These will be automatically loaded into the application directory by the Install program on the floppy disk provided with this book. The files will only be downloaded if the version of the .dll files on your PC is older than the files contained in the install program file.

To install the Steam.exe program, insert the floppy disk into your A:\drive, move to the STEAM subdirectory and type SETUP. The program will be installed into a directory of your choice by the three files Setup.arv, Setupmn.arv, and Setup.exe. Steam can be run within Microsoft Windows by clicking on its icon or by other standard means.

To generate steam properties using the program, first select the units using the check boxes (English units: Btu and degrees F or metric units: kcal or kjoules and degrees C).

Then, for example, for the metric case, enter the steam temperature in °C, the feedwater temperature in °C, and the steam pressure in atm (absolute) in the white text boxes. The calculators at the top of the screen simplify conversion from other temperature or pressure units. When the steam and feedwater conditions have been entered, click on the "Calculate Steam Properties" bar and the enthalpies, entropies, etc., will appear. A command to print the results is available on a pull-down menu under FILE.

Appendix G

Thermal Stability Indices

The destruction efficiency of a hazardous waste incinerator for a given material is, in large part, a function of the combustion temperature, the residence time, the oxygen concentration, and the adequacy of mixing processes. The temperature, time, and oxygen concentration effects relate to the kinetics of combustion. A ranking of incinerability derived from the thermal stability of compounds was shown as the best among several proposed correlating parameters. The ranking shown in the following tables were based on gas phase thermal stability under oxygen-starved conditions. The ranking is based primarily of data taken at the University of Dayton Research Institute, limited studies reported in the open literature, and theoretical considerations (394).

The two tables that follow are first in order of relative incinerability rank and then alphabetically. In the first table, the compounds are broken into nine thermal stability classes: very stable, moderately stable, fragile, etc., based on natural divisions in predicted stability or theory that suggest different mechanistic pathways. Although few changes occur, the U.S. EPA reviews the list and semiannually considers changes in the relative rank.

Table 1 Thermal Stability Index (Listed by Rank)

Compound	Synonym	Source	Rank
Class 1			
Cyanogen	Ethane dinitrile	3	1
Hydrogen cyanide	Hydrocyanic acid	1	2
Benzene	—	1	3
Sulfur hexafluoride	—	3	4
Naphthalene	—	1	5
Fluoranthene	Benzo[j,k,]Fluorene	3	6
Benzo[j]fluoranthene	7,8-BenzoFluoranthene	3	7
Benzo[b]fluoranthene	2,3-BenzoFluoranthene	3	8
Benzo anthracene	1,2-Benz[a]Anthracene	3	9

(*continued*)

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Chrysene	1,2-BenzPhenanthrene	3	10
Benzo[a]pyrene	1,2-BenzoPyrene	3	11
Dibenz[a,h]anthracene	1,2,5,6-DibenzAnthracene	3	12
Indeno(1,2,3-cd)pyrene	1,10-(1,2-Phenylene)Pyrene	3	13
Dibenzo[a,h]pyrene	1,2,5,6-DebenzoPyrene	3	14
Dibenzo[a,i]pyrene	1,2,7,8-DebenzoPyrene	3	15
Dibenzo[a,e]pyrene	1,2,4,5-DebenzoPyrene	3	16
Cyanogen chloride	Chlorine cyanide	3	17–18
Acetonitrile	Ethane nitrile	1	17–18
Chlorobenzene	—	1	19
Acrylonitrile	2-Propene nitrile	1	20
Dichlorobenzene	1,4-DichloroBenzene	3	21–22
Chloronaphthalene	—	1	21–22
Cyanogen bromide	Bromine cyanide	3	23–24
Dichlorobenzene	1,2-DichloroBenzene	1	23–24
Dichlorobenzene	1,3-DichloroBenzene	1	25
Trichlorobenzene	1,3,5-TrichloroBenzene	1	26–27
Trichlorobenzene	1,2,4-TrichloroBenzene	1	26–27
Tetrachlorobenzene	1,2,3,5-TetrachloroBenzene	1	28
Chloromethane	Methyl chloride	1	29–30
Tetrachlorobenzene	1,2,4,5-TetrachloroBenzene	3	29–30
Pentachlorobenzene	—	1	31–33
Hexachlorobenzene	—	1	31–33
Bromomethane	Methyl bromide	1	31–33
Tetrachloro dibenzo-p-dioxin	2,3,7,8-TCDD	3	34
	Class 2		
Toluene	Methyl benzene	1	35
Tetrachloroethene	Tetrachloro ethylene	1	36
Chloroaniline	Chlorobenzen amine	3	37
DDE	1,1-Dichloro-2,2-bis(4-Chlorophenyl) ethylene	3	38
Formic acid	Methanoic acid	3	39–40
Phosgene	Carbonyl chloride	3	39–40
Trichloroethene	Trichloro ethylene	1	41
Diphenylamine	n-Phenylbenzen amine	3	42–44
Dichloro ethene	1,1-Dichloro ethylene	1	42–44
Fluoro acetic acid	—	3	42–44
Dimethylbenz[a]anthracene	7,12-Dimethylbenz anthracene	3	45
Analine	Benzen amine	3	46–50
Formaldehyde	Methylene oxide	3	46–50
Malono nitrile	Propane dinitrile	3	46–50
Methylchloro carbonate	Methyl carbonochloridate	3	46–50
Methyl isocyanate	Methyl carbyl amine	3	46–50
Amino biphenyl (4)	[1,1′-Biphenyl]-4-Amine	3	51
Naphthyl amine (1)	—	3	52–53
Naphthyl amine (2)	—	3	52–53

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Dichloroethene (1,2-trans)	trans-1,2-Dichloro ethylene	1	54
Fluoroacetamide (2)	—	3	55–56
Propyn-1-ol (2)	Propargyl alcohol	3	55–56
Phenylene diamine (1,4)	Benzene diamine	3	57–59
Phenylene diamine (1,2)	Benzene diamine	3	57–59
Phenylene diamine (1,3)	Benzene diamine	3	57–59
Benzidine	[1,1-Biphenyl]-4,4′ diamine	3	60–64
Acrylamide	2-Propen amide	3	60–64
α,α-Dimethyl phenethyl amine	—	3	60–64
Methyl methacrylate	2-Propenoic acid, 2-methyl-, methyl ester	3	60–64
Vinyl chloride	Chloro ethene	1	60–64
Dichloromethane	Methylene chloride	1	65–66
Methacrylonitrile	2-Methyl-2-propene nitrile	1	65–66
Dichlorobenzididine (3,3)	—	3	67
Methylchloroanthrene (3)	—	3	68
Toluene diamine (2,6-)	Diamino toluene	3	69–77
Toluene diamine (1,4-)	Diamino toluene	3	69–77
Toluene diamine (2,4-)	Diamino toluene	3	69–77
Toluene diamine (1,3-)	Diamino toluene	3	69–77
Toluene diamine (3,5-)	Diamino toluene	3	69–77
Toluene diamine (3,4-)	Diamino toluene	3	69–77
Chloro-1,3-butadiene (20)	Chloroprene	3	69–77
Pronamide	3,5-Dichloro-N-[1,1-dimethyl-2-propynyl]benzamide	3	69–77
Acetylaminofluorene (2-)	Acetamide,N-[9H-fluoren-2-yl]-	3	69–77
	Class 3		
DimethylBenzidiene (3,3′)	—	3	78
n-Propylamine	1-Propanamine	3	79
Pyridine	—	1	80
Picoline (2-)	Pruidine,2-methyl-	3	81–84
Dichloropropene (1,1-)	—	1	81–84
Thioacetamide	Ethane thioamide	3	81–84
Trichloro (1,2,2)trifluoro (1,1,2)ethane	—	1	81–84
Benz[c]acridine	3,4-Benzacridine	3	85–88
Dichlorodifluoromethane	—	1	85–88
Acetophenone	Ethanone, 1-phenyl-	1	85–88
Trichlorofluoromethane	—	1	85–88
Dichloropropene (trans-1,2-)	—	3	89–91
Ethyl cyanide	Propio nitrile	1	89–91
Benzoquinone	1,4-Cyclohexadienedione	3	89–91
Dibenz[a,h]acridine	1,2,5,6-Dibenzacridine	3	92–97
Dibenz[a,j]acridine	1,2,7,8-Dibenzacridine	3	92–97
Hexachlorobutadiene (trans-1,3)	—	1	92–97
Napthoquinone (1,4)	1,4-Naphthalenedione	3	92–97
Dimethyl phthalate	—	1	92–97

(*continued*)

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Acetyl chloride	Ethanoyl chloride	1	92–97
Acetonylbenzyl-4-hydroxycoumarin (3-α-)	Warfarin	3	98–99
Maleic anhydride	2,5-Furandione	3	98–99
Phenol	Hydroxybenzene	3	100–101
Dibenzo[c,g]carbazole (7H-)	3,4,5,6-Dibenzcarbazole	3	100–101
Chlorophenol	—	3	102
Cresol(1,3)	Methylphenol	3	103
Cresol(1,4)	Methylphenol	1	104–105
Cresol(1,2)	Methylphenol	3	104–105
Acrolein	2-Propenal	3	106–107
Dihydroxy-alpha-[methylamino]methyl benzyl alcohol	—	3	106–107
Methyl ethyl ketone	2-Butanone	1	108–109
Diethylstilbesterol	—	3	108–109
Benzenethiol	Thiophenol	1	110
Resorcinol	1,3-Benzenediol	3	111
Isobutyl alcohol	2-Methyl-1-propanol	1	112
Crotonaldehyde	2-Butenal	1	113–115
Dichlorophenol (2,4-)	—	3	113–115
Dichlorophenol (2,6-)		3	113–115
Methylactonitrile (2-)	2-hydroxy-2-methyl propanenitrile	3	116–118
Allyl alcohol	2-Propen-1-ol	3	116–118
Chlorocresol	4-Chloro-3-methylphenol	3	116–118
Dimethylphenol (2,4-)	—	3	119
	Class 4		
Chloropropene 3	Allyl chloride	1	120
Dichloropropene (cis-1,3)	—	3	121–125
Dichloropropene (trans-1,3-)	—	3	121–125
Tetrachloroethane (1,1,2,2-)	—	1	121–125
Trichlorophenol (2,4,5-)	—	3	121–125
Trichlorophenol (2,4,6-)	—	3	121–125
Chloroethane	Ethyl chloride	2	126
Dichloropropene (2,3)	—	3	127–130
Hydrazine	Diamine	2	127–130
Benzyl chloride	Chloromethyl benzene	1	127–130
Dibromomethane	Methylene bromide	1	127–130
Dichloroethane (1,2-)	—	1	131
Mustard gas	bis[2,Chloroethyl]sulfide	3	132–134
Nitrogen mustard	—	3	132–134
N,N-Bis(2-chloroethyl)2-naphthylamine	Chlornaphazine	3	132–134
Dichloropropene (3,3-)	—	3	135
Dichloro-2-butene (1,4-)	—	3	136–140
Tetrachlorophenol (2,3,4,6-)	—	3	136–140

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Tetrachloromethane	Carbon tetrachloride	1	136–140
Bromoacetone	1-Bromo-2-propanone	3	136–140
Hexachlorophene	2,2′-Methylene bis[3,4,6-trichlorophenol]	3	136–140
Dioxane (1,4)	1,4-Diethylene oxide	1	141
Chlorambucil	—	3	142
Nitrobenzene	—	1	143–144
Chloropropionitrile (3-)	3-Chloropropane nitrile	1	143–144
Dichloro-2-propanol (1,1-)	—	3	145–146
DDD	Dichlorodiphenyldichloroethane	3	145–146
Dichloro-2-propanol (1,3)	—	3	147
Phthalic anhydride	1,2-Benzenedicarboxylic acid anhydride	3	148–150
Methyl parathion	—	3	148–50
Nitrophenol	—	3	148–150
Chlorodifluoromethane	—	1	151–153
Pentachlorophenol	—	3	151–153
Hexachlorocyclohexane	Lindane	1	151–153
Dichlorofluoromethane	—	3	154–157
Dinitrobenzene	—	3	154–157
Nitroaniline	4-Nitrobenzenamine	3	154–157
Pentachloroethane	—	1	154–157
Dinitrobenzene (1,4-)	—	3	158–161
Dinitrobenzene (1,2-)	—	3	158–161
Trichloroethane (1,1,2-)	—	1	158–161
Trichloromethane	Chloroform	1	158–161
Dieldrin	—	3	162–164
Isodrin	—	3	162–164
Aldrin	—	3	162–164
Dichloropropane (1,3-)	—	2	165
Nitrotoluidine (5-)	Benzenamine,2-methyl-5-nitro-	3	166–167
Chloroacetaldehyde	—	3	166–167
Trichloropropane (1,2,3-)	—	1	168–173
Dinitrotoluene (2,4-)	—	3	168–173
Dinitrotoluene (2,6-)	—	3	168–173
Hexachlorocyclopentadiene	—	3	168–173
Benzal chloride	Alpha, alpha-dichlorotoluene	1	168–173
Dichloro-1-propanol (2,3-)	—	3	168–173
Ethylene oxide	Oxirane	2	174
Dichloroethane (1,1-)	Ethylidene dichloride	2	175–178
Dimethylcarbamoylchloride	—	3	175–178
Glycidyaldehyde	1-Propanol-2,3-epoxy	3	175–178
DDT	Dichlorodiphenyl trichloroethane	3	175–178
Dichloropropane (1,2-)	Propylene dichloride	2	179
Auramine	—	3	180–181
Heptachlor	—	3	180–181
Dichloropropane (1,1-)	—	2	182
Chloro-2,3-epoxypropane (1-)	Oxirane,2-chloromethyl-	3	183–186

(*continued*)

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Dinitrophenol (2,4-)	—	3	181–186
Bis(2-chloroethyl) ether	—	1	183–186
Trinitrobenzene	1,3,5-Trinitrobenzene	3	183–186
Butyl-4,6-dinitrophenol (2-sec-)	DNBP	3	187–188
Cyclohexyl-4,6-dinitrophenol (2-)	—	3	187–188
Bis(2-chloroethoxy) methane	—	3	189–192
Chloral	Trichloroacetaldehyde	3	189–192
Trichloromethanethiol	—	3	189–192
Dinitrocresol (4,6-)	Phenol,2,4-dinitro-6-methyl-	3	189–192
Heptachlor epoxide	—	3	193
Diepoxybutane (1,2,3,4-)	2,2′-Bioxirane	3	194
	Class 5		
Benzotrichloride	Trichloromethyl benzene	3	195–196
Methapyrilene	—	3	195–196
Phenacetin	N-[4-Ethoxyphenyl]acetamide	3	197–198
Methyl hydrazine	—	2	197–198
Dibromoethane (1,2-)	Ethylene dibromide	3	199
Aflatoxins	—	3	200
Trichloroethane (1,1,1-)	Methyl chloroform	1	201
Hexachloroethane	—	1	202–203
Bromoform	Tribromomethane	1	202–203
Chlorobenzilate	—	3	204–207
Ethyl carbamate	Urethan, carbamic acid, ethyl ester	3	204–207
Ethyl methacrylate	2-Propenoic acid, 2-methyl-, ethyl ester	3	204–207
Lasiocarpine	—	3	204–207
Amitrole	1H-1,2,4-Triazol-3-amine	3	208–209
Muscimol	5-Aminomethyl-3-isoazotol	3	208–209
Iodomethane	Methyl iodide	3	210
Dichlorophenoxyacetic acid (2,4-)	2,4-D	3	211–213
Chloroethylvinyl ether (2-)	Ethene,[2-Chloroethoxy]-	1	211–213
Methylene bis(2-chloroaniline) (4,4-)	—	3	211–213
Dibromo-3-chloropropane (1,2-)	—	3	214
Tetrachloroethane (1,1,1,2-)	—	1	215
Dimethylhydrazine (1,1-)	—	2	216–217
N,N-Diethylhydrazine	1,2-Diethylhydrazine	3	216–217
Chloromethylmethyl ether	Chloromethoxymethane	3	218–220
Dimethyl-1-methylthio-2-butanone, O-(methylamino)-carbonyl oxime (3,3)	Thiofanox	3	218–220
Dimethylhydrazine (1,2-)	—	3	218–220
Chlordane (alpha and gamma isomers)	—	3	221
bis-(chloromethyl) ether	Methane-oxybis[2-chloro-]	3	222–223
Parathion	—	3	222–223

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Dichloropropane (2,2-)	—	2	224
Maleic hydrazide	1,2-Dihydro-3,6-pyridazinedione	3	225
Bromophenyl phenyl ether (4-)	Benzene,1-bromo-4-phenoxy-	3	226
bis-(2-chloroisopropyl) ether	—	3	227–228
Dihydrosafrole	1,2-Methylenedioxy-4-propylbenzene	3	227–228
Methyl methanesulfonate	Methanesulfonic acid, methyl ester	3	229
Propane sulfone (1,3-)	1,2-Oxathiolane,2,2-dioxide	3	230
Saccharin	1,2-Benzoisothiazolin-3-one,1,1-dioxide	3	231
Methyl-2-methylthio-propionaldehyde-O-(methylcarbonyl)oxime (2-)	—	3	232–233
Methyomyl	—	3	232–233
Hexachloropropene	—	1	234
Pentachloronitrobenzene	PCNB	3	235–239
Diallate	S-(2,3-Dichloroallyl)diisopropyl thiocarbamate	3	235–239
Ethyleneimine	Aziridine	3	235–239
Aramite	—	3	235–239
Dimethoate	—	3	235–239
Trichlorophenoxyacetic acid (2,4,5-)	2,4,5-T	3	240–241
Trichlorophenoxypropionic acid (2,4,5-)	2,4,5-TP, Silvex	3	240–241
tris(2,3-Dibromopropyl) phosphate	—	3	242
Methylaziridine (2-)	1,3-Propylenimine	3	243–244
Methoxychlor	—	3	243–244
Brucine	Strychnidin-10-one,2,3-dimethoxy-	3	245–246
Kepone	—	3	245–246
Isosafrole	1,2-Methylenedioxy-4-allylbenzene	3	245–249
Safrole	1,2-Methylene-4-allylbenzene	3	245–249
tris(1-Azridinyl)phosphine sulfide	—	3	245–249
Dimethoxybenzidine (3,3′-)	—	3	250
Diphenylhydrazine (1,2-)	—	3	251
O,O-Diethyl phosphoric acid,o-p-nitrophenyl ester	—	3	252

Class 6

n-Butylbenzyl phthalate	—	1	253
O,O-Diethyl-O-2-pyrazinyl-phosphorothioate	—	3	254
Dimethylaminoazobenzene	—	3	255
Diethyl phthalate	—	3	256–267
O,O-Diethyl-S-methyl ester of phosphoric acid	—	3	256–267
O,O-Diethyl-S-[(ethylthio)methyl]ester of phosphorodithioic acid	—	3	258–259

(*continued*)

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Citrus red no. 2	2-Naphthol-1-[2,5-Dimethoxyphenyl)azo]	3	258–259
Trypan blue	—	3	260
Ethyl methanesulfonate	Methanesulfonic acid, ethyl ester	3	261–265
Disulfoton	—	3	261–265
Diisopropylfluorophosphate	DFP	3	261–265
O,O,O-Triethyl phosphorothioate	—	3	261–265
Di-n-butyl phthalate	—	3	261–265
Paraldehyde	2,4,6-Trimethyl-1,3,5-trioxane	2	266
Di-n-octyl phthalate	—	3	267
Octamethylpyrophosphoramide	Octamethyldiphosphoramide	3	268
bis(2-Ethylhexyl)phthalate	—	3	269–270
Methylthiouracil	—	3	269–270
Propylthiouracil	—	3	271

Class 7

Strychnine	Strychnidin-10-one	3	272
Cyclophosphamide	—	3	273–276
Nicotine	(S)-3-[1-Methyl-2-pyrrolidinyl]pyridine	3	273–276
Reserpine	—	3	273–276
Toluidine hydrochloride	2-Methyl-benzenamine hydrochloride	3	273–276
Tolylene diisocyanate	1,3-Diisocyanatomethylbenzene	3	277
Endrin	—	3	278
Butanone peroxide (2-)	Methyl ethyl ketone, peroxide	3	279
Tetraethylpyrophosphate	—	3	280
Nitroglycerine	Trinitrate-1,2,3-propanetriol	2	281
Tetraethyldithiopyrophosphate	—	3	282
Ethylenebisdithiocarbamic acid	—	3	283
Tetranitromethane	—	2	284
Uracil mustard	5-[bis(2-chloroethyl)amino]Uracil	3	285
Acetyl-2-thiourea (1-)	Acetamide,N-[aminothioxomethyl]-	3	286–290
Chlorophenyl thiourea (1-)	Thiourea,[2-chlorophenyl]-	3	286–290
N-Phenylthiourea	—	3	286–290
Naphthyl-2-thiourea (1-)	Thiourea,1-naphthalenyl-	3	286–290
Thiourea	Thiocarbamide	3	286–290
Daunomycin	—	3	291–292
Ethylene thiourea	2-Imidazolidinethione	3	291–292
Thiosemicarbazide	Hydrazinecarbothioamide	3	293–294
Melphalan	Alanine,3-[p-bis(2-chloroethyl)amino]Phenyl-,L-	3	293–294
Dithiobiuret (2,4-)	Thiomidodicarbonic diamide	3	295–296
Thiuram	bis[Dimethyl thiocarbamoyl]disulfide	3	295–296
Azaserine	L-serine,diazoacetate ester	3	297

Table 1 Thermal Stability Index (Listed by Rank) (*cont.*)

Compound	Synonym	Source	Rank
Hexaethyl tetraphosphate	—	3	298
Nitrogen mustard N-oxide	—	3	299–300
Nitroquinoline-1-oxide (4)	—	3	299–300
Cycasin	beta-D-glucopyranoside,[methyl-ONN-azoxy]methyl-	3	301
Streptozotocin	—		302
N-Methyl-N′-nitro-N-nitrosoguanidine	—	3	303–318
N-Nitroso-diethanolamine	[2,2′-Nitrosoimino]bis ethanol	3	303–318
N-Nitroso-di-N-butylamine	N-Butyl-N-nitrosoimino]bis ethanol	3	303–318
N-Nitroso-N-ethylurea	N-Ethyl-N-nitrosocarbamide	3	303–318
N-Nitroso-N-methylurea	N-Methyl-N-nitrosocarbamide	3	303–318
N-Nitroso-N-methylurethane	—	3	303–318
N-Nitrosodiethylamine	N-Ethyl-N-nitrosoethanamine	3	303–318
N-Nitrosodimethylamine	Dimethylnitrosamine	3	303–318
N-Nitrosomethylethylamine	N-Methyl-N-nitrosoethanamine	3	303–318
N-Nitrosomethylvinylamine	N-Methyl-N-nitrosoethenamine	3	303–318
N-Nitrosomorpholine	—	3	303–318
N-Nitrosonornicotine	—	3	303–318
N-Nitrosopiperidine	Hexahydro-N-nitrosopyridine	3	303–318
N-Nitrososarconsine	—	3	303–318
N-Nitrosopyrrolidine	N-Nitrosotetrahydropyrrole	3	303–318
Di-n-propylnitrosamine	N-Nitroso-di-n-propylamine	3	303–318
Oxabicyclo[2,2,1]heptane-2,3-dicarboxylic acid (7-)	Endothal	3	319
Endosulfan	—	3	320

Source 1 indicates compound thermal stability was experimentally evaluated with ranking based on University of Dayton Research Institute (UDRI) experimental data coupled with reaction kinetic theory.
Source 2 indicates compound thermal stability was ranked based on literature experimental data coupled with reaction kinetic theory.
Source 3 indicates compound thermal stability was ranged based on either UDRI or literature experimental data coupled with reaction kinetic theory.

Table 2 Thermal Stability Index (Listed Alphabetically)

Compound	Synonym	Source	Rank
α,α-Demethyl phenethyl amine	—	3	60–64
Acetonitrile	Ethane nitrile	1	17–18
Acetonylbenzyl-4-hydroxycoumarin (3-α-)	Warfarin	3	98–99
Acetophenone	Ethanone, 1-phenyl-	1	85–88
Acetyl chloride	Ethanoyl chloride	1	92–97
Acetyl-2-thiourea (1-)	Acetamide,N-[aminothioxomethyl]-	3	286–290
Acetylaminofluorene (2-)	Acetamide,N-[9H-fluoren-2-yl]-	3	69–77
Acrolein	2-Propenal	3	106–107
Acrylamide	2-Propen amide	3	60–64
Acrylonitrile	2-Propene nitrile	1	20

(*continued*)

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
Aflatoxins	—	3	200
Aldrin	—	3	162–164
Allyl alcohol	2-Propen-1-ol	3	116–118
Amino biphenyl (4)	[1,1′-Biphenyl]-4-amine	3	51
Amitrole	1H-1,2,4-Triazol-3-amine	3	208–209
Analine	Benzen amine	3	46–50
Aramite	—	3	235–239
Auramine	—	3	180–181
Azaserine	L-Serine,diazoacetate ester	3	297
Benzal chloride	Alpha, alpha-dichlorotoluene	1	168–173
Benzene	—	1	3
Benzenethiol	Thiophenol	1	110
Benzidine	[1,1-Biphenyl]-4,4′diamine	3	60–64
Benzo anthracene	1,2-Benz[a]anthracene	3	9
Benzoquinone	1,4-Cyclohexadienedione	3	89–91
Benzotrichloride	Trichloromethyl benzene	3	195–196
Benzo[a]pyrene	1,2-Benzopyrene	3	11
Benzo[b]fluoranthene	2,3-Benzofluoranthene	3	8
Benzo[j]fluoranthene	7,8-Benzofluoranthene	3	7
Benzyl chloride	Chloromethyl benzene	1	127–130
Benz[c]acridine	3,4-Benzacridine	3	85–88
bis(2-Chloroethyl) ether	—	1	183–186
bis(2-Chloroethoxy)methane	—	3	189–192
bis(2-Ethylhexyl)phthalate	—	3	269–270
bis-(2-Chloroisopropyl) ether	—	3	227–228
bis-(Chloromethyl) ether	Methane-oxybis[2-chloro-]	3	222–223
Bromomethane	Methyl bromide	1	31–33
Bromoacetone	1-Bromo-2-propanone	3	136–140
Bromoform	Tribromomethane	1	202–203
Bromophenyl phenyl ether (4-)	Benzene,1-bromo-4-phenoxy-	3	226
Brucine	Strychnidin-10-one,2,3-dimethoxy-	3	245–246
Butanone peroxide (2-)	Methyl ethyl ketone, peroxide	3	279
Butyl-4,6-dinitrophenol (2-sec-)	DNBP	3	187–188
Chloral	Trichloroacetaldehyde	3	189–192
Chlorambucil	—	3	142
Chlordane (alpha and gamma isomers)	—	3	221
Chloronaphthalene	—	1	21–22
Chloroaniline	Chlorobenzen amine	3	37
Chlorobenzene	—	1	19
Chloromethane	Methyl chloride	1	29–30
Chloro-1,3-butadiene (20)	Chloroprene	3	69–77
Chloro-2,3-epoxypropane (1-)	Oxirane,2-chloromethyl-	3	183–186
Chloroacetaldehyde	—	3	166–167
Chlorobenzilate	—	3	204–207
Chlorocresol	4-Chloro-3-methylphenol	3	116–118
Chlorodifluoromethane	—	1	151–153
Chloroethane	Ethyl chloride	2	126
Chloroethylvinyl ether (2-)	Ethene,[2-chloroethoxy]-	1	211–213
Chloromethylmethyl ether	Chloromethoxymethane	3	218–220

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
Chlorophenol	—	3	102
Chlorophenyl thiourea (1-)	Thiourea,[2-chlorophenyl]-	3	286–290
Chloropropene 3	Allyl chloride	1	120
Chloropropionitrile (3-)	3-Chloropropane nitrile	1	143–144
Chrysene	1,2-Benzphenanthrene	3	10
Citrus red no. 2	2-Naphthol,-1-[(2,5-dimethoxyphenyl)azo]	3	258–259
Cresol(1,3)	Methylphenol	3	103
Cresol(1,2)	Methylphenol	3	104–105
Cresol(1,4)	Methylphenol	1	104–105
Crotonaldehyde	2-Butenal	1	113–115
Cyanogen bromide	Bromine cyanide	3	23–24
Cyanogen	Ethane dinitrile	3	1
Cyanogen chloride	Chlorine cyanide	3	17–18
Cycasin	beta-D-Glucopyranoside,[methyl-ONN-azoxy]methyl-		301
Cyclohexyl-4,6-dinitrophenol (2-)	—	3	187–188
Cyclophosphamide	—	3	273–276
Daunomycin	—	3	291–292
DDD	Dichlorodiphenyldichloroethane	3	145–146
DDE	1,1-Dichloro-2,2-bis(4-chlorophenyl) ethylene	3	38
DDT	Dichlorodiphenyl trichloroethane	3	175–178
Di-n-butyl phthalate	—	3	261–265
Di-n-octyl phthalate	—	3	267
Di-n-propylnitrosamine	N-Nitroso-di-n-propylamine	3	303–318
Diallate	S-(2,3-Dichloroallyl)diisopropyl thiocarbamate	3	235–239
Dibenzo[a,e]pyrene	1,2,4,5-Debenzopyrene	3	16
Dibenzo[a,h]pyrene	1,2,5,6-Debenzopyrene	3	14
Dibenzo[a,i]pyrene	1,2,7,8-Debenzopyrene	3	15
Dibenzo[c,g]carbazole (7H-)	3,4,5,6-Dibenzcarbazole	3	100–101
Dibenz[a,h]anthracene	1,2,5,6-Dibenzanthracene	3	12
Dibenz[a,h]acridine	1,2,5,6-Dibenzacridine	3	92–97
Dibenz[a,j]acridine	1,2,7,8-Dibenzacridine	3	92–97
Dibromo-3-chloropropane (1,2-)	—	3	214
Dibromoethane (1,2-)	Ethylene dibromide	3	199
Dibromomethane	Methylene bromide	1	127–130
Dichloroethene	1,1-Dichloro ethylene	1	42–44
Dichlorobenzene	1,3-Dichlorobenzene	1	25
Dichloroethene (1,2-trans)	trans-1,2-Dichloro ethylene	1	54
Dichlorobenzene	1,2-Dichlorobenzene	1	23–24
Dichlorobenzene	1,4-Dichlorobenzene	3	21–22
Dichloro-1-propanol (2,3-)	—	3	168–173
Dichloro-2-butene (1,4-)	—	3	136–140
Dichloro-2-propanol (1,1-)	—	3	145–146
Dichloro-2-propanol (1,3)	—	3	147
Dichlorobenzdidine (3,3)	—	3	67

(*continued*)

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
Dichlorodifluoromethane	—	1	85–88
Dichloroethane (1,1-)	Ethylidene dichloride	2	175–178
Dichloroethane (1,2-)	—	1	131
Dichlorofluoromethane	—	3	154–157
Dichloromethane	Methylene chloride	1	65–66
Dichlorophenol (2,4-)	—	3	113–115
Dichlorophenol (2,6-)	—	3	113–115
Dichlorophenoxyacetic acid (2,4-)	2,4-D	3	211–213
Dichloropropane (1,3-)	—	2	165
Dichloropropane (1,2-)	Propylene dichloride	2	179
Dichloropropane (1,1-)	—	2	182
Dichloropropane (2,2-)	—	2	224
Dichloropropene (2,3)	—	3	127–130
Dichloropropene (3,3-)	—	3	135
Dichloropropene (trans-1,3-)	—	3	121–125
Dichloropropene (cis-1,3)	—	3	121–125
Dichloropropene (1,1-)	—	1	81–84
Dichloropropene (trans-1,2-)	—	3	89–91
Dieldrin	—	3	162–164
Diepoxybutane (1,2,3,4-)	2,2′-Bioxirane	3	194
Diethyl phthalate	—	3	256–267
Diethylstilbesterol	—	3	108–109
Dihydrosafrole	1,2-Methylenedioxy-4-Propylbenzene	3	227–228
Dihydroxy-alpha-[methylamino]methyl benzyl alcohol	—	3	106–107
Diisopropylfluorophosphate	DFP	3	261–265
Dimethoate	—	3	235–239
Dimethoxybenzidine (3,3′-)	—	3	250
Dimethyl phthalate	—	1	92–97
Dimethyl-1-methylthio-2-butanone,O-[(methylamino)-carbonyl] oxime (3,3)	Thiofanox	3	218–220
Dimethylaminoazobenzene	—	3	255
Dimethylbenzidiene (3,3′)	—	3	78
Dimethylbenz[a]anthracene	7,12-Dimethylbenz anthracene	3	45
Dimethylcarbamoylchloride	—	3	175–178
Dimethylhydrazine (1,2-)	—	3	218–220
Dimethylhydrazine (1,1-)	—	2	216–217
Dimethylphenol (2,4-)	—	3	119
Dinitrobenzene	—	3	154–157
Dinitrobenzene (1,4-)	—	3	158–161
Dinitrobenzene (1,2-)	—	3	158–161
Dinitrocresol (4,6-)	Phenol,2,4-dinitro-6-methyl-	3	189–192
Dinitrophenol (2,4-)	—	3	183–186
Dinitrotoluene (2,6-)	—	3	168–173
Dinitrotoluene (2,4-)	—	3	168–173
Dioxane (1,4)	1,4-Diethylene oxide	1	141
Diphenylamine	N-Phenylbenzen amine	3	42–44
Diphenylhydrazine (1,2-)	—	3	251

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
Disulfoton	—	3	261–265
Dithiobiuret (2,4-)	Thiomidodicarbonic diamide	3	295–296
Endosulfan	—	3	320
Endrin	—	3	278
Ethyl methacrylate	2-Propenoic acid, 2-methyl-,ethyl ester	3	204–207
Ethyl carbamate	Urethan, carbamic acid, ethyl ester	3	204–207
Ethyl methanesulfonate	Methanesulfonic acid, ethyl ester	3	261–265
Ethyl cyanide	Propionitrile	1	89–91
Ethylene oxide	Oxirane	2	174
Ethylene thiourea	2-Imidazolidinethione	3	291–292
Ethylenebisdithiocarbamic acid	—	3	283
Ethyleneimine	Aziridine	3	235–239
Fluoranthene	Benzo[j,k,]fluorene	3	6
Fluoroacetic acid	—	3	42–44
Fluoroacetamide (2)	—	3	55–56
Formaldehyde	Methylene oxide	3	46–50
Formic acid	Methanoic acid	3	39–40
Glycidyaldehyde	1-Propanol-2,3-epoxy	3	175–178
Heptachlor epoxide	—	3	193
Heptachlor	—	3	180–181
Hexachlorobutadiene (trans-1,3)	—	1	92–97
Hexachlorobenzene	—	1	31–33
Hexachlorocyclohexane	Lindane	1	151–153
Hexachlorocyclopentadiene	—	3	168–173
Hexachloroethane	—	1	202–203
Hexachlorophene	2,2′-Methylene bis[3,4,6-trichlorophenol]	3	136–140
Hexachloropropene	—	1	234
Hexaethyl tetraphosphate	—	3	298
Hydrazine	Diamine	2	127–130
Hydrogen cyanide	Hydrocyanic acid	1	2
Indeno(1,2,3-cd)pyrene	1,10-(1,2-Phenylene)pyrene	3	13
Iodomethane	Methyl iodide	3	210
Isobutyl alcohol	2-Methyl-1-propanol	1	112
Isodrin	—	3	162–164
Isosafrole	1,2-Methylenedioxy-4-allylbenzene	3	245–249
Kepone	—	3	245–246
Lasiocarpine	—	3	204–207
Maleic hydrazide	1,2-Dihydro-3,6-pyridazinedione	3	225
Maleic anhydride	2,5-Furandione	3	98–99
Malono nitrile	Propane dinitrile	3	46–50
Melphalan	Alanine,3-[p-bis(2-chloroethyl)amino]phenyl-,L-	3	293–294
Methacrylonitrile	2-Methyl-2-propene nitrile	1	65–66
Methapyrilene	—	3	195–196
Methoxychlor	—	3	243–244
Methyl parathion	—	3	148–150

(*continued*)

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
Methyl ethyl ketone	2-Butanone	1	108–109
Methyl methacrylate	2-Propenoic Acid, 2-Methyl-, methyl ester	3	60–64
Methyl hydrazine	—	2	197–198
Methyl methanesulfonate	Methanesulfonic acid, methyl ester	3	229
Methyl isocyanate	Methyl carbyl amine	3	46–50
Methyl-2-Methylthio-Propionaldehyde-O-(Methylcarbonyl)oxime(2-)	—	3	232–233
Methylactonitrile (2-)	2-hydroxy-2-methyl propanenitrile	3	116–118
Methylaziridine (2-)	1,3-Propylenimine	3	243–244
Methylchloanthrene (3)	—	3	68
Methylchloro carbonate	Methyl carbonochloridate	3	46–50
Methylene bis(2-chloroaniline) (4,4-)	—	3	211–213
Methylthiouracil	—	3	269–270
Methyomyl	—	3	232–233
Muscimol	5-Aminomethyl-3-Isoazotol	3	208–209
Mustard gas	bis[2,Chloroethyl]sulfide	3	132–134
n-Butylbenzyl phthalate	—	1	253
N-Methyl-N′-Nitro-N-Nitrosoguanidine	—	3	303–318
N-Nitroso-diethanolamine	[2,2′-Nitrosoimino]bis ethanol	3	303–318
N-Nitroso-di-N-butylamine	N-Butyl-N-nitroso-1-butanamine	3	303–318
N-Nitroso-N-ethylurea	N-Ethyl-N-nitrosocarbamide	3	303–318
N-Nitroso-N-methylurethane	—	3	303–318
N-Nitroso-N-methylurea	N-Methyl-N-nitrosocarbamide	—	303–318
N-Nitrosodiethylamine	N-Ethyl-N-nitrosoethanamine	3	303–318
N-Nitrosodimethylamine	Dimethylnitrosamine	3	303–318
N-Nitrosomethylethylamine	N-Methyl-N-nitrosoethanamine	3	303–318
N-Nitrosomethylvinylamine	N-Methyl-N-nitrosoethenamine	3	303–318
N-Nitrosomorpholine	—	3	303–318
N-Nitrosonornicotine	—	3	303–318
N-Nitrosopiperidine	Hexahydro-N-nitrosopyridine	3	303–318
N-Nitrosopyrrolidine	N-Nitrosotetrahydropyrrole	3	303–318
N-Nitrososarconsine	—	3	303–318
N-Phenylthiourea	—	3	286–290
n-Propylamine	1-Propanamine	3	79
Naphthalene	—	1	5
Naphthylamine (2)	—	3	52–53
Naphthylamine (1)	—	3	52–53
Naphthyl-2-thiourea (1-)	Thiourea,1-naphthalenyl-	3	286–290
Napthoquinone (1,4)	1,4-Naphthalenedione	3	92–97
Nicotine	(S)-3-[1-Methyl-2-pyrrolidinyl]pyridine	3	273–276
Nitroaniline	4-Nitrobenzenamine	3	154–157
Nitrobenzene	—	1	143–144
Nitrogen mustard	—	3	132–134
Nitrogen mustard N-oxide	—	3	299–300
Nitroglycerine	Trinitrate-1,2,3-propanetriol	2	281

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
Nitrophenol	—	3	148–150
Nitroquinoline-1-oxide (4)	—	3	299–300
Nitrotoluidine (5-)	Benzenamine,2-methyl-5-nitro-	3	166–167
N,N-bis(2-Chloroethyl)2-naphthylamine	Chlornaphazine	3	132–134
N,N-Diethylhydrazine	1,2-Diethylhydrazine	3	216–217
Octamethylpyrophosphoramide	Octamethyldiphosphoramide	3	268
O,O-Diethyl-O-2-pyrazinyl phosphorothioate	—	3	254
O,O-Diethyl-S-methyl ester of phosphoric acid	—	3	256–267
O,O-Diethyl-S-[(ethylthio)methyl]ester of phosphorodithioic acid	—	3	258–259
O,O-Diethylphosphoric acid,O-p-nitrophenyl ester	—	3	252
O,O,O-Triethyl phosphorothioate	—	3	261–265
Oxabicyclo[2,2,1]heptane-2,3-dicarboxylic acid (7-)	Endothal	3	319
Paraldehyde	2,4,6-Trimethyl-1,3,5-trioxane	2	266
Parathion	—	3	222–223
Pentachlorobenzene	—	1	31–33
Pentachloroethane	—	1	154–157
Pentachloronitrobenzene	PCNB	3	235–239
Pentachlorophenol	—	3	151–153
Phenacetin	N-[4-Ethoxyphenyl]acetamide	3	197–198
Phenol	Hydroxybenzene	3	100–101
Phenylenediamine (1,4)	Benzene diamine	3	57–59
Phenylenediamine (1,2)	Benzene diamine	3	57–59
Phenylenediamine (1,3)	Benzene diamine	3	57–59
Phosgene	Carbonyl chloride	3	39–40
Phthalic anhydride	1,2-Benzenedicarboxylic acid anhydride	3	148–150
Picoline (2-)	Pruidine,2-methyl-	3	81–84
Pronamide	3,5-Dichloro-N-[1,1-dimethyl-2-propynyl]benzamide	3	69–77
Propane sulfone (1,3-)	1,2-Oxathiolane,2,2-dioxide	3	230
Propylthiouracil	—	3	271
Propyn-1-ol (2)	Propargyl alcohol	3	55–56
Pyridine	—	1	80
Reserpine	—	3	273–276
Resorcinol	1,3-Benzenediol	3	111
Saccharin	1,2-Benzoisothiazolin-3-one,1,1-dioxide	3	231
Safrole	1,2-Methylene-4-allylbenzene	3	245–249
Streptozotocin	—	—	302
Strychnine	Strychnidin-10-one	3	272
Sulfur hexafluoride	—	3	4

(*continued*)

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
Tetrachlorobenzene	1,2,4,5-Tetrachlorobenzene	3	29–30
Tetrachloroethene	Tetrachloro ethylene	1	36
Tetrachlorobenzene	1,2,3,5-Tetrachlorobenzene	1	28
Tetrachlorodibenzo-p-dioxin	2,3,7,8-TCDD	3	34
Tetrachloroethane (1,1,2,2-)	—	1	121–125
Tetrachloroethane (1,1,1,2-)	—	1	215
Tetrachloromethane	Carbon tetrachloride	1	136–140
Tetrachlorophenol (2,3,4,6-)	—	3	136–140
Tetraethyldithiopyrophosphate	—	3	282
Tetraethylpryophosphate	—	3	280
Tetranitromethane	—	2	284
Thioacetamide	Ethanethioamide	3	81–84
Thiosemicarbazide	Hydrazinecarbothioamide	3	293–294
Thiourea	Thiocarbamide	3	286–290
Thiuram	bis[Dimethyl thiocarbamoyl]disulfide	3	295–296
Toluene diamine (2,6-)	Diamino toluene	3	69–77
Toluene diamine (1,4-)	Diamino toluene	3	69–77
Toluene diamine (3,5-)	Diamino toluene	3	69–77
Toluene	Methyl benzene	1	35
Toluene diamine (3,4-)	Diamino toluene	3	69–77
Toluene diamine (1,3-)	Diamino toluene	3	69–77
Toluene diamine (2,4-)	Diamino toluene	3	69–77
Toluidine hydrochloride	2-Methyl-benzenamine hydrochloride	3	273–276
Tolylene diisocyanate	1,3-Diisocyanatomethylbenzene	3	277
Trichloro benzene	1,2,4-Trichlorobenzene	1	26–27
Trichloro(1,2,2)trifluoro(1,1,2)ethane	—	1	81–84
Trichlorobenzene	1,3,5-Trichlorobenzene	1	26–27
Trichloroethene	Trichloro ethylene	1	41
Trichloroethane (1,1,2-)	—	1	158–161
Trichloroethane (1,1,1-)	Methyl chloroform	1	201
Trichlorofluoromethane	—	1	85–88
Trichloromethane	Chloroform	1	158–161
Trichloromethanethiol	—	3	189–192
Trichlorophenol (2,4,6-)	—	3	121–125
Trichlorophenol (2,4,5-)	—	3	121–125
Trichlorophenoxyacetic acid (2,4,5-)	2,4,5-T	3	240–241
Trichlorophenoxypropionic acid (2,4,5-)	2,4,5-TP, Silvex	3	240–241
Trichloropropane (1,2,3-)	—	1	168–173
Trinitrobenzene	1,3,5-Trinitrobenzene	3	183–186

Table 2 Thermal Stability Index (Listed Alphabetically) (*cont.*)

Compound	Synonym	Source	Rank
tris(1-Azridinyl)phosphine sulfide	—	3	245–249
tris(2,3-Dibromopropyl) phospate	—	3	242
Trypan blue	—	3	260
Uracil mustard	5-[bis(2-chloroethyl)amino]Uracil	3	285
Vinyl chloride	Chloro ethene	1	60–64

Source 1 indicates compound thermal stability was experimentally evaluated with ranking based on University of Dayton Research Institute (UDRI) experimental data coupled with reaction kinetic theory.
Source 2 indicates compound thermal stability was ranked based on literature experimental data coupled with reaction kinetic theory.
Source 3 indicates compound thermal stability was ranged based on either UDRI or literature experimental data coupled with reaction kinetic theory.

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