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Advances in the application of molecular microbiological methods in the oil and gas industry and links to microbiologically influenced corrosion

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ABSTRACT

While the oil and gas industry has witnessed increased applications of molecular microbiological methods (MMMs) for diagnosing and managing microbiologically influenced corrosion (MIC) in the past decade, the process for establishing clear links between microbiological conditions and corrosion mechanisms is still emerging. Different MMMs provide various types of information about microbial diversity, abundance, activity and function, all of which are quite different from the culture-based results that are familiar to oil and gas industry corrosion professionals. In addition, a multidisciplinary process for establishing the significance of molecular microbiological data in regard to corrosion threat identification, mitigation and monitoring has yet to be clearly established. As a result, the benefits of employing MMMs for MIC management are not yet being fully realized or appreciated. Regardless of advances in technology, the microbiological insights being afforded by MMMs will not be embraced by many oil and gas asset operators until their significance relative to corrosion management and asset integrity are made more transparent. The need for an initiative to link corrosion, microbiological technologies and disciplinary experts together to reach a common understanding is discussed here.
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1. Introduction

While von Wolzogen Kühr and van der Vlugt (1934) demonstrated decades ago that microorganisms could be responsible for corrosion, the legitimacy of MIC as a degradation mechanism in the oil and gas industry was only fully realized in the 1980s, as evidenced by research initiatives that developed at that time e.g., Pope et al. (1988). In the 1980s the majority of research and field testing in oil and gas was based on data obtained using the most-probable number (MPN) method with liquid culture media, such as that developed for evaluating sulfate reducing bacteria (SRB) in publications on recommended practice API RP-38 (1975). Although other more sophisticated test methods were employed by researchers, in practice industry favored the perceived simplicity of culture methods for routine monitoring, which were promoted by the Gas Research Institute (GRI) in a popular MIC field guide by Pope (1992).

Early oil industry sampling programs, as described by Pope (1990) and NACE (1994) also generally focused on collection and culturing of planktonic microorganisms with a lack of focus on the significance of biofilms and the vast differences between sessile and planktonic microbiological populations. Culture media were often limited to general formulations for SRB (e.g., using Postgate B medium) and acid producing bacteria (APB). Corrosion mitigation programs and biocide treatments were typically based on culture test results, often with some bacterial growth threshold being arbitrarily established (e.g. 1000 CFU/mL) to drive the mitigative action. Zintel et al (2003) described how culture media results were used by operators as a sole criterion to determine whether the potential for MIC was high, low or nonexistent. Overall, the industry was predominantly focusing on the role of SRB in corrosion and souring, and other functional groups of microorganisms (e.g., metal oxidizing or reducing bacteria, sulfur oxidizing bacteria, etc.) were generally not considered.

Moghissi et al. (2000) showed how researchers involved in early MIC work in the oil and gas industry attempted to move industry's

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over-emphasis on culture results towards a more balanced approach that considered operating conditions, metallurgy and system chemistry in conjunction with microbiology. In investigating the role of microorganisms in corrosion failures, Stoecker (1984) encouraged operators to consider the environmental requirements (temperature, redox potential) and chemical requirements (terminal electron acceptors, carbon sources, salinity, pH) of microorganisms suspected of involvement. Eckert and Cookingham (2002) identified that at least some operators partially perceived the significance of sessile populations and the conjoined effects of solids and biofilms and employed monitoring programs (NACE, 2012) that focused more on surface/biofilm interactions to drive internal corrosion mitigation programs (Skovhus and Eckert, 2014).

Today we have access to a variety of MMMs that provide more and different information about the microbiology of an environment than culture methods, including the ability to measure the types of microorganisms present and their abundance, their specific functions and their level of activity. Examples of the data made accessible by MMMs and their applications are shown in Table 1.

Whitby and Skovhus (2011) showed how MMMs are increasingly being employed in oilfield microbiology and Skovhus et al. (2014) also demonstrated that MMMs are finding more practical applications in industrial microbiology, environmental sciences and medical diagnostics. Gray et al. (2009) examined the roles of methanogens in North Sea crude oil formations using Archaeal 16S rRNA gene sequences. Using molecular methods, Mand et al. (2016) found that carbon steel was the predominant electron donor for microbiological acetate production and methane formation in certain oil fields, indicating that Methanogens and Acetogens that were found could contribute to MIC. Numerous examples exist of MMMs being employed to address oil and industry microbiological issues.

Culture methods continue to be widely used in the oil and gas industry today. However; because no common process exists for establishing clear links between microbiological observations (by MMMs or culture based methods) and materials degradation mechanisms, i.e., distinguishing between biotic and abiotic corrosion, the potential role of microorganisms in corrosion is still only inferred in various ways from the available data. As a result, industry is not realizing the full advantage of using molecular microbiological data in the process of managing corrosion and other biodeterioration issues. Considering that those who employ MMMs are presented with very different microbiological information than was previously available with culture methods, what appears to be needed is a process for applying and interpreting the information and data such that knowledge, upon which actions can be based, is produced.

Information alone cannot be equated with knowledge. Knowledge comes from applying information in a logical, structured manner to produce a specific outcome. This paper discusses some methods currently used to apply microbiological information to corrosion problems and examines some potential routes for the evolution of improvements.

2. MMMs and MIC management

At its core, the corrosion management process essentially consists of three primary activities; assessing corrosion threats, identifying preventive and mitigative barriers, and monitoring the effectiveness of those barriers. The cycle of activities is continuous; with each of the three activities providing input to the subsequent activity as illustrated in Fig. 1.

Information about system microbiology is typically needed in each of the three corrosion management activities, and MMMs can help provide that information. However; corrosion engineers also need a way to connect that microbiological information with other relevant information, such as data from corrosion monitoring (e.g., coupons, probes, inspection), operating conditions, fluid composition, mitigation measures, etc. The following overview briefly describes each of the three corrosion management activities that are focused on internal corrosion of oil and gas assets.

During the internal corrosion threat assessment, the likelihood of each potential corrosion threat mechanism is evaluated. Corrosion engineers typically review data about the asset design and overall process; operation, chemical treatment, corrosion monitoring data, and leak/failure history data to help identify probable corrosion threats. The potential damage rate of some threats, such corrosion caused by acid gases, can be estimated using mathematical models, although there are no widely accepted damage rate models for MIC. In assessing the potential for MIC, the corrosion engineer typically attempts to infer some type of relationship between the biofilm and localized corrosion. MMMs can be used in this step to characterize baseline microbiological conditions throughout the asset and to look for associations between biofilm community distribution, biofilm chemical composition, and the frequency, distribution or severity of localized corrosion. The threat assessment may also seek to relate biofilm and corrosion characteristics to operating conditions, such as changes in flow (e.g., periods of no flow), temperature, or fluid composition (e.g. increases in nutrients or electron acceptors). Significant operating condition changes may affect the initiation and/or propagation of MIC. A

Table 1
Molecular microbiological methods and the types of information they produce.

	Microbiological characteristics		
	Diversity & abundance	Function	Activity
Type of information obtained on the *in situ* microbial consortia	*Who is there and how many?*	*What are they doing?*	*How active are they?*
Microbial ecology disciplines	Abundance, types of microbes (community diversity) and spatial distribution	Functional characteristics of microbial consortia and expression of functional genes	Cellular activity and expression of metabolic pathway genes
Selected methods to answer the question	• qPCR of 16S rRNA and key functional genes • Microscopy with FISH • Enzymatic assays • Culturing specific strains • Live/dead stains • DGGE/T-RFLP • Next Generation Sequencing (NGS)	• NGS (e.g. MiSeq) • Metagenomics • Metatranscriptomics • Metaproteomics • Micro-Arrays • qFISH	• Quantification of RNA levels (RT-qPCR) • Metabolomics • Measure of ATP levels • General or specific enzymatic activity assays • Stable isotope probing (SIP) • Specific Process measurements • CARD-FISH • MAR-FISH



Figure. 1. Core activities of the corrosion management process. (Skovhus and Eckert (2014)).

number of investigators such as Eckert et al. (2012), Skovhus et al. (2010) and Larsen and Hilbert (2014), have demonstrated the utility of MMMs in forensic corrosion investigation, where more sophisticated methods such as next generation sequencing and metagenomics may be applicable. Handelsman (2004) described metagenomics as "…genomic analysis of microorganisms by direct extraction and cloning of DNA from an assemblage of microorganisms", providing insights into energy and nutrient cycling within microbiological communities, gene function, population genetics and gene transfer among members of an uncultured community. Metagenomics can be used to understand the microbiological community as a whole, rather than just the activities of one particular organism. This is particularly relevant to MIC.

Based on the threat assessment, the preventive and mitigative measures needed to manage the applicable corrosion threats are selected in the second step of the process. Options for internal corrosion mitigation include the use of biocides, corrosion inhibitors, or oxygen scavengers; velocity control; mechanical cleaning (e.g. pigging or flushing); process vessels (e.g., filters, separators, etc.); or control of fluid quality (or sources) to the extent possible. Larsen et al. (2010) showed how MMMs can be beneficial for evaluating the effectiveness of new chemical treatments when corrosion incidence rate and severity are linked with observations about the types, numbers and activities of microorganisms after the treatment is applied. One of the most significant challenges to this process is the collection of biofilm samples from the asset being treated and processing/analyzing the samples in a timely manner so that genetic information is not lost. Another significant challenge is the lack of standards for determining biocide 'efficacy' based on microbiological information, since the conditions promoting MIC may be quite different from system to system.

The third core activity in the corrosion management process is measuring the effectiveness of the methods used to reduce the likelihood and/or severity of corrosion. Various corrosion monitoring techniques and inspection methods can provide information about the rate of metal loss due to corrosion; however, these methods generally do not identify the mechanism of the corrosion. Corrosion engineers typically attempt to integrate operating data, corrosion monitoring data, chemical/microbiological fluid and deposit analysis results, in-line inspection (ILI) and other inspection data, and flow/corrosion rate model output to ascertain the apparent short-term and long-term effectiveness of mitigation measures. Short-term effectiveness (i.e., hours, days, weeks) may be evaluated through different parameters or measurements than those used to monitor long-term (i.e., months, years) effectiveness. For example, short term effectiveness monitoring could focus on controlling bacteria populations in biofilms, whereas long term effectiveness would focus more on controlling corrosion damage that resulted from biofilms. As mentioned previously, MMMs produce data that are useful in the third activity in the corrosion management process; however, an established, widely accepted process for integrating MMM data with corrosion data has not been developed. Often microbiological data are incorporated into decision-making by inferring the activities and roles of microorganisms in corrosion mechanisms, and mitigation measures are adjusted based on empirical observations.

3. Linking microbiology with corrosion

3.1. How is it generally done today?

The general approach to linking microbiological activity to corrosion is to consider the metabolism of the predominant, active, functional groups of microorganisms that are present in biofilms on the material and connect the electron acceptors and metabolic byproducts of those microorganisms to a probable anodic and/or cathodic corrosion reaction or some intermediate reaction. While this approach is logical, it is also complicated by the lack of understanding in regard to how microorganisms behave in mixed communities. Research has long used both pure and mixed microbiological cultures to evaluate the effects of microorganisms on the corrosion of materials. While corrosion research using cultures of specific organisms provides some information about their behavior, metabolism and energy sources, it does not necessarily demonstrate the behavior and effects of microorganisms in the natural environment. In natural biofilms containing a wide variety of microorganisms there are demonstrated synergies in microbial metabolism and different genes expressed as a result of microorganisms functioning within a biofilm. A number of models have been postulated (Sooknah et al. (2007), Pots et al. (2002)) on the behavior of microorganisms in biofilms and their resulting effects on corrosion. Since many microorganisms are capable of using different energy sources and electron acceptors (metabolic pathways) than those normally associated with their functional groups, accurately determining the actual behavior of microorganisms in mixed cultures is difficult. Using a metabolomics approach, Lenhart et al. (2014) studied microbiological metabolites in communities associated with internal corrosion of pipelines, and Suflita et al. (2012) used RT-qPCR to understand gene expression in microorganisms responsible for MIC. These two methods are being used to understand the types of microbiological behavior that is actually occurring, rather than simply inventorying the microorganisms that are present.

The arrangement of bacteria in the biofilm structure can also reflect synergistic effects on corrosion, as for example when facultative anaerobes are concentrated in the outermost layer exposed to more oxygen than the strict anaerobes located deeper in the biofilm, near the metal surface where conditions are highly reduced. However; understanding the spatial arrangement of microorganisms in biofilm is not a simple matter, so the effects of biofilm structure relative to anodic and cathodic reactions and the bulk environment is not generally considered or understood when evaluating the potential for MIC.

For forensic analysis of corrosion damage, Little et al. (2006) identified that the following information are generally accepted by industry and academia as being suitable evidence for identifying MIC;

1. A sample of the corrosion product from the affected surface that has not been altered by collection or storage (i.e. contamination, oxidation, etc.),
2. Identification of a complete corrosion mechanism (or a combination of mechanisms) including anodic and cathodic reactions,

3. Identification of microorganisms capable of growth in the particular environment, and,
4. Demonstration of an association of those microorganisms with the observed corrosion, both spatially and chemically/electrochemically.

From a practical perspective, retrieving such samples that meet these criteria from oil and gas industry assets that have corrosion damage is highly challenging. Sulfate reducing prokaryotes (SRP) are nearly always present in oil and gas assets and different forms of iron sulfide minerals are attributed to their activities; however, maintaining these readily oxidizable minerals in an anoxic condition during sampling presents a challenge. Although as soon as a pipeline is opened it is exposed to air and other contaminants. Even the process of deinventorying a pipeline might destroy the native biofilm conditions. The same challenge exists for preserving minerals resulting from the activities of iron utilizing bacteria where exposure to oxygen irreversibly changes the composition of the corrosion deposits. Simply obtaining biofilm samples from flowing high pressure pipelines in locations with high susceptibility to MIC is difficult and rarely achievable.

In practice, oil and gas operators seldom have access to sophisticated sampling and analysis techniques. Microbiological information is often obtained from bulk fluid or commingled maintenance pigging samples using culture methods and/or MMMs and assumptions about biofilms and corrosion mechanisms are made from that data. Although Larsen et al. (2008) established that planktonic microbiological populations do not correlate closely with sessile populations, operators continue to make assumptions and base costly mitigation measures mainly on planktonic data.

In summary, while a general approach for diagnosing the influence of microorganisms on corrosion exists, there are two major limitations that prevent the rigorous application of this approach;

1. Microbiological activities and community synergies, and the spatial distribution of microorganisms in biofilms relative to corrosion reactions are not well understood;
2. Optimum collection of biofilms and corrosion product samples from operating assets is seldom possible given the current capabilities and technologies being used in the oil and gas industry.

These challenges cannot be simply overcome by applying more or better molecular methods; what is needed is a better way to link microbiological information to corrosion mechanisms, the potential for MIC, and the core processes of corrosion management. Since the introduction of MMMs to the oil and gas industry researchers (Zhu et al. (2003) and Larsen et al. (2005)) recognized the need for a linkage.

3.2. How can microbiological information be better linked to corrosion?

There are a number of ways in which one could approach the challenge of improving the linkage between microbiological data and corrosion, including better data integration schemes, employing new monitoring technologies, promoting functional interdisciplinarity, focusing on damage mechanisms, and establishing large scale collaborative projects. These approaches are briefly explored here.

3.2.1. Data integration schemes

Undoubtedly, characterizing all of the physical, chemical and microbiological parameters associated with any given environment where MIC occurs is both essential and complicated. Microbiologists have long understood the significance of the environment in regard to proliferation of microorganisms that find the current physical and chemical conditions to be ideal, while numerous other microorganisms with different needs are only present in a dormant or inactive state. Chemical and physical characteristics of the environment are therefore, quite significant in determining the microorganisms that are likely to be thriving and how they might interact with materials in terms of corrosion.

Chemical and physical conditions also have an abiotic effect on corrosion or the potential for corrosion. When the liquid chemistry indicates a strong tendency for mineral scale formation, for example, the mineral scale may prevent direct exposure of the metal substrate to the biofilm, thereby reducing the potential for MIC and increasing the potential for abiotic mechanisms. When pipeline fluid velocities are high the potential for solids deposition and water accumulation is reduced, while the potential for flow assisted corrosion (FAC) or erosion could be increased. High fluid velocities may also reduce the ability for biofilm formation or cause the biofilm to be more isolated to crevices, welds or other micro niches. Thus, physical and chemical conditions affect both biotic and abiotic corrosion mechanisms and the potential for both mechanisms to exist concurrently or episodically.

Within the categories of physical, chemical and microbiological conditions there exist numerous independent and interdependent parameters. For example, pipeline design features (e.g. low points or dead legs) can influence the potential for water or solids accumulation, which influences the potential for biofilm formation. Operating temperature influences microbiological selection and growth rate along with corrosion reaction rates and solubility of different species in the fluid phase. Thus, it is clearly important that physical, chemical and microbiological factors are understood and carefully evaluated when attempting to link microbiological data to corrosion. When microbiological data is presented or analyzed it should be done in the context of the physical and chemical conditions associated with the data. These parameters are discussed further in section 4.

3.2.2. Improved technologies for monitoring

One of the first challenges in obtaining any type of reliable microbiological and corrosion data from an industrial asset such as a pipeline is sample collection, preservation and transportation. As discussed earlier most oil and gas systems are anaerobic. Exposure of biofilms to air, dehydration and contamination during sample collection is not uncommon and this affects the validity of subsequent test results. Handling of samples for analysis by laboratory MMMs is also challenging due to the remote origins of some samples and the time required for shipping, during which DNA degradation could occur; again affecting the validity of the results. Eroini et al. (2015) presented a method for maintaining samples in anoxic conditions for use in the field to preserve pipeline solid and sludge samples. Price (2012) presented a novel approach for preserving DNA in the field using nucleic acid extraction cards however, these are not widely used by the oil and gas industry and standards that guide sample preservation are lacking. Sample collection and preservation is one area where improved technology and training of operators is highly needed.

The collection of surface related samples of biofilm and corrosion is also quite difficult, and operators incorrectly assume that planktonic samples are sufficient, even though it has been clearly established by Wrangham and Summer (2013) and others that planktonic populations can be completely different from sessile populations. Some operators use weight loss or extended analysis coupons per NACE 3T199 (2012) for corrosion monitoring and Sublette et al. (2014) demonstrated a method to collect and analyze biofilm layers on the coupons using MMMs and other techniques

such as ATP analysis and microscopy. Installing coupons in susceptible locations on remote, buried pipelines is often impractical. Some operators use pig returns as a source for surface deposit samples, however the samples are commingled and only represent the collective entirety of the pipeline - not localized conditions. In plant facilities or on offshore platforms Schwermer et al. (2008) showed that it is possible to use a side stream or Robbins device (Hall-Stoodley et al. (1999)) to collect surface samples and test mitigation chemicals. Overall, technologies for concurrently monitoring surface deposits and corrosion have not advanced in many years and there is a need for better and more standardized monitoring concepts.

A few online probes for monitoring both corrosion and biofilm formation exist however, these are not widely used in oil and gas applications in part due to reliability and also due to the same limitations as experienced with coupon monitoring. Fouling and shorting of probes using electrodes due to iron sulfide or organic deposits is another problem. Corrosion monitoring probes using multiple electrodes to detect localized corrosion are available but again they are not widely used. In some cases the electrical field method or permanent ultrasonic wall thickness probes have been applied to monitor growth of existing corrosion damage in pipelines, but these methods do not provide direct information about biofilms or surface deposits.

3.2.3. Interdisciplinarity

Biodeterioration is clearly a multi-disciplinary subject, requiring knowledge of corrosion and materials science, microbiology, electrochemistry, advanced analytical methods, production chemistry, pipeline design and operation, fluid mechanics, etc., to even begin to describe the phenomena. While this fact is acknowledged by most individuals who work in some way with biodeterioration, putting interdisciplinarity into practice is challenging. Numerous social, political, economic, institutional and disciplinary barriers exist, which must be overcome to effectively conduct truly interdisciplinary work. Ledford (2015) discussed one cause for the general lack of interdisciplinarity as being organizations "underestimating the depth of commitment and personal relationships needed for a successful interdisciplinary project…"

Sciences sometimes exist in silos. It is easier to discuss scientific matters with those who speak our own scientific or technical language. Successful multidisciplinary efforts today have resulted from personal relationships that develop between researchers in different scientific disciplines. This is one way that institutional and other barriers are overcome and collaborative work is accomplished.

Technical forums also provide the opportunity for interdisciplinary exchange to occur. Two examples of such forums are the International Symposium on Applied Microbiology and Molecular Biology in Oil Systems (ISMOS) conferences held every other year and the Reservoir Microbiology Forum (RMF), where industry and academic exchange occur with the focus being microbiological phenomena, e.g., souring, bioremediation, biofuels and MIC. Joint industry projects (JIP) also provide an opportunity for collaboration between multiple technical disciplines and industry. In these forums, informal frameworks for technical exchanges between disciplines are beginning to be formed.

3.2.4. Striving to understand mechanistic causes of biodeterioration

MIC and other forms of biodeterioration have numerous mechanistic causes, including some that are not clearly understood or well documented. While industry and academia have general concepts of biodeterioration mechanisms, a detailed understanding of the effects of specific types of biofilms and microbiological processes on a material's surface is much less accessible. The roles of microorganisms in corrosion initiation and propagation in a given environment are not always clear and there are multiple ways in which microbiological presence and activity can influence cathodic and anodic reactions. For example, Enning and Garrelfs (2014) presented a comprehensive review of SRB-related corrosion mechanisms, elucidating the differences between chemical MIC (CMIC) and electrical MIC (EMIC). CMIC was described as involving corrosive hydrogen sulfide, formed by SRB as a dissimilatory product of sulfate reduction using organic compounds or hydrogen; whereas, EMIC was described as being associated with only certain SRB that could attack iron via direct withdrawal of electrons by metabolic coupling. The observed corrosion rates of EMIC and CMIC by SRB were also considerably different.

It has been established that the mere presence of microorganisms in an environment does not mean that MIC has occurred or will occur. Since, in addition to SRB, diverse microbiological phyla seem to be ubiquitous in all oil and gas assets, there is still insufficient understanding of the conditions that result in MIC vs. those that do not. Often a diagnosis of MIC is rendered when no other abiotic mechanism seems plausible. In the past (and today in many cases) the presence of certain numbers of bacteria in a pipeline trigger the application of biocides "to prevent MIC". Biocide application appears to work (to reduce corrosion) in some cases, yet in other cases it does not, as shown by Campbell and Johnson (2011) and adjustments to biocide regimens are typically made based solely on empirical evidence.

As experienced in the past, for example with ethanol stress corrosion cracking (Beavers et al. (2011)), an improved understanding of a damage mechanism generally leads to improved preventive and mitigative measures. While some advances have been realized in new biocides for MIC mitigation there have been no breakthroughs in regard to a scientific approach to MIC prevention or mitigation. Working to understand the mechanistic causes of MIC and other biodeterioration in specific environments is one way that improved control measures are likely to evolve.

One significant deterrent to making progress in understanding MIC mechanisms is the lack of industry support for basic research in this area. Given the current economic conditions in the oil and gas industry this problem is likely to continue in the foreseeable future. The support for basic MIC research, in general, is lacking in the US; as a result, the ability to put together cohesive MIC research programs on a larger scale is limited. Therefore, there is a need for industry and academic researchers to collaborate and share information in order to advance the greater understanding of MIC mechanisms.

3.2.5. An organized "movement"

The need for extensive data integration, interdisciplinarity, and better mechanistic understanding to effectively address biodeterioration also points to the need for an organized approach or a "movement". Such a movement would need to involve scientists, researchers, oil and gas operators, academics, industry organizations, government, and various other types of technical experts.

Dubilier et al. (2015) recently discussed an initiative by scientists to study the earth's microbiome or biosphere. The researchers in this effort maintained that, "A holistic understanding of the role of Earth's microbial community and its genome — its microbiome — in the biosphere and in human health is key to meeting many of the challenges that face humanity in the twenty-first century."

Based on past experience in attempting to form a global, united effort, the researchers "identified two major stumbling blocks to advancing an understanding of microbes' role in the biosphere", those being fragmentation of the life-sciences field and a lack of coordination among the various research endeavors. Although eight different research programs had been started to study the

human microbiome since 2005, after 10 years the initiatives only generated vast amounts of data that were not easily comparable. In part this failure was due to differences in choice of PCR primers, analytical platform, software systems, etc. used in each research program, although these shortcomings were not technically insurmountable. This example illustrates the difficulties that deter the success of large scale research efforts, even when the cause (human health) is more endearing to humanity than MIC. Similar challenges would also be faced by any large-scale effort to improve the understanding and control of MIC.

4. Discussion

4.1. Challenges to effectively linking MMMs and corrosion

The goal of establishing clearer relationships between microbiological and corrosion data is not without challenges. A plethora of parameters affect biodeterioration on many levels and these parameters are often interconnected, as discussed earlier. In addition, different information and concepts from each scientific discipline must be applied and integrated to fully describe microbiological deterioration processes. Further, interrelated parameters that vary dynamically may drive the resulting corrosion mechanism(s); yet these parameters are often viewed as being static. Finally, parameters that drive biodeterioration phenomena also occur on different scales (macro-micro) that are seldom reconciled with each other.

Another challenge to developing a better understanding of the relationships between microbiology and corrosion is the lingering misconception that there exists some universal MIC mechanism. Some have insightfully observed that the development of a universal model for MIC is highly unlikely since each set of environmental conditions determines the microbial ecology that exists within it, and from there the corrosion interactions arise. Engineered materials are simply a part of the overall environment available to microorganisms; providing a physical substrate and sometimes chemical species that are used in the metabolism of microorganisms in a biofilm.

Advancing the development of a coordinated, holistic understanding of biodeterioration that is inclusive of multiple scientific viewpoints would be an extensive undertaking; requiring support from both basic and applied research. Few organizations or institutions have the resources or the motivation to take on such a broad effort alone; therefore, future advancements in the understanding of MIC will most likely be the result of effective, global collaboration. Conceptual frameworks may provide a structure to aid communications between those involved in an MIC movement; facilitating a coordinated multidisciplinary approach.

4.2. Two potential tools to help link microbiology and corrosion

Two potential “tools” that could be singly or concurrently employed to develop more tangible connections between microbiology and corrosion are 1) a conceptual MIC framework to promote better communication between MIC researchers, and, 2) a ‘translational science’ approach for moving MIC research efforts toward practical solutions.

Assuming that there is unanimous agreement that MIC is a multi-disciplinary topic, a conceptual framework is a tool that could be used to improve essential communication between different groups of researchers and those responsible for managing the threat of MIC. A conceptual MIC framework could provide benefits, such as;

Table 2
Macro-scale conditions - conceptual framework example.

Physical		Chemical/Electrochemical		Microbiological	
Temperature	Minimum, Maximum, frequency and range of changes	Bulk fluid chemistry	Electron donors/acceptor, metabolites	Planktonic community	Microbial abundance, diversity, activity, condition relative to corrosion location and severity; metabolism in reference to corrosion mechanisms
Flow Characteristic	Minimum, maximum, frequency and range of changes, flow regime		Redox potential, pH, salinity		Potential relationships within consortia relative to, or enhanced by, corrosion mechanisms, location or severity
Fluid Physical Properties	Viscosity, specific gravity, percent of different phases present		Aqueous phase composition (Cations, anions, TDS, TSS, organic carbon)		Growth/activity rates or cycles relative to operating conditions (e.g., flow rate, temperature, fluid sources, etc.)
Pressure	Dissolved gases, partial pressure of gas species, density		Mitigation chemicals used, frequency, dose (Inhibitor, biocide, methanol, scale preventer, glycols, emulsion breaker, flocculants, polymers, etc.)		Growth/activity rates or cycles relative to chemical environment (e.g. energy sources, growth suppression, biocide)
Surface disturbance	Severity of disturbance, frequency of occurrence		Dissolved gas (CO_2, H_2S, O_2)		Changes in microbial community composition and activity over time or between locations in the same asset; metagenomic and metabolomic characterization of the biofilm consortium
Design Elements	Elevation profile, diameter changes, connections		Organic phase composition		
Inorganic Solids/Particles	Size, shape, density, distribution		Composition of solid particles		
Organic solids, sludge	Type of solids, physical characteristics				
Surface condition	Roughness, location of crevices and frequency of occurrence; ILI and inspection results; corrosion distribution and severity; history, step-changes, rates				

Table 3
Micro-scale conditions - conceptual framework example.

Physical		Chemical/Electrochemical		Microbiological	
Biofilm/Deposit Physical Structure	Permeability, stability, surface area	Chemistry within biofilm and deposit layer	Electron donors/acceptors, metabolites	Sessile community	Microbial abundance, diversity, activity, and condition in biofilms relative to corrosion location and severity; metabolism in reference to corrosion mechanisms; sessile phenotype
Inorganic Solids/Particles	Size, shape, density, distribution within biofilm		Redox potential, pH, salinity		Potential relationships within biofilm consortia relative to, or enhanced by, corrosion mechanisms, location or severity
Organic solids, sludge	Type of solids, physical characteristics		Aqueous phase composition (Cations, anions, TDS, TSS, organic carbon)		Biofilm response relative to operating conditions (e.g., flow rate, temperature, fluid sources, etc.)
Flow Characteristics	Minimum, maximum, frequency and range of changes, flow regime		Mitigation chemicals used, frequency, dose (Inhibitor, biocide, methanol, scale preventer, glycols, emulsion breaker, flocculant, polymers		Biofilm response relative to chemical environment (e.g. energy sources, growth supression, biocide)
Form of Corrosion Damage	Shape of pit profile, aspect ratio, surface area, roughness		Dissolved gas (CO_2, H_2S, O_2)		Changes in microbial community composition over time or between locations in the same asset
			Organic phase composition		Microbial response (microbial growth/activity, consortia composition) and corresponding corrosion response to mitigation
			Composition of solid particles		
		Metal Surface/Metallurgy	Alloy/Composition; (PREN)		
			Microstructure		
			Welding/Metallurgical Surface treatments		
			Thermo-mechanical history/condition		

- A categorized “place” for the information from different disciplines and stakeholders to reside.
- Perspective on the context and significance of different types of data associated with MIC.
- A data library that promotes the integrated study of relationships between different factors associated with biodeterioration.
- An open source web interface for uploading and sharing relevant information on MIC.

Providing a clear view of context is possibly the most significant benefit achievable by adopting a conceptual MIC framework, since all microbiological data must exist within the context of physical and chemical environmental conditions, and vice versa. Lomans et al. (2016) emphasized that there is a clear need for a standardized reporting system that requires contextual data to be recorded at the time of genetic sequence submission. An initial example of a proprietary microbiological data set produced using MMMs was presented by Geissler et al. (2014), although the need for sufficient and accurate contextual data (metadata) to meaningfully apply the microbiological results was acknowledged. In regard to MIC, there is a need for more complete and standards-compliant metadata to be included with each sequenced sample. Glass et al. (2014) discussed the Genomic Standards Consortium (GSC) MIxS minimal metadata standard with a unique Built Environment (BE) extension containing a suggested list of parameters to record and report for each sequenced sample; allowing comparison of data across different studies.

Tables 2 and 3 illustrate (in two dimensions) a crude MIC framework that includes physical, chemical/electrochemical, and microbiological factors, both on a macroscopic scale and on a microscopic scale. For the sake of space, these tables do not include the possible and known interrelationships between different types of information, e.g., temperature and planktonic growth rates, or flow rate and the rate of anodic/cathodic reactions; however, these would also be an essential part of such as framework. In essence, the conceptual MIC framework provides a template for describing each particular MIC mechanism that is observed, and all of the parameters within which that mechanism has been observed.

Although the framework provides a place for information, it does not coordinate the efforts needed to populate the data and perform interdisciplinary analysis. As is currently being explored in collaborative work between the US military, academia and industry (NACE (2015)) translational science is a process that has been used to efficiently move research findings into improvements and solutions in medicine. Zerhouni (2005) discussed how this process was originally developed and implemented by the US National Institutes for Health (NIH). Translational research and translational medicine are now integral parts of National Center for Advancing Translational Sciences (NCATS) at NIH. The parallels between microbiological deterioration and human health issues are numerous, and this speaks to the need to invoke the use of translational science in the former. In the world of medicine, it is known that thousands of diseases can affect humans, yet only around 500 have any type of treatment. NCATS (2015) reported that a “novel drug, device or other intervention can take about 14 years and cost $2 billion or more to develop, and about 95 percent never make it past clinical trials”. To overcome the numerous barriers to bringing new technologies and solutions to medicine, NCATS applies translational science principles to expedite the development of medical improvements; demonstration of their effectiveness, and finally their delivery to the patients. This same process could certainly be

used to address the microbiological deterioration problems, MIC, biofouling, and fuel degradation, where the symptoms are widespread, complex and diverse, but the solutions are few.

5. Conclusion

A multidisciplinary process for establishing the significance of microbiological data (particularly from molecular methods) in regard to MIC threat identification, mitigation and monitoring has yet to be clearly established. As a result, MMMs will not be embraced by oil and gas asset operators until their significance relative to corrosion management and asset integrity are made more transparent. Further, solutions to MIC and other biodeterioration problems will continue to be based on weak data foundations, leaving industry with only empirically-based options for response. Some possible ways to better link microbiology with corrosion information were discussed, and include;

- Using information/knowledge from new scientific tools more effectively.
- Fostering functional interdisciplinarity.
- Creating a discipline-neutral, open source and conceptual MIC framework to manage information and place microbiological sequencing and corrosion/environmental metadata in context.
- Employing a Translational Science process – using information to efficiently produce real-world solutions.

References

American Petroleum Institute, 1975. API RP-38 Recommended Practice for Biological Analysis of Subsurface Injection Waters, Washington, D. C.

Beavers, J., Gui, F., Sridhar, N., 2011. Ethanol stress corrosion cracking of carbon steels. In: Revie, R.W. (Ed.), Uhlig's Corrosion Handbook, third ed. John Wiley & Sons, Inc., Hoboken, NJ, USA http://dx.doi.org/10.1002/9780470872864.ch50.

Campbell, S., Johnson, A., Conventional Application of Biocides May Lead to Bacterial Cell Injury rather than Bacterial Kill within a Biofilm". Corrosion 2011-Paper 11234, NACE InternationalHouston, TX.

Dubilier, N., McFall-Ngai, M., Zhao, L., 2015. Microbiology: create a global microbiome effort. Nature 526, 631–634. http://dx.doi.org/10.1038/526631a.

Eckert, R., Cookingham, B., 2002. Field use proves program for managing internal corrosion in wet-gas systems. Oil Gas. J. 100 (3).

Eckert, R., Bensman, L., Weichel, S., May 2012. Forensic Corrosion Engineering Supports a Corrosion Management System, Materials Performance. NACE International, Houston, TX.

Enning, D., Garrelfs, J., 2014. Appl. Environ. Microbiol. 80 (4), 1226–1236. http://dx.doi.org/10.1128/AEM.02848-13.

Eroini, V., Anfindsen, H., Mitchell, A.F., 2015. Investigation, classification and remediation of amorphous deposits in oilfield systems. Soc. Petroleum Eng. 3. http://dx.doi.org/10.2118/173719-MS.

Geissler, B., De Paula, R., Keller-Schultz, C., Lilley, J., Keasler, V., Data Mining to Prevent Microbiologically Influenced Corrosion?CORROSION 2014-paper 4080, NACE InternationalHouston, TX.

Glass, E.M., et al., 2014 Jan. MIxS-BE: a MIxS extension defining a minimum information standard for sequence data from the built environment. ISME J. 8 (1), 1–3. http://dx.doi.org/10.1038/ismej.2013.176. Published online 2013 Oct 24.

Gray, et al., 2009. Extremophiles, vol. 13, pp. 511–519.

Hall-Stoodley, L., et al., 1999. Establishment of experimental biofilms using the modified Robbins device and flow cells. In: Edwards, C., et al. (Eds.), Methods in Biotechnology. Humana Press, Totowa, NJ, p. 3.

Handelsman, J., 2004. Metagenomics: application of genomics to uncultured microorganisms. Microbiol. Mol. Biol. Rev. 68 (4), 669–685. http://dx.doi.org/10.1128/MMBR.68.4.669-685.2004.

ISMOS: http://www.ismos-6.org (accessed 10/23/2016).

Larsen J, Hilbert LR, Investigation into Under Deposit Corrosion in Halfdan Production Tubulars, Corrosion 2014-Paper 3746, NACE International, Houston, TX.

Larsen, J., Zwolle, S., Kjellerup, B.V., Froelund, B., Nielsen, P.H., Nielsen, J.L., Identification of Bacteria Causing Souring and Biocorrosion in the Halfdan Field by Application of New Molecular Techniques Corrosion 2005-Paper 05629, NACE InternationalHouston, TX.

Larsen, J., Skovhus, T.L., Saunders, A.M., Højris, B., Agerbæk, M., Molecular Identification of MIC Bacteria from Scale and Produced Water: Similarities and DifferencesCorrosion 2008-Paper 08652, NACE International; Houston, TX.

Larsen, J., Rasmussen, K., Pedersen, H., Sørensen, K., Lundgaard, T., Skovhus, T.L., March 2010. Consortia of MIC Bacteria and Archaea Causing Pitting Corrosion in Top Side Oil Production Facilities. CORROSION 2010- Paper 10252. NACE International, Houston, TX.

Ledford, H., 2015. How to solve the world's biggest problems. Nature 525, 308–311. http://dx.doi.org/10.1038/525308a.

Lenhart, T.R., Duncan, K.E., Beech, I.B., Sunner, J.A., Smith, W., Bonifay, V., Biri, B., Suflita, J.M., 2014. Identification and characterization of microbial biofilm communities associated with corroded oil pipeline surfaces. Biofouling 30 (7), 823–835. http://dx.doi.org/10.1080/08927014.2014.931379.

Little, B.J., Lee, J.S., Ray, R.I., Nov 2006. Diagnosing microbiologically influenced corrosion: a state-of-the-art review. Corrosion 1006–1017.

Lomans, B.P., de Paula, R., Geissler, B., Kuijvenhoven, C.A.T., Tsesmetzis, N., 2016. Proposal of Improved Biomonitoring Standard for Purpose of MIC Risk Assessment. SPE-179919-MS. Society of Petroleum Engineers, Richardson, TX.

Mand, J., Park, H.S., Okoro, C., Lomans, B.P., Smith, S., Chiejina, L., Voordouw, G., 2016. Microbial methane production associated with carbon steel corrosion in a nigerian oil field. Front. Microbiol. 6 http://dx.doi.org/10.3389/fmicb.2015.01538. Article 1538.

PRTG-15–9916 Moghissi, O., Eckert, R., Sridhar, N., Cookingham, B., Angell, P., 2000. The Interdependent Effects of Bacteria, Gas Composition, and Water Chemistry on Internal Corrosion of Steel Pipelines. PRCI, Pipeline Research Committee International.

NACE Standard Test Method TM0194, 1994. Field Monitoring of Bacterial Growth in Oil and Gas Systems. NACE International, Houston, TX.

NACE/DoD Joint Conference, Translational Science Workshop, Nov. 19, 2015, Pittsburgh, PA.

NACE Technical Report 3T199, 2012. Techniques for Monitoring Corrosion and Related Parameters in Field Applications. NACE International, Houston, TX.

NACE Standard Test Method TM0212, 2012. Detection, Testing, and Evaluation of Microbiologically Influenced Corrosion on Internal Surfaces of Pipelines. NACE International, Houston, TX.

National Center for Advancing Translational Sciences (NCATS), Winter 2015. Fact Sheet. Transforming Translational Research.

GRI Field Guide Pope, D.H., 1992. Microbiologically Influenced Corrosion (MIC) II: Investigation of Internal MIC and Testing Mitigation Measures. Gas Research Institute, Chicago.

Pope, D.H., 1990. GRI-90/0299 Field Guide: Microbiologically Influenced Corrosion (MIC): Methods of Detection in the Field. Gas Research Institute, Chicago, IL.

Pope, D.H., et al., 1988. Guide to the Investigation of Microbial Corrosion in Gas Industry Facilities. Gas Research Institute, Chicago.

Pots, B.F.M., Kapusta, S.D., John, R.C.. Thomas, M.J.J.S., Rippon, I.J., Whitham, T.S., Girgis, M., Improvements on De Waards-milliams Corrosion Prediction and Applications to Corrosion Management Corrosion 2002-Paper 02235, NACE International; Houston, TX.

Price, A., Novel DNA Extraction and Preservation for Identification of Micro-organisms On-site Using Novel Nucleic Acid Extraction Cards for the Oil and Gas Industry Corrosion 2012-Paper 1758, NACE International; Houston, TX.

Reservoir Microbiology Forum (https://www.energyinst.org/events/reservoir-microbiology-forum).

Schwermer, C.U., et al., May 2008. Appl. Environ. Microbiol. 74 (9), 2841–2851. http://dx.doi.org/10.1128/AEM.02027-07.

Skovhus, T.L., Eckert, R., Practical Aspects of MIC Detection, Monitoring and Management in the Oil and Gas Industry Corrosion 2014-Paper 3920, NACE International; Houston, TX.

Skovhus, T. L., Sorensen, K., Larsen, J., Rasmussen, K., & Jensen, M., Rapid determination of MIC in oil production facilities with a DNA-based diagnostic kit, SPE 130744, SPE international conference on oilfield corrosion held in aberdeen, U. K., 24–25 May 2010.

Skovhus, T.L., Caffrey, S., Hubert, C., 2014. Molecular Methods and Applications in Microbiology. Horizon Press, Norfolk, UK, ISBN 978-1-908230-31-7.

Sooknah, R., Papavinasa, S., Revie, R.W., Modelling the Occurrence of Microbiologically Influenced CorrosionCorrosion 2007-Paper 07515, NACE International; Houston, TX.

Stoecker, J., Aug 1984. Guide for the investigation of MIC. Matls Perf. 48–55.

Sublette, K., Ogles, D., Baldwin, B., Clark, K., Eckert, R., Molecular Analysis of Aramid Polymer Film Impressions of Corrosion Coupon Biofilms Corrosion 2014-Paper 4477, NACE International; Houston, TX.

Suflita, J., Atkas, D., Duncan, K., Oldham, A., 2012. Molecular tools to track bacteria responsible for fuel deterioration and microbiologically influenced corrosion. Biofouling 28 (9), 1003–1010. http://dx.doi.org/10.1080/08927014.2012.723695.

Whitby, C., Skovhus, T.L., 2011. Applied microbiology and molecular Biology in oil field systems. Springer Publisher, ISBN 978-90-481-9251-9, p. 17.

von Wolzogen Kühr, C.A.H., van der Vlugt, L.S., 1934. The graphitization of cast iron as an electrobiochemical process in anaerobic soil. Water 18, 147–165.

Wrangham, J.B., Summer, E.J., Planktonic Microbial Population Profiles Do Not Accurately Represent Same Location Sessile Population Profiles Corrosion 2013-Paper 2780, NACE InternationalHouston, TX.

Zerhouni, E.A., 2005. Translational and clinical science - time for a new vision. N. Engl. J. Med. 353, 1621–1623.

Zhu, Xiang Y., Lubeck, J., Kilbane II, J.J., 2003. Characterization of microbial communities in gas industry pipelines. Appl. Environ. Microbiol. 69 (9), 5354–5363. http://dx.doi.org/10.1128/AEM.69.9.5354-5363.2003.

Zintel, T., Kostuck, D., Cookingham, B., Evaluation of Chemical Treatments in Natural Gas Systems vs. MIC and Other Forms of Internal Corrosion Using Carbon Steel Coupons CORROSION 2003-Paper 03574, NACE International; Houston, TX.