

**Practical Aspects of MIC Detection, Monitoring and
Management in the Oil and Gas Industry**

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ABSTRACT

Historically, assessment of Microbiologically Influenced Corrosion (MIC) in the oil and gas industry has focused on sulfate-reducing bacteria (SRB) using cultivation-based techniques. Today, the use of molecular microbiological methods (MMM) for investigation of troublesome microbes provides improved accuracy and timeliness of results. While microorganisms abound in nearly every oil and gas production environment, determining their role in internal corrosion and identifying appropriate corrosion management strategies requires a consistent and methodical approach. Since microorganisms can influence corrosion in different ways, MIC diagnostics using MMM must be done in consideration of other factors that support corrosion such as operating history, the presence of scale and deposits, fluid composition, and mitigation history.

The corrosion management process is based on the assessment of corrosion threats; the identification of mitigation or barriers to those threats; and monitoring of barrier effectiveness. MIC diagnostics can be incorporated within these fundamental corrosion management processes; improving the operator's ability to manage MIC threats. In this paper several case studies are used to illustrate the use of MIC diagnostics in the context of supporting a corrosion management program. The paper also discusses the implementation and applicability of the newly published NACE standard TM0212-2012 for operating companies.

Key words: Practical Case Stories, Oil and Gas, MIC Diagnostics, MMM, Mitigation, Corrosion Management, TM0212-2012.

INTRODUCTION

Corrosion Management Systems and MIC Management

Morshed^{1,2,3} has described a corrosion management system (CMS) as “a suite of procedures, strategies, and systems designed and intended to maintain asset integrity through preventing or mitigating corrosion throughout the operations phase of the asset life cycle.” Others⁴ have defined corrosion management as “...part of the overall management system, which is concerned with the development, implementation, review and maintenance of the corrosion policy.” Industry generally agrees that a fundamental objective of a CMS is to establish processes to manage the threats associated with corrosion. Therefore, corrosion management is focused on reducing the likelihood of corrosion threats resulting in an unintended outcome (e.g., a leak or failure) rather than addressing consequence or overall risk (i.e., likelihood x consequence). At the core of corrosion management is the process of assessing corrosion threats, identifying preventive and mitigative barriers and monitoring the effectiveness of those barriers. This process is shown in Figure 1.

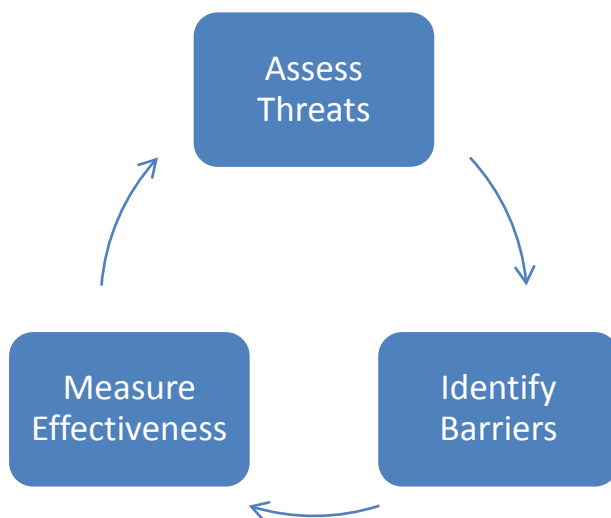


Figure 1 - Fundamental process of managing corrosion.

Molecular microbiological methods can be incorporated within these fundamental corrosion management processes; improving the operator’s ability to manage MIC threats.

During corrosion threat assessment, the likelihood of each potential corrosion threat mechanism is evaluated on each system and circuit for the asset. In this step corrosion engineers review design, process, operation, chemical treatment, corrosion monitoring, and inspection data to help identify the likely corrosion threats affecting different locations in the system. Pipelines and circuits may be further broken down by segments in which different operating conditions or fluid composition change the severity of the applicable corrosion threats. In assessing the potential for MIC it is important to establish a clear relationship between the biofilm and localized corrosion. MMMs can be used in this step to characterize baseline microbiological conditions, to look for associations between biofilm, biofilm composition and corrosion and to relate biofilm characteristics with operating conditions. Interaction between various corrosion threats must also be considered, e.g., biofilm establishment may be enhanced by solid deposits that promote under deposit corrosion (UDC). When adequate data is available, programmatic integration and analysis can help verify the predicted corrosion threats. Investigation of corrosion damage or failures using formalized field and laboratory analysis procedures may also be used to verify the corrosion mechanisms in a pipeline.

In the next step, the types of preventive and mitigative barriers needed to manage the corrosion threats are selected. Typically the choices for internal corrosion mitigation include the use of treatment chemicals (corrosion inhibitor, biocide, oxygen scavenger, etc.), mechanical cleaning (maintenance pigging), velocity control, and control of fluid quality. When assessing mitigation options prior to full implementation, MMMs are beneficial for evaluating the effect of candidate treatments on corrosion and the biofilm, and to monitor for shifts in the types or numbers of microorganisms after treatment is applied. Evaluation of mitigation targeted at controlling the biofilm best performed using a side-stream test or in a limited portion of the actual system where actual (not simulated) fluids are present. Data provided by MMM are also useful in determining the optimum approach to MIC mitigation and for selecting the appropriate biocides or anti-microbial chemicals.

The third step in the process is measuring the effectiveness of the barriers employed to reduce the likelihood and/or severity of the corrosion threats. Corrosion monitoring typically provides information about the rate of metal loss due to corrosion; not the mechanism of corrosion. However; review and integration of operating condition data, monitoring data from coupons, probes and inspection, chemical/microbiological fluid and deposit analysis results, and output from flow regime and corrosion models can lead to a better understanding the corrosion mechanisms driving the corrosion damage. Extended laboratory analysis of coupons^{5,6} can provide direct evidence of the active corrosion mechanisms in the system.

Methods used to monitor MIC must demonstrate that microorganisms and their activities provide the predominant influence over the corrosion mechanism⁷, as opposed to other abiotic mechanisms that may be present. Generally this means that monitoring must integrate measurements of surface/biofilm characteristics with localized corrosion. In this regard, MMMs are valuable for monitoring long term and short term effects of mitigation, and changes in chemical treatment effectiveness relative to biofilm characteristics.

Table 1 - Benefits of Applying MMM to MIC Management

Corrosion Management Process Step	Benefits of Applying MMM
MIC Threat Assessment	<ul style="list-style-type: none"> • Characterize baseline microbiological conditions • Look for associations between biofilm, biofilm composition and corrosion • Relate biofilm characteristics with operating conditions
MIC Mitigation Selection	<ul style="list-style-type: none"> • Evaluating the effect of candidate mitigation measures on corrosion and biofilm • Aid in selection of biocides or anti-microbial chemicals
MIC Barrier Monitoring	<ul style="list-style-type: none"> • Monitor long term and short term effects of mitigation on biofilm • Monitor changes in chemical effectiveness • Watch for shifts in microbiological populations

Separating the contributions of abiotic and biotic environmental and surface characteristics in regard to corrosion is perhaps the most challenging aspect of managing MIC, since there is no single method that can provide adequate information to fully discern the predominant corrosion mechanism. Typically the integration of microbiological and corrosion monitoring data is required.

PROCEDURES

Evaluating Biotic Contributors to Corrosion

Molecular microbiological methods, also referred to as genetic methods, are culture-independent approaches that provide direct analysis of samples without the bias introduced by the growth process used during culturing. As such, MMMs are particularly valuable in supporting different aspects of MIC management. Because no prior growth of microorganisms is required, MMMs accept very small amounts of any type of sample (liquid, biofilm, solid, and scale) with or without live microorganisms. After genetic materials are extracted from the sample, assays that are very specific and render a more precise quantification of various types of microorganisms than culture tests are performed in the laboratory^{8,9}. A comparison of several MMMs is shown in Table 2⁷.

Table 2 - Comparison of Molecular Microbiological Methods¹⁰

Method (MMM)	Method Based On	Living Cells Counted?	Dead Cells Counted?	Quantitative Method?	Information Yielded
DAPI	Microscopy	Yes	Yes	Yes	Total cell counts (live and dead)
FISH	Microscopy	Yes	No	Yes	Total numbers of live bacteria Total numbers of live <i>Archaea</i> Total numbers of live SRB Total numbers of live SRA
DGGE	PCR	Yes	Yes	No	Comparison of populations Identification of abundant microorganisms
qPCR	PCR	Yes	Yes	Yes	Numbers of total bacteria Numbers of total <i>Archaea</i> Numbers of SRB Numbers of SRA Numbers of three groups of methanogens ¹¹

Table 2 only gives an overview of selected types of microorganisms that are found to cause MIC in oil production facilities. For each given case the relevant microbial population must be evaluated. Knowledge of the types and numbers of microorganisms present in a system provides insight into their preferred environmental conditions for growth¹², the types of nutrients typically used for metabolism, and the waste products (sulfide, organic acids, etc.) associated with metabolism. This information may also provide insight into synergies between microorganisms in the biofilm and their potential effect on corrosion.

Evaluating Abiotic Contributors to Corrosion

The separation of abiotic and biotic factors that influence corrosion is not always clear since abiotic factors (e.g., nutrient availability, flow rate, temperature, salinity, dissolved gases, etc.) that affect corrosion also affect the growth of microorganisms. Aside from their influence of microbial growth, the independent effect of abiotic factors on localized corrosion must also be considered. Abiotic factors include physical, chemical and operational conditions that separately or in combination, can promote or contribute to corrosion without the influence of microorganisms. See Table 3.

Table 3 - Abiotic Factors Influencing Internal Corrosion

Category	Examples
Physical	Temperature, pressure, flow rates, (including periods of no flow), superficial velocity, phases present, equipment design and material of construction, erosion
Chemical	Salinity, anions, cations, pH, organic carbon sources, dissolved gases, treatment chemicals used, redox potential, composition of solids/deposits
Operational	Cleaning and maintenance pigging, change in product conveyed, system upsets that affect fluid corrosivity, system outages

The effects of abiotic factors on the likelihood or rate of internal corrosion can be surmised from monitoring and inspection data, and/or from the application of corrosion prediction models.

The following examples demonstrate how MMMs have been applied to different steps in the corrosion management process, and integrated with other information to determine the influence of microorganisms on corrosion.

CASE STUDIES

The following case studies illustrate the approach to identifying MIC, selecting mitigation, and monitoring effectiveness. Case studies A through D are based on previously published material and additional information can be obtained from the original articles. Case study E has yet to be published.

Case A: Subsea seawater injection pipeline rupture and subsequent actions¹³

A 10-3/4" nominal diameter subsea water injection pipeline 32 km in length transports seawater from the offshore Siri oil production platform to the Nini platform. In Q4 2007 a rupture of the pipeline occurred 2 km from the Siri platform. A close-up of the internal surface of the pipe at the rupture site is shown in Figure 2.



Figure 2 – Cleaned pipeline surface at the rupture location with pitting corrosion present.

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The failure was investigated in detail and the cause of the damage leading to the rupture determined to be MIC. The investigation revealed that the MIC deposit at the rupture site was a mixture of iron sulfide and other corrosion products, plus microbes and polysaccharide slime. These deposits allowed sulfate-reducing prokaryotes (SRP) and other troublesome microbes to grow protected from biocides.

Several actions were taken after the rupture shut down production in 2007. One major step was to establish a robust microbiological monitoring program based on MMM. The improved microbiological monitoring program implemented in early 2008 was designed to capture selected water samples, pigging solids and corrosion coupons from the CMU (Corrosion Monitoring Unit). An integrated part of the new monitoring program was training of the offshore personnel in correctly obtaining and handling samples for microbiological analysis. Sampling locations, frequency and relevant analysis parameters were defined and agreed upon with the operator for optimal resource allocation.

Another important step used to gain better control of microbial growth in the process system was testing and evaluation of biocides under realistic field conditions before implementation into the process. For this purpose, a dynamic biocide test rig was designed and operated in the laboratory¹⁴. The biocide test rig was developed to simulate the flow conditions in the pipeline. The test reactor was based on the rotary torque principle with an internal rotating cylinder that provided an evenly distributed shear stress on the biofilm; comparable to the shear stress at the pipeline wall in production environments. The reactor could be inoculated with microbes from the field environment or a consortium of relevant microorganisms as appropriate for testing a particular biocide formulation. This new approach of testing biocides proved to be a powerful tool for the selection of the optimal antimicrobial strategy to avoid future MIC problems in the production system.

Case B: Leakage of hydrocarbons from subsea multiphase pipeline likely due to MIC¹⁵

The Rolf platform produces 400 barrels of oil per day. The unmanned offshore platform Rolf is linked by a 17 km long pipeline to the Gorm platform where the oil from the Rolf platform is processed and transferred to shore. The pipeline inlet temperature was 80°C (176°F) and the outlet temperature was 40°C (104°F). In-line inspection (ILI) of the pipeline conducted in 2009 showed significant corrosion damage that corresponded to a corrosion rate of 0.7 mm/year (27.6 mpy). A total of 900 features were found with ILI and the deepest pit was 19% of the nominal wall thickness¹⁵.

The produced fluid from the multiphase pipeline was regularly monitored with MMM. In debris from the pipeline the abundance of SRP was 2.86×10^8 cells/g and the abundance of methanogens was 8.81×10^9 cells/g. Application of a proprietary MIC model indicated a “High MIC Threat” for the Rolf A to Gorm E pipeline. The model calculates two figures: The Integrated MIC Risk Factor (IMRF) and the pit generation rate. IMRF is defined as the number of days before a clean system will first see signs of MIC. For the Rolf A to Gorm E pipeline this number was calculated to only 15 days. The pit generation rate was calculated to have been as high as 2.4 mm/year. Further details on definitions and calculations are provided in the original paper¹⁵.

The morning of March 2, 2011, a few months after the MIC threat was determined to be “High”, a hydrocarbon leak was observed near the Rolf platform. Subsequently, the production from the field was shut down and a detailed root-cause analysis was initiated. A Remotely Operated Vehicle (ROV) was deployed to investigate a portion of the pipeline between the Rolf and Gorm platforms to see whether there was a breach. The case is still under investigation and mitigation initiatives are being evaluated.

Case C: MIC failure investigation of oil export system and improved mitigation strategy¹⁶

Since the water content in the Halfdan oil export system is relatively low (Basic Sediment and Water, BS&W < 1-2%) MIC had not been considered to be a significant integrity threat to the system. However; initial results from wall thickness inspection of pipe spools from the oil export pipeline

indicated on-going corrosion. As a result the spools were replaced, enabling samples to be obtained from the cut-out sections for detailed examination and analysis. These cut-out sections were sent onshore for further investigation of general corrosion, MIC and scale composition. Examination of the samples confirmed that the Halfdan oil export spool sections were highly corroded. Visual inspection of the cut-out sections revealed the presence of under-deposit and pitting corrosion underneath thick layers of solid scale material. In support of the visual indications of corrosion, it was demonstrated that MIC-related microorganisms were present in the solids in close contact with the metal surface together with corrosion products. In particular, high numbers of the hydrogen consuming methanogens (10^8 - 10^9 cells/g) were situated in the scale directly in contact with the carbon steel pipe wall. Good correlations were found between the microbiological results obtained with qPCR, the chemical results obtained with X-Ray, the observed corrosion rates and the visual inspection data from the spool pieces.

The direct outcome of the study was increased focus on material selection, chemical injection and improved microbiological monitoring. The following actions were taken for improving asset integrity:

- Installation of a new chemical injection point downstream of the separator (oil side)
- Actively applying new knowledge obtained on the potential MIC threat in the oil export system
- Ongoing evaluation of scale and MIC control strategies (new chemistry to be introduced)
- Installation of new 254 SMO (UNS⁽¹⁾ S31254) spools in the produced water system
- Flush mounted corrosion coupons were installed to provide improved monitoring and detection of scale and MIC issues (and to monitor the effects of applied chemistry)
- Focus on the importance of close collaboration between corrosion group, chemistry group and oilfield microbiologists (Quarterly follow-up meetings)

Since the biocide injected upstream of the separator settled out with the water phase in the separator, a new chemical injection point was installed on the crude oil outlet. Injection of biocide and/or scale inhibitor is expected to prevent the development of an actively growing biofilm/scale on the inner surfaces and stop/reduce corrosion. Field tests are on-going to determine “best in class” biocide for the system in terms of product, rate and injection frequency. In addition to wall thickness measurements, the operator installed weight loss coupons in the oil leg from the separator and the crude oil export to allow for monitoring the effectiveness of the applied chemistry. Coupons were also being installed on each well flow line. In summary, the study improved the operator’s ability to mitigate corrosion and MIC in a vital piece of the production system. The mitigation strategy is not yet finalized, but the tools to determine the better strategy have greatly improved.

Case D: Evaluation of biofouling of a deaeration tower and actions to obtain control¹⁷

On South Arne platform, the injection water is prepared from seawater that is run through a system of coarse and fine filters, followed by a membrane filtration package for reduction of sulfate content. The oxygen is then removed in a deaerator tower. The challenge in this case was biofouling of the injection water system and potential loss of injectivity to the oil reservoir.

Historically, biocides have been applied upstream of the deaerator tower in order to control biofouling, but the expected beneficial effect was not previously verified by adequate analyses. The microbial status of the injection water upstream and downstream of the deaerator tower at South Arne began being evaluated once a year using MMM in April 2009. An increase in planktonic numbers of both total microorganisms and SRB across the deaerator tower was observed. This increase in microorganisms is often the case as the packing material in the deaerator constitutes a very large surface area where a biofilm can establish and create dense layers of biomaterial that in effect works as a protective barrier towards most biocides. Generally, when a biofilm has been established, it can be difficult to regain control by means of chemicals and therefore mechanical cleaning will often be needed.

¹ Unified Numbering System for Metals and Alloys (UNS). UNS numbers are listed in Metals & Alloys in the Unified Numbering System, 10th ed. (Warrendale, PA: SAE International and West Conshohocken, PA: ASTM International, 2004).

As follow-up on the observations of increased planktonic numbers, the deaerator was visually inspected during a planned shutdown in May 2011. The visual inspection revealed a massive biofilm build-up, from which solid samples were collected (Figure 3).

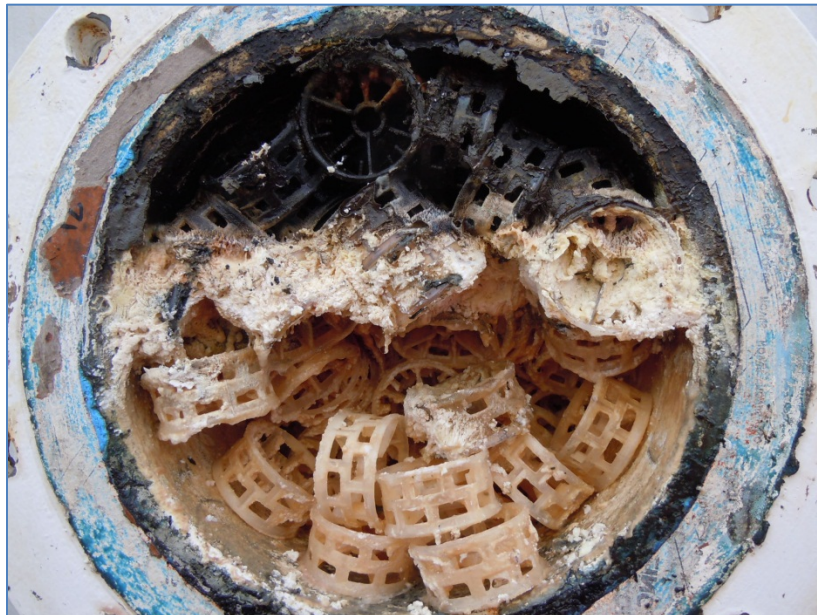


Figure 3 – Packer material covered in biofilm from the deaerator (May 2011).

The samples were analyzed using MMM and wavelength dispersive X-ray fluorescence spectroscopy. The results revealed high Bacteria and SRB numbers and showed that the material consisted mainly of organic material which is usually associated with biofilm growth. The inorganic fraction consisted mostly of iron, calcium and silicon.

Based on monitoring and inspection data it was concluded that the applied biocide strategy was *insufficient* to prevent biofilm build-up. Therefore, it was decided to soak the deaerator tower with a batch treatment of biocide during the upcoming water injection shutdown. It was also decided to add new packing material to the deaerator on the next possible occasion. The deaerator was opened in May 2012 and the packing material appeared to be much cleaner than the previous year. A sample of deposit was recovered and analyzed for microbial abundance. The data showed that the abundance of Bacteria and SRB in the solids was similar to the previous measurement¹⁷. Knowing that the solid sample contained similar concentrations of Bacteria and SRB as one year earlier simply emphasized the need for a biocide to keep microorganisms at a low planktonic level. Biofilm samples are generally of higher value in MIC threat assessment and the high concentration of cells in the biomaterial indicates a high growth potential. Therefore, continued focus on the biocide strategy was important. The deaerator was cleaned and the packer material was changed in May 2012. It is expected that a clean system will make it possible to keep planktonic and sessile microbial growth under control. Moreover, water quality will be monitored over time to catch possible increases in microbial loading to the reservoir. In summary, the following initiatives were taken by the operator based on the MMM findings from this case:

1. Annual biocide soaking and replacement of packing material in the deaerator.
2. Routine monitoring of planktonic levels of microorganisms upstream and downstream of the deaerator with MMM in order to verify biocide efficacy.
3. Increased focus on consistency in biocide treatment.
4. Using monitoring and inspection data as feedback to biocide optimization.

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Case E: Assessment of troublesome microbes in a crude pipeline and suggested monitoring

A new crude oil transmission pipeline was assessed for the threat of MIC and other internal corrosion threats. A review of the pipeline design and operating parameters was conducted, along with sample collection from routine maintenance pigging. Although the crude quality had tariff limit of 0.5% BS&W, episodic upsets of water and solids needed to be considered. While the fluid velocity was intended to keep water and solids entrained, accumulation could occur during periods of reduced flow due to operations or maintenance issues, or at geometry changes in the pipeline.

Comprehensive analysis of maintenance pigging residues was performed using MMM, a variety of chemical analysis techniques (XRD, EDS, GC-MS), and particle sizing. The following microbial numbers were determined using qPCR:

Total Bacteria as high as 3.4×10^8

Total Archaea as high as 3.4×10^7

Total SRB as high as 4.0×10^6

Total methanogens as high as 6.6×10^7

Based on the preferred growth conditions for the microorganisms present, it was determined that the pipeline conditions were suitable for microbial proliferation at certain times of the year. It was also determined that adequate energy sources were present to support the microorganisms identified. The solids present in the system varied with the location of sample collection and differed based on the source of the crude transported by the pipeline. The solids included fine clay particles, salts, iron oxides and sulfides, and sand; sometimes associated with heavier organic materials. Water was also recovered at some sample points.

The results of the study indicated that the pipeline had a potential for MIC and under-deposit corrosion wherever water and/or solids would accumulate. To verify the presence of the threat, a direct means of monitoring was recommended. The operator is now installing flush mounted, extended analysis coupons⁷ to evaluate the effect of solids deposition and biofilm on localized corrosion and to evaluate the beneficial effect of maintenance pigging. The use of flush mounted coupons allows the passage of cleaning pigs without the need to remove the coupons during pigging. Installation of coupons in piping that does not have the capability for maintenance pigging will also allow the effectiveness of velocity control to be evaluated in terms of deposit/corrosion mitigation.

MMM in this example was used to establish a microbiological “baseline” and to evaluate the potential MIC threat. The MIC threat will be validated and quantified using flush mounted coupons. The coupons will be subjected to MMM characterization of the biofilm and deposits, and microscopic examination for localized pitting corrosion.

DISCUSSION

As seen in the case studies a number of very diverse and complex problems caused by microbial activity have over the years been investigated and solved with the combined approach of good corrosion management practice and the application of MMM.

The approach of using MMM for improving the corrosion management program can be applied both in the lab and in the field.

Keasler et al. (2010) showed the benefit of selecting the correct biocide in the lab using a dynamic flow loop and combining it with MMM¹⁸. First, the problem was identified as being caused by microorganisms in the 18 year-old offshore pipeline system in Nigeria that suffered from severe internal corrosion. The main cause was attributed to MIC. After identifying the problem, it was demonstrated

that the combination of molecular tools (i.e. DGGE and DNA sequencing) and a dynamic flow loop setup could be used to provide insight to the bacteria genera/species present in the system and allow for a scientific basis for biocide selection, dosage, and contact time. Specifically, the work identified a synergistic two-component product that enhanced biofilm penetration, increased bacterial kill, and delayed biofilm regrowth in laboratory studies. Field trials were initiated to evaluate the effectiveness of this new treatment.

In a field scenario, Mitchell et al. (2012) investigated the conflicting microbiology results obtained from traditional culturing methods (serial dilution) and MMM¹⁹. The system involved encompassed dual 10 inch flow lines transporting unprocessed hydrocarbons and water 10.7 km from a subsea field to the host platform. Solids, a mixture of organic and inorganic, had been causing fouling and plugging problems in the process system. The corrosion rate was estimated to be 1-3 mm per year (39-118 mpy). Comparative microbial analyses were performed on the recovered solids from the system. The comparison of results obtained by culture and molecular techniques showed both recording low levels of SRB (<10⁶ cells/g), but the molecular technique provided a more definite indication of methanogen and SRA (sulfate-reducing Archaea) abundance (both groups in the range of 10⁷-10⁹ cells/g). It is possible that if the culture technique enumeration was used in isolation, there could be a risk of assuming false negative results. The authors concluded that with serial dilution results alone it would have been challenging to diagnose and mitigate MIC. Also it was concluded by the authors that MIC is one of the causes of the high observed corrosion rates leading to the need to replace the flow lines. For future work they suggested that the trends in microbial numbers obtained with MMM should be a key part of the routine monitoring program once the pipeline is re-commissioned to ensure that an effective mitigation strategy is in operation.

Management of MIC as a corrosion threat is based on the process of threat assessment, mitigation selection and implementation, and monitoring of mitigation effectiveness (Figure 1). In each of these steps the use of MMM has been demonstrated to be a particularly useful tool to operators. A summary of each case study (A – E) presented in this paper is shown in Table 4.

Table 4 – Overview of the Evaluated Case Studies and Use of MMM in Corrosion Management

Case	System overview	Problem identified	MMM results	Mitigation strategy
A ^{13,14}	10" 32 km long subsea water injection pipeline offshore Denmark.	Sudden rupture at the sea bed. Loss of pressure support to operating oilfields.	MMM introduced after event as a result of inadequate results from serial dilutions.	Corrosion management program in place including MIC monitoring. Testing and evaluation of new chemicals/biocides.
B ¹⁵	17 km long multiphase production pipeline offshore Denmark.	Sudden leak of hydrocarbons from the subsea pipeline into the marine environment.	High abundance of SRP and methanogens. High MIC threat calculated.	Investigation and mitigation initiatives are ongoing. Onwards strategy is being determined.
C ¹⁶	Carbon steel oil export spool d/s separator containing crude with low water content (BS&W < 1-2%). Platform is offshore Denmark.	Increased corrosion rates observed leading to replacement of entire spool section. Extensive pitting, under deposit corrosion and MIC were observed.	High numbers of the hydrogen consuming methanogens (10 ⁸ -10 ⁹ cells/g) measured. Model calculations show that there is a high threat of MIC.	New chemical injection point installed. New 254 SMO spools installed. Flush Corrosion Coupons installed. Focus on close collaboration between technical disciplines.

D ¹⁷	Water injection system with a deaerator tower. Sulfate removal from seawater is in place. Platform is offshore Denmark.	Biofouling of deaerator tower could lead to plugging of the injection system and loss of injectivity to the oil reservoir. Fouling was identified when analyzing water samples with MMM.	Increased growth (several orders of magnitude) over the deaerator tower was measured with qPCR and DAPI. Growth of SRB was taking place inside the deaerator tower (qPCR).	Soak the deaerator tower with biocide at first occasion. Replacement of old packer material during planned shutdown. Optimize biocide strategy to keep the system clean onwards.
E	Onshore, crude oil transmission pipeline.	Potential for MIC and under-deposit corrosion where water settles out or where deposits form.	High levels of Bacteria and Archaea determined in pig returns. System conditions are suitable for microbial growth/MIC.	Implement flush mount extended analysis coupons at piggable and non-piggable locations to verify threat and effect of mitigation strategy.

As the oil and gas industry gains experience with molecular microbiological methods (MMM), knowledge of the strengths and weaknesses of MMM in relation to managing microbiological problems (including corrosion) will continue to increase. Data produced through molecular methods must be interpreted and applied properly to truly take advantage of these techniques, and molecular microbiological data is not directly comparable to culture test results, with which the industry is most familiar. A recent report from the Energy Institute compared a range of traditional oil industry microbiological techniques with MMM to help advance the use of the most applicable technology for microbiology assessment in the oil and gas industry²⁰.

Assessment of MIC is not accomplished solely through the use of microbiological data, and NACE Standard Test Method TM0212-2012 emphasizes the importance of integrating data from both microbiological and corrosion assessment methods when diagnosing MIC. The newly published standard explains the benefits and limitations of MMM and other techniques, and provides guidance to pipeline operators who are seeking to assess and manage the threat of MIC in their systems. Because both corrosion and microbiological activity may occur directly on the internal surfaces of a pipeline, the analysis of samples associated with surfaces typically provides the most meaningful information. Establishing meaningful correlations between localized corrosion and surface microbiology, has led to practical improvements in operators' corrosion management programs.

CONCLUSIONS

MIC diagnostics can be incorporated into the processes of MIC threat assessment, identification of mitigation or barriers, and monitoring of barrier effectiveness; improving the operator's ability to manage MIC threats. Further, MIC diagnostics have been demonstrated in multiple case studies to support operators' corrosion management systems. These case studies have demonstrated a number of key concepts that operators should consider in their MIC and corrosion management strategies, including:

- Reducing the impact of microorganisms in the design phase through the inclusion of pigging facilities, chemical injection nozzles, facilities for coupon pulling, access points for monitoring, velocity control, etc.
- Establishing a CMS that includes a strategy for MIC assessment, monitoring and mitigation over the life of the asset.

- Evaluating the microbiological baseline of the system and defining the optimal sampling frequency to monitor for changes over time.
- Including the right experts in the development of the MIC management strategy, including oilfield microbiologists, corrosion and materials engineers, chemical treatment specialists and those familiar with system operation.
- Providing a means for efficient communication between technical disciplines when working to assess or manage the MIC threat as part of the CMS.
- Implementing the proper mitigative treatment only when the problem has been properly diagnosed (both microbiology and corrosion).
- Knowing the strength and weaknesses of selected sample types (water, solids and removable surfaces) and locations, as well as analytical approaches used (MMM vs. culture based methods) before building the monitoring program.
- Establishing proof-of-concept through laboratory or limited field studies where possible, before fully implementing new mitigation measures for MIC.
- Monitoring using multiple parameters (microbiology, operation, corrosion, etc.) to ensure the applied MIC mitigation strategy is effective.
- Continue to become educated and aware of advancements in technology, their optimal application and correct interpretation. Use published references (e.g. NACE TM0212-2012) to help develop MIC management strategies.

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