# OBSERVATIONS IN THE ASSESSMENT OF MICROBIOLOGICALLY INFLUENCED CORROSION

Steven Loftus

MSc BSc (Hons) NACE SICT

Senior Corrosion Engineer
ROSEN UK, Newcastle-upon-Tyne, UK

**ABSTRACT**

The presence of microorganisms and their associated activity is increasingly recognised as a major concern in the oil and gas industry. Microbiological activity can adversely affect pipeline systems in a number of ways from biofouling causing operational problems to microbiologically influenced corrosion (MIC).

MIC is the process by which corrosion is initiated and/or accelerated by the activities of microorganisms. Detecting microbiological activity from pipeline system samples (in deposits, scales, biofilms and fluids) is a critical initial step in evaluating the system risk of MIC. But how do we predict, assess and evaluate the risk of MIC in a pipeline system? This paper gives a review of different MIC modelling approaches and an overview of how we can look to successfully assess and evaluate the risk of MIC for pipeline systems.

## 1. INTRODUCTION

In oil and gas pipeline systems, internal corrosion is caused by the presence of water at the metal surface, providing an electrolyte for corrosion reactions to occur in an otherwise non-conductive environment. Internal pitting corrosion and metal wall loss is possible in pipeline systems with very low basic sediment and water (BS&W) contents (<0.5%) at locations where sediments are able to accumulate [1,2]. Such sediments, often termed 'sludges' are composed of varying combinations of hydrocarbons, sand clays, corrosion by-products, microorganisms and water. Biologically active pipeline sludges are known to accumulate and concentrate water from the oil, and create a metal-water interface, leading to the formation of localised under-deposit corrosion [3]. These sludges can support the formation and proliferation of microbial colonies, creating conditions that are conducive to microbiologically influenced corrosion (MIC).

Microbiological activity can adversely affect oilfield systems in a number of ways; general heterotrophic bacteria (GHB) are directly involved in biofouling (biofilm formation) which can contribute to a reduced efficiency of production and associated equipment operation. The formation of biofilms can provide favourable environments for anaerobic sulphate-reducing bacteria (SRB), for example, which produce hydrogen sulphide ($H_2S$); the production of $H_2S$ not only reduces the quality of the oil and gas produced (souring of production fields), but also increases the risk of corrosion. The process by which corrosion is initiated and/or accelerated by the activities of microorganisms is commonly recognised as MIC. One important factor to understand in the assessment of MIC is how the microorganisms initially enter pipeline systems.

The presence of microorganisms and their associated activity is increasingly recognised as a major concern in the oil and gas industry. Microorganisms can enter a pipeline system from a number of sources at varying enumerations. In addition to existing endogenously in petroleum reservoirs, microbes can often be introduced into oilfield systems at the initial stages of drilling and well completion, during shut-in periods, and during secondary and tertiary recovery of hydrocarbons. Microorganisms may also enter pipeline systems and remain viable for long periods from as early as the pipeline construction phase, particularly during commissioning when untreated hydrotest waters are used. Operational pipelines may sometimes receive bacterially contaminated fluids from upstream production systems, which if untreated will remain a source of persistent contamination requiring continuous mitigation if the source is not eradicated (if this is even possible!). It is therefore a fair assumption that most pipeline systems will host microorganisms of various species and enumerations at some stage during their life cycle. However, it should be noted that the presence of microorganisms in a system does not necessarily equate to the realisation and occurrence of MIC. The occurrence or risk of MIC is primarily dependent upon the pipeline environmental conditions being viable for sustained biofilm formation and steady state growth and proliferation of microorganisms. Additionally the system must be systematically and routinely monitored for the presence of microorganisms to support the risk assessment. With an understanding of which microbial species are present in a system, the pipeline environmental conditions, and whether they are able to support the MIC process, we can begin to appreciate whether a system is at risk of MIC occurring.

## 2. MICROBIOLOGICALLY INFLUENCED CORROSION MECHANISM

MIC is, like any other corrosion mechanism, an electrochemical process; microorganisms are able to initiate, facilitate or accelerate corrosion reactions through the interaction of three components that make up this system – metal, solution and microorganisms.

Owing to the importance of MIC in the oil and gas industry it has been the subject of extensive studies and several models have been proposed to explain the mechanism of biocorrosion [4]. There are two recognised mechanisms that explain microbial action in corrosion processes; the 'classical mechanism' and the 'modern mechanism'.

The classical mechanism of MIC dictates that microbial activities in a system produce chemicals that participate in a corrosion reaction and accelerate the associated corrosion rate. There are predominantly four microbial species that are known to influence corrosion in such a way: sulphate-reducing bacteria (SRB), acid producing bacteria (APB), iron-reducing bacteria (IRB) and iron-oxidising bacteria (IOB). Of these, SRB is most frequently encountered in pipeline systems in oil and gas production. SRB metabolism converts 'sulphate' ($SO_4^{2-}$) into 'sulphide' ($S^{2-}$); this reaction requires hydrogen atoms, therefore in the presence of SRB the cathodic hydrogen reaction is accelerated and the corrosion rate increases. Other species such as sulphur oxidising bacteria, manganese oxidising bacteria, methanogens and slime formers are also known to be associated with MIC. Despite extensive studies there still remains some uncertainty as to how many actual species contribute to corrosion; however the predominant species are those that are used as markers in determining the risk of MIC to an asset internally or externally.

MIC typically results in localised corrosion and the modern mechanism differentiates from the classical in that it proposes that the initial step is the formation of a biofilm. Biofilms are the glue that hold microbes together and are typically believed to contain about 95% water. The key steps in biofilm formation are presented in Figure 1 and outlined as follows [5,6]:

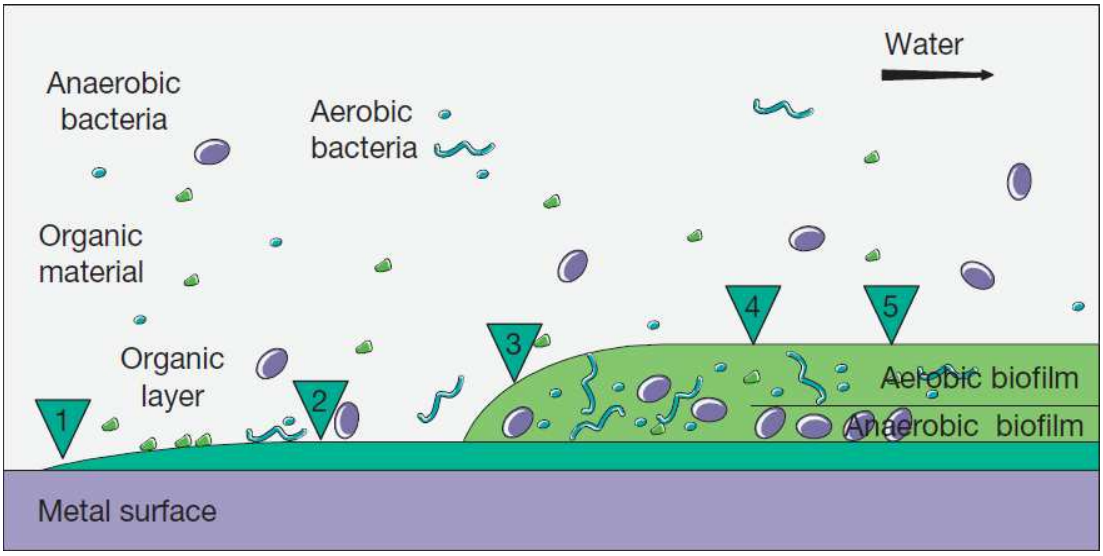


**Figure 1: Key steps in biofilm formation [5].**

1. Biofilm formation begins when small amounts of organic material attach to the metal surface. This 'conditioning film' accumulates at the metal surface.
2. Microbes attach onto the organic layer. Planktonic bacteria from bulk water form colonies on the metal surface and become sessile by excreting extracellular polymeric substances (EPS) that anchors the cells to the surface. Difference species of sessile bacteria replicate at the metal surface.
3. A thick biofilm develops on the metal surface. Micro-colonies of difference species continue to grow and eventually establish close relationships with each other on the metal surface.
4. The biofilm becomes thick enough to exclude oxygen at the metal surface, allowing the formation of an anaerobic zone near the metal surface. The biofilm increases in thickness and the electrochemical conditions beneath the biofilm begin to differ from those of the bulk environment.
5. Aerobic and anaerobic bacteria develop where conditions are most favourable for them. In practice, the classical mechanism associated with SRB activity can take place beneath the established biofilm.

The biofilm continues to thicken until parts of it are torn away by flowing fluids; this allows the process to begin again when the detached biofilm adsorbs onto another part of the metal surface. Localised corrosion can develop on the metal surface beneath such a biofilm and lead to corrosion pitting.

Under the MIC mechanisms described, microorganisms can initiate or contribute to electrochemical corrosion by the following 'modes of attack' [5]:

a) Direct chemical action of metabolic products such as sulphides (SRB and the classical mechanism).
b) Generation of electrochemical cell by deposition of cathodic and conducting metal sulphides *e.g.* iron sulphide (FeS), often in conjunction with a) (SRB and the classical mechanism).

c) Cathodic depolarisation by removal of hydrogen associated with anaerobic growth, often in conjunction with a) and b) (SRB and the classical mechanism).

d) Localised electrochemical effects due to local chemical changes which establish local differential cells, often in conjunction with a) and b). Biofilm formation can also contribute to this (modern mechanism).

e) Removal of inhibitory substances such as nitrite corrosion inhibitors.

f) Direct degradation of protective coatings by using the coating components as a source of carbon – reduce efficiency of the protective system.

MIC is relatively difficult to predict as well as diagnose compared to other corrosion mechanisms. The mechanisms involved in MIC are complex due to the diversity of contributing factors as well as the occurrence of synergistic effects [7]. For example, the growth of a biofilm is governed by a number of physical, chemical and biological processes, commonly termed abiotic and biotic processes, which is a critical point to note when considering the susceptibility of a system to MIC.

## 3. DETECTING MICROBIOLOGICAL ACTIVITY IN OILFIELD SYSTEMS

Detecting microbiological activity from oilfield samples (in deposits, scales, biofilms and fluids) is an important initial step in evaluating the system risk of MIC. Detection methods focus on the application and implementation of biological techniques by making use of the features of the bacteria. In the oil and gas industry, detecting microbiological activity is still primarily based on cultivation techniques.

Culture-based methods involving bacterial culturing in specific artificial growth media have long been established as the standard technique in the oil and gas industry for the identification and enumeration of bacteria [8]. The most commonly used culture-based method is the 'serial extinction dilution technique', with the test comprising of a 'serial dilution step' followed by an 'incubation step' using a growth media selective for the bacteria of interest. For example, if the bacteria of interest is SRB, vials containing specifically formulated SRB growth medium will be used in the test. If possible the serial dilution part of the test should be carried out within a few hours of obtaining the subject samples (typically done on site). Following the incubation period, the SRB population density in the original sample is determined to the nearest order of magnitude by the number of vials in each dilution series that turn black because of bacterial sulphide production. According to current standards [8], the prescribed incubation period for SRB is a minimum of 28 days, but a very good indication of the SRB count can usually be obtained after 10-14 days of incubation. To improve the accuracy of such methods, typically threefold or fivefold replicate serial dilution enumeration is carried out to allow a mean probable number (MPN) of bacteria to be determined from standard MPN tables [5].

A common criticism of the culture-based methods such as serial extinction dilution MPN is their inherent bias regarding strain isolation and growth, meaning that only a small proportion (usually less than 1%) of the microorganisms in a sample are cultivable and therefore analysed [9,10]. These techniques may therefore not be adequate in detecting all of the microorganisms potentially involved in the corrosion processes (it is important to note that within a biofilm, only some of the bacteria directly cause MIC while other bacteria in the biofilm community contribute to MIC indirectly [11]). Consequently, the culture-based methods may severely misinterpret/misrepresent the actual system condition [12] by underestimating the bacterial population size and failing to reflect the role of the uncultivated (and therefore 'undetected') bacteria potentially involved in MIC [13]. Conversely, field situations have been reported where significant levels of SRBs have been enumerated but the system shows little or no MIC, which has been attributed to the selective enrichment of SRB not heavily involved in MIC [12,14].

The limitations associated with the culture-based methods have led to the development of other culture-independent methodologies, which are gaining increasing acceptance in the oil and gas industry [15]. There are several different types of culture-independent methods such as measurement of adenosine triphosphate (ATP) levels, measuring specific enzyme activity, and the most powerful, molecular microbiological methods (MMM) [16]. MMM involve the extraction of DNA directly from the microorganisms present in a sample; the polymerase chain reaction (PCR) is then used to amplify copies of a particular gene in the sample to such an extent that the DNA fragments can be used to identify the bacteria. An advancement of the traditional PCR method is the real-time quantitative PCR (qPCR) technique, which in addition to bacterial characterisation can provide more accurate and reproductive enumeration (quantitative) data regarding microbial communities [17].

Microbiological monitoring based on advanced molecular microbiological analysis has successfully been applied to offshore production pipelines [18], leading one North Sea operator to no longer conduct traditional MPN culturing methods as part of microbiological monitoring programs [16]. These molecular techniques have been demonstrated to be a faster and more accurate means of microbiological monitoring [13], allowing for the rapid identification and quantification of all microorganisms present in a sample, including the vast majority that are not able to be cultured [19].

## 4. PIPELINE INTERNAL MIC RISK ASSESSMENT MODELLING

There are a number of approaches to MIC threat assessment including analysis of corroded components, chemical and microbiological surveys in conjunction with corrosion monitoring, and the use of MIC susceptibility and MIC pitting models. To accurately diagnose MIC, the affected surface and associated corrosion product must be obtained and analysed to determine the corrosion mechanism, the pit morphology characteristic of MIC and identify any causative microorganisms at the metal surface associated with the corrosion observed. It must also be shown that these microorganisms are capable of growth and able to sustain the corrosion process in the particular system environment. Accordingly, the key element to the identification of MIC is to have access to a sample of the corroded surface which is not practicable when we are concerned with live operating pipelines. We are therefore limited to and reliant upon routine monitoring and analysis of comingled corrosion products within pigging debris and microbial survey data, used in conjunction with susceptibility modelling.

With respect to predicting MIC in oil and gas pipelines several qualitative susceptibility models have been presented. Pots *et al.* [20] devised a model for predicting the MIC rate based on pipeline operational parameters and water chemistry influencing activities of SRB mainly. The Maxwell and Campbell [21] MIC risk model is a modified version of the Pots et al. model involving the combination of bacterial kinetics models. The model is based on a sulphide-generating biofilm on the metal surface, which is only corrosive in the presence of an MIC initiation factor. A further model has been generated to determine the MIC susceptibility through consideration of pipeline operating conditions that influence microbial growth and biofilm formation [22]. This model has been subsequently updated [23] with the integration and consideration of MIC-related mitigation measures, such as biocide application and pipeline internal cleaning. This model has also been validated through several case studies and as such, is one of the preferred approaches to-date in determining the MIC susceptibility of a pipeline system. The model itself provides a qualitative likelihood of MIC based on key operational data parameters. It is a two-step process which considers first the potential for biofilm formation and subsequent microbial growth steady-state condition. The most recent published model proposed by Skovhus [24] combines elements of previous models in a qualitative assessment of the Probability of Failure (PoF) of topside production facilities due to MIC. The Skovhus approach includes a MIC screening followed by PoF ranking process. The Skovhus approach is the only published approach to-date that links to the Risk Based Inspection (RBI) philosophy.

Table 1 presents some of the predominant MIC risk assessment models and the key parameters considered for their use.

**Table 1: Summary review of various MIC assessment models available in open literature sources (adapted and updated from [24]).**

| No. | Authors | Basis of Model | MIC Risk Evaluation | Parameters Considered | Comment | Reference |
|---|---|---|---|---|---|---|
| **1 (1970s)** | King | Index ranking | Index ranking | Abiotic parameters: flow rate, oxygen, heavy metals, nitrogen and phosphorus | Specific to open seawater marine sediment | [25] |
| **2 (1980s)** | Farinha | Modified King model | Index ranking | Additional parameters to King; sulphate concentration | Restricted to sea sediment and SRB specific | [6] |
| **3** | CHECWorks | Prediction Model Susceptibility to MIC = $(MWF \times TFx\ OFx\ BF \times BD \times DF \times VF)^{1/a}$ | Susceptibility to MIC scale of 0 (no susceptibility) to 10 (high susceptibility) | Materials-Water, Temperature, Operations, Biocide, Surface Discontinuities, Velocity | Specific to service cooling water systems | [26] |
| **4** | Union electric Callaway | MIC Index ranking 0-100 (Index = 4.5446 [(29-SRB)/4.83 + (6-CLOS) + (9-GALL)/1.5 + Silt Factor + Visual Factor | Measure of the degree of severity of MIC | SRB, CLOS, GALL culture, Silt, Visual indicators | High significance on sampling and microbial numbers. Does not factor abiotic parameters of a system. | [26] |
| **5** | Lutey/Stein | MIC Index; Index = [(BF) + (DFF) + (SF)] x | Measures potential/severity of MIC. | Considers 4 bacteria only SRB, Slime formers, MOB, APB. | Restricted to the bacteria types assessed. Can also | [26] |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | (MF) | | Materials, sediment and fouling factors | be used to detect biocide effects on these bacteria. | |
| **6 (1992)** | Gas Research Institute (Bioindustrial Technologies Inc.) | Key parameter questions | Likelihood based on question answer ranking | Bacteria nos., type. Corrosion products. Pit shape and characteristics | No longer available. Unreliable corrosion rates | [27] |
| **7 (2002)** | Pots *et al.* | MIC susceptibility and rate | MIC corrosion rate: $CR = C \times F^P$ (where C = constant (2 mm/yr.) P = 0.57 and F = f1 x f2 xf3 *etc.*) | Pipeline operational parameters and water chemistry influencing activities of SRB mainly; temperature, pH, TDS, and nutrients. Pigging and biociding | Concept is good. Provides very high corrosion rate predictions. Depends on ability to validate if bacteria will grow under pipeline conditions Specific to SRB and parameter use is limited to specifics | [20] |
| **8 (2006** | Maxwell & Campbell | modified Pots et al model through the combination of bacterial kinetics models | Increasing basis on RA of MIC | Incorporates rated field data in model; bacteria no.'s, sulphide conc., water modelling | Insufficient evidence as to how certain parameter would be used to modify the Pots model. | [21] |
| **9 (2007) (2008)** | Sooknah *et al.* | Determination of the risk of biofilm formation based on operational parameters | MIC susceptibility, based on likelihood of biofilm formation under pipeline operational parameter. Provides a risk factor and not a corrosion rate like Pots model. | Temperature, Pressure, Flow rate, Water quality, Oxygen. Pigging | Concept similar to Pots model; if a biofilm could form then MIC is a risk. No negative weighting on missing data Good approach, but no corrosion rate prediction and no weighting on microbial types and enumeration | [22,23] |
| **10 (2012)** | Sorensen *et al.* Skovhus *et al.* | Determination of Integrated MIC risk Factor (IMRF) and Potential Pit Generation Rate (PPGR) | Rate of Iron dissolution = $4xN_{SRB}xS_{SRB}$ + $4xN_{SRA}xS_{SRA}$ + $4xN_{MET}xS_{MET}$ | Model based on in-situ MMM, does not include physical or chemical parameters. | Primarily based on biotic data and does not factor in abiotic parameters. | [14,24] |

It is noted that all corrosion models or assessment procedures will have some degree of inherent uncertainty. It is clear that there is no definitive MIC modelling solution available that will correctly predict MIC in every situation. One must use model predictions only as indicative to plan continuous integrity management monitoring and mitigation measurements until situation realisation is fully understood. Disagreement will remain with respect to the nature of the risk factors utilised in the process and their importance weighting when determining biofilm development and MIC susceptibility of a system. It should be noted that it is unlikely that an *ideal* model will be developed for predicting MIC in the near future, as there remains a great deal of uncertainty in the understanding of the MIC mechanism(s) and the influence of all the associated variables. With this fact in mind the appropriate approach is to consider all present models proposed and bring together aspects of each considered ideal for the process of determining the MIC threat, risk and associated PoF for risk based inspection / management. By adopting this philosophy it allows for flexibility and the incorporation of new model ideas and key data from future research to be easily incorporated to update the methodology for MIC risk assessment.

## 5. PROPOSED MIC SUSCEPTIBILITY RISK ASSESSMENT PROCEDURE

In order to facilitate a RBI philosophy, the proposed methodology for determining the MIC risk encompasses elements of the Skovhus approach [24] to provide a process for determining the PoF of MIC. The methodology follows a modified version of the Skovhus MIC screening process, where it has already been confirmed that MIC is being realised and managed under a suitable MIC corrosion management strategy (referred to as 'MIC Screening Assessment'). If the MIC risk realisation is unconfirmed then a more detailed MIC susceptibility process should be undertaken (referred to as 'New MIC Susceptibility Assessment'), assessing key abiotic and biotic parameters identified in the Sooknah [22,23] and Pots [20] models to establish the potential for biofilm formation and the development of a steady-state microbial system. The overall MIC Susceptibility Risk Assessment procedure is outlined in Figure 2.

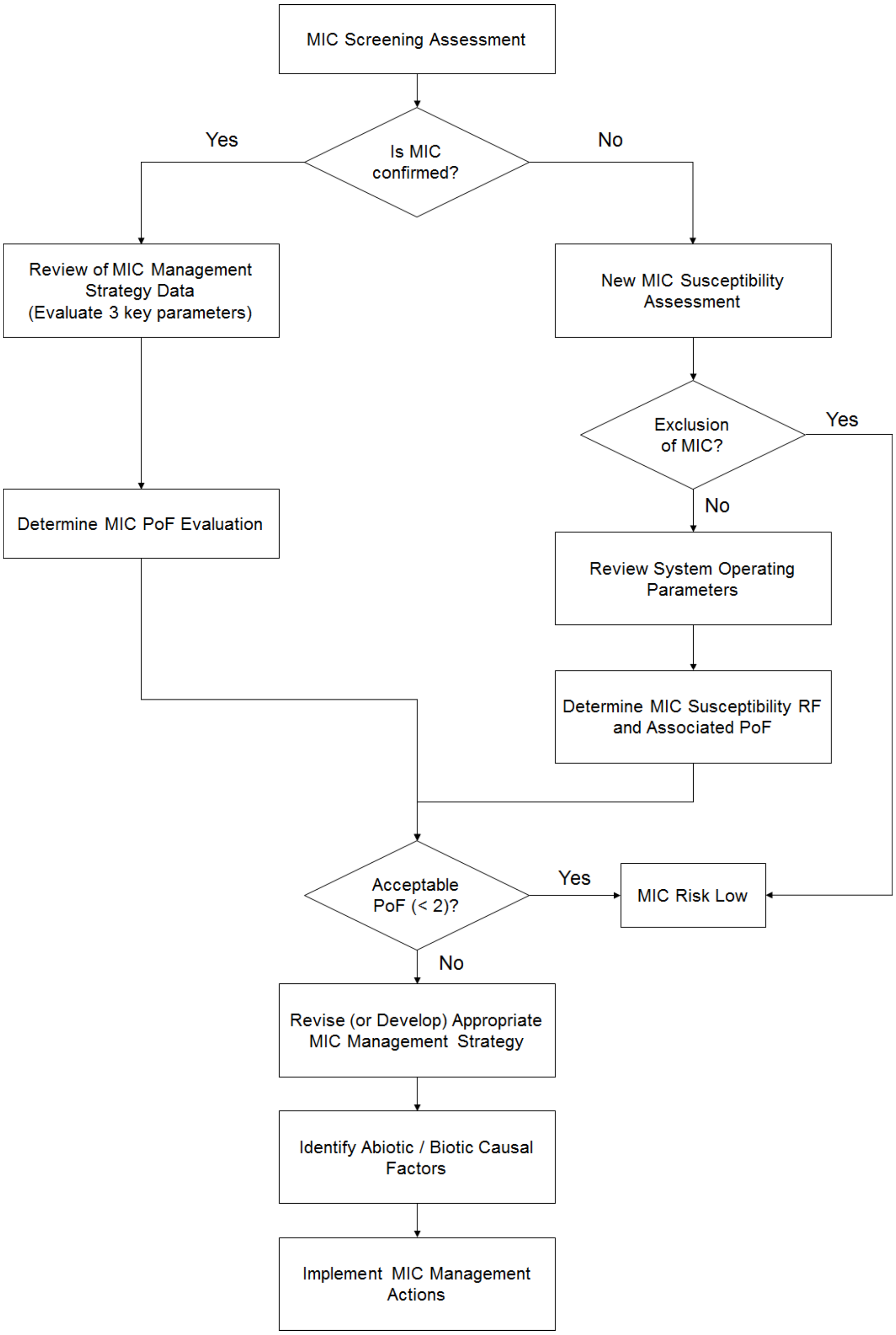


**Figure 2: Process flow diagram of MIC Susceptibility Risk Assessment Procedure.**

### 5.1 MIC Screening Assessment and PoF Evaluation

#### 5.1.1 MIC Screening Assessment (Is MIC confirmed?)

The MIC Screening Assessment is only applicable to a system in which MIC has already been confirmed through one of the following routes:

1. Confirmation of the presence of microorganisms associated with causing corrosion through routine detection and monitoring methods (*i.e.* culture-based methods or MMM), which are being managed under a MIC control strategy. Although the exact species that contribute to corrosion may be unknown, the predominant species associated with corrosion are SRB, IRB, IOB, APB and methanogens.
2. Active MIC has been confirmed *via* correlation of corrosion rate evaluation and the presence of microorganisms on the internal surfaces (*i.e.* on corrosion coupons, bio-probes, pipe sectioning, scale / deposits analysis, *etc.*).
3. Corrosion is occurring and through the elimination of active abiotic corrosion mechanisms, MIC has been determined as the most probable cause and is being managed under a MIC control strategy.

### 5.1.2 MIC PoF Evaluation

If the occurrence or likelihood of MIC has already been confirmed and is being managed under a MIC control strategy, then a periodic annual review of the controls is required to ascertain whether MIC is being effectively and remains a credible threat. In order to establish the status of MIC control, and determine an updated qualitative PoF based on the MIC susceptibility ranking, three key parameters have been determined with respect to mitigation, inspection and monitoring for assessment in the MIC Screening PoF ranking interaction matrix. The individual parameter PoF denotations are based on the following:

***Corrosion Control Availability (%):***

This parameter is the sum of the percentage availability of all MIC control methods that, within the fraction of time in a given period, have been compliant to the respective target. The basis of the inclusion of the parameters stems from its consideration in the Pots *et al.* corrosion rate prediction model, which links corrosion rate prediction with field application data and the availability of the corrosion control system, as expressed in the following equation:

$$CR = F \times CRm + (1-F) \times CRu$$

*Where F is the availability of the corrosion control system (fraction of time in a year that the system has been compliant to target), CRm is the residual corrosion rate at mitigation conditions, and CRu is the unmitigated corrosion rate obtained from the corrosion rate prediction model equation.*

In determining the value ranges to assign to the five PoF groups, no literature or field data could be sourced. Accordingly, a simple percentage division criteria has been used to suit the five PoF ranking levels.

***Localised Corrosion Rate (mm/year):***

The localised corrosion rate is a key parameter to consider in determining the realisation of MIC and the effectiveness of associated MIC controls. As a result, the PoF assignment of the corrosion rates for the five categories is in accordance with the corrosion rates and ranking denotations outlined in NACE SP0775 [28], as shown in Table 2. Without knowledge of the localised corrosion rate the MIC screening model assigns ‘Unknown’ as a filth value range. The ‘Unknown’ values and its interaction with corrosion control availability and microbial numbers has been interpreted utilising corrosion engineering knowledge in the PoF interaction diagrams (Figure 3) to establish a PoF ranking.

**Table 2: NACE SP0775 corrosion rate severity rankings.**

| Corrosion Rate Category | Average Corrosion Rate | | Maximum Pitting Rate | |
|---|---|---|---|---|
| | mm/yr. | mpy | mm/yr. | mpy |
| Low | < 0.025 | < 1.0 | < 0.13 | < 5.0 |
| Moderate | 0.025 – 0.12 | 1.0 – 4.9 | 0.13 – 0.20 | 5.0 – 7.9 |
| High | 0.13 – 0.25 | 5.0 – 10 | 0.21 – 0.38 | 8.0 – 15 |
| Very High | > 0.25 | > 10 | > 0.38 | > 15 |

***Microorganism Enumeration:***

The number of microorganisms within a system detected using either culture-based methods or MMM techniques have been used in the assessment of the MIC risk since MIC was initially recognised as a credible mechanism. The routine monitoring of bacterial numbers is also a means of determining the effectiveness of the mitigation strategy implemented. The threshold total number of either sessile or planktonic microorganisms which make a system susceptible to MIC have been communicated in literature [5,24] as; sessile numbers ≥ $10^2$ and planktonic numbers ≥ $10^3$ (cells/ml, cells/cm$^2$ or cells/g).

Figure 3 outlines the process for determining the PoF ranking based on the evaluation of the three key parameters. The individual PoF rankings can be tailored to be synonymous with client-specific Pipeline Integrity Management System (PIMS) documentation and risk ranking matrices.

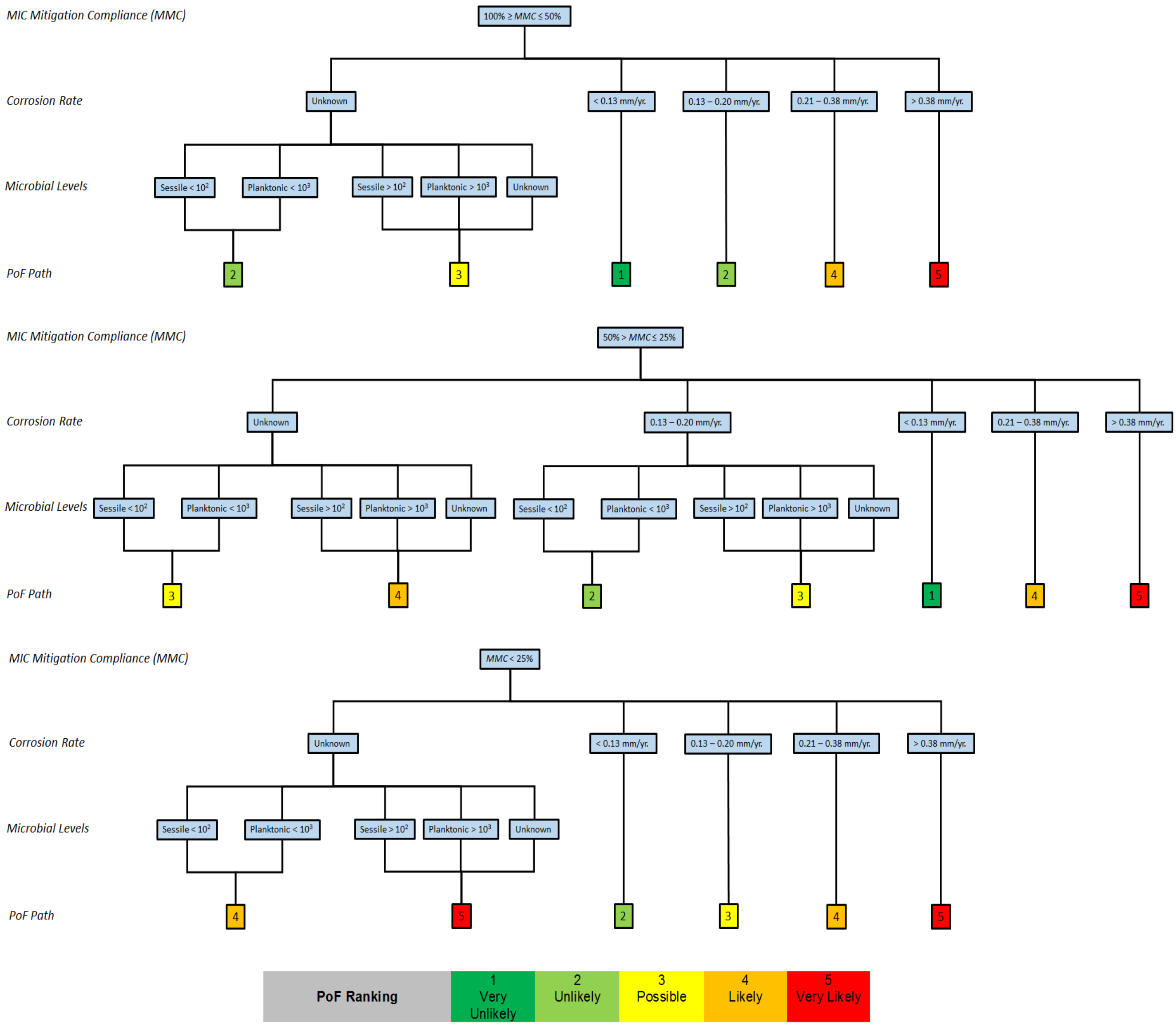


**Figure 3: MIC Screening Assessment and PoF Evaluation, interaction diagrams and rankings.**

## 5.2 New MIC Susceptibility Assessment

### 5.2.1 Susceptibility to Biofilm Formation

In the assessment of pipeline systems, engineers are often required to make an initial appraisal of the MIC susceptibility and associated corrosion rate with limited information regarding the corrosion history and little or no historic microbiological data. Determining the MIC susceptibility of a system is difficult process due to the complex physio-chemical and biological interactions of the surface, biofilm, microorganisms and environment, thus predicting an associated corrosion rate is equally difficult. The complexity of MIC means that most corrosion rates predicted are unreliable, because of the uncertainty of the onset of pitting and the rate at which it proceeds. As such the corrosion rates calculated are not absolute and should not be used as such.

Despite the complexity of any abiotic / biotic system there are certain key abiotic parameters that strongly influence the compatibility of a system with the conditions required for biofilm development and survival of sessile microorganisms. Therefore, a preliminary analysis of the systems abiotic operating conditions may be sufficient to exclude the MIC threat when these conditions are not favourable [22].

With respect to the abiotic system parameters biofilm growth can be reasonably excluded under any of the following conditions:

- Operating temperature of the system is >120°C;
- Internal pipeline surfaces are not accumulating any moisture or hygroscopic deposits (*e.g.* dry gas operations in gas pipeline systems); without water bacteria motability and nutrient availability is reduced and osmotic pressures are less viable to most bacteria.
- Organic/inorganic nutrients for the development of microorganisms are absent or availability is reduced.

In the absence of any of the above conditions, the approach is to predict the susceptibility of MIC inside the pipeline based on the influence of pipeline operational parameters on the potential for biofilm formation and development, with the combined growth of microorganisms. The operational parameters used in the MIC susceptibility predictive model are those that can be practically measured under continuous normal operating conditions. The rates of growth and death of microorganisms are greatly influenced by environmental factors such as:

- Presence of water;
- Nutritional requirements;
- Oxygen levels, redox potential;
- Temperature;
- pH;
- Salinity;
- Pressure;
- Flow rate;
- Water quality;
- Cleaning frequency.

A pipeline internal MIC susceptibility model [23] has been developed to allow for qualitative evaluation of the MIC risk based on the factors listed above. It should be noted that industry-wide acceptance of this or any MIC prediction model is yet to be confirmed, and it is unlikely that any such model will ever be approved or accurate in predicting MIC corrosion rates. As discussed previously this model is a preferred practical approach to determining MIC susceptibility. The model has been updated to include an MIC susceptibility, which corresponds to a PoF ranking. The New MIC Susceptibility Assessment has a corresponding engineering spreadsheet. The engineering spreadsheet is used to input or select the required operating parameters that will be used to determine the MIC susceptibility ranking or the likelihood of the potential for MIC to occur under the operating conditions. Each contributing operational parameter is ranked individually. Each parameter is assigned a ranking factor, F, with a value between 0 and 5 (ranking is from F = 0 (no susceptibility) to F = 5 (highest susceptibility or greatest potential for occurrence of MIC). The MIC risk factor (RF) is calculated as the sum of the ranking F values for each contributing factor, divided by the total number of these factors. Once the MIC RF value is established the MIC susceptibility can be determined and the associated PoF based on the indices given in Table 3.

**Table 3: MIC susceptibility index.**

| **0 - 1** | **1.1 - 2** | **2.1 - 3** | **3.1 - 4** | **4.1 - 5** |
|---|---|---|---|---|
| **1**<br>**Very Unlikely** | 2<br>Unlikely | 3<br>Possible | 4<br>Likely | 5<br>Very Likely |

The New MIC Susceptibility Assessment procedure also gives consideration to the Pots [20], Sooknah [23] and Skovhus [24] models in the engineering spreadsheet as a means of cross-reference to the proposed approach to MIC susceptibility.

### 5.2.2 New MIC Susceptibility Assessment Procedure and Contributing Parameter Ranking

The assessor will conduct the New MIC Susceptibility Assessment procedure through the following stages, which correspond to the engineering worksheet.

***Stage 1: Exclusion of MIC***

The initial stage of the process is to determine if the threat of MIC can be excluded based on the absence of water to sustain microbial growth, the temperature range suitability and the availability of key nutrients related to specific known corrosion-influencing bacteria.

The susceptibility to MIC can be established as very low risk based on the parameter values and their ranking factor (F) presented in Table 4. It is important to note that any variation outside of the parameters may result in initiating microbial activity, however, if the operating parameters return to within the ranges in a short time (within 14 days) then further microbial growth will be arrested and the system would return to the MIC susceptibility status outlined in Table 4. If the anomalous operational period extends beyond 14 days then a more detailed assessment to ascertain the MIC risk should be conducted and the New MIC Susceptibility Assessment procedure should be undertaken to determine the mitigation actions.

In the New MIC Susceptibly Assessment engineering spreadsheet the assessor is required to enter the values in the “Response” cell. If the conditions for exclusion of the threat of MIC are not met then the engineering spreadsheet will indicate this and further assessment of the operating parameters are required to establish the susceptibility of biofilm formation and microbial growth. The assessor will be prompted to move to Stage 2 of the New MIC Susceptibility Assessment procedure. If the conditions are met then no further assessment is required and a MIC RF = 0 and PoF rank = 1 will be generated within the engineering spreadsheet, indicating that there is a very low susceptibility of MIC manifesting in the system. If this is the case the assessor will be prompted to go to evaluate the corrosion management actions required as provided in Table 6.

**Table 4: Pipeline operational parameters and associated value ranges that can be used to exclude the threat of MIC.**

| Parameter | Value Range | Ranking Factor (F) | MIC Susceptibility | Comment |
|---|---|---|---|---|
| **Water Present** | No | 0 | No susceptibility | If water is present then a more detailed assessment is required to determine the Mic susceptibility based on other operational parameters |
| **Temperature (°C)** | <-10≤120 | 0 | Very low susceptibility | Only extreme strains of prokaryotes can exist outside of this range |
| **Nutrients:**<br>**Sulphate**<br>**Carbon (from organic acids)**<br>**Nitrogen**<br>**Carbon/Nitrogen Ratio**<br>**Carbon/Nitrogen/Phosphorus Ratio** | <br><10 mg/l<br><20 mg/l<br><5 mg/l<br><10<br>100-500(C)/1(N)/0.25(P) | 0 | Very low susceptibility | Only if all nutrient parameters are met. |

***Stage 2: Biofilm Formation, Microbial Adhesion and Growth***

As MIC cannot be excluded, further assessment of the system operating parameters to determine the susceptibility and associated MIC RF and PoF ranking is required by the assessor. In Stage 2 the assessor determines the systems susceptibility to MIC based on the potential of a) biofilm formation, though the formation of the surface conditioning layer and b) microbial adhesion and growth. The assessor is required to input the data in the “Response” cell of the New MIC Susceptibility Assessment engineering spreadsheet.

The operating parameters that contribute to biofilm formation through the formation of the surface conditioning layer and subsequent microbial adhesion and growth and their associated individual risk ranking factor (F) are given in Table 5.

It is imperative that the assessor completes all "Response" fields, by inputting "Unknown" where no data is available, so that the negative impact of the absence of that data can be considered in modelling the MIC susceptibility.

***Stage 3: MIC Risk Assessment***

Based on the operating parameters available for the system, the likelihood of the occurrence of MIC is evaluated for each contributing parameter in terms of Table 5. The contributing operating parameter data are assigned an F numerical value between 1 and 5. Numbers approaching 1 signify values with minimum risk, the reverse signifies values of high risk. The overall MIC RF is determined as the sum of all the contributing F values assigned for each operational contributing factor, divided by the total number of contributing operational parameters. After establishing the RF value the susceptibility of the system to MIC is determined based on the indices given in Table 3, which correspond to the PoF indices 1 to 5.

**Table 5: Pipeline operational parameters, associated value ranges and risk ranking factor used in determining MIC susceptibility.**

| Operational Parameter | Parameter Value(s) | Parameter Risk Factor (F) |
|---|---|---|
| **Flow Velocity** | ≥3 m/s<br>≥2<3 m/s<br>>0<2 m/s<br>0 m/s<br>Unknown | 1<br>2<br>3<br>4<br>5 |
| **Solids** | In the MIC susceptibly assessment it is assumed that all pipeline systems contain organic and/or inorganic particulates, therefore the assessor shall default to answering 'Yes'.<br>If the system has been demonstrated to be solids free, then answer 'No' | 3<br>2 |
| **TDS** | ≤60 g/l<br>>60 g/l | 4<br>3 |
| **Pipe Geometry** | Vertical<br>Horizontal<br>Low Point (Section of fluid hold-up/stagnation)<br>Dead-leg | 1<br>4<br>5<br>4 |
| **ρCO2/ρH2S** | >20<br>≤20 | 5<br>2 |
| **Oxygen** | If > 50ppb (mg/l):<br>if false<br>Unknown | 5<br>3<br>3 |
| **Redox Potential** | if -50 to 150 mV then<br>Outside of range<br>Unknown | 5<br>3<br>3 |
| **pH** | if 1-4 F=3<br>if 4-9 F=5<br>if 9-14 F=2 | 3<br>5<br>2 |
| **Sulphide** | if yes and +ve<br>if yes and -ve<br>if no or unknown | 5<br>1<br>3 |
| **Corrosion Rate** | <0.13 mm/yr.:<br>0.13-0.20 mm/yr.:<br>0.21-0.38 mm/yr.:<br>>0.38 mm/yr.:<br>Unknown: | 1<br>2<br>3<br>4<br>3 |

| | | |
|---|---|---|
| **Operating History** | <0.5 yrs.<br>>0.5 yrs. & 1 week downtime<br>>0.5 yrs. & 50 weeks downtime | 1<br>1<br>2 |
| **Prokaryote Numbers** | Sessile <10^2<br>Sessile >10^2<br>Planktonic <10^3<br>Planktonic >10^3<br>Unknown | 3<br>4<br>2<br>3<br>3 |

### 5.3 Corrosion Management Actions

The PoF rankings generated using either the MIC Screening Assessment and PoF Evaluation, or the New MIC Susceptibility Assessment to determine the next course of action. The assessor is required to cross-reference the generated PoF ranking with Table 6, which indicates the appropriate MIC management activities to be implemented.

**Table 6: Required MIC Management Actions associated with MIC PoF rankings.**

| PoF Ranking | MIC Management Action |
|---|---|
| 1<br>Very Unlikely | • No immediate action required.<br>• Continue with present MIC mitigation, monitoring and inspection.<br>• Current monitoring and inspection frequencies may be reduced with sufficient knowledge of the data trends.<br>• Mitigation activities may also be reduced, but would requires additional monitoring above the present frequency to monitor effectiveness. |
| 2<br>Unlikely | • As PoF Ranking 1, no additional actions required. |
| 3<br>Possible | • Identify which abiotic / biotic parameter is leading to a possible MIC threat. If this is not immediate then it may be necessary to conduct a new MIC susceptibility assessment.<br>• Regain control of that parameter through the current MIC control strategy, through increasing the current mitigation element along with more frequent monitoring and inspection to determine if control has be regained.<br>• If control is not regained over a 6 to 12 month period using current mitigation practices then the PoF ranking shall be elevated to PoF 4 and associated actions undertaken. |
| 4<br>Likely<br><br>**AND**<br><br>5<br>Very Likely | • Conduct a new MIC detailed assessment to determine which abiotic / biotic parameters of the system are causing an elevated risk of MIC.<br>• Review operational history to determine if there has been any change to the system parameters that has led to a high-risk evaluation.<br>• Conduct a review of the present MIC strategy to determine why it is not being effective.<br>• The present biocide used with respect to both planktonic kill efficacy and biofilm penetration efficacy is potentially limited and selection of a new biocide or increased dose regime may be required.<br>• Continuous injection of the same biocide has led to microorganism phenomic adaptation resulting in a strain that now has resistance to the biocide. At best the biocide is resulting in injury rather than kill. Utilisation and frequent variation of at least two blends of specific microbially-targeted biocides is required. Dose and frequency will be established through consultation with the chemical manufacturers based on laboratory and field testing. *Note; Ensure suitable biocide testing protocols are followed with specific consideration to; bacterial kill, biofilm penetration, regrowth, contact time and dosage.*<br>• Pipeline cleaning frequency may be insufficient, if so consider increasing the frequency and conduct additional microbial monitoring to determine if the additional control has been effective.<br>• The type of cleaning (cleaning pig) utilised may not be efficient. Try an alternative (more aggressive) cleaning pig type more suitable to the removal and disruption of stubborn biofilms.<br>• With any mitigation change it will be necessary to conduct further corrosion and microbial monitoring to determine the effectiveness of the new strategy.<br>• If corrosion rates are unknown then the installation of appropriately located corrosion coupons, probes, bio-studs should be considered.<br>• Alternatively monitor corrosion rates through direct assessment at appropriate locations which have been determined to be high-risk locations for MIC. |

## 6. SUMMARY

This paper presents a MIC Risk Assessment Procedure, including a MIC Screening Assessment and PoF evaluation for those systems with confirmed MIC issues, and a New MIC Susceptibility Assessment for systems where MIC is unconfirmed. The procedure has been developed based on a literature review of recently developed strategies for the assessment of MIC.

In order to facilitate a RBI philosophy, the proposed methodology for determining the MIC risk encompasses elements of the Skovhus approach to provide a process for determining the PoF of MIC. The methodology follows a modified version of the Skovhus MIC screening process, where it has already been confirmed that MIC is being realised and managed under a suitable MIC corrosion management strategy (referred to as 'MIC

Screening Assessment'). If the MIC risk realisation is unconfirmed then a more detailed MIC susceptibility process is undertaken (referred to as 'New MIC Susceptibility Assessment'), assessing key abiotic and biotic parameters identified in the work of Sooknah and Pots, to establish the potential for biofilm formation and the development of a steady-state microbial system.

Based on the PoF scores generated by the proposed assessment procedures, the appropriate MIC management actions can be implemented as part of an integrated MIC control strategy in order to successfully manage the threat of MIC.

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