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ABSTRACT

Operating offshore oil and gas production facilities is often associated with high risk. In order to manage the risk, operators commonly use aids to support decision making in the establishment of a maintenance and inspection strategy. Risk Based Inspection (RBI) analysis is widely used in the offshore industry as a means to justify the maintenance and inspection strategy adopted.

The purpose of this thesis is to develop a procedure for the assessment of microbiologically influenced corrosion in RBI analysis.

RBI analysis is a decision making technique that enables asset managers to identify their most critical systems and components, with regards to safety, environment and business (DNV, 2010). In this thesis, risk is considered in accordance with DNV GL practise as a two dimensional combination of probability of failure and consequence if failure. Thus, the RBI analysis is based upon this risk picture as well.

Microbiologically Influenced Corrosion (MIC) is a degradation mechanism that has received increased attention from corrosion engineers and asset operators in the recent years. In the thesis, the most important aspect of MIC is presented and discussed. Further, previous models that have been developed in order to assess the impact of MIC on asset integrity are presented. From a risk perspective, MIC is not satisfactorily assessed by the current models and the models lack a proper view of the MIC threat. Therefore, a review of parameters that affect MIC is presented.

The mapping and identification of parameters is based on the review of past models and extensive literature study of the subject. The parameters are discussed and subsequently combined in a suggested procedure that allows assessment of MIC in a RBI analysis. The procedure is sub-divided into one screening step and one detailed assessment, which fits the recommended approach to assess risk in a RBI analysis.

Interface between the suggested procedure and the RBI concept is discussed. Several recommendations are made in the identification of what, when, where and how to inspect, as well as what to report. Lastly, an example that illustrates application of the procedure is given.

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CHAPTER 1: Introduction

Microbes can have a negative impact on asset integrity by influencing internal corrosion in offshore production systems. Few methods have been developed to systematically map this phenomenon, commonly referred to as Microbiologically Influenced Corrosion (MIC). The main reasons why so few methods exist today are; microbes are highly unpredictable, disagreement among scientists regarding which groups of microbes influence corrosion the most, and limited knowledge about which (physical, chemical and biological) factors cause MIC.

As a result of this, asset managers lack a good procedure that allows them to put the MIC threat into perspective and compare its impact with other degradation mechanisms. Some of the methods previously developed try to describe the risk associated with operating a system with MIC, but their approach is solely based on the rate of MIC. Although the degradation rate impacts the risk of operating a system, it is not equivalent to the risk as suggested in the models presented in this thesis. An inspection analysis which is solely based on the result of applying those methods is considered to be deficient. A more holistic view of probability of failure (PoF) and consequence of failure (CoF) due to MIC is seen as crucial in order to establish satisfactory inspection routines. Risk Based Inspection (RBI) analysis is a common way to establish inspection routines based on the risk of system failure.

There have been cases where the RBI analysis and corrosion management practices have failed to adequately recognise MIC as a significant threat. A well-known failure case in the North Sea, which was attributable to MIC, was on the Valhall platform in 2009. The failure lead to hydrocarbon leak and subsequent platform shut down for 10 weeks leading to a significant loss in production. According to NPD (2014) production fell with 4 420 000 barrels of oil equivalents during the period April to June of 2009 compared with 2008. If production had been maintained it could have given an income of 2 210 million NOK in gross revenue given an oil price of 100 USD/bbl. and a USD price of 5 NOK/USD. Improvements in the process to consistently assess the likelihood of MIC would therefore be of great benefit to the oil and gas industry.

Some RBI methods identify MIC as a threat, but decision makers are often left with nothing more than engineering judgement to assess its significance. This thesis presents a review of key elements related to MIC and a procedure for incorporating the threat of MIC into RBI programs.

1.1 Aim of the thesis

This thesis presents an engineering approach to examine the influence of microbes on internal corrosion and further assess their impact on asset integrity in a risk-based inspection (RBI) analysis. The described procedure is intended to aid in decision making by incorporating microbiologically influenced corrosion in RBI programs.

1.2 Scope of work

The thesis focuses on the following;

- Introduction of Microbiologically Influenced Corrosion (MIC) and the Risk Based Inspection (RBI) approach
- Evaluation of existing MIC threat assessment models
- Identification of the most important parameters that affect MIC and MIC management
- Development of a procedure for assessing MIC and suggest integration of the procedure with the RBI concept
- Exemplify application of the developed procedure

1.3 Limitations

- The procedure developed is limited to internal corrosion in topside production facilities on offshore platforms – It is intended by be applied from wellhead to export lines
- The procedure is based on groups of microbes that are known to influence corrosion; Sulfate-Reducing Prokaryotes (SRP) and methanogens

1.4 Structure of thesis

Chapter 1 contain the background, aim, scope, limitations, structure of the thesis as well as abbreviations and terminology used is the text.

Chapter 2 addresses key features of microbiologically influenced corrosion (MIC) and Risk Based Inspection (RBI) analysis.

Chapter 3 presents and discusses several existing MIC assessment models.

Chapter 4 identifies parameters which can be used to establish the probability of failure due to MIC. Physical, chemical and biological factors are presented and discussed.

Chapter 5 presents and discusses a suggested two-step procedure for qualitatively assessing the probability of failure due to MIC.

Chapter 6 is concerned with the integration of the suggested procedure with the RBI concept.

Chapter 7 contain an industrial example that illustrates application of the procedure.

Chapter 8 and chapter 9 contain conclusions and suggestions for future work, respectively.

1.5 Abbreviations

CC	Corrosion Circuit
CoF	Consequence of Failure
CS	Carbon Steel
DNV GL	Det Norske Veritas Germanischer Lloyd
IMRF	Integrated MIC Risk Factor
LOC	Loss of Contaminant
MIC	Microbiologically Influenced Corrosion

MMM	Molecular Microbiological Methods
PoD	Probability of Detection
PoF	Probability of Failure
PPGR	Potential Pit Generation Rate
RBI	Risk-Based Inspection
SRA	Sulfate-Reducing Archaea
SRB	Sulfate-Reducing Bacteria
SRP	Sulfate-Reducing Prokaryotes
WI	Water Injection

1.6 Definitions

Corrosion circuit: The grouping of components versus failure modes analysis within a materials operating envelope.

Facultative: Microbes able to live in both aerobic and anaerobic environments, i.e. in the presence or absence of oxygen.

Microbes: Organisms with cellular life, invisible to the naked eye. (Microbes/microorganisms are interchangeably used in literature).

Microbiologically Influenced Corrosion (MIC): Corrosion influenced by the activity of microbes.

Risk: "A measure of possible loss or injury, […] expressed as the combination of the incident *probability* and its *consequence*" (DNV, 2010, p. 9).

Risk based inspection (RBI) analysis: An analysis where inspection need is established based on the risk associated with operating a system or corrosion circuit.

Threat: A potential cause of failure.

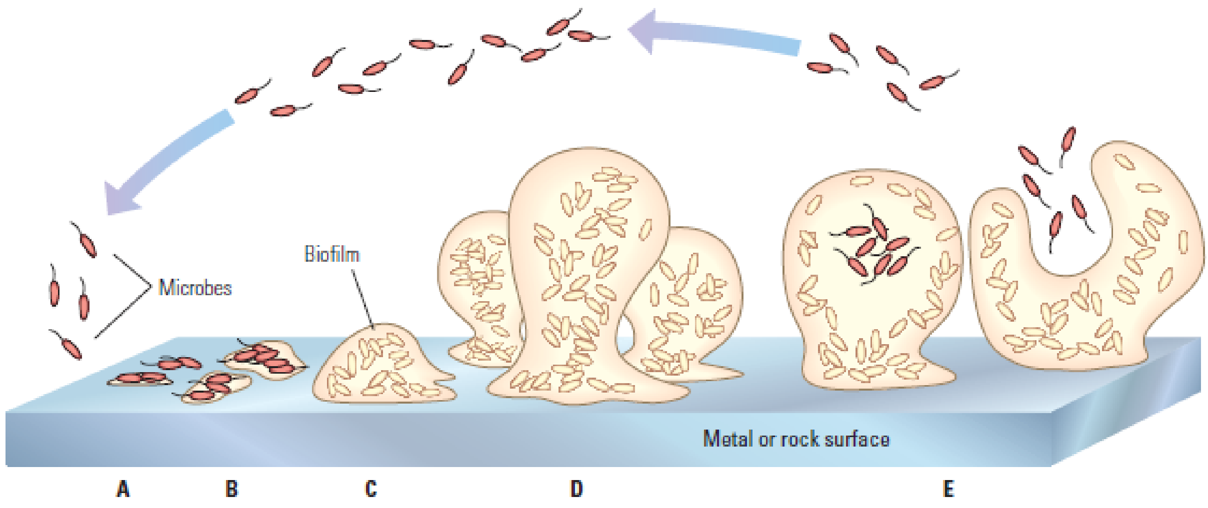
CHAPTER 2: Introduction to MIC and the concept of RBI analysis

In this chapter key factors regarding microbes and microbiologically influenced corrosion (MIC) is discussed. Further, molecular microbiological methods (MMM) and the risk based inspection (RBI) approach are briefly presented.

2.1 Microbes and MIC

Organisms can be divided in two main groups; those that are visible to the naked eye and those that are not. Microbes are characterised by the latter, their presence can only be determined by using aids, such as a microscope, or by identifying their activity as a “collective entity”, e.g. by the use of molecular microbiological methods (MMM).
The microbe “collective entity” refers to the situation when microbes have transferred from the planktonic to the sessile state and formed a biofilm. Once in a biofilm they can collectively transport nutrients, multiply and degrade the material to which they are attached. Biofilm formation is therefore a prerequisite for degradation of metal by microbes.

Figure 1 illustrates how microbes settle and form a biofilm.



^ Biofilm formation. The growth of biofilms is a stepwise process that begins with the transport of microbes to a metal or rock surface (A). The microbes absorb organic molecules from their surroundings to form a film (B) composed of exopolymers—sugars—that allow the microbes to stay attached to the surface as well as to each other (C). As the biofilm expands (D), its size gives the interior microbes protection from biocides. Eventually, when the biofilm grows to a certain size, some microbes are released (E) to form new areas of growth.

Figure 1: Biofilm formation, from Augustinovic et al. (2012)

Microbes are normally divided into groups based on their biological characteristics (Todar, 2009). The main groups are prokaryotes, which can be sub-divided into bacteria and archaea and eukaryotes, which can be sub-divided into algae, protozoa and fungi.

As a result of their metabolic processes, microbes indirectly affect, by initiating and/or accelerating, other types of corrosion. The result is often high local corrosion rates, commonly referred to as pitting corrosion. This, if left undetected, can lead to loss of containment (LOC) and result in safety, environment and business related issues as well as potential reputational repercussions for an organisation.

Figure 2 shows the inside of a pipeline previously subject to MIC.

Figure 2: Pitting corrosion caused by MIC. (Obtained from an undisclosed operator in the North Sea)

2.1.1 Microbial groups linked to MIC

As stated, microbes are initially grouped based on their biological characteristics. However, when identifying the microbes present in a system it is suggested that investigation of the surrounding environment (e.g. presence of oxygen) is more suiting. Also, the different microbial groups function (e.g. what they produce or oxidize) within a biofilm is significant when determining their contribution to corrosion.

In figure 3, both the surrounding environment and function is the basis for categorization of microbes. The categorization is based on several papers review in preparation for this thesis (Beech and Gaylarde, 1999, Melchers, 2007, ISO, 2010, NACE, 2012, Energy Institute, 2014) This grouping is suggested to more easily identify which microbial group(s) that cause MIC. Note that some of the microbial groups placed in the facultative branch are known to have constituents that are either strictly aerobes or anaerobes.

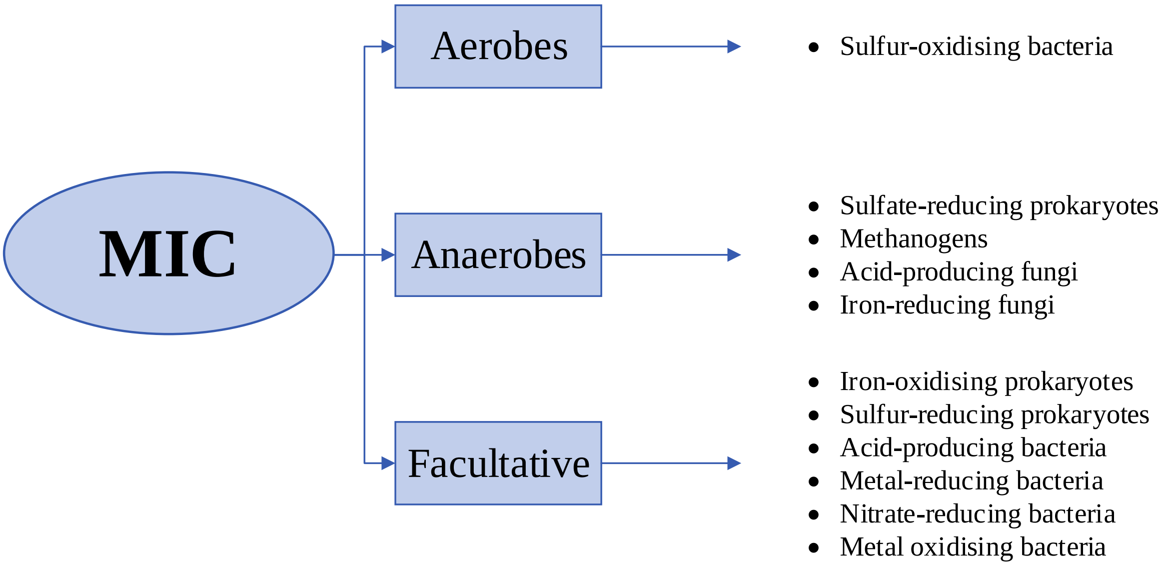


Figure 3: Different microbial groups contributing to MIC (Energy Institute, 2014, ISO, 2010, NACE, 2012, Beech and Gaylarde, 1999, Melchers, 2007)

On review of the categorisation shown in Figure 3 no direct link between MIC and the facultative and aerobe branches was found. However, an indirect link is discussed where a suitable environment is created for growth of anaerobes (by removing oxygen). This implies that the actual microbial contribution to corrosion is performed under anaerobic conditions.

Sulfate-reducing prokaryotes (SRP), methanogens and two groups of fungi are within the anaerobes grouping given in Figure 3. According to Schlegel and Jannasch (2006, p. 141) eukaryotes (thus including fungi) contribution to anaerobic degradation “appears to be negligibly small”. Therefore SRPs and methanogens are believed to be the microbial groups that can be directly linked to MIC. These groups have also received most attention in the literature in recent years and are the only groups who are directly linked to increasing corrosion rates in oil and gas facilities (Larsen et al., 2008, Mitchell et al., 2012, Jensen et al., 2013).

2.1.2 Sulfate-reducing prokaryotes and methanogens

SRP are microbes (bacteria and archaea) which reduce sulfate (SO_4^{2-}) as a part of their metabolic processes and methanogens are microbes (archaea) which produce methane (CH_4) as a part of their metabolic process.

The impact of sulfate-reduction has been connected to MIC for decades and previously sulfate-reducing bacteria (SRB) were the only microbial group that methods focused on (Pots et al., 2002, Maxwell, 2006, Maxwell and Campbell, 2006). In recent years, sulfate-reducing archaea (SRA) have also been considered directly impacting corrosion (NACE, 2012, Sørensen et al., 2012, Rodrigues and Akid, 2014). SRB and SRA are often referred to as sulfate-reducing prokaryotes (SRP).

Even though the role of methanogens is deemed as unclear by Energy Institute (2014), most recent findings support the idea that methanogens can also directly influence the rate of corrosion (Skovhus and Whitby, 2011). This has actually been known for several decades, but it has been largely ignored as available detection methods were limited.

Daniels et al. (1987) and Boopathy and Daniels (1991) were, to the authors knowledge, the first to suggest a correlation between presence of methanogens and degradation rate of iron. A more recent paper documenting iron oxidation of an oil storage tank found “data indicating that MIC is generated […] by methanogens” (Uchiyama et al., 2010, pp. 1786-1787). These findings were supported by use of molecular microbiological methods (MMM) to identify microbes, allowing and assessment of the *in situ* microbial activity and their effect on the corrosion rate (Larsen et al., 2008, Mitchell et al., 2012).

Developments in MMM have allowed establishment of a clear relation between the activity and growth of SRP and methanogens, and corrosion. Several new methods and assessment protocols already include methanogens in addition to SRP (Skovhus et al., 2012, Sørensen et al., 2012, Rodrigues and Akid, 2014).

Based on the above discussion, methanogens and SRP are the microbial groups focused upon in this thesis. However, further developments within MMM may show a direct link between activity of other above stated microbial groups and corrosion in the future.

2.1.3 How microbes influence corrosion

Several attempts are made to capture the essence of microbial influence on corrosion (Energy Institute, 2014). Commonly, removal of a protective hydrogen (H_2) layer from a metal surface is suggested as a driving step in MIC caused by both SRP and methanogens (Sørensen et al., 2012, Augustinovic et al., 2012). SRPs are also believed to contribute to generation of H_2S (souring), subsequently resulting in generation of iron-sulfide (FeS), which can behave as a cathode to the metal surface and further enhance the rate of degradation (Markoff and Larsen, 2010). This is due to galvanic interaction of localized cells on the metal surface.

Figure 4 shows how the above described elements relate to each other (left) and significant production of FeS leading to plugging of a hydrocyclone in a topsides production system (right).

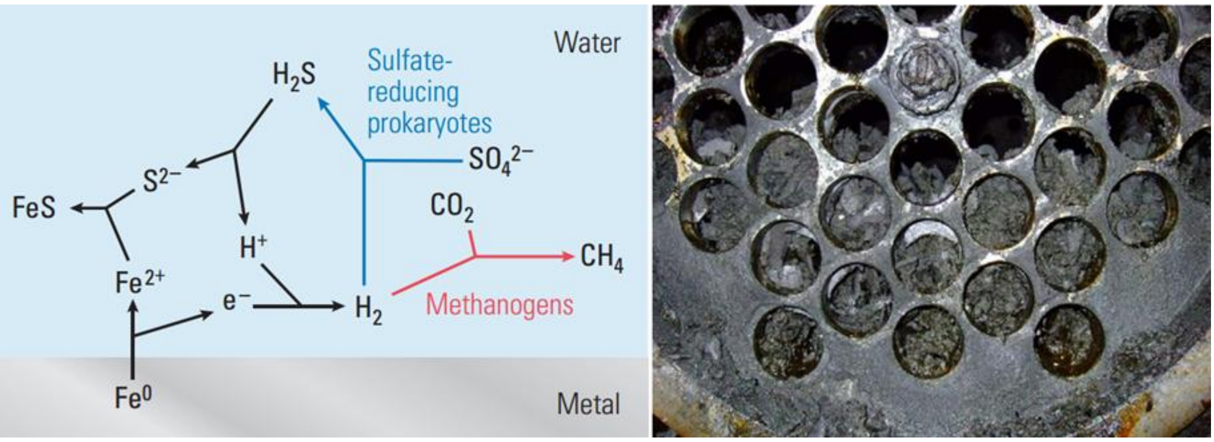


Figure 4: Influence of SRP and methanogens on corrosion (left) (Augustinovic et al., 2012), FeS in a hydrocyclone (right) (Mitchell et al., 2012)

2.2 Molecular microbiological methods

Molecular microbiological methods (MMM) is a collective term employed for techniques that enable identification of all *in situ* microbes in a sample (Skovhus and Whitby, 2011, NACE, 2012). MMM is considered superior to methods that require culturing (e.g. most probable number (MPN)) to accurately define the abundance, identity and activity of microbes within a system. Figure 5 compares three different MMMs to MPN. This demonstrates that application of MMM instead of MPN provides a more precise picture of the microbes in a system. Therefore, ideally MIC management programs should employ test performed by MMM rather than MPN that enumerates a minor proportion of the microbes.

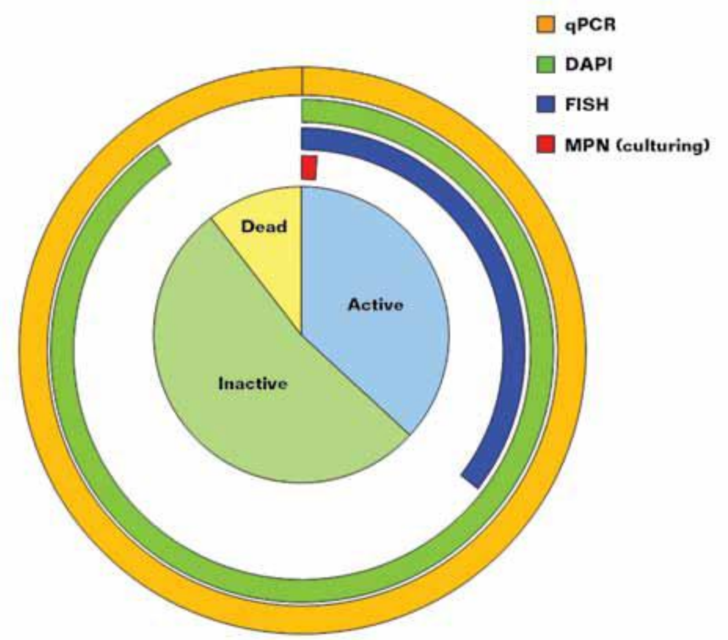


Figure 5: Molecular microbiological methods (MMM) versus Most Probable Number (MPN), from Skovhus and Whitby (2011)

2.3 Risk based inspection

Risk based inspection (RBI) analysis is a decision making technique that enables asset managers to identify their most critical systems and components, with regards to safety, environment and business (DNV, 2010). The approach is widely used in the offshore industry as a means to justify the maintenance and inspection strategy adopted.

In this thesis, risk is considered in accordance with DNV GL practise as a two dimensional combination of PoF and CoF (see Equation 1). Thus, the RBI analysis is based upon this risk picture as well.

$$Risk = Probability\ of\ failure\ (PoF)\ x\ Consequence\ of\ failure\ (CoF) \qquad (1)$$

Several factors are considered when identifying PoF and CoF. In figure 6, the main factors included in an RBI analysis are shown in a bowtie format. MIC is a potential degradation mechanism and is therefore to be included on the left-hand side of the figure together with other factors that are considered in establishing the PoF.

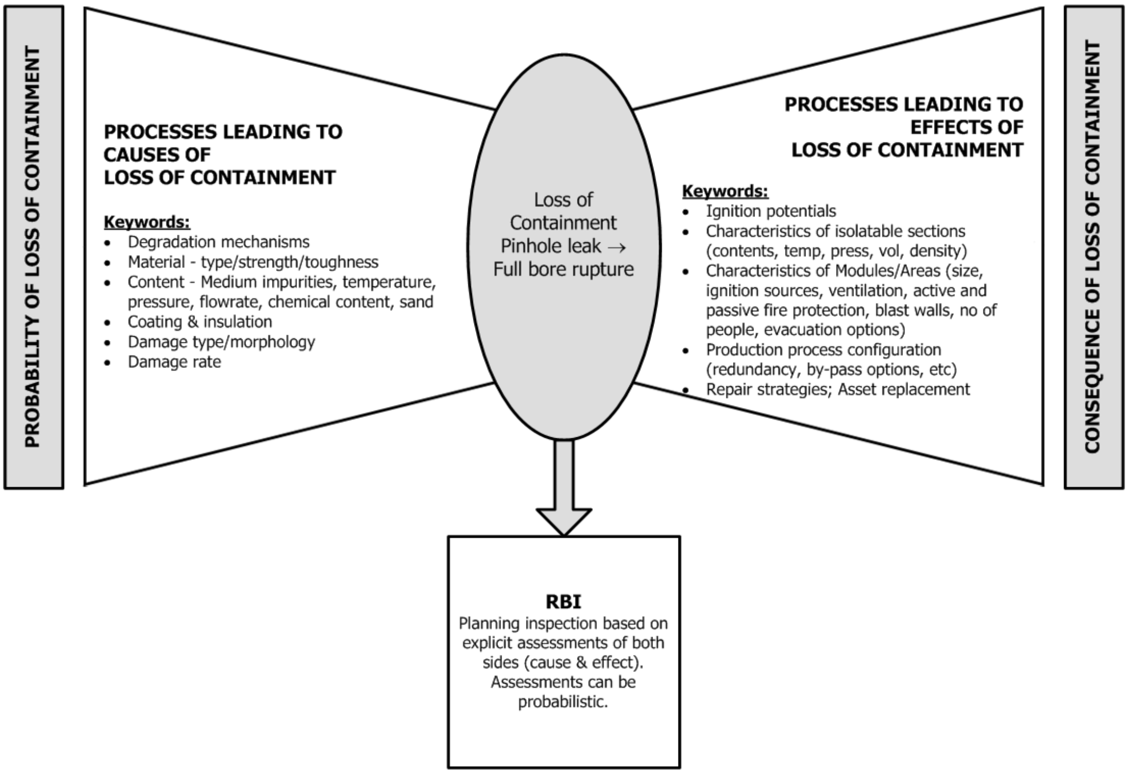


Figure 6: Constituents of an RBI analysis DNV (2010)

In DNV GLs “Recommended practice”, five deliverables are identified as the outcome of an RBI program; *what*, *when*, *where* and *how* to inspect as well as *what* to report (DNV, 2010). Figure 7 illustrates how the five deliverables are derived from the RBI program. All factors are identified based on an assessment of the risk associated with operating a system. The procedure described in this thesis has the purpose of giving assessors insight into these deliverables, with regards to MIC.

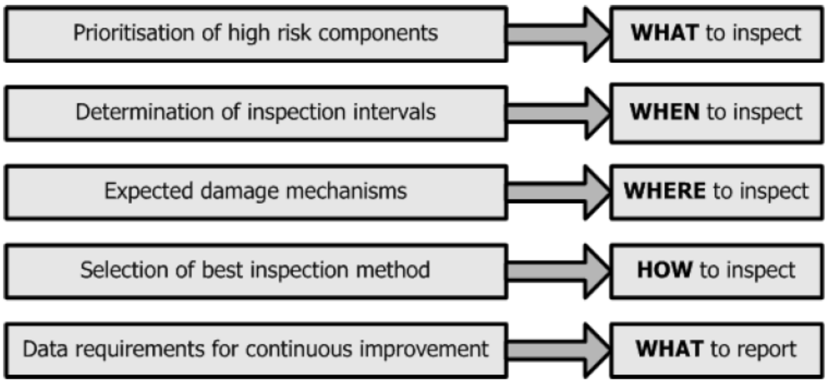
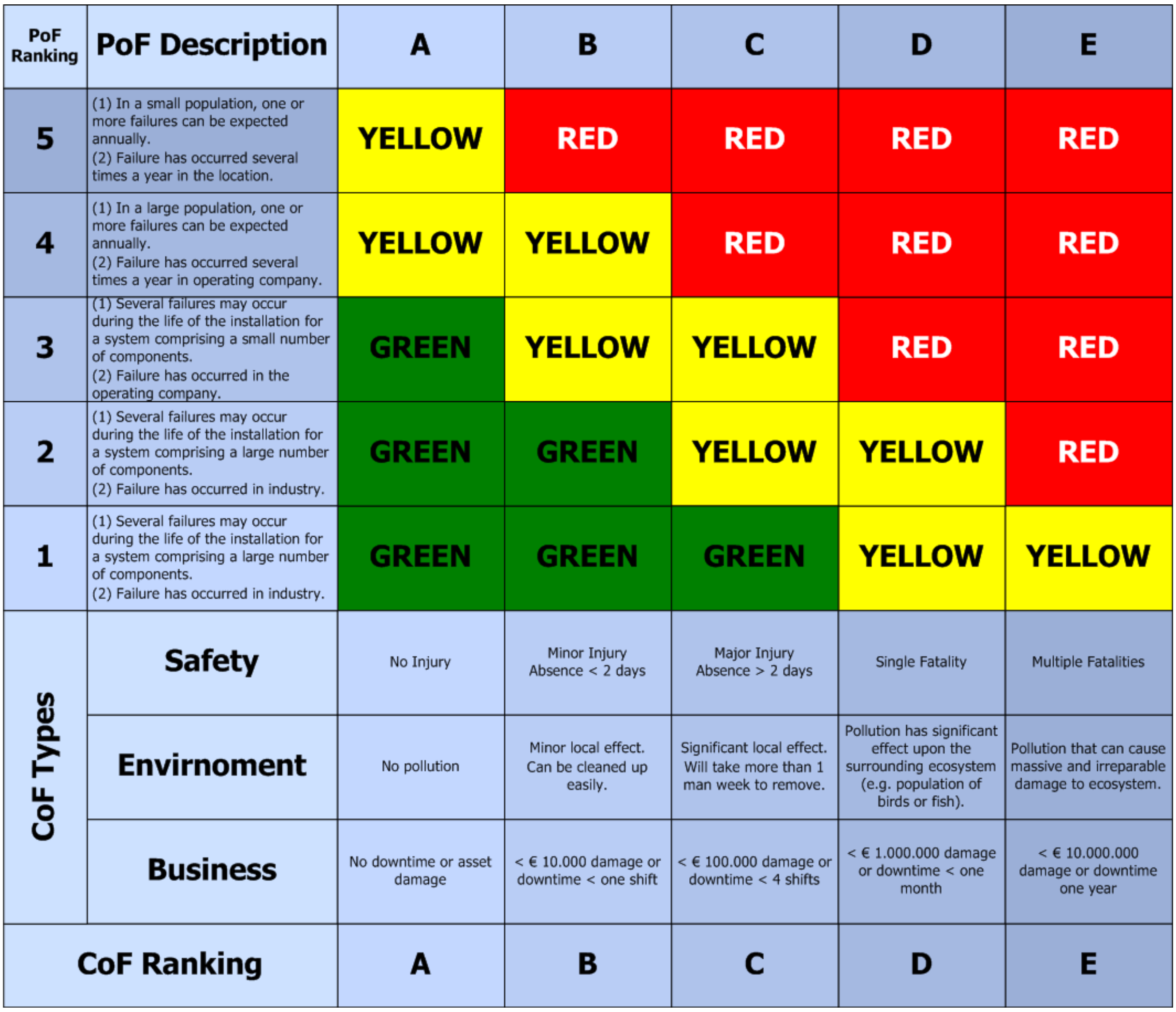


Figure 7: Deliverables of an RBI analysis DNV (2010)

Risk can be described quantitatively, semi-quantitatively or qualitatively. However, PoF and CoF is normally ranked in three, four or five categories and subsequently combined in a risk matrix.

See figure 8 for an example of a 5x5 risk matrix.



PoF Ranking	PoF Description	A	B	C	D	E
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	YELLOW	RED	RED	RED	RED
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	YELLOW	YELLOW	RED	RED	RED
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	GREEN	YELLOW	YELLOW	RED	RED
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	YELLOW	YELLOW	RED
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	GREEN	GREEN	GREEN	YELLOW	YELLOW
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirnoment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

Figure 8: Risk matrix DNV (2010)

The RBI concept is commonly applied in order to transparently define what systems, at what time, where and with what techniques information should be gathered to make decisions based on the actual condition of a topside production system.

A procedure for the establishment of the PoF of MIC is presented in chapter 5, while an RBI program that includes MIC is discussed in chapter 6.

CHAPTER 3: Mapping and evaluation of existing MIC assessment models

There are few known RBI analysis that comprehensively include the threat of MIC due to; unpredictability of microbial activity, disagreement among scientists, and limited knowledge about which factors govern MIC. In this chapter some methods that previously have been developed to allow an estimation of degradation caused by microbial activity are reviewed and discussed.

The methods presented use qualitative, semi-quantitative and quantitative measures to help assess the rate of degradation caused by MIC. Commonly, the rate of degradation is named "MIC risk", implying that the rate of degradation is proportional to the risk associated with system failure. This is technically incorrect as risk is the product of the probability and consequence of failure, the rate of degradation is merely a factor in the estimation of the probability of failure (PoF). Consequence of Failure (CoF) is usually determined in conjunction with the asset operator and is specific to a corrosion circuit and it is not considered in any of the models reviewed.

The risk approach adopted in this thesis relates to the actual technical risk i.e. the PoF * CoF. See Equation 1.

The MIC models described are:

- Pots et al. (2002) improvements on De Waard-Milliams corrosion model
- Maxwell and Campbell (2006) model for monitoring the mitigation of MIC risk in pipelines
- Maxwell (2006) model for predicting MIC in seawater injection pipelines
- Allison et al. (2008) strategies for predicting the risk of MIC
- Sørensen et al. (2012) model for MIC management
- Taxèn et al. (2012) model for under deposit corrosion

3.1 Pots et al. (2002) improvements on De Waard-Milliams corrosion model

The prediction model from Pots et al. (2002) was, to the authors knowledge, the first effort to quantify the rate (mm/year) of corrosion caused by microbial activity. The model and the ranges used are based on where and when SRB grow. The objective of this model is to calculate a corrosion rate based on a wide range of physical and chemical parameters. The parameters are given a suggested factor, ranging from 0 to 5, that reflects their impact on the rate of MIC. Further, they are combined in order to semi-quantitatively calculate a yearly corrosion rate.

The corrosion rate is derived from equation 2, presented below:

$$Corrosion\ rate = Constant\ x\ (\prod_{i=1}^{n} f_i)^p \qquad (2)$$

The constant is set to 2 mm/year, f_i is the value (from 0 to 5) suggested to represent the impact of parameter *i*, and *p* is a power law index (0.57). The following parameters are included in the model:

- pH
- Temperature
- Total dissolved solids
- Nutrient content in liquid
- Flow velocity
- Debris
- Pigging frequency
- Prolonged oxygen ingress
- Usage of biocide
- Age of pipeline
- Length of downtime

The models greatest strength is that, although there are a lot of calculation parameters, they should be easily identifiable by the assessors with input from asset based operational personnel. The model gives a degradation rate that can be connected to the PoF, thus incorporated in a RBI analysis.

However, many of the ranges within the model are not justified, as they have been established based on operational experience, which has resulted in some of the limits being rejected by other authors (Maxwell and Campbell, 2006). Additionally the ranges are only based on SRB characteristics, which, as described in later chapters, differ from those of SRA and methanogens.

3.2 Maxwell and Campbell (2006) model for monitoring the mitigation of MIC risk and Maxwell (2006) model for predicting MIC in seawater injection pipelines

These two models are described together as the approaches to predicting MIC are identical and as with the Pots et al. (2002) model, only SRB are considered. However, the models include different parameters in the suggested calculation of the corrosion rate (CR) due to MIC which will be described in more detail in the following section.

The methods add a prerequisite to the Pots et al. (2002) model; namely a biofilm on the metal surface which contains a significant amount of sulfide must be present before MIC can occur. Sulfide is regarded as significant when concentration is > 10 µg sulfide per cm^2. The time until such a biofilm is established can be calculated by the following equation:

$$Time = \frac{10}{(S\ x\ M_S\ x\ N_S)} \tag{3}$$

S is moles sulfide produced per cell per day, suggested by the modellers to be set as a constant (1×10^{-14}). M_s is the molecular weight sulfide (µg), and N_s is the number of cells per cm^2.

Identification of cell numbers per cm^2 is not described in the paper, but it is understood from other papers that molecular microbiological methods (MMM) are required to establish the *in situ* sessile microbial population, i.e. N_s (Sørensen et al., 2012). The CR does not rely on parameters that are specific to any one microbial group, but rather the generation of sulfide through their metabolic processes. Thus, the step considers the activity of sulfate-reducing microbes, but not methane producing microbes (methanogens).

When a significant sulfide concentration is in place, MIC will be initiated. The rate of MIC can be calculated by the same equation as presented in the Pots et al. (2002) model. In this calculation the models include different parameters;

Maxwell and Campbell (2006) model includes the following parameters:

- Deposits
- Pigging frequency
- Oxygen ingress
- Fluid velocity

Maxwell (2006) model includes the following parameters:

- Deposits
- Pigging frequency
- Oxygen ingress
- Sulfide
- System age

Why the methods use different parameters is not known. However, Maxwell (2006) discuss that system age is not a good parameter to include, but suggest an inclusion of another parameter that the Maxwell and Campbell (2006) model uses; velocity. Therefore, Maxwell and Campbell (2006) model is believed to be the most developed of the two.

Maxwell and Campbell (2006) use of the term risk in the context of this thesis is considered to be incorrect as mentioned previously.

3.3 Allison et al. (2008) strategies for predicting the risk of MIC

The three step model developed by Allison et al. (2008) uses nutrient availability, number of SRBs present and number of general heterotrophic bacteria present to qualitatively establish the potential for MIC in a system. SRA and methanogens are not considered in the model. “MIC management” is understood to be the primary objective, rather than the estimation of the rate of MIC.

Predicting the “risk” of MIC is suggested through a three step process;

1. Calculate the potential for H_2S generation by SRB activity
2. Identify potential rate of H_2S generation by SRB, based on amount of SRB present
3. Identify amount of other bacteria present

Step one is calculated based water chemistry, steps two and three are identified through microbiological analysis to measure the cells per ml, i.e. a planktonic, rather than sessile count. This is in contrast to most models, which use sessile cells as a numerical measure. The general opinion is that there is no direct link between the number of planktonic cells and the rate of MIC.

3.4 Sørensen et al. (2012) model for MIC management

The idea behind Sørensen et al. (2012) model is similar to what Maxwell and Campbell (2006), and Maxwell (2006) developed; dividing the calculation into two steps. The first step estimates the processes that occur prior to initiation of MIC and the second calculates the corrosion rate when MIC has occurred. Even so, the model is based on use of MMM to study the *in situ* microbial consortia and does not include physical or chemical parameters.

Solely focusing on biotic components largely differentiates the model from those discussed above, where abiotic components have been considered the major contributing factors on the CR. The information gathered in the study is used to calculate stage 1; Integrated MIC Risk Factor (IMRF) and stage 2; Potential Pit Generation Rate (PPGR). IMRF represents mechanisms occurring prior to MIC initiation, while PPGR calculates degradation rate after the time limit in IMRF is reached. The method includes SRP and methanogens.

In what is called a MIC risk assessment tool the authors suggest that the rate of iron dissolution caused by microbial activity can be calculated as follows:

$$Rate\ of\ iron\ dissolution = 4xN_{SRB}xS_{SRB} + 4xN_{SRA}xS_{SRA} + 4xN_{MET}xS_{MET} \qquad (4)$$

N is the number of cells per cm^2, S is the cell specific activity of the microbial group, MET is methanogens. It is understood that the modeller reasons that degradation rate is proportional to the risk. This shows again that the view of risk is different from the approach adopted in this thesis. Threat would be a more technically appropriate term to use.

3.5 Taxèn et al. (2012) model for under deposit corrosion

This model is not directly focused upon MIC, but rather corrosion occurring under deposits. Taxèn et al. (2012) state that under deposit corrosion results from either oxygen corrosion or MIC. The model is a data simulation, based on mathematical analysis, of the chemical reactions that are expected to take place at the metal surface under a deposit, and the result of the reactions. Only MIC considerations in the model will be discussed.

Microbe influence the environment under deposits as follows: Oxygen is consumed proportional to the following equation:

$$Oxygen\ consumption = \frac{cO_2}{1000\ x\ aSRB} \qquad (5)$$

The factors included in the equation are not explained, but it is assumed that cO_2 is amount of oxygen and aSRB is the amount of SRB.

As oxygen is consumed its concentration decreases at the pipeline surface. This limits the magnetite formation through reduction in the number of chemical reactions taking place on the pipeline surface. This reduces the protective layer on the pipeline surface, which correspondingly increases the corrosion susceptibility of the pipeline.

Taxèn et al. (2012) does not provide any justification as to why equation 5 is assumed to have any connection to the activity of microbes.

Microbe consumption of oxygen is suggested to be proportional to the MIC rate. This view of MIC and driving parameters for MIC is very narrow, as it suggests that the rate of MIC is only influenced by oxygen ingress. However, it does try to examine the role of oxygen in relation to corrosion product formation. So the equation, if properly evaluated and confirmed, could be a step in the direction of a quantitative model for the MIC threat.

3.6 Discussion of existing models

Historically, MIC has not been a focus research area for the oil and gas industry. With recent significant developments in the area of MIC modelling this is starting to change. Therefore, authors and companies want to protect business advantages by limiting the published information about their models. The papers reviewed for this thesis are publically available conference papers and this may therefore affect the interpretation of the models.

Pots et al. (2002), Maxwell and Campbell (2006), and Maxwell (2006) all state that the corrosion rate is a best estimate and is to be used with caution as it is a “guide to the potential severity of the MIC”. This is important because it indicates that the models relying solely on one parameter, such as Sørensen et al. (2012) and Taxèn et al. (2012), could be unbalanced and lead to an erroneous estimation of the MIC threat, compared to models with a wider spread of input factors.

If further work shows that models relying solely on one parameter do in fact provide a good representation of the actual MIC rate then there is no reason not to use the model. However, at present, these models require evaluation and confirmation. Therefore, they are considered at this time to be unsatisfactory to establish PoF from MIC.

Another aspect in regards to the models applied by Sørensen et al. (2012) and Taxèn et al. (2012) is that they use MMM and data modelling, respectively. The use of more advanced techniques is progressing and could be the future of assessing MIC, but the underlying business motives for use may affect their credibility. It is not suggested that it is the case with the reviewed models, but precaution is advised in the model selection process.

Collectively, the papers give insight into the impact of physical, chemical and biological parameters associated with MIC. However, there are several aspects that are considered limiting in regards to the development of a procedure for the assessment of MIC in RBI analysis. The models have an incorrect view of risk; risk and degradation rate caused by MIC are treated as equal. Secondly, none of the models consider topside production systems, but rather production pipelines or water injection facilities/pipelines. In addition, the models lack a proper integration with operation and maintenance management tools (like RBI analysis). This thesis attempts to cover the three gaps identified in the current models by addressing a procedure for assessment of the threat of MIC in topside facilities resulting in a PoF which can be used in RBI analysis.

The suggested procedure presented in chapter 5 gives the assessor(s) a tool which can be used for establishing the PoF of a topside production system. Before the procedure is presented, different parameters to be included in the procedure are discussed in chapter 4.

CHAPTER 4: Identification of important parameters that affect MIC

Many parameters are believed to impact the onset and rate of MIC. In this chapter the parameters that have a documented effect on MIC are presented.

Information about the parameters was determined from literature describing hydrocarbon systems, but where information was limited or missing it was supplemented by general data found within the literature on microbial activity.

Microbes appear in one of three states; active, inactive and dead. Microbes can change between the active and inactive states, but when dead they do not change state and cannot cause corrosion. Inactive microbes do not cause corrosion, but may change to an active state if the environment changes where upon they may.

Planktonic microbes are commonly inactive or dead, while sessile microbes are usually active. The following parameters are based on where and when microbes can become active and possibly cause corrosion.

4.1 Parameters

The thesis focusses on three different groups of microbes; SRB, SRA and methanogens which have dissimilar ranges for optimal growth. The ranges presented in the subsequent paragraphs are based on a collective view of all groups and their survivable zones.

The parameters are grouped in three main groups; physical, chemical and biological.

4.1.1 Physical

4.1.1a Temperature

Now that more microbe groups are known to cause MIC, the temperature range in which they grow is more complex to establish. DNV (2010) operates with an optimal range for MIC of 25 °C – 45 °C and a possible range for MIC of 0 °C – 80 °C. This differs with the ranges presented in this thesis. Figure 9 shows DNV (2010) suggested relationship between temperature and PoF.

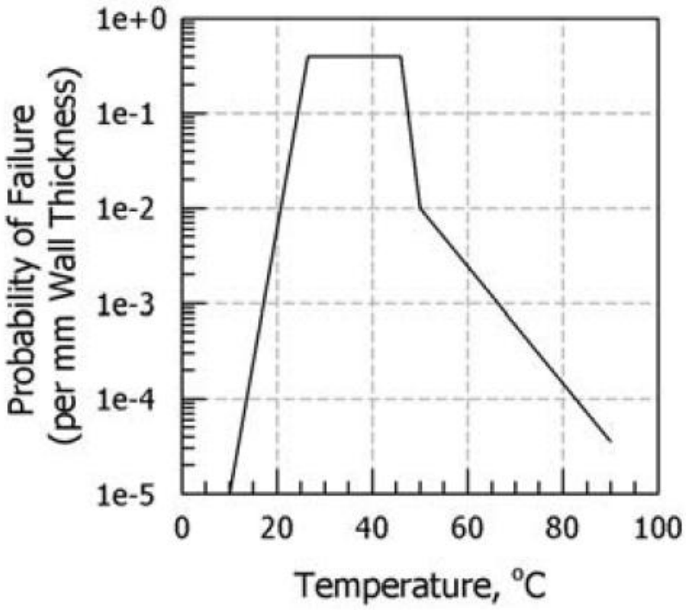


Figure 9: Relationship between temperature and PoF due to MIC DNV (2010)

Current literature focusses on Sulfate-reducing bacteria (SRB), therefore, the opinions about their optimal growth temperature is well documented. The uppermost temperatures of 65 °C, 85 °C and 110 °C have been stated in papers reviewed in preparation of this thesis, and the lower temperature is subject to less controversy being just above 0 °C (Pots et al., 2002, Sørensen et al., 2012, Kakooei et al., 2012). Pots et al. (2002) suggests an optimal growth range of 10 – 45 °C for SRB which is in line with DNV (2010) range of 25 °C – 45 °C.

Sulfate-reducing archaea (SRA) has a growth range of 60 – 95 °C, with optimal growth of 83 °C (NACE, 2012). These limits have been confirmed in measurements performed in topside production systems (Skovhus et al., 2011). Thus, the overall range of SRB and SRA, collective known as SRP, is 0 – 95 °C, which corresponds well with the range set by Energy Institute (2014), of 4 – 90 °C.

Growth of methanogens in hydrocarbon systems is not very well documented and therefore the range has been determined on general literature review. Methane production has been confirmed at temperatures of 4 °C to > 100 °C, with an optimal temperature around 35 °C (Formolo, 2010). A growth range of $4\ °C \leq T \leq 110\ °C$ is suggested. However, more information regarding methane production in hydrocarbon systems should be investigated to confirm the upper limit of 110 °C, although methane production above this limit is considered unlikely. A suggested optimal temperature range for SRP and methanogen activity is proposed as $10\ °C \leq T \leq 90\ °C$. This temperature range is included in the MIC assessment procedure, see figure 14 in chapter 5.

4.1.1b Settlement potential

As described in chapter 3, there are efforts made to quantify the impact of settlements (under deposit corrosion) on corrosion rate. The model presented by Taxèn et al. (2012) is not directly aimed at assessing MIC, though trying to factor in the impact of SRB activity on under deposit corrosion. Quantitative efforts based on the limited knowledge present are believed to introduce imperfect data in form of being precise yet uncertain, as depicted by Singh et al. (2013). Therefore, this thesis presents a qualitative approach to assess the settlement potential in the system based on system dead legs, geometry and flow velocity.

Operational history is an important factor in assessing the settlement potential as a system can show periods of stagnated flow, due to downtime, when biofilm has time to establish. When a biofilm has been established, flow-velocity within a system has less impact on MIC than prior to biofilm establishment.

Figure 10 illustrates a wide range of unfavourable geometry and possible dead legs which are considered areas often subject to MIC, particularly in cases of stagnant flow. As dead legs commonly have low flow or are closed off to standard operation, nutrient scarcity can limit microbe growth. However, the means of biofilm mitigation will not reach systems components outside the regular flow. Unfavourable geometry should always be considered in relation to the flow-velocity to establish the dead leg status. A suggested ranking of settlement potential is presented in chapter 5.

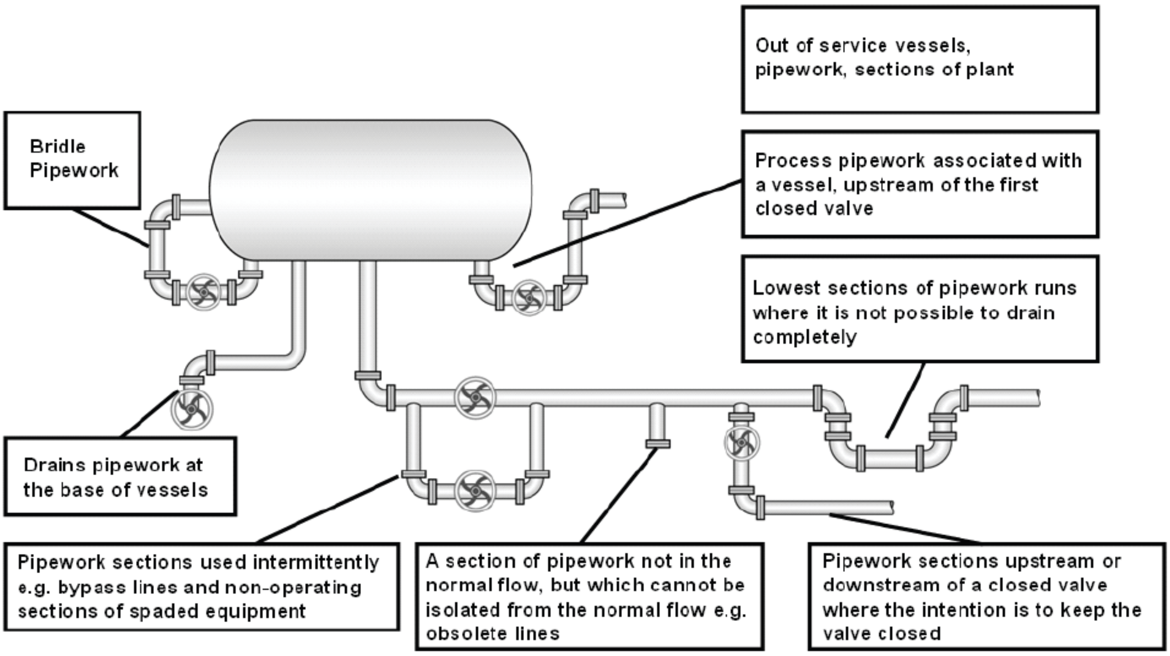


Figure 10: Examples of dead-legs and unfavourable geometry (Energy Institute, 2008)

4.1.1c Material

MIC normally occurs in carbon steel (CS) (ISO, 2010). That does not necessarily mean that CS is more susceptible to MIC than other metal alloys, it may simply be a result of CS being the preferred metal alloy for construction. Most metals are reported to suffer degradation as a result of microbial activity, and it appears that all metals and metal alloys can be subject to MIC (Javaherdashti, 2011). Studies by Torres-Sanchez et al. (1996) and Vargas-Avila et al. (2009) have shown pitting as a result of MIC on stainless steel and duplex stainless steel. Little et al. (1998) have found aluminium alloys to be particularly susceptible to MIC.

A more recent paper by Energy Institute (2014) describes MIC on a wide range of metal alloys. Based on their findings, no clear indication of one metal alloy being more susceptible to MIC than the other is found. More research regarding MIC susceptibility for metals and metal alloys should be presented before this parameter can be included in the procedure. At the present stage the author finds the knowledge related to material type too limited to be used for ranking MIC, thus the parameter is not included in the procedure.

4.1.2 Chemical

4.1.2a pH

When establishing optimal ranges for MIC, with regards to the pH, some of the same problems experienced in identifying the temperature ranges were met. New microbial groups are considered and available information is limited.

NACE (2012) uses a pH range of 6-12 for SRB growth, while Pots et al. (2002) and Energy Institute (2014) states that a pH between 5 and 9.5 is the growth range for SRB, with optimal growth between 5.5 and 6.5 for SRP.

As stated earlier, knowledge regarding methanogens is limited in comparison to SRP. Therefore, the pH range is based on articles investigating impact of pH on methane production in other environments than hydrocarbon systems. Fukuzaki et al. (1990) states that optimal pH is between 6 and 8 when methane is produced from acetate (a common fatty acid), while methane production is inhibited in the range 0 to 6. Boopathy and Daniels (1991) tested carbon steel corrosion caused by methane producing microbes subject to water with pH ranges from 5.4 to 7.4. Their findings showed that corrosion rates was higher at a pH of 5.4 than at 7.4, which indicated an increased corrosion rate with pH lower than those stated by Fukuzaki et al. (1990). Laboratory experiments has shown a pH optimum of 5.5 for methane production in peatlands (Ye et al., 2012). The same experiments found a possible growth at pH as low as 3.5, though very limited compared to the growth at pH 4.5 – 6.5.

The author recognises an imperfection in the limits for methane production in hydrocarbon systems, as the articles discuss impact of pH on methanogen production in environments that differ from those found in hydrocarbon production systems. Nonetheless, it is believed that including imperfect ranges (in form of imprecision, as depicted by Singh et al. (2013)), which is subject to alternation is better than leaving the parameter blank for others to establish.

Based on the above discussion, an optimal pH range has been established, covering both SRP and methanogens, of 4.5 – 6.5, with possible growth between 3.5 and 12. Without establishing a range, Energy Institute (2014, p. 15) states that MIC "often occurs […] at near-neutral pH". The suggested range is around neutral, i.e. in line with their statement.

The suggested pH range of possible growth (3.5 – 12) is included in the procedure presented in chapter 5. Due to the considerable level of imperfection in the pH range, the optimal growth range is, unlike temperature, not considered to be adequate to reject MIC as a possibility.

4.1.2b Oxygen ingress

Under normal circumstances oxygen is not present in production stream, but it can be introduced from injection of chemicals or through imperfectly sealed components (e.g. valves, pumps, compressors) (ISO, 2010). As both SRP and methanogens are anaerobes they are unable to become active in the presence of oxygen. Within the literature there is evidence that oxygen ingress can greatly increase the rate of MIC, at least when corrosion is influenced by sulfate-reduction (Pots et al., 2002, Maxwell and Campbell, 2006, NACE, 2012, Enning and Garrelfs, 2014). Estimates made by Maxwell and Campbell (2006) indicate an increase of 2.5 – 3.5 times higher pitting rates when a biofilm containing sulfide is subject to oxygen ingress. (Sulfide (S^{2-}) is produced through hydrogen consumption by SRP, as shown in figure 4 in chapter 1).

Again, methanogens are not given the same emphasis in the papers reviewed. However, Beech and Gaylarde (1999) states that the activity of methanogens can increase as a result of oxygen ingress. Therefore, oxygen ingress is believed to have a negative impact on MIC regardless if the microbial consortium is mainly SRP or methanogens.

Several groups of microbes can be present in one biofilm (Borenstein, 1994, NACE, 2012). Their interaction and combined effect on corrosion rate is not thoroughly investigated in any of the papers reviewed, but as Beech and Gaylarde (1999) states the presence of several microbes in a biofilm can increase the MIC rates. This can explain the increased MIC rate in cases with oxygen ingress as the activity of aerobe microbes creates an environment that facilitates anaerobic activity. I.e. the aerobe microbes in the upper layers of the biofilm consume oxygen, simultaneously producing nutrients that SRP and methanogens can utilize in the lower, anaerobe layers of the biofilm. Thus, the activity at the metal surface is increased by ingress of oxygen.

4.1.2c MIC mitigation techniques

Mitigating the threat of MIC is often a concern from the moment the production system is taken into operation as a cautionary measure. The means of MIC mitigation can be either direct or indirect. Following are some direct and indirect MIC mitigation techniques:

- Direct
    - Cleaning
    - Chemical injection (e.g. biocides)
    - Water jetting
- Indirect
    - Design features
    - Sulfate removal units

Cleaning and water jetting are corrective techniques, while chemical injection is preventive. Cleaning and water jetting is not the easiest techniques to use in production facilities as they require intervention and often makes production deviate from its intended state. Therefore, chemical injection is usually the preferred tool for biofilm prevention in production facilities. From the model developed by Pots et al. (2002) it is understood that the rate of MIC is believed to be five times higher when biocide is not applied to a system.

Design features, e.g. avoiding attachment sites for microbes, is commonly used to minimized the settlement potential within a system and limit the biofilm formation and the threat of MIC.

Sulfate Removal Units, such as Sulfate Rejection Membranes, can be used to reduce the amount of sulfate in the liquid. This will have impact on SRP ability to reduce sulfate to sulfide and thus limit/prevent souring (H2S generation) and MIC. Note that sulfate removal units are most commonly applied in water injection facilities to reduce the amount of sulfate in the seawater and not that common in hydrocarbon production systems.

The procedure presented in chapter 5 considers MIC mitigation in both the screening and the detailed assessment. In the screening MIC mitigation is considered either present or not. In the detailed assessment the MIC mitigation effectiveness is be considered. How to identify the MIC mitigation effectiveness is discussed in the next section.

4.1.2d MIC mitigation effectiveness

If possible, the actual MIC mitigation effectiveness should be established. This requires identification of either sessile or planktonic SRP and/or methanogens through sampling. Sessile samples for analysis can be acquired in several ways. For example, when cleaning the system one can collect samples from solids. Perhaps more applicable to production systems, who operates continuously for long time periods, installation of *biofilm monitoring probes* can provide sessile samples.

Figure 11 shows one type of biofilm monitoring probe that can be used in topside production facilities to sample sessile microbes.

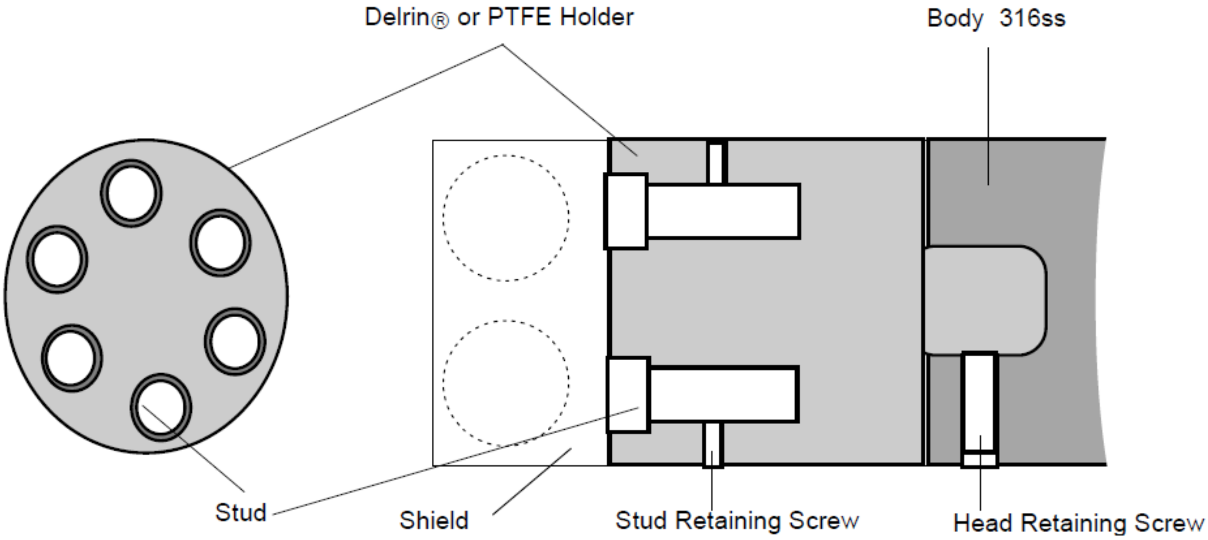


Figure 11: Biofilm monitoring probe (CORMON, 2014a)

The easiest way to assess your MIC mitigation effectiveness is simply to identify the amount of sessile SRP and/or methanogens. If you have a high number of sessile microbes in your system, your MIC mitigation techniques are not effective. If planktonic microbes are present and the amount of sessile microbes is low, your technique is probably effective.

If sessile samples are not acquired from the system, one can use planktonic sampling to calculate a % efficacy. This can only be established when the MIC mitigation technique is applied in intervals, because data must be trended over time. Maxwell and Campbell (2006) suggests the following calculation of a % efficacy:

$$\% \, efficacy = \frac{(N_g - N_k)}{N_g} \, x \, 100 \qquad (6)$$

Where N_g = Number of cells growing between treatments
N_k = Number of cells killed during treatment

Ideally, the establishment of N_g and N_k should be based on sessile samples, but planktonic samples can be used to establish a best estimate of the MIC mitigation effectiveness. This requires planktonic sampling at several places of the system, to allow identification of increasing number of microbes. As illustrated in figure 1, microbes are released when the biofilm reaches a certain size. These microbes can be trended over time to assess the biofilm growth between two sample points, and thus the growth between treatments (N_g) at that point.

Further, the number of cells killed during a treatment can be assessed by identifying the amount of planktonic microbes before and after the technique has been applied. According to Maxwell and Campbell (2006) Equation (6) it is now possible to establish an estimated % efficacy.

Maxwell and Campbell (2006) rank the efficacy in three groups; poor (90 % kill), moderate (99 % kill) or good (99.9 % kill).

If your technique has a 99.9 % efficacy, but only applied once a year, the actual MIC mitigation effectiveness is probably not good. Thus, the efficacy must be seen in relation to the time between applications. As the presence of microbes differ from system to system, the kill rate and application interval will differ as well.

There are other ways to assess the MIC mitigation effectiveness. Examples are application of bioassays and dynamic biocide testing. These techniques are well explained by Hansen et al. (2009) and Jensen et al. (2012), though they are not discussed further within this thesis.

MIC mitigation effectiveness is included on the procedure presented in chapter 5.

4.1.2e Availability of nutrients

The concept of high availability of nutrients resulting in an increased growth rate is something that is easily relatable to the macrobiological world, and also well described in the literature (Melchers, 2007). The issue is therefore to identify which nutrients support the growth of SRPs and methanogens, and the availability of supporting data to justify the availability ranges. Pots et al. (2002) considers sulfate, carbon from fatty acids and nitrogen, as well as carbon to nitrogen ratio significant to the growth of SRB. This view is shared by Allison et al. (2008) who consider the availability of sulfate and two significant fatty acids (acetate and propionate) to limit the growth of SRBs.

The author suggest that a parameter which comprises nutrients in general, rather than trying to identify the specific contribution from each nutritional group or type of carbon source is both easier to identify in operation and more robust when using in the procedure. For example, it is difficult to define limits connected to each specific carbon from a fatty acid. Therefore, using a measure such as “carbon from fatty acids” is considered better than specific limits for each fatty acid.

SRA and methanogens have been included in MIC literature more recently and the research is limited. It is assumed that SRA have metabolic processes similar to SRB, thus their growth is influenced by the availability of the same nutrients. As understood from the model developed by Sørensen et al. (2012) the rate of methane production is dependent on amount of CO_2. CO_2

is not a fatty acid, thus adding a measure of CO_2 content in the water to the other nutrients could make the evaluation more complete. However, at the present stage this is not done.

Nutritional groups considered and their limits in the procedure are based on Pots et al. (2002). The limits are shown in chapter 5, table 4.

4.1.2f Water breakthrough

The assumption that PoF is proportional to system age is considered to be false by some (Maxwell, 2006), rather it is concluded that water breakthrough, is a more relevant factor. Water breakthrough is the term commonly applied where water injected to maintain reservoir pressure via injection wells breaks through to one or more of the producing wells. As part of asset development water breakthrough is estimated based on several factors; reservoir characteristics and production strategy over time to determine production profile and processing needs. It is commonly agreed that high levels of water breakthrough increase the potential for introduction of microbes into the production systems which can coincidently increase the likelihood of MIC. Water breakthrough is not directly mentioned in any of the material reviewed for this project.

Water injection (WI) is a very common production enhancing technique used in the North Sea. The cost of operating is high, so the asset owners often use WI to keep reservoir pressure and thus production levels high in compensation. Introduction of seawater to use for WI is a very common source of microbes and nutrients. Most literature on MIC in offshore production systems is concerned with water injection systems and / or pipelines.

Water breakthrough is not used as a measure in the suggested procedure. If literature describing its significance becomes available in the future the parameter should be considered. However, availability of nutrients and sampling of microbes will give assessors insight into the effect of water breakthrough so the parameter is indirectly considered.

4.1.2g Salinity

Salinity of liquid was first brought up by Pots et al. (2002), in relation to amount of total dissolved solids, but is left out of later models. One can only speculate as to why that is, but limited impact on MIC or lack of knowledge is two possible reasons. Energy Institute (2014) states that a salinity of 6 % is optimal for growth of SRP, this represents the only known tangible measure of the impact of salinity on MIC. There is no knowledge about relation between salinity and growth of methanogens. Therefore, the present knowledge is found too limited to be considered in a MIC procedure.

4.1.3 Biological

Biological parameters has previously been difficult to establish because the techniques that were used (e.g. MPN) had limited correlation to the actual amount and activity of the *in situ* microbial groups in a system. By the introduction of MMM several new doors were opened. One possible utilization of these techniques is to establish the expected rate of metal dissolution.

This parameter is based on the method presented by Sørensen et al. (2012), described in chapter 3. The dissolution of metal caused by microbial activity is assumed to be proportional to the rate of SRP activity plus the rate of methanogens activity.

The calculation requires DNA based measures (MMM) in order to establish the number of sessile microbes present in a biofilm (N_x) and their cell specific activity (S_x). For further insight into the procedure, see Sørensen et al. (2012) and the references therein. It is believed that the calculation is good in order to establish the current rate of metal dissolution caused by microbial activity, based on the *in situ* microbes, although this measure cannot be used to set up the initial inspection program if sessile microbes are yet to be identified.

Even though this measure was initially developed to calculate the rate of iron dissolution, the measurement is assumed to be transferable and used to calculate the rate of metal dissolution in general as well. If the expected value calculated is reflecting the actual contribution of microbial activity on corrosion rate can be investigated by use of reverse transcript (RT)-qPCR (Sørensen et al., 2012), or by comparing the result with results obtained from weight loss coupons (see figure 12).

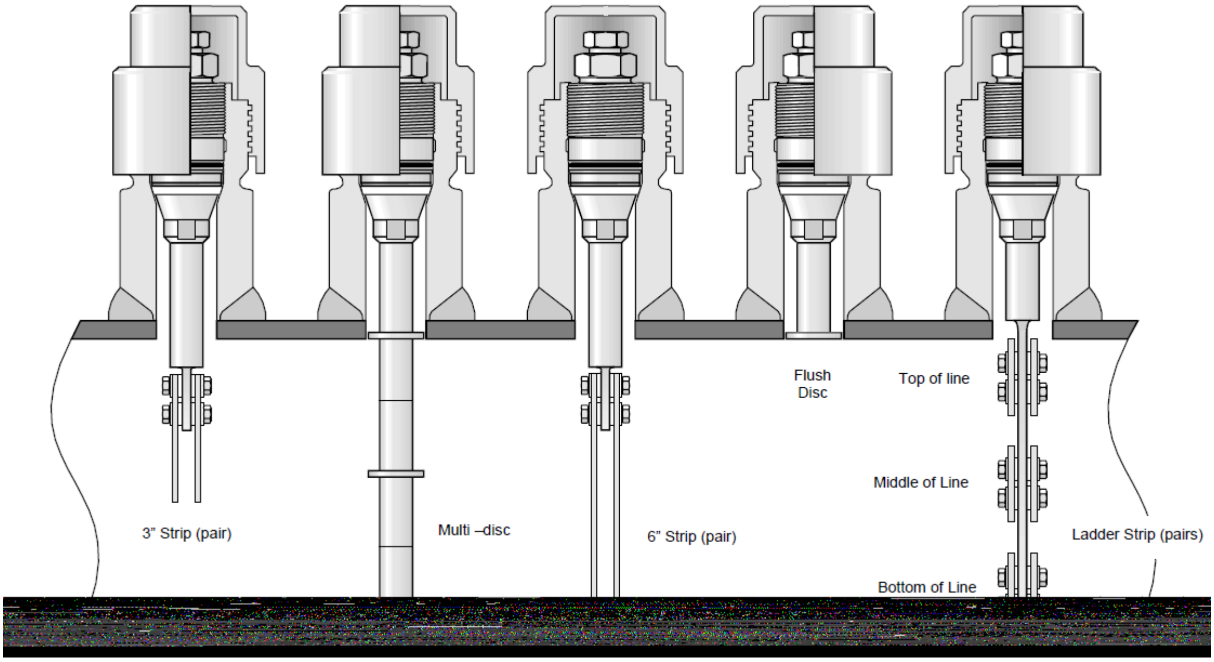


Figure 12: Weight loss coupons (CORMON, 2014b)

Research and experience indicates that microbes other than SRP and methanogens also affect MIC. Whether the other groups of microbes create an environment that facilitate growth (e.g. by utilizing oxygen) of SRP and methanogens or if their activity can be directly linked to metal dissolution lack a conclusion. Thus, the expected rate of metal dissolution should be seen in combination with other parameters. If the other microbes only facilitate the activity of SRP and methanogens, then the expected rate is correct. If not, then the calculation will underestimate the rate of metal dissolution due to microbial activity as the metal dissolution is proportional to the rate of SO_4^{2-} reduction and CO_2 reduction.

Biological parameters have not been introduced in the assessment of PoF unless microbial activity is documented.

4.1.4 Summary of parameters and relation to MIC procedure

Below, table 1 shows a summary of the identified parameters, whether they are included in the MIC assessment procedure and how the parameter can be ranked.

Parameter	*Suggested ranking*	*Included in step*
Physical		
Temperature	Within range / Outside range	Flowchart
Settlement potential	High/Medium/Low	PoF rank
Material type		Not included
Water Breakthrough		Not included
Chemical		
pH	Within range / Outside range	Flowchart
Oxygen ingress	Yes/No	PoF rank
MIC mitigation technique	Yes/No	Flowchart
MIC mitigation effectiveness	High/Low	PoF rank
Availability of nutrients	High/Low	PoF rank
Biological		
Expected rate of metal dissolution	High/Low	PoF rank

Table 1: Summary of parameters and suggested ranking

4.2 Discussion of parameters

In this chapter, parameters that impact the PoF due to MIC are considered. In the suggested procedure for the assessment of MIC, not all parameters can be weighted equally. Therefore, background information about the parameters is important to understand why some parameters are included in the procedure and some are left out. The above discussions can also give insight into the order they are included in the PoF ranking tool as well.

The information presented and discussed in this chapter has not always been gathered from hydrocarbon systems. Therefore, the suggested ranges need evaluation and confirmation when used for decision making through the suggested procedure in chapter 5.

The parameters are presented and discussed in isolation. Realistically, some of the parameters are interconnected. For example, low nutrient availability can be a result from effective MIC mitigation.

The exact mechanisms causing MIC is not satisfactorily mapped and the microbial influence can differ from one asset to another, based on the surrounding environment. The findings described in this chapter may not be a valid representation of the impact in all environments. Therefore the procedure for the assessment of MIC has been developed including several parameters.

A procedure for the assessment of MIC, based on the above parameters, is presented in chapter 5.

CHAPTER 5: Proposed procedure for qualitatively assessing the probability of failure of a topside production facility due to MIC

This chapter describes the suggested procedure for qualitatively assessing the PoF of a topside production facility due to MIC. The procedure is sub-divided into two processes; a screening flowchart and a PoF ranking tool. The screening process is intended to use existing data to establish if the probability of MIC is negligible or if a more detailed analysis is required via the ranking tool.

The screening step looks at qualitative data; historical/inspection data, microbe monitoring, temperature, pH and whether any MIC mitigation effort is used in the plant. The ranking tool incorporates semi-quantitative parameters; settlement potential, oxygen ingress, MIC mitigation effectiveness, availability of nutrients and expected rate of metal dissolution.

The relationship between the two processes is shown in table 1, while the screening flowchart and the PoF ranking are shown in figures 14 and 15, respectively.

5.1 Applying the procedure

The procedure is intended to be applied across a complete topside production system. Given the complexity of a production system, it is usual to sub-divide the production system under review into smaller zones that have the same operating parameters etc. and therefore have the same likelihood of MIC. These zones/common areas are often referred to as “corrosion circuits”. Once the corrosion circuits have been defined, the assessment can more easily be undertaken. See figure 13 for an example of a corrosion circuit. Note that corrosion circuit divisions are usually bigger than the one illustrated here.

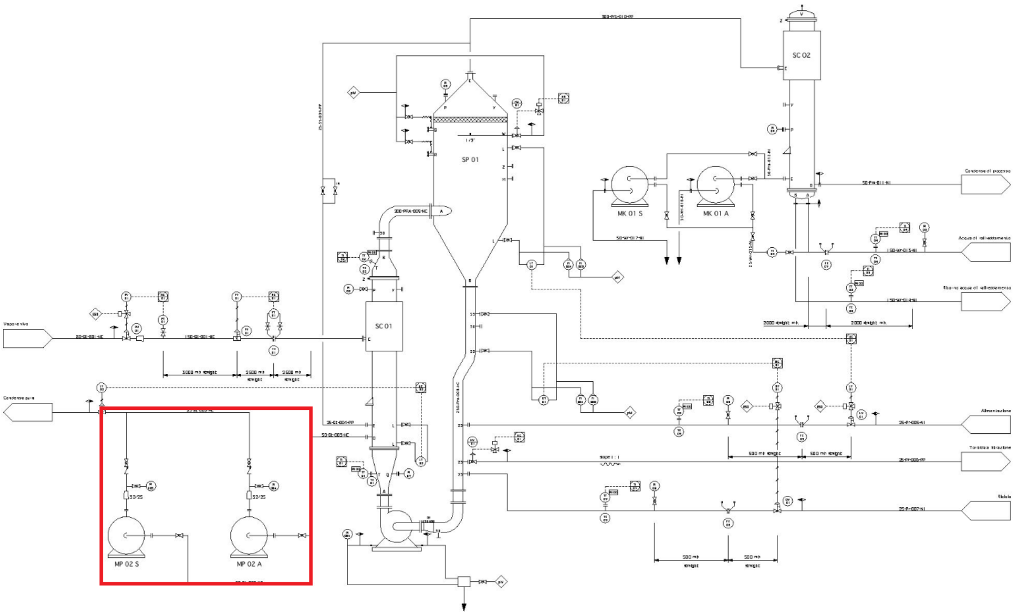


Figure 13: Example of a corrosion circuit (Creative Commons, 2001)

5.2 Screening

The flowchart shown in figure 14 can be used in two ways; if the MIC threat is a part of current assessments, or for a new assessment. Application of the procedure is exemplified in chapter 7.

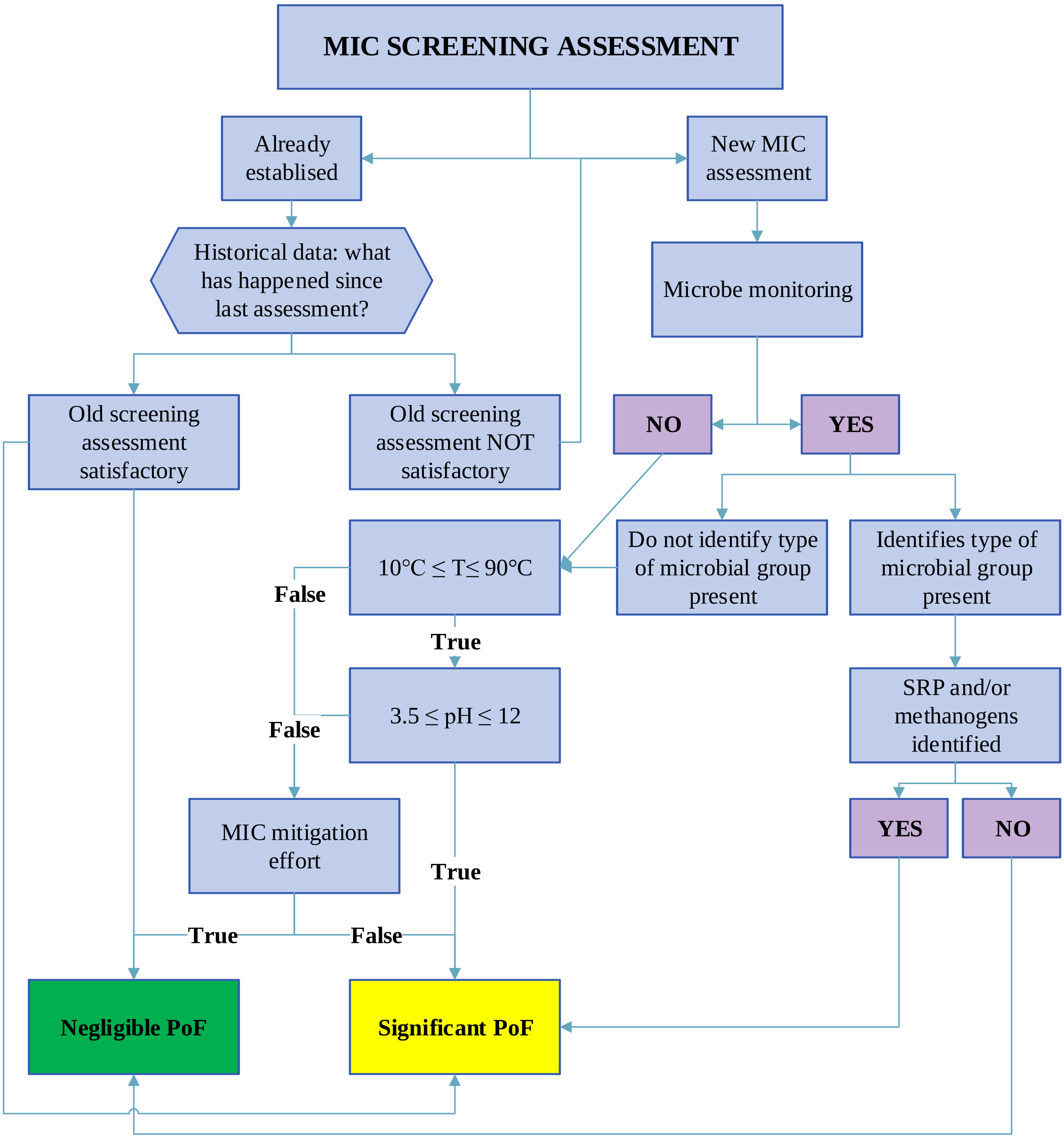


Figure 14: Flowchart for MIC screening assessment

5.2.1 MIC screening assessment already established

If MIC has already been identified as a threat to asset integrity, the flowchart shows this as “already established” (see figure 14). However, the parameters included in the flowchart can still be used to assess whether MIC is a credible threat based on review of available data such as:

- Inspection (wall loss) or operational findings (biofouling)
- Loss of containment (LOC) failures
- Changes in production (e.g. wells) or operating strategy (e.g. down time)
- Introduction of microbe monitoring

If a system characterized as having a negligible MIC PoF has shown to have deleterious inspection or operational findings, or LOC incidents attributable to MIC then the previous MIC categorization and assessment requires review. The review should lead to a detailed MIC assessment through the PoF ranking tool which should encompass establishment of suitable inspection, mitigation and monitoring requirements. Typically LOC failures will involve a management of change process which includes risk assessment as well as definition of the required maintenance activity (replacement spools).

The impact of a change in production strategy is complex to assess with respect to the impact it could have on the activity of microbes and therefore the likelihood of MIC. Changes may include the following:

- Startup of new wells
- Change in use of wells (e.g. production to water injection)
- Change in temperature/flow regime/pH of fluids
- Change in chemical treatment e.g. biocide routines

It is important to note that changes considered small in the overall production strategy can be significant in regards to microbial activity. Therefore, accurate assessment requires input from knowledgeable personnel. For example, assessors may fail to understand the impact of production downtime, which can significantly influence the settlement of microbes – increasing the areas of a plant which may be susceptible to MIC.

Changes in microbe monitoring may increase the quality of the input data available, for example quantification of the type of sessile microbes present in the system, and this needs to be included in the evaluation of the previous MIC screening assessment.

5.2.2 New MIC screening assessment

When screening a system or individual corrosion circuit for the first time, as seen in figure 14, the initial step is to consider the microbe monitoring and if it identifies the type of microbes that are present. Ideally microbe monitoring should be performed on sessile samples, as planktonic samples do not directly link to MIC (Maxwell and Campbell, 2006).

If only planktonic SRP/methanogens are identified, it indicates the possibility of biofilm formation and MIC. However, this measure is insufficient to categorize the system. If sessile monitoring is performed, the corrosion circuit can be categorized. If no SRP/methanogens are found, the PoF is considered “negligible”, but if they are detected a more comprehensive assessment via the PoF ranking tool is required. Detection limit of sessile SRP and methanogens is $< 10^2$ cells per g^{-1} (Jensen and Leenen, 2013).

Where monitoring of microbes is absent or inadequate - temperature, pH and usage of MIC mitigation measures can be used to evaluate and categorize the corrosion circuit, see figure 14. Usage of MIC mitigation measures should be either “yes”, present, or “no”, not present. The effectiveness of MIC mitigation measures is not considered at this stage, but it is included as a part of the detailed assessment process. Parameters and the ranges used in the MIC screening flowchart are discussed in chapter 4.

5.3 PoF rank

The screening will guide the assessor to identify the need for a more detailed assessment where required via the PoF ranking tool, which is focused on the following parameters:

- Settlement potential
- Availability of nutrients / expected rate of metal dissolution
- MIC mitigation effectiveness
- Oxygen ingress

Based on the combination of the parameters, the PoF due to MIC of a corrosion circuit is ranked qualitatively in one of five PoF groups (see table 2). Five groups are used in order to allow the result of the PoF ranking to be combined with the CoF of the corrosion circuit. This will help determine the overall risk and therefore provide direct input to the RBI analysis.

PoF
Very high
High
Medium
Low
Very Low

Table 2: Ranking groups for PoF

Figure 15 shows the relationship between the parameters and a suggested ranking of the PoF due to MIC.

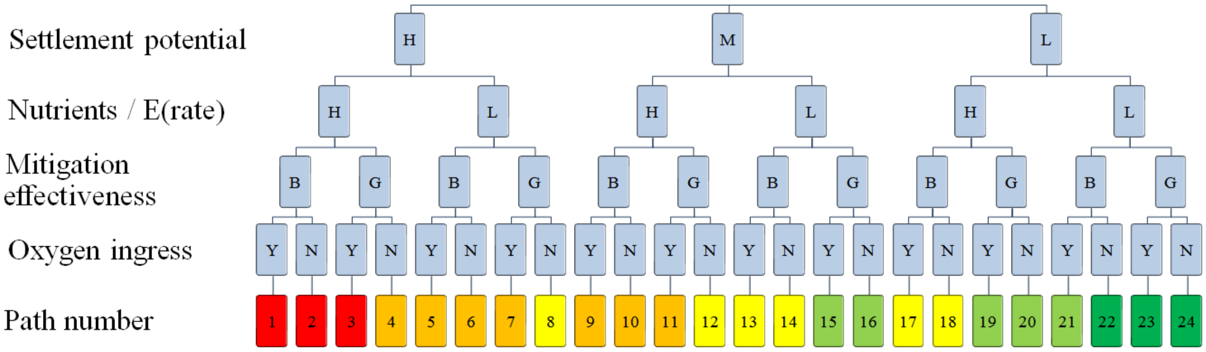


Figure 15: PoF rank for detailed assessment of MIC susceptibility of a corrosion circuit

5.3.1 Individual ranking of parameters

The parameters are ranked individually following the classification presented in table 3 below.

Parameter	***Suggested ranking***	***Denoted in PoF rank***
Settlement potential	High/Medium/Low	H/M/L
Availability of nutrients / Expected dissolution rate	High/Low	H/L
MIC mitigation effectiveness	Good/Bad	G/B
Oxygen ingress	Yes/No	Y/N

Table 3: Parameters included in the PoF ranking

Settlement potential – The aspects that dictate the settlement potential can be established based on operational parameters, physical inspection and/or review of diagrams such as production and instrument diagrams.

The settlement potential can be established based on the following factors:

- Dead leg: Yes/No
- Geometry: Horizontal/Vertical
- Flow-velocity (FV): $0 \text{ m/s} \leq FV \leq 1 \text{ m/s}$, $FV > 1 \text{ m/s}$

With the following ranking:

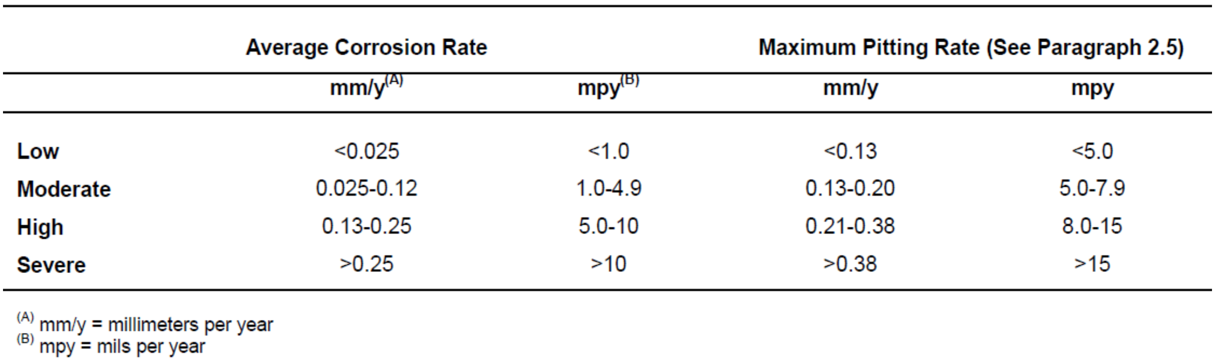
- Dead leg and/or horizontal section and $0 \text{ m/s} \leq FV \leq 1 \text{ m/s}$ → "High"
- Dead leg and/or horizontal section and $FV > 1 \text{ m/s}$ ***or*** $0 \text{ m/s} \leq FV \leq 1 \text{ m/s}$, but no dead leg or horizontal section → "Medium"
- No dead leg and no horizontal section and $FV > 1 \text{ m/s}$ → "Low"

Availability of nutrients / Expected dissolution rate – The next step is either to calculate the expected rate of metal dissolution (E(rate)) or identify the availability of nutrients. When sessile sampling is performed, the E(rate) can be established by use of MMM and Sørensen et al. (2012) equation presented in chapter 2 and 4.

Ideally a mean E(rate) would be determined from sessile sampling performed at several locations if direct samples are not available from the subject corrosion circuit.

The E(rate) can be ranked qualitatively as "high" or "low" using the "maximum pitting rates" in NACE (2005), shown in figure 16.

- E(rate) > 0.20 mm/y → "High"
- E(rate) < 0.20 mm/y → "Low"



	Average Corrosion Rate		Maximum Pitting Rate (See Paragraph 2.5)	
	mm/y[A]	mpy[B]	mm/y	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
Severe	>0.25	>10	>0.38	>15

[A] mm/y = millimeters per year
[B] mpy = mils per year

Figure 16: Qualitative ranking of quantitative corrosion rates (NACE, 2005)

Nutrients considered in the procedure are derived from Pots et al. (2002) and given in table 4. The nutrient availability is considered “high” if any nutrient in the corrosion circuit exceeds the limit. Otherwise the availability of nutrients is considered “low”.

Nutrient	***Limit***
Sulfate	> 10 mg/l
Carbon from fatty acids	> 20 mg/l
Nitrogen	> 5 mg/l

Table 4: Nutrients considered in the PoF rank

Initially, the availability of nutrients is identified by well test samples or produced water sampling across the production process. The level of nutrients can change from one corrosion circuit to another, e.g. due to processing/separation or use of sulfate-reduction units. The amount should therefore be assessed individually in the PoF ranking of each corrosion circuit and conservatism used where not confirmed (use of upstream figure is acceptable).

Note that nutrients which influence the activity of methanogens are not included in the procedure as the literature is incomplete.

MIC mitigation effectiveness – Characterizing the MIC mitigation effectiveness is often difficult and clear guidelines on how to measure this parameter are not identified. Rather, the MIC mitigation effectiveness should be assessed on a case-by-case approach based on considerations discussed in chapter 4. MIC mitigation effectiveness is suggested ranked as either “good” or “bad”.

Oxygen ingress – Oxygen ingress can be identified by fluid assessments or by assessing the potential for oxygen ingress due to pumps, etc. Oxygen ingress is considered either present or absent, i.e. ranked as either “yes” or “no”. While presence of oxygen is considered to increase the threat of MIC, current knowledge regarding the significance of continuous or intermittent ingress and the amount of oxygen introduced into the system is limited with regard to the impact of oxygen ingress on MIC.

For an in-depth discussion of the parameters see Chapter 4.

5.3.2 Considerations in using the PoF rank

It is important that the assessment not only considers the present operating condition, but also past and future. For example, if the current production can maintain a high flow-velocity this is not necessarily representative when looking at historical production data or trying to identify the future operating conditions of the corrosion circuit.

The parameters included in the PoF rank and its granulation is based on two factors:

- Ease of identification
- The authors' subjective view of the parameters effect on the likelihood and rate of MIC.

All the parameters included in the PoF rank, nominally; settlement potential, availability of nutrients, E(rate), MIC effectiveness and oxygen ingress are known to be significant in influencing the PoF of MIC and are well described in existing literature. Other parameters, e.g. material type and water breakthrough, have not shown clear correlation to the PoF of MIC and are therefore not considered. Equally, the order they are included is based on the author's interpretation of their significance, based on extensive literature review.

5.4 Discussion of developed stepwise procedure

The procedure has been developed based on a subjective view of MIC. As this is a novel approach to integration of MIC in RBI analysis, potential further improvement of the procedure are discussed in chapter 6.

The parameters included in the flowchart are considered to be practical, straight forward for an operator to identify and time efficient to complete.

The more detailed assessment undertaken in the PoF rank is also pragmatic and intended to provide granulation via readily available information. While the parameters selected are the most significant drivers for MIC, some may argue that the order of the considered parameters should differ.

E(rate) may be considered more important than the settlement potential. The expected rate of metal dissolution is based on a sessile sample, for a sessile sample to be available it means that microbes have already settled. However, if the settlement potential in the corrosion circuit is low, the microbes are unlikely to settle in the actual corrosion circuit. Therefore, the microbes will not influence the corrosion in that corrosion circuit, regardless of how high the E(rate) is.

Another important aspect is that the E(rate) calculation is based on the activity of SRP and methanogens alone, correlation between Sørensen et al. (2012) equation and the actual MIC rate is not well understood. Settlement potential is a more robust parameter and therefore given primary focus within the PoF ranking. The other parameters are also ordered based on current understanding and interpretation of their significance in the role to MIC.

The procedure will not give a direct measure of the loss of containment of the corrosion circuit due to MIC - the procedure provides a MIC susceptibility measure. In order to establish the total PoF of a corrosion circuit the outcome of the MIC assessment must be combined with other credible degradation mechanisms within the corrosion circuit. The integration of the procedure and the RBI concept is discussed in chapter 6.

CHAPTER 6: Interface between the procedure and the RBI concept

This chapter explains how the procedure described in chapter 5 can be incorporated into an RBI analysis and allow the threat of MIC to be combined with other degradation mechanisms. The focus will be on; 1) how the PoF procedure can be incorporated in the “generic RBI process” (see figure 17) 2) how the PoF procedure, and considerations made in the application of the procedure, can be used when establishing the five deliverables of an RBI analysis.

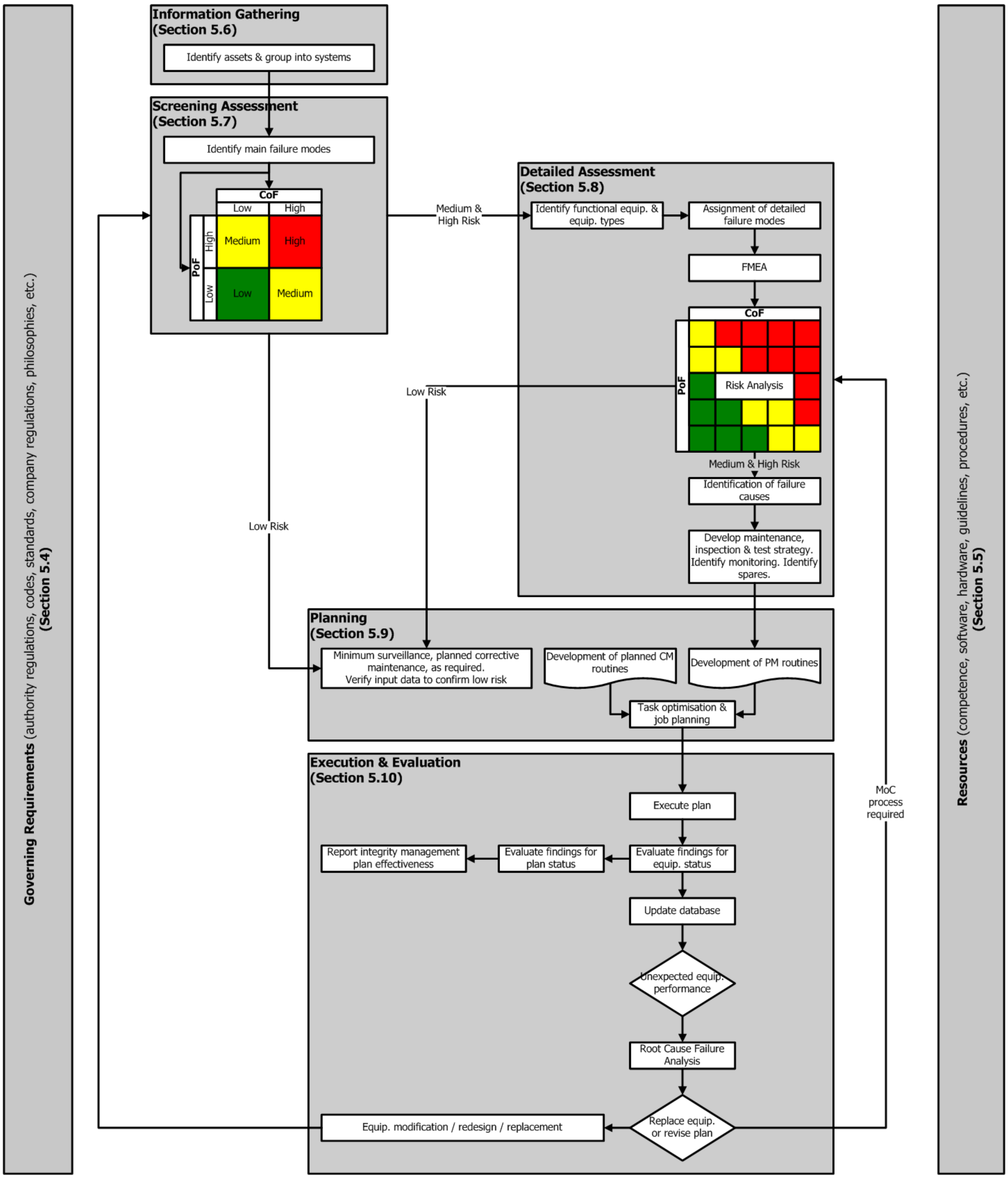


Figure 17: Generic RBI analysis, from DNV (2010)

6.1 Prioritisation of high risk components (WHAT to inspect)

As stated in chapter 2, the risk associated with operating a system is a combination of PoF and CoF (See Equation 1 in chapter 1). The following section will focus on how the procedure presented in chapter 5 can help the prioritisation of high risk components by including the PoF due to MIC in an RBI analysis. The prioritisation is done according to the process shown in figure 17 by performing a screening, followed by a detailed assessment in medium or high risk cases.

6.1.1 Screening

In the initial steps of the RBI analysis the degradation mechanisms are assessed by performing a screening assessment. MIC is one of many potential degradation mechanisms, which can be considered by applying the procedure described in chapter 5. In the "screening assessment", the MIC threat of a given corrosion circuit is ranked as either "negligible" or "significant" according to the flowchart (see figure 14). Secondly, the PoF due to MIC is combined with other degradation threats. Lastly, the PoF and CoF are combined to establish the risk of operating the corrosion circuit. The risk can be illustrated in a simplified risk matrix used for screening purposes, see figure 18 below.

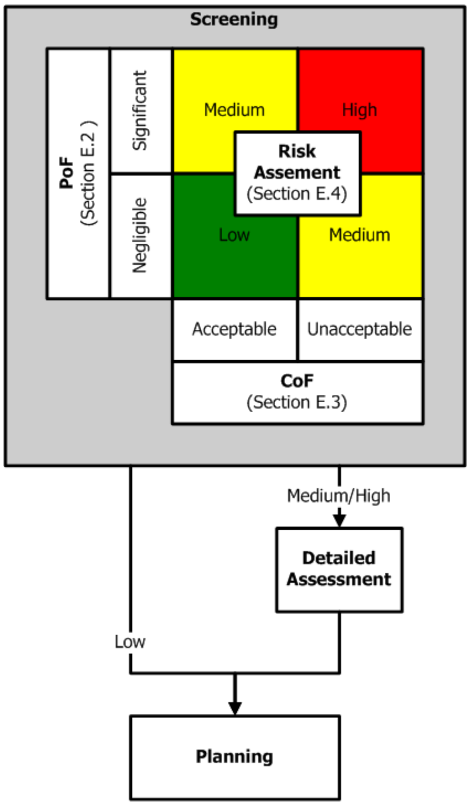


Figure 18: Screening risk matrix, from DNV (2010)

In low risk cases, the corrosion circuit is not subject to further risk assessment; rather, it is taken forward to the maintenance planning stage. In practise this means that the corrosion circuit is subject to corrective maintenance.

If the risk is raked as medium or high in the screening assessment, a detailed assessment is required to establish a more comprehensive risk analysis.

6.1.2 Detailed assessment

In the detailed assessment each degradation mechanism is mapped in detail. The PoF due to MIC can be identified by applying the “PoF rank” presented in chapter 5. Subsequently, the PoF of MIC is combined with the overall PoF and further incorporated in the risk analysis. The result is often presented in a risk matrix to support decision-making. Figure 8 in chapter 2 shows an example of a risk matrix. Note that the outcome of the “PoF rank” has five PoF categories, thus best suited to be used in a 5x5 risk matrix.

As seen in figure 17, low risk corrosion circuits identified in this step are subject to the same maintenance-planning as the ones separated during the screening assessment. Medium and high risk items need to be evaluated and should be subject to inspection planning before maintenance needs are identified based on inspection findings and evaluation.

What the inspection should cover relies on several factors:

- Outcome of the assessment: High and medium risk items
- Risk acceptance
- Inspection window

The outcome of the detailed assessment will give the assessors an overview of the operational risk associated with all corrosion circuits. Combining the risk with the operators risk acceptance and the inspection window (e.g. when inspection campaigns take place) will be the basis for identifying the inspection focus.

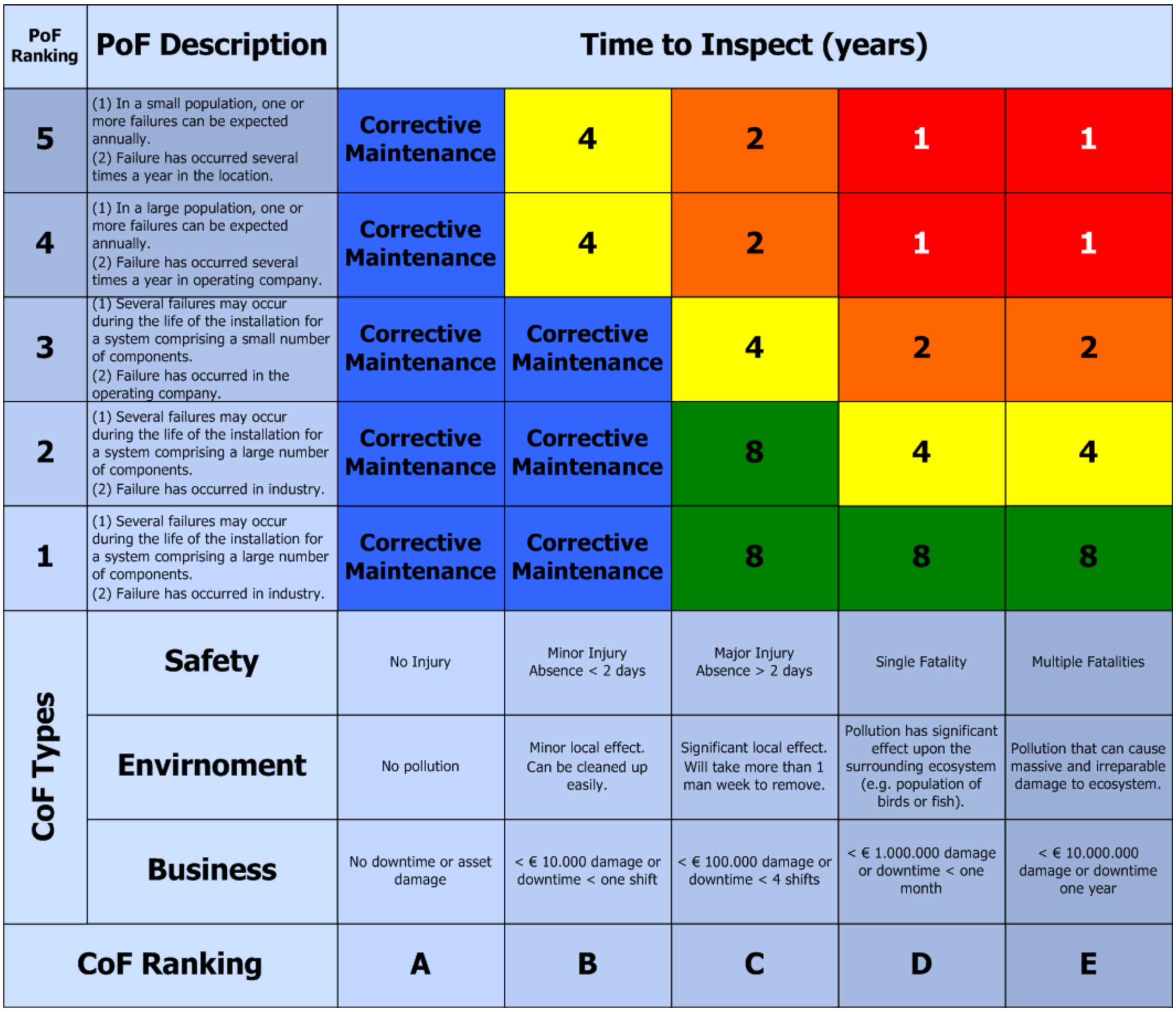
For example, operators may decide to inspect 100% of high risk and 25% of medium risk items during an annual inspection campaign. That way, both high and medium risk components are covered and their risk status and maintenance needs can be evaluated based on inspection findings.

Following the generic RBI process (see figure 17) medium and high risk failure items are derived from the detailed assessment as well as the failure threats. The next four sections focus on how MIC can be considered in the inspection program when it has been identified as a threat to the integrity. However, MIC is one of several threats and the inspection program should always be established based on a collective view of all degradation mechanisms.

6.2 Determination of inspection intervals (WHEN to inspect)

The determination of PoF and CoF depends in part on the operators risk acceptance criteria (within the statutory limits) and may differ from one operator to another. This has implications to the establishment of inspection intervals.

Each failure mechanism (e.g. MIC, erosion, O_2 corrosion) can be considered separately, the following is in regards to *when* to inspect for MIC. The DNV RP suggests two ways to establish inspection intervals; decision risk matrix (figure 19) and a maximum time to inspect, time to PoF_{Limit} (Equation 7)



PoF Ranking	PoF Description	Time to Inspect (years)				
5	(1) In a small population, one or more failures can be expected annually. (2) Failure has occurred several times a year in the location.	Corrective Maintenance	4	2	1	1
4	(1) In a large population, one or more failures can be expected annually. (2) Failure has occurred several times a year in operating company.	Corrective Maintenance	4	2	1	1
3	(1) Several failures may occur during the life of the installation for a system comprising a small number of components. (2) Failure has occurred in the operating company.	Corrective Maintenance	Corrective Maintenance	4	2	2
2	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	4	4
1	(1) Several failures may occur during the life of the installation for a system comprising a large number of components. (2) Failure has occurred in industry.	Corrective Maintenance	Corrective Maintenance	8	8	8
CoF Types	Safety	No Injury	Minor Injury Absence < 2 days	Major Injury Absence > 2 days	Single Fatality	Multiple Fatalities
	Envirionment	No pollution	Minor local effect. Can be cleaned up easily.	Significant local effect. Will take more than 1 man week to remove.	Pollution has significant effect upon the surrounding ecosystem (e.g. population of birds or fish).	Pollution that can cause massive and irreparable damage to ecosystem.
	Business	No downtime or asset damage	< € 10.000 damage or downtime < one shift	< € 100.000 damage or downtime < 4 shifts	< € 1.000.000 damage or downtime < one month	< € 10.000.000 damage or downtime one year
CoF Ranking		A	B	C	D	E

Figure 19: Example of a decision matrix, from DNV (2010)

Since the outcome of the MIC procedure is qualitative, a decision risk matrix is best suited to establish inspection intervals. There are several aspects related to MIC that should be considered when setting up a decision risk matrix.

When microbes have started to colonise, i.e. established in a biofilm, they multiply very quickly (possibly within an hour) (NACE, 2012). As the number of microbes increase, the total metabolic rate increase, and finally, the influence on corrosion increase. Consequently, when MIC is initiated, the corrosion rate can be very high. This has been confirmed in case studies (Mitchell et al., 2012). Therefore, it is suggested that inspection is performed very frequently in corrosion circuits or on specific items therein are ranked as very high or high MIC PoF, and an unacceptable CoF. Under these circumstances inspection may take place in intervals of less than a year.

Another problem with MIC that should be considered in the establishment of *when* inspection should take place is that biofilm tend to establish during downtime (stagnation). So, opposed to inspection for other degradation mechanisms, e.g. oxygen corrosion or erosion, which increases with increased flow-velocity, MIC can be a concern after a system has been shut down over a period of time, paradoxically in some cases to look for degradation.

Time to $\mathrm{PoF}_{\mathrm{Limit}}$ can be established and give a quantitative estimate of the maximum time between inspections, based on the expected rate of metal dissolution. The maximum time to inspect can be calculated as follows (DNV, 2010):

$$Time\ to\ PoF_{Limit} = a\frac{t_0 - t_{release}}{d_{mean}} \tag{7}$$

Where PoF_{limit} is the probability of failure acceptance limit, a is a confidence factor, t_0 is the current wall thickness in mm., $t_{release}$ is the thickness at which a release is expected in mm. and d_{mean} is the mean damage rate in mm.

t_0 and $t_{release}$ is assumed to be established in the RBI analysis regardless whether or not MIC is included, i.e. no extra effort is required in order to acquire those factors. The confidence factor, a, is suggested to be established in a case-by-case approach following the guide in DNV (2010, p.56). The expected rate of metal dissolution (described in chapters 3,4 and 5) can be used as the “mean damage rate”, $\mathrm{d}_{\mathrm{mean}}$, which allows assessors to calculate the time to $\mathrm{PoF}_{\mathrm{limit}}$.

Energy Institute (2014) suggests a MIC rate of 1 – 2.5 mm/year. If no data regarding MIC rate can be found when MIC is identified in a corrosion circuit this rate can be used as a reference point until further inspection can evaluate the rate of MIC. Note that this $\mathrm{PoF}_{\mathrm{limit}}$ would only represent degradation caused by MIC, in practical cases $\mathrm{d}_{\mathrm{mean}}$ should be based on all relevant damage mechanisms that are expected in a corrosion circuit.

As mentioned, the risk acceptance of the operator as well as availability for inspection will play a role in setting up inspection intervals.

6.3 Expected damage mechanisms (WHERE to inspect)

Where to inspect is established based on the level of risk, followed by an identification of the threats found therein by an “identification of failure causes” (see figure 17). Presence of several threats within a corrosion circuit is common, therefore a holistic view of all threats is crucial in order to inspect at locations where the overall risk is highest. Combination of several threats will not be discussed in detail in this section, but rather important considerations regarding the location of MIC “hot spots” within high risk corrosion circuits are presented below. Nonetheless, combining the identified MIC “hot spots” with other threat mechanisms and their “hot spots” is crucial to create a realistic view of where to inspect for the most value.

The following factors are suggested to help pinpoint where to inspect for MIC:

- Inspection findings
- Flow characteristics
- Settlement potential
- Chemical treatment injection point

Inspection findings – Areas where past inspection has identified degradation is important in setting up where to inspect.

Flow characteristics – In a general system, two considerations are important; Single phase flow often show MIC around the 6 o'clock position, while multiphase flow often show MIC in the 6 o'clock position, and the 3 o'clock and 9 o'clock position (dependent on the location of the water/oil interface) (NALCO, 2004). In a topside production system the water/oil interface may vary from one corrosion circuit to another making it an important consideration during assessment. Figure 20 shows pitting corrosion at 6 o'clock position caused by MIC (left) and an illustration of the geometry of a pipeline cross section (right).

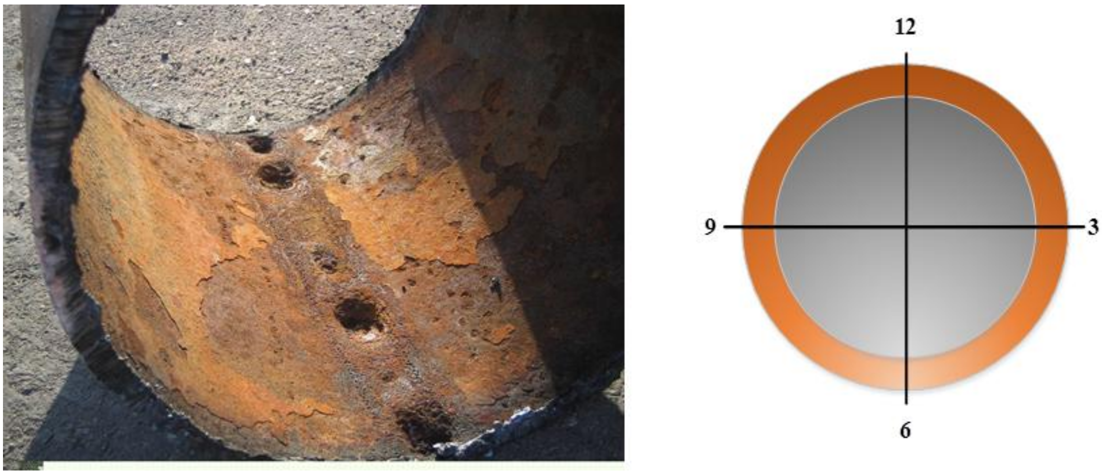


Figure 20: Internal MIC pitting (left) (from an undisclosed operator in the North Sea), geometry of a pipeline cross section (right)

A comprehensive flow assessment, e.g. a flow regime assessment, can provide more differentiation of inspection locations. This can be useful because the flow characteristics can be very different from one system to another. As an example see figure 21 which shows a hydrocarbon leak due to MIC at the 1 o'clock position. If the failure occurred at water/oil interface is not known.

Figure 21: Internal MIC failure (from an undisclosed operator in the North Sea)

Settlement potential – Areas with high settlement potential are identified in the PoF ranking. The corrosion circuits that are characterised as having a high settlement potential should be put under further examination to identify the specific location of the settlements. This can be dead-legs or areas with poor geometry with regards to settlement. Examples are shown in figure 10 in chapter 4

Surface deformations, where known, should be identified as possible “hot spots”. They are significant areas that are non-smooth, thus can accumulate deposits as well as providing attachment sites for microbes. Deformations can be intentional, due to the system design (couplings, welds, transitions, crossings) or unintentional, due to erroneous manufacturing, transportation, installation or operation.

Chemical treatment injection point – The injection point can be of interest because of two aspects. The first aspect is that chemical injection can be a source of oxygen being introduced downstream of the injection point (ISO, 2010). If this is the case, increased rates of MIC can be found at areas where biofilm has established. The second aspect is that upstream of the chemical injection point, high corrosion rates are often found due to a lack of chemicals in the liquid. Figure 22 illustrates the latter.

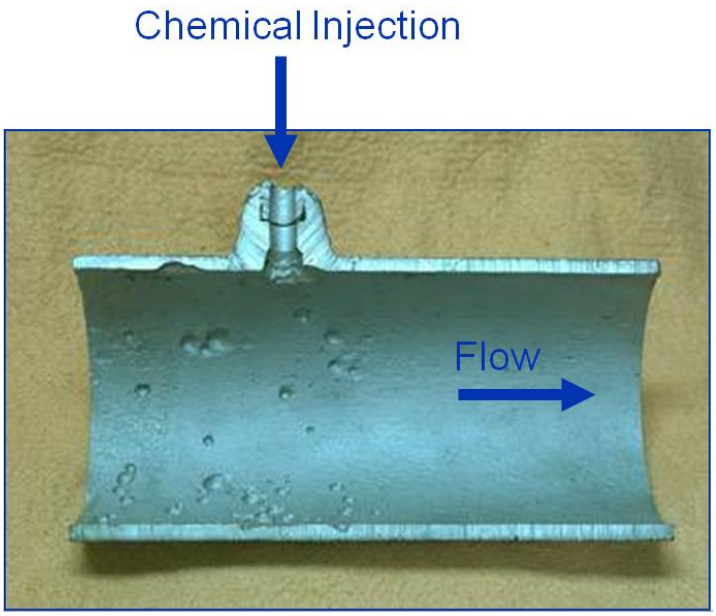


Figure 22: Corrosion as a result of no corrosion inhibiting chemicals in the liquid

6.4 Selection of best inspection method (HOW to inspect)

The selection process itself is a comprehensive task and considered outside the scope of this thesis. The following section will focus on:

- General considerations for inspecting topside production facilities
- Listing of techniques used to identify MIC
- How to compare different techniques
- Considerations in identifying how to inspect for MIC

The inspection methods that can be applied to topside production systems differ from simpler systems, such as deluge and utility systems or subsea pipelines. This is due to factors such as;

- Complex system design
- Continuous operation of the system

System design limits the use of techniques such as intelligent pigging, which is not possible because pigging require free passage of the pig (no valves, intrusive tees, sharp bends etc.) as well as pig launchers and catchers that take up a lot of space. Usage of intrusive techniques is also limited in production facilities that are in continuous operation.

6.4.1 Inspection techniques

Suggested inspection techniques to identify MIC are (DNV, 2010):

- Ultrasonic-testing
- Radiographic testing
- Close visual inspection
- Video inspection
- Magnetic flux leakage

The above presented techniques can be used in the general identification of MIC. Identification of internal degradation and the exact cause of that degradation can be difficult. Therefore, thorough inspection and determination of the cause of degradation may require using several inspection techniques.

The techniques can be separated between non-intrusive and intrusive. Non-intrusive techniques, like ultrasonic, magnetic-flux leakage and radiographic testing, are good at identifying internal degradation. However, intrusive techniques, such as close visual and video inspection, will in most cases be required to categorically determine the damage mechanism is MIC.

DNV (2010) suggest the following calculation to allow a comparison of the inspection techniques:

$$Technique\ with\ the\ highest\ value = \frac{PoD}{Cost\ x\ Confidence\ \ CoV} \tag{8}$$

Where PoD is the probability of detection, Cost is the cost of inspection (e.g. in NOK per hour) and Confidence CoV is a confidence factor which can be found in DNV (2010). Both PoD and cost in regards to MIC detection should be given by vendors.

6.4.2 Considerations in identifying how to inspect for MIC

The following factors should be considered when selecting inspection technique to identify MIC:

- Validation of PoD and cost of inspection
- Damage morphology
- Accessibility of inspection point

Because most inspection plans lack proper consideration of MIC, assessors commonly lack knowledge and experience to validate suggested PoD and cost of inspecting. Adding to this, post-failure assessments often show that MIC was more “localized and defined than assumed when selecting inspection program” (Markoff and Larsen, 2010, p.5). Further, the layout of an offshore production system will differ from one asset to another due to constraints posed by the differences in design basis; this will impact the applicability of different inspection techniques.

Experimenting with different techniques and transfer of knowledge can therefore benefit the validation of PoD and cost of inspection, as well as better identification of MIC in high risk, inaccessible places.

6.5 Data requirements for continuous improvement (WHAT to report)

The fifth deliverable, “What to report”, is considered to be a part of the planning and, execution and evaluation steps in the RBI process (see figure 17). Therefore, this part will be presented in two sections; *Planning* and *Execution & Evaluation*. Emphasis will be on aspects related to the inclusion of MIC in the Planning and the Execution & Evaluation steps.

In order to more clearly illustrate how the different steps lead into each other, consider the inspection cycle in figure 23. Note that all steps shown in the inspection cycle can be found in the “generic RBI process”, illustrated in figure 17. The figure gives a good illustration of how the “inspection strategy”, here being risk based, leads into maintenance (modifications and repairs) through the steps discussed in this chapter.

Figure 23: The inspection cycle; how all steps relate to each other (Bureau Veritas, 2014)

6.5.1 Planning

At the present stage in the RBI process, the entire topside production system has been reviewed and risk is identified for all corrosion circuits. Low risk corrosion circuits or components are subject to corrective maintenance, i.e. they run to failure. Medium and high risk corrosion circuits or components should be subject to planned inspection, which will determine the need for maintenance prior to failure.

The most important MIC aspects are covered in the past sections. In the inspection planning it is vital to focus on:

- Properly incorporate MIC considerations made in the identification of *what, when, where* and *how* to inspect
- Human and organizational factors

Inspection is often carried out by subcontractors. Cooperation and discussion between the operator and the inspectors is important to create a collective understanding of MIC management and what actions are required if MIC is identified. Involving the inspectors in the early phases of the inspection planning will benefit the execution as their take on *what, when, where* and *how* to inspect is discussed in a timely manner. When MIC considerations are introduced into the RBI analysis for the first time, this is particularly important.

When the MIC assessment procedure is included in the RBI analysis it needs evaluation and confirmation, as discussed in chapter 5. Assessors should find a clear correlation between the outcome of the procedure; PoF due to MIC, and the inspection findings. The scope of work in the initial inspection campaign for MIC should gather enough inspection data to allow assessors to evaluate the procedure. This will also better the understanding of MIC and how to properly integrate the MIC threat with the RBI concept.

6.5.2 Execution & evaluation

Knowledge and experience is important to properly assess the inspection findings and separate between MIC and other causes of degradation. This is to initiate the proper measures and mitigate the root cause of degradation. For example, it can be difficult to separate under-deposit corrosion and H_2S corrosion from MIC, because MIC can result in souring (through generation of H_2S in metabolic processes) as well as occurring under deposits.

If sessile sampling is performed during the inspection, professionals should be involved with the sampling process. Professionals can be microbiologists or specially trained inspection engineers. This is to ensure that quality samples are gathered and the *in situ* microbial activity can be assessed properly. Assessments usually take place in onshore laboratories, so proper transportation of samples is an important factor in preserving the sample.

Lastly, the inspection findings are evaluated. Accepted results make grounds for identification of plant maintenance needs, before being the basis for establishing a new RBI analysis.

6.6 Discussion

Cost-benefit analysis plays a role in the establishment of an inspection maintenance program (DNV, 2010). This step is not considered in this thesis. However, it is acknowledged that performing a cost-benefit analysis may impact some features presented in the above chapter. For example, inspection of medium risk components can be justified or rejected by a cost-benefit evaluation.

In DNV (2010) the screening outcome “negligible” PoF and “significant” PoF is suggested to be separated at a probability of 10^{-5} per year. Because the procedure suggested in chapter 5 is qualitative, it is difficult to correlate the categorization of “negligible” PoF to a quantitative value (10^{-5} per year). Evaluation of the screening process should be performed in order to investigate correlation between the parameters in the procedure, their ranges leading to system characterization and a yearly probability of failure.

The procedure suggested in chapter 5 provides the assessor with an overview of unfavourable features which require further examination discussed in chapter 6. This information, e.g. detailed assessment of settlement potential, can also be used to initiate preventive measures. If operators incorporate the findings in other operational procedures, degradation may be more effectively handled.

Chapter 7 explores use of the procedure with real data up to the RBI input step.

CHAPTER 7: Industrial example

In this chapter the procedure presented in chapter 5 is applied to two corrosion circuits (CC) in a topside production facility. This is done to to illustrate how to use the procedure up to – but not including RBI integration.

Data has been provided by an operator in the North Sea. On request of the operator, detailed information, names and references are kept secret. A short presentation of parameters and the subject CC is given below.

7.1 Description of the facility

CC 1 is located downstream of the 1st stage separator on the outlet pipework to the 2nd stage separator. CC 2 is located downstream from the degasser in the pipework to the water injection system.

Currently no formalized MIC assessment exists, but MIC has been identified as a credible threat to asset integrity and both microbe monitoring and biocide is in use on the facility.

Key operating parameters of the CC are given in table 5.

Parameter	*Corrosion circuit 1*	*Corrosion circuit 2*
Temperature	74 °C	45 °C
pH	6.4 (production wells)	6.4 (production wells)
MIC mitigation effort	Sulfate removal, biocide	Sulfate removal, biocide
Microbe monitoring	Sessile and planktonic	Sessile and planktonic
Flow velocity	2.8 m/s	0,4 m/s
Sulfate content	> 10 mg/l (production wells)	> 10 mg/l (production wells)
Carbon from fatty acids	-	-
Nitrogen content	-	-
Mitigation effectiveness	Not established	Not established
Oxygen ingress	No	Yes

Table 5: Key operating parameters for the corrosion circuits

7.2 Screening

The plant has no established MIC screening assessment, thus a new assessment has been initiated. The screening is performed by applying the flowchart given in figure 14 to each corrosion circuit. The result is presented in table 6.

New screening assessment		
Input	*Corrosion circuit 1*	*Corrosion circuit 2*
Microbe monitoring	Yes	Yes
Identifies type of microbes present	Yes, sessile sample available	Yes, sessile sample available
SRP and/or methanogens identified	Yes, both	Yes, both
Result	“Significant PoF”, require detailed assessment	“Significant PoF”, require detailed assessment

Table 6: Outcome of MIC screening assessment

Sessile microbes are sampled in both CC and the samples show presence of SRP and methanogens. According to the procedure, both CC need to be assessed in detail as the result is “Significant PoF”.

7.3 Detailed assessment

A detailed assessment is performed by applying the PoF ranking given in figure 15 to each corrosion circuit. The outcome of the detailed assessment is shown in table 7.

PoF ranking		
Parameter	*Corrosion circuit 1*	*Corrosion circuit 2*
Settlement potential	Horizontal sections, flow velocity > 1 m/s → Medium	Horizontal sections, flow velocity < 1 m/s → High
Nutrient availability	High	High
MIC mitigation effectiveness	Bad	Bad
Oxygen ingress	No	Yes
Result	Path 10 → “High”	Path 1 → “Very High”

Table 7: Outcome of PoF ranking

The settlement potential differs from CC1 to CC2 because of differences in the flow velocity. It is normal to have a drop in flow-velocity, thus increase in settlement potential, throughout the process facility, even though the overall geometry is similar.

Sessile sampling is in place, but the assessors have not used MMM to identify the cell specific activity of the microbes. As explained in chapters 3 and 4, identifying the cell specific activity of the *in situ* microbes is necessary to calculate the expected rate of metal dissolution due to MIC. Therefore, the expected rate of metal dissolution cannot be established and the availability of nutrients has been used within the assessment process of each of the CC.

The chemical composition of the production fluids is usually derived from production well test samples. As the production fluids flow through the topsides process facility, depending on the sampling location the relative composition of the fluids may differ from the well test samples. However, use of these samples is considered satisfactory for ranking purposes. While the mean sulfate-content is less than 10 mg/l, (under the limit suggested in chapter 5), the data set is incomplete, as information regarding the amount of carbon from fatty acids and nitrogen is missing. Therefore, the nutrient availability is ranked as “High” in regards to both CC due to a lack of knowledge.

Biocide is injected upstream of both CC1 and CC2 to mitigate microbial growth. Based on the microbial growth, found by both sessile and planktonic sampling, the MIC mitigation effectiveness is ranked as “Bad”.

It is very unlikely that oxygen is introduced in CC1 as there are few potential sources to introduce oxygen at this stage. Consequently, this part of the system is considered strictly anaerobic. Pumps in CC2 have a high potential to introduce oxygen into the system. Thus, CC2 is believed to have some potential oxygen ingress.

Below, figure 24 illustrates the paths identified for CC1 and CC2.

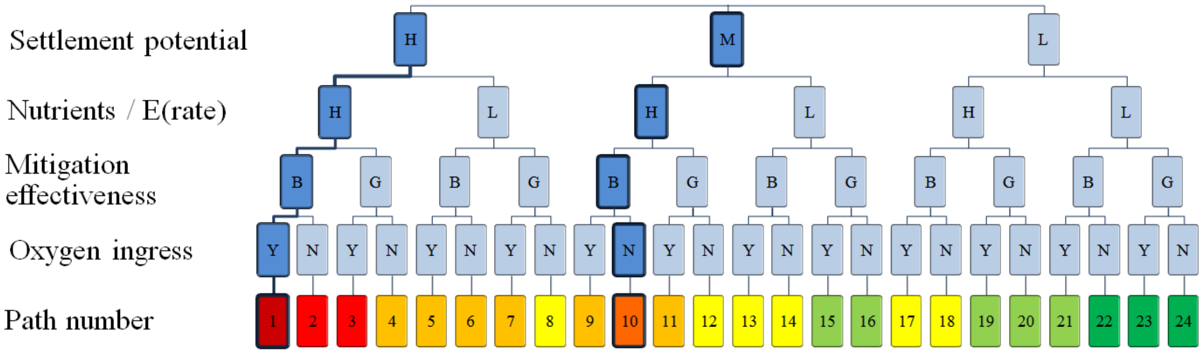


Figure 24: Illustration of paths identified for the different corrosion circuits

7.4 Discussion

In this chapter the procedure has been applied using real data to two corrosion circuits. The example provided, highlight that through applying the procedure; assessors can easily differentiate the PoF due to MIC for different corrosion circuits.

It is recognized that in real cases the interface between the ranking procedure and input to the overall inspection plan derived from the RBI analysis will probably be challenging. Considerations made in chapter 6 and a post-inspection evaluation of the procedure will help identify future refinements required within the procedure.

CHAPTER 8: Conclusions

This thesis presents a novel procedure for inclusion of a threat assessment of microbiologically influenced corrosion (MIC) in a risk based inspection (RBI) analysis as no complete procedures or models are currently available. Several of the existing threat models where reviewed in order to identify current practices that consider MIC. While they give insight into the parameters that affect MIC, no model was found that adequately integrated with the RBI concept.

Based on extensive literature review, several key parameters where identified and selected for inclusion within the procedure. The developed procedure is sub-divided into two steps; a screening flowchart and a detailed PoF ranking tool. This allows the MIC threat to be suitably assessed and the PoF of a corrosion circuit to be established, allowing the MIC threat to be incorporated in the RBI analysis.

The result of the work is a procedure for the assessment of MIC which is easy and practical in application and considers the key drivers for MIC. Through its use it identifies the areas of a topside production system that are most likely to be susceptible to MIC and facilitate integration with an RBI analysis.

CHAPTER 9: Suggestions for further work

Although an example that illustrates the application of the procedure is presented in chapter 7, a more comprehensive application of the procedure would provide valuable information in evaluating the suggested procedure. It would also be interesting to see the procedure applied to ancillary systems e.g. fire-water systems to further test its usefulness.

Further examining the possibilities of incorporating MMM and the impact of biotic parameters on the PoF due to MIC should be further investigated and understood. That way, a more precise description of processes driving MIC can be established. Understanding the potential that MMM represents can be the first step towards a quantitative model.

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