

Microbiologically influenced corrosion of mooring systems for floating offshore installations

Mooring Integrity Joint Industry Project Phase 2

Prepared by the **Joint Industry Project Steering Committee**
for the Health and Safety Executive

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Research Report

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Mooring Integrity for floating offshore installations is an important safety issue for the offshore oil and gas industry. This report is one outcome from Phase 2 of the Joint Industry Project on Mooring Integrity. This work ran from 2008 to 2012 and had 35 industry participants. It followed the Phase 1 work described in HSE Research Report RR444 (2006). The Phase 2 work compiled research on good practice and an overview is given in HSE Research Report RR1090 (2017).

Microbiologically Influenced Corrosion (MIC) is corrosion stimulated or caused by the presence of bacteria, algae or fungi on the surface of components. This report describes a study into MIC on offshore mooring system components. It is based on the literature, industry field cases and discussion with MIC specialists. It describes possible MIC mechanisms and identifies that uncertainties make it difficult to unambiguously determine whether MIC has taken, or is taking, place. It is found that although none of the field cases unambiguously confirms MIC damage, there are possible indications that sulphate-reducing bacteria play a role and that the most vulnerable parts of mooring systems may be at or just above the sea bottom and close to the splash zone. The report: sets out MIC diagnostics; outlines a draft procedure for industry inspection, testing, sampling and analysis of MIC on mooring systems; and identifies some measures that could potentially reduce the likelihood of MIC, such as avoiding pollution from oil drilling and oil production activities, or other depositions of nutrients.

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Mooring Integrity Joint Industry Project Phase 2

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1 PREFACE

The purpose of this sub-report is to provide an update of the current views and understanding of relevant mechanisms and likelihoods for Microbiologically Influenced Corrosion (MIC) on mooring system components for floating offshore installations. By combining this with available field experience and good investigation practices, the objective has been to provide guidelines for assessing the risks of MIC and procedures for verification.

To this end this sub-report first examines and explains, as far as possible within the current knowledge, how microbial activity influences corrosion, before going on to examine field experience. An outline procedure is then provided as guidelines for Operators that suspect that MIC may be taking place on their mooring system, before drawing together in conclusion some of the unknown MIC factors.

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2 INTRODUCTION

2.1 PURPOSE

The purpose of this report is to provide an update of the current views and understanding of relevant mechanisms and likelihoods for Microbiologically Influenced Corrosion (MIC) on mooring system components. By combining this with available field experience and good investigation practices, the objective has been to provide guidelines for assessing the risks of MIC and procedures for verification.

2.2 MOTIVATION

Corrosion influenced by microbiology has been reported from a range of industries for a variety of components and environments. Examples are: on the outside of buried pipe lines, submerged steel structures in harbours, water injection systems and in oil storage tanks. Several examples have been reported with exceptionally high corrosion rates.

There have been reports of corrosion attacks on mooring system components, allegedly caused by MIC, that are severe in terms of the measured corrosion rates or that have lead to failures.

This has created concerns among operators of moored floating systems regarding potential threats to the integrity of mooring systems from MIC.

It is important to note that the main concern to the industry is that unexpected failures have occurred and/or abnormal corrosion detected. Whether this is caused by MIC or not will not necessarily lead to solutions that can remove the threat. However, understanding the mechanisms and risks may enable improved procedures and better decision making in connection with integrity management.

2.3 SOURCES OF INFORMATION

The study has been based on

- Available literature including those specified in the Reference section and several of the references specified within these publications.
- A number of investigation reports from mooring chains with alleged MIC have been available but these have not been referenced to avoid traceability.
- Discussions with external experts including:
 - Dr. Stephen Maxwell, Commercial Microbiology, Aberdeen
 - Prof. Roy Johnsen, NTNU, Trondheim
 - Dr. Eilen Vik, Aquateam, Oslo
 - Dr. Brenda Little, Naval Research Laboratory, Washington

2.4 DEFINITIONS

SRB	Sulphate Reducing Bacteria
MIC	Microbiologically Influenced Corrosion
Sulphate	Strictly a salt of Sulphuric acid (e.g. Na ₂ SO ₄). Mainly refer to the sulphate ion SO ₄ ²⁻
Redox	Redox potential is the tendency for a solution to gain or lose electrons
pH	pH is a measure of the acidity of a solution
ppm	Parts per million

3 MICROBIOLOGICALLY INFLUENCED CORROSION

3.1 BACKGROUND ON CORROSION OF STEEL

Corrosion of a metal (like steel) is an electrochemical process where metallic atoms are oxidized, normally ending up as oxides or salts. For normal corrosion of steel the iron atoms oxidize into positive ions (Fe^{2+}) that go into solution in the surrounding water. Here they normally react with other ions and molecules to form oxides and salts. The locations on the metal surface where the metal ions are oxidized, represent anodic sites where the surplus electrons are left in the metal. For the overall corrosion process, there must be a complementary cathodic reaction (reduction) at cathodic sites, where surplus electrons leave the metal to take part in the cathodic reaction. For oxygen driven corrosion the cathodic reaction results in the formation of OH^- ions involving oxygen, water and electrons from the metal. The OH^- ions will react with the iron ions and oxygen to form Ferrous Oxide (Fe_2O_3). The overall reaction is: $4\text{Fe} + 3\text{O}_2 \rightarrow 2\text{Fe}_2\text{O}_3$.

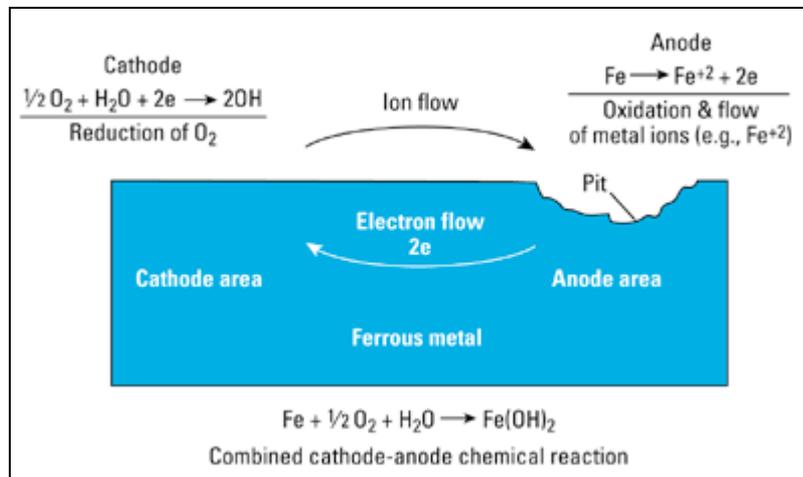


Figure 3-1: Schematic of Anodes, Cathodes and Pitting

The basic requirement for a corrosion reaction to take place is that it results in a lower “energy state”. The different electrode reactions involved in corrosion processes are characterised by an electrical potential relative to a defined standard potential and therefore also in relation to each other. An anode reaction has to have a lower potential than the corresponding cathode reaction for corrosion to take place. Different metals will exhibit different electrical potentials for the anode reaction. A less “noble” metal can thus be used as a sacrificial anode when in electrical contact with a selected metal object. All surfaces of the protected material will electrically be driven to become cathodic thus avoiding any anodic reaction. Based on the same principles of forcing a material to become fully cathodic corrosion can be prevented by impressing an adequate electrical potential (and a corresponding electrical current) relative to a standard potential.

Normally steel will undergo general corrosion where the entire surface corrodes at a relative uniform rate. This means that anodic and cathodic sites will change location in a fairly random pattern. The rate of corrosion is normally limited by the formation of oxides on the surface that partly prevent the transport of ions and molecules that are required for the reactions. This is also referred to as passivation and effectively modifies the galvanic potential of the metal in the “noble” direction.

Pitting corrosion will take place when anodic and cathodic sites stay in the same locations over time. There are many reasons for this such as:

- Local break down of passivation or other protective films
- Conditions where localised “aggressive” environments (pH and availability of ions and molecules) are allowed to establish and prevail. (This can be due to deposits or other circumstances creating stagnant conditions).
- Variation in metal properties (inhomogeneities) affecting the galvanic potential (such as welds or the macro structure of tempered steels)

When a corrosion pit has developed the conditions created by the topography and chemistry may favour further corrosion in the same location at a relatively high rate. Another reason for high corrosion rates in pits is that they represent small anodic areas relative to much larger cathodic regions. This means that “anodic pits” become sacrificial relative to the cathodic regions.

3.2 DEFINITION AND DESCRIPTION OF MIC

Microbiologically influenced corrosion (MIC) is defined as corrosion that is stimulated or caused by the presence of micro organisms on the surface of the material under question. The micro-organisms are bacteria, algae or fungi. The organisms do not induce unique corrosion mechanisms but will rather enhance or stimulate known mechanisms through their activities. Bi-products of their metabolism may stimulate corrosion related reactions, or their consumption or uptake of molecules can modify the local environment in such a way as to change reaction rates.

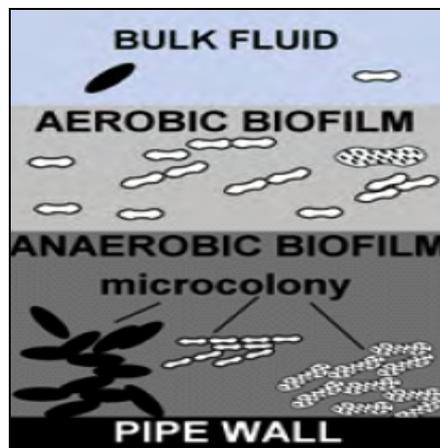


Figure 3-2: Illustration of build-up of bio film on a steel surface (represented by pipe wall)

Micro-organisms settle and multiply as parts of bio-films (as illustrated in Figure 3-2) that normally develop on all surfaces subsea, such as for instance steel exposed to water.

There is a huge variety of bacteria in the sea environment, and there are probably more bacteria that have not been identified and characterised yet, than those that have. Figure 3-3 shows what typical Sulphate Reducing Bacteria look like when enlarged.

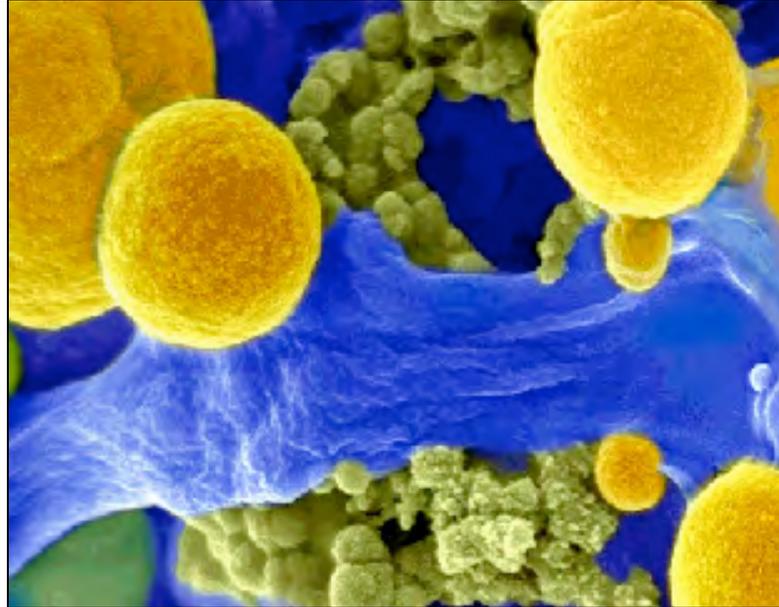


Figure 3-3: Example of Typical Sulphate Reducing Bacteria

For respiration bacteria will need electron acceptors of which oxygen is the most common. However, in anaerobic conditions (oxygen depleted) types of bacteria have developed that use SO_4^{2-} (sulphate), NO_2^- , CO_2 or others as electron acceptors. Some bacteria are strictly aerobic or strictly anaerobic while there are also strands of bacteria that are active both in the presence and absence of oxygen, as well as bacteria that use low levels of oxygen.

For bacteria to be active, they need nutrients for energy and growth. For this, they typically need Carbon, Nitrogen, Phosphor and Sulphur. For a given type of bacteria, these elements must be available in the right proportions, as lack of nutrients will limit the activity of the bacteria.

As a result of their metabolism bacteria will produce compounds or bi-products from their energy conversion. This can be organic acids, reduced metal ions, hydrogen sulphide or other substances. These compounds may modify the microenvironment and surface chemistry and thus possibly influence reactions that take part in corrosion processes.

Bio-films will normally be a heterogeneous composition of different bacteria, slime substances called extra cellular polymeric substances, organic macromolecules etc. It will consist of clusters of cells and bacteria, voids and channels. The adhesion to a steel surface will depend on a number of factors depending on the surface properties and film composition and chemistry. Bio-films will often be very irregular and can thus create concentration cells for certain compounds and thus influence the development of anodic and cathodic regions that can result in corrosion. Lateral variations in the bio-film build up can result in low oxygen concentrations in some regions creating anodic sites with cathodic sites in locations where oxygen is more abundant. Possible variation in oxygen concentration is shown in Figure 3-4.

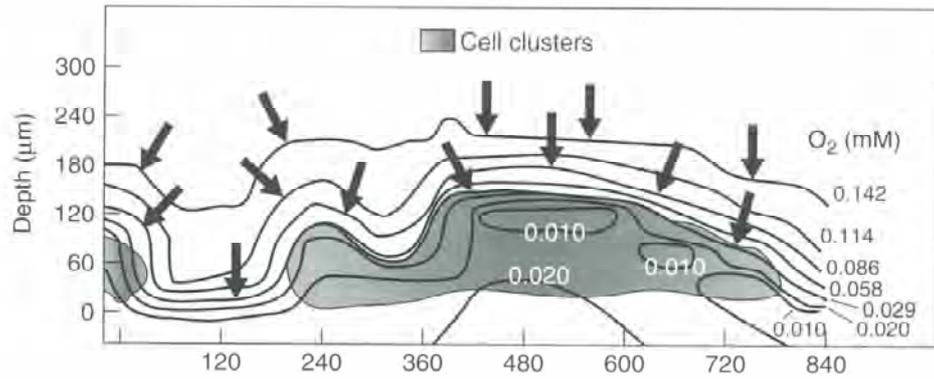


Figure 3-4: Illustration to show how the concentration of Oxygen can vary in a bio-film

When a bio film builds up in thickness (but still thin in comparison to macro fouling) there will typically be high consumption of oxygen on the surface. This results in a reduction in oxygen concentration as function of depth into the film possibly resulting in anaerobic conditions close to the steel surface, such as shown in Figure 3-5. Thus the bio film can generate environments where anaerobic bacteria can become active provided that they are present together with the components/elements they require for their metabolism.

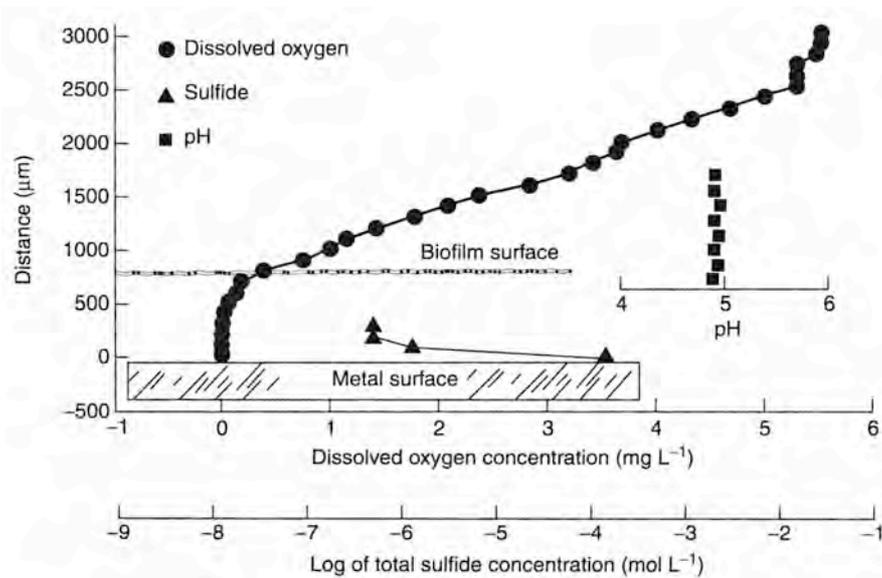


Figure 3-5: Typical variation of significant properties as function of biofilm depth

Through the thickness or bulk of a bio-film there will be gradients of different substances that can be important for the activity of different bacteria. In some regions of a biofilm the bacterial activity can be high and in other regions very low, reflecting the local conditions. The product of the metabolism of some bacteria, as well as dead bacteria, can constitute nutrients for other bacteria.

There are several ways bacteria can influence corrosion. Relevant examples are:

- a) Formation of local concentration cells due to the heterogenic nature of biofilms. Anodic sites can establish where the oxygen concentration is low while cathodic sites can develop where oxygen is allowed to reach the steel surface. Also other compounds can affect the corrosion through higher concentrations in selected areas.

-
- b) Corrosion caused by Sulphate Reducing Bacteria (SRB) is the type of bacteria that has been most widely connected to MIC. A separate section is devoted to describing their actions and impact and most of the work for this report has been directed at SRB.
 - c) Corrosion caused by acids produced by bacteria. There are several bacteria that produce organic acids that can modify the pH of the local environment and thus influence corrosion. There are also bacteria that oxidize elemental sulphur or sulphides producing sulphuric acid (H_2SO_4)
 - d) Iron oxidizing bacteria (IOB) will turn Fe^{2+} to Fe^{3+} . The former is soluble and therefore available in the surrounding water while the latter has a low solubility and will end up as ferric oxides or salts either in the bacteria or released to the surrounding. The consumption of Fe^{2+} may stimulate the anodic reaction on the steel surface and thus enhance pitting corrosion.
 - e) Iron Reducing Bacteria (IRB) oxidize ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}). The ferric iron is present in ferric oxides and salts and IRB can result in the loss of oxide films that that protect against corrosion. The ferrous ions can end up in the bacteria or can be released as ions in the surrounding environment. Changes in the concentration of Fe^{2+} can also influence the corrosion processes. It has also been suggested that IRB can make the local environment suitable for SRBs. However, nobody claims to fully understand the roles and potential impacts of IRB.
 - f) Magnetic bacteria is another type of bacteria that can influence corrosion. They contain nano-sized magnetic particles based on iron. It is suggested that these bacteria could influence corrosion in a similar way to IRB but this is not fully understood. There is evidence that magnetic bacteria can influence the formation and activity of other bacteria that can cause MIC such as SRB.

One essential question is the importance of the different types of bacteria and to what degree they are relevant for the conditions that mooring lines operate under. Some bacteria will not leave any evidence that can be directly traced to their activity and can probably only be recognised through identification of their organisms. Some bacteria though, and in particular SRB, can leave measurable evidence of their activity. Their production of hydrogen sulphide, for instance, that reacts with iron to form iron sulphides, which has an extremely low solubility in water, may potentially provide a quantifiable footprint. As through this process they will accumulate sulphur, from sulphate in the sea, which may be at a higher level than other available sources of sulphur and so will stand out.

It essential to note than none of these bacteria will exist on their own and it may well be their coexistence and the way that they influence each other that is crucial to the potential for MIC. In this context it is worth making not of the following statement from within the references: *“it is recognised that while the corrosion may be attributed to a single group of organisms, the most aggressive microbiologically influenced corrosion (MIC) occurs with natural populations containing many types of microorganisms. Furthermore, a single type of microorganism can simultaneously affect corrosion via several mechanisms.”*

It should also be noted that biofilms and bacteria can contribute to slowing down or inhibiting corrosion. Biofilms can slow down the transport of oxygen to the steel surface thus reducing the rate of the cathodic reaction. There are also reports of different bacteria that through their activity modify reactions in such a way as to slow down corrosion processes. In the literature, one can find discussions of

possible use of Iron Reducing Bacteria or Magnetic bacteria to control or mitigate MIC caused by other bacteria.

So far all allegations of MIC in connection with mooring systems have been based on SRB and is still considered by many to be the main threat under the conditions that mooring chains operate. Even though there can be other MIC explanations or threats the rest of this report deals with SRB. The need to address other or mixed MIC causes may come out of future investigations into SRB. Through this prioritization we do not dismiss other causes but it is necessary to address allegations of SRB first through available evidence and further investigations based on a sound scientific approach.

3.3 SULPHATE REDUCING BACTERIA

3.3.1 Definitions

Sulphate Reducing Bacteria (SRB) are anaerobic bacteria using SO_4^{2-} (sulphate ion) as electron acceptors. It is the group of the micro-organisms that probably has been most widely connected to corrosion influenced by microbiology. The result of their metabolism is the production of S^{2-} that reacts with hydrogen or metal ions to form hydrogen sulphides or metal sulphides. There are different types of SRBs that can favour activity in different temperature ranges and tolerate different pH levels. In terms of mooring system conditions there will be SRBs that can be active over all relevant temperature and pH ranges.

SRB require oxygen depleted conditions (anaerobic) in water environments and an adequate supply of Sulphate, Carbon, Nitrogen and Phosphor, mainly in the form of organic compounds, for their activity. If any of these “nutrients” are short the activity of the SRB will be limited accordingly. In environments that are free from essential nutrients there will be no activity of the SRB.

The activity of aerobic bacteria in the outer part of a bio film will consume oxygen for their metabolism creating anaerobic conditions close to the steel surface. Sulphate will permeate through the film and nutrients will be available from organic material inside the bio film resulting in good conditions for SRB activity.

3.3.2 Sources accumulation of sulphur

In connection with possible identification of SRB corrosion it is important to be aware of relevant sources of sulphur since sulphur, could become a part of the identification process. Specifically there have been allegations of SRB based on measured high concentrations of sulphur on the steel surface or in corrosion products. To use high sulphur concentration as an indicator one needs to know what the “natural” occurrence of sulphur is on steel surfaces in marine environments.

Sources of sulphur are:

Seawater

Sulphur in seawater exists primarily as sulphate ions (SO_4^{2-}), which are highly soluble in water, with a typical concentration of 2.7g/kg. This corresponds to 0.9g/kg of Sulphur atoms only.

There can also be traces of other sulphur compounds such as hydrogen sulphide (H₂S), sulphur dioxides (SO₂) and others. However, the amounts will be negligible compared to the amount of sulphur in sulphate.

Steel

Steel contains small amounts of sulphur (impurities) – typically less than 0.05% by weight. This means that for every 1000 Iron atom there will on average be one or less sulphur atoms. For lower concentrations the ratio of sulphur atoms to iron atoms will go down proportionately. One of the purposes of adding Manganese (Mn) to steel is that sulphur reacts with Mn to form manganese sulphide (MnS). (At steel manufacturing temperatures the sulphur reacts preferentially with Manganese to avoid the formation of iron sulphides that form undesirable phases with iron). The MnS exists in the form of particles that during rolling or drawing of steel will end up as “flakes”, which are needle like impurities.

During the manufacturing process steel oxides will form on the surface and it would be reasonable to assume that within the oxide layer there will also be some sulphur present. This will depend on the manufacturing process and the degree of removal of slag and oxides after manufacturing.

Accumulation of sulphur compounds on steel surfaces.

When steel corrodes, iron oxides and iron hydroxides will be formed and precipitate on the corroded surface from the dissolved iron ions. When iron from the steel surface is being consumed the associated MnS impurities will also be released from the steel. This Manganese Sulphide has a low solubility in water and will most likely remain within the corrosion products. It is reasonable to assume that the sulphur concentration within the solid corrosion products originating from the corroding steel can be in the order of a few hundred ppm by weight. As a coarse estimate it is reasonable to assume that there will be in the order of one or less sulphur atom per 1000 iron atoms within the corrosion products provided all dissolved iron and sulphur end up in the corrosion products, and this will be in the form of MnS.

Sulphate is very soluble in water so as long as the steel component is submerged in sea water the natural concentration of sulphate in water will prevail. Thus there will be no accumulation. However, when a steel component is taken out of the sea or more specifically corrosion products from a corroded surface, it will be soaked with water. Water that does not run off will eventually dry out leaving salts behind in the corrosion products. Some of this salt will be sulphate salt.

Let us for illustration assume that 20% of the weight of corrosion products is water. A sample of 1.25g of wet corrosion product will end up as 1g of dry corrosion product. 0.25g of water will leave behind $0.9 \times 0.25 / 1000 = 0.23\text{mg}$ of sulphur (atomic). By comparison the corrosion product will contain in the order of 0.2 – 0.3mg of sulphur originating from the steel. Thus we would talk about in the order of 0.5mg of sulphur atoms per gram of corrosion product.

Please note that the estimates made regarding the concentrations of sulphur are based on a number of assumptions and should be regarded as indicative. If the sulphur concentration in corrosion products shall be used as a indicator of SRB it is essential that the typical sulphur concentration in the original steel is measured.

Possible accumulation of sulphur from SRB.

SRB reduce sulphate and produce S^{2-} ions or H_2S . The S^{2-} ions will quickly react with Fe^{2+} ions to form iron sulphides. Iron sulphide has a very low solubility in water and will thus precipitate as solid material. Possible structures of this solid material will be discussed in a later section. At this stage we are making the point that SRB turns water soluble sulphate into insoluble sulphides. In effect SRB can facilitate accumulation and increase the effective concentration of sulphur on a steel surface.

3.3.3 Possible mechanisms for SRB corrosion

There are still significant uncertainties regarding the mechanisms for how SRB initiate or stimulate corrosion of steel. One explanation has been depolarisation of cathodic sites on steel surfaces through the consumption of atomic hydrogen. However, this theory seems to be partly abandoned. More focus has recently been given to role of Iron Sulphides that will form when H_2S or S^{2-} ions react with Iron and Iron oxides on the steel surface. The described reactions and processes involved are complex.

Iron Sulphide has a very low solubility in water and will precipitate on the steel surfaces and generally be black in colour - see for example . Iron Sulphide films/layers attached to the steel surface can act as a cathodic site and thus promote Iron to go into solution at anodic sites thus stimulating the corrosion. In conditions with uniform exposure of steel surfaces to water with dissolved H_2S the FeS film will protect the surfaces as long as it is intact while high corrosion rates can develop where the film is damaged.



Figure 3-6: Black Coloured Link when first recovered on the back of an Anchor Handling Tug

In principle Iron Sulphides on steel surfaces subsea can originate from the following:

- From the steel itself as described in the previous section.
- Exposure to hydrogen sulphides dissolved in the surrounding water. This can react with iron from the steel to form iron sulphide. Sources of hydrogen sulphides could be from SRB activity in sediments. In open sea water the concentration will be very low but mooring components buried or partially buried in mud or sediments with adequate nutrients for SRB can be exposed to hydrogen sulphide environments.
- Exposure to active SRB in biofilms covering the surface producing H_2S or S^{2-} ions that react with iron or iron oxide films.

A verification of the presence of iron sulphide cannot uniquely be used to prove SRB corrosion. However, if the measured concentration of FeS is much higher than can reasonably be expected from other sources (as described above) the evidence could point to SRB corrosion. Patches with high concentration of FeS among surfaces with very low concentrations of FeS could also favour explanations in terms of SRB corrosion.

Iron Sulphides can form a range of (crystalline) structures such as Mackinawite $\{FeS_{(1-x)}\}$, Greigite (Fe_3S_4), Pyrrhotite ($FeS_{(1+x)}$) Pyrite (FeS_2) and others (including amorphous FeS). In biofilms with SRB activity on steel surfaces Mackinawite is the first structure to form according to literature sources. It is claimed in the literature that Mackinawite is unlikely to form through other mechanisms under normal sea water conditions. It is relatively stable under conditions where SRB are active, but will gradually transform to Greigite that again after time transform to Pyrrhotite. The diagram in figure 2.4 illustrates formations and transformations of iron sulphide structures at pipeline corrosion sites. (Although this is not entirely relevant for corrosion on mooring chains it has been included for illustration purposes.) The rate of transformation will depend on pH, temperature and redox conditions. Mackinawite and Greigite are less stable in fresh sea water conditions and will transform even faster. It is also claimed that only pyrite is stable under conditions that can prevail in relevant sea water conditions and that it forms relatively easily in non-biological H_2S conditions. However, the only likely sources of H_2S are bacterial activity in locations where mooring systems under consideration here are deployed.

The natural source of H_2S in sea water is SRB either in biofilms on the metal surfaces or in anaerobic layers of mud or sediment with adequate nutrients.

It has been suggested in the literature that the Iron Sulphide structures produced as a result of SRB could be more corrosive than iron sulphides produced chemically in non-biological environments.

Reported investigations indicate that some of the most severe corrosion related to SRB can take place when the conditions vary between anaerobic and aerobic conditions. It has been indicated that the corrosion rate can be highest in aerobic conditions in between anaerobic conditions. It is not clear what the cause is but the stability of some of the iron sulphide structures will change when the oxygen level increases.

Under certain conditions Iron sulphides can react with oxygen and water to form sulphuric acid H_2SO_4 acid, which in itself could potentially contribute to corrosion, as well as elemental sulphur. This could be one of the reasons why changes from anaerobic to aerobic conditions can create high corrosion rates.

Sulphuric acid is a strong acid and dissociates into 2H^+ and SO_4^{2-} (sulphate ion). This can in principle be one route where sulphur can escape from the iron sulphide state and thus reduce the accumulation of sulphur in the form of iron sulphide.

Dr. B. Little has through direct communication (and reference to the literature) indicated that SRB are unlikely to cause severe corrosion under stable conditions such as under permanent and protected biofilms. Under such conditions an iron sulphide film will develop on the steel surface and partly protect the steel from further corrosion. However, if the conditions change in terms of oxygen getting access or mechanical disturbance the iron sulphide film will be damaged and corrosion will accelerate. Sulphur oxidising bacteria and the production of sulphuric acid may play an important role in this process. There are hypotheses of a complete sulphur cycle where different bacteria participate, converting sulphate to sulphide to elemental sulphur and back to sulphate.

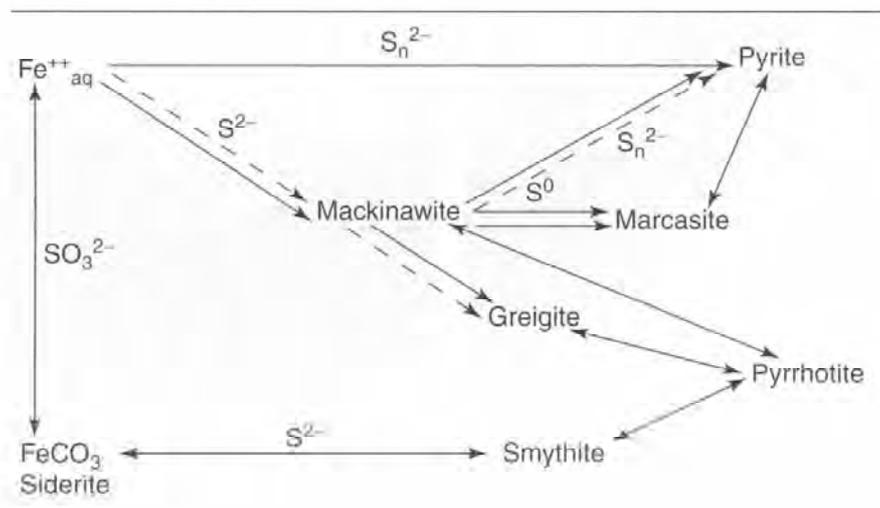


Figure 3-7: Illustration of formation and transportation of iron sulphide structures at pipeline corrosion sites

However, there are still other hypotheses for the mechanisms for corrosion under the influence of SRB. One is that some strains of SRB can use iron in combination with other compounds for reduction of sulphate. Another hypothesis is that SRB in very close contact to the steel surface can take electrons directly from the metal thus providing the cathodic reaction for the corrosion process.

With a range of possible mechanisms that can cause the corrosion and the complexity of bio films it is reasonable to assume that several types of organisms will jointly influence corrosion.

It should also be noted that reports indicate that SRB can enhance the danger of hydrogen embrittlement and hydrogen induced cracking (HIC). The cathodic reaction in the corrosion process will result in the formation of atomic hydrogen that can diffuse into the steel and cause embrittlement. SRB activity in itself will generate hydrogen thus adding to hydrogen from the cathodic reaction. Cathodic protection will tend to enhance the cathodic reaction and thus the generation of hydrogen on the steel surface. A high protection potential in combination with SRB may therefore enhance the risk of HIC.

3.4 DIAGNOSTIC FOR MIC

As described above there are many uncertainties regarding the mechanisms for MIC. The processes and reactions taking place are complex and many potential mechanisms are extremely difficult to prove. This makes it difficult to unambiguously determine whether MIC has or is taking place.

The first step to determine whether MIC is influencing the corrosion is to explore all possible other causes for the corrosion. Only if this does not lead to a plausible explanation one should go down the route of investigating the possibility of MIC.

In general, experts within the field prescribe a combination of 4 different types of investigation:

1. Identification of the causative organisms
2. Characterise the corrosion pit morphology
3. Characterisation of the chemical environments and the corrosion products
4. Simulation of environment under laboratory conditions to prove hypothesised process

3.4.1 Causative organisms

In the environments we consider for corrosion on mooring chain components there will be a large number of different bacteria present and most of them will not take direct part in MIC. SRB will be present in the environment in varying concentrations and generally the concentration level and/or conditions will not lead to abnormal corrosion.

Samples from bio films can be collected and taken to laboratory for investigation using culture techniques or others. One may demonstrate that SRB are present in either small concentrations, less than 10/ml, or in very high concentrations, with more than 10 000/ml. If the count is very low, it is unlikely that SRB is a problem at the time of the sampling. If the number is very high, then there is clearly SRB activity although that does not prove that MIC is taking place, but there will clearly be a higher risk of SRB. With concentration counts in between the low and the very high the conditions are undetermined and it is not possible to draw any conclusions.

Today we do not have any data with regard to the typical and natural variation of the concentrations of SRB (or other causative organisms) on steel components in sea water similar to those prevailing for mooring systems. If one wants to characterise and quantify SRB in connection with corrosion on mooring components it is essential to collect and analyse samples from not only the locations with corrosion pits but also from other locations where corrosion has not been detected.

3.4.2 Pit Morphology

From literature or other consulted sources there is no unambiguous information regarding the pit morphology caused by MIC distinguishing it from the morphology of pits formed by other types of corrosion under conditions relevant to corrosion of mooring system components.

The following statement from Tatnall and Pope may be useful in this context:

“Surface morphology relates to the chemistry at the metal surface, not to the presence or absence of micro-organisms”.

3.4.3 Chemical environments and corrosion products

The chemical environment must provide necessary conditions for the micro-organisms under question to be active. For SRB this will mean anaerobic conditions, availability of sulphates and adequate supply of other “nutrients” normally in the form of organic material. Further more, the temperature and local pH must be within acceptable ranges. High SRB activity can in itself modify properties and conditions of the environment sufficiently to slow down their activity. This could be changes in pH or depletion of certain necessary nutrients. Out in the field, one could in principle measure pH, redox potential and the concentration of certain constituents in the biofilm using micro-sensors during inspection when chains are retrieved to deck. Such investigations would have to be carried out immediately after retrieval to deck before ingress of oxygen and would only be of value in well protected biofilms.

As described in an earlier section, active SRB on steel surfaces could produce accumulation of sulphur through turning sulphate into iron sulphide. If one measures a concentration of sulphur in corrosion products that is significantly higher than the concentration of sulphur found in corrosion products not affected by SRB Corrosion, it will be a good indication of SRB activity (it is difficult to see other sources for accumulation of sulphur). This approach will require systematic investigations of “natural” concentrations of sulphur in sea water corrosion products.

SRB can as earlier mentioned lead to the formation of certain iron sulphide structures that can only be formed through biological activity. Thus detection of these structures will be a strong indication of MIC. However, the iron sulphide structures such as mackinawite and greigite are not stable especially when exposed to aerated environments and may over time convert to pyrite which is stable. It has been suggested that when corrosion products are removed from locations affected by this kind of corrosion the surfaces will be metallic shiny. X-ray diffraction of samples from corroded surfaces can be used to confirm specific iron sulphide structures. It is important that the samples are taken according to defined procedures and brought to a suitable laboratory as soon as possible in a container that is sealed to minimise ingress of oxygen.

The following approaches can be followed to determine the likelihood of SRB corrosion:

- SRB activity results in the generation of H₂S that smells like rotten eggs. When chains or mooring components are taken on deck it can be useful to note whether there is any smell of H₂S. One should also be aware of this during removal of marine growth. In particular one should be aware of and report any evidence of H₂S when handling chains that have been in the mud on the sea floor. Signs of H₂S should be taken as a sign of SRB activity that could trigger a more detailed investigation into SRB corrosion.
- Black patches or flakes among the corrosion products can be iron sulphide, which is likely to be linked to SRB activity. To verify FeS one can apply hydrochloric acid that will react with FeS and produce hydrogen sulphide that will have the distinct smell of rotten eggs.

-
- In reported investigations, analysis has been carried out to measure the concentration of different elements in corrosion products from corroded surfaces using (EDS) Energy Dispersive Spectroscopy. High sulphur concentrations have been taken as indication of MIC. To use this as an indication of SRB corrosion it is essential that comparisons are made to the sulphur concentration in corrosion products from locations without indications of SRB, as described earlier in this section.
 - X-ray diffraction to detect and characterise iron sulphide structures:
 - If Mackinawite, Greigite or a few other iron sulphide structures can be detected one has very strong evidence of SRB activity influencing corrosion processes.
 - If Pyrite is detected there is a strong evidence of MIC as pyrite will tend to be the stable end product when other structures convert.

For all these investigations, and in particular those specified in the last 2 bullets, it will be important to analyse scrapings of surface films from areas with general corrosion for comparison. Evidence used to indicate SRB must stand out clearly from equivalent measurements in other locations.

3.5 PREVENTION OF MIC / SRB

Measures to avoid or prevent MIC could be:

- Avoid pollution from oil drilling and oil production activities or other depositions of nutrients.
- Use of cathodic protection with anodes or impressed current, however, avoid using overprotection potential as it can promote hydrogen embrittlement and hydrogen induced cracking (HIC).
- In principle avoiding anaerobic conditions can prevent SRB activities. This can, however, be difficult to achieve if the anaerobic conditions develop under bio-films. Intermittent cleaning can make things worse as it has been seen that changes between oxic and anoxic conditions could be the most important factor for SRB corrosion.

3.6 MIC ON MOORING SYSTEMS

3.6.1 Susceptibility of mooring system

Mooring systems considered within the Mooring Integrity JIP are generally located in open sea water environments. A mooring system will go through all parts of the water column and a substantial part of it will typically be on or in the sea bed.

In general, sea water will contain a variety of micro-organisms and have a dissolved oxygen concentration ranging from around 8 ppm and lower. In surface water, the oxygen content can effectively be higher as air is mixed in as a gas phase. Anaerobic bacteria such as SRB will also be present, but they will not be active until they end up in locations suitable for their metabolism.

3.6.2 Bottom part

The conditions on the sea bottom can vary significantly. There will be varying degrees of mud, sand, gravel and other sediments. Micro organisms need nutrients

to be active and their activity on the sea bottom will depend on the availability of organic material such as dead plants and sea “animals”. This will vary between sea regions and with water depth.

A typical scenario is that there is a steady supply of organic material that bacteria will consume for their metabolism. If the sea bottom is soft, with a significant layer of mud and sand, one will expect bacterial activity in the surface layer with aerobic bacteria at the top and possibly anaerobic bacteria just below if oxygen is depleted by consumption from the aerobic bacteria. If there is no organic material mixed into the soft bottom layer, there will be no bacterial activity below the surface layer.

Pollution in terms of drill cuttings and other disposals can result in hydrocarbons mixed in with sediments on the sea bottom, creating the right environment for high bacterial activity and enhanced risk of MIC.

High levels of organic material can also come from other sources, such as nearby rivers, both in the form of natural organic material in the river water and as pollution from human activities.

Chains in the touch down region will part of the time be stationary on the bottom and at other times pulled up into the water above the bottom. This can result in conditions around the chain that vary between anoxic and oxic. These kinds of changing conditions have been reported in the literature to generate high corrosion rates.

3.6.3 Upper part

This is the part of the mooring system from just above the sea level down to depths where the impact from waves on the movement of water is limited.

Key relevant features and characteristics are

- A limited part of this section will be in and out of water during wave action
- Ample supply of oxygen
- Significant marine growth
- High speed of water from wave action and FPSO motion during high sea states
- In several geographical regions there will be seasonal variations of the waves activity and temperature
- Some mooring systems will be partially protected against corrosion by anodes or impressed current systems on the floater

Bio films will develop on steel surfaces in combination with macro fouling that will vary significantly over the surfaces in terms of type and density. The macro fouling may facilitate the creation of protected pockets allowing a variety of bacterial activities within the biofilm. The macroscopic marine growth can also be a source of nutrients for the bacteria in the bio film.

In principle, the conditions are suitable for MIC to develop both in terms of corrosion “cells” with different oxygen levels and the development of anaerobic conditions.

At the same time, in the splash zone area there is likely to be significant oxygen corrosion that would be of a more general nature.

Due to seasonal or periodic conditions with high waves both macro fouling and bio-film can be removed creating aerated conditions in locations that may have been anaerobic when the bio film was intact. It is reported in section 3.3.3 that 'some of the most severe corrosion related to SRB can take place when the conditions vary between anaerobic and aerobic conditions'. Hence the significance of removal of macro fouling and bio-film should not be underestimated.

4 FIELD EXPERIENCE

4.1 FIELD EXPERIENCE CASES

There have been several cases where corrosion damage on mooring chains have been alleged to be caused by SRB. The basis for explaining the corrosion attacks in terms of SRB have been varied:

- Type and unexpectedness of the corrosion attack
- Measured high sulphur contents
- Identification of Iron sulphides

There are cases where mooring chain ruptures have been attributed to SRB corrosion pits as the possible cause of stress concentration leading to crack growth. It has also been suggested that SRB has been the source of hydrogen-induced cracking (HIC), but material analyses of cracks have not shown signs of this.

Input from participants of the Mooring Integrity JIP and information sought from other sources has resulted in information and data from 5 field cases, with these cases being presented in Table 4-1.

Case	Cause of investigation	Position on mooring system	Corrosion pattern	Evidence of MIC	Depth of attack or pits
1	Planned inspection	Bottom / touch down	Pitting and irregular corrosion	High sulphur, black patches and corrosion products → FeS, Add HCl → H ₂ S	1-2mm
2	Failure	At FPSO	Pitting and weld corrosion	High sulphur in corrosion products	2.1mm
3	Failure	Above seabed - occasional seabed contact	Pitting small and large	Black patches on retrieval suggesting Fe high sulphur in corrosion pits	5-6mm
4	Planned inspection	Touch down & above touch down	Severe material loss / pitting	Suggested based on severity of metal loss, pit topography, black patches and foul smell	14mm loss of segment; 2-4mm deep pits
5	Planned inspection	At FPSO	Pits	Suggested based on topography and black patches. Unique compared to neighbouring chains	3-4mm

Table 4-1: Summary of key information from field cases with suspected MIC

4.2 EVALUATION AND PICTURES FROM 3 FIELD CASES

4.2.1 Case 1

In Figure 4-1 and Figure 4-2 provide pictures from case 1 showing the corrosion pattern and profile of pits detected.



Figure 4-1: Corrosion pattern from case 1

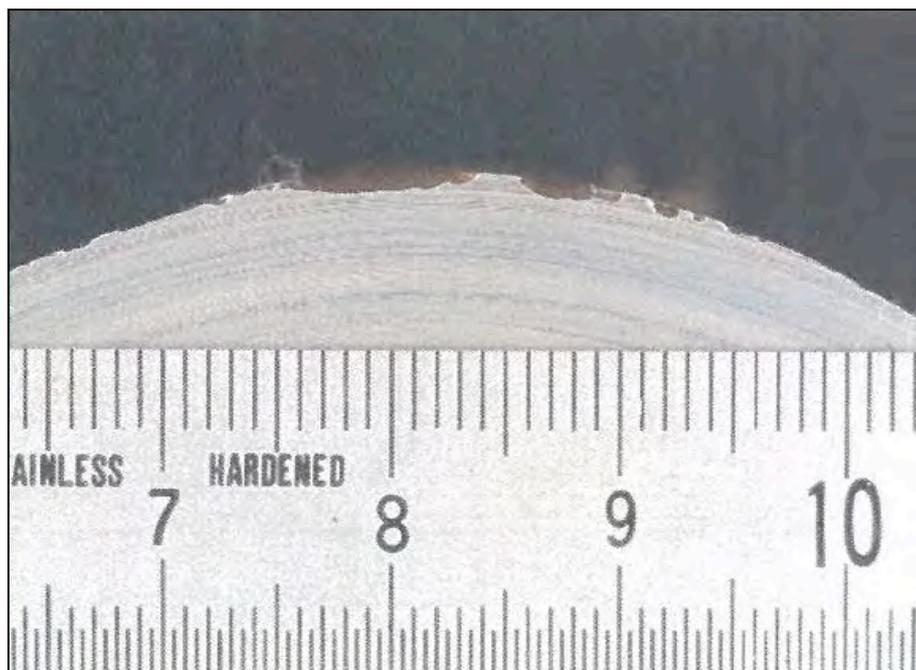


Figure 4-2: Pit profile from case 1 corrosion

Important information to note:

- Some areas among extensive corrosion were partly black coloured. This was found after the chain had been taken onshore for laboratory investigation.
- Application of hydrochloric acid to black patches resulted in the generation of H₂S observed through its smell. This is a strong indication of the presence of iron sulphides.

4.2.2 Case 4

Figure 4-3 and Figure 4-4 show details of some of the affected links from case 4.



Figure 4-3: Corrosion pits among black patches from case 4



Figure 4-4: Corrosion pattern from case 4 showing significant loss of material

Important information to note from Case 4:

- There was a foul smell on deck when these chains were taken on board suggesting H₂S from the sediments and surface fouling.
- There were black patches on the steel when growth and sediment were removed.
- Significant amount of steel - around 14mm on investigated links - was lost along the link surface line that was resting on the sea floor with identical pattern on consecutive links. One possible explanation for the severe corrosion in these locations may be that there have been mechanical damage of iron sulphide films caused by friction forces during interaction with a hard sea bottom.
- There was a significant amount of pitting in addition to the loss described above.
- The severe loss of material and pitting did only take place in the touch down region where the chain was going in and out of the mud. Further out along the chain where it was stationary on the bottom there was no corrosion.

The evidence suggests that it is highly likely that the corrosion is related to SRB activity either in the mud and/or on the chain surfaces. It is the variation between the presumably anaerobic conditions in the mud and occasional exposure to oxygenated water that seems to be the cause of the corrosion. From earlier discussions it is possible that oxygen reacts with iron sulphides produced on the steel surface from H₂S generated by SRB thus promoting the severe corrosion. Mechanical interaction with the sea bottom may also play a role.

It has been speculated whether observed corrosion can be connected to “pollution” or deposits promoting the bacterial activity.

4.2.3 Case 5

Figure 4-5 shows corrosion pitting from Case 5:



Figure 4-5: Link with corrosion pits with black patches from Case 5

Observations from Case 5:

- The corrosion was on the top chain close to the surface within the turret region.
- The observed corrosion was only found on 1 of several chains that were inspected thus the corrosion damage is exceptional and difficult to explain
- Indications of black patches suggest that it could be MIC / SRB
- Break tests were also carried out on several chain links showing that the break load dropped by around 7% compared to the average.

4.3 INVESTIGATION OF CAUSATIVE ORGANISMS FROM FIELD

The presence and concentration of relevant micro-organisms (causative organisms) have been investigated both to explain anomalous corrosion and to evaluate the risks for MIC. Samples of corrosion products and mud have been collected and analysed primarily through cultivation to determine the number of SRB. Some of these investigations can be summarised in the following:

- Mud/water from polluted river: 500,000 SRB/ml water
- Mud at a mooring touch down: 2 to 130 cells/g
- Surface scraping from a chain link ranging up to 27,000,000 cells/swab
- Cultivation of corrosion products from a chain link resulted in 9,300 SRB/g

The methods for collecting samples and quantification of the results make it difficult to compare the results and there are no defined criteria for evaluating or comparing the results. It is reasonable to assume that 500,000 SRB/ml and 27,000,000 cells/swab represent readings with high concentrations that are likely to represent ongoing or recent high SRB activity.

To enhance the value of sampling for causative organisms it is important to standardise the sample taking and the analyses methods. The standardization has to cover:

- How to collect samples of
 - Corrosion products
 - Mud
 - Water
- How to cultivate and analyse to ensure that the results are comparable

One will also need procedures for handling (storage and transport) of samples - see section 6.

Since analyses of causative organisms seem to be less conclusive than other investigations no further guidelines on this area have been provided in this document.

5 DISCUSSIONS AND RECOMMENDATIONS

5.1 LESSONS FROM FIELD EXPERIENCE

None of the field cases provide evidence that unambiguously confirm (in a scientifically robust way) that the corrosion damage is caused by SRB or MIC. Based on available information some of the cases provide mere suggestions of SRB as the explanation.

5.1.1 Iron sulphides

There is, however, evidence that fairly strongly suggests that SRB plays a role in some of the corrosion cases. In particular evidence that fairly high concentrations of iron sulphides are present provides a strong indication of SRB. The strength of proof vary – black patches on its own provide much weaker evidence than additional confirmation of the generation of H₂S when samples from the black patches have been exposed to hydrochloric acid.

5.1.2 Locations and conditions

There are two distinct parts of the mooring lines where there are indications of SRB influenced corrosion:

- At or just above the sea bottom and in particular in the touch down region
- In the top chain close to the splash zone

In the literature there are suggestions that the highest corrosion rates can occur in locations where the conditions change between oxic and anoxic. This seems to fit with the field data where the touch down region is vulnerable.

It may also be possible to explain possible SRB corrosion in top chain in terms of conditions changing from oxic to anoxic. For parts of the season with calm weather bio-films and macroscopic fouling can establish and create anaerobic conditions for SRB on the surface. In the winter season with heavy weather, parts of the surface growth may be ripped off due to high flow rate of water resulting in exposure to oxygen. (It should be noted that this is one hypothesis).

One should be aware of possible MIC / SRB causes (or enhancement) from pollution or deposits from oil activity. High levels of nutrients and bacterial activity well below the surface layer within sea floor sediments/mud would be an indication of higher risks for MIC.

5.1.3 Corrosion rates

There is very limited information available to estimate the corrosion rate. It is reasonable to believe that the reported findings are the results of the first inspection after installation. The detected corrosion can have taken place continuously from installation but it can also have taken place over a more limited time period.

The case with the most severe corrosion attack would end up with around 1.5mm/year if there was an even corrosion rate over the full service life. While the other cases would range from 0.3 to 0.6 mm/year if the reported corrosion depth had developed since installation. However, considering the randomness of reported SRB occurrences it is more likely that the detected corrosion damage has taken place over a more limited period of time. This would result in much higher corrosion rates. With no further evidence it is impossible to assign any credible numbers to the corrosion rate.

5.1.4 Collection and quality of evidence

Information from the field cases show that the value with respect to the mechanisms could have been enhanced significantly by better procedures and additional inspection/sampling. This concerns:

- Visual inspection and observations in the field combined with systematic reporting.
- Measurements and testing in the field.
- Collection and handling of samples and subsequent analysis.
- Data and information on how the mooring lines have been operated.

With more and better quality evidence it would have been possible to come up with a more unambiguous interpretation.

5.1.5 The mechanisms

All reported cases focus on SRB as the cause of the observed corrosion. With explanations centred around iron sulphides, and based on this a hypothesis that SRB has been involved.

One can envisage two different ways in which SRB influence corrosion on mooring chains, in particular in mud on the sea floor:

- SRB activity in the mud or sediments produce H_2S that reacts with the steel on the chain surface and forms Iron sulphides
- SRB activity on the chain surface under bio-films create conditions that result in corrosion.

It is important to note that there are strong suggestions that SRB related corrosion of mild steel becomes severe when conditions change between anaerobic and aerobic. This has become a stronger realisation within the scientific community over the last few years. At the same time the presented evidence from mooring systems tend to support this hypothesis.

5.1.6 Consequences

Possible consequences of SRB can be:

- Higher metal loss rates than the design normally allowed for can take chain links below the minimum break load.
- Sharp pits can be the initiation for fatigue cracks.
- It is possible that hydrogen generated from SRB activity can lead to embrittlement and HIC but no conclusive evidence has been found for chain failures.

5.2 MISCELLANEOUS THOUGHTS AND SPECULATIONS

This subsection has been introduced to allow presentation of a few thoughts and speculations that have been triggered during the process of preparing this report.

We have described the concept that active SRB may not cause corrosion under stable conditions (such as under biofilms) since “protective” iron sulphide films may develop on the steel surface. Severe corrosion may take place mainly when these sulphide films are damaged from ingress of oxygen or through mechanical interaction. In this context there is the potential for active SRB over larger parts of the steel surfaces and could in principle contribute to limiting the corrosion. This should be taken into consideration if one goes ahead with quantification of sulphur contents on steel surfaces in general.

It is also be worth reflecting on mechanisms that can cause damage to iron sulphide films.

- These films will in general be fairly brittle and might crack when subjected to strain above certain limits. It is worth considering whether there are locations on chain links on a mooring system where the strain under extreme loads can lead to such cracking or partial de-cohesion. This could promote localised corrosion.
- In the intergrip regions on chains one assumes that biofilms will not be able to establish due to mechanical interaction between neighbouring chain links. However, in positions near the intergrip region there may be mechanical contact only in extreme conditions or under special operation. This could lead to a scenario where stable biofilm conditions could be damaged intermittently and contribute to higher corrosion rates in extremities of the intergrip zone.
- One should also be aware that regular cleaning for inspection purposes in the same location may disturb stable conditions with limited corrosion.

6 OUTLINE PROCEDURES FOR INFORMATION COLLECTION

6.1 GENERAL

The following is a draft outline procedure for inspection, testing, sampling and analyses:

1. Make a thorough evaluation of the mooring systems operation and configuration including such things as chain locations, motion etc. This will be important both for preparation of procedures and evaluation of the results.
2. Prepare specific procedures and make necessary equipment and tools available (Camera, sample jars, chemicals (HCl, NaOH), equipment to measure Redox and pH etc).
3. Inspection, observations and sample collection

6.2 ON DECK WHEN CHAINS ARE LIFTED UP FOR INSPECTION

1. Observe and take pictures of the chain sections and chain links.
2. Make note of smells that resemble H₂S (rotten eggs) and try to locate the source.
3. Where MIC is suspected: when removing marine growth and deposits from the surface of the chain links take pictures and observe and make notes regarding appearance and smell. Wherever possible remove layer by layer and observe colour and possible shininess.
4. If there are indications of MIC then collect samples in small jars together with sea water. The jars shall be topped up to the rim with sea water to minimise the amount of air trapped in the jar. Sample collection should, where relevant, include the full thickness of the deposits in selected jars, and limited scrapings of corrosion products close to the surface in other jars. The pH in the jar should be measured before closing (One should consider increasing the pH by adding NaOH to reduce the potential for unstable FeS structures transforming).
5. If black corrosion products are found, testing should be carried out by applying HCl to determine whether H₂S is being generated.
6. *Inspection, observation and sample collection should also be done in locations where there is no suspicion of MIC (including locations with general oxygen corrosion). Such comparison is essential to assess the significance of finding from MIC locations.*
7. An option can be to use micro-sensors to measure properties such as oxygen concentration, Redox potential, pH, CO₂ as function of depth into the bio-film.
8. Measure the profile and depth of the most severe pitting found.

6.3 IN SITU INSPECTION BY DIVER OR ROV

1. General observations with video / pictures of condition of chain and links to be inspected
2. When marine growth is removed careful observation should be made of colour and shininess.

3. Samples of marine growth/ bio-films and corrosion products should be done using a syringe type device (with a large opening where particles are sucked in). The device should be operated so that no air is trapped inside the container. When the container comes onboard it should be sealed with no air trapped

4. Also take samples in locations with no suspicion of MIC

6.4 HANDLING OF SAMPLES

Plans should have been made to transport samples onshore and to a laboratory for analysis as soon as possible, for example by helicopter and then hand delivered to the lab. If possible the samples should be kept cold (e.g. by ice).

6.5 ANALYSIS OF SAMPLES

The following analyses should be considered:

- Verify HCl tests for H₂S
- Carry out X-ray diffraction on possible samples of FeS to determine specific structure
- Measure concentration of sulphur (and other elements) in corrosion products, and possibly the content of sulphates
- Optical microscopy and Scanning Electron Microscope (SEM)

Whenever possible chain links with MIC like corrosion should be taken out for laboratory investigation including:

- Analysis of surface deposits
- Topography
- Material properties including actual chemical composition

7 CONCLUSIONS

7.1 GENERAL

A general observation is that the number of reported alleged cases of SRB / MIC seem to be limited considering the number of mooring lines that have been inspected without any reports of abnormal corrosion. Some of the reported cases show limited damage and questions can be asked whether they represent MIC. However, one should be aware that the number of permanent mooring systems with significant service history will increase over the next years and thus enhance the possible impact of MIC.

Investigation of chain failures that have occurred cannot uniquely be related to MIC but cannot be ruled out since investigations show possible indications of SRB.

The most vulnerable parts of mooring systems seem to be the touch down region and just below the splash zone. There are indications that conditions that change between oxic and anoxic can enhance corrosion and possibly create the most severe corrosion.

For bottom chains, high bacterial activity in mud or sediments caused by pollution or deposits of high nutrient material will enhance of MIC risks.

Most of the reported cases are from cold regions, while the case with the most severe corrosion is from a warmer region.

There are significant uncertainties regarding the corrosion rate for the reported cases.

The evidence collected from the field could have provided more valuable information to enable clearer conclusions to be drawn through comprehensive procedures for inspection, sampling and testing. An outline of such procedures has been proposed and should be applied to ensure better information from future investigations.

7.2 RECOMMENDATIONS

7.2.1 Risks of corrosion of bottom chains:

If there are reasons to believe that there are risks for corrosion of bottom chain analyses should be made of mud and bottom sediments for pollution in different layers (typically top layer, 3-5 cm into mud, 15-25 cm and 50-100 cm depth) to measure and quantify organic nutrients, bacterial activity, sulphides, metals etc.

7.2.2 Information collection

It is recommended that operators implement the proposed procedures for inspection, testing and analysis during inspection when there is suspicion of MIC.

It is recommended that a program is initiated to collect information in a systematic way regarding relevant conditions/properties on chains to determine bio-films properties, concentration of sulphur and iron sulphides. The use of micro sensors should be considered to determine conditions in bio-films. By understanding the normal variability of relevant properties and conditions it will be possible to draw clearer conclusions from future investigations.

(One hypothesis is that SRB activity to some degree is fairly common but special conditions are necessary for excessive corrosion to take place)

To build a better understanding of MIC mechanisms, conditions under which they will cause damage and quantification of corrosion rate, a program should be initiated for testing in locations where MIC has been observed.

This report is intended for the sole use of the person or company to whom it is addressed and no liability of any nature whatsoever shall be assumed to any other party in respect of its contents.

GL NOBLE DENTON

Signed: _____ Signed original on file
Morten Eriksen, Phd

Countersigned: _____ Signed original on file
Eur Ing Andrew Comley, CEng MRINA BEng (hons)

Dated: Aberdeen, 31 March 2010

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Microbiologically influenced corrosion of mooring systems for floating offshore installations

Mooring Integrity Joint Industry Project Phase 2

Mooring Integrity for floating offshore installations is an important safety issue for the offshore oil and gas industry. This report is one outcome from Phase 2 of the Joint Industry Project on Mooring Integrity. This work ran from 2008 to 2012 and had 35 industry participants. It followed the Phase 1 work described in HSE Research Report RR444 (2006). The Phase 2 work compiled research on good practice and an overview is given in HSE Research Report RR1090 (2017).

Microbiologically Influenced Corrosion (MIC) is corrosion stimulated or caused by the presence of bacteria, algae or fungi on the surface of components. This report describes a study into MIC on offshore mooring system components. It is based on the literature, industry field cases and discussion with MIC specialists. It describes possible MIC mechanisms and identifies that uncertainties make it difficult to unambiguously determine whether MIC has taken, or is taking, place. It is found that although none of the field cases unambiguously confirms MIC damage, there are possible indications that sulphate-reducing bacteria play a role and that the most vulnerable parts of mooring systems may be at or just above the sea bottom and close to the splash zone. The report: sets out MIC diagnostics; outlines a draft procedure for industry inspection, testing, sampling and analysis of MIC on mooring systems; and identifies some measures that could potentially reduce the likelihood of MIC, such as avoiding pollution from oil drilling and oil production activities, or other depositions of nutrients.

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