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Corrosion Failures in Oil and Gas Fields: Review and Case Studies

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Abstract

Corrosion failures are most common in the oil and gas fields. Pipelines carrying oil and gas resources that suffer corrosion severely threaten the economy. High operating pressures and corrosion can drastically reduce the structural integrity and shorten the service life of pipelines. The major types of corrosion in the oil and gas industry are sour corrosion, sweet corrosion, oxygen corrosion, crevice corrosion, galvanic corrosion, erosion corrosion, stress corrosion cracking (SCC), and microbiologically influenced corrosion (MIC). This paper aims to briefly review the basic types of corrosion and place much of the focus on the MIC- especially in stainless steel and carbon steel piping applications. Even though standard stainless-steel grades used in oil and gas pipelines have considerable corrosion resistance, MIC may severely affect their integrity by the action of microorganisms. Three cases of MIC are addressed and discussed. Two cases of stainless-steel pipes, AISI 304 and 316LN, and one case of 5L grade A pipes. The leaking and perforation of the pipe and tube wall occurred 3 months after the hydro-test with bacteria-infected water. The high damage rate in carbon and stainless-steel pipes indicated that stainless steel is not immune to bacterial-assisted corrosion. The preventive actions of the MIC in these cases were also presented.

Keywords: Stainless Steel; Corrosion; Oil and gas; Microbiological; MIC; Firefighting

1. Introduction

Corrosion is the detrimental degradation of a material due to its reaction with the surrounding environment [1]. Global reports have verified that certain oil corporations experienced pipeline ruptures attributed to corrosion [2,3]. This review briefly discusses the most common corrosion failures in the oil and gas industry. The MIC is discussed in more detail as it is necessary to understand how to categorize bacteria, the common bacteria types associated with MIC, and the MIC of stainless steels before reviewing recent case studies of MIC failure in which the MIC is shown in stainless steels- and carbon steel- pipes after a very short operating time showing the severe effect of this type of corrosion in a good corrosion resistant material like stainless steels.

Before discussing the common corrosion failures in oil and gas fields, it is worth mentioning that Hydrogen sulfide (H_2S), Carbon dioxide (CO_2), and free water—as a corrosion catalyst—are examples of such extremely corrosive media in oil and gas wells and pipelines [4,5]. The following environmental reactions occur when water reacts with CO_2 and H_2S [2,6].

$$\mathrm{H_2CO_3\ reaction: Fe + H_2CO_3 \rightarrow FeCO_3 + H_2}$$
$$\mathrm{H_2S\ reaction: Fe + \ H_2S + \ \ H_2O \rightarrow FeS + 2H}$$

In the presence of both gases, a combination of the two processes may transpire [6].

It is exceedingly challenging to consistently categorize the numerous types of corrosion in the oil and gas sector. However, the major types are sour corrosion, sweet corrosion, oxygen corrosion, crevice corrosion, galvanic corrosion, erosion corrosion, stress corrosion cracking (SCC), and microbiologically influenced corrosion (MIC) [5].

The available literature on corrosion is huge and diverse, so it might not be possible to grasp insights into the subject by reading these many sources of information. The need for a brief and informative document to provide the necessary understanding of corrosion in oil and gas is more urgent now than before.

Thus, the purpose of this paper is to provide a brief review of corrosion damages in the oil and gas field to satisfy a larger number of seekers of this knowledge in just a few pages. Deeper attention was placed on the MIC damages due to their aggressiveness in terms of very rapid attack, the ability to affect all engineering alloys, and the abundance of variety of bacteria in almost all environments.

2. Sour Corrosion

Sour Corrosion, also known as H_2S corrosion, is the metal degradation caused by contact with hydrogen sulfide (H_2S) [5,6]. There are three types of sour corrosion: pitting, uniform, and stepwise cracking [1]. Although H_2S is not corrosive, it becomes extremely corrosive when mixed with water. When H_2S is dissolved in water transforms into a weak acid that produces hydrogen ions [7]. The corrosion products are iron sulfides (Fe_xS) and hydrogen. The NACE association published a globally recognized standard MR0175/ISO 15156 addressing the requirements and recommendations for selecting, and qualifying materials for H_2S service in oil and natural gas production. The following reaction is the sour corrosion reaction [2]:

$$Fe + H_2S + H_2O \rightarrow Fe_xS + H_2O + 2H$$

3. Sweet Corrosion

Sweet Corrosion, or CO_2 Corrosion, can be defined as metal degradation in aqueous CO_2 environments. Like H_2S, dry CO_2 is not corrosive, however, it becomes corrosive in the aqueous phase [6,8,9]. Several mechanisms for CO_2 corrosion have been proposed, but they all include forming either the carbonic acid or the bicarbonate ion when CO_2 dissolves in water. The most accepted mechanism was proposed by de Waard *et al.* and is as follows [6]:

$$H_2CO_3 + e^- \rightarrow H + HCO_3{}^-$$

$$2H \rightarrow H_2$$

The reaction on the steel surface:

$$Fe \rightarrow Fe^{+2} + 2e^-$$

So, the overall equation is:

$$Fe + CO_2 + H_2O \rightarrow FeCO_3 + H_2$$

4. Oxygen Corrosion

Oxygen, a potent oxidant, interacts swiftly with the metal. Drill pipe corrosion is largely caused by dissolved oxygen in drilling fluids. Oxygen accelerates metal anodic oxidation by acting as a depolarizer and electron acceptor in the cathodic processes [10]. The corrosive effects of the previously discussed acid fumes (H_2S and CO_2) are heightened by the presence of oxygen [11]. Uniform corrosion and pitting-type corrosion are the major types of corrosion related to oxygen [4].

5. Crevice Corrosion

Crevice Corrosion often occurs as localized corrosion when the crevice opening gap is typically so small that ionic species migration or diffusion into the crevice can be limited where the fluid becomes stagnant. This results in variations in the concentration of corrodents on a metal surface [12,13].

6. Galvanic Corrosion

Galvanic Corrosion is one of the most common types of corrosion, which occurs when one metal meets another conducting metal with different electrochemical potentials in a corrosive medium [14]. In this instance, the metal with the lowest or most negative potential serves as an anode and starts to corrode. The anode emits metal ions to balance the flow of electrons [14].

7. Erosion Corrosion

The term "Erosion Corrosion" refers to the process of material deterioration in which corrosion is brought on by surface oxidation along with mechanical wear due to the impact of solid particles, liquid, or a combination of both processes [14,15]. The corrosion rate is increased by continuously removing the passive layer of corrosion products [14].

8. Stress Corrosion Cracking

Stress Corrosion Cracking (SCC) is a severe degradation mechanism of metals that occurs suddenly and is very hard to forecast [14,16]. Engineering materials that experience delayed, environmentally driven crack propagation are said to be subjected to SCC, which is a term used to describe such failures [14]. The interplay of mechanical stress and corrosion reactions leads to the observed fracture growth in a combined and synergistic manner [17].

The main corrosion damages, addressed in the previous sections, constitute the major concern of corrosion in ordinary services and conventional corrosion rates. The incorporation of bacteria in the corrosion process would change the process kinetics dramatically, so that much higher corrosion rates and deeper localized damages would occur in shorter time compared to the previous types of corrosion.

9. Microbiologically Influenced Corrosion

Microbiologically influenced corrosion (MIC) can be defined as a type of corrosion where the corrosion of materials is brought on and/or accelerated by the actions of microorganisms [18,19].

The following insights can be drawn from the above definition [20]:

1. The MIC process is electrochemical.
2. Microorganisms can influence the severity, course, and extent of corrosion.
3. There must also be a carbon supply, an energy source, and microorganisms.
4. There must also be an electron donor, an electron acceptor, and water – even very low amounts- is necessary to start MIC [19,20].

Nearly every type of metal, environment- including soil, freshwater, and seawater-, as well as every type of industry- including the oil, electricity, and marine sectors- are susceptible to MIC damages [19,20].

9.1. Bacteria Categorizing

Microbiologists employ some "features" to distinguish between different species of bacteria. Among these categorization criteria are appearance and shape, temperature, and consumption of oxygen [20]. Figure 1 shows the bacteria categorization.

9.2. Common Types of Bacteria Associated With MIC

MIC rarely gets linked to a specific mechanism or a single type of microbes [19, 21]. However, sulfate-reducing bacteria (SRB), sulfur-oxidizing bacteria (SOB), iron-reducing bacteria (IRB), and iron-oxidizing bacteria (IOB) are among the microorganisms found in natural environments that are also regarded as corrosion-causing microbes [19].

9.2.1. Sulfate Reducing Bacteria

Sulfate Reducing Bacteria (SRB) has the unusual capacity to respire in anaerobic environments by reducing the sulfate to hydrogen sulfide using sulfate as a terminal electron acceptor [20]. SRB flourishes in various natural conditions, including salt marshes and freshwater sediments, as well as in deep underground locations like oil wells, hydrothermal vents, and industrial processing plants [20, 22, 23]. Figure 2 shows the influence of SRB on steel corrosion.

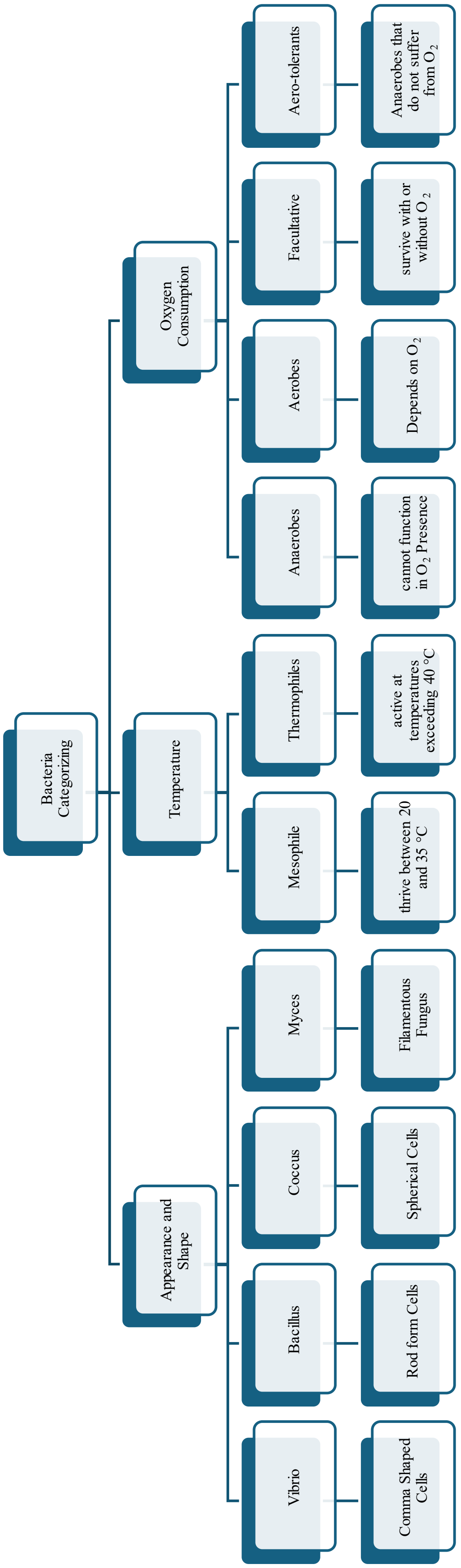

Fig. 1. The bacteria categorization. [20]

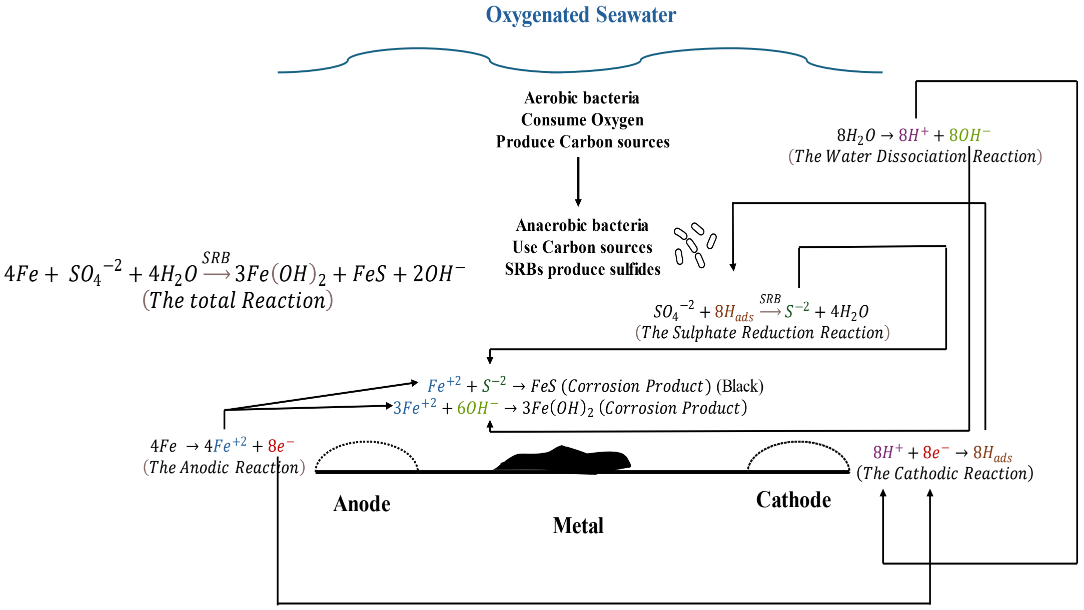

Fig. 2. The influence of SRB on iron corrosion.

9.2.2. Sulfur Oxidizing Bacteria

Sulfur Oxidizing Bacteria (SOB) are aerobes that oxidize the reduced sulfur compound (*e.g.* H_2S) to produce elemental sulfur (S^0) or sulfate (SO_4^{-2})- as a by-product- forming sulfuric acid (H_2SO_4) [24, 25]. The corrosion products of sulfur-oxidizing bacteria (SOB) are yellow [20].

9.2.3. Iron Reducing Bacteria

Iron Reducing Bacteria (IRB) can convert Fe^{3+} to Fe^{2+} under anaerobic conditions using ferric ions as the final electron acceptor [26]. IRB are facultative anaerobes, which, as illustrated in Fig. 1 can thrive in anaerobic environments, but they will choose oxygen IRB can alter the environment to make it appropriate for SRB due to its facultative behavior [20].

Figure 3 shows the possible interaction between IRB and SRB. The dark greenish color is an excellent indicator of the existence of iron-reducing bacteria when they are present and actively reducing iron [20].

9.2.4. Iron Oxidizing Bacteria

Iron Oxidizing Bacteria (IOB) behave in a metabolically opposite manner from iron-reducing bacteria. IOB oxidizes iron from Fe^{2+} to Fe^{3+} under aerobic conditions [20, 26]. Deposits that are reddish-brown in color are a good indication of IOB [20].

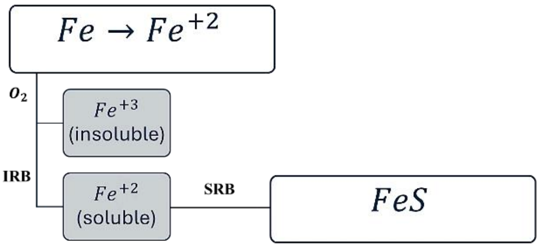

Fig. 3. Possible interaction between IRB and SRB.

9.2.5. MIC of Stainless Steels

MIC may affect the corrosion process of typical grades of stainless steel. This usually involves the presence of sulfur-degrading bacteria, which produce a restricted environment with hydrogen sulfide and low pH level [27, 28].

Pitting at or near welds is one of the most frequent types of MIC attack in austenitic stainless steels [29]. The austenite and delta ferrite phases may both be vulnerable to MIC in 304L and 316L weldments, and several combinations of filler and base materials failed, including matching, lower-, and higher-alloyed filler combinations. Chromium and molybdenum micro-segregation with chemically deficient areas enhances susceptibility to localized damage [29].

MIC occurs most frequently on welds and heat-affected zones in stagnant or slowly moving waters [30]. For many materials, seawater is an extremely corrosive environment [31]. Stainless steels face difficulties due to seawater's high chloride concentration and many stainless steels' vulnerability to chloride-induced localized corrosion [31]. Lower-alloyed stainless steels, such as the 304, 316, and 317 grades, are insufficiently resistant to corrosion for prolonged exposure to seawater. Due to the impacts of biofouling, types 304 and 316 stainless steels experience extensive pitting when seawater flow rates fall below approximately 1.5 m/s (5 ft/s) [27].

In the coming sections, three cases of MIC damages are presented in more detail to highlight specific features of the MIC process as related to the environment, the severity of the attack, and short service time to leaking incidents in piping systems.

9.3. Case Studies of MIC in Stainless Steel

Two cases of MIC corrosion of stainless-steel pipes and tubes were previously investigated [32, 33]. Both cases were reported after a hydro test with bacteria-infected water, and the leaking incidents were observed after three months in each case. In the first study [32], pipes of stainless-steel TP-316LN were damaged by intergranular corrosion attack. The pipe was four inches in diameter and 1/8 inch thick, welded by a tungsten inert gas process. Fine and deep pits were observed at weld and far heat-affected zones. The pits were attributed to microbiologically influenced corrosion. Excessive bacteria colonies were observed on the pit surface. The EDS line scan across the pit zone confirmed the leaching of Cr, Ni and Mo from grain boundaries. The depletion of Cr was highly pronounced in these analyses. The mechanism of intergranular attack was suggested accordingly. The root cause was the improper practice in terms of retaining demineralized water in the pipes after the test.

The total dissolved solids (TDS), chloride, and fluoride levels were 478, 255.6, and 0.081 mg/l, respectively, in the collected sample of water remaining inside the pipes. Bacterial count was assessed via culture technique after 24 hours at 35oC and 48 hours at 22–25ºC. The total number of bacteria colonies was too numerous to count. Thus, the number of planktonic bacteria was huge, which indicated the microorganisms attacked.

In the second study, the MIC of a stainless-steel 304 firefighting system in an oil field was investigated using the failure analysis procedure. The firefighting liquid was seawater with foaming additions. The system started to leak after only 3 months of commissioning. Figure 4 shows a schematic diagram of the damage.

The visual and macroscopic examinations showed that the firefighting fluid was left stagnant until the leakage. The damage occurred at several locations, especially at five to seven O'clock positions of the lower part of the pipe, where the water was left stagnant. This indicated that the water played a major role in the failure incident. The widespread pitting at the far HAZ and the base metal suggested that the corrosion was irrelevant to the welding process [33].

The main pit had a yellow- colored corrosion products, which was probably an indicator of the SOB [33, 34]. Besides the main leaking pit, two additional types of pits were found on the pipe internal surface as can be seen in Fig. 5.

One type showed green corrosion products, which might indicate the IRB, while the other was bright white with no corrosion products. Both types had a cup-type morphology, which is characteristic of MIC pits [33].

The microstructure examination showed that the pipe material had an enormous number of inclusions, which indicates the low quality of the material. Tunneling- a horizontal grain attack- was also shown in the optical micrographs ensuring that the main failure mechanism is MIC [33]. The Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) examinations were done for the green pit inner surface. The micrographs showed grains and subgrain structures, likely due to tunnelling. The bacteria and bacteria colonies were seen in the micrographs of the white pits. These findings confirmed that the MIC was the main corrosion type of the firefighting pipes [33]. The EDS analysis of the corrosion products in two locations of deposits at the bottom of the corrosion pits showed high levels of oxygen (40.02 w% (location 1) and 48 w% (Location 2)), chlorine (6.81 w% (location 1) and 5.35 w% (Location 2)), and sulfur (2.37 w% (location 1) and 1.91 w% (Location 2)). The high oxygen level indicated the oxides of the corrosion products. The high chlorine level, on the other hand, indicated the chloride attack associated with the MIC process. This partially justifies the rapid damage. The high level of sulfur, no doubt, indicated the activity of SRB during the corrosion process [33].

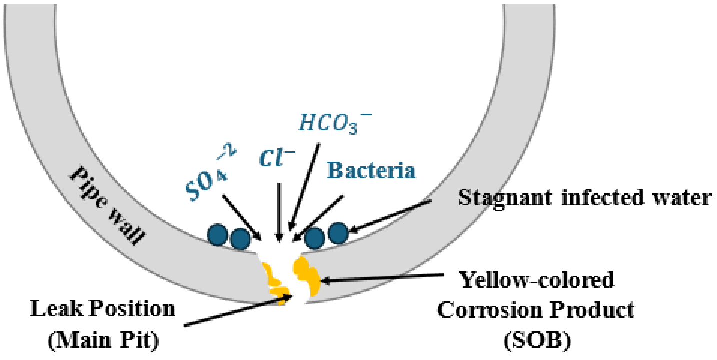

Fig. 4 Schematic for the main leaking pit in this study.

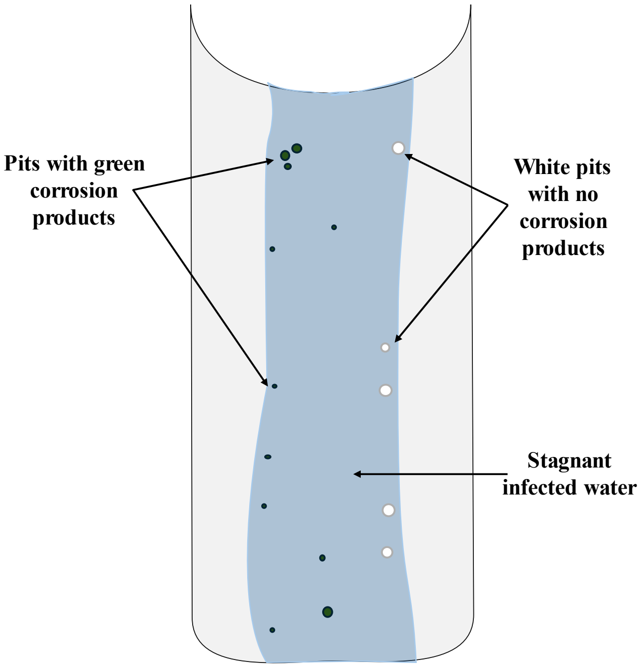

Fig. 5 Schematic for the white and green pits at the lower inner surface of pipes.

The firefighting fluid analysis showed a high level of total dissolved solids (TDS = 40.5 g/l), which was suitable for the growth of the Halophilic SRB. The high level of chemical oxygen demand (COD = 1703 mg/l), which indicates the concentration of electron donors available for metal and sulfate reduction, is necessary for the growth and reproduction of SRB and/or IRB microorganisms [33].

The pH of 8.01 is quite suitable for the growth of the SRB, and probably other types, which typically grow in environments of 2.9 to 9.9 pH. The bicarbonate level of 1866.6 g/l supplied the carbon necessary for the MIC bioactivities. While the 222 mg/l of sulfate was also vital for the MIC process.

The chemical analysis results showed the conformity of the pipe material to the stainless steel 304 according to ASTM A312, which complies with the specified pipe materials. The results of this investigation suggested and confirmed that the main corrosion damage mechanism was the MIC corrosion. Therefore, the observed leaking and corrosion of the firefighting system was mainly due to manufacturing and hydro testing mistakes, which allowed the hydro test medium of bacteria-infected sea water to stay stagnant in the pipes for 3 months after testing [33].

9.3.1. Preventive Actions for MIC

MIC can be prevented by getting rid of the bacteria either by mechanical cleaning (if applicable) or using properly treated fluids to eliminate bacteria or strong, aggressive biocide such as chlorine. In addition, the firefighting tubes and pipes must be dried completely after the hydro test by passing a warm flow of dry air for a sufficient period of time. Selecting proper alloys with good resistance to bacteria attacks is another way to prevent MIC. Duplex stainless steels provide better resistance to MIC attacks than the austenitic grades.

This paper could not consider MIC preventive measures in different environments due to the subject's diversity, possibilities, and information.

9.4. Case Study of MIC in Carbon Steel

MIC of 12-mm-thick low carbon steel API 5L grade A fire water piping was investigated recently [35]. The leakage was due to corrosion penetrating the wall in only 3 months of service. The MIC of 12-mm-thick low-carbon steel API 5L grade A fire water piping was investigated recently. The leakage was due to corrosion penetrating the wall in only 3 months of service, forming a 20 X 22 mm elliptical hole. Investigations revealed localized attacks at grain boundaries and observation of bacteria at the leak location. Both of bimetal and localized MIC worked simultaneously until perforation and flushing of water.

The prevention of such failure aligns well with the countermeasures in Sec 9.3.1.

10. Conclusions and Main Findings

It might be difficult to classify the different forms of corrosion that occur in the oil and gas industry. This paper briefly reviewed these damage mechanisms in the oil and gas industry. The stress corrosion cracking (SCC), erosion, sour, sweet, oxygen, crevice, galvanic, and microbiologically influenced corrosion (MIC) processes were covered in this work. Table 1 lists the brief of each process and highlights mechanisms and related issues. The bacteria associated with MIC are usually categorized based on several parameters. The sulfate-reducing bacteria (SRB), sulfur-oxidizing bacteria (SOB), iron-reducing bacteria (IRB), and iron-oxidizing bacteria (IOB) are among the microorganisms associated with the MIC mechanisms. MIC is a serious attack on stainless steel despite its good corrosion resistance. Three case studies were presented in this work for the MIC attack of stainless and carbon steel firefighting systems. The preventive actions were also presented.

This paper clearly addresses the basic types of corrosion that affect the equipment of oil and gas fields. It serves as a brief source of balanced information. It provides an elaborate treatment of the MIC incidents with several case studies, highlighting the effect of the environment, the severity of damages, and the short service life until failure.

Table 1. Brief on basic types of corrosion.

1. Sour Corrosion is the degradation of a metal when it is in contact with aqueous H_2S.
2. Sweet Corrosion is the metal degradation in aqueous CO_2.
3. The role of the Oxygen in corrosion is not only accelerating the metal anodic oxidation, but also heightens the H_2S and CO_2 acid fumes.
4. Crevice Corrosion is a localized corrosion occurring in crevices where fluid becomes stagnant.
5. Galvanic Corrosion occurs when one metal meets another conducting metal with different electrochemical potentials in a corrosive medium.
6. Erosion Corrosion is the material deterioration brought on by surface oxidation along with mechanical wear due to the impact of solid particles, liquid, or a combination of both processes.
7. Stress Corrosion Cracking (SCC) is a delayed, environmentally driven crack propagation interplay of mechanical stress and corrosion reactions.
8. Microbiologically influenced corrosion (MIC) can be defined as a type of corrosion where the corrosion of materials is brought on and/or accelerated by the actions of microorganisms
9. MIC is an electrochemical process among electron donor, electron acceptor, and water. Carbon supply, energy source, and bacteria must exist.
10. MIC occurs via several mechanisms and types of microbes.
11. MIC may affect the corrosion process of typical grades of stainless steel.
12. MIC frequently occurs on welds and heat-affected zones in stagnant or slowly moving waters.
13. Lower-alloyed stainless steels, e.g., 304, are insufficiently resistant to corrosion for prolonged exposure to seawater and high chloride concentration environments, and are vulnerable to chloride-induced localized corrosion.

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