Microbiologically influenced corrosion in floating production systems

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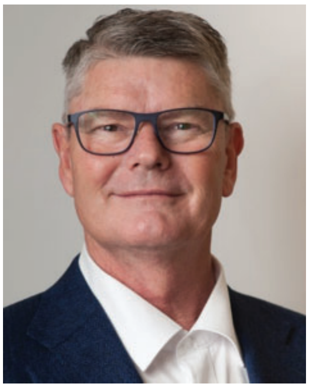

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Microbiologically influenced corrosion (MIC) represents a serious and challenging problem in Floating, Production, Storage and Offloading vessels (FPSOs), one of the most common type of offshore oil production facilities in Australia. Microorganisms can attach to metal surfaces, which under certain conditions, can result in corrosion rates in excess of 10 mm per year (mmpy) leading to equipment failure before their expected lifetime. Particularly, increasing water cut (ratio of water vs. total fluids produced), normally resulting from the age of the assets, results in an increased risk of MIC. This paper provides an overview of causative microorganisms, their source of contamination and the areas within FPSOs that are most prone to MIC. Although mitigation practices such as chemical treatments, flushing and draining and even cathodic protection are effective, MIC can still occur if the systems are not properly monitored and managed. A case study is presented that describes the microorganisms identified in a FPSO operating in Australia suspected of having MIC issues.

The production of oil and gas is of major importance to the stability of the world's energy supply. With the depletion of onshore reserves, offshore exploration and production of oil and gas has increased sharply. In particular, Western Australia's oil and gas industry is a vital component of Australia's national economy, producing over 70 per cent of Australia's natural gas, crude oil, and condensate[1]. A Floating, Production, Storage and Offloading vessel (FPSO) is currently the production facility of choice for oil accumulations uneconomic for fixed installations like platforms with around 70 FPSOs in operation worldwide, including seven in Australia (Figure 1). FPSOs carry all necessary production and processing facilities, tanks for storage of oil recovered from the reservoir as well as oil offtake systems. Typically the production fluids are separated into crude oil, formation water and gas. FPSOs are secured on site by mooring and station keeping systems and are connected to production wells in the seabed via subsea flowlines and flexible risers.

FPSO are designed to have an expected service life of 5–20+ years depending on reservoir size. For many FPSOs existing trading tankers have been converted to a FPSO so that the marine systems are already >10 years old. For FPSOs in operation, maintaining the asset as fit for service is critical. Water production increases with time as the oil in the reservoir is produced. As the assets get closer to the end of their service life, there is more need for managing corrosion[2]. In addition, improving facility economics can involve tie-in of new oil accumulations to existing ageing FPSOs[3]. This can bring new challenges to operations due to the mixing of water chemistries and oil with different properties.

In particular, microbial contamination and consequent microbiologically influenced corrosion (MIC) represents a serious problem to FPSO operations, which can incur significant costs, and be difficult to control[4,5]. The number of FPSOs that have been in operation for significant time has increased worldwide and the issues are usually common to all operators. However, conditions in Australia can be different from other oil and gas producing regions thus particular challenges can arise.

Microorganisms in petroleum reservoirs and FPSOs

Due to the *in situ* presence of substantial amounts of electron donors and electron acceptors for bacteria growth, diverse populations of microorganisms with a wide range of physiological and metabolic activities have been found in oilfield systems[6]. Microorganisms inhabiting petroleum reservoirs are typically capable of surviving in environments with high temperature, pressure and

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Figure 1. Floating Production Storage and Offloading (FPSO) vessel operating in Australia.

salinity. Oil reservoirs with a water leg at temperatures less than 80°C are likely to have been biodegraded *in situ*[7]. Microorganisms commonly identified in these environments include sulphate-reducing prokaryotes (SRP), iron-reducing bacteria, fermenting bacteria and methanogenic archaea[8]. The majority of these microorganisms are strictly anaerobic. Largely, the availability of electron donors governs the type of metabolic activities within oil field ecosystems[9]. Typically, sulphate and carbonate are the most common electron acceptors present which suggests that the most significant metabolic processes occurring *in situ* are sulphate reduction, methanogenesis, acetogenesis and fermentation. In particular, the widespread presence of SRP in crude oil and formation waters and the concomitant production of H_2S have been extensively linked to deleterious processes in the oil and gas industry such as reservoir souring of crude oil systems and corrosion[10]. However, all of the aforementioned microbial groups have been previously associated with corrosion via different mechanisms[5]. To limit corrosion and microbial activity, produced water is typically treated with chemicals including corrosion and scale inhibitors, biocide and oxygen scavengers.

Source of microbial contamination of FPSOs

The presence of microorganisms in oilfield systems is usually the result of contamination by any number of mechanisms including from a biodegraded reservoir, contaminated mud during well-drilling operations, the use of raw seawater during subsea and topsides flushing operations, re-circulating waste oil from bilges back into the process as well as seawater injection into the oil reservoir for pressure support. However, several microorganisms retrieved from petroleum reservoirs are potentially indigenous to these ecosystems. Likewise, subsea flexible flowlines comprising an inner castellated or ribbed stainless steel carcass can become infected with microorganisms and provide a large surface area for sessile bacterial growth with estimates in the order of 2×10^{13} cells per m^2 (A. Polomka, Confidential Report, 2015). This provides a ready supply of bacteria to the FPSO as well as biogenic H_2S.

Typically, a FPSO is installed initially on a single field and provided the reservoir is consistent across the field, production will be the same. However, in several cases oil production from various reservoirs is co-mingled into one FPSO. In this case, different water chemistries are mixed with subsequent risk of scale formation and additional nutrients and microorganisms, which could result in an increased risk of MIC. Bacteria present at the front end will spread through the entire system including the back end oil offtake system in the water phase. Likewise, a FPSO can combine seawater injection with production that can potentially result in souring (sulphide production) and MIC in the facility thus requiring biocide injection into the reservoir. Values of >3000 ppm of H_2S

have been detected in the gas exiting the high-pressure separator on board the facility under these scenarios thus requiring H_2S scavenger chemical dosing to control the risk of sulphide stress cracking of carbon steel[11].

Major areas of MIC threat

The vast majority of MIC on FPSOs occurs on carbon steel components. Although MIC of corrosion-resistant alloys (CRAs), e.g. stainless steels, can occur in aerobic environments (e.g. seawater utility systems), hydrocarbon-processing trains on FPSOs are anaerobic and MIC of CRAs is not an issue. Souring of the reservoir is a common outcome of facilities that conduct produced water reinjection. This generally results in a higher than anticipated H_2S content in well, process and rundown streams.

Topsides process: Any carbon steel process piping, dead leg (a length of pipe which is rarely or never used) or vessel with free water contacting the surface, nutrients and a microbial consortia is prone to MIC. Increasing water cut results in increased nutrient levels and water wet carbon steel with very high sessile bacteria densities and high resultant corrosion rates. Topsides corrosion rates greater than 10 mmpy have been detected with no or inadequate control of MIC (e.g. full wall penetration of 12 mm thick produced water piping in 12 months). Maximum corrosion rates have been observed in the 30–50°C temperature range. Examples of MIC in topside facilities are shown in Figures 2, 3.

Cargo tanks: MIC can occur at the bottom of oil cargo tanks where anaerobic bacteria can thrive in the water layer that collects in the bottoms of the tanks and the tank coating has broken down or been damaged. MIC corrosion rates in the order of 1 mmpy under normal operation can occur but can be higher if excessive produced or seawater levels are allowed to sit in the tanks underneath the crude oil (A. Polomka, personal observation).

Slops tanks (cargo and bilges waste water handling system): Biogenic H_2S generation can be a concern with the inert gas vented to atmosphere. Corrosion can be further complicated if the tank has heater tubes to aid emulsion breaking as a galvanic component of the corrosion is possible. Corrosion rates, resulting from a combination of galvanic and MIC, in the order of 6–9 mmpy can be observed if untreated (A. Polomka, personal observation).

Crude offtake system: Although the crude offtake system typically contains less than 0.5% basic sediment and water (BS&W), MIC risk increases for pump room and offtake piping as offtake frequencies decrease and water settling out of the crude is left sitting in low points for longer. In addition, this can lead to internal coating breakdown. Regular flushing of the offtake system with raw seawater can markedly increase MIC rates due to the addition of trace oxygen and nutrients. Corrosion rates in the order of 3–4 mmpy have been seen with regular seawater flushing after each offtake (A. Polomka, personal observation).

Mitigation of MIC

Control of acid gas (CO_2 and H_2S) corrosion of carbon steel in oil and gas production requires the continuous dosing of an organic filming corrosion inhibitor at the ppm level upstream of the carbon steel. For MIC control, batch or shock dosing of a biocide (e.g. 250 ppm for 4 hours weekly) is used to limit MIC in the topsides process[12]. As part of this treatment any dead leg needs to be flushed to drain during the treatment to control MIC in the dead leg.

On some facilities, de-sulphated (via ultrafiltration and sulphate removal membranes) customised water flood (CWF) is used to maintain reservoir pressure while limiting souring and corrosion due to the activity of SRP. Removal of sulphate should dramatically change the microbiome of production facilities. In addition, since

Figure 2. Microbiologically influenced corrosion of high pressure separator horizontal baffle.

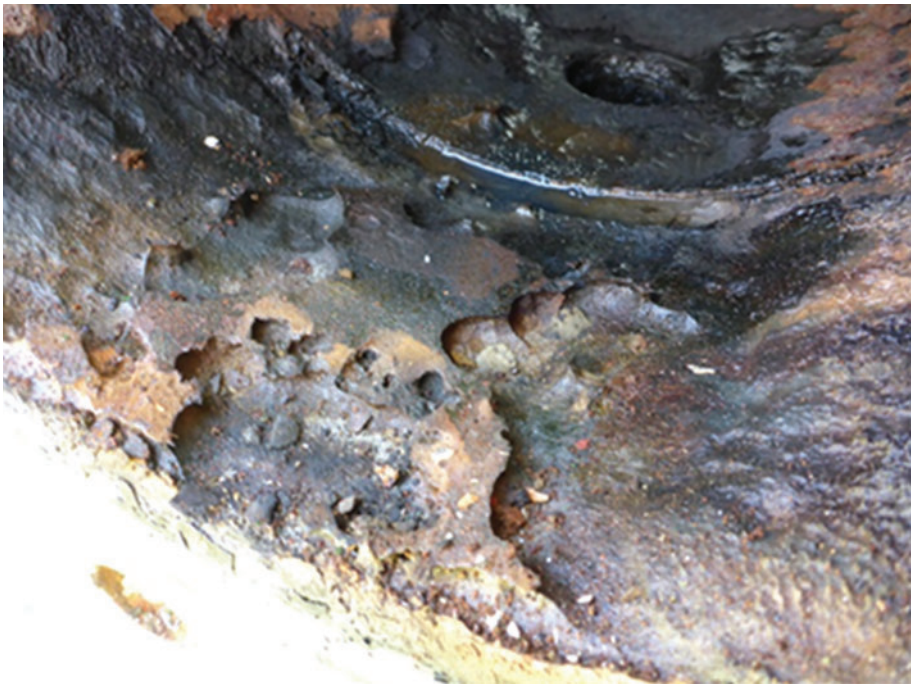

Figure 3. Microbiologically influenced corrosion of crude line to cargo storage (0.5% water cut).

FPSOs process oil from different reservoirs (dissimilar formation water chemistries and reservoir temperatures) differences in the microbial communities inhabiting these systems are also expected from site to site[6].

For crude rundown into the cargo tanks, a continuous dose of biocide e.g. 200–500 ppm based on the BS&W percentage present in the oil is carried out. Target BS&W levels of <0.5% are normal. In slops tanks generating H_2S, MIC control involves draining of the tank, application of batch dose biocide based on volume of water in tank (treat and soak) and repeat after in-boarding of water or time based depending on H_2S levels. MIC control in slops tanks involves the use of sacrificial anodes (cathodic protection) to maintain surface potentials more negative than –900 mV vs silver/silver chloride reference electrode (Ag/AgCl) to prevent MIC and galvanic corrosion as well as regular biocide for biogenic H_2S control.

Case study: identification of microorganisms in an Australian FPSO

MIC monitoring has traditionally been done via the serial dilution or most probable number (MPN) techniques. These techniques may only detect a small proportion (1–10%) of the natural community. More recently techniques measuring adenosine triphosphate and adenosine monophosphate (ATP/AMP) levels and molecular microbiological methods including next generation sequencing (NGS) have been implemented which provide better insights into the microbial community and their activity in the system[13,14].

Background: Produced water samples were gathered from a FPSO in operation in Australia that experienced recurring corrosion issues, for microbiological characterisation and MIC assessment. The FPSO processes oil, produced water and gas from a biodegraded reservoir. Produced water from this facility is known to have limited concentrations of sulphate. Temperature at the sampling location was 60°C. In addition, samples from a corroded surface (corrosion products on the metal piece) were also collected. Samples were inoculated in various culture media for the detection and enumeration of several metabolic groups. In addition, culture-independent 16S rRNA gene sequencing (Illumina MiSeq) was used to identify microbial populations and their relative proportion (%) in the samples using primers 341F and 806R for the detection of both bacteria and archaea.

Results: The most active populations detected via culture-dependent methods corresponded to methanogens and fermenting microbes with capabilities to reduce sulphur and thiosulphate into hydrogen sulphide (sulphidogenic species). Sulphate-reducing bacteria were not detected. DNA sequence analysis showed that methanogenic archaea were the predominant populations in the system. Specifically, the archaeal taxa *Methanobacterium*, *Methanothermobacter thermoautotrophicus*, *Methanothermococcus*, *Methermicoccus shengliensis* and *Methanoculleus* dominated in produced water and even more notably in corroded equipment. The dominant bacterial populations identified in the samples were *Thermovirga* and *Thermoanaerobacter* although populations including *Thermosipho, Thermothoga*, *Petrotoga*, *Kosmotoga* and *Anaerobaculum*, were also identified, albeit at low proportions. In agreement with cultivation analysis, SRP species were not identified via DNA analysis.

Discussion: The low abundance of SRP appears to be associated with the lack of sulphate in produced waters. The abundance and predominant activity of methanogenic archaea and fermenting-sulphidogenic microbes possesses a risk of MIC. Methanogens have been described as corrosive microorganisms due to their hydrogenotrophic (hydrogen scavenging) capability that cause cathodic depolarisation thus accelerating corrosion. Direct electron extraction from iron by methanogens has also been postulated as an important MIC mechanism[5]. In addition, the dominance of active fermenting-sulphidogenic microbes suggests the presence of intermediate forms of sulphur in produced water such as elemental sulphur (S_0) and thiosulphate ($S_2O_3^{2-}$). These microorganisms can contribute to corrosion via sulphide generation and acid production[15]. There are also reports of deposits in pipelines harbouring mainly methanogens and sulphur/thiosulphate-reducing bacteria that have been associated with localised corrosion[16,17]. These results highlight the importance of studying and monitoring microbial populations other than SRP (SRP are commonly associated with corrosion of oil production equipment) since these microorganisms can potentially contribute to corrosion, particularly in systems exposed to production fluids with low levels of sulphate where such conditions are usually deemed low risk for MIC.

Conclusions

Carbon steel is a common material of construction of FPSO's due to its commercial attractiveness. However, carbon steel is subject to MIC in offshore oil and gas production at even low water cuts (<0.5%) under the right combination of nutrient availability, microbial populations and operating conditions supporting microbial activity. Control of MIC via regular batch or shock dosing of biocides and in tanks by continuous biocide dosing and cathodic protection is used to prevent leaks. Monitoring of bacterial numbers, speciation and activity is required to validate management strategies or to validate alternative control options. Molecular microbiological methods (MMM) are critical to enable biocide assessment for MIC control and to elucidate possible MIC mechanisms.

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Biographies

Dr Laura L Machuca leads research and industry projects on microbiological influenced corrosion (MIC) at the Curtin Corrosion Centre (Curtin University). She is an environmental microbiologist and a corrosion specialist whose research and teaching activities focus on the interaction of microbes with metals and the role of microbes in deterioration processes particularly, those relevant to the oil and gas and marine industries.

Anthony Polomka is a consulting materials and corrosion engineer with over 30 years' experience in the upstream oil and gas industry. Anthony has worked directly for Santos Ltd, Woodside Energy Limited and BHPBilliton Petroleum and consulted to a number of other operating companies and engineering contractors in the areas of materials selection, coatings, cathodic protection, production chemicals, failure analysis and operations corrosion management.