

Utilizing Corrosion Damage Morphology as an Indicator of Microbiologically Influenced Corrosion (MIC) in Oilfield Waters

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ABSTRACT

Microbiologically Influenced Corrosion (MIC) is a major concern in process industries, particularly in the Oil and Gas sector. MIC has been linked to numerous corrosion failures and it is estimated that 25-30% of corrosion related failures in pipelines and industrial equipment can be attributed to MIC, costing billions of dollars.

Close examination of extensive sessile bacteria data, water chemistry and the corrosion damage morphologies observed on corresponding corrosion coupons in different oil field waters (brackish, recycled, produced, effluent) over a period of some 10 years, indicated that there was a distinct relationship between the bacteria type, water chemistry and the corrosion damage pattern. The water analysis data indicated that waters with different TDS levels, influences the species of viable bacteria that existed. Very high TDS waters (such as effluent waters) are not viable for SRB (sulfate reducing bacteria) but are viable for GAnB (general anaerobic bacteria) and anaerobic APB (acid producing bacteria). A mixed consortia of SRB/GAB/GAnB can co-exist in lower TDS waters (such as brackish waters). The localized corrosion damage morphology is dependent on the bacteria species that is present. It may be possible to develop a pictorial guideline for identifying MIC on the basis corrosion damage morphology as an aid to developing biocide treatments and the forensic analysis of corrosion failures .

Key words: Microbiologically Influenced Corrosion, SRB, APB, GAB, GAnB, Corrosion Morphology

INTRODUCTION

Microbiologically Influenced Corrosion (MIC) is a major concern in process industries, particularly in the Oil and Gas sector. It is estimated that 25-30% of corrosion related failures in pipelines and industrial equipment can be attributed to MIC. The cost of metallic corrosion has been estimated to range between 2-3% of the gross domestic product (GDP) in developed countries^{1,2} and MIC certainly

accounts for a significant fraction of the total cost of corrosion^{3,4,5} amounting to billions of dollars due to unexpected shutdowns, equipment replacement, mitigation strategies, etc.

Under anoxic (anaerobic) conditions such as in oil and gas pipelines or deaerated oil-field waters, SRB (sulfate reducing bacteria) are commonly considered the main culprits of MIC.⁶ Besides SRB, a number of different types of other bacterial strains under the classification of GAB (general aerobic bacteria) and GAnB (general anaerobic bacteria) have been implicated in the MIC process.⁷ These include among others, thiosulfate reducing bacteria (TRB), acid producing bacteria (APB), iron oxidizing bacteria, iron fixing bacteria, sulfur oxidizing bacteria, sulfide generating bacteria, nitrate reducing bacteria and slime forming bacteria. Bacteria can be seen to intensify rather than to act as the original cause of many corrosion incidents.⁸

MIC typically results in localized corrosion attack akin to under-deposit corrosion, but the damage morphology has some characteristic features depending on the type of environment and the sessile bacteria species involved. It is reported in the literature⁹ that the corrosion damage in case of SRB manifests itself as wide pits with terraced features. The damage morphology created by TRB, which is a sulfide producer like SRB, is very similar to SRB attack but much more intense¹⁰⁻¹³ and sometimes difficult to differentiate. Some strains of acid producing bacteria (APB) cause corrosion damage which show pits within pits or tunneling.⁹

Bacteria Sampling, Analysis and Monitoring

Sampling for bacteria, its analysis/identification and monitoring can be challenging. But these are essential activities for determining subsequent mitigation strategies. The first step is to establish the presence and type of bacteria in the fluid stream (or in the corrosion products) which has to be accomplished by proper sampling followed by appropriate analysis.

Bacteria Sampling

The importance of collecting bacteria samples cannot be over emphasized. Utmost care is required for the sampling process and there are excellent guidelines in NACE standards.^{14,15} Bacteria can be either 'planktonic' (those floating in fluid streams) or 'sessile' (those adherent or attached to the surface). Planktonic bacteria samples are obviously collected from fluid streams while sessile bacteria samples are obtained by carefully scraping the corrosion products or deposits from the surface.

Bacteria Analysis and Monitoring

The collection and analysis of planktonic samples is the most frequently used method of monitoring bacteria in the industry. However, sessile bacteria samples are more useful since they indicate the population of bacteria living on the system surfaces and play direct role in the corrosion process. Hence, the sessile bacteria count is the more important parameter to monitor. The concentration of the planktonic bacteria is quantified in terms of colonies or counts per unit volume (counts/mL) while sessile bacteria is quantified as colonies or counts per unit area (counts/cm²). A large planktonic bacteria count may not necessarily mean that MIC is occurring in a system since the bacteria need time to colonize and form biofilms for the corrosion process to start and propagate. Similarly a low planktonic bacteria count does not mean that MIC will not occur. However, the presence of planktonic bacteria does indicate that MIC is likely to happen in due course at stagnant locations and under deposits.

The most widely used procedure for analyzing bacteria in the industry is the Serial Dilution Technique as per NACE TM0194.¹⁵ This technique can indicate the type of bacteria (SRB, GAB, GAnB/APB) and the bacteria count in the sample. But the procedure has limitations and is time consuming, requiring 2-4 weeks to get results. Quick Test Kits (based on ATP photometry, APS Reductase, etc.) are available but these are not very accurate and have limitations. A new field test kit which is claimed to be very accurate has been developed by Schlumberger¹⁶ but is not available commercially.

The most recent technique for bacterial analysis and quantification is based on Molecular Microbiological Methods (MMM) such as qPCR (quantitative polymerase chain reaction), advanced qPCR, NGS (Next Generation Sequencing) etc. which can be used to identify, characterize, and quantify bacteria to the genus and species level. qPCR is a DNA based MMM to accurately quantify total bacteria, total archaea, and specific microorganisms like SRB that are commonly responsible for MIC and reservoir souring. The advanced qPCR method can simultaneously quantify a broad spectrum of targets in a single run. NGS is a DNA based technique used to identify the microorganisms present in a sample and provide a profile of the microbial community. The literature is replete with information on MMM.¹⁷⁻²³ MMM methods are the most reliable and accurate, but expensive requiring highly trained staff and a large capital investment in equipment. On-site bacteria monitoring based using a handheld qPCR device²⁴ has been reported but is not yet commercially available.

Morphological Features of MIC

As mentioned previously, MIC manifests itself as localized corrosion (pits) and the morphology of the pits is often considered as an indicator of MIC. The presence of a terraced pit is usually attributed to SRB while pits within pits, or tunneling effects are signs of acid producing bacteria. It should be noted that localized corrosion can also be caused by other non-biological mechanisms such as under-deposit corrosion. Hence, the identification of a corrosion failure as being MIC should include, besides morphology, detection of bacteria in the corroded area and detection of metabolic products (e. g. sulfides, organic acids, etc.) showing that the bacteria were active in the area.

Present Paper

The present paper is a representation of the cumulative work performed over a period of more than 10 years at an Oil and Gas production facility in the Middle East which shows a correlation between the sessile bacteria data, water chemistry and the corrosion damage morphologies observed on corresponding corrosion coupons in different types of oil field process waters.

EXPERIMENTAL WORK AND METHODOLOGY

The experimental work consisted of the following:

1. Retrieval of on-line corrosion coupons including collection of sessile bacteria samples
2. Analysis of sessile bacteria samples
3. Photographic documentation of the corrosion morphology on the coupons.
4. Water sampling and chemical analysis.

1. Retrieval of on-line corrosion coupons and sessile bacteria sampling

Several hundred standard pre-weighed corrosion coupons are installed at various strategic locations in the Middle East Oil and Gas facility which are retrieved according to a planned schedule, depending on the process fluid. These coupons are exposed to different types of waters consisting of brackish water (BRW), recycled water (RCW), produced water (PDW), and effluent water (EFW) which are encountered in different parts of the facility. The retrieval period varies from 45 days to 120 days.

As soon as a coupon was retrieved from a particular location, the surface deposits were immediately scraped off with a sterile scalpel and put into a sterile media following guidelines in NACE standards^{14,15} and kept aside for analysis of the bacteria species and population. The corrosion coupon was then put into a protective sleeve for further processing at the laboratory to determine general and localized corrosion rates as well as document the type of corrosion morphology on the coupon.

2. Analysis of sessile bacteria

The Serial Dilution Technique as outlined in NACE TM0194¹⁵ was used to determine the sessile bacteria species and the corresponding bacteria population (represented as counts/cm² based on the coupon surface area). Commercially available bacteria analysis media bottles were used to determine the population of SRB, GAB and GAnB/APB species.

3. Photographic documentation of the corrosion morphology on the coupons

The corrosion coupons were processed as per NACE^{14,15} guidelines to clean any remaining surface deposits to determine the general and localized (pitting) corrosion rates. The coupons were then photographed with a high resolution digital camera to document the morphological features of the corrosion damage.

4. Water sampling and chemical analysis

Samples of different types of waters consisting of brackish water (BRW), recycled water (RCW), produced water (PDW), and effluent water (EFW) were collected from various process streams of the Oil and Gas production facility. Most of the water sampling locations were close to the coupon locations. The water samples were subsequently analyzed in the laboratory using standard analytical techniques to determine the water chemistry. The following common parameters were determined: TDS (total dissolved solids), pH, Cl⁻, SO₄⁻², S⁻², HCO₃⁻, CO₃⁻², Mg, Ca, Fe, Mn.

RESULTS AND DISCUSSION

Detailed results of the corrosion rates, sessile bacteria analysis and water chemistry are not presented here as these are available in other publications²⁵⁻²⁷ and are not required for the main focus of the paper which is a correlation between the water type, bacteria type, and corrosion damage morphology.

Relationship Between Water Type, Bacteria Type and Corrosion Damage Morphology

The extensive water and sessile bacteria analysis data collected over a period of some 10 years, indicated that oil field process waters with different TDS levels influenced the species of viable bacteria that existed in the various waters. Close examination of the sessile bacteria data and corrosion damage morphologies on the corresponding corrosion coupons in these waters indicated that there was a distinct relationship between the bacteria type and the corrosion damage pattern. Table 1 shows typical sessile bacteria analysis data obtained from coupon deposits after different exposure periods in different waters. Severe MIC attack on the coupons were observed and some equipment failures due to MIC have also been encountered.^{26, 27} An important finding was that SRBs do not exist in very high TDS waters, such as effluent water. A mixed consortia of SRB/GAB/GAnB/APB can co-exist in lower TDS waters.

An analysis of the corrosion data showed that coupons retrieved from different water streams (BRW, PDW, RCW and EFW) had high and severe general corrosion and pitting (localized) corrosion rates as per NACE Classification.²⁸ Both general corrosion and localized corrosion rates were in the severe category when the sessile bacteria count exceeded the compliance target value of 100 counts/cm². This was particularly noticeable for the GAB or GAnB species, and sometimes for SRB. Final EFW in some facilities are very high in TDS content (in the range of 150,00 to 230,000 ppm), and SRB counts in such waters were found to be zero or very low but had high counts of GAnB/APB. Severe general and localized corrosion on coupon samples were encountered in these high TDS waters. The morphology of corrosion damage was rather unique, consisting of serrations (deep, parallel scratches)