Hydrotesting is a common practice to assess pipeline integrity before service. Different from pneumatic testing that is used only for leak testing, hydrotesting is applied to test for both leaks and strength. During hydrotesting, a pipeline is filled with a liquid and pressurized to a pressure (usually 10%) greater than the anticipated future operating pressure.

**Background**

In general, hydrotesting itself lasts only eight to 10 h. In the oil and gas industry, however, it is often the case that water is left in the system afterward for many months before the system is actually commissioned. During this holding time or when the pipeline is first exposed to an aqueous environment like wet lay-up, corrosion due to microbiologically influenced corrosion (MIC) can commence.¹

When the system makes contact with the ground² or is even exposed to air,³ there are further possibilities for microbial contamination. Reuse of water also increases chances for MIC. Improper hydrotesting practices can cause MIC pitting attacks and also black powder problems.⁴ MIC pitting during hydrotest itself may not be a big problem because of the limited hydrotest time frame. The biofilms left behind during hydrotest, however, may present a serious threat once the pipelines become operational, because fluids transported in pipelines may contain sufficient nutrients for biofilms to flourish and a pipeline is often expected to be operational for several decades.

**Seawater in Pipelines**

Seawater is routinely used in the hydrotesting of subsea pipelines. Occasionally, other water sources may be used and they mainly come from aquifer water and/or produced water. Any water source for hydrotesting can contain mi-

This work investigated the microbiologically influenced corrosion (MIC) threat in pipeline hydrotesting using offshore seawater samples for coupon tests in anaerobic vials. Longer-term sulfate-reducing bacteria pitting was predicted using a MIC prediction software program calibrated with short-term pitting data from the tests.
TABLE 1

| Major element comparison between typical natural seawater and untreated GoM seawater |
|---------------------------------|-----|-----|-----|-----|-----|-----|-----|
|                                 | Ca²⁺ (ppm) | Na⁺ (ppm) | Cl⁻ (ppm) | F⁻ (ppm) | SO₄²⁻ (ppm) | K⁺ (ppm) | TOC (ppm) |
| Typical natural seawater        | 400 to 412  | 10,500 to 10,770 | 18,800 to 19,300 | 1.2 to 1.3 | 2,655 to 2,715 | 380 to 390 | <1 to 2   |
| GoM seawater                    | 421         | 10,800      | 19,700     | 1.41      | 2,655        | 398       | Not detected |

TABLE 2

| Major element comparison between typical natural seawater and Qurrayah seawater[^A] |
|---------------------------------|-----|-----|-----|
|                                 | Na⁺ (ppm) | SO₄²⁻ (ppm) | TOC (ppm) |
| Typical natural seawater        | 10,500 to 10,770 | 2,655 to 2,715 | <1 to 2   |
| Qurrayah seawater (seawater)    | 16,580     | 4,330       | 498       |

[^A] The assay for Na⁺ and SO₄²⁻ in Qurrayah seawater was done by ENC Labs (Albuquerque, NM), and TOC was assayed by San Antonio Testing Laboratory, Inc. (San Antonio, Texas).

croorganisms. Natural seawater contains viruses, prokaryotes, protists (mainly flagellates), and algae. Water used in hydrotecting is sometimes treated with biocides. Even treated water can be a source of sulfate-reducing bacteria (SRB) inoculum. Two other methods to treat the hydrotect water are adjusting pH and using water sources without sulfate. The pH adjustment (within a basic range), however, could increase the possibility of mineral scale formation on the pipe surface, and using a large amount of water without sulfate is usually costly and inconvenient when hydrotecting takes place offshore. Furthermore, the method of pipeline laying or water filling makes water treatment very difficult, if possible at all.

**Sulfate-Reducing Bacteria Metabolism**

It has been known that some SRB are able to utilize hydrocarbons or even live on carbon dioxide-hydrogen (CO₂-H₂) autotrophically, which means they can live without organic carbon intakes. Ross-moore found that a variety of bacteria have the capability to reduce in size, decreasing energy consumption during starvation and residing in smaller pores. These bacteria can then wait to thrive when the appropriate environmental conditions are met. This unique feature of bacteria makes predicting and preventing the MIC in hydrotecting difficult. Steel corrosion in seawater sometimes has been misdiagnosed as attack induced only by conventional chloride corrosion. Borenstein found that microorganisms contained in a stagnant chloride-bearing medium can cause steel failure much faster than in conventional chloride crevice corrosion alone. This increased corrosion rate may come from sulfate and other nutrients in the seawater, which cause souring and pipeline corrosion due to SRB activities.

**Use of Oxygen Scavengers**

In the field, oxygen scavengers are usually added to the hydrotecting water to prevent oxygen-caused corrosion. This provides an anaerobic environment for anaerobic bacteria such as SRB. MIC occurs when several favorable factors are present simultaneously, such as suitable water chemistry, temperature, nutrients (organic and inorganic), microorganisms, and pressure. The majority of SRB can thrive at pH ranges from 5 to 9, and except for thermophiles, are unable to thrive at temperatures >45 °C. Availability of a carbon source is usually considered to be the most important factor for SRB growth; SRB growth will be severely restricted if utilizable carbon in organic nutrients in the form of volatile fatty acids such as formate, acetate, and propionate, is <20 ppm. Pots, et al. also indicated that SRB growth would be the most prominent if the ratio of carbon to utilizable nitrogen was 10:1. Synergistic microorganisms can enrich the nutrients (such as organic carbons) in the local environment and thus promote SRB growth and accelerate the MIC process even though the initial environmental conditions are not suitable for SRB growth. Fermentative acid-producing bacteria (APB) should be considered in MIC forensics, especially in zero-sulfate and low-sulfate environments.

**Laboratory Testing**

Performing MIC tests in a laboratory setting for hydrotect has always been a challenge. Pipeline fluids (especially those in subsea pipelines) can be at very high local pressures. Barophilic SRB are adapted to this kind of pressure. In a laboratory, however, it is difficult and cost prohibitive to perform many tests in high-pressure reservoir simulators. It is possible that laboratory tests at one atmosphere may be able to simulate SRB growth at a high pressure because it has been reported that barophilic SRB isolated from a high-pressure oil reservoir...
Investigation of Microbiologically Influenced Corrosion in Pipeline Hydrotesting Using Seawater

The experimental methods involved the use of anaerobic 125-mL vials filled with 100-mL liquid. These vials were deoxygenated with nitrogen gas to provide an anaerobic environment. X65 carbon steel coupons were used, which typically had dimensions of 47.6 by 10.9 by 1.6 mm. Prior to use, the coupon surfaces were polished successively with 200 and 400 grit SiC abrasive papers, rinsed with alcohol, and then sonicated in a beaker filled with alcohol. The ratio of coupon surface to liquid volume was close to that in 0.30-m (12-in) inside diameter (ID) pipes.

All liquids in the tests were deoxygenated using nitrogen sparging for at least 30 min before use to reflect oxygen scavenger use in the field. Planktonic SRB (Desulfovibrio alaskensis (ATCC 14563)) was used in this work as a laboratory strain of SRB. Some experimental results as indicated were obtained by enriching artificial seawater and natural seawater samples with 1 g/L yeast extract, 3.5 g/L sodium lactate, and 200 ppm Fe²⁺.

Biofilm observations under SEM, unless mentioned specifically, were pretreated according to the following procedures: coupons were removed from vials and were immediately treated with 4% w/w glutaraldehyde for around 1 h to immobilize the biofilm, and then were dehydrated with 30%, 50, 75, and 100% alcohol in sequence. Before observing the biofilm, the coupons were first treated using a Bal-Tec CPD 030 critical point dryer and then coated with a gold film.

Results and Discussion

**Gulf of Mexico Seawater**

Table 1 shows that the Gulf of Mexico (GoM) seawater had a similar chemical composition to that of typical natural seawater. The total organic carbon (TOC) in the first GoM sample was <1 ppm compared to <1 to 2 ppm TOC for typical seawater while the TOC of a second GoM sample was 4.6 ppm. The GoM seawater sample analyzed using polymerase chain reaction (PCR) was actually very clean. It had a total bacterial concentration of only 13.3 cells/mL, and its SRB cell count was below the detection limit of 1 to 3 SRB cells/L. The sample was taken from an offshore platform.

When Hardy measured seven seawater samples from two similar locations of the North Sea, he obtained SRB numbers from 0 to 90 cells/mL, the average being 22 SRB/mL. Lee, et al., using the most probable number enumeration method, detected ~10 and 100 SRB/mL in Persian Gulf and Florida Key West seawaters, respectively. These two water samples came from 1.2 to 1.5 m deep and near-shore (within 100 m) locations that could be contaminated by sewage, agricultural run-off, or other waste streams.

**Temperature Effect**

Figure 1 shows how temperature affected planktonic SRB growth, where 37 °C is the optimum growth temperature for the lab strain SRB. Compared to the full nutrient medium (ATCC 1250 modified Baar’s medium), the enriched artificial seawater with limited nutrients is an acceptable environment for SRB growth, especially at 37 °C, and those added chemicals provided adequate nutrients for SRB growth. In general, mesophilic SRB grow well at 37 °C. Thermophilic SRB prefer even a higher...
temperature, but 37 °C is likely sufficiently high for pipelines in a shallow seabed in a hot climate. This means increased SRB growth with increasing temperature is generally expected in practical situations. It should be pointed out that planktonic cell counts may be used to help indicate the sessile cell health in laboratory tests, but the planktonic cell counts should not be used to correlate with sessile cell counts.

**Microbial Growth**

No microbial growth was detected after one month and six months in vials containing untreated GoM seawater. After cleaning with Clark’s solution, SEM images showed roughness on the entire surface of a coupon with one-month exposure to the seawater in a vial at 37 °C, and also of a coupon with six-month exposure at 25 °C. Due to lack of microbial activities and a hydrogen sulfide (H₂S) smell at the end of the test, the roughness was likely not caused by SRB. Similar roughness was also observed in tests using heat sterilized GoM seawater.

**Quarrayah Seawater**

The Quarrayah seawater from the Persian Gulf is much saltier than the GoM seawater, as seen in Table 2. In-house quantitative PCR analysis did not detect SRB in the Quarrayah seawater. Figures 2(a1) and (a2) show that a mineral layer covered the coupon surface after a three-month exposure at 37 °C. Figures 2(b1) and (b2) show scattered pits after the coupon surfaces were cleaned. They were likely due to factors such as a trace amount of oxygen leaking through the capped rubber septum rather than microbial activities. Oxygen leakage was not a problem, however, in the tests for vials that were a few weeks long. Some three-month vials were discarded in tests because of visible oxygen rust. A wax seal around the aluminum cap was subsequently used but it did not completely eliminate oxygen egress. An anaerobic chamber would be the last solution other than using an oxygen scavenger to prevent oxygen egress in long-term tests.

The EDS analysis of the surface in Figure 2(c) indicates the absence of the sulfur element, which means that SRB activity was likely absent.

Due to the lack of native viable microbes and the lack of nutrients, no MIC pitting was observed in untreated seawater samples. To simulate a contaminated hydrotest fluid and to speed up laboratory testing, worst-case scenario tests were carried out by enriching seawater samples and spiking them with the laboratory SRB strain. Figure 3(a) shows the SEM image of the biofilm on a one-week old coupon. Kidney bean-shaped SRB cells are clearly visible. Pits characteristic of MIC attack were revealed after acid cleaning of the coupon surface, as seen in Figures 3(b1) and (b2). An EDS analysis shown in Figure 3(c) indicates the presence of iron sulfide (FeS).

**Kinetics-Based Mechanistic Model**

Recently, Gu, et al. introduced an electrochemical kinetics-based mechanistic model for MIC using a new biocatalytic cathodic sulfate reduction (BCSR) theory. It assumes that a corrosive SRB
biofilm is present on an iron surface, causing the following reactions to go forward due to biocatalysis:

Anodic: $4\text{Fe} \rightarrow 4\text{Fe}^{2+} + 8\text{e}^-$ (iron oxidation) (1)

Cathodic: $\text{SO}_4^{2-} + 9\text{H}^+ + 8\text{e}^- \rightarrow \text{HS}^- + 4\text{H}_2\text{O}$ (BCSR) (2)

By using charge transfer and mass transfer theories and electrochemical kinetics, a mechanistic model was developed and solved numerically. The software based on the model is known as MICORP. It incorporates BCSR, proton reduction, and organic acid reduction to account for low pH at a pit bottom due to organic acids. Figure 4 shows the model prediction and experimental data obtained in this work. The model was calibrated with a single pit depth data to predict long-term pitting.

*Tetrakis hydroxymethyl phosphonium sulfate* (THPS) is a biodegradable biocide that is most often proposed for hydrotest fluid treatment. A minimum dosage is needed to prevent biofilm establishment. Tests were carried out in anaerobic vials to evaluate the THPS degradation profiles in artificial seawater, GoM seawater, and Qurrayah seawater. A mechanistic model of THPS degradation under alkaline pH was obtained and reported elsewhere.

**Conclusions**

This work provided a framework for laboratory testing of MIC in hydrotreating. Arguments were made for laboratory testing at one atmosphere instead of a high pressure expected in a subsea pipeline during hydrotreating. Clean offshore seawater samples from the Gulf of Mexico and the Persian Gulf were found to lack native viable microbial activities. The seawater samples were enriched and spiked with a laboratory strain SRB to simulate contaminated seawater used in hydrotesting. Biofilms and MIC pits were observed in the accelerated tests. A software package based on the BCSR theory was used to predict the pit growth.
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References


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