# Pipeline Failure Investigation: Is it MIC?

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*The investigation of pipeline corrosion failures, including those caused by microbiologically influenced corrosion (MIC), requires multiple lines of evidence to identify causative mechanisms and contributing factors. The types of evidence needed for the corrosion analysis include information about the design and history of operation of the asset; the physical, environmental, and metallurgical conditions present where corrosion is observed; and microbiological conditions. Next, this information is integrated and analyzed to assess whether biotic or abiotic processes were responsible for the failure. While the ability to diagnose MIC in the oil and gas industry is improving, practical limitations associated with sample collection in remote locations or from inside pipelines still present challenges to conclusively determine the cause.*

**Failure investigation and root cause** analysis are useful tools to pipeline operators who are seeking ways to optimize performance, control costs, and reduce risks. In the United States, regulated gas and liquid hydrocarbon pipeline operators are required to maintain incident investigation procedures as a part of their operations and maintenance manual. The incident investigation procedures are normally viewed as being applicable only in the event of significant incidents as defined under federal codes[1-2] rather than for all corrosion findings.

Understanding why internal or external corrosion has occurred (beyond the investigations performed after major incidents) is important for optimizing mitigation and prevention measures, and generally worth the minor investment required. The degree of analytical rigor can be proportional to the severity of the corrosion or the level of risk associated with the asset. Whenever corrosion is found on a pipeline, an opportunity presents itself to understand the mechanism causing the corrosion and the contributing factors that supported it. Such an understanding increases the ability to manage the threat of corrosion in the future and extension of asset life.

While there are many potential pipeline corrosion mechanisms, they can be generally divided between biotic (caused or promoted by microorganisms and/or their activities) and abiotic (corrosion in the absence of any direct microbiological contribution). Abiotic mechanisms, for example, include corrosion of steel in an electrolyte in the presence of dissolved carbon dioxide ($CO_2$), hydrogen sulfide ($H_2S$), or oxygen. The definition of biotic corrosion is more complicated because microbiological activities may be intertwined with chemical/electrochemical processes that cause corrosion. Biotic and abiotic processes are also affected by complex transformations of chemical species that have growth, inhibitory, or synergistic effects on biotic activities that cause microbiologically influenced corrosion (MIC).[3]

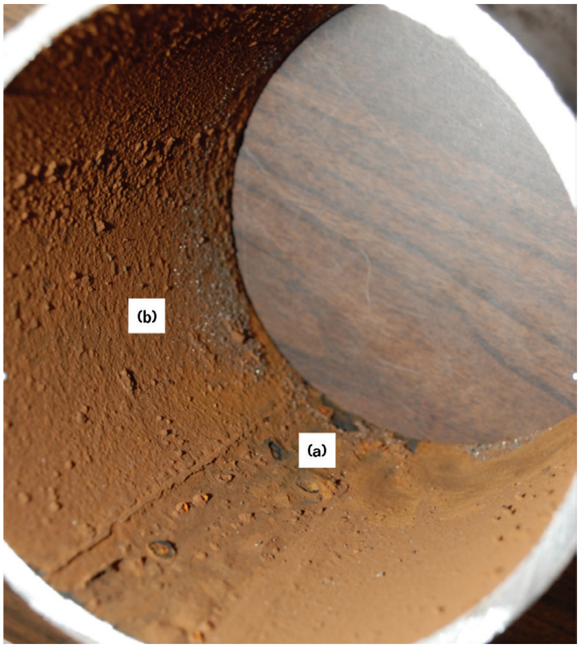

**FIGURE 1** Deposits inside a 6-in (152.4-mm) nominal diameter pipe sample, showing locations where comparative samples could be collected for chemical and microbiological analysis: (a) a corrosion pit beneath deposits and nodules in a "channel" of deposits ~2-in (51-mm) wide at the 6:00 position in the pipe, and (b) an area on the side wall of the pipe that is above the "channel" of deposits on the bottom of the pipe.

## MIC Analysis Process

While there is a lack of industry consensus procedures specifically for MIC failure investigation, there is some helpful guidance available. For example, NACE TM0212[4] for internal MIC and NACE TM0106[5] for external MIC of pipelines provide information about sampling and test methods that can be used to support corrosion investigations.

ASTM G161-00[6] provides a useful overview of the corrosion failure analysis process and a checklist that can be used when collecting information that will be used to support the corrosion failure analysis, as do the appendices of the two aforementioned NACE standards.

## Samples are Essential

Sampling and preservation of biofilms from inside an operating pipeline is difficult. Removable devices, such as coupons or spool pieces,[7] provide representative surface samples if the removable devices are located properly or if a removed section of the pipeline is prepared and transported correctly. Samples should be:

- Collected using sterile tools and placed into the recommended containers
- Collected as soon as possible after exposure to atmospheric conditions to avoid changes to corrosion products and consortia of microorganisms
- Protected from contamination and stored/shipped under recommended conditions to avoid degradation/alteration

Sampling can be performed to provide material to characterize the liquid phase, layers of deposits and biofilm on the metal surface, and the corroded metal surface itself. It is helpful to collect samples from corroded and uncorroded locations on the same sample, and from multiple locations for comparison. An example is shown in Figure 1; the deposits in the pipe sample have a reddish color due to oxidation from the atmosphere of iron compounds that are present.

Since most crude oil, gas, and products pipelines operate with little or no oxygen present, exposing the corrosion products to air before sampling can change the mineral composition of the deposits. Figure 2 shows an example of this, where a pipe section with internal corrosion near a girth weld was left uncovered outside for several days before samples could be collected. Although the pipeline carried water-saturated natural gas with 10 to 50 ppm of $H_2S$, no sulfur or iron sulfides were found in the corrosion deposits. Exposure to air and dehydration also affected any biofilm that would have been present, hampering the ability to understand if microorganisms were involved in the corrosion.

Typically, samples for microbiological laboratory analysis are shipped in an insulated box or portable cooler with ice packs and delivered within 24 h whenever possible to a specialist laboratory. Other preservation methods are sometimes used when samples cannot be shipped overnight. In Norway, Equinor,[8] for example, used 100-mL volume screw top glass bottles and a lid with two hose connections to purge the bottle with inert gas (nitrogen) after sampling solid deposits and pigging debris. This approach also helped to keep oxygen from changing the corrosion products. ASTM E1492-11[9] is a resource that provides practices for receiving, documenting, storing, and retrieving samples for laboratory analysis.

## Chemical Analyses

Chemical composition information is desirable for samples such as:

- Liquid (water) phase
- General surface deposits

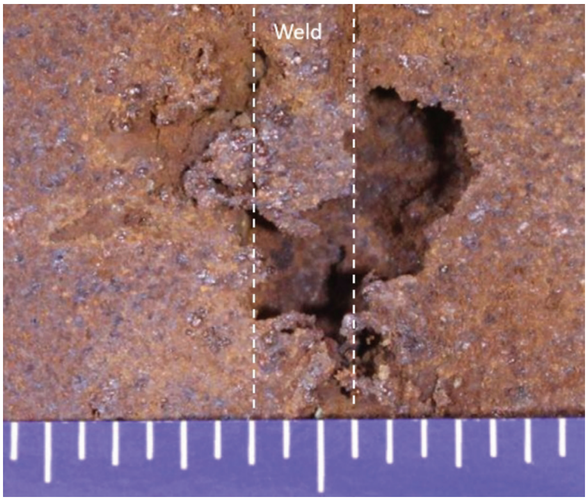

**FIGURE 2** Sample showing localized internal corrosion located at a girth weld in a pipeline carrying water-saturated natural gas with 10 to 50 ppm of $H_2S$. After removal from the pipeline, the sample was left exposed outdoors, causing oxidation of the surface and alteration of the corrosion deposits such that no sulfur could be detected by compositional analysis.

**TABLE 1.** EXAMPLES OF FUNCTIONAL GROUPS OF MICROORGANISMS, CHEMICAL SPECIES ESSENTIAL FOR GROWTH AND END PRODUCTS

| Functional Group | Chemical Species Essential for Growth | End Products |
|---|---|---|
| Acid producers | Organic carbon compounds, hydrocarbons, oxygen | Organic acids |
| Nitrate reducers | Nitrate, nitrite, nitrogen, oxygen | $N_2$, $NO_2$, NO |
| Iron reducers | Ferric iron, sulfur, oxygen, nitrate | Soluble ferrous iron |
| Iron/manganese oxidizers | Ferrous iron in solution, $Mn^{2+}$ | Insoluble ferric iron |
| Sulfur oxidizers | Elemental sulfur, sulfate, thiosulfate, $CO_2$, oxygen, organic compounds | Sulfuric acid ($H_2SO_4$) |
| Sulfate reducers | Alcohols, organic acids, $H_2$, sulfate, elemental sulfur, thiosulfate | Sulfide |
| Methanogens | $CO_2$, carbonate, bicarbonate, $H_2$ | Methane, CO |

**TABLE 2.** EXAMPLE OF DIFFERENT MICROBIOLOGICAL METHODS DESCRIBED IN NACE TM0212-2018

| Method | Method Based On | Measurement Principle |
|---|---|---|
| Adenosine triphosphate (ATP) | Enzyme assay | Quantification of ATP through enzymatic light reaction |
| Flow cytometry | Laser-based biophysical technology | Automated counting of fluorescently labeled cells in a stream of fluids |
| qPCR | DNA amplification (PCR) | Real-time quantification of specific genes (DNA) of interest from live and dead target organisms |
| Microbial community analysis (Speciation) | DNA amplification (PCR) and sequencing of DNA amplicons | Amplified and sequenced 16S rRNA genes are compared to public databases to identify microbial Genera, Phyla, and Species |

- Corrosion products removed from isolated pits
- Deposits collected from on top of or beneath coatings
- Surface films adhered to the metal surface

For corrosion failure analysis, it is common to cut the metal specimen into smaller samples that can be prepared as metallographic cross sections or placed directly in a scanning electron microscope for energy dispersive x-ray spectroscopy, or other techniques that allow compositional analysis of the deposits in situ. Corrosion products are often analyzed using x-ray diffraction to characterize the composition of the crystalline phases present, such as corrosion products (iron sulfides, iron oxides, etc.).

API 45, "Recommended Practice for Analysis of Oilfield Waters,"[10] is a useful resource that describes the types of analysis that can be performed on aqueous samples to characterize cations, anions, and other parameters that are relevant to corrosion.

The chemical composition of the environment, including the pH, salinity, organic carbon sources, and chemical species usable by microorganisms, is determined to help identify the types of microorganisms that could grow in that environment. Table 1 shows some examples of functional groups of microorganisms, the chemical species needed for growth, and some typical end products produced because of their metabolism. The metabolism of microorganisms is dependent on the availability of water, an energy source (electron donor), carbon source, nutrients, and electron acceptors (e.g., oxygen, sulfate, nitrate, iron (III), or $CO_2$).[3]

## Microbiological Analyses

The environment present where corrosion is occurring and the most prolific members of the active microbial consortia often reflect one another. Microorganisms exist under wide ranges of temperature, water activity, salinity, pH, and oxygen conditions, and can use many substrates for growth. However, functional groups for which the environment is optimal for growth will tend to dominate. The use of molecular microbiological methods (MMM) can help provide insights for diagnosis of MIC.

Generally, microbiological characterization is focused on determining the diversity, abundance, and activity of the various microorganisms present in a sample. It is not enough to know only "who" is there and "how many," but also their activity level. Genetic methods, such as next-generation sequencing, may identify hundreds of different types of microorganisms to be present in a sample, but many may be in a dormant stage—waiting for episodic events when conditions change to their advantage.

In NACE TM0212, Table 2 provides a very useful resource for comparing the benefits and limitations of several microbiological methods; a short example of the list of methods is shown here in Table 2.

One of the challenges that industry has faced with implementing MMM is that data from different labs may not be comparable because of differences in the methods used. A group of NACE International members is working in Task Group (TG) 561 to establish standards to promote consistency in the molecular analytical methods used by different labs, specifically with regards to sampling/transportation, DNA extraction, and the primers used in quantitative polymerase chain reaction (qPCR) methods and sequencing.

## Data Integration

The need for using multiple lines of evidence to diagnose MIC has been an industry mantra since the 1980s, and it continues to be relevant today. Longstanding MIC experts Drs. Jason Lee and Brenda Little, FNACE recently wrote a chapter on MIC analysis, identifying these requirements for an accurate diagnosis:[11]

1) A sample of the corrosion product or affected surface that has not been altered
2) Identification of a corrosion mechanism that is consistent with the vulnerabilities of the material being examined
3) Identification of microorganisms capable of growth and maintenance of the corrosion mechanism in the particular environment
4) Demonstration of an association of the microorganisms with the observed corrosion.

The objective is to have three independent types of measurements (metallurgical, chemical, and microbiological) that are consistent with a mechanism for MIC.

Some questions that may be helpful to consider when integrating MIC failure analysis data are as follows:

- What differences in the types and numbers of microorganisms were observed between corroded vs. uncorroded areas?
- Does the chemical environment that was present include the necessary chemical species for the groups of microorganisms that were identified?
- Are there chemical indicators (sulfides, organic acids, etc.) that could be indicative of activity of specific groups of microorganisms?
- Which microorganisms are capable of growth under the conditions of pH, flow, temperature, oxygen levels, and salinity present in the environment?

## More Information on MIC Failure Analysis

There are many publications and technical events where more can be learned about MIC failure analysis. Industry case studies and examples of failures from the field can be helpful in demonstrating how MMM are used in MIC failure analysis.[12-13]

The NACE Northern Area Western Conference is holding a half-day forum on "Assessment of Microbiologically Influenced Corrosion (MIC) Threats and Failures: Approaches and Challenges," as a part of its conference on February 7, 2019, in Calgary, Alberta, Canada.

A forum will be held at CORROSION 2019 in Nashville, Tennessee, USA: "Update on Latest MIC Developments in Onshore and Offshore Oil and Gas." Multiple symposia and TG meetings on MIC will also be held throughout the week.

Another venue for more information is the 7th International Symposium on Applied Microbiology and Molecular Biology of Oilfield Systems (ISMOS-7) that will take place on June 18 to 21, 2019 in Halifax, Nova Scotia, Canada.[14]

More MIC guidelines, models, and technologies will be among the deliverables from the project, "Managing Microbial Corrosion in Canadian Offshore and Onshore Oil Production," which received $7.9 million in funding through Genome Canada.[15]

## References

1 U.S. Code of Federal Regulations (CFR) Title 49, "Investigation of Failures," Part 192.617 (Washington, DC: Office of the Federal Register).

2 U.S. Code of Federal Regulations (CFR) Title 49, "Operating Procedures," Part 195.402(c) 5 (Washington, DC: Office of the Federal Register).

3 A. Ibrahim, et al., "Review and Analysis of Microbiologically Influenced Corrosion: The Chemical Environment in Oil and Gas Facilities," *Corrosion Engineering, Science and Technology* 53, 8 (2018): pp. 549-563.

4 NACE TM0212-2018, "Detection, Testing, and Evaluation of Microbiologically Influenced Corrosion on Internal Surfaces of Pipelines" (Houston, TX: NACE International, 2018).

5 NACE TM0106-2016, "Detection, Testing, and Evaluation of Microbiologically Influenced Corrosion on External Surfaces of Pipelines" (Houston, TX: NACE, 2016).

6 ASTM G161-00, "Standard Guide for Corrosion-Related Failure Analysis" (West Conshohocken, PA: ASTM International, 2018).

7 T. Skovhus, R. Eckert, E. Rodrigues, "Management and Control of Microbiologically Influenced Corrosion (MIC) in the Oil and Gas Industry—Overview and a North Sea Case Study," *J. of Biotechnology* 256, 8 (2017).

8 V. Eroini, H. Anfindsen, A.F. Mitchell, "Investigation, Classification and Remediation of Amorphous Deposits in Oilfield Systems," SPE-173719, SPE International Symposium on Oilfield Chemistry, Society of Petroleum Engineers (London, UK: SPE, 2015).

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10 API 45, "Recommended Practice for Analysis of Oilfield Waters" (Washington, DC: API: 1998).

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12 F.M. Al-Abbas, "MIC Case Histories in Oil, Gas and Associated Operation," *Microbiologically Influenced Corrosion in the Upstream Oil & Gas Industry,* T.L. Skovhus, J. Lee, D. Enning, eds. (Boca Raton, FL: CRC Press, 2017).

13 R. Eckert, *CorrCompilations: Introduction to Corrosion Management of Microbiologically Influenced Corrosion* (Houston, TX: NACE, 2015).

14 ISMOS-7: http://www.ismos-7.org/

15 Project web page for "Managing Microbial Corrosion in Canadian Offshore and Onshore Oil Production," http://www.geno-MIC.ca

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