

Using Failure Analysis to Optimize Corrosion Mitigation Costs

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ABSTRACT

Failure analysis and root cause analysis (RCA) of corroded pipelines and piping system components can provide operators with valuable information to help prevent future failures while optimizing mitigation costs. If a corroded pipe sample is not handled or preserved properly because of inadequate planning, the ability to diagnose the corrosion mechanism(s) is lost. Using some basic steps for preparation and investigation, operators can determine the applicable corrosion mechanism(s) causing the corrosion and implement or adjust the measures taken to mitigate the corrosion. Collecting multiple lines of evidence about chemical and microbiological conditions, corrosion products, and operating parameters is essential. Further, with the increasing use of molecular microbiological methods (MMM), the role of microorganisms can be determined with greater certainty than has been possible in the past. Targeting mitigation measures to only the applicable corrosion mechanism(s) can support mitigation cost optimization, such as by applying only the correct chemical treatments rather than an all-encompassing “security blanket” approach.

Key Words: Corrosion failure analysis, microbiology, pipeline integrity, RCA, MIC, FCE, qPCR

INTRODUCTION

Failure and Root Cause Analysis of Pipelines

Forensic corrosion engineering (FCE) is a practice that seeks to understand the contributing causes and underlying mechanisms of corrosion damage and apply this knowledge to mitigate risk resulting from corrosion threats. FCE focuses on the physical and circumstantial evidence associated with materials degradation or failures resulting from corrosion. The objectives of FCE include characterizing the basic electrochemical mechanisms of the corrosion damage, identifying the environmental factors that supported the corrosion mechanism, and proposing effective means of mitigating corrosion for similar facilities or equipment.¹

The first phase of the investigation involves determination of the immediate cause. For a pipeline internal or external corrosion failure, the “immediate” (or direct) cause of the failure relates to the findings of a metallurgical laboratory analysis performed on the removed pipe section or component. The laboratory analysis is used to determine the damage mechanism that caused the leak or failure.

The second phase of the investigation involves identification of the “basic” (or “contributing”) cause(s) of the failure. Basic causes relate to issues that may have contributed to the immediate cause. For example, high carbon dioxide (CO₂) levels in the gas may have promoted the corrosion mechanism (i.e. immediate cause), and the contributing causes may include exceeding the capacity of the gas processing equipment and poor maintenance of the processing equipment.

The final phase of the investigation is a review of management systems to determine the root cause(s) of the failure. There are many different tools for conducting a root cause analysis, but the end objective is generally to look for systemic issues that, if addressed, would prevent a similar incident from occurring in the future.

Pipeline corrosion forensic investigations sometimes end up with unclear or vague conclusions as to the causative mechanism because there is insufficient data to decisively discern between microbiologically influenced corrosion (MIC) and abiotic corrosion mechanisms, e.g. CO₂, hydrogen sulfide (H₂S), etc. Inadequate sample analysis data, or even misleading information from improper sample preservation procedures, can greatly detract from the ability to clearly determine a corrosion mechanism.² This situation is compounded by the fact that microorganisms can be found nearly everywhere, but corrosion is not.

Examples of Information Loss

In many cases, the corroded sample is not handled or preserved properly and the ability to diagnose the corrosion mechanism is lost. Some common examples of incorrect handling and sampling include:

- Buried pipelines that have been cut and flooded with ground water
- Cut-out pipe samples being exposed to air, heat, dust, and rough handling
- Pipe samples being chemically cleaned with solvents / soaps or mechanically cleaned by blasting
- Liquid or solids sample collected in used or non-sterile containers
- Liquid or solids sample collected and left for days or weeks before sending to lab for analysis
- Failure to adequately photo document the failed sample at the time of removal from service

Samples that are handled and preserved properly provide reliable and accurate analytical results. In some cases, alteration or contamination of the sample is unavoidable, such as when the failure results in a fire or the failure origin is exposed to water, mud, or dirt in post-rupture events. When a corroded sample has been altered, a representative sample may still be available if corrosion is present at another location on the pipe that was not affected by post-rupture events or other forms of contamination.³

Corrosion Failure Analysis

Improved Practices for Sample Collection and Handling

Two ways to improve the ability to distinguish corrosion mechanisms on pipelines are to 1) be prepared with a plan, supplies, and training for sample collection and preservation and 2) be willing to invest in the effort and cost to collect multiple lines of evidence.

In the US, regulated hazardous liquid and natural gas pipelines must be examined for external corrosion whenever they are exposed. The operator must determine the extent of any external corrosion that is found and document the inspection. The need to determine the cause of the corrosion is also included in ASME B31.4, 461.3 (2006).⁴ Similarly, regulated pipelines must be inspected for internal corrosion whenever the internal surface is exposed, e.g., during a pipe-line repair. If corrosion is found, this provides the operator an opportunity to collect samples and other information to help determine why the corrosion occurred and to determine the appropriate mitigation measures. Advance planning to have materials available for sample collection and requirements to collect the right data and information about any observed corrosion is essential for meeting these regulatory requirements.

Standards are also available to provide guidance on sampling and determining the cause of corrosion. For example, ASTM G 161⁵ provides a useful overview of the corrosion analysis process and a checklist that can be used when collecting information that will be used to support the corrosion failure analysis. NACE Standard Test Method TM0212-2018⁶ for internal MIC of pipelines and, similarly, NACE Standard Test Method TM0106-2016⁷ for external MIC of pipelines provide guidance on sampling, sample preservation, and test methods that can be used to properly characterize samples associated with corrosion. ASTM E 1492⁸ provides details on practices for receiving, documenting, storing, and retrieving samples for laboratory analysis.

Since pipeline corrosion is often a localized phenomenon, it is important to consider the environment from the macro to micro scale, and potential changes that may have occurred over time. Sampling should ideally be performed to provide material to characterize the bulk phase, the layer between the bulk phase and metal, and the metal surface itself. Also, it is useful to collect samples from both corroded and uncorroded areas for comparison of chemical and microbiological conditions.

To obtain reliable samples for analysis of corrosion, it is essential that the samples are:

- Collected immediately, if feasible, (or as soon as possible) upon exposing the corroded metal to atmospheric conditions in order to avoid oxidation of corrosion products and changes in living conditions for microorganisms
- Collected using appropriate, sterile tools and placed into the recommended types of containers
- Protected from contamination and stored/shipped under recommended conditions to avoid damage and degradation of the samples during transit

Field Testing

Field testing is performed to measure sample compositional parameters that can change quickly after a sample is collected. Degradation can occur equally in corrosion deposits and soils. Chemical and microbiological changes can occur due to dissolved gas evolution, the introduction of oxygen in solution, temperature changes, contamination, and oxidation. Chemical field test methods are often used for measuring dissolved gases, e.g. CO₂, H₂S, and oxygen (O₂), in aqueous samples. The pH and alkalinity of an aqueous sample are also typically measured immediately after a sample is collected, as these parameters will change due to gas evolution and oxygen entrainment. Chemical field test methods are also often used for measuring the presence of calcium, carbonates, and sulfide, as well as ferric and ferrous iron in external corrosion samples. The color, smell, and texture of all collected samples, including the presence of any distinct phases, should be documented.

Current field tests that produce immediate microbiological test results are generally limited to adenosine triphosphate (ATP) measurement. Adenosine triphosphate is a measure of microbiological activity and the test value is converted into an equivalent number of active microorganisms in a sample. Liquid or gel culture test media may also be inoculated in the field as soon as samples are collected; however, the results are not available until after days to weeks of incubation. Samples for molecular microbiological analysis (based on DNA analysis) are also collected and preserved in the field and results are produced after laboratory analysis.

Laboratory Testing

Samples of corroded pipe, collected surface deposits, coatings, soils, surface swabs, and liquids may be submitted to a laboratory for various types of analyses. For corrosion failure analysis, the primary goal of laboratory testing is to confirm the mechanism that caused the corrosion. The ability to accurately determine the mechanism through laboratory testing is directly tied to the types and quality of samples provided and the receipt of sufficient background information about operating and design conditions. Laboratory testing may involve mechanical testing; nondestructive testing; various types of microscopy including optical and scanning electron microscopy; chemical composition analysis using x-ray diffraction (XRD), energy dispersive spectroscopy (EDS), wet chemistry, and chromatography; and laser scanning of the remaining wall thickness to record the extent and distribution of wall loss.

The goal of field and laboratory testing is to develop data to support multiple lines of evidence⁹ to be used in determining the mechanistic cause of corrosion.

MULTIPLE LINES OF EVIDENCE

The main categories of evidence used to diagnose the causes of corrosion damage include: 1) operation and design, 2) the chemical environment, 3) the microbiological environment, and 4) materials and corrosion products. Each of these categories and the typical types of information they contain are shown in Figure 1. These data sets are integrated to evaluate the potential for abiotic corrosion vs. biotic corrosion. Bayesian network approaches are one way of using multiple lines of evidence in a quantitative manner.

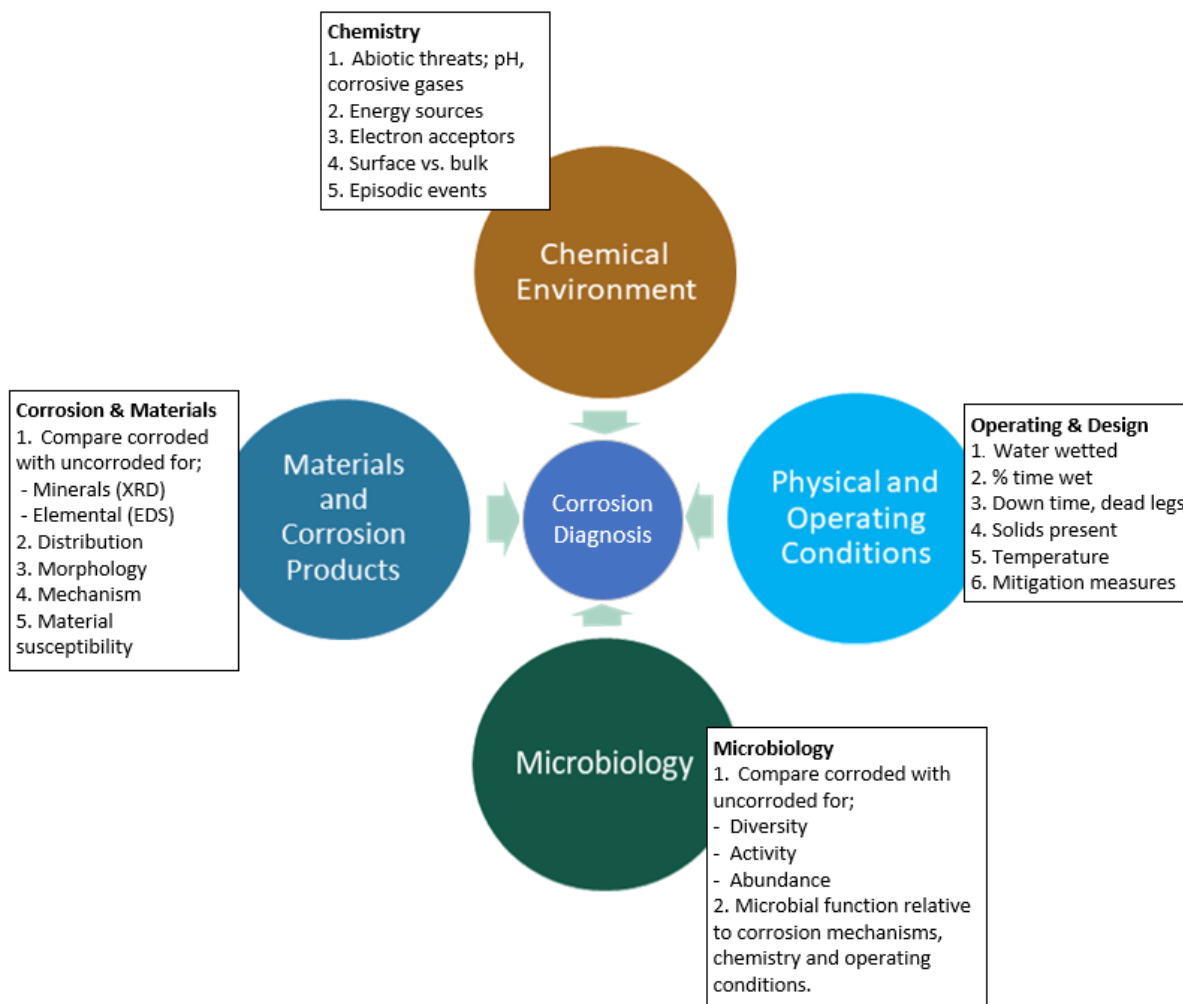


Figure 1 - Multiple lines of evidence contribute to accurate corrosion diagnosis.

Operation and Design

Operating conditions that can significantly affect corrosion include temperature, fluid velocity, and the amount of time the metal surface is exposed to water. In crude oil gathering and transportation, the crude composition itself can affect the potential for water wetting of the pipe surface.¹⁰ Flow regime, e.g. stratified, laminar, slug, etc., also affects exposure to water and the presence of surface deposits. The operating pressure affects the resulting partial pressure of gas species that are present, and temperature affects corrosion reaction rates and microbiological activity. Pipelines that flow infrequently or that are dead legs, may accumulate deposits and water that can lead to corrosion.

Asset design factors that should be known when performing a corrosion failure analysis include material type and grade; heat treatment; welding or other processing of the material; method of fabrication; methods of material handling prior to construction; pipeline elevation profile in the corroded area; location of connections, inlets, and outlets; proximity to processing facilities, etc.