Minimizing Infrastructure Corrosion

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Abstract

Pipeline operators in the United States will be faced with many issues relative to infrastructure installation, upgrading and replacement. Of concern is system integrity, to minimize service disruptions and the risk of failures and product release. The majority of service interruptions of large infrastructure can be attributed to corrosion. Costs associated with system infrastructure are very high, and monies need to be expended prudently. Understanding infrastructure condition and corrosion exposure is an important part of the overall Infrastructure Master Plan for existing and new piping systems.

Introduction

In the management of large infrastructure, the cost of corrosion prevention is relatively small when compared to the cost of total replacement or substantial rehabilitation. Therefore the goal is to prevent failures from occurring, extending the service life of the capital plant. This approach is preferred to a program of failure management, where service interruption, product contamination, losses to personal property and personal injury are all possibilities. Although there are other infrastructure failure mechanisms, corrosion is a major factor in the deterioration and failure of pipeline metallic infrastructure.

It has been reported by the National Bureau of Standards that the annual cost of corrosion in the United States is on the order of $70 billion per year. This cost can be attributed to loss of useful life of equipment, cost of corrosion mitigation, litigation and downtime. Considering the substantial mileage of pipe, number of storage tanks and the variety of metallic components in the pipeline transmission and distribution industries, a considerable percentage of that annual cost is borne by these industries.

There are several corrosion engineering studies and analyses that can be employed to define the condition of the infrastructure of concern as well as define potential corrosion problems that might be encountered for new construction. By understanding the current infrastructure condition, defining the corrosion mechanisms, delineating corrosion rates and understanding the environment corrosivity, projected life calculations can then be made. These studies are then utilized to develop infrastructure life extension options for economic analysis.

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Cause of Corrosion

Corrosion activity occurs as a natural reaction between a metallic structure and its environment. With available oxygen and water, exposed metal will under go a process called oxidation. When a metal experiences oxidation, the basic element of construction ie. iron, reacts with the hydroxide ion to form corrosion films. The most readily observed corrosion films are rust, iron oxide and copper patina. As the base material is consumed to form the corrosion films, the base material experiences corrosion degradation, leading to loss of material.

Corrosion is established as direct current, DC, circuits. Alternating current, AC, is not typically a factor in the corrosion exposure of water piping. DC circuits are defined by the relationship called Ohms Law, E=IR, where E is the driving voltage of the circuit, I is the current magnitude and R is the resistance of the circuit. The greater the current flow in the corrosion circuit, the greater the metal loss. Ferrous materials corrode at the rate of 20 pounds per ampere-year. How the corrosion circuit is established and where corrosion would be experienced is complex, however some examples presented in this paper should be useful.

General Corrosion

General corrosion will occur on structures exposed to several environments or electrolytes encountered in the water treatment, storage, and transmission and distribution industry. Electrolytes include raw and treated water, salt water and fresh water, soil of many varieties, atmospheric rain and air borne contaminants. Corrosion aggressiveness of these electrolytes is influenced by many contaminants contained in the electrolyte:

- Chlorine from water treatment
- Chloride ions from road de-icing
- Marine environments, salt water
- Variations in soil
- Clay soil
- Organic soil
- Air borne contaminants effecting pH

These are some of the primary contributors of corrosion normally encountered in the industry. The effect that these contaminants generally have on environment corrosivity is a reduction in the environment resistivity. Lower resistivity, or circuit resistance, would produce larger corrosion currents for a given circuit. This can be seen in a modified Ohms Law where I=E/R. As the resistance decreases for a given voltage, the value of current increases. Field experience would support this relationship: salt water environments are very corrosive as the resistivity is very low, conversely little corrosion would be found in uncontaminated dry sand.

Soil resistivity, the reciprocal of conductivity, has been used for years as an indicator of the corrosivity of soil. The lower the resistivity, the easier current will flow through the soil. Of the measurable soil characteristics, resistivity is generally accepted as the primary indicator of soil corrosivity

Galvanic Corrosion

Galvanic corrosion results when two different metals are electrically connected and surrounded by the same electrolyte. This is the electrochemical basis for the lead acid battery. The material with the highest electrochemical energy level would experience corrosion, called the anode, and the other material, called the cathode, would not experience corrosion.

In the water industry, galvanic corrosion could be expected from connections between ferrous materials such as, steel and ductile iron, and copper, stainless steel and brass. In this corrosion cell the ferrous materials would corrode relative to the other materials. This relationship is normally depicted in a table referred to as the galvanic series.

The following table lists the common piping and construction materials in order of galvanic activity:

Material	Potential	Activity
Magnesium	1.70	Most active, Anodic
Steel	0.50 – 0.60	
Ductile iron	0.30 – 0.40	
Corroded steel	0.30 – 0.40	
Cast iron	0.10 – 0.20	
Copper	0.15 – 0.20	
Brass	0.15 – 0.20	
Stainless steel	0.10 – 0.20	Least active, Cathodic

This chart indicates that for two dissimilar metals being electrically connected, the one towards the most active end would be anodic or experience corrosion, and the one towards the least active end would be cathodic or not experience corrosion. For the corrosion cell to establish, both materials need to be in a common electrolyte and electrically connected. Common examples would be a copper service connected to a ferrous metal main in soil and stainless steel pipe repair clamp with alloy steel bolts. In these examples, the copper and stainless steel would be cathodic, and the ferrous materials anodic and experience corrosion.

Stray Current

Stray current corrosion results from sources outside the influence of the pipe and it's environment. To cause stray current on a pipeline, the current must flow onto the pipe at one location and then flow off the pipe at another location. Where the stray current leaves the affected pipe, corrosion will occur. Common sources of stray current in the water industry are primarily rapid transit systems and transmission pipeline operations that employ impressed current cathodic protection.

Current flow in a pipeline which provides a continuous metallic path to the power neutral ground grid will not cause corrosion damage. If the current discharges from the pipeline into the environment, it will cause corrosion loss at the rate of 20 pounds of metal loss in one year per ampere of discharge. Therefore, a current discharge of 0.5 amperes for 1 year would remove 10 pounds of metal. At a density of 450 lbs/ft^3 of cast iron for example, this equates to 38 in^3 of metal removed in one year. This type of corrosion manifests itself on the pipe surface by a clean, sharp, pocked surface.

The primary source of stray current in large metropolitan areas comes from the operation of rapid transit systems. Those that operate on direct current, DC, with the running rail or track functioning as the negative return are capable of generating stray current. The other source of stray current comes from the operation of impressed current cathodic protection systems. Impressed current cathodic protection is utilized to protect long pipelines, poorly coated structures, above ground storage tank farms and other type of structures.

Defining Corrosion Exposure

Corrosion manifests itself on metallic structures in contact with electrolytes. Therefore the concern for corrosion exposure applies to the interior and exterior of piping system, the interior and exterior of storage facilities and the mechanical equipment utilized in process and treatment plants. To ensure that the proper corrosion control method(s) are employed and the infrastructure service life is realized, corrosion exposure must be understood. This is important in the planning and design phases of major infrastructure projects. For the purpose of both design and operations, it is important to define the corrosivity of the installation. Where experience or analysis indicate that the environment is corrosive and aggressive, corrosion control methods need to be developed and initiated.

For the external pipe surfaces, the effects of soil, water, and air vary depending on the pipe material that exists in the ground or being considered for installation. The following conditions should be understood to facilitate definition of environment corrosivity.

Soil Assessment

The measurement of soil resistivity has been used for years as an indicator of the corrosivity of soil. Soil resistivity is the reciprocal of conductivity, the lower the resistivity, the easier current will flow through the soil. Of the measurable soil characteristics, resistivity is generally accepted as the primary indicator of soil corrosivity. Resistivity is a property of the bulk volume of soil and electrolytes.

Although no standard has been developed and accepted by such organizations as the American Society for Testing and Materials or the National Association of Corrosion Engineers, it is generally agreed that the classification shown below, or other similar classifications, reflect soil corrosivity.

Resistivity (Ohm-Cm)	**Corrosivity**
below 500	Very Corrosive
500 to 1,000	Severely Corrosive
1,000 to 2,000	Moderately Corrosive
2,000 to 10,000	Mildly Corrosive
Above 10,000	Progressively Less Corrosive

Not only is the resistivity useful in predicting relative corrosion rates, but it is equally important to identify whether soil resistivity varies along a given route. Structures such as pipes, which are electrically continuous along significant portions of their length, will be susceptible to long line galvanic influences arising from variations in soil resistivity along the pipe route. Portions of a structure in the lower soil resistivity environments tend to become anodic, and therefore corrode, relative to other portions of the same structure.

Soil resistivity can be measured in several ways, and all may be utilized during an evaluation as conditions warrant. Resistivity can be measured in-situ, typically via the Wenner four-pin method (ASTM G-57). This method measures the average resistivity of large volumes of soil based on the spacing of the measuring pins. Resistivity can also be measured in-situ with a Collins rod and Whetstone bridge. This method measures a small volume of soil in the area surrounding the tip of the rod.

Corrosivity of a particular soil is also affected by several other parameters, including chemicals present in the soil, moisture content and soil type. For this evaluation, there are a few other soil parameters that may warrant investigation. This information is typically determined through laboratory assessment. These are listed:

- soil moisture
- pH
- sulfide concentration
- chloride concentration

Structure Electrical Continuity

As mentioned in the discussion of soil resistivity above, electrically continuous pipe can be subject to long line galvanic cells. Electrically continuous pipe can also gather current along a long length, from a foreign pipeline. These factors would therefore lead one to believe that discontinuous pipe would be desirable. However, in order mitigate the effects of long line galvanic cells, and current flow due to foreign pipelines, cathodic protection would typically be used. Cathodic protection relies on the piping being electrically continuous over its length, so that anodes in one location can be utilized to protect other locations.

Pipeline Excavation

Condition assessment described to this point provides qualitative information about the structure corrosion exposure, both for new design considerations and in the evaluation of existing infrastructure. Much more quantitative information on existing infrastructure can be obtained through physical examination, non-destructive evaluation and statistical analysis. For this type of study of an existing pipeline, the number of excavations is determined from a practical approach to assessing corrosion activity along the pipe route.

In analyzing extreme values encountered in statistical samples, the deepest pit in the pipe is of primary interest to the analysis. This method of analysis, together with studies of factors influencing the corrosion of the structure of concern, such as soil resistivity and soil moisture content, allows the prediction of the magnitude of corrosion penetration problems that will be encountered on a given structure. This can be done by inspecting only a very small portion of the structure.

Typically, the statistical unit of one-square foot is selected based on maximizing the accuracy of the statistical analyses and this size unit is preferred based on experience in applying extreme values statistical analysis. Ideally, a sufficient number of locations are selected to be representative of the corrosion conditions affecting the structure throughout the study area. The size and number of inspection locations will vary with the length of the structure, the nature of the corrosion conditions to which it is subjected and cost considerations.

The pipe must be excavated at one (1) or more locations, with ten linear feet of pipe available for inspection at each location. The size of each statistical unit is further reduced by dividing the pipe within the excavation into small statistical units. Therefore, a ten-foot long excavation for a 36-inch pipe can lead to the division of the pipe within this excavation into one hundred (100) sections of one (1) square foot each. Having established the size of the statistical unit, the depth of the deepest pit in a given statistical unit is measured and recorded. In practice it is necessary to measure a number of the apparently deepest pits to determine which is the deepest.

When the values of the deepest pits for all units selected for a given structure or section of structure have been recorded, these values are then arranged and plotted on extreme value probability paper. This paper is similar in nature to normal probability paper, with the probability scale distorted. Extreme value probability paper and extreme value probability statistical methods must be used when the area of concern is not near the middle of the range (mean and mode), but at one end. Since we are not concerned with pits to some median depth, but rather with the deepest pits on the structure, extreme value statistics are used.

By a similar analysis, a prediction can be made, with a relatively high correlation, regarding the total number of penetrations that will occur by some future date. The number of pits to a given depth that exist on the entire structure is determined using the extreme probability graphs. The annual corrosion rate is calculated by dividing the pit depth by the age of the pipe. An assumption is made that the corrosion rate is linear (i.e. a pit of 0.1 inches in ten years will progress to 0.2 inches in 20 years). This result is typically expressed in mils (0.001 inches) per year.

The depth of the existing pits is subtracted from the wall thickness to yield the remaining thickness. The remaining thickness is then divided by the corrosion rate to yield the number of years to penetration. Since the rate of corrosion is not a linear function of time and the wall thickness is not absolutely uniform, adjustments must be made. Specifically, the analysis would deal with a range, or band of time. If the contents of the pipe are under pressure, penetration can occur once the remaining wall thickness becomes insufficient to handle the stress.

Corrosion Analysis

At the conclusion of the field investigation, data is analyzed and correlated to determine the present condition of the pipe or structure under study and the expected remaining life. Data can be used in life cycle cost analysis to delineate how the economics of management of leaks costs verses management of failure prevention costs are justified. As critical operation and reliability of the structure increases, the importance of corrosion assessment/definition and control increases.

This type of study may be conducted concurrently with other investigations, or independently of other investigations depending on what is being considered for the structure. There may be other considerations independent of corrosion requiring structure modification or replacement.

Corrosion Mitigation

Once the corrosion mechanisms are defined and the pipe condition is understood, the decision for continued operation can be made. Corrosion mitigation solutions would depend on what was determined in the initial phases of the study. Poorly engineered corrosion solutions will not perform as required in the long run, thereby falling short of expectations. The goal of this phase of the study, is to implement solutions that facilitate management of the operating water system, not continued management of failures and leaks.

Corrosion mitigation solutions may involve a number of applications, often applied in combination. Which corrosion mitigation solution(s) are to be applied is dependant on material, coating quality, electrical continuity, exposure from structure corrosion failure and sensitivity due to the location of the structure with respect to other facilities, communities or environments. Generally, the corrosion mitigation solutions for existing infrastructure include some or all of the following:

- Cathodic Protection (Impressed Current or Sacrificial Anode)
- Electrical continuity
- Electrical isolation
- Coating/lining systems

These options are also utilized extensively in new design of infrastructure with the additional consideration of the materials of construction. Corrosion problems can be eliminated through the utilization of other materials, based on the corrosion survey and analysis performed during the design phase of a project.

Cathodic Protection (Impressed Current or Sacrificial Anode)

Application of cathodic protection is a proven electrochemical method for arresting corrosion on metallic structures. Cathodic protection converts all active anode sites on the structure, the areas that corrode, into cathode sites that do not corrode. New anode sites are provided through the installation of anode groundbeds.

It is important to understand that corrosion is only mitigated on the structure metallic surfaces that are in contact with the electrolyte. In the case of a water storage tank, only the portions below the water line would receive cathodic protection. The roof and wall sections out of the water receive corrosion protection through the protective coating system. For underground piping, cathodic protection would provide protection to the bare metal in contact with the soil. Where there is intact, well bonded coating isolating the metal from soil contact, no cathodic protection is required. Therefore, cathodic protection requirements and efficiency is dependant on the structure coating system.

Anode size, quantity, location and other operating parameters, need to be designed to ensure proper operation. Much of the field data obtained in the earlier phases of the investigation would be used in the system design. These include soil resistivity, structure electrical continuity and stray current exposure.

Energy for an impressed current system is provided by a power supply or rectifier. This is an electrical device which converts AC power to DC power. The rectifier provides a positive current supply to the anodes and a negative current return from the structure. For this circuit, Ohms law applies: $E=IR$, where E is the driving voltage of the rectifier output voltage, I is the current magnitude that results from the resistance of the circuit R. Proper system design seeks to minimize the resistance of the circuit through anode groundbed design. Impressed current systems are capable of small to very large energy output levels through proper design. This range of ability allows protection possibilities for poorly coated pipe, large structures, automatic control and other options in design and operation.

Sacrificial anode cathodic protection provides protection in the same manner as the impressed current system, except there is no power source or rectifier. Sacrificial anodes are provided through the system design to corrode, thereby protecting the steel structure of interest.

Energy for the sacrificial anode system is provided by the difference in energy level between the anode and the structure being protected. Typically, magnesium anodes are utilized to protect steel structures. Referring back to the galvanic series chart under the section on galvanic corrosion, it is indicated that the magnesium anode would corrode preferentially when connected to steel. There is approximately a 1.0 volt difference between these two materials.

A sacrificial anode installation is also a DC circuit with positive current supplied from the anodes and a return negative current supplied from the structure. Again, Ohms law applies: E=IR, where E is the driving voltage of the circuit or approximately 1.0 volts, difference between magnesium and steel, I is the current magnitude that results from the resistance of the circuit R. Proper system design seeks to minimize the resistance of the circuit through anode groundbed design.

Sacrificial anode systems do not provide as much energy output as the impressed current design. Therefore, they would not function properly in many applications where cathodic protection would be required. Sacrificial systems require that the structure is coated with a tightly adhered coating system, and is electrically isolated from all other metallic structures and system components.

Electrical Continuity

In order to get effective protective current distribution, the pipe must be electrically continuous and its internal resistance must be very low. This data is obtained in the field investigation phase of the study.

For the majority of riveted steel, lock-bar steel and welded steel piping systems, electrical continuity is established by mechanical metal to metal connections. Cast iron lead joints and ductile iron joints are often not electrically continuous. Should it be determined that adequate electrical continuity does not exist, electrical bonding would be required to provide adequate pipe resistance for application of cathodic protection.

In areas affected by stray current activity, electrical continuity may be desirable to enable control and mitigation of any corrosive effects. While it may seem that stray current operations are not near the project area, it is not uncommon for stray currents to travel along piping and other grounding systems for miles between DC traction substations.

It may be desirable to maintain electrical continuity during pipe upgrade operations to ensure that the stray current activities are not interrupted and then cause corrosion problems. Should the electrical properties of a piping network change i.e. by the installation or removal of isolation joints, valves or other appurtenances, severe stray current corrosion could occur.

Electrical Isolation

Electrical isolation of the pipeline or structure from other nearby structures is important to contain the spread of the impressed current effects, and provide a distinct structure for the cathodic protection system. Electrical isolation may also be required to control stray current from outside sources and to control galvanic corrosion exposure

Electrical isolation is provided between adjacent structures, materials of construction and AC electrical ground. Establishing isolation requires the installation of insulating flange components or electrically insulating mechanical couplings.

Summary

Evaluation and definition of the corrosion exposure on existing infrastructure is a very cost effective means for prioritizing repair, rehabilitation and replacement of piping infrastructure. Defining the corrosivity of the environment and implementing corrosion control during the design process for new infrastructure is prudent in ensuring long term service life.

Corrosion control is essential to the efficient long term performance of capitalized infrastructure in the water utility industry. Once a corrosion control program is undertaken, the economic benefits become apparent. Elimination of many pipeline failures and corrosion related equipment failures reduce maintenance costs, and ensures clean water delivery to the customer. Basic survey techniques and methods to identify and mitigate the corrosion processes in the water utility industry have been presented in this paper. Following a comprehensive corrosion control program allows water system operators to be proactive in management of the system rather than managing corrosion failures and associated problems.