

Corrosion In Water Systems An Overview

by

David H. Kroon, P.E.
Vice President, Engineering
Corrpro Companies, Inc.
Houston, Texas

corrpro[®]

Corrpro Companies, Inc.
1090 Enterprise Drive
Medina, OH 44256
330.723.5082
WWW.CORRPRO.COM

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Introduction

Corrosion impacts the design, operation and maintenance of every element of a water system. Water wells, treatment equipment, storage facilities and piping systems are all vulnerable to accelerated deterioration from corrosion. Numerous studies have been published that document causes of corrosion and successful methods of control.¹⁻³

The problems related to corrosion in water systems are not new. As early as 1939, the results from a survey performed by the Illinois State Water Survey indicated that 41% of the water systems responding were experiencing corrosion problems involving well pumps, water mains, storage facilities and service lines.⁴ Over the years, the basic problems have changed very little, although our understanding and technology for controlling corrosion have improved significantly.⁵

Corrosion in water systems must be addressed by every operator to ensure economical supply of high quality water and safe operation of fire protection systems. By properly addressing corrosion mitigation through material selection, coatings and cathodic protection, system life will be extended and operational costs reduced. The economic benefits accrue to both the system operator and ultimately the consumer.

Impact of Corrosion

Corrosion impacts water systems in many more ways and to a far greater degree than many of us regularly consider (Table 1).

TABLE 1
Impact of Corrosion

1. Costly System Repairs and Replacements
2. Disruption of Service
3. Expensive Loss of Water
4. Structural and Environmental Damage
5. Reduced Water Quality
6. Improper Treatment
7. Decreased System Capacity
8. Impairment of Fire Protection Systems

The construction of water systems is frequently financed through public revenue bonds with a 30 year term. The systems are often designed for a minimum 40 year life, but neither the financial projections nor design life adequately account for the impact of corrosion. Expensive repairs and replacements of system components can financially cripple the water operator, and directly cost the consumer far more than necessary for an inferior product. An infrastructure study in New York determined that the direct cost of leak repair for the Wa-

ter Supply Bureau was \$7,323 per failure.⁶ An extreme case is the City of Winnipeg, where a \$7.7 million program is required to reduce the leak frequency to 2200 annually, which is equivalent to 1.8 leaks/mile of pipe per year.⁷

Disruption of service and loss of water are also expensive with respect to public relations and operating costs. The consumer pays for a continuous supply of high quality water. He/she has every right to be irate when service is interrupted due to a system failure. Public safety is jeopardized because fire water systems are inoperable.

Purified water is also a precious commodity that deserves protection. The City of Boston, for example, loses half its fresh water each year due to failures, at an annual cost of \$7 million.

The indirect costs of a water leak include structural and environmental damage, and increased public liability. The referenced study in New York indicates that damage settlements average approximately \$1460 per occurrence. In Houston, the city loses 20 to 30 percent of its purified water (70 million gallons daily) resulting in thousands of damage complaints each year for destroyed lawns, undermined pavements and structural damage. Exposure to public liability is also increased due to the potential for accidents as a direct result of water losses.

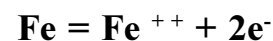
Internal corrosion of piping systems, storage tanks and treatment equipment can result in reduced water quality, improper treatment and decreased system capacity. Rusty water or “red water” results from the suspension of hydrated iron oxide particles in the water. Tuberculation, which is caused by the build-up of corrosion products in the form of nodules, can cause blockage and dramatic increases in the roughness of the internal piping surfaces, resulting in loss of system capacity. The water pressure is reduced at the point of use, which can create very serious supply problems for fire fighting and service to tall buildings.

Corrosion Rates

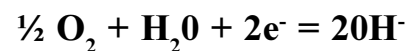
The primary concern in any water system is to evaluate the rate of corrosion and determine whether the resultant deterioration is commensurate with the design life and operating parameters. Corrosion is inevitable on all submerged, buried and embedded metallic structures. The rate of corrosion is a key factor to anticipate for new construction and to analyze on existing structures.

Corrosion results from oxidation-reduction reactions occurring on a metal surface. Anodic (more electro-negative) and cathodic (more electro-positive) areas are created due to differences in the metal surface or differences in the electrolyte (soil, water, concrete, etc.). The potential difference between the anodic and cathodic areas is the driving force in the corrosion cell. The resistance between the anode and cathode determines the flow of corrosion current according to Ohms Law ($E=IR$). The corrosion current (charge transfer/unit time), and concentration of the current, defines the rate at which metallic structures will fail due to corrosion.

Oxidation, which is defined as the loss of electrons occurs at the anode. The oxidation reaction at the anodic area is largely dissolution of the metal, which for ferrous alloys at ambient temperatures, would be primarily the oxidation of iron atoms to ferrous ions:



Other anode reactions include the evolution of oxygen and the evolution of chlorine. The most common reduction reaction in a neutral pH environment where the electrolyte is sufficiently aerated, is the reduction of oxygen in the presence of water to form hydroxyl ions:



Notice that reduction involves the gain of electrons. Electrons must flow within the metal circuit, from the anode to cathode in a corrosion cell, and positive ions must move away from the anode, toward the cathode, in the electrolyte. Inherent to the electrochemical corrosion of metals are two natural phenomena that help reduce corrosion rates: passivation and polarization.

Passivation occurs when a protective oxide layer is formed evenly over the metal surface, This phenomena is responsible for the corrosion resistance of aluminum in the atmosphere where a light grey oxide protects the metal substrate from further corrosion. It is also responsible for the corrosion resistance of stainless steel in an oxidizing environment where a very protective, and invisible, film is formed preventing further oxidation of the metal. Note that the proper conditions must be satisfied and the film must be uniformly formed to provide the protective barrier.

Polarization is the tendency for the potential difference between the anode and cathode (driving force in the corrosion cell) to decrease with the flow of corrosion current. Activation polarization results from slow reactions on the metal surface and concentration polarization results from slow molecular movement in the electrolyte. The actual rate at which metals corrode in practice, are therefore largely governed by factors that either prevent or enhance passivation and polarization.

Table 2 lists a number of factors that influence the rate of corrosion in water systems. Although there are always exceptions to general rules, the rate of corrosion in water systems tends to be increased by:

- * Direct connection between different metals or alloys
- * Stressed areas due to welding or cold working
- * High conductivity electrolyte (soil, water or concrete)
- * Aeration, dissolved oxygen, and differences in oxygen concentration
- * High concentrations of chlorides and sulfates versus carbonates
- * Acidic conditions
- * Elevated temperatures
- * High flow rates and turbulence
- * Presence of sulfate reducing bacteria

TABLE 2
Factors Influencing the Rate of Corrosion

- | | |
|---|--------------------------|
| * | Bimetallic Couples |
| * | Stressed Areas |
| * | Conductivity |
| * | Aeration |
| * | Ion Concentrations |
| * | pH |
| * | Temperature |
| * | Flow Rate and Turbulence |
| * | Anearobic Bacteria |

The bi-metallic couples and stressed areas increase the potential difference between points on the structures thereby increasing the driving force in the corrosion cell. The higher the conductivity, the lower the resistance between the anode and cathode, and hence, the greater the corrosion current. All of the other factors contribute to interfering with the polarization and/or passivation of the metal surface.

Types of Corrosion

Water systems are unique in that every conceivable type of corrosion can occur. Table 3 lists a number of common forms and mechanisms of corrosion that may be encountered in water systems.

TABLE 3
Types of Corrosion

- | | |
|---|---------------------|
| * | Uniform |
| * | Pitting |
| * | Stress Corrosion |
| * | Corrosion Fatigue |
| * | Dissimilar Metal |
| * | Concentration Cells |
| * | Crevice |
| * | Stray Current |
| * | Dezincification |
| * | Graphitization |
| * | Impingement Attack |
| * | Cavitation |

The corrosion of a metal may appear uniform due to microscopic anodic and cathodic areas formed on what appears to be a homogeneous metal surface. In actual fact, a metal consists of numerous grains, some of which will be anodic to adjacent grains due to the different metallurgical make up. For the same reason, it is not unusual for the most active (anodic) areas to be at the grain boundaries.

Pitting corrosion is initiated by a localized anodic point on the metal surface. The penetration of the metal continues at this point, because a relatively large area around the pit is cathodic to the pit itself. Pitting corrosion is commonly encountered at pinholes or flaws in dielectric coating systems. For steel and stainless steel, chloride ions are well known as a cause of pitting attack.

Stress corrosion and corrosion fatigue result from tensile stresses on the metal surface. Stress corrosion often takes place at the grain boundaries where the metal has been stressed by cold working, or elevated temperature, such as within the heat affected zone adjacent to a weld seam. Corrosion fatigue is generally a more rapid process, involving alternating conditions of stress and stress relief, that disturbs the formation of protective films in the anodic region.

Dissimilar metal corrosion occurs due to the interconnection of more active metal to a more noble metal. Table 4 lists the galvanic series of metals in seawater. The more active metal will be the anode in the corrosion cell where failure will eventually occur. Corrosion caused by the connection of different metals is obvious. Less obvious is the interconnection of new metal (active) to old metal (noble); active stainless steel to passive (noble) stainless steel; and buried steel (active) to steel embedded in concrete (noble).

Oxygen concentration cells are the most prevalent type of corrosion on underground piping. More oxygen is available at the top of the pipe than the bottom. Since oxygen is required for the reactions at the cathode, the top of the pipe is cathodic to the bottom. The corrosion is therefore concentrated along the bottom surface of the pipe. This type of cell is also a primary contributor to corrosion of a submerged surface, where more oxygen

TABLE 4
Galvanic Series

Active	Magnesium zinc Aluminum Mild steel Ductile Iron Stainless Steel (Active) Lead Muntz Metal Yellow. Brass Admiralty Brass Red Brass Copper Cupro Nickel Bronze Stainless Steel Silver Graphite
Noble	Platinum

is available at the water line than with increasing depth at uniform temperature.

Concentration cells can also be created due to differences in dissolved oxygen, hydrogen and hydroxyl ions, chlorides, sulfates, carbonates and metal ion activity. Crevices formed by the interconnection of metallic components provide excellent sites for concentration cells to develop with the area just inside the crevice normally anodic to the adjacent surface.

Stray DC earth currents, produced by DC transit systems, DC motors, high voltage DC transmission systems, neighboring cathodic protection systems and improper grounding during arc welding, can cause electrolytic corrosion of buried structures. Although possible, this type of corrosion is rarely found on the internal, submerged, metallic surfaces in water systems. The structure must share the same electrolyte (e.g. earth) with the source of the DC current. At the point where positive DC current flows from the water structure into the electrolyte, very rapid rates of corrosion can occur, depending upon the magnitude and concentration of current.

Two types of preferential corrosion of metal alloys are dezincification and graphitization. Dezincification results from the removal of zinc from brass alloys, with copper remaining as the zinc is dissolved. Muntz metal and yellow brass are particularly susceptible to this type of corrosion in soft water with a high concentration of carbon dioxide. Graphitization occurs on cast iron and ductile iron piping when the iron silicon metal in the alloy corrodes, leaving behind a graphite matrix. The graphite which remains is hard, but brittle, and subject to fracture from soil stress, frost heaves and water hammer effects (Figure 1).



Figure 1
Fracture of Cast Iron Pipe Weakened by Corrosion

Impingement attack and cavitation corrosion are both examples of the physical movement of water enhancing the corrosion process. Impingement attack is caused by an erosion process where the water flow removes the protective films from the metal surface. Copper pipe is susceptible to this type of attack where flow rates are greater than 5 fps and where the direction of flow changes, such as elbows.

Cavitation is usually associated with high velocity and sudden changes in velocity that cause gas pockets to form at low pressure points. As the gas bubble collapses, the metal surface can be severely corroded. This type of corrosion can occur inside piping at a constricted area such as a valve or joint, and is often encountered on water well, pump impellers.

Examples Of Corrosion

Examples of corrosion failures can be found in every operation of water systems, from supply, through treatment, transmission, storage and distribution.

Water wells and intake structures are subject to attack from bimetallic couples, cavitation, pitting and crevice corrosion.

Figure 2 shows water treatment equipment where accelerated rates of corrosion are caused by chemical treatment, stressed areas due to welding, and crevices. Both chlorine and aluminum sulfate treatment hinder passivation and polarization of the metal surface causing accelerated rates of attack



Figure 2
Water Treatment Clarifier

Prestressed concrete cylinder pipe and mortar coated steel cylinder pipe are often used for water transmission lines. When embedded in concrete, steel forms a very protective $\text{Gamma-Fe}_2\text{O}_3$ film which inhibits corrosion of the steel. The protective properties of this film, however, will be destroyed by chloride ions and carbonation of the concrete. Where joints are not properly coated and steel remains exposed, a very strong galvanic cell is developed between the exposed steel and the steel in concrete. In the case of prestressed concrete cylinder pipe, the corrosion process is compounded by stress effects that can lead to catastrophic failure (Figure 3).

In water storage tanks, corrosion is often concentrated at holidays (pin holes) in the coating. All coating sys-

tems will contain some flaws which will allow pitting corrosion to initiate. Once started, this type of corrosion accelerates until the tank wall is penetrated. Figure 4 shows a plate from a half inch thick steel tank Pitting corrosion penetrated the tank wall in less than seven years.

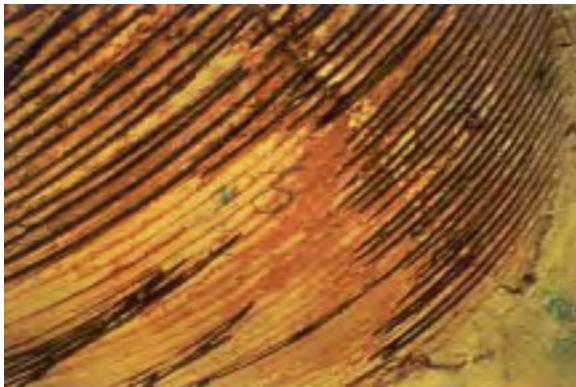


FIGURE 3
Corrosion of Prestressing Wires on Prestressed
Concrete Cylinder Pipe



FIGURE 4
Penetration of Tank by Pitting Corrosion

In distribution systems, cast iron water mains fail due to corrosion (Figure 5). Ductile iron piping differs from grey cast iron in the form of the graphite in the microstructure of the alloy. In cast iron, the graphite is in the form of flakes, whereas in ductile iron, it is in modular form. The corrosion process is therefore identical. Because ductile iron is stronger than graphite, the wall thickness of the pipe is reduced, which in turn, reduces the time to failure from corrosion.

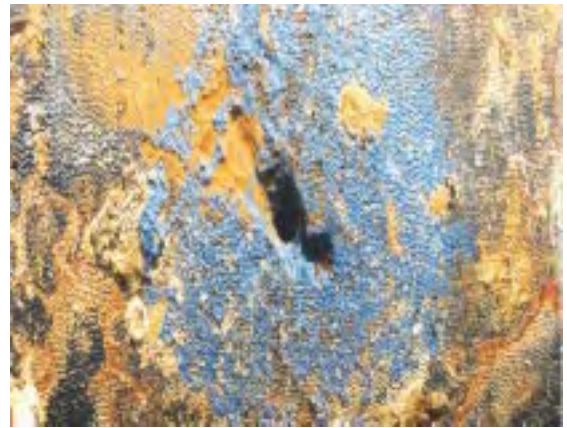


FIGURE 5
Corrosion of Cast Iron Piping



FIGURE 6
Penetration of Copper Water Lines

Copper enjoys a good reputation as a corrosion resistant material. To a large degree, this is unfounded, because copper service lines are usually connected to steel or cast iron where it is the protected electrode in the corrosion cell. Where salts, cinders or fertilizers are present in the soil, copper can corrode extremely rapidly. Figure 6 shows pitting and penetration of a 2-inch copper pipe that occurred underground within 6 months of installation. The accelerated rate of corrosion was caused by high concentrations of natural salts.

Conclusion

The forms of corrosion are many, and each can cause premature failures in water systems. Fortunately for all of us, corrosion tends to be the greatest problem for certain types of construction in certain environments. Recognize that corrosion is a problem. Design to avoid forming corrosion cells. Protect against corrosion where necessary, and work towards managing the problem of corrosion.

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