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The Epidemic of Corrosion, Part 1: Examining Pipe Life

In ancient and modern medicine the term epidemic is used to identify when new cases of a certain disease, in a given population, and during a given period, substantially exceed what is expected based on recent experience. An epidemic may be restricted to a locale; however, if it spreads to other regions, it may be termed a pandemic. The declaration of an epidemic usually requires a good understanding of a baseline rate of incidence with an increase in the number of occurrences (Wikipedia, 2011).

In the water and wastewater utility industry, if corrosion is defined as the disease, the distribution and collection systems are defined as the population, and main breaks are defined as the occurrences, then we must accept the fact that there exists a serious epidemic. This corrosion epidemic is driving up utility operating, maintenance, and capital costs while also degrading water quality and jeopardizing the public health. The US Environmental Protection Agency (USEPA) recognizes deterioration of the quality of water in our distribution systems as an important public health concern. Research has improved the scientific foundation for identifying and assessing the risks associated with our aging water distribution systems (USEPA, 2011a).

THE CORROSION DOCTORS

Corrosion is the degradation of metal and is caused by oxidation or chemical action. If corrosion occurs in water distribution pipelines, valves, and fixtures, it can cause the degradation of the quality of our drinking water. Therefore, corrosion is a big problem for our drinking water distribution systems. The USEPA has estimated that $138 billion will be needed over the next 20 years to maintain and replace existing drinking water systems and that $77 billion of this will be dedicated to repairing and rehabilitating pipelines. Many water distribution systems in the United States are approaching 100 years old; an estimated 26% of distribution system pipeline is unlined cast-iron and steel and is in poor condition. Corrosion by-products that form on the surface of pipes and fixtures affect the solubility of lead, copper, and iron, and ultimately their levels in water at the consumer's tap. Furthermore, contamination entering our distribution systems is responsible for a

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significant percentage of the waterborne disease outbreaks reported in recent years (USEPA, 2011b).

NACE International was originally known as "The National Association of Corrosion Engineers" when it was established in 1943 by 11 corrosion engineers in the pipeline industry. These founding members were involved in a regional cathodic protection (CP) group formed in the 1930s when the study of CP was introduced. With more than 60 years of experience in developing corrosion prevention and control standards, NACE International has become the largest organization in the world committed to the study of corrosion (NACE, 2011a).

The National Physical Laboratory (NPL) is the United Kingdom's National Measurement Institute. NPL was established in 1900 and is a world-leading center of excellence in developing and applying the most accurate measurement standards, science, and technology available to humanity. NPL's core mission is to provide the measurement capability that underpins the UK's prosperity and quality of life. One area of national focus is corrosion considering the social and economic impacts that are vital to the UK economy (NPL, 2011).

DIAGNOSING THE DISEASE

The Beginners Guide to Corrosion (NPL, 2003a) explains that the process of corrosion produces a new and less desirable material from the original metal and can result in a loss of function of the component or system. Corrosion falls under two major categories, uniform corrosion and localized corrosion. Corrosion, like a virus, has different forms. Each type of localized corrosion requires expensive prescriptions to help control the onset and spread of the disease. These expensive prescriptions increase maintenance, operations (energy costs), and renewal and replacement capital budgets for a utility. The prescribed doses are based on the individual environment of a utility.

INCREASING PRESCRIPTION COSTS

Various corrosion-control measures are available, one or more of which might be appropriate. Before procurement of a pipe material, the full life-cycle costs must be considered and compared against an alternative pipe material, because corrosion for metallic pipes may occur at any life-cycle stage. Materials selection, fabrication, shape, and cost are all significant. Corrosion-control measures must be able to reduce risk to a quantifiable and appropriate low level in situations in which the consequences of failure are serious. In some types of projects, uncontrolled corrosion could amount to 30% of the total commitment of capital expenditure. Corrosion control begins during the design process. Uncontrolled corrosion can lead to increased costs, premature failure and asset replacement, reduced safety, and negative environmental and public health effects.

UNIFORM CORROSION IS 30% OF FAILURES

Uniform corrosion, as the name suggests, occurs over the majority of the surface of a metal at a steady and often predictable rate. Although it is unsightly, its predictability facilitates easy control, the most basic method being to make the material thick enough to function for the lifetime of the component.

The spread of uniform corrosion can be slowed by

- slowing or stopping the movement of electrons;
  - coat the surface with a nonconducting medium such as paint, lacquer, or oil;
  - reduce the conductivity of the solution in contact with the metal in extreme cases to keep it dry.
  - wash away conductive pollutants regularly;
  - apply a current to the material (CP);
- slowing down or stopping oxygen from reaching the surface; this is difficult to do completely, but coatings can help;
- preventing the metal from giving up electrons by using a more corrosion-resistant metal higher in the electrochemical series. Use a sacrificial coating that gives up its electrons more easily than the metal being protected;
  - apply CP;
  - use inhibitors;
- selecting a metal that forms an oxide that is protective and stops the reaction. Control and consideration of environmental and thermal factors are also essential in the management of corrosion.

LOCALIZED CORROSION IS 70% OF FAILURES

The consequences of localized corrosion can be a great deal more severe than uniform corrosion, generally because the failure occurs without warning and after a surprisingly short period of use or exposure. This epidemic is occurring all over the United States as corrosion claims victims of all ages of metallic, cement, and even clay pipes. In the previous century the home remedy included making and installing a thick-walled cast-iron pipe to achieve a greater than 100-year design life. Today the steel and ductile-iron pipe (DIP) walls are much thinner and as a result require the additional initial capital costs of corrosion-control measures and the expensive ongoing maintenance, monitoring, and operational corrosion activities.

Reports of early pipe failure caused by corrosion are occurring coast to coast affecting communities and creating the need for boil-water notices. One example out of hundreds in which cast-iron water pipes that were supposed to last as long as 100 years are being corroded by soils just 17 years after they were installed is in upstate New York. The clay soils in a particular subdivision there are reacting with the pipes and corroding them from the outside in, resulting in main failures even though the DIP was laid correctly and built to standards (NACE, 2011b).

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TYPES OF LOCALIZED CORROSION AND THEIR PRESCRIPTION

Galvanic corrosion. This occurs when two different metals are placed in contact with each other and is caused by the greater willingness of one metal to give up electrons than the other. Three special features of this mechanism need to operate for corrosion to occur:

- the metals need to be in contact electrically,
- one metal needs to be significantly better at giving up electrons than the other, and
- an additional path for ion and electron movement is necessary.

Prescription. Break the electrical contact using plastic insulators or coatings between the metals. Select metals close together in the galvanic series. Prevent ion movement by coating the junction with an impermeable material, or ensure the environment is dry and liquids cannot be trapped.

Pitting corrosion. Pitting corrosion occurs in materials that have a protective film such as a corrosion product or when a coating breaks down. The exposed metal gives up electrons easily, and the reaction initiates tiny pits with localized chemistry supporting rapid attack.

Prescription. Select a resistant material and ensure a high enough flow velocity of fluids in contact with the material for frequent washing; controlling the chemistry of fluids and use of inhibitors; using a protective coating; maintaining the material's own protective film. Pits can be crack-initiators in stressed components or those with residual stresses resulting from forming operations. Side effects can lead to stress corrosion cracking.

Selective attack. This occurs in alloys such as brass when one component or phase is more susceptible to attack than another and corrodes preferentially, leaving a porous material that crumbles.

Prescription. This type of corrosion is best avoided by selection of a resistant material, but other means can help, for example coating the material, reducing the aggressiveness of the environment, and using CP.

Stray current corrosion. This type of corrosion happens when a direct current flows through an unintended path and the flow of electrons supports corrosion. This can occur in both soils and flowing or stationary fluids.

Prescription. The most effective remedies involve controlling the current by insulating the structure to be protected from the source of the current, earthing up sources and/or the structure to be protected, applying CP, and using sacrificial targets.

Microbial corrosion. This general class covers the degradation of materials by bacteria, molds, and fungi or their by-products. It can occur by a range of actions such as attack on the metal or protective coating by acid by-products, sulfur, hydrogen sulfide, or ammonia; and direct interaction between the microbes and metal that sustains the attack.

Prescription. Selection of resistant materials, frequent cleaning, control of chemistry of surrounding media and removal of nutrients, use of biocides, and CP.

Intergranular corrosion. This is a preferential attack on the grain boundaries of the crystals that form the metal. It is caused by the physical and chemical differences between the centers and edges of the grain.

Prescription. Selection of stabilized materials, control of heat treatments and processing to avoid susceptible temperature range.

Concentration cell corrosion (crevice). If two areas of a component in close proximity differ in the amount of reactive constituent available, the reaction in one of the areas is speeded up. An example of this is crevice corrosion, which occurs when oxygen cannot penetrate a crevice and a differential aeration cell is set up. Corrosion occurs rapidly in the area with less oxygen.

Prescription. Avoiding sharp corners and designing out stagnant areas, using sealants, using welds instead of bolts or rivets, selecting corrosion-resistant materials.

Thermogalvanic corrosion. Temperature changes can alter the corrosion rate of a material. A good rule of thumb is that a 10^{o}C rise doubles the corrosion rate. If one part of a component is hotter than another, the difference in the corrosion rate is accentuated by the thermal gradient, and local attack occurs in a zone between the maximum and minimum temperatures.

Prescription. The best method of prevention is to design out the thermal gradient or supply a coolant to even out the difference.

Corrosion caused by combined actions. This is corrosion accelerated by the action of fluid flow, sometimes with the added pressure of abrasive particles in the stream. The protective layers and corrosion products of the metal are continually removed, exposing fresh metal to corrosion.

Prescription. Reducing the flow rate and turbulence, using replaceable or robust linings in susceptible areas, avoiding sudden changes of flow direction, streamlining or avoiding obstructions to the flow.

Corrosion fatigue. The combined action of cyclic stresses and a corrosive environment reduces the life of components below that expected by the action of fatigue alone.

Prescription. Coating the material, using a good design that reduces stress concentration, avoiding sudden changes of sections, and removing or isolating sources of cyclic stress.

Fretting corrosion. The relative motion between two surfaces in contact by a stick-slip action can cause breakdown of protective films or welding of the contact areas, allowing other corrosion mechanisms to operate.

Prescription. Designing out vibrations, lubricating metal surfaces, increasing the load between the surfaces to stop the motion, and applying surface treatments to reduce wear and increase the friction coefficient.

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Stress corrosion cracking. This is the combined action of a static tensile stress and corrosion that forms cracks and eventually causes catastrophic failure of the component. This is specific to a metal material paired with a specific environment.

Prescription. Reducing the overall stress level and designing out stress concentrations, selecting a suitable material not susceptible to the environment, using designs to minimize thermal and residual stresses, developing compressive stresses in the surface of the material, and using a suitable protective coating.

Hydrogen damage. A surprising fact is that hydrogen atoms are very small and hydrogen ions even smaller and can penetrate most metals. Hydrogen, by various mechanisms, embrittles a metal—especially in areas of high hardness—causing blistering or cracking, especially in the presence of tensile stresses.

Prescription. Using a resistant or hydrogen-free material; avoiding sources of hydrogen such as CP, pickling processes, and certain welding processes; removing hydrogen in the metal by baking.

THE CORROSION PANDEMIC

In the United States, corrosion costs more than $276 billion a year with $121 billion going toward corrosion treatments (Koch, et al, 2001). The increasing costs and economic impacts of corrosion are not isolated to the United States and North America. Corrosion costs the United Kingdom a significant percentage of its gross national product. Engineering projects use similar materials world-wide; therefore, comparable proportions of corrosion costs are found in other industrialized countries. It has been estimated that 25% of all corrosion problems could be easily prevented by using well-established techniques. The economic, social, or ecological consequences of major corrosion failures can be ruinous. Corrosion increases running costs and reduces plant efficiency, availability, and product quality.

Emergency recommendations. The corrosion profession highly recommends selecting corrosion-resistant materials and embracing best practice guidelines. The corrosion profession advises utilities

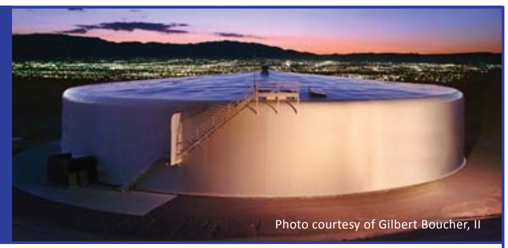
- not to use data without checking that the environment and conditions in use relate to those under which the data were collected,
- not to ignore the possibility that small changes in the environment or operating conditions could have a dramatic effect on corrosion control,
- not to ignore the possibility that combined action such as stress and corrosion could significantly reduce lifetimes,
- not to use rate data for uniform corrosion to estimate lifetimes for localized corrosion, and
- not to use calculation of corrosion rates as a basis for design when a better design could eliminate the corrosion problem (NPL, 2003b).

LIFE EXPECTANCY FOR PIPES

The general rule of thumb for the life expectancy of water systems' pipes is about 70 years before corrosion creates the need for replacement, said the chair of AWWA's corrosion-control committee for the California–Nevada section. The longevity of pipes is roughly comparable to that of the very objects the pipes serve. Pipes have about the same lifespan as humans. Many utilities have set the expected life for pipes at 50 years to be cautious and stay ahead (NACE, 2011c). However, replacing pipes every 50 years is neither reasonable nor cost-effective and requires condition assessment and asset management to better match the timing of the investment to the need of the asset. Many agencies are dissatisfied with 1-year warranties and also request pipes with 100 years of life, which, for metallic pipes, requires large amounts of maintenance and preservation of the pipe including anticorrosion treatments among other preventive measures.

POSTMORTEM EXAMINATION: BUREAU OF RECLAMATION'S CORROSION STANDARDS

The committee established for the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe conducted by the



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National Research Council (NRC) in 2009, had experts evaluate the expected life and sustainability of DIP. The committee was fortunate to have represented among its members a broad spectrum of skills and areas of expertise relating to metal pipeline corrosion and corrosion control, including experience in pipeline design and installation as well as metallurgy and corrosion research.

Cast-iron is a material that was used for years to fabricate pipe for applications such as water transmission and distribution. About 50 years ago DIP was introduced as a more economical and better-performing product. DIP is similar to cast-iron pipe in that it contains a percentage of carbon distributed as graphite in an iron matrix.

As with iron or steel pipes, DIP is subject to corrosion, the rate of which depends on the environment in which the pipe is placed. Corrosion-mitigation protocols that depend on the corrosivity of the soil are used to slow the corrosion process to an acceptable rate for the application. A popular corrosion-mitigation method for DIP in buried applications is the use of polyethylene encasement (PE), consisting of a sheet of polyethylene wrapped around the pipe or a tube of polyethylene sheeting slipped over the pipe at the time of installation. Another protective method is to use bonded dielectric coatings comprising various polymers applied as coatings on prepared surfaces or to wrap tapes with adhesives on the same prepared surfaces. Bonded dielectric coatings are commonly used on steel pipes but are less commonly used on DIP. CP can also be used to protect metal pipes, including DIP. CP electrochemically protects the metal structure either by imposing a direct current electrical potential to the pipeline or by connecting the pipeline to a sacrificial anode made of a more electrochemically active metal. The decision to use corrosion mitigation systems and the choice of the system to use for buried DIP depend on the corrosivity of the soil in which the pipeline is buried. Many methods of assessing the corrosivity of soils have been developed. All use the resistivity of the soil either as the defining parameter or as one parameter in conjunction with others, such as the presence or concentration of specific chemical species that foster corrosion. Soils with low resistivity are more corrosive than soils with high resistivity.

The Bureau of Reclamation (BOR) of the US Department of the Interior has from its inception fostered water transmission projects in the western United States designed to provide water for agricultural and municipal uses in areas otherwise deficient in local water supplies. In doing so, the BOR has specified the types of materials appropriate for particular applications and the type of corrosion-mitigation systems appropriate for each pipeline material depending on the corrosivity of the soils. When BOR issued modified corrosion-protection requirements in a technical memorandum (TM 8140-CC-2004-1), PE was specified as the corrosion-mitigation method for DIP in soils of low corrosivity. For DIP used in moderately corrosive soils, PE and CP were specified. For highly corrosive soils, BOR specified that bonded dielectric coatings and CP were needed for adequate corrosion protection of DIP. In the past, bonded dielectric coatings on DIP were available, and a limited amount of such pipe was installed and is in use. However, the current specification of bonded dielectric coatings for DIP is difficult to meet, because in recent years the US manufacturers of DIP have discouraged the application of bonded dielectric coatings on their products and will not supply DIP with such coatings, citing the difficulty of preparing the surface for coating application and the expense of applying such coatings to a relatively rough surface.

BOR has requested that the NRC form a study committee to make recommendations concerning corrosion protection for DIP in highly corrosive soils. In response to BOR's request, the NRC established the Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe. This committee of experts was convened to study corrosion protection of DIP in highly corrosive soils. Specifically, the charge to the committee was that it provide advice to BOR concerning the following:

- Does PE with CP work on DIP installed in highly corrosive soils?
- Will PE and CP reliably provide a minimum service life of 50 years?

With regard to the first question, the committee found that if manufactured and installed correctly, PE with CP provides a betterment to bare and as-manufactured DIP without CP in highly corrosive soils.

Regarding the second question, the committee asked BOR for a definition of what level of reliability it seeks for the 50-year service life. The response was that ideally BOR preferred that pipeline systems be designed in such a way that no failures would take a system out of service during a service life of 50 years. However, it is recognized that no engineering system can be designed to ensure that absolutely no failures will occur, and BOR advised the committee that the level of reliability experienced by the extensive natural gas pipeline systems in the United States is a reasonable benchmark to strive for in its water pipeline systems.

The committee then studied the available research data on the corrosion rates of DIP protected by PE and by PE with CP. It went on to find and evaluate known failures on water pipelines using these corrosion-mitigation systems. The committee found that the limited data available and the scientific understanding of corrosion mechanisms show that DIP with PE and CP is

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not likely to provide a reliable 50-year service life in highly corrosive soils (< 2,000 ohm/cm). After considerable study and deliberation, the committee found that using the performance of bonded dielectric coatings on steel pipe with CP as a benchmark for reliability, and on the basis of available information, it is unable to identify any corrosion-control method for DIP that would provide reliable 50-year service in highly corrosive soils.

The committee considered other corrosion-mitigation methods such as anti–microbiologically influenced corrosion PE, microperforated PE, zinc coatings with epoxy top coat, controlled low-strength-material backfill, and the building in of a corrosion allowance. The committee findings are that these other corrosion-mitigation methods show promise, but the evidence is too limited to make any recommendations for their use at this time. Despite these shortcomings in surface preparation and in ensuring adequate CP, the committee found that bonded dielectric coatings with CP may provide superior protection to DIP when compared with the protection provided by PE with CP. Additional soil conditions and risk assessment factors should be considered on a case-by-case basis for each specific project and operation, maintenance, replacement, and energy costs for CP for each pipe type should be evaluated (NRC, 2009).

THERE IS NO MIRACLE DRUG FOR CORROSION

The historical investments made in our water and wastewater systems included metallic pipes subject to the natural laws of corrosion. Although many different types of expensive preventative remedies can be applied, the fact is that we will have to deal with internal and external corrosion in our pipes for a long time.

Elimination of corrosion. In modern medicine, disease is first controlled (reduction of corrosion through preventive measures), next comes the elimination of disease (material selection of noncorrosive, nonmetallic pipes), then the elimination of infections (stopping the spreading of corrosion), and finally eradication and extinction. As an industry we will not be able to eradicate corrosion in our distribution, transmission, and collection systems; however, we can set in place best practices and standards to allow for the selection and financial analysis of alternative noncorrosive materials like polyvinyl chloride (PVC).

Sustainable water infrastructure. Sometimes, the best medicine is just a matter of making a lifestyle change or, in this case, a material selection change. PVC and similar materials are 30–70% less expensive (Baird, 2011), easy to install, some with 50-year warranties, environmentally friendly, noncorrosive, and durable with an expected design life of more than 100 years (AwwaRF, 2006) without the extensive and expensive corrosion treatments. PVC meets the demands and expectations of sustainable water infrastructure by reducing maintenance, operational, and capital budgets without degrading water quality or jeopardizing the public health. It is time to fight the epidemic of corrosion as part of our asset management capital-replacement strategies.

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