

Corrosion Control of Large Diameter Piping Cathodic Protection a Proven Method

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Abstract

Cathodic Protection of Large Diameter Water Transmission pipe systems is a viable means of extending the service life of this valuable infrastructure, as well as insuring that new infrastructure meets the demands for the desired service life. This technology has been successfully applied to many miles of steel and ductile iron piping systems.

The 55,000 water systems in the United States will be faced with many issues relative to infrastructure installation, upgrading and replacement. Costs associated with the system infrastructure are very high, requiring that monies need to be expended prudently. Understanding where cathodic protection can be successfully utilized in extending the service life of infrastructure is an important part of the overall Infrastructure Master Plan.

This paper presents the studies performed, the basic technology of cathodic protection and the conclusions of the pilot program. A case history for a pair of large diameter water transmission lines in Rochester, NY is presented. The field test procedures and cathodic protection design parameters are applicable to new piping systems as well as other infrastructure service life extension projects.

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 water industry metallic infrastructure.

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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 water pipe, number of storage tanks and the variety of metallic components in the water treatment plant, a considerable percentage of that annual cost is borne by the water utility industry.

In addition, it has been reported by the American Water Works Association that the cost to water utilities over the next 20-years will be approximately \$325 billion to upgrade and replace losses caused primarily by corrosion. It is clear that many of the decisions as to how these monies should be allocated need to be based on a clear understanding of the corrosion exposure that exists on existing and new infrastructure. Critical systems cannot be installed and forgotten, but instead must be constantly managed to provide lower life cycle costs and ensure that undesirable failures do not interrupt operation.

Much of the existing infrastructure, installed as early as the late 1800's, is in good condition and with modification could be upgraded to provide many more years of reliable service. There are several corrosion engineering studies and analyses that can be employed to define the condition of the infrastructure of concern. 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.

Corrosion control is important for both design of new infrastructure and continued utilization of existing infrastructure. Many systems have been deemed structurally unsound or replaced due to corrosion. In some cases, these systems had not reached 50% of their design life. These structures could have been in service today if proper corrosion mitigation measures had been applied. For the structures under consideration in the context of this paper, the additional provision of uninterrupted service lives in excess of 50-plus years should be realized.

In 1997, the City of Rochester's Bureau of Water & Light (RBW&L) commissioned an infrastructure evaluation of the transmission pipelines identified as Conduits I, II and III. These conduits are part of the City's Upland Water Supply Conduit Transmission System which extends from Hemlock Lake in the south to Cobb's Hill and Highland Reservoirs in the north, a total of approximately 28 miles. Conduit I was installed in 1874 and is primarily constructed of cast iron. Conduit II was installed in 1894 and is primarily constructed of riveted steel. Conduit III was installed between 1914 and 1918 and is primarily constructed of lock bar steel. Both Conduits II and III were originally coated with coal tar at the time of manufacture. Sections of Conduit II were excavated and recoated in the early 1900's after corrosion pitting was observed in many areas.

The purpose of the study was to assess the existing condition of the conduits, predict the likelihood of leaks in the future and develop recommendations for action by the RBW&L to minimize corrosion problems. The study focused on soil side corrosion, and did not attempt to assess the corrosion environment inside the conduits.

Test Protocol

During the initial infrastructure condition assessment performed in 1997 – 1998 a series of field evaluations were made to define the condition of the infrastructure. In a follow-up contract in 2001 - 2002, to begin the process of applying cathodic protection to the conduits, additional field testing was performed. The following describes testing that was performed in both study periods.

Pipe Continuity

Longitudinal pipe continuity was evaluated over approximately 55 locations along the conduits. Access to the pipe was made via existing test stations and test wires. Temporary wires were run between two test stations in order to perform the test. An external battery was used to impress a current and resistance was calculated by dividing the resulting change in voltage by the applied current.

Excavations

In each excavation, the exposed areas of the conduits were divided into grid squares, approximately one foot square. Within each square, a pit depth gauge was used to measure the deepest pit. In practice, a number of apparently deepest pits must be measured in order to determine which pit is deepest. Along each exposed section of conduit, a number of ultrasonic thickness measurements were made. The measured values can then be compared to the nominal thickness.

In addition, photographs were taken in each excavation to document the existing conditions. The presence and condition of the coatings on the conduits was also evaluated.

Soil samples were taken from two locations within each excavation. These samples were then laboratory tested for the following: pH, moisture content, sulfate ion concentration, and chloride ion concentration.

Cooperative Interference Testing

Co-operative interference testing was performed with three utilities that own pipelines that are near or cross the conduits. Each utility cycled the nearest operating impressed current rectifier while various tests were performed on the conduits. Pipe-to-soil voltage measurements for the conduits were made with the foreign pipeline's (the utility) rectifier cycling. In some cases, the voltage between two test stations on the water conduits was monitored with the foreign rectifier cycling as well. This voltage

is proportional to current flow in the conduit, between the two test stations. The voltage difference is proportional to that portion of the current flow due to the foreign rectifier system.

Statistical Analysis

The present state of technology offers no other practical way of determining corrosion pit depths on operating underground piping systems other than direct physical examination of the pipe surface. This presents a difficult problem, both from a practical and theoretical standpoint. The pits of greatest interest are the deeper ones yet these are the pits that occur most rarely. The probability of finding the deepest pit, on a mile of pipe, by randomly inspecting only one percent of the pipe would be very small.

For this study, the number of excavations was determined from a practical approach to assessing corrosion activity along the pipe route. Although 1% of the pipe surface would be ideal for analysis, this was not considered to be required or economically prudent. Data analysis indicates that the line of expected extremes is valid as all the data falls within the control curves. This indicates that the data acceptably agrees with the extreme probability theory. Therefore this evaluation of approximately 0.06% of the pipe surface is considered to be an acceptably accurate analysis.

In analyzing extreme values encountered in statistical samples, the deepest pit in the pipe is what we are concerned with. Gumbel's 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 us to predict the magnitude of corrosion penetration problems that will be encountered on a given structure.

Discussion

Soil Resistivity

Of the measurable soil characteristics, resistivity is generally accepted as the primary indicator of soil corrosivity. It is generally agreed that the classification shown below, or other similar classifications, reflect soil corrosivity.

Table 1	Soil Resistivity
Ohm – Cm	Description
below 500	Very Corrosive
500 to 1,000	Corrosive
1,000 to 2,000	Moderately Corrosive
2,000 to 10,000	Mildly Corrosive
above 10,000	Progressively less corrosive

The 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 warrant investigation. These are soil moisture and soil type.

Test results indicate that there are significant portions of the conduits in corrosive soil, and that there is variation in resistivity along the conduits. Analyses indicate that soil resistivity along the pipe route ranges from 463 ohm-cm to 60,000 ohm-cm. To the extent that electrical continuity exists in the pipeline of concern, long line galvanic corrosion from soils would be expected.

Three general areas have been identified as exhibiting resistivity values of concern. Statistical analyses indicate that approximately 35% of the resistivity data points are less than 3,500 ohm-cm. Soils less than 3,500 have been correlated with pitting activity on these conduits. A study of the pits that were found in excavations and the soil resistivity measured in the excavations with pitting showed a correlation between pitting and soils with less than 3,500 ohm-cm resistivity. These are the pipe sections that are currently experiencing corrosion activity, and would require corrosion mitigation for continued utilization.

Pipe Electrical Continuity

Theoretical resistance of 36-inch steel pipe was calculated based on a resistance per foot of 1.6×10^{-6} ohms. This value was derived from the cross sectional area of the steel pipe and physical properties of steel. Measured values correlate well with the theoretical as evidenced by several test segments between 0.8 and 1.2 times theoretical.

For cast iron pipe, a theoretical value of 8.0×10^{-6} ohms per foot was used for 36-inch diameter and 4.0×10^{-6} ohms per foot for 24-inch diameter. These values are the theoretical resistance of modern ductile iron pipe. Typically, cast iron pipe is not assumed to be continuous because push-on joints (especially with modern rubber gaskets) may not have metal to metal contact between adjacent pipe lengths. Modern ductile iron pipe is typically bonded via thermite welded wires if cathodic protection is to be applied.

For the purposes of this study, where the measured resistance was determined to be more than five times the theoretical resistance value, the pipe was considered electrically discontinuous. This higher limit has been considered because of the riveted pipe joints and to avoid what may be unnecessary excavation and bonding of "discontinuities". Of the 141,710-feet of individual pipe tested, 103,610-feet, 73% was found to be electrically continuous.

Cooperative Interference Testing

Cooperative interference testing was performed with three transmission companies whose pipelines cross the conduits. Test results indicate that the effect from these operators is relatively small. The primary effect of these operators was identified on the cross-over pipe section. The crossover pipe section is experiencing corrosion from both galvanic corrosion and stray interference corrosion activity. As a result of this and other factors, the crossover pipe was replaced in 2001.

Expected Conduit Life and Projected Leaks

The corrosion evaluation of conduits I, II, and III was performed by CorrTech's engineering personnel utilizing extreme value statistical analytical methods. This portion of the study focused on corrosion of the external surface of the conduits and included visual inspection, ultra-sonic thickness measurements and pit depth measurements.

A total of ten excavations were made to expose the conduits. Two excavations contained conduit I, nine excavations contained conduit II, and eight excavations contained conduit III. Within each excavation, approximately 10-feet of each conduit was lightly surfaced cleaned and the existing coating evaluated and evidenced corrosion evaluated.

Steel, or iron pipe including cast iron, corrodes when buried as a result of several major factors. The primary factor for these conduits is corrosion due to soils. This type of corrosion typically results in pitting of the steel surface and is particularly vicious when initiated in areas of coating faults. Of concern would be pitting activity that would lead to through-wall penetrations, resulting in loss of structural integrity and product. Generally, there tends to be small areas of metal loss (pits) in larger areas of uncorroded or lightly corroded metal surface.

Field indicates that no pits greater than ten (10) mils were found on conduit I. This is too small of a sample to run extreme value statistical analyses, but it is considered that no significant pitting activity would be found on the cast iron conduit.

Extreme value statistical analysis of the pit depth data obtained for conduit II indicates that there are approximately 5,360 pipe penetrations existing on the conduit at the time of this evaluation. It is considered that these through pits do not typically manifest as leaks because of the internal concrete lining which has the ability to bridge corrosion holes.

Based on calculations utilizing present corrosion rates, the pit depths measured and age of the structure, it is concluded that multiple through wall penetrations will continue to occur. Currently there are approximately 22,780 existing pits, 75% through the wall (280 mils deep), that would penetrate the pipe in approximately 35 years or less.

Based on pitting correlation with soil resistivity, it is considered that the majority of these failures would occur in soils less than 3,500 ohm-cm. For these conduits, these are considered to cover approximately 16.8 miles of the 25 miles of pipe route.

Conduit III extreme value statistical analysis of the pit depth data obtained indicates that there are no existing pipe penetrations at the time of this study. Based on calculations utilizing present corrosion rates, the pit depths measured and age of the structure, it is concluded that multiple through wall penetrations will begin to occur. Currently there are approximately 130 existing pits, 50% through the wall (187 mils deep), that would penetrate the pipe in approximately 90 years or less.

Based upon test results, field observations and data analysis, active corrosion is occurring on the subject dual pipe lines. It was recommended that for long term useful service life and continued utilization of the raw water transmission mains, impressed current cathodic protection be installed on selected segments of pipe. The intent of this recommendation, for the approximately 17 miles of pipe, is to arrest the majority of the corrosion exposure. This recommendation was made in comparison to the cost of replacement of approximately \$35 million dollars.

Phase I

In the spring of 2001 the RWW & L contracted with CorrTech for the next phase of work, titled "Cathodic Protection of Water Transmission Conduits – Phase I". This phase of the project involved additional field testing, pilot program development and design for the selected pilot program.

Current Requirement Testing

In order to determine the amount of cathodic protection current required to protect a given length of pipe, a current requirement test was performed. At Test Station 27.22, a temporary current was established between Conduit II and Conduit III. This current simulated a cathodic protection system for Conduit II, with Conduit III acting as a temporary anode.

The current requirement test shows that the pipe can be protected with 1.3 milliamperes per square foot of bare pipe surface. One square foot of pipe with coating adhered to 66% of the total surface area (33% bare) would comprise 0.33 square feet of bare area. Excavations done under the 1997 study showed that the coating was well adhered over 90% of the surface area for Conduit I, 50% for Conduit II and 75% for Conduit III.

Cathodic Protection System

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 dependent 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, as magnesium alloys would corrode preferentially when connected to steel in an underground environment. 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.

Based on the current requirement test results, size of the pipes requiring protection and coating quality, impressed current cathodic protection was selected as the most economic approach for the Rochester water conduits. A general target of 75-amperes per mile of twin conduit pipes was set.

Pilot Program Choices

A total of 5 pilot program locations were detailed in Phase I. For each pilot program considered, electrical separation between the cathodically protected pipe and adjacent pipe would be required. This requires that insulated couplings be installed in the conduits receiving CP at both the northerly and southerly limits.

Pilot System Installation

Following submission of the design report and presentation of the program by CorrTech in February 2002, it was decided to install the pilot program site 5, south of Bridge No 5 over Honeoye Creek. This section offered a number of advantages for both construction and access for detailed testing and evaluation following construction. Bid documents were produced by CorrTech and the low bidder selected in August 2002. Construction of the pilot program was completed in December 2002.

CorrTech, Inc. activated the cathodic protection system in February 2003. This testing was performed to verify that the contractor had completed the installation properly and that all cathodic protection components were functioning properly. Further testing will be performed once the system has been allowed to stabilize. It is not uncommon for a system with large surface area, and poor coating quality, to take several weeks or months to completely stabilize.

Based on the field testing protocol for the 5,000-ft pilot program site, it was determined that the rectifier has been properly installed and is producing protective current as intended. The rectifier is currently operating at an output of 29.9 Volts and 17.5 Amps and providing cathodic protection to the pipelines. The anode ground bed was determined to have been installed properly and is functioning as intended. The anode bed resistance is approximately 0.5 ohms with respect to remote earth. This resistance will allow the full current output of the rectifier to be used if desired for additional pipe protection in the future.

As part of the construction of the pilot program, insulated couplings and new valves were installed on the southern end of the pilot program piping. These electrically

separate the cathodically protected pipe section from the unprotected piping. These are important devices to control current flow and provide protective current density to specific buried piping components. Field testing confirmed that these devices had been installed properly and were functioning as intended.

It was determined that an interference bond will be required to eliminate adverse effects from the new cathodic protection system on the high pressure gas transmission pipes crossing the water line. A bond resistance solution will be determined during follow-up field testing to be performed in 2003.

The application of cathodic protection for 17-miles of transmission mains associated with the City of Rochester Water supply is a long term, on-going project. Based on the pilot program tests results to determine specific operating parameters, Phase II of the design project would proceed in 2003. Specific design work for the remaining portions of the cathodic protection systems would begin and construction of the systems would commence in the fall of 2003.