External Corrosion and Corrosion Control of Buried Water Mains

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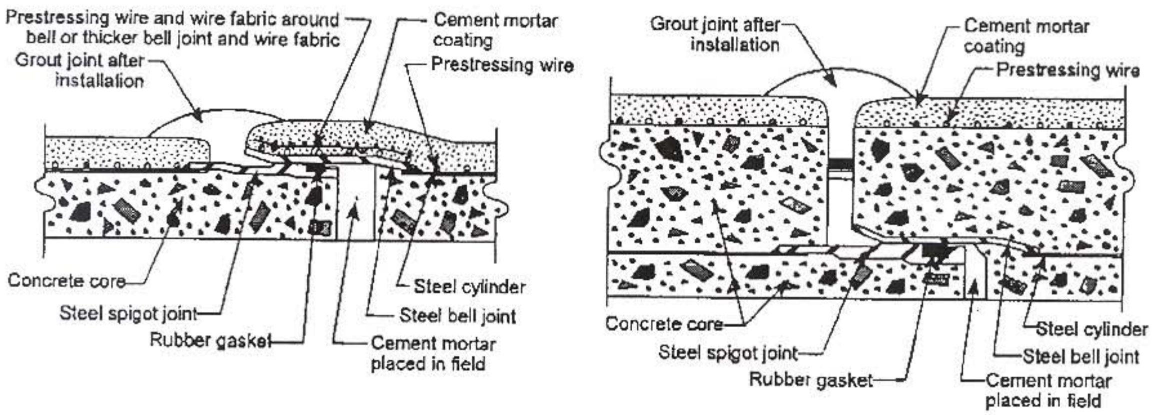
APPENDIX B-1
CATHODIC PROTECTION OF NOTCHED PRESTRESSING WIRE IN PCCPAMERON INTERNATIONAL, SOUTH GATE, CALIFORNIA

INTRODUCTION

Description of PCCP

PCCP is a rigid, durable pressure pipe designed to take optimum advantage of the compressive strength and corrosion-inhibiting property of portland cement concrete and mortar and the tensile strength of prestressing wire. It includes a rigid concrete core, steel cylinder, circumferentially wrapped prestressing wire, and a protective mortar coating. In embedded-cylinder type pipe, the wire is wrapped on the concrete core in which the steel cylinder is embedded. In the lined-cylinder type, the wire is wrapped directly on the steel cylinder. The components of an installed PCCP are identified in Figure B-1.1.



A. Lined Cylinder Pipe

B. Embedded Cylinder Pipe

Figure B-1.1 Components of installed PCCP

Stress Levels of Prestressing Wire in PCCP

The prestressing wire, which conforms to ASTM A 648 after 1972 and to ASTM A 227 prior to 1972, is helically wrapped around the concrete core or steel cylinder at 75 percent of its minimum nominal tensile strength. The minimum yield strength as given in AWWA C304 (1992b) is 85 percent of its minimum nominal tensile strength. The stress decreases to a range of 55 to 65 percent due to initial losses which occur when anchoring the wire and creep and shrinkage of the concrete core and relaxation of the wire and other minor losses which occur during the life of the pipe. Prestressing places the concrete core in compression which makes it possible to design PCCP to withstand the combined effects of internal pressure and external load without exceeding the tensile strength of the core. Experience and extensive testing have shown that this design approach ensures that the protective cement-mortar coating will be free of visible cracks under operating conditions.

Uses of PCCP

PCCP is used in water and wastewater systems that serve virtually every major city in North America. It is primarily used for distribution of water for industrial, agricultural, and residential uses. It is manufactured in sizes from 16 inches (410 mm) to 21 feet (6.40 m) in diameter with pressure ratings up to 500 psi (3.45 MPA). It is typically manufactured and designed in accordance with AWWA C301 and C304 (AWWA 1992a and 1992b). Approximately 19,100 miles (30,700 km) of PCCP have been installed in North America from 1945 to 1995 (Clift 1991 and Prosser 1996).

Passivation of Prestressing Wire and Performance of PCCP

Due to the passivating (corrosion inhibiting) properties of the highly alkaline portland cement, the cement slurry and mortar coating over the prestressing wire provides the only protection that PCCP normally requires. One survey showed that concrete pipe had the lowest problem occurrence rate and that the average level of satisfaction was highest for concrete pipe in more than 115,000 miles (185,000 km) of pipe surveyed (AWWA 1986). Another survey stated that the overall performance of PCCP has been excellent. Only 30 out of a total of 19,165 projects have had any type of problems with external corrosion and that, in most cases, only one or two pipe sections were affected (Prosser 1996). Chloride-induced corrosion was the most common form of external corrosion found in the 30 projects (Prosser 1996) and could have been prevented by the use of supplemental coatings or cathodic protection.

In unusual circumstances, such as in high chloride environments, the passivating properties of the highly alkaline cement may be compromised. In such environments, supplemental protection may be necessary. Supplemental protection is usually in the form of barrier coatings such as coal-tar epoxy or, in rare cases, cathodic protection.

Use of Cathodic Protection

Since extreme conditions are required to cause corrosion of PCCP, cathodic protection has rarely been used. One investigator reported that it appears that less than 0.5 percent of all PCCP in the United States is under cathodic protection (Benedict 1989). Another report indicated that only about 20 projects of a total of 28,900 PCCP projects (less than 0.1 percent) are under cathodic protection (Clift 1991).

Use of Notched Prestressing Wire

Under constant extension rate test (CERT) and slow strain rate test (SSRT), notched specimens are used to compare quickly the susceptibility of a steel to hydrogen embrittlement. The use of notched specimens can resolve disparities between wire quickly using CERT and SSRT. Under CERT and SSRT, the disparities between smooth specimens are not resolved due to the shorter duration of the test. The use of smooth specimens requires a much longer time before the susceptibility of the material is resolved but is more indicative of the real world practical aspects of cathodic protection of PCCP where it has taken many months to decades for failure to occur due to excessive cathodic protection (Hall 1998).

Although the stress on prestressing wire on PCCP typically ranges from 55 to 65 percent, it is possible that the stress on wire can be greater due to reduction of its cross-section by corrosion. This corrosion may also produce the "notch" effect which is trying to be simulated by machining a notch in the wire used during CERT and SSRT testing. However, corrosion has not been shown to be as severe as the notch manufactured for CERT and SSRT testing. For passive, noncorroding wire neither an increase in stress will occur nor notches will be produced since corrosion has not occurred. In this project, a saturated calcium hydroxide solution was used to simulate the high pH environment surrounding passive prestressing wire.

If corrosion does occur, it is often due to high levels of chloride ions in the soils and groundwater which penetrates the mortar coating and can depassivate the steel and initiate corrosion. The corrosion process can reduce the pH around the wire. The pH of a severely corroded area has been measured to be as low as 2 to 3 (Hall 1998). In this project, a saturated calcium hydroxide solution was acidified to pH 3 using hydrochloric acid to simulate the environment surrounding severely corroding wire in mortar caused by high chloride levels at the wire surface.

Hydrogen Embrittlement of Prestressing Wire

Due to the small number of cathodically protected PCCP lines, many corrosion engineers and technicians did not recognize that the prestressing wire in PCCP, as a high tensile steel, is susceptible to hydrogen embrittlement. As a result, some pipelines were cathodically protected as if they were oil and gas pipelines. Unfortunately, hydrogen embrittlement of the prestressing wire due to excessive cathodic protection appeared to have occurred to three pipelines which resulted in rupture of one or two pipe sections in each pipeline (Prosser 1996 and Hall 1998).

Due to the use of high-strength prestressing wire in PCCP, the effect of high levels of cathodic protection at the potential required to cause hydrogen embrittlement must be addressed. The most probable reaction occurring on the pipe under excessive cathodic protection at pH greater than 7 is the electrolysis of water, $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$. During the formation of H_2, hydrogen atoms (H_o) are produced on the metal surface. Prior to combining to form hydrogen gas, atomic hydrogen may penetrate the steel. This entry causes a loss of ductility, or embrittlement, of the prestressing wire.

Based on the above reaction of electrolysis of water, the potential at which hydrogen evolution occurs can be calculated using the Nernst Equation (Hall 1998). Thus at typical pHs of portland cement mortar of 12.5 to 13.5, the hydrogen evolution potential is –1,055 mV to –1,114 mV referenced to a CSE, respectively, indicating that hydrogen is produced at potentials more negative than this.

Effect of pH on Hydrogen Production Potential

In carbonated mortar or around corroded reinforcement or prestressing wire, the pH at the steel surface may be substantially reduced. Completely carbonated mortar has a pH of approximately 7. The pH of corrosion products can be as low as 2 to 3. Based on the Nernst equation, the calculated potential for hydrogen evolution is more positive by approximately 59.2 mV for each decrease in one pH unit at 25°C. At a pH of 2 or 7, the hydrogen evolution potential is -434 or -730 mV (CSE), respectively. However, under cathodic protection, the pH at the wire surface will increase rapidly in a few hours or days to a value greater than 12.4 due to the production of hydroxide ions or consumption of hydrogen ions in accordance with the following reactions at the given potentials (E) and predominantly at the given pH:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad \text{at } E < (-0.0592)(pH) - 0.316 \quad \text{and } pH>7 \qquad (1)$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad \text{at } E > (-0.0592)(pH) - 0.316 \quad \text{and } pH>7 \qquad (2)$$

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{at } pH < 7 \qquad (3)$$

Since hydroxide ions but no hydrogen are produced in reaction (2), low levels of current at the indicated potential can be used to increase the pH without the production of hydrogen at pHs greater than 7. At a low current density of 1 μA/ft^2 (11 μA/m^2), it would require only 70 hours to bring the pH in a 1 μm thick layer around a steel rod from 7 to 12.45 in accordance with Faraday's Law. A current density of 1 μA/ft^2 is not expected initially to polarize the steel to values more negative than -730 mV [(-59.2)(7)-316], the value where hydrogen production begins at a pH of 7. The hydrogen production potential will decrease to –1,055 mV as the pH increases to 12.45.

Under much higher current densities and at pHs greater than 7, the predominant reaction is reaction (1). Hydrogen is produced but the pH also increases. Based on a higher current density of 100 μA/ft^2 (1,080 μA/m^2), it would require only 42 minutes to increase the pH in a 1 μm thick layer around a steel rod from 7 to 12.45.

At pHs less than 7, the predominant hydrogen ions are converted to hydrogen gas under any level of cathodic protection or corrosion as given in reaction (3) but the pH also increases since hydrogen ions are being consumed in the reaction. Reaction (3) will convert to predominantly reactions (1) or (2) once the pH becomes greater than approximately 7.

NACE RP0100-2000 Requirements

NACE International RP0100-2000 "Cathodic Protection of Prestressed Concrete Cylinder Pipelines" (NACE 2000) provides that the polarized potential on PCCP "more negative than -1,000 mV (CSE) shall be avoided to prevent hydrogen generation and possible hydrogen embrittlement of the high strength prestressing wire." It also provides for a more positive potential initially when corrosion is present to reduce the amount of hydrogen evolution and possible early failure of the wire.

Objective of Project

The objective of the project was to determine the effect of cathodic protection on the performance of notched prestressing wire immersed in solutions simulating sound mortar and mortar surrounding severely corroded wire. The susceptibility of split and nonsplit prestressing wire to hydrogen embrittlement and the potentials to produce hydrogen embrittlement and eventual wire failure were determined. The data and results are presented.

PRESTRESSING WIRE TEST SPECIMENS

In this project, three prestressing wire samples, all made in accordance with ASTM A 648, were evaluated. However, they were made under different versions of the standard. In the 1972 and 1973 version (reapproved 1980), only a minimum tensile strength and chemical composition were specified. In 1984, reduction of area was added, and in 1986, a maximum tensile strength was added. In 1988, torsion testing was added and the chemical requirements were tightened. In 1995, the number of turns in torsion was increased and the type of primary shear break was added. These changes were instituted to produce a wire that had a lower susceptibility to hydrogen embrittlement and stress corrosion cracking.

The 6-gauge wire used in this project was made in 1989 to 1990 in accordance with ASTM A 648-88 with a minimum tensile strength of 252 ksi (1,740 MPa) and was never placed on a pipe. It also meets the 1995 version of the standard. Number of turns to break and type of break in torsion have been determined to be an important factor in the susceptibility of wire to hydrogen embrittlement (Hall 1998). The number of turns to break of the 6-gauge wire was greater than 12 turns per 8-inch test length which was much higher than the 8 turns to break given in the 1995 standard. The type of break was 100 percent shear indicating that the wire should have low susceptibility to hydrogen embrittlement. In general, the greater the turns to break the less susceptible the wire is to hydrogen embrittlement.

The 8-gauge (Hall 1998) and 1/4-inch diameter wire samples were both made in the late 1970s and early 1980s and contained longitudinal splits that reportedly were due to hydrogen embrittlement caused by high levels of cathodic protection during service. It was previously observed (Hall 1998) that longitudinal splits occurred to wire with low turns to break in torsion while subjected to cathodic protection at <-1,200 mV (CSE) but not to wire with high turns to break that meet or exceed the eight turns per 8-inch length given in ASTM A 648-95. Hence, it is speculated that these two samples may not have met the torsion requirements specified in ASTM A 648 since 1988. The number of turns to break in torsion could not be determined for the 8-gauge wire samples since wire without splits were not available and the split wire is not expected to be indicative of the properties of the wire prior to service.

The 8-gauge wire was produced with a minimum tensile strength of 262 ksi (1,809 MPa) and was removed from a pipeline cathodically protected at polarization (interrupted or current-off) potentials as negative as –1,250 mV (CSE) (Hall 1998). A longitudinal split which extended almost to the center of the wire was found along the entire length of the 8-gauge wire after a rupture occurred to the pipeline.

The 1/4-inch diameter wire was produced with a minimum tensile strength of 240 ksi (1,650 MPa). MWDSC removed the wire from an adjacent pipe in the Allen-McColloch Pipeline after an adjoining pipe ruptured, reportedly due to surge, in December 1999 after 20 years of service. A longitudinal split that extended almost to the center of the wire was found on approximately half of the 1/4-inch diameter wire specimens used in this project. The pipeline was exposed to a foreign cathodic protection system since installation and was bonded to the foreign pipeline to return the "stray current." The bonds were disconnected in 1997. Pre-1997 potentials were in the –1,300 mV (CSE) range. Post-1997 potentials were in the –900-mV range.

TEST PROCEDURES

Notched ASTM A 648, Class III prestressing wire specimens from three sources were subjected to no cathodic protection and to cathodic protection polarization potentials of –1,000 mV (CSE) as well as cathodic overprotection polarization potentials of –1,100 mV and <-1,200 mV. The specimens were immersed in a saturated calcium hydroxide solution to simulate a portland cement mortar environment or in a saturated calcium hydroxide solution acidified to pH 3 using concentrated hydrochloric acid to simulate a portland cement mortar in which chloride ions have reached the wire surface and caused severe corrosion. The temperature was maintained between 70°F and 72°F (21°C to 22°C).

Prior to exposure, the wire specimens were stressed and maintained at 45 to 105 percent of their specified minimum tensile strength. Cantilever-type wire tensioning apparatus with plastic enclosures for immersing approximately 32 inches of the 60-inch (81 cm of the 152 cm) long wire specimens were used. Potentiostats were used to control the potential. Up to six specimens were exposed in each solution at any one time. Six-gauge (0.192 inch, 0.488 cm diameter), eight-gauge (0.162 inch, 0.411 cm diameter), and 1/4-inch (0.635 cm) diameter ASTM A 648, Class III prestressing wire specimens were used during the investigation.

The calcium hydroxide and acidified calcium hydroxide solutions were prepared with reagent grade calcium hydroxide and/or concentrated hydrochloric acid and with ASTM D 1193-91 Type IV reagent distilled water. Saturated calcium hydroxide solution was added weekly to the calcium hydroxide solution to ensure that a bulk pH of 12.45 was maintained and to adjust for evaporation. The saturated calcium hydroxide solution acidified to pH 3 with hydrochloric acid was added weekly to the acidified solution to adjust for evaporation. The pH of each solution was determined periodically. No attempt was made to maintain the pH of the acidified calcium hydroxide solution to pH 3 since, in practice, the acidified solution around a corroded prestressing wire will become more alkaline upon application of cathodic protection due to either the consumption of hydrogen ions or the production of hydroxide ions as given in Reactions 1 to 3 in the Hydrogen Embrittlement of Prestressing Wire Section.

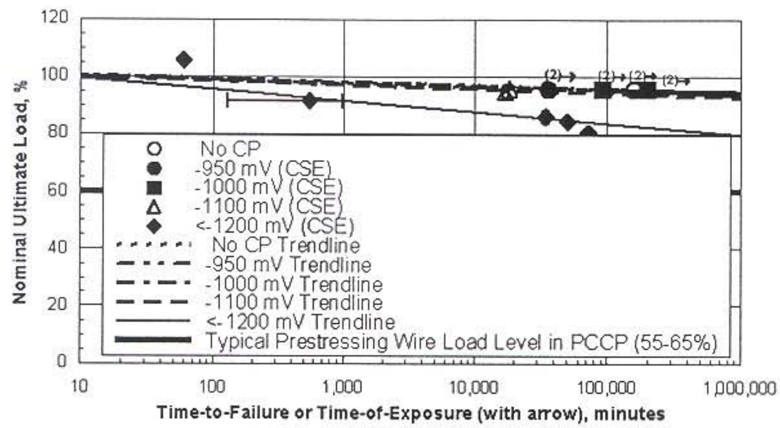
Each prestressing wire specimen was notched as described in Sections 10.2 and 10.3 and Figure 3b in ASTM G 142-98. The notch is considered to be a severe condition and may or may not correlate with the service experience of PCCP lines.

Time-to-failure or time-of-exposure of prestressing wire specimens was determined at no cathodic protection or at various levels of cathodic protection.

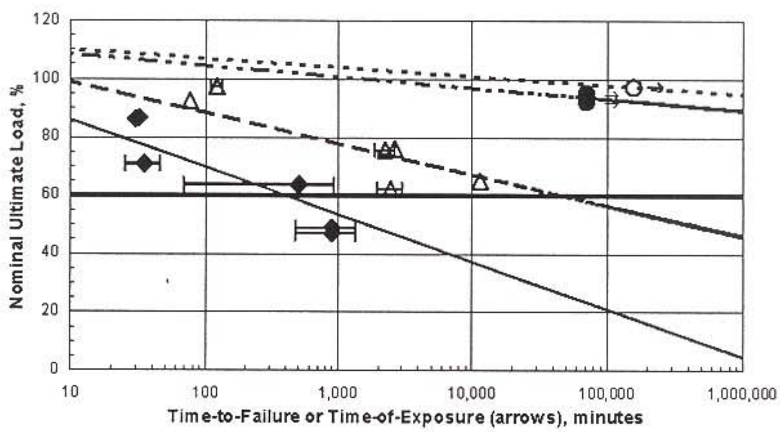
Specimens were removed from exposure if they had not failed after at least 60,000 minutes (1,000 hours) of exposure to allow exposures at another potential. Some specimens are continuing to be exposed.

TEST RESULTS

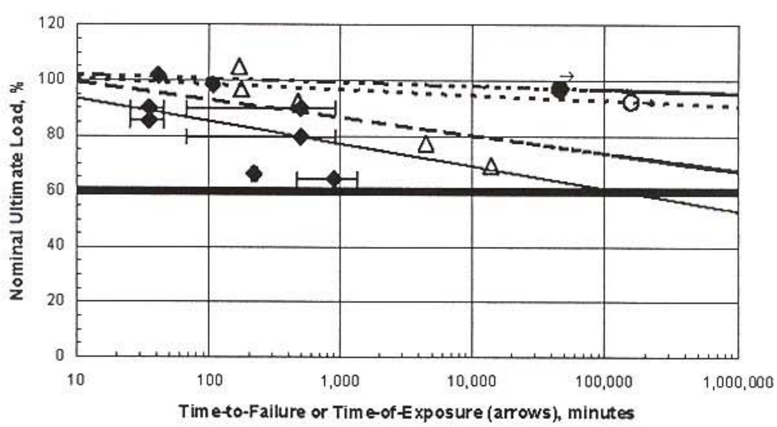
The time-to-failure and time-of-exposure of the 6-gauge, 8-gauge, and 1/4-inch diameter prestressing wire in a saturated calcium hydroxide solution and in an acidified calcium hydroxide solution are shown in Figures B-1.2a, b, and c and B-1.3a, b, and c, respectively. The saturated calcium hydroxide solution represented the portland cement mortar that the wire is encased in PCCP and that passivates the steel. As determined in the lab, the average tensile strengths of the 6-gauge, 8-gauge, and 1/4-inch diameter wire in air were 103 percent (260 ksi), 116 percent (304 ksi), and 105 percent (252 ksi) of the minimum nominal tensile strengths of the Class III wire of 252 ksi, 262 ksi, and 240 ksi, respectively. They are plotted at 0.1 minute in the figures and are used as data points in the trend line. In the initial stages of testing, primarily for the <-1,200 mV (CSE) exposure, a timer was not used so the error bars represent the interval between checking on the condition of the wire. In the later stages of testing, the error bars are one minute due to the accuracy of the timer and are not shown. The typical prestressing wire load level in PCCP ranges from 55 to 65 percent of the minimum nominal tensile strength and is shown in the figures as a bold line at 60 percent. The data points followed by an arrow represent a wire removed from exposure prior to failure or a wire still under exposure.



A. Six-gauge prestressing wire

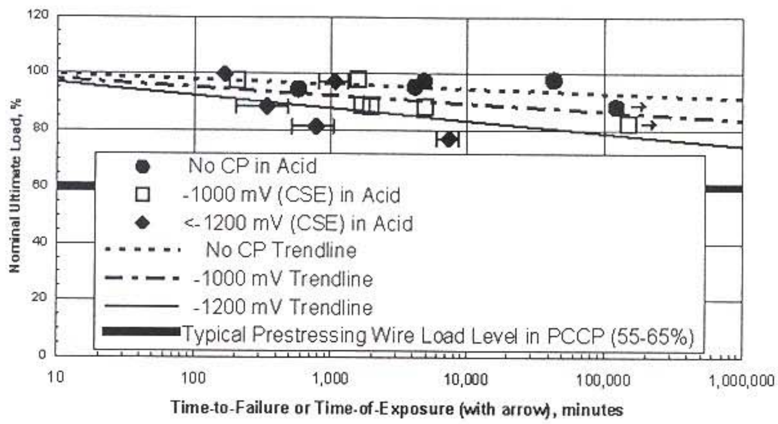


B. Eight-gauge prestressing wire with split

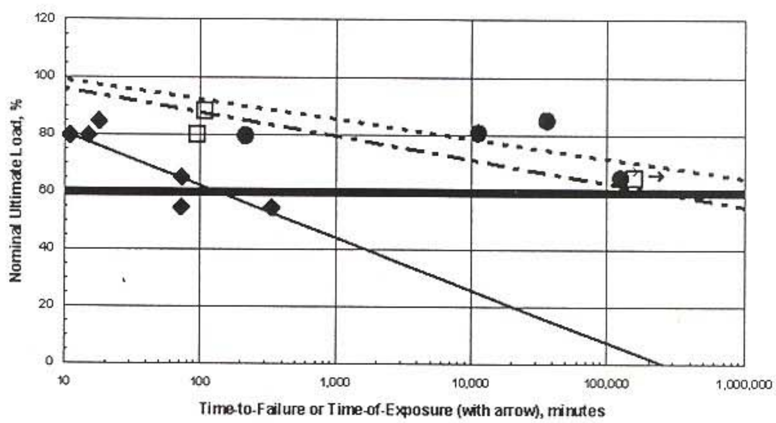


C. Quarter-inch diameter prestressing wire with split

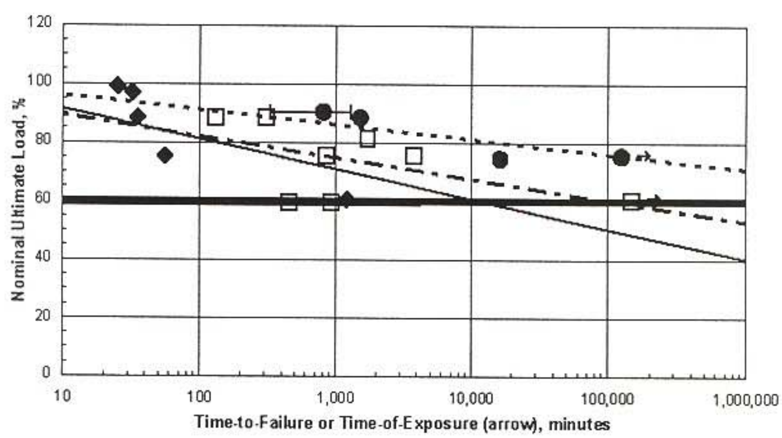
Figure B-1.2 Effect of cathodic protection on time-to-failure of notched prestressing wire in a saturated calcium hydroxide solution



A. Six-gauge prestressing wire



B. Eight-gauge prestressing wire with split



C. Quarter-inch diameter prestressing wire with split

Figure B-1.3 Effect of cathodic protection on time-to-failure of notched prestressing wire in a saturated calcium hydroxide solution acidified with hydrochloric acid to pH 3

Susceptibility of Prestressing Wire to Hydrogen Embrittlement in a Calcium Hydroxide Solution (Figures B-1.2a, B-1.2b, and B-1.2c)

In the saturated calcium hydroxide solution under no cathodic protection, the three wire samples never failed during the 158,400 minutes (110 days) of exposure even when subjected to a load greater than 92 percent of their minimum nominal tensile strength since hydrogen evolution and hydrogen embrittlement were not expected.

At –950 mV (CSE) in the saturated calcium hydroxide solution, the three wire samples never failed during the greater than 36,000 minutes (25 days) of exposure even when subjected to a load greater than 95 percent of their minimum nominal tensile strength. Extrapolating the trend lines, it would take more than 100,000,000 minutes (190 years) for the wire to fail at loads greater than 90 percent. Exposure is continuing.

At –1,000 mV in the saturated calcium hydroxide solution, the 6-gauge wire never failed after up to 201,500 minutes (140 days) at loads of 95 percent before being removed. Extrapolating this trend line, it would take more than 100,000,000 minutes (190 years) for the wire to fail at loads greater than 90 percent. Exposure of the 8-gauge and ¼-inch diameter wire will occur at a later date.

At –1,100 mV in the saturated calcium hydroxide solution, where hydrogen was collected (Hall 1998), the 6-gauge wire failed at 17,000 minutes (283 hours) at 95 percent load. However, upon extrapolating the –1,100 mV trend line of the 6-gauge wire, it would require 100,000,000 minutes (190 years) for failure to occur at a load of 90 percent. This is consistent with the low susceptibility of the 6-gauge wire to hydrogen embrittlement. The 8-gauge and 1/4-inch diameter wire failed earlier and at lower loads than the 6-gauge wire and are indicative of their greater susceptibility to hydrogen embrittlement.

At <-1,200 mV in the saturated calcium hydroxide solution, where hydrogen was copiously produced and visually observed from the three wire samples, the extrapolated time-to-failure of the notched 6-gauge wire indicated that the wire would fail at 100,000,000 minutes (190 years) at a load greater than 70 percent. This time-to-failure is greater than that found for smooth 6-gauge wire from the same coil which failed between 26 and 41 months at <-1,200 mV and 60 percent load (Hall 1998). The 8-gauge and 1/4-inch diameter wire failed earlier and at lower loads than the 6-gauge wire and are indicative of their greater susceptibility to hydrogen embrittlement.

The failures at <-1,200 mV are consistent with the observation that copious amounts of fine bubbles were produced and collected from the specimens at <-1,200 mV. No bubbles were seen or collected at –1,000 mV. This is consistent with the calculated hydrogen evolution potential of –1,055 mV (CSE) at a pH of 12.45.

Susceptibility of Prestressing Wire to Hydrogen Embrittlement in a Calcium Hydroxide Solution Acidified with Hydrochloric Acid to pH 3 (Figures B-1.3a, B-1.3b, and B-1.3c)

The acidified calcium hydroxide solution simulated the environment around corroding steel in concrete. For the three wire samples in both solutions, time-to-failure increased with decreasing load and more positive potentials, as expected. Medium to copious amounts of hydrogen bubbles were observed evolving on the three wire samples under no cathodic protection, -1,000 mV, and <-1,200 mV. Using the Nernst equation discussed in an earlier section, hydrogen is produced in a pH solution at potentials more negative than -493 mV (CSE) at 25°C and atmospheric pressure. As such, it is reasonable to conclude that, under no cathodic protection where the potential of the wire would be approximately -600 mV to -650 mV (CSE), corrosion would occur with the evolution of hydrogen of which both were evident in this project.

Under no cathodic protection in the acidified calcium hydroxide solution, the notched 6-gauge wire failed at loads of 98 percent at 4,800 and 42,000 minutes. Upon extrapolating the trend line, it would require 100,000,000 minutes (190 years) for the notched 6-gauge wire to fail at a load of 88 percent based on a combined hydrogen embrittlement and corrosion mechanism. However, the no cathodic protection trend lines of the notched 8-gauge and 1/4-inch diameter wire samples indicate that it would require 5,000,000 minutes (9.5 years) and 100,000,000 minutes (190 years), respectively, for failure at a service load of 60 percent, the typical load level of wire on PCCP. This is consistent with the low susceptibility of the 6-gauge wire to hydrogen embrittlement. The 8-gauge and 1/4-inch diameter wire failed earlier and at lower loads than the 6-gauge wire and are indicative of their greater susceptibility to hydrogen embrittlement.

Extrapolating the trend lines at –1,000 mV (CSE) in the acidified calcium hydroxide solution, it requires 100,000,000 minutes (0.19 years) for failure of notched 6-gauge, 8-gauge, and 1/4-inch diameter wire specimens at loads of 86, 63, and 60 percent, respectively. This is consistent with the low susceptibility of the 6-gauge wire to hydrogen embrittlement. The 8-gauge and 1/4-inch diameter wire failed earlier and at lower loads than the 6-gauge wire and are indicative of their greater susceptibility to hydrogen embrittlement. During hydrogen production when the wire is under cathodic protection, the hydrogen ions are consumed in accordance with Equation 3 thereby increasing the pH. In a very short period of time, such as a few hours to days (Hall 1998), the pH of the wire surface in a confined, quiescent space, such as concrete, would drastically increase and hydrogen production would cease.

Extrapolating the trend lines at <-1,200 mV (CSE) in the acidified calcium hydroxide solution, it requires 1,000,000,000 minutes (1,900 years), 140 minutes, and 11,000 minutes (183 hours) for failure of the notched 6-gauge, 8-gauge, and 1/4-inch diameter wire specimens at a load of 60 percent. This is consistent with the low susceptibility of the 6-gauge wire to hydrogen embrittlement and the higher susceptibility of the 8-gauge and 1/4-inch diameter wire with splits.

It appears that wire with higher turns to break in continuous torsion (greater ductility) has a lower susceptibility to hydrogen embrittlement. This supports the continuous torsion requirement in AWWA C301 (1999a) and the use of the torsion test to differentiate wires with different susceptibilities to hydrogen embrittlement.

In a previous study (Hall 1998), two 6-gauge and two 8-gauge smooth wire specimens from the same source as the notched specimens at –1,000 mV in an acidified solution had not failed after 29 months of exposure even though pitting occurred during the first two weeks of corrosion and hydrogen generation occurred at the wire surface during the entire exposure. This indicates that the pitted prestressing wire specimens in an acidic environment were not extremely sensitive to hydrogen embrittlement. No failures of the pitted specimens had occurred after 29 months even though gas evolved continually from the wire surface and a slight reduction of ductility and slight increase in hydrogen content in the wire occurred.

The pH of the acidified solution initially increased to 4 surrounding the cathodically protected wire. In this case, the diffusion of hydrogen ions from the bulk solution was sufficient to prevent the pH from continuing to increase since the hydrogen ions continually diffused to the wire in this test. The wire in this project is expected to eventually fail since hydrogen is penetrating the wire. In a pipe, the total amount of hydrogen ions surrounding a corroding prestressing wire is substantially less than the amount in the bulk acid solution used in this test. The pH will increase substantially during cathodic protection as the hydrogen ions are consumed in accordance with reaction (3) followed by reaction (2). The hydrogen ions cannot be replaced

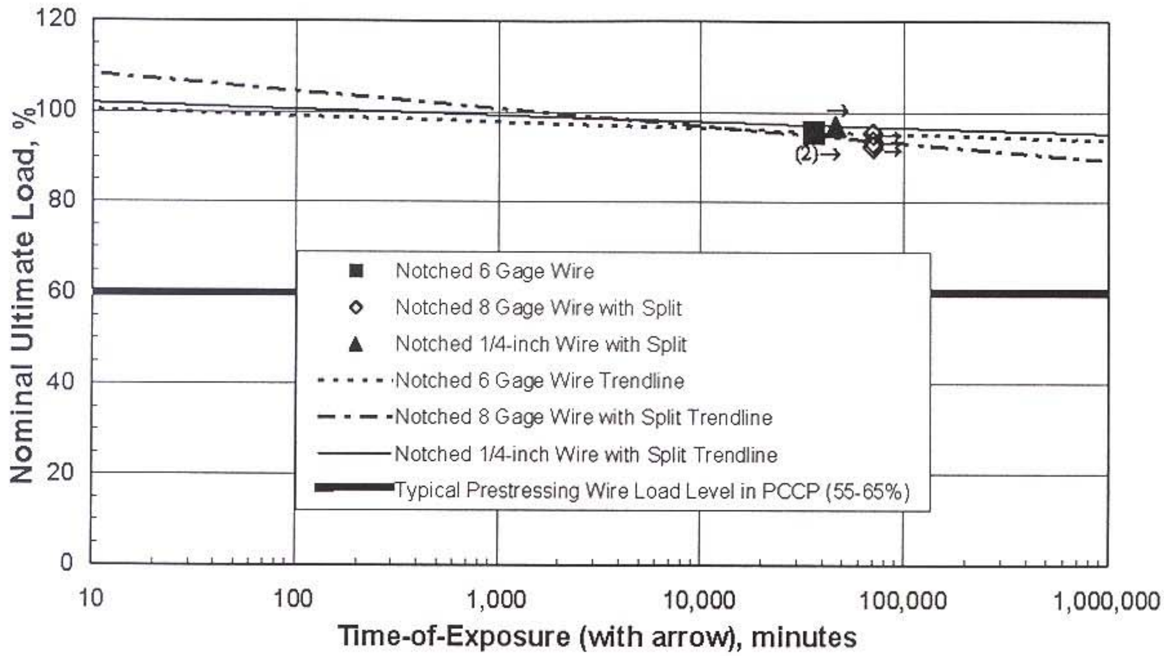


Figure B-1.4 Comparison of three different notched prestressing wire samples at polarization potentials of -950 mV (CSE) in a saturated calcium hydroxide solution

as in the bulk solution used in this study. Since the hydrogen ions are continually diffusing to the wire in this project, the wire is expected to fail eventually.

Comparison of Three Prestressing Wire Samples at –950 mV in Saturated Calcium Hydroxide Solution

As shown in Figure B-1.4, the three wire samples in a saturated calcium hydroxide solution at –950 mV have not failed after more than 36,000 minutes (25 days) at a load greater than 95 percent even though the yield strength of the wire is 85 percent of the tensile strength. Upon extrapolating the –950 mV trend line, it would require greater than 100,000,000 minutes (190 years) for the wire samples to fail at loads greater than 90 percent. Exposure is continuing.

DISCUSSION

When a serious corrosion problem exists, cathodic protection can be installed to mitigate any further corrosion. Typically corrosion does not affect the entire prestressing wire surface. Much of the wire is still passive and not corroding. Requiring the pipeline to be cathodically protected to -850 mV (CSE), as typically required for oil and gas pipelines, is unnecessary and uneconomical since only the corroding areas need to be protected. Even though -850 mV is typically used for buried and submerged pipelines in the oil and gas industry, NACE International RP0169 (NACE 1996) allows a 100 mV polarization or depolarization shift. This 100 mV shift is also used as a criterion in RP0290 (NACE 2000) to protect the steel in atmospherically exposed reinforced concrete structures, such as bridges and parking garages. This shift needs to occur at the corroding, anodic sites of the pipeline. In addition, polarization shifts of only 20 mV have been found to effectively protect corroding steel in mortar (Hall et al. 1994).

Cathodic protection requires that the steel elements be electrically continuous. In most cases, the pipe joints have a bell-and-spigot configuration with a rubber gasket. This configuration requires that the joints between adjacent pipe be electrically bonded for cathodic protection to be effective. Most PCCP lines installed in the Western United States in the last 20 years have been bonded. In the Eastern United States, most pipelines are not bonded.

In the tests performed in this project, hydrogen embrittlement did not occur to the nonsplit 6-gauge prestressing wire specimens at –1,000 mV or to the three wire samples at –950 mV when loaded at levels greater than 90 percent.

ADDITIONAL RESEARCH

Additional exposure at polarization potentials at and more positive than –1,000 mV (CSE) is continuing.

SUMMARY

- Prestressed concrete cylinder pipe is inherently corrosion resistant. The use of impacted mortar coatings passivates the underlying prestressing wire and reduces chloride ion penetration.
- Due to PCCP's inherent corrosion resistance, cathodic protection is rarely required. If corrosion is found, cathodic protection can be an effective means to mitigate corrosion.
- Prestressing wire is susceptible to hydrogen embrittlement at potentials negative enough to generate hydrogen. The polarization potential should be maintained more positive than -1,000 mV (CSE) to avoid hydrogen embrittlement. More negative potentials can embrittle and split prestressing wire, greatly increase the cost of cathodic protection, and do not improve corrosion protection.
- Cathodic protection increases the pH around the prestressing wire in carbonated mortar or around corroding wire to initial uncarbonated or noncorroding levels.