Cathodic Protection Requirements of Prestressed Concrete Cylinder Pipe

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Abstract

Concrete pressure pipe (CPP) is used in water and waste water systems that serve virtually every city in North America. Due to the passivating (corrosion inhibiting) properties of the highly alkaline portland cement, the cement mortar coating provides the only protection that CPP normally requires. Under certain conditions, such as high chloride environments, the steel can depassivate, leading to corrosion. Under these conditions, cathodic protection (CP) can be used to protect the encased steel elements. The purposes of this project were to determine current density requirements of CPP with and without supplemental barrier protection and to determine the effect of cathodic over-protection on the properties of the encased prestressing wire.

This project consisted of installing a CP system on a 73 m (240') long by 1.22 m (48") diameter prestressed concrete cylinder pipe (PCCP) line and measuring current, polarization, and depolarization of the pipeline during two to three months of system activation. It also consisted of subjecting prestressing wire to cathodic over-protection and determining the effect of CP on time-to-failure, hydrogen content, tensile strength, and reduction of area of the prestressing wire.

Introduction

PCCP is used in water and waste water systems that serve virtually every city in North America. It is primarily used for distribution of water for industrial, agricultural, and residential use. The pipe is typically designed and manufactured in accordance with AWWA Standards C304 and C301, respectively. It is manufactured in sizes from 410 mm (16") to 6.4 m (21') in diameter.

Approximately 29,000 km (18,000 miles) of PCCP have been installed in North America during the past 50 years (Clift 1991).

Due to the passivating (corrosion inhibiting) properties of the highly alkaline portland cement, the cement slurry and mortar coating provides the only protection that CPP normally requires. One survey showed that concrete pipe had the lowest problem occurrence rate and that the average level of satisfaction was highest for more than 185,000 km (115,000 miles) of pipe surveyed (AWWA Research Foundation). Another survey stated that the overall performance of PCCP has been excellent. Only about 1 project out of 700 (25 out of 17,400 projects) has had any type of problem with external corrosion and that, in most cases, only 1 or 2 pipe sections were affected (Clift 1991).

In unusual circumstances, such as in high chloride environments, the passivating properties of the highly alkaline cement may be compromised. In such environments, it may be necessary to provide supplemental protection for PCCP. Supplemental protection is usually in the form of barrier coatings, barrier membrane encasement, or, in rare cases, CP.

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

Since CP is rarely required, potential criterion and current density requirements for buried PCCP are generally not available. The authors have seen current density design requirements of 10.8 to 21.6 mA/m^2 (1 to 2 mA/ft^2) in project specifications for buried PCCP. This appears to be derived from the design current densities used for CP of reinforced concrete bridge components. It is expected that buried pipelines will require considerably less current density than an atmospherically-exposed bridge.

The potential criterion required to achieve protection of underground organically-coated oil and gas pipe lines has been under considerable debate for the past 10 years. The most accepted criterion of -850 mV versus a copper-copper sulfate electrode (CSE) is often used on bare or organically coated steel (RP0169 1992). A potential of -500 mV (CSE) was reported as a criterion to protect uncorroded steel in an alkaline environment in the presence of high levels of chloride ions (Hausmann 1969). A potential of -710 mV (CSE) was found to prevent further corrosion once corrosion was

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initiated (Hausmann 1969). A 100 mV polarization or depolarization shift is another criterion that is used to protect steel from corrosion of either organically coated steel or steel in concrete (Benedict 1989; RP0169 1992; RP0290 1990). Polarization shifts of only 20 mV have been found to effectively protect corroding steel in mortar (Hall et al. 1994).

One of the authors (Hall) obtained current and potential data for a 4.5 mile long, 60" and 66" coal-tar-epoxy-coated PCCP under CP from a water district. The supplemental barrier coating of coal tar epoxy and CP was specified due to the possibility that stray current from a nearby electric rail system may cause stray current interference on the pipeline. Based on 12 years of available data, current density requirements were approximately 120 $\mu A/m^2$ (11 $\mu A/ft^2$) to achieve polarization potentials ranging from -600 mV to -800 mV and approximately 43 $\mu A/m^2$ (4 $\mu A/ft^2$) to achieve polarization potentials ranging from -400 mV to -450 mV. This is at least a 100 to 150 mV shift from the baseline potential.

Due to the use of high strength prestressing wire in the pipe, the effect of high levels of CP at the potential required to cause hydrogen embrittlement must also be addressed. The most probable reaction occurring on the pipe under excessive CP 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, atomic hydrogen may penetrate the steel. This entry causes a loss of ductility, or embrittlement, of the prestressing wire.

Based on this reaction, the potential at which hydrogen evolution occurs can be calculated using the Nernst Equation (eq. 1) below:

$$E = E^o - (RT/nF)\ln([H_2O]^2/[H_2][OH^-]^2) \qquad (1)$$

where E = Hydrogen evolution potential, V
E^o = Oxidation potential = +0.828 V (SHE)
R = 8.314 J/°K·mole
T = 298.2°K
F = 96,500 coulombs/equivalent
n = 2 equivalents/mole (electrons in reaction)
$[H_2O]$ = Activity of water = 1
$[H_2]$ = Activity of hydrogen = 1 atmosphere
$[OH^-]$ = Hydroxide ion activity = antilog(pH minus 14)

Therefore, at a pH of 12.5, E = +0.739 volt (SHE) for the oxidation reaction. For the reduction reaction (hydrogen production), the sign is changed and -0.316 volt is added to convert from the standard hydrogen electrode (SHE) to the copper-copper sulfate electrode (CSE). Thus at typical pHs of portland cement mortar of 12.5 to 13.5, the hydrogen evolution potential is -1055 mV to -1114 mV (CSE), respectively. The calculated potential for hydrogen evolution is more positive by approximately 59.2 mV for each decrease in one pH unit. In carbonated concrete, under CP, the pH at the wire surface will increase rapidly 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:

$2H_2O + 2e- \rightarrow H_2 + 2OH^-$ at $E < -0.0592pH-0.316$ and $pH>7$
$O_2 + 2H_2O + 4e- \rightarrow 4OH^-$ at $E > -0.0592pH-0.315$ and $pH>7$
$2H^+ + 2e- \rightarrow H_2$ at $pH < 7$

Since hydroxide ions, but no hydrogen, are produced in the second reaction, low levels of current at the indicated potential can be used to increase the pH without producing hydrogen.

The purpose of this project was to determine the current density requirements of PCCP with and without supplemental barrier protection, such as coal tar epoxy coatings and polyethylene encasement, at polarization and depolarization shifts of 100 mV. The project also consisted of determining the effect of CP on time-to-failure, hydrogen content, tensile strength, and reduction of area of prestressing wire.

Test Setup

Cathodic Protection of PCCP Line

The project consisted of installing an impressed current CP system and applying current to attain a 100 mV shift to a 73 m (240') long by 1.22 m (48") diameter embedded cylinder PCCP line. Ten 7.3 m (24') long PCCP sections were manufactured and installed. The pipe was manufactured with two 2.54 cm (1") wide shorting straps, 180° apart to reduce the electrical attenuation along the prestressing wire in each pipe section. CP requires that all steel elements within the pipe and between each pipe section be electrically continuous (or bonded). In most cases, the pipe joints have a bell and spigot configuration with a rubber gasket. This configuration requires that the joints be bonded for CP to be effective. Most PCCP lines installed in the Western United States in the last 15 years have been bonded. In the Eastern United States, most pipelines are not bonded. The prestressing wire was made electrically continuous to the steel cylinder at each end of each pipe. The steel joints were specially manufactured with oversized bells, epoxy coated, and installed with oversized gaskets to ensure electrical discontinuity between adjacent pipe sections so that only the joint bonds provided electrical continuity between joints. Additional details of the pipeline are reported elsewhere (Hall 1994).

Two of the pipe sections were coated with a 660-micron (0.026") thick supplemental coal tar epoxy (CTE) coating and two of the sections were encapsulated in a 200-micron (0.008") thick polyethylene (PE) encasement. Pinholes and holidays were present in both coating systems. Six sections had no additional supplemental protection beyond the highly alkaline cement slurry and mortar coating.

The pipe sections were installed with 1.8 m (6') of cover in an arid environment in Palmdale, California. Mortared night caps were provided at each end with two access manholes. The site was selected to be representative of arid environments.

The native soil at the site is a sandy gravel. Soil-box resistivity ranged from 100,000 to 200,000 ohm·cm dry and 16,000 to 30,500 ohm·cm saturated. The pH of the soil samples ranged from 7.8 to 8.2. Water-soluble chloride and sulfate contents were less than 10 mg/kg which indicates that the soil is non-corrosive. The pipeline was backfilled with sand from an adjacent aggregate pit which had similar chemical properties. The Wenner four-pin soil resistivity values of the backfilled area at 1, 1.5, and 3.0 m (3', 5', and 10') spacings ranged from 13,400 to 63,200 ohm·cm when wet or dry.

Provisions were made to allow electrical connection or disconnection between adjacent pipe sections to simulate bonded and unbonded pipelines. This was done by connecting insulated 4/0 copper cables to the joints and bringing them to a test station at the surface above each joint.

Permanent copper-copper sulfate reference electrodes (CSE) and soil moisture cells were installed. The reference cells were buried 0.6 m (2') from the pipe at the pipe top, both springlines, and bottom, and 1.2 m (4') above the pipe top. They were placed at and midway between each joint. The lead wires were brought to a common junction box.

A 10 cm (4") diameter by 114 cm (45") long steel pipe buried 6.1 m (20') perpendicular to the last pipe was used as the anode. This is expected to simulate CP systems where anodes are installed close to the pipeline because of space limitations. Gypsum was placed around the anode as backfill. A variable power supply was used to supply the current.

A baseline potential survey was taken prior to activating the CP system. Potentials were measured approximately every 1.5 m (5 feet) along the centerline of the pipeline. Upon activation, an over-the-line potential survey was taken at intervals from 90 minutes to up to 3 months of CP. Current-on and polarization (current-interrupted) potentials and current were recorded. The polarization potentials were measured manually approximately 1 second after current interruption in the first series of surveys with the line at 4640 to 5180 $\mu A/m^2$ (430 to 480 $\mu A/ft^2$) and in the second series at 540 $\mu A/m^2$ (50 $\mu A/ft^2$). The polarization potentials were measured using a datalogger 300 ms after the current was interrupted in the remaining surveys. At selected intervals, the CP system was deactivated and an over-the-line survey was performed at intervals from 4 hours to 1 month during pipeline depolarization. The current density was calculated based on the mortar coating surface area. The actual surface area of the prestressing wire and steel cylinder is 57% and 88%, respectively, of the mortar coating surface area.

Cathodic Over-protection of Prestressing Wire

Prestressing wire was subjected to no CP and to CP polarization potentials of -850 mV and -1000 mV as well as cathodic over-protection values of -1200 mV to determine the effect of cathodic protection on the performance of prestressing wire. The wire was stressed to 60% of its specified minimum tensile strength in a saturated calcium hydroxide solution. This is the approximate stressed value of the wire on PCCP.

Cantilever-type wire tensioning apparatus with plastic enclosures for immersing approximately 32" of 60" long wire specimens were used. Potentiostats were used to control the potential. Twenty-four specimens were exposed at any one time. Six and eight gage, ASTM A648, class III prestressing wire specimens were used during the investigation.

The specimens were immersed in a saturated calcium hydroxide solution. Calcium hydroxide is the principle soluble compound of portland cement which provides for the high alkaline, corrosion inhibiting environment. The solution was prepared using reagent grade calcium hydroxide and ASTM D1193-77 type IV reagent water. Calcium hydroxide was periodically added to ensure that a pH of 12.45 was maintained. The pH was determined periodically.

At 6 and 12 months, two wire specimens from manufacturer "A" at each CP level were removed from test. At 3 months, two wire specimens from manufacturer "B" at each CP level were removed from test. Reduction of area, normal-load-rate tensile strength, and presence of longitudinal splits of the immersed, air-exposed, and control specimens were determined in accordance with ASTM A648-90a.

A 2" long piece from each removed specimen and a control, non-exposed specimen were immediately cleaned, immersed in liquid nitrogen to prevent hydrogen diffusion, placed in a plastic bag in an ice chest containing dry ice, delivered by overnight delivery to a laboratory, and analyzed for hydrogen content using a LECO DH103 Total Hydrogen Determinator.

Two specimens each from coils with different performance properties in continuous torsion remained under exposure at no CP, -850 mV, -1000 mV, and -1200 mV and the time-to-failures of the specimens were recorded. Continuous torsion of the wire specimens prior to exposure was determined in accordance with ASTM A648-90a.

Test Results and Discussion

Cathodic Protection of Uncoated PCCP

The current-on and polarization (current-interrupted) potentials of the entire pipeline at 4 hours and 5 days at 1.74 A (5180 $\mu A/m^2$; 480 $\mu A/ft^2$) and 1.56 A (4640 $\mu A/m^2$; 430 $\mu A/ft^2$), respectively, are shown in Figure 1. The baseline potentials prior to CP are also shown and indicate that the pipeline was passive prior to CP activation. The actual current flowing to each type of pipe was measured and the average current density based on the mortar coating surface area is shown. This current density is excessive since the pipe polarized 400 mV on the uncoated pipe sections, more than 600 mV on the CTE-coated sections, and exceeded even the commonly-used -850 mV criterion on the PE-encased sections during the initial 4 hours of CP. The potential of the end PE-encased section exceeded -1000 mV. This indicates possible hydrogen embrittlement of the prestressing wire on this section. Potentials taken at 5 days indicate that the pipeline was continuing to polarize. The potentials of the CTE-coated sections exceeded -850 mV at 5 days of CP. In addition, the difference in potential between the current-on and polarization (I-interrupted) potentials indicate that the IR drop in the CTE-coated and PE-encased sections is excessive at high current density.

The current was then reduced by approximately a factor of 8 to 200 mA (540 $\mu A/m^2$; 50 $\mu A/ft^2$). The current-on and polarization potentials and the resulting average current density on each coating type five weeks after reducing the current are shown in Figure 2. The polarization (I-interrupted) potentials were greatly reduced but still exceeded the 100 mV polarization shift criterion. The IR drop on the CTE-coated and PE-encased system was still excessive. At 5 weeks of CP, the system was deactivated. The 4-hr and 1-week depolarization potentials of the pipeline are shown in Figure 2. The average depolarization shifts at 4 hours were 220 mV on the PE-encased sections, 180 mV on the CTE-coated sections, and 120 mV on the uncoated sections which is greater than the 100 mV depolarization required. At 1 week, the potential had depolarized to approximately the baseline potential. The average depolarization shifts at 1 week were 420 mV on the PE-encased sections, 400 mV on the CTE-coated sections, and 280 mV on the uncoated sections.

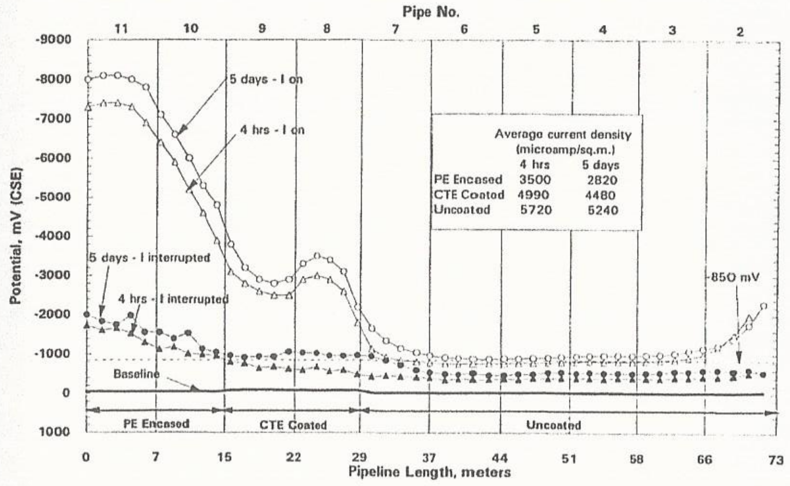

Figure 1. Current-on and Polarization Potentials of Entire PCCP Line At Approximately 4640 to 5180 $\mu A/m^2$ (430 to 480 $\mu A/ft^2$)

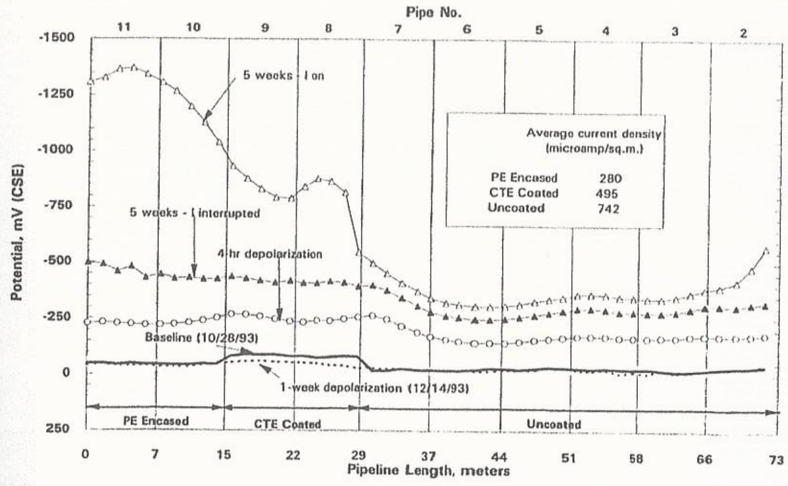

Figure 2. Current-on, Polarization, and Depolarization Potentials of Entire PCCP Line at 540 $\mu A/m^2$ (50 $\mu A/ft^2$)

Since the various coating systems polarized to varying levels, it was decided to protect each type of coating system separately. The CTE-coated and PE-encased pipe sections were electrically disconnected from the uncoated pipe sections. Since the uncoated sections had polarized 280 mV at 540 $\mu A/m^2$ (50 $\mu A/ft^2$), the current to the uncoated sections was reduced by a factor of two to 270 $\mu A/m^2$ (25 $\mu A/ft^2$). Polarization potentials at 9 and 13 weeks of CP are shown in Figure 3 and are approximately the same. This indicates that the pipeline was not continuing to polarize during the 13 weeks of CP. At 13 weeks, the CP system was deactivated. The depolarization at 4 hours and 1 week are also shown in Figure 3. The depolarization shift at 4 hours was approximately 100 mV indicating that the 100 mV depolarization shift criterion was met. The pipeline continued to depolarize during the week until it depolarized another 100 mV and returned to a slightly more passive potential than its baseline potential. Since 540 $\mu A/m^2$ produced a depolarization shift of 280 mV and 270 $\mu A/m^2$ produced a shift of 200 mV, a lower current density is expected to produce a 100 mV shift.

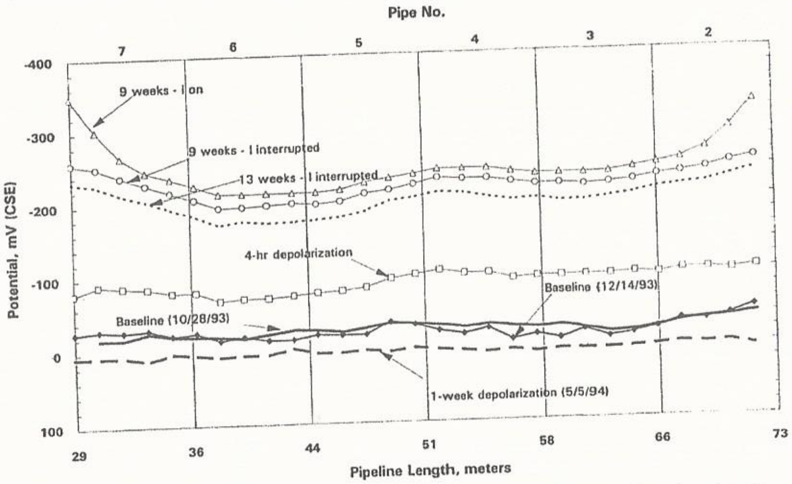

Figure 3. Current-on, Polarization, and Depolarization Potentials of Uncoated PCCP Line at 270$\mu A/m^2$ (25 $\mu A/ft^2$)

The CTE-coated sections were cathodically protected at 108 $\mu A/m^2$ (10 $\mu A/ft^2$). The polarized potentials 90 minutes after CP activation are shown in Figure 4. The polarization shift at 90 minutes was greater than 100 mV so the current density was reduced to 54 $\mu A/m^2$ (5 $\mu A/ft^2$). The polarized potentials 2 months at 54 $\mu A/m^2$ are given in Figure 4. The polarization shift is still greater than 100 mV so the current density was further reduced to 32 $\mu A/m^2$ (3 $\mu A/ft^2$).

The polarized potential at 2 months is shown in Figure 4. The polarization shift from the baseline potential was approximately 150 mV at 32 $\mu A/m^2$ at 2 months of CP.

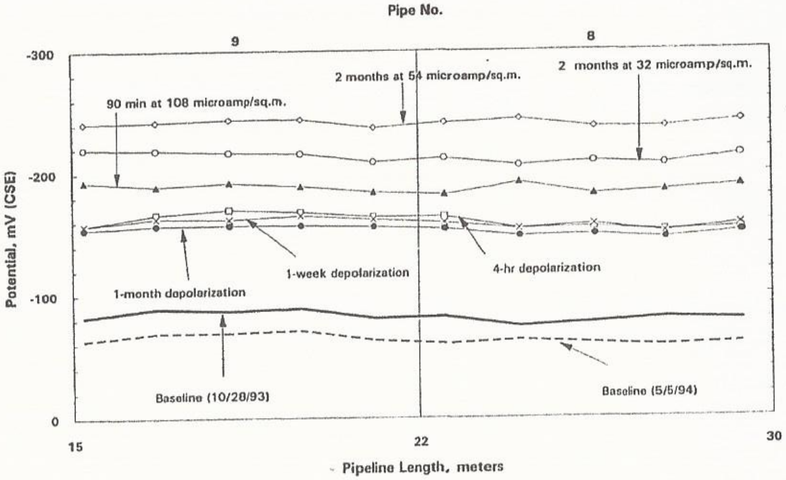

Figure 4. Polarization and Depolarization of CTE-Coated PCCP Line

Depolarization of the CTE-coated sections after 2 months at 32 $\mu A/m^2$ is shown in Figure 4. The pipeline depolarized 65 mV during the first 4 hours with less than 15 mV occurring during the following month. Although depolarization to the baseline potential did not occur, it is believed that complete depolarization of the CTE-coated sections would eventually occur.

The PE-encased sections were cathodically protected at 32 $\mu A/m^2$ (3 $\mu A/ft^2$). Polarization at 3 hours, 1 week, 5 weeks, and 3 months of CP are shown in Figure 5. Polarization of approximately 100 mV was achieved at 3 hours and remained essentially unchanged for the following 3 months.

Depolarization of the PE-coated sections after 3 months at 32 $\mu A/m^2$ (3 $\mu A/ft^2$) is shown in Figure 5. The pipeline depolarized 140 mV during the first 4 hours and 200 mV at 1 week. It depolarized to levels more positive than the initial baseline.

Polarized potentials of the uncoated section using the permanent reference cells buried around the pipe every 3.5 m (12') are shown in Figure 6. The potentials were within 25 mV of the over-the-line potentials. Differences in potential around the pipeline or at different depths are not apparent, indicating uniform distribution of current around the pipe circumference.

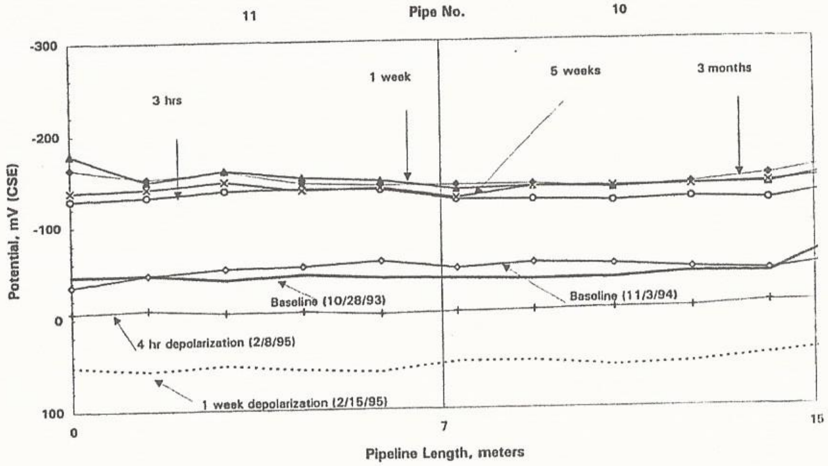

Figure 5. Polarization Potential of PE-Encased PCCP Line at 32 $\mu A/m^2$ (3 $\mu A/ft^2$)

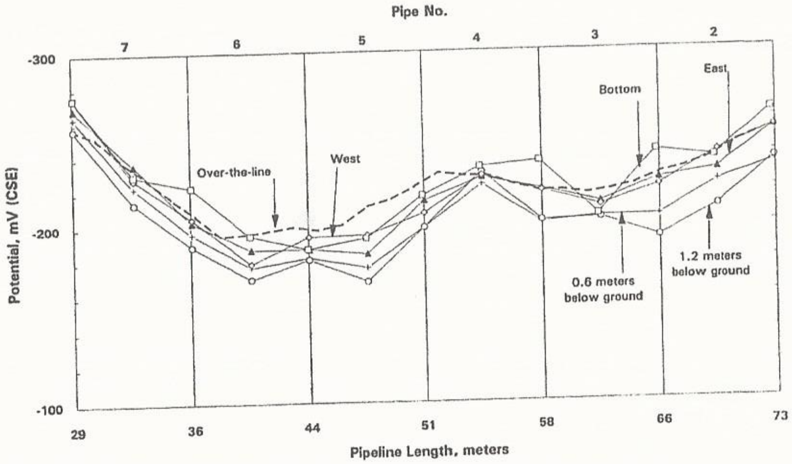

Figure 6. Effect of Reference Electrode Position on Polarization Potential of Uncoated PCCP Line at 270 $\mu A/m^2$ (25 $\mu A/ft^2$)

Current density requirements of uncoated, CTE-coated, and PE-encased PCCP to achieve or exceed a polarization or depolarization shift of 100 mV were determined to be 270, 32, and 32 $\mu A/m^2$ (25, 3, and 3 $\mu A/ft^2$), respectively.

Cathodic Over-protection of Prestressing Wire

The effect of CP on the tensile strength and reduction of area of 6 gage prestressing wire from manufacturers "A" and "B" maintained at 60% of its specified minimum tensile strength in a saturated calcium hydroxide solution for 3, 6, and 12 months is shown in Figure 7. For plotting purposes, the potentials of the non-cathodically protected specimens were arbitrarily selected to be -200 mV which is within the passive range of 0 to -300 mV (CSE) measured during the exposure.

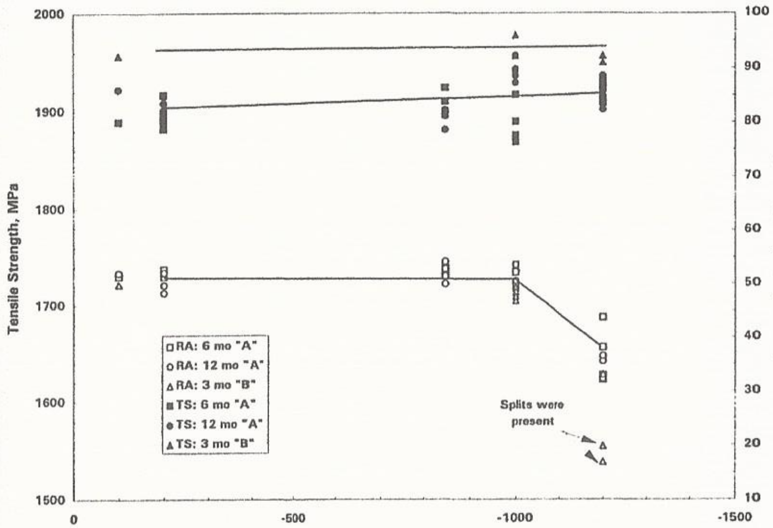

Figure 7. Reduction of Area and Tensile Strength of Prestressing Wire Loaded at 60% of Its Tensile Strength & Subjected to CP in a Saturated Calcium Hydroxide Solution

For comparison purposes, the reduction of area of the control specimens are plotted at -100 mV even though they were never loaded, immersed, or subjected to CP. Reduction of area of 16% and 19% of wire "B" at -1200 mV was due to splits found in the wire. The splits opened up at the ends resulting in a lower but erroneous reduction of area value. A significant decrease in reduction of area is evident at polarization potentials of -1200 mV with no significant decrease at -1000 mV. These results were consistent with the authors' unpublished results using unloaded prestressing wire which showed that excessive CP at -1100 mV (CSE) or more negative values decreases the ductility of prestressing wire. Normal-load-rate tensile strength did not change at any level of CP.

The effect of CP on the hydrogen content of the immersed specimens is plotted in Figure 8. For comparison purposes, the hydrogen contents of the control specimens are plotted at -100 mV even though they were never loaded, immersed, or subjected to CP. A significant increase in hydrogen content is evident at polarization potentials of -1200 mV. This is consistent with the observation that copious amounts of fine bubbles were produced on the specimens at -1200 mV. No bubbles were seen at -1000 mV. This is consistent with the calculated hydrogen evolution potential of -1055 mV (CSE) at a pH of 12.45. The increase in hydrogen content is consistent with the decrease in reduction of area shown in Figure 7.

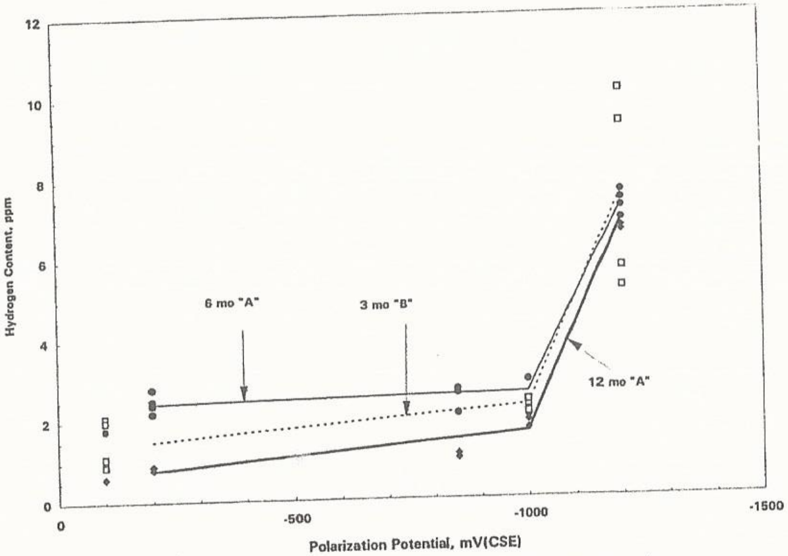

Figure 8. Hydrogen Content of Prestressing Wire Subjected to CP

Time-to-failure of prestressing wire specimens held at -1200 mV at 60% of its specified minimum tensile strength is shown in Figure 9. It is plotted as a function of its initial ductility, as expressed by turns to break in continuous torsion. The time-to-failure varied from 9 to 41 months and is dependent on the number of turns to break in continuous torsion determined on non-exposed (control) specimens. The fractures were all brittle in nature and the reduction of area at the failure point was less than 2%. This indicated that embrittlement of the wire occurred. Longitudinal splits terminating near the center of the wire were found on some of the specimens held at -1200 mV. Hydrogen contents of the fractured end were similar to those shown in Figure 8. It appears that wire with lower turns to break in continuous torsion has a greater susceptibility to hydrogen embrittlement. This supports the continuous torsion requirement in AWWA C301.

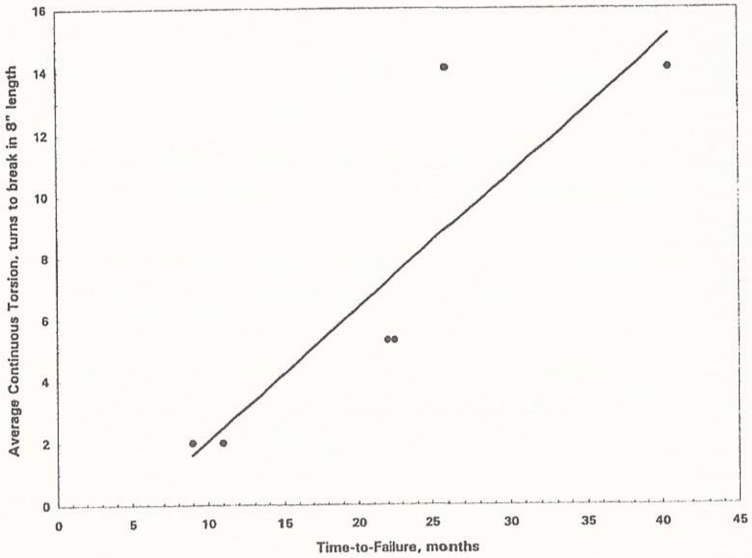

Figure 9. Time-to-Failure of Prestressing Wire Held at -1200 mV as a Function of Continuous Torsion

Prestressing wire held at -1000 mV or more positive potentials, where hydrogen is not produced, have not failed after up to 53 months of exposure. Exposure of the specimens at these more positive potentials is continuing.

It is evident that prestressing wire is susceptible to hydrogen embrittlement at potentials negative enough to generate hydrogen. Polarization potential should be maintained at potentials less negative than -1000 mV to avoid hydrogen embrittlement.

Conclusions

- Current density required to achieve or exceed a 100 mV polarization or depolarization shift of uncoated, CTE-coated, and PE-encased PCCP in a non-corrosive environment was approximately 270, 32, and 32 $\mu A/m^2$ (25, 3, and 3 $\mu A/ft^2$), respectively.

- If CP of PCCP is necessary, the polarization potential should be maintained at potentials less negative than -1000 mV to avoid subjecting PCCP to hydrogen embrittlement which could lead to failure of the pipe.

Acknowledgment

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Appendix I. References

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