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CORROSION 98

CATHODIC PROTECTION CRITERIA FOR PRESTRESSED CONCRETE PIPE

AN UPDATE

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ABSTRACT

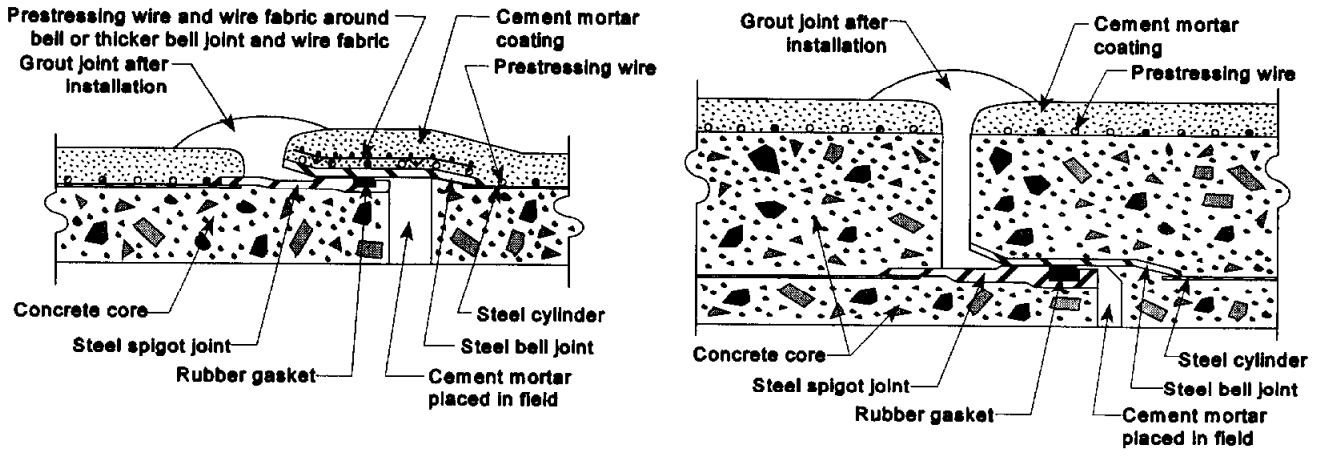
Prestressed concrete cylinder pipe (PCCP) is used in water and waste water systems that serve virtually every major city in North America. Under certain conditions, such as high chloride environments, the steel can depassivate, leading to corrosion. Under these conditions, cathodic protection (CP) can be used to protect the encased steel elements.

This paper provides the theoretical consideration and the results of laboratory and field investigations performed during the past decade to determine the effects of CP on the performance of passivated, corroded, and split prestressing wire immersed in an environment to simulate sound mortar and mortar surrounding severely corroded wire. The current densities required to achieve a 100 mV polarization or depolarization shift and the maximum potential criterion to prevent hydrogen embrittlement were determined. The effect of low pH due to corroding wire, the susceptibility of prestressing wire to hydrogen embrittlement, and the approximate length of time and potentials to produce hydrogen embrittlement and eventual wire failure were determined. The effect of discontinuing high levels of CP on the diffusion of hydrogen from wire and the recovery of ductility was evaluated. The amount of current flowing to the prestressing wire and steel cylinder at various current densities were also determined. Case histories of five cathodically protected pipelines are given. The data and results are presented and the minimum and maximum potential levels are recommended. The use of potential monitoring of PCCP to locate corrosion and possible causes of corrosion requiring CP is also presented.

Keywords: Cathodic protection criteria, concrete pressure pipe, hydrogen embrittlement, monitoring, PCCP, prestressing wire.

INTRODUCTION

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 1.



A. Lined Cylinder Pipe

B. Embedded Cylinder Pipe

FIGURE 1 - Components of installed PCCP

PCCP is used in water and waste water 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" (410 mm) to 21' (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[1] and C304.[2] Approximately 19,100 miles (30,700 km) of PCCP have been installed in North America from 1945 to 1995.[3,4]

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.[5] 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.[4] Chloride-induced corrosion was the most common form of external corrosion found in the 30 projects[4] and could have been prevented by the use of supplemental coatings or cathodic protection.

The prestressing wire, which conforms to ASTM A648, is helically wrapped around the concrete core or steel cylinder at 75% of its minimum nominal tensile strength. The stress decreases to a range of 55 to 65% due to initial creep and shrinkage of the concrete core and relaxation of the wire and 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.

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 (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 Unites States is under CP.[6] Another report indicated that only about 20 projects of a total of 28,900 PCCP projects (less than 0.1%) are under CP.[3]

Since CP is rarely required, potential criteria and current density requirements for buried PCCP are generally not available. The author has seen current density design requirements of 1 to 2 mA/ft^2 (10.8 to 21.6 mA/m^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 require considerably less current density than an atmospherically-exposed structure.

The potential criteria required to achieve protection of underground organically-coated oil and gas pipelines have been under considerable debate for the past 10 years. The most accepted criterion of -850 mV (CSE) is often used on bare or

organically coated steel.[7] 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.[8] A potential of -710 mV (CSE) was found to prevent further corrosion once corrosion was initiated.[8] A 100 mV depolarization shift is another criterion that is used to protect steel from corrosion of either organically coated steel or steel encased in concrete.[6,7,9] Polarization shifts of only 20 mV have been found to effectively protect corroding steel in mortar.[10] Recommendations for CP are provided by several associations, manufacturers, and corrosion engineering firms.[11,12]

This paper provides the theoretical consideration and the results of laboratory and field investigations performed during the past decade to determine the effects of CP on the performance of passivated, corroded, and split prestressing wire immersed in an environment to simulate sound mortar and mortar surrounding severely corroded wire. The current densities required to achieve a 100 mV polarization or depolarization shift and the maximum potential criterion to prevent hydrogen embrittlement were determined. The effect of low pH due to corroding wire, the susceptibility of prestressing wire to hydrogen embrittlement, and the approximate length of time and potentials to produce hydrogen embrittlement and eventual wire failure were determined. The effect of discontinuing high levels of CP on the diffusion of hydrogen from wire and the recovery of ductility was evaluated. The amount of current flowing to the prestressing wire and steel cylinder at various current densities was also determined. Case histories of five cathodically protected pipelines are presented. The data and results are presented and the minimum and maximum potential levels are recommended. The use of potential monitoring of PCCP to locate corrosion and possible causes of corrosion requiring CP is also presented.

THEORETICAL CONSIDERATIONS

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 CP appeared to have occurred to three pipelines which resulted in rupture of one or two pipe sections in each pipeline.[4] The most negative polarization (instant current off) potential on one line was -1265 mV versus a copper-copper sulfate reference electrode (CSE) with rupture adjacent to an anode bed occurring 12 months after activation of the CP system. On a second pipeline, it was -1250 mV with rupture occurring 16 months after CP activation. On a third, it was -1330 mV with rupture occurring 18 years after activation. The third pipeline was in an area of frequent lightning storms which may have disrupted the power supplies often enough to allow the hydrogen to diffuse from the wire and return the ductility of the wire to normal[13] so that sufficient hydrogen could not build up in the wire until circumstances were present to allow power to be uninterrupted for enough time to cause the rupture. Additional information on the pipelines and the CP system is given in a later section entitled Case Histories.

Due to the use of high strength prestressing wire in PCCP, the effect of high levels of CP at the potential required to cause hydrogen embrittlement must 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 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 following Nernst Equation:

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

where E = Hydrogen evolution potential, V
E^o = Oxidation potential = +0.828 V (Standard hydrogen electrode, SHE)
R = 8.314 J/°K·mole
T = 298.2°K (25°C)
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, indicating that hydrogen is produced at potentials more negative than this.

Effect of pH on the 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 above 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 CP, 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:

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

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad \text{at } E > -0.0592pH-0.316 \text{ and } pH>7 \quad (3)$$

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{at } pH < 7 \quad (4)$$

Since hydroxide ions but no hydrogen are produced in reaction (3), 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 $\mu A/ft^2$ (11 $\mu A/m^2$), 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 $\mu A/ft^2$ 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 -1055 mV as the pH increases to 12.45.

Under much higher current densities and at pHs greater than 7, the predominant reaction is reaction (2). Hydrogen is produced but the pH also increases. Based on a higher current density of 100 $\mu A/ft^2$ (1080 $\mu A/m^2$), 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 CP or corrosion as given in reaction (4) but the pH also increases since hydrogen ions are being consumed in the reaction. Reaction (4) will convert to predominantly reactions (2) or (3) once the pH becomes greater than approximately 7.

Effects of Temperature on Hydrogen Production Potential. Using Equation (1), the hydrogen production potentials at various temperatures typical for buried pipe were calculated and are shown in Table 1. As the temperature decreased from 25 to 5°C, the potential became more positive by 40 mV at pH 12.45, by 28 mV at pH 7, and by 8 mV at pH 2. At the higher pHs, the hydrogen production potential increased the most as temperature decreased. However, calcium hydroxide, present in portland cement, is one of only a few compounds which is more soluble as temperature decreases. As the temperature decreases from 25 to 5°C, the solubility of calcium hydroxide increases the pH from 12.45 to 13.21, respectively. Hence, the hydrogen production potential increased only 8 mV in a temperature range typical for buried water pipelines.

TABLE 1
EFFECT OF TEMPERATURE ON HYDROGEN PRODUCTION POTENTIAL

Temperature, °C (°F)	Factor (2.303RT/F)	Hydrogen ProductionPotential, mV (CSE)			
		pH 12.45	$Ca(OH)_2$	pH 7	pH 2
25 (77)	0.0592	-1053	-1053 (pH 12.45)	-730	-434
15 (59)	0.0572	-1028	-1048 (pH 12.81)	-716	-430
5 (41)	0.0552	-1003	-1045 (pH 13.21)	-702	-426

MONITORING OF PCCP FOR CORROSION

Due to the passivating properties of portland cement, corrosion of the encased steel elements seldom occurs. As such, CP should not be indiscriminately used on PCCP unless corrosion is found or environmental conditions, such as high chloride soils or groundwaters, indicate that serious corrosion of the prestressing wire could or is occurring.

Potential monitoring techniques are often used to determine whether the encased steel in PCCP is corroding. The techniques are identical to that used for cathodically protected gas and oil pipelines. However, for PCCP lines, the occurrence of corrosion or passivation of the steel is determined rather than protection. Potentials more positive than -300 mV (CSE) typically indicate that the steel is passive (non-corroding). Potentials more negative than -300 mV can indicate corrosion, current pickup, or that the line is being cathodically protected. Changes in potential greater then 20 mV at discrete locations on the pipeline, even though more positive than -300 mV, can also indicate corrosion.[14] These changes produce a jagged appearance in a pipe potential profile. When corrosion occurs, the seriousness of it should be determined prior to applying CP. It can be due to high levels of chloride ions at the wire surface; missing mortar coating caused by improper handling during transportation, installation, and backfilling; by excessive pressure surges during operation or over-loading due to higher soil cover than designed or by heavy equipment; or to missing grout at the joint due to improper grouting during installation. If corrosion is found only within a pipe section, excavation and repair of the pipe may prevent the use of CP. If corrosion is confined to the steel joint with adequate remaining steel thickness, then the grout surrounding the joint can be removed and replaced. When repairing or replacing the affected pipe sections is not practical or economically feasible, CP can be used to protect PCCP.

LABORATORY PHASE

The objective of the laboratory phase of the project was to determine the effect of CP on the performance of passivated, corroded, and split prestressing wire immersed in an environment to simulate sound mortar and mortar surrounding severely corroded wire. The effect of low pH due to corroding wire, the susceptibility of prestressing wire to hydrogen embrittlement, and the approximate length of time and potentials to produce hydrogen embrittlement and eventual wire failure were determined. The effect of discontinuing high levels of CP on the diffusion of hydrogen from wire and the recovery of ductility was evaluated. In addition, the maximum CP potential that high strength prestressing wire can be subjected to without causing failure in those environments was determined.[15]

Test Procedure

ASTM A648, Class III prestressing wire specimens from three wire manufacturers were subjected to no CP and to CP polarization potentials of -850 mV and -1000 mV (CSE) as well as cathodic over-protection values of -1200 mV in a saturated calcium hydroxide solution for up to 86 months. Prestressing wire specimens from one of the three manufacturers were also immersed in a 0.01 M hydrochloric acid solution (pH 2), allowed to corrode for 2 weeks, and subjected to CP at -1000 mV for more than 18 months. Prestressing wire specimens from a fourth manufacturer, which contained longitudinal splits and which were removed from a pipeline cathodically protected at polarization (interrupted or current-off) potentials as negative as -1250 mV (CSE), were also immersed in a 0.01 M hydrochloric acid solution (pH 2) and subjected to CP at -1000 mV for more than 7 months.

Prior to exposure, most of the wire specimens were stressed and maintained at 60% of its specified minimum tensile strength, which is the approximate stressed value of the wire on PCCP. Cantilever-type wire tensioning apparatus with plastic enclosures for immersing approximately 32" of the 60" (81 cm of the 152 cm) long wire specimens were used. Potentiostats were used to control the potential. Twenty-four specimens were exposed at any one time. Six (0.192", 0.488 cm diameter) and eight (0.162", 0.411 cm diameter) gage, ASTM A648, class III prestressing wire specimens were used during the investigation. A coal tar epoxy coating was applied to the wire specimen surface 1" (2.5 cm) above and below the solution level to prevent failure at the air/solution interface.

The specimens were immersed in either a saturated calcium hydroxide solution to simulate the high alkaline, corrosion inhibiting environment provided by portland cement or in a 0.01 M hydrochloric acid solution (pH 2) to simulate the condition around a severely corroded wire in mortar. The solutions were prepared with either reagent grade calcium hydroxide or concentrated hydrochloric acid and with ASTM D1193-91 type IV reagent distilled water. Calcium hydroxide and distilled water were added weekly to the calcium hydroxide solution to ensure that a bulk pH of 12.45 was maintained and to adjust for evaporation. Distilled water was added weekly to the hydrochloric acid solution to adjust for evaporation. The pH of each solution was determined periodically. No attempt was made to maintain the pH of the hydrochloric acid solution.

CP of Passive Wire in Simulated Mortar at pH 12.45. At 6 and 12 months, two 6 gage stressed wire specimens from manufacturer "A" at no CP, and at -850 mV, -1000 mV, and -1200 mV (CSE) were removed from exposure. At 3 months, two stressed wire specimens from Manufacturer "B" at each CP level were removed. At 80 months of exposure, the two remaining stressed wire specimens from manufacturer "A" at no CP and -850 mV were removed. At 68 and 74 months of exposure, the four remaining stressed wire specimens from manufacturer "B" at no CP and -850 mV were removed. The normal-load-rate tensile strength, reduction of area, and occurrence of longitudinal splits of the immersed, air-exposed, and control specimens were immediately determined in accordance with ASTM A648-90a. A 2" (5 cm) long piece from each removed specimen and from a control, non-exposed specimen were immediately and carefully cleaned to remove any foreign material on the wire, immersed in liquid nitrogen to prevent hydrogen diffusion, placed in a plastic bag in an ice chest containing dry ice, and delivered by overnight mail or the same day by hand to a laboratory. At the lab, they were kept in a freezer prior to analysis and analyzed for hydrogen content using a LECO DH 103 Total Hydrogen Determinator within two days of receiving the wire.

Time-to-failure of the wire specimens exposed at polarization potentials of -1200 mV (CSE) was determined. Time-to-failure was related to the number of turns to break in continuous torsion of the non-exposed wire. Continuous torsion of the wire before exposure was determined in accordance with ASTM A648-90a. Two wire specimens from manufacturers "A", "B", and "C" continue to be exposed in the calcium hydroxide solution at -1000 mV (CSE) to determine time-to-failure.

Susceptibility of Prestressing Wire to Hydrogen Embrittlement. The ductility of prestressing wire after high levels of CP were determined using reduction of area, determined in all of the above tests, and continuous torsion. Reduction of area is a well known measure of ductility, or embrittlement, of a metal. Continuous torsion is not as well known or used. The ductility of the wire as expressed by turns to break in continuous torsion before CP was related to the time-to-failure of the wire under CP.

The ductility of prestressing wire, after heating the wire to simulate possible wire temperatures during the drawing process, were determined using continuous torsion. Prestressing wire specimens conforming to ASTM A648, class III with a diameter of 1/4" (0.635 cm) were placed in an oven at 300°F, 325°F, 350°F, and 375°F (149,163,177, and 190°C) for 15 minutes, removed, and allowed to cool. The number of turns to break in continuous torsion was determined in accordance with the test method given in ASTM A648. The specimen length between the grips was 50 times the wire diameter or 12.5" (31.7 cm).

Six gage prestressing wire specimens from manufacturer "A" were immersed in a calcium hydroxide solution and subjected to CP at a current density of 3.00 amps/ft^2 (32.4 amps/m^2). The pH and level of the solution was maintained at 12.45 by weekly additions of a saturated calcium hydroxide solution with excess calcium hydroxide. At 6 months of exposure, continuous torsion, tensile strength, and reduction of area of the wire were determined within 10 minutes after removing the specimens from exposure.

CP of Severely Corroded Wire at pH 2. After 2 weeks of immersion in the hydrochloric acid solution (pH 2) followed by 2 months at -1000 mV, two 6 gage stressed wire specimens from manufacturer "A" were removed. The normal-load-rate tensile strength, reduction of area, and presence of longitudinal splits of the immersed, air-exposed, and control specimens were immediately determined in accordance with ASTM A648-90a. A 2" (5 cm) long piece from each removed specimen and a control, non-exposed specimen were immediately and carefully cleaned to remove any foreign material on the wire. They were then immediately placed in a plastic bag in an ice chest containing dry ice to prevent hydrogen diffusion, delivered by hand the day they were removed to a laboratory, and analyzed for hydrogen content using a LECO DH 103 Total Hydrogen Determinator. Four additional stressed specimens continue to be exposed in the hydrochloric acid solution at -1000 mV (CSE) to determine time-to-failure.

CP of Longitudinally Split Wire at pH 2. Two 8 gage stressed wire specimens from manufacturer "D" were immersed in the hydrochloric acid solution (pH 2) and CP immediately applied at -1000 mV (CSE). They were previously removed from a PCCP which ruptured 16 months after applying CP at polarization potentials as negative as -1250 mV (CSE). They contained a longitudinal split along the full length of the wire which extended almost to its center. The split was produced either during the wire manufacturing process or due to the excessive level of CP while buried. Time-to-failure is being determined.

Recovery of Ductility. The effect of discontinuing high levels of CP on the diffusion of hydrogen from the wire and recovery of ductility as expressed by reduction of area was determined. Unstressed prestressing wire specimens which were not cathodically protected and cathodically protected at -800 mV, -1000 mV, -1100 mV, -1180 mV, and -1260 mV (CSE) for 26 weeks to 3 years were removed from CP and reduction of area of the specimens was determined 4 and 8 weeks later.

The hydrogen content of the immersed section of two stressed specimens held at -1200 mV for 6 months were also determined immediately after removing them from exposure and 7 weeks later. A 2" (5 cm) long piece from each removed specimen and a control, non-exposed specimen were immediately and carefully cleaned to prevent diffusion of hydrogen from the wire and to remove any foreign material on the wire. They were then immediately placed in a plastic bag in an ice chest containing dry ice, delivered by hand the day they were removed to a laboratory, and analyzed for hydrogen content using a LECO DH 103 Total Hydrogen Determinator.

Test Results

CP of Passive Wire in Simulated Mortar at pH 12.45. The effects of CP on tensile strength and reduction of area of prestressing wire from two manufacturers maintained at 60% of its specified minimum tensile strength in a saturated calcium hydroxide solution for 3, 6, and 12 months at no CP and at -850 mV, -1000 mV, and -1200 mV are shown in Figures 2 and 3, respectively. The tensile strength and reduction of area of the prestressing wire at no CP and at -850 mV for 68, 74, and 80 months of exposure are also shown. For plotting purposes, the potentials of the non-cathodically protected but immersed specimens were arbitrarily placed at -200 mV which is within the passive range of 0 to -300 mV (CSE) measured during the exposure. For comparison purposes, the tensile strength and reduction of area of the control specimens determined at 3, 6, and 12 months are plotted at -100 mV even though they were never loaded, immersed, or subjected to CP. The tensile strength and reduction of area of the control specimens determined at 68, 74, and 80 months are also plotted at -100 mV even though they were never immersed or subjected to CP but were loaded to 60% of their specified minimum tensile strength.

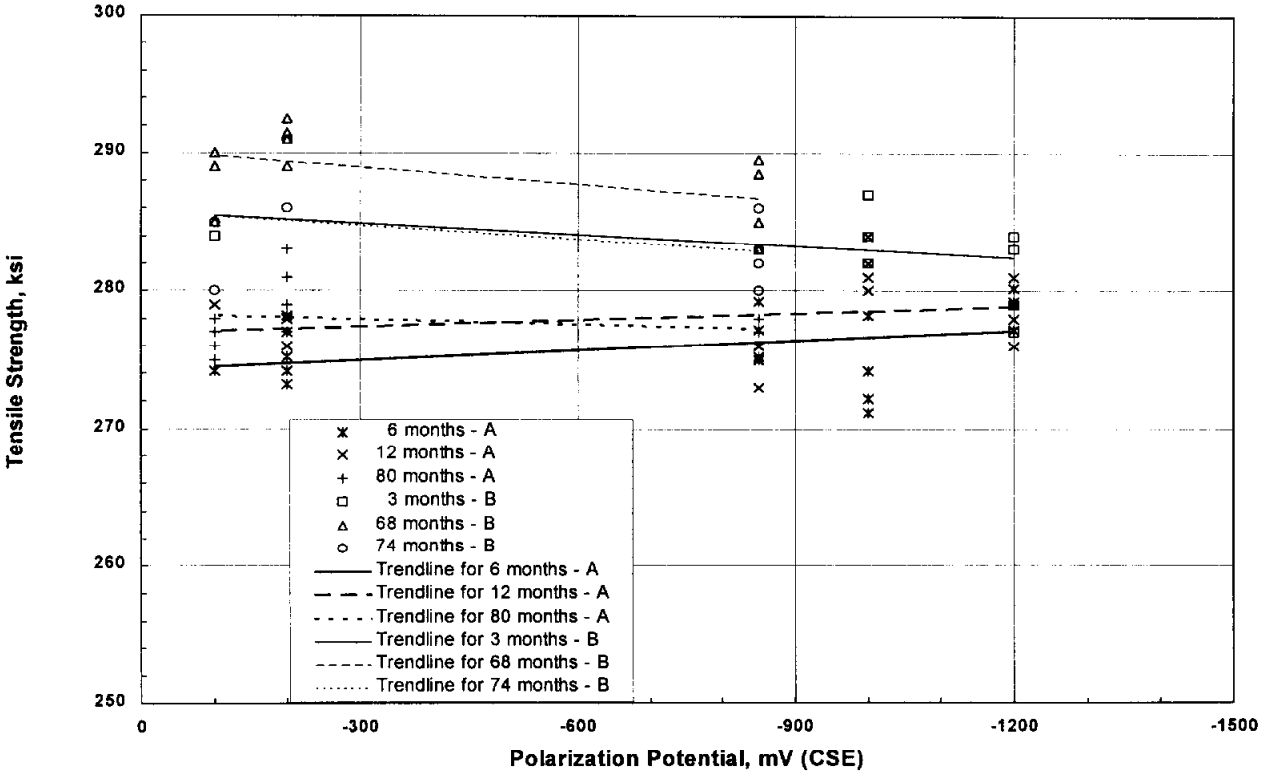


FIGURE 2 - Tensile strength of 6 gage prestressing wire from manufacturers A and B stressed at 60% of its tensile strength and subjected to CP in a saturated calcium hydroxide solution

The normal-load rate tensile strength was not affected by the level of CP and indicates that the tensile strength cannot be used to determine whether the wire was subjected to excessive CP. The scatter in the tensile strength is typically seen within a coil. These strength determinations are performed at a stress rate of roughly 50,000 to 100,000 psi (345 to 690 MPa) per minute and should not be confused with the tensile strength determined using slow strain rate tests (SSRT) or constant extension rate tests (CERT) often used to determine the effect of CP on embrittlement in a laboratory environment. It may be possible to use SSRT and CERT with wire removed from a pipe thought to have been subjected to excessive CP if the wire is cut using water to prevent heat buildup during cutting and then immersing it in liquid nitrogen or dry ice within a few minutes of removing CP

to prevent diffusion of hydrogen from the wire and performing the test within a few days. The normal-rate tensile strength can then be compared to the SSRT or CERT strength. If the SSRT or CERT strength is significantly lower than the normal-rate strength, hydrogen embrittlement can be considered.

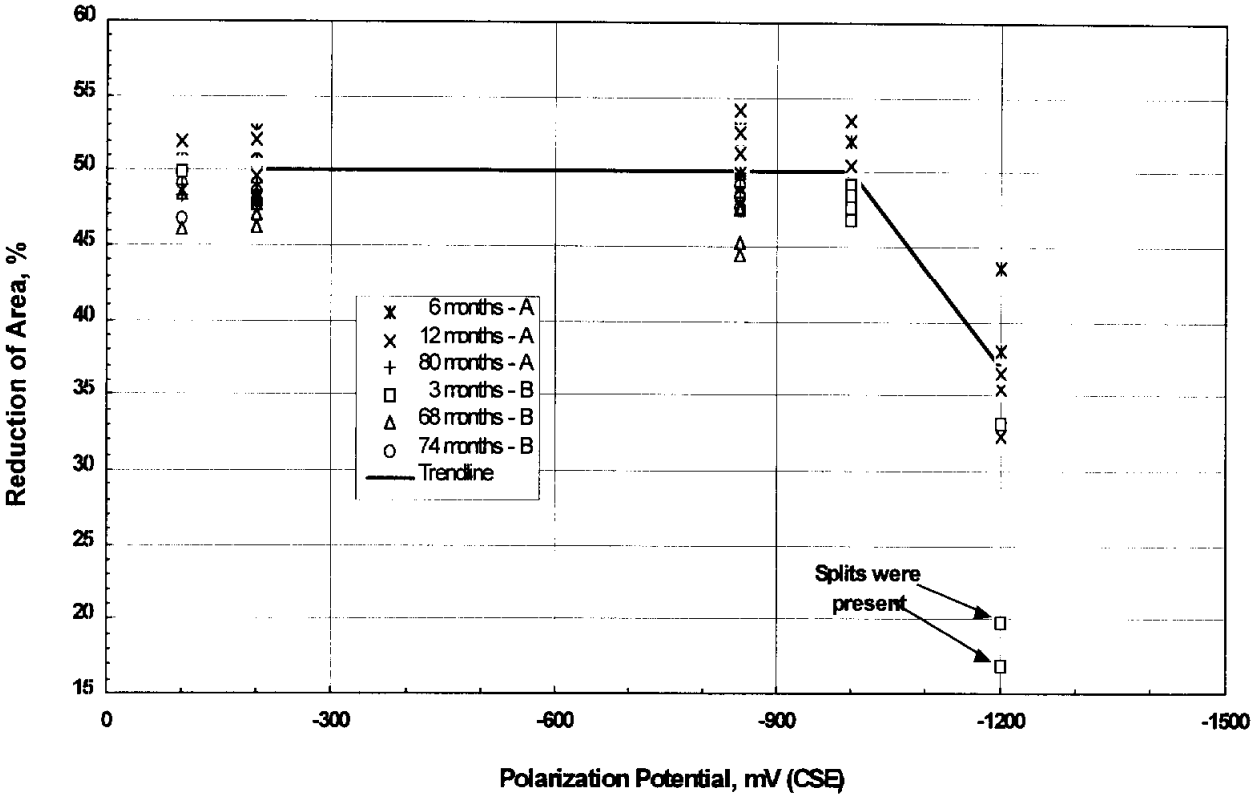


FIGURE 3 - Reduction of area of 6 gage prestressing wire from manufacturers A and B stressed at 60% of its tensile strength and subjected to CP in a saturated calcium hydroxide solution

A significant decrease in reduction of area to 32 to 43% is evident at polarization potentials of -1200 mV but no significant decrease occurred at polarization potentials of -1000 mV and more positive values. Reduction of area was approximately 50% at no CP and CP levels of -850 mV and -1000 mV at all exposure lengths and for both wire manufacturers. The scatter in reduction of area is typically seen within a coil. These results were consistent with results from unloaded prestressing wire which showed that excessive CP at -1100 mV (CSE) slightly decreased the ductility of prestressing wire. As such, the drastic change in slope plotted at -1000 mV probably occurs closer to -1100 mV. This is consistent with the calculated hydrogen evolution potential of -1055 mV (CSE) at a pH of 12.45.

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.

The effect of CP on the hydrogen content of the immersed specimens is shown in Figure 4. For plotting purposes, the potentials of the non-cathodically protected but immersed specimens were arbitrarily placed at -200 mV which is within the passive range of 0 to -300 mV (CSE) measured during the exposure. For comparison purposes, the hydrogen contents of the control specimens determined at 3, 6, and 12 months are plotted at -100 mV even though they were never loaded, immersed, or subjected to CP. The hydrogen contents of the control specimens determined at 68, 74, and 80 months are also plotted at -100 mV even though they were never immersed or subjected to CP but were loaded. 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 and collected on the specimens at -1200 mV. No bubbles were seen or collected 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 also consistent with the decrease in reduction of area at -1200 mV. As such, the drastic change in slope plotted at -1000 mV probably occurs closer to -1100 mV.

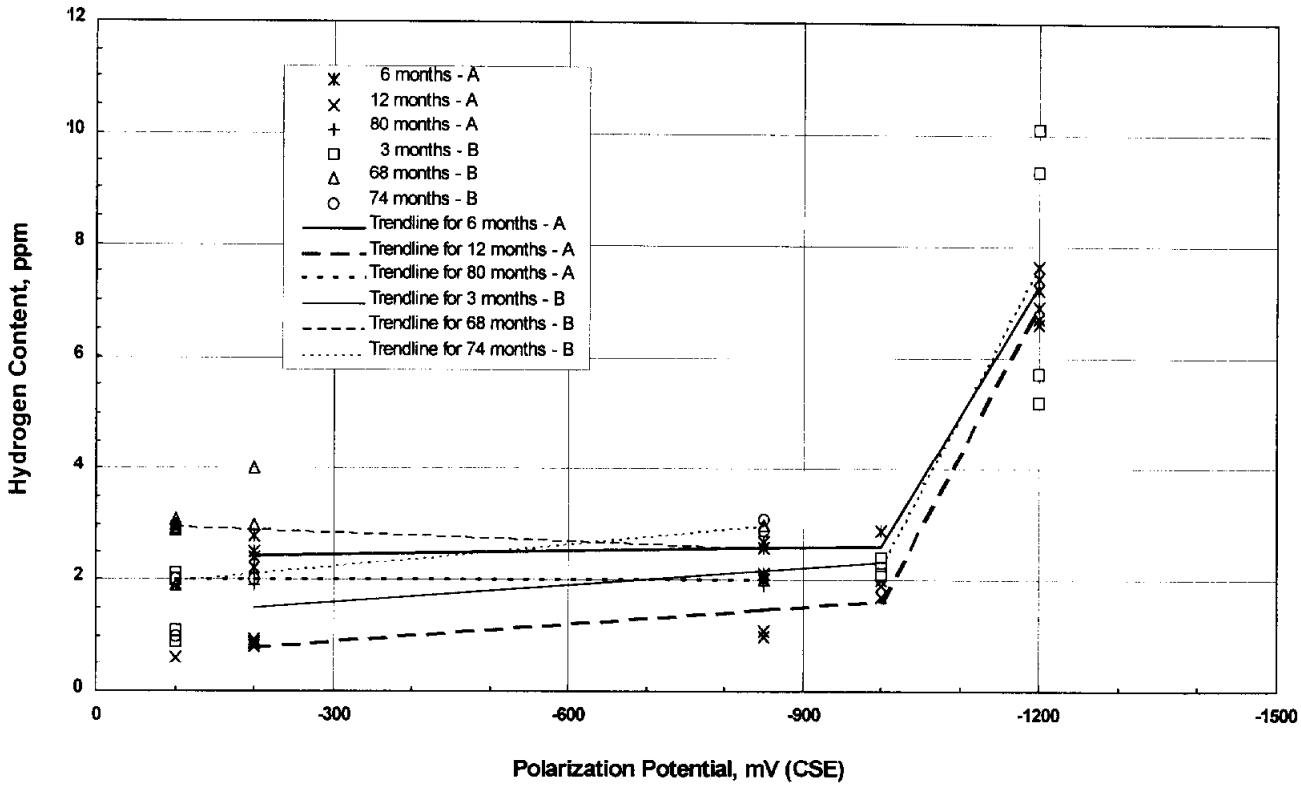


FIGURE 4 - Hydrogen content of 6 gage prestressing wire from manufacturers A and B stressed at 60% of its tensile strength and subjected to CP in a saturated calcium hydroxide solution

Time-to-failure of prestressing wire specimens from manufacturers "A", "B", and "C" held at -1200 mV at 60% of its specified minimum tensile strength is shown in Figure 5. 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 jagged and the reduction of area at the failure points was less than 2%, considerably less than the approximately 50% shown in Figure 3. This indicated that embrittlement of the wire occurred. Longitudinal splits terminating near the center of the wire were found on the two specimens from manufacturer "B" which were immersed in the calcium hydroxide solution and held at -1200 mV. No splits were found in the non-immersed portion of the specimens indicating that exposure at -1200 mV caused the splits. Hydrogen contents of a 1" (2.5 cm) long piece containing the fractured end from each specimen were 5 to 20 ppm, higher than the 0.5 to 3 ppm typically found in wire never exposed and at the lower CP levels. These levels were probably greater at the time of failure since the wire specimens could have failed up to 64 hours prior to it being discovered. 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 and the use of the test to differentiate wires with different susceptibilities to hydrogen embrittlement.

Prestressing wire from manufacturers "A" and "B" at no CP and at -850 mV have not failed after 68 to 80 months of exposure at which time CP was discontinued and the specimens removed from exposure. Wire specimens from manufacturer "C" were not exposed at these levels. Prestressing wire specimens from manufacturers "A", "B", and "C" held at -1000 mV have not failed after 86, 80, and 74 months of exposure, respectively. Exposure at -1000 mV is continuing. This indicates that hydrogen embrittlement of prestressing wire in a simulated mortar environment does not occur at potentials more positive that -1000 mV (CSE).

Susceptibility of Prestressing Wire to Hydrogen Embrittlement. As shown in Figure 5, the quality of the wire, as expressed by the number of turns to break in continuous torsion before exposure, substantially affects its susceptibility to hydrogen embrittlement and subsequent fracture. As required in the specification (ASTM A648) for prestressing wire for concrete pipe, the minimum number of turns to break in continuous torsion is 8 per 8" (20 cm) test length for 6 gage wire. The

continuous torsion requirement was established in 1988 and was increased in AWWA C301 in 1992 and ASTM A648 in 1995. Before this, continuous torsion was not routinely determined so the susceptibility of the wire in pipe made prior to this is probably not known. However, wire can be removed from pipe especially during tapping operations and continuous torsion determined to have this information available if CP were ever required.

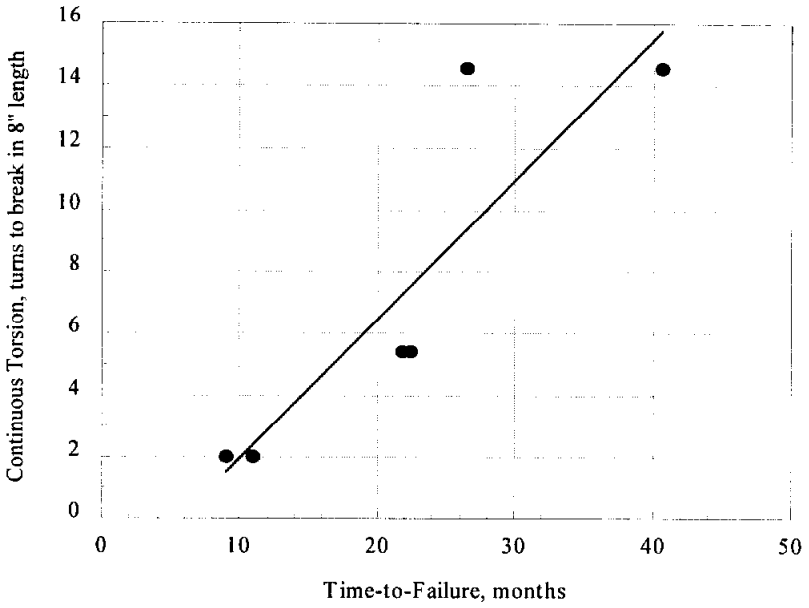


FIGURE 5 - Time-to-failure of prestressing wire held at -1200 mV (CSE) as a function of continuous torsion.

The ductility as expressed by continuous torsion appears to be significantly affected by an increase in wire temperature during the drawing process.[5,13] The effect of temperature on continuous torsion is shown in Table 2. The wire was severely damaged at 375°F. The number of turns to break decreased substantially as temperature increased to 375°F and the type of break went from a smooth transverse break, which indicates a very ductile material, to a jagged transverse break with a helical crack, which indicates a very brittle material.[13] Due to this effect, AWWA C301 was revised in 1992 to require that the surface temperature of the wire should not exceed 360°F (182°C) during the drawing process. Temperatures above this level are believed to detrimentally strain-age the wire making it more brittle and increasing the wire's susceptibility to hydrogen embrittlement.[4]

TABLE 2
EFFECT OF TEMPERATURE ON 1/4" PRESTRESSING WIRE

Test	Temperature, °F (°C)				
	73 (23)	300 (149)	325 (163)	350 (177)	375 (190)
Continuous Torsion (Turns to and type of break in 12.5" length)	15a 18a	19a 15a 21a,b	16a,aj 17a,b 2aj	12a 16a,b 18a,b	1aj 3aj,c 1aj,c

"a" refers to smooth transverse break; "b" refers to inclined break;
"aj" refers to jagged transverse break; "c" indicates a helical crack.

The effect of extremely excessive cathodic current of 3.00 amps/ft^2 (32.4 amps/m^2) on prestressing wire immersed in a saturated calcium hydroxide solution for 6 months is shown in Table 3. The polarization potentials ranged from -1060 mV to -1280 mV (CSE). Continuous torsion and reduction of area substantially decreased during the 6 months of exposure which demonstrates the drastic effect that excessive CP can have on the ductility of the wire. The type of break went from a ductile smooth transverse break to a jagged transverse break also indicating the drastic effect that excessive CP can have on the ductility of the wire.

TABLE 3
CONTINUOUS TORSION, REDUCTION OF AREA, AND TENSILE STRENGTH OF 6 GAGE PRESTRESSING WIRE SUBJECTED TO CP AT 3 AMPS/FT² IN A CALCIUM HYDROXIDE SOLUTION FOR 6 MONTHS

Exposure	Continuous Torsion (turns to & type of break)		Reduction of Area (%)		Tensile Strength, ksi (MPa)	
	Individual	Average	Individual	Average	Individual	Average
CP at 3 amps/ft² for 6 months	1 aj 2 aj 2 aj	2	30.4 28.7 31.5	30.2	279 (1930) 276 (1900) 280 (1930)	278 (1920)
No CP	36 a 28 a 37 b,a,b	34	50.7 50.2 53.0	51.3	278 (1920) 278 (1920) 277 (1910)	278 (1920)

a = smooth transverse break; b = inclined break; aj = jagged transverse break

CP of Severely Corroded Wire at pH 2. The effect of CP on tensile strength, reduction of area, and hydrogen content of prestressing wire from manufacturer "A" maintained at 60% of its specified minimum tensile strength in a 0.01 M hydrochloric acid solution for 2 weeks without CP, simulating an acidic condition possible around severely corroded wire, followed by 2 months at -1000 mV is shown in Table 4. Slight to moderate levels of hydrogen gas were evolved from the wire surface during the entire exposure. The pH at the wire surface increased to approximately 4 during the first week and maintained that level. Tensile strength was not affected by either the 2 weeks of corrosion or the 2 months of CP in the highly acidic solution. A slight decrease in reduction of area and a slight increase in hydrogen content were evident indicating that low levels of hydrogen were diffusing into the wire.

TABLE 4
TENSILE STRENGTH, REDUCTION OF AREA, AND HYDROGEN CONTENT OF 6 GAGE PRESTRESSING WIRE IN A HYDROCHLORIC ACID SOLUTION AT -1000 mV (CSE)

Exposure	Tensile Strength, ksi (MPa)	Reduction of Area (%)	Occurrence of Splits	Hydrogen Content (ppm)
None	279 (1930) 277 (1910) 282 (1940)	48.4 51.4 48.9	None None None	2 3
2 weeks corroding	263 (1810) 282 (1940)	49.3 49.6	None None	2 2
2 weeks corroding PLUS 2 months at -1000 mV	280 (1930) 278 (1920) 273 (1880) 273 (1880)	42.7 45.5 46.6 46.9	None None None None	4 3

The cross section of a wire specimen exposed to 2 weeks of corrosion plus 2 months at -1000 mV is shown in Figure 6. Pits caused by the two weeks of corrosion are evident and can be sites for possible fractures to occur while under excessive levels of CP.

The remaining 4 specimens at -1000 mV have not failed after 18 months of exposure even though pitting occurred during the first 2 weeks of corrosion and hydrogen generation occurred at the wire surface during the entire exposure. This indicates that prestressing wire specimens in an acidic environment are not extremely sensitive to hydrogen embrittlement. Exposure will continue until failure occurs. This test represented the worse case of corroding wire in PCCP which can produce a pH of 2 to 4 around the wire surface. No failures have occurred after 18 months even though gas evolved continually from the wire surface and a slight reduction of ductility and slight increase in hydrogen content occurred.

The pH 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 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. In a pipe, the pH will increase substantially during CP as the hydrogen ions are consumed in accordance with reaction (4) followed by reaction (3).

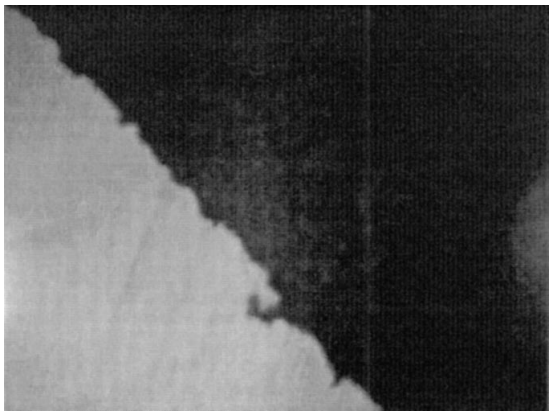


FIGURE 6 - Cross section of 6 gage prestressing wire after corroding for 2 weeks in a pH 2 hydrochloric acid solution followed by 2 months at -1000 mV (CSE). The pits are possible initiation sites for fractures during excessive CP. 0.001"

CP of Longitudinally Split Wire at pH 2. This exposure represented a severely notched prestressing wire specimen subjected to an acidic environment that can occur around a severely corroding prestressing wire. Two ASTM A648, Class III, 8 gage prestressing wire specimens with longitudinal splits immersed in a pH 2 hydrochloric acid solution are being cathodically protected at -1000 mV while stressed to 60% of its minimum ultimate strength. Slight to moderate amounts of hydrogen gas are evolving from the wire and the pH increased initially from 2 to 4 as discussed in the preceding section. No failures have occurred after 8 months of exposure indicating that even severely notched prestressing wire in an acidic environment prior to exposure are not extremely sensitive to hydrogen embrittlement.

As discussed in a previous section, the pH surrounding the corroding wire in a pipe is expected to increase substantially during CP as the hydrogen ions are consumed and the hydrogen ions cannot be replaced as in the bulk solution used in this exposure. Since the hydrogen ions are continually diffusing to the wire in this test, the wire is expected to eventually fail.

Recovery of Ductility. The effect of CP on the diffusion of hydrogen from the wire and recovery of ductility as expressed as reduction of area is shown in Table 5. Essentially, no change in reduction of area occurred at no CP and at -850 and -1000 mV since no hydrogen was generated at these potentials to cause embrittlement. At -1100 mV, reduction of area slightly decreased and recovered to its initial, pre-exposure value within 4 weeks. Ductility of the wire decreased at -1180 and -1260 mV and essentially recovered to its initial, pre-exposure value within 8 weeks. Most of the recovery occurred during the first four weeks, but at least 8 weeks were required for full recovery. This indicates that the loss of ductility, or embrittlement, is reversible.

TABLE 5
DIFFUSION OF HYDROGEN AND RECOVERY OF DUCTILITY
OF PRESTRESSING WIRE AFTER DISCONTINUING CP

Polarization Potential (mV, CSE)	Average Reduction of Area, % (n=2)		
	Immediately Upon Removing CP	4 Weeks After Removing CP	8 Weeks After Removing CP
No CP	47.5	47.0	48.8
-800	47.1	47.7	49.8
-1000	47.4	48.3	48.1
-1100	44.5	48.1	46.7
-1180	40.6	45.0	47.4
-1260	37.0	46.2	48.0
	Hydrogen Content, ppm		
-1200	7.4	--	4.1 (7 weeks)

The hydrogen contents decreased from an average of 7.4 ppm immediately after removal to 4.1 ppm seven weeks after removal. This is consistent with the above findings in which recovery of reduction of area after discontinuing CP took at least 8 weeks.

Due to the reversible nature of hydrogen diffusion from and into the wire, a pipeline subjected to excessive CP may be able to be returned to service by turning off or reducing the CP level to allow hydrogen to diffuse from the steel. Turning off or reducing the level of CP should prevent any additional splitting or breakage from occurring. Determination of reduction of area along with the normal-load rate tensile strength of a prestressing wire specimen cut from the pipe within a day of removing CP and a few weeks later after allowing any hydrogen to diffuse out of the wire provides a good indication whether the wire was subjected to excessive CP. It is also possible to speed up this diffusion process by heating the wire at 300°F (149°F) for a day followed by determination of reduction of area and tensile strength.

FIELD PHASE

The objective of the field phase was to determine the approximate current density requirements of PCCP with and without supplemental barrier protection, such as an organic coating, to obtain a minimum 100 mV shift and a maximum polarization potential of -1000 mV (CSE) while realizing that the actual current density required for other pipelines will differ depending on the specific conditions of the line. In addition, the amount of current flowing to the prestressing wire and to the embedded steel cylinder was determined.

Test Setup

This project consisted of installing an impressed current CP system on a 48" (1.22 m) diameter by 240' (73 m) long PCCP line and measuring polarization and depolarization potentials and current of the pipeline during up to 1 year of system activation. The pipeline consisted of ten 24' (7.3 m) long PCCP sections. Each pipe was manufactured with two 1" (2.5 cm) wide shorting straps, 180° apart to reduce the electrical attenuation along the prestressing wire in each pipe section.

CP requires that the steel elements to be protected be electrically continuous. In this project, the prestressing wire was made electrically continuous to the steel cylinder at each end of the 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 the joints. Additional details of the pipeline are reported elsewhere.[14,15]

Two of the pipe sections were coated with a 0.026" (660 micron) thick supplemental coal tar epoxy (CTE) coating and two of the sections were wrapped in a 0.008" (200 micron) thick polyethylene (PE) film. Pinholes 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 6 feet (1.8 m) 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 was 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 ion contents were less than 10 mg/kg which indicates that the soil is not corrosive. The pipeline was backfilled with sand from an adjacent aggregate quarry which had similar chemical properties. The Wenner four-pin soil resistivity of the backfilled area at 3', 5', and 10' (1, 1.5, and 3.0 m) 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 station at the surface above each joint.

A 4" (10 cm) diameter by 45" (110 cm) long steel pipe buried 20' (6.1 m) 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 5 feet (1.5 m) along the centerline of the pipeline. An over-the-line potential survey was taken 90 minutes to up to one year after CP activation. Current-on and polarization (instant current-off) potentials and current were recorded.

Results

Current Density to Achieve 100 mV Shift and -1000 mV (CSE). The baseline potentials of the six uncoated pipe sections were approximately 0 (CSE) as shown in Figure 7. Since previous work[15] showed that 25 μA/ft^2 (270 μA/m^2) produced a polarization shift of 180 mV during three months of CP, the current density on the six sections of uncoated PCCP was adjusted to 12 μA/ft^2 (130 μA/m^2) based on the mortar coating surface area. The polarization (instant current-off) potentials at 3 weeks of CP are shown in Figure 7. The polarization shift was approximately 120 mV. The depolarization shift after 3 weeks of polarization was 100 mV in 4 hours and 120 mV after 1 week. At six months of CP, the polarization potentials were approximately 220 mV. At 14 months of CP, the polarization potentials were approximately 130 mV. This shows the fluctuations that occurred during the year. The IR drop between the current-on and current-off (interrupted) potential ranged from 50 to 70 mV at 1 month of CP, 10 to 50 mV at 6 months of CP, and roughly 300 mV at 14 months in the relatively dry, sandy soil.

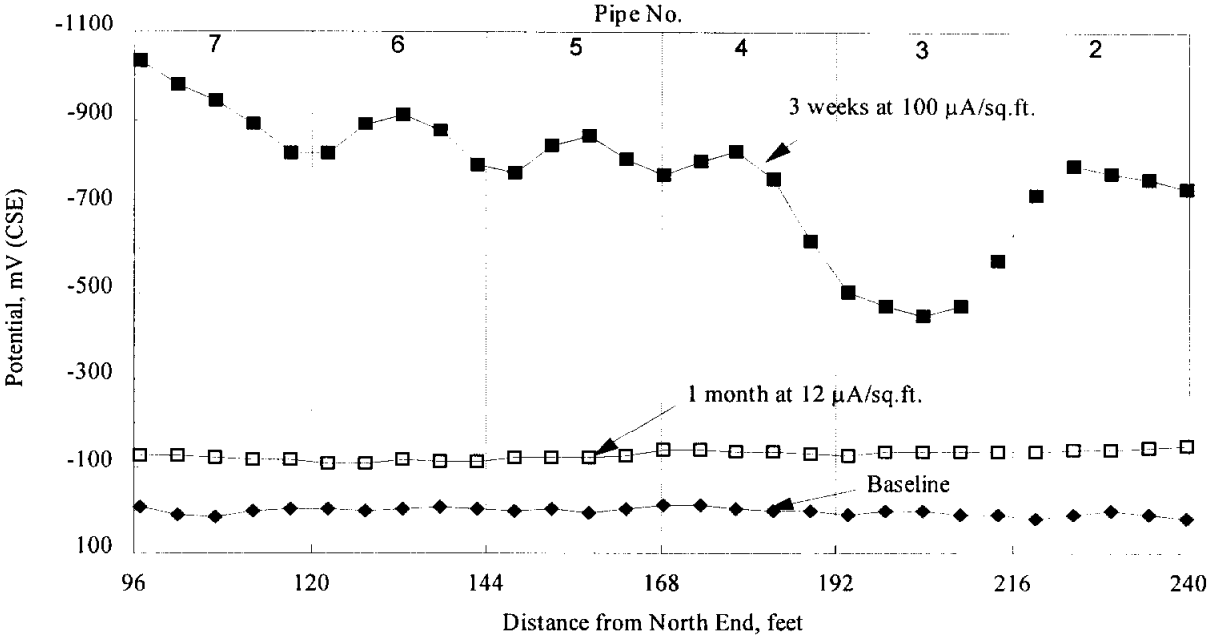


FIGURE 7 - Baseline and polarization potentials of PCCP line under CP at 12 and 100 µA/ft^2 (130 to 1080 µA/m^2)

In addition, the average current density required to achieve polarization potentials not less than -1000 mV (CSE) on the pipe nearest the anode was 100 μA/ft^2 (1080 μA/m^2). The polarization potentials of the pipeline are given in Figure 7. This indicates that the design current density for PCCP is roughly 100 μA/ft^2 (1080 μA/m^2). Within each 24' (7.3 m) long PCCP section which were produced with shorting straps, the most negative potential is in the center of each pipe section, not at the joint. It is believed that a close interval survey of older pipelines, which do not have shorting straps, will adequately indicate the level of polarization in the center of each pipe section. The reason for the large dip in potential at pipe 3 has not been determined. The IR drop between the current-on and current-off (interrupted) potential ranged from 100 to 200 mV in the relatively dry, sandy soil.

Cathodic protection is rarely required on a supplementally-coated PCCP. If monitoring shows that corrosion is occurring,[14] cathodic protection is a suitable means to control it.[10] For supplementally-coated pipe, the following results were achieved:

- A current density of approximately 3 μA/ft^2 (32 μA/m^2) on coal-tar epoxy coated PCCP produced a polarization shift of 150 mV at 2 months and a depolarization shift of 65 mV during the first 4 hours and 75 mV at one month. Depolarization of a coated pipeline is expected to take longer than an uncoated pipeline since diffusion of oxygen is low.

- A current density of approximately 3 μA/ft^2 (32 μA/m^2) on PE-encased PCCP produced a polarization shift of 100 mV at 3 hours and remained essentially unchanged during the next 3 months of CP. It produced a depolarization shift of 140 mV during the first 4 hours and 200 mV at one week.

Current Flow to Prestressing Wire and Cylinder. The amount of current flowing individually to the prestressing wire and cylinder was also determined at current densities of 25, 100, and 700 $\mu A/ft^2$ (270, 1080, and 7600 $\mu A/m^2$ - 9.8, 38, and 258 mA) based on the mortar coating surface area. A 1-ohm resistor was placed between the end of the prestressing wire and the power supply and another between the end of the cylinder and the power supply on one pipe section. The prestressing wire surface area was 65% of the cylinder surface area. It was found that 47% to 49% of the current flowed onto the prestressing wire and the remaining 51% to 53% flowed onto the cylinder. At 25 $\mu A/ft^2$, the current density on the wire was 22 $\mu A/ft^2$ compared to 16 $\mu A/ft^2$ on the cylinder. At 100 $\mu A/ft^2$, the current density on the wire was 86 $\mu A/ft^2$ compared to 61 $\mu A/ft^2$ on the cylinder. At 700 $\mu A/ft^2$, the current density on the wire was 605 $\mu A/ft^2$ compared to 409 $\mu A/ft^2$ on the cylinder. Current density on the prestressing wire was 40% to 50% greater than that of the underlying embedded cylinder. The surface area of the prestressing wire and steel cylinder was 57% and 88%, respectively, of the mortar coating surface area.

CASE HISTORIES

The following are five pipelines placed under CP during the past 26 years. Two have been successfully cathodically protected for at least 23 years at potentials less negative than -1000 mV (CSE). One pipe section on two of the other pipelines failed within 16 months of CP activation where potentials as negative as -1330 mV were measured following rupture.

Los Angeles County, California

A 3200-foot (975 m) long, 201" (5.10 m) diameter PCCP line with an impressed current CP (ICCP) system which consisted of a single anode bed located at one end of the pipeline was installed in 1971. The CP system was installed due to the requirement of another water agency that the PCCP line be cathodically protected if it was connected to its line. The polarized potential of the pipeline ranged from -900 mV (CSE) adjacent to the anode bed to -400 mV (CSE) at the far end with an average current density of 140 $\mu A/ft^2$ (1.5 mA/m^2) based upon the surface area of the mortar coating. The pipeline contained two layers of prestressing wire which would reduce the actual current density on the wire. The system is checked monthly and the pipeline is being successfully cathodically protected.

East Bay Area of San Francisco, California

A pipeline consisting of 3800 feet (1160 m) of 60" (1.52 m) diameter PCCP and 20,480 feet (6250 m) of 66" (1.68 m) diameter PCCP was protected by a sacrificial CP system due to concerns about stray current interference from a nearby electric transit system. The pipeline was coated with a supplemental coal tar epoxy coating to decrease the possibility of current pick up and discharge. The CP system was installed with the pipeline in 1974. The system consisted of 86 magnesium anodes individually spaced every 200 to 352 feet (60 to 110 m) along the length of the pipeline. In 1975 the polarization potentials ranged from -600 mV to -800 mV (CSE) with an average current density of 11 $\mu A/ft^2$ (120 $\mu A/m^2$) based on the surface area of the mortar coating. In 1987, the potentials ranged from -400 mV to -450 mV with an average current density of 4 $\mu A/ft^2$ (43 $\mu A/m^2$). At this same time, the anodes were temporarily disconnected and the pipeline depolarized to potentials more positive than -300 mV within two weeks indicating that the pipeline was polarized at least 100 mV. Several anodes were replaced and the system was reactivated. The pipeline is being successfully cathodically protected.

Utah near Salt Lake City

An 11,160-foot (3400 m) long, 66" (1.68 m) diameter PCCP line was protected by an ICCP system consisting of three anode beds that were designed as deep wells spaced at approximately equal distances along the pipeline. The deep wells could not be drilled to the required depth and the top anode was, as a consequence, within 10 feet (10 m) of the bottom of the pipeline. The pipeline and CP system was installed in 1981. The CP system was activated in April 1983 and polarization potentials in July 1983 were -1150, -1180 mV, and -1250 mV (CSE) at the three rectifiers. Although the minimum and maximum potential criteria was -850 and -1100 (CSE), respectively, no attempt was made to reduce the excessive potentials at the rectifiers. The line was placed in service in July 1984. In August 1984, a pipe rupture occurred 150 feet (45 m) from one of the rectifiers, where potentials were more negative than -1200 mV (CSE). In February 1985, the potentials ranged from approximately -850 mV (CSE) midway between anode beds to approximately -1250 mV (CSE) adjacent to the anode beds with an average current density of 250 $\mu A/ft^2$ (2.7 mA/m^2) based upon the surface area of the mortar coating. The soil and ground water were considered non-corrosive to PCCP.

San Francisco, California

A 33,000-foot (10,060 m) long, 66" (2.0 m) diameter PCCP line was protected by an ICCP system consisting of 4 anode beds. The pipeline was installed in 1980. In 1984, a potential survey indicated that corrosion was occurring so an ICCP system

was installed in late 1988 and early 1989. The most negative measured potential upon system check out in early 1989 was -930 mV (CSE). In January 1990, one pipe section ruptured adjacent to a rectifier where the potential was more negative than -1200 mV (CSE). A survey performed in February 1990 recorded polarization potentials ranging from -816 mV to -1265 mV (CSE). It appears that during the year after system activation the pipeline continued to polarize resulting in potentials more negative than -1000 mV.

Texas near Houston

A 74,000-foot (25,000 m) long, 108" (2.74 m) diameter PCCP line was protected by an ICCP system consisting of 19 anode beds. The pipeline was installed between 1971 and 1974 and the CP system was activated in 1974. The polarized potentials ranged from -770 mV to -1330 mV (CSE) with an average current density of 100 $\mu A/ft^2$ (1.1 mA/m^2) based on the surface area of the mortar coating. In 1992, two pipe ruptures occurred at the location of the more negative potentials.

It is speculated that frequent electrical storms in the area may have disabled the rectifiers for sufficient lengths of time during the 18 years of CP. This would allow the hydrogen in the wire to diffuse out during the outage returning the ductility of the wire to the pre-embrittlement level. Eventually, sufficient time elapsed without an outage to cause rupture.

General Comments

The above case histories indicate that pipe ruptures have occurred to pipelines where the potentials were more negative than -1000 mV but not at less negative potentials verifying the theoretical and laboratory phases of the project. They also show the importance of periodic monitoring of the system to ensure that potentials more negative than -1000 mV (CSE) are not exceeded. Two of the three pipelines which ruptured were not monitored after initial CP system activation.

DISCUSSION

When a serious corrosion problem exists, CP 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 [7] allows a 100 mV polarization or depolarization shift. This 100 mV shift is also used as a criterion in RP0290[8] 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.[10]

CP 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 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.

In the tests performed, embrittlement did not occur at -1000 mV but signs of embrittlement were evident at -1100 mV (CSE). As such, the potential of -1000 mV was chosen as the maximum limit. This provides an approximately 50 mV safety factor from the -1053 mV calculated in accordance with the Nernst equation at a pH of 12.45 and 25°C.

<u>Cathodic Protection Design Concept</u>. When applying cathodic protection to a PCCP line, the polarization potential should not be more negative than -1000 mV (CSE) to prevent hydrogen embrittlement of the prestressing wire. This criterion also applies to prestressing wire in carbonated mortar and to corroding wire where the pH around the wire is acidic. In these two cases, the pH surrounding the wire quickly increases to levels where hydrogen is not produced. Any hydrogen which initially diffuses into the wire does not concentrate at a high enough level to cause failure and when production of hydrogen stops, the hydrogen can diffuse out returning the ductility of the wire to initial values.

If a few pipe sections are corroding, only those sections need to be protected, not the entire pipeline. This may require only one anode at the corroding site. The location of the anode bed should be marked on applicable drawings so that polarization which occurs is not confused with corrosion. Under circumstances when only one anode bed is anticipated, the corroding areas furthest from the anode bed should polarize at least 100 mV from its corroding potential with potentials never more negative than -1000 mV (CSE).

As shown in Figure 8, when the corroding portion of the line is longer and more than one anode bed is anticipated, the potential of the pipe nearest to the anode bed, where the most negative potentials are expected, should not be more negative than -1000 mV. The potential will become more positive along the length of the pipeline until a potential 100 mV more negative than the baseline potential is reached. Additional anode beds would be placed further down the line to achieve this criteria. The distance between the two anode beds would be the approximate distance for any additional anode beds required. This is a simplified version of a design since it is possible that the most negative potential can occur at locations other than at the anode bed and that the most positive potential can occur at locations other than at the furthest location from the anode bed(s).

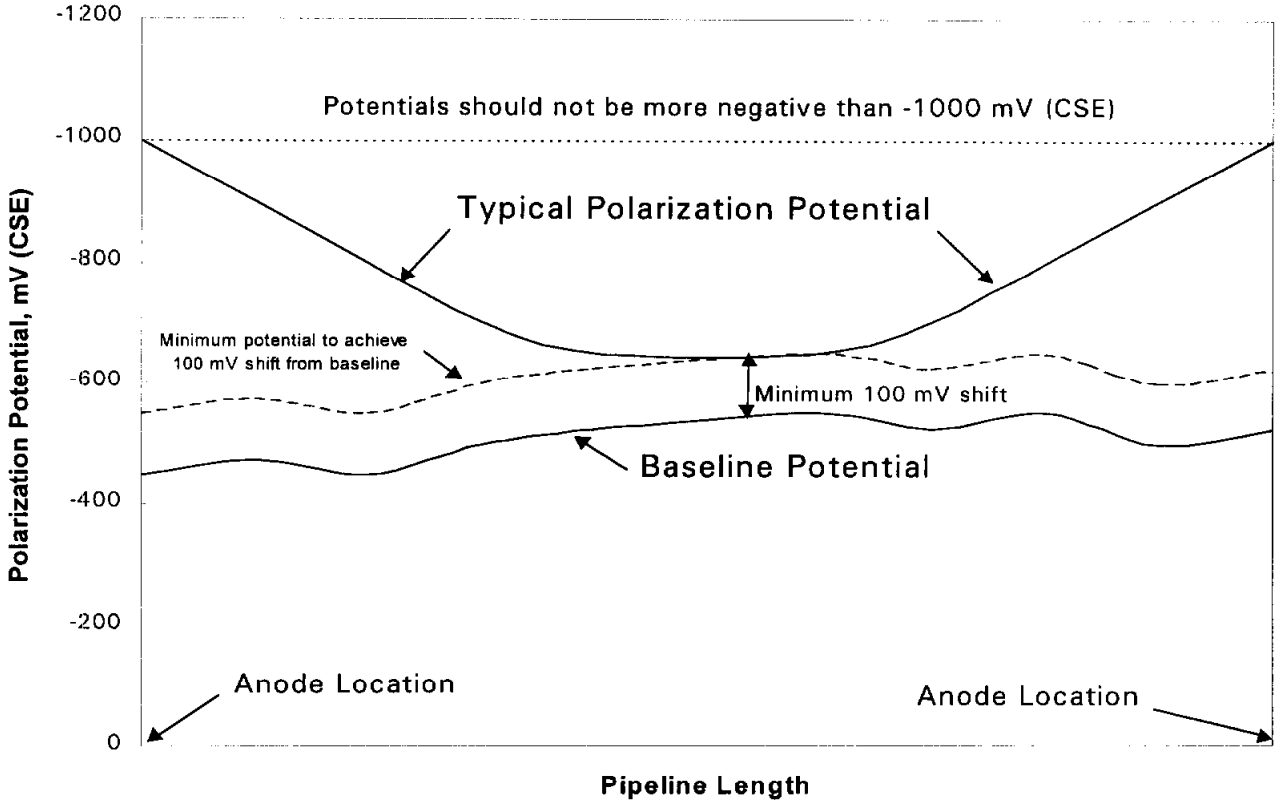


FIGURE 8 - Simplified diagram to illustrate the CP design concept of a pipeline to meet the minimum and maximum CP criteria

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, CP can be an effective means to mitigate corrosion.
- The minimum cathodic protection potential shift criterion is 100 mV polarization or depolarization. A current density of 12 μA/ft^2 (130 μA/m^2) achieved a shift of approximately 120 mV.
- Prestressing wire is susceptible to hydrogen embrittlement at potentials negative enough to generate hydrogen but required months to years before a failure occurred. The polarization potential should be maintained more positive than -1000 mV (CSE) to avoid hydrogen embrittlement. More negative potentials can embrittle and split prestressing wire, greatly increase the cost of CP, and do not improve corrosion protection. An average current density of 100 μA/ft^2 was required to achieve a polarization potential of -1000 mV.
- The ductility of prestressing wire under excessive CP recovered after CP was discontinued. Most of the recovery occurred during the first four weeks but at least eight weeks were required for full recovery.

- Cathodic protection increases the pH around the prestressing wire in carbonated mortar or around corroding wire to initial uncarbonated or non-corroding levels. Due to the rapid increase in pH around the wire during CP, limiting potentials do not need to be adjusted to values more positive than -1000 mV.

- The continuous torsion test in ASTM A648 is an excellent means to determine the susceptibility of prestressing wire to hydrogen embrittlement. The higher number of turns to break in continuous torsion indicates a less susceptible wire.

- Limiting the prestressing wire drawing temperature to 360°F (182°C) greatly increases the ductility of the wire and significantly reduces its susceptibility to hydrogen embrittlement.

- The current from a CP system distributes equally to the prestressing wire and steel cylinder in PCCP

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