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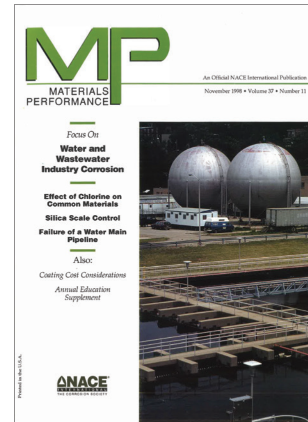

Cathodic Protection Criteria for Prestressed Concrete Pipe—An Update

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Prestressed concrete cylinder pipe is used in water and wastewater systems that serve virtually every major city in North America. Under certain conditions, such as high chloride environments, steel elements can depassivate, leading to corrosion. Under these conditions, cathodic protection (CP) can be used to protect the encased steel elements. This article provides the results of 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 (HE) were determined. Also determined were the effect of low pH caused by corroding wire, the susceptibility of prestressing wire to HE, and the approximate length of time and potentials to produce HE and eventual wire failure. The effect of discontinuing high levels of CP on the diffusion of hydrogen from wire and the recovery of ductility were evaluated.

Prestressed concrete cylinder pipe (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. Figure 1 identifies the components of an installed PCCP.

PCCP used primarily for water distribution is manufactured in sizes from 16 in. (410 mm) to 21 ft (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]

The cement slurry and mortar coating over the prestressing wire provide the only protection that PCCP normally requires because of the passivating (corrosion-inhibiting) properties of the highly alkaline portland cement. One survey showed that concrete pipe had the lowest problem occurrence rate and the highest average level of satisfaction.[4] Of 19,165 projects, <0.1 % had any type of problems with external corrosion. Chloride-induced corrosion was the most common form found and could have been prevented by the use of supplemental coatings or cathodic protection (CP).

The prestressing wire, which conforms to ASTM A648,[5] 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% because of initial creep and shrinkage of the concrete core and relaxation of the wire and minor losses that occur during the life of the pipe. Prestressing places the concrete core in compression, which makes it possible to design for the combined effects of internal pressure and external load without exceeding the tensile strength of the core.

*Sylvia C. Hall established her corrosion engineering company, Sylvia Hall Engineering (SHE), in May 2014.

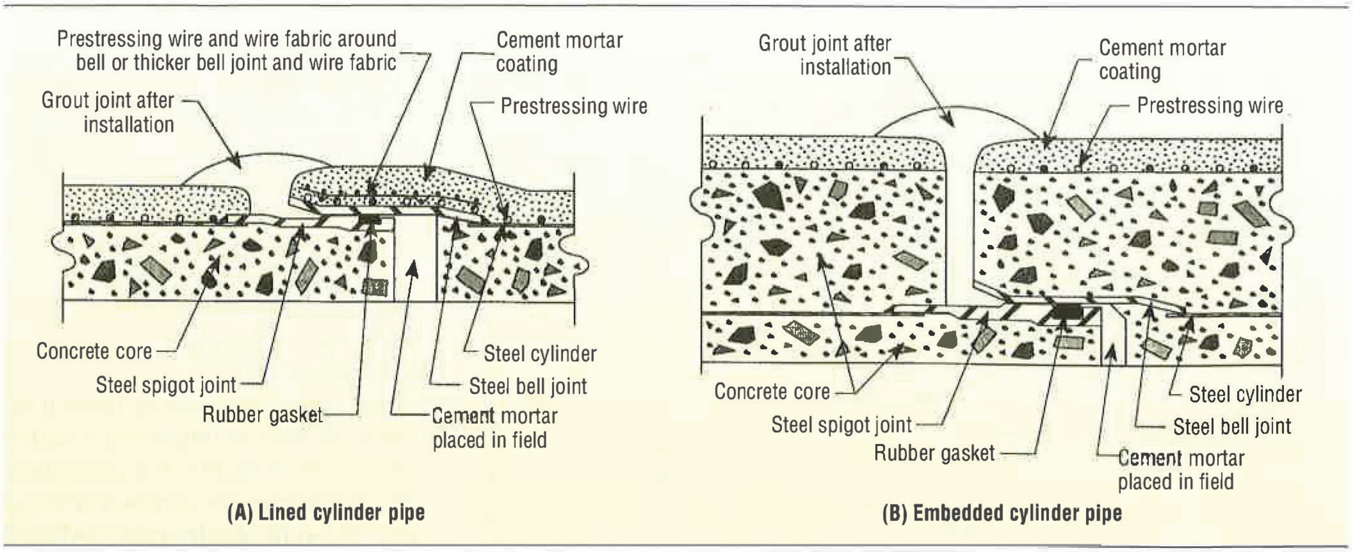

FIGURE 1
Components of installed PCCP.

In unusual circumstances, such as in high-chloride environments, the passivating properties of the highly alkaline cement may be compromised. Then, supplemental protection may be necessary. This is usually in the form of barrier coatings (i.e., coal tar epoxy). In some rare cases, CP is provided.[6]

Potential criteria and current density requirements for buried PCCP are generally not available. Current density design requirements of 1 mA/ft^2 to 2 mA/ft^2 (10.8 mA/m^2 to 21.6 mA/m^2) have been used.

The most accepted criterion of –850 mV copper-copper sulfate reference electrode (CSE) often is 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, with –710 mV$_{CSE}$ enough to prevent further corrosion, once initiated.[8] A 100 mV depolarization shift is another criterion used.[6-7,9] Polarization shifts of only 20 mV have been found to effectively protect corroding steel in mortar.[10]

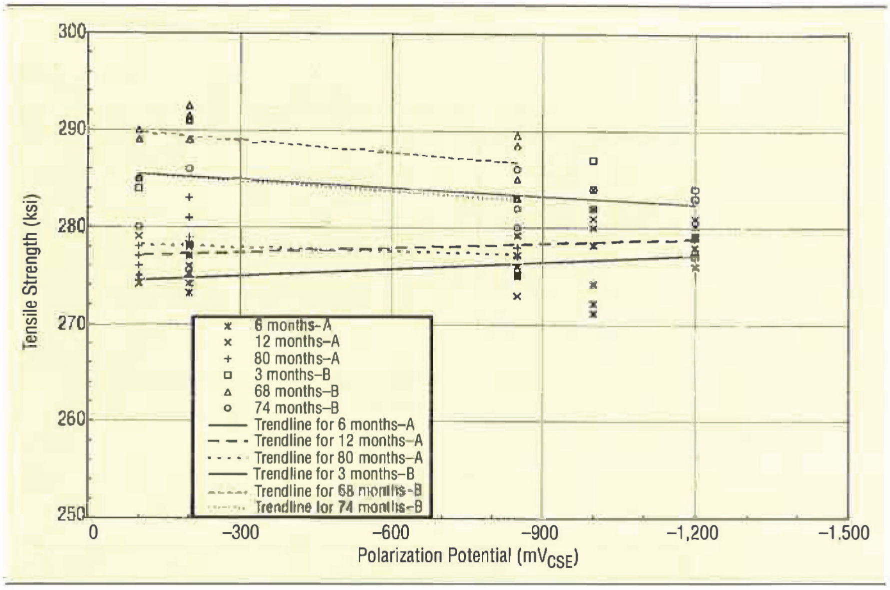

FIGURE 2
Tensile strength of 6-gage prestressing wire from manufacturers A and B stressed at 60% of its tensile strength and subjected to CP in a saturated $Ca(OH)_2$ solution.

Theoretical Considerations

HE of Prestressing Wire

Many corrosion engineers and technicians did not recognize that the prestressing wire in PCCP, as a high tensile steel, was susceptible to hydrogen embrittlement (HE). Some pipelines were cathodically protected as if they were oil and gas pipelines. Unfortunately, HE of the prestressing wire from excessive CP appeared to have caused isolated ruptures.[3] The most negative polarization (instant current-off) potential on one line was –1,265 mV$_{CSE}$, with rupture adjacent to an anode bed 12 months after CP activation. On the other, it was –1,330 mV with rupture occurring 18 years after activation. This pipeline was in an area of frequent lightning

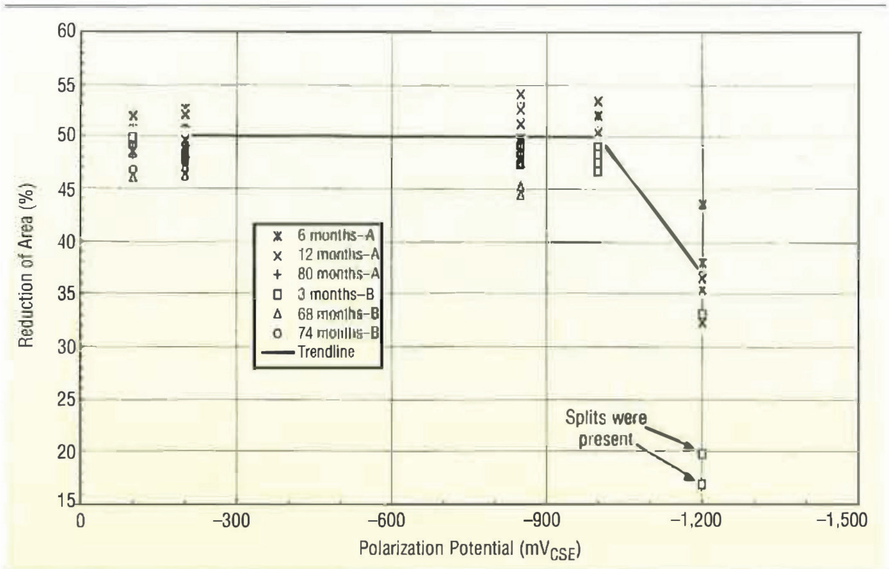

FIGURE 3
Reduction of area of 6-gage prestressing wire from manufacturers A and B stressed at 60% of its tensile strength and subjected to CP in a saturated $Ca(OH)_2$ solution.

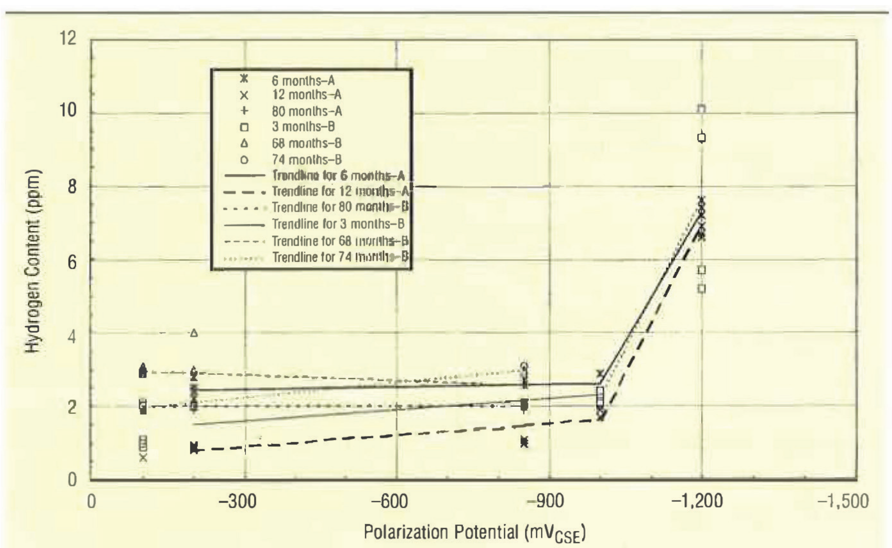

FIGURE 4
Hydrogen content of 6-gage prestressing wire from manufacturers A and B stressed at 60% of its tensile strength and subjected to CP in a saturated $Ca(OH)_2$ solution.

storms that may have disrupted the power supplies often and allowed the hydrogen to diffuse from the wire and return the wire ductility to normal.[11] Sufficient hydrogen could not build up in the wire until power was uninterrupted long enough to cause rupture.

The effect of high levels of CP at the potential required to cause HE must be addressed because of the use of high-strength prestressing wire in PCCP. The most probable reaction occurring on the pipe under excessive CP at pH >7 is the electrolysis of water. During the formation of H_2, hydrogen atoms are produced on the metal surface. Before combining to form hydrogen gas, atomic hydrogen may penetrate the steel. This entry of hydrogen causes a loss of ductility, or embrittlement, of the prestressing wire.

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 ~7. The pH of corrosion products can be as low as 2 to 3. However, under CP, the pH at the wire surface will increase rapidly in a few hours or days to a value > 12.4 because of the production of hydroxide ions or the consumption of hydrogen ions.

At a low current density of 1 µA/ft² (11 µA/m²), it would require only 70 h to bring the pH in a 1-µm thick layer around a steel rod from 7 to 12.45 in accordance with Faraday's Law. A current density of 1 µA/ft² is not expected initially to polarize the steel to values more negative than –730 mV, the value where hydrogen production begins at a pH of 7.

Monitoring of PCCP for Corrosion

Corrosion of the encased steel elements seldom occurs because of the passivating properties of portland cement. 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 is occurring.

Potential monitoring techniques often are used to determine whether encased steel in PCCP is corroding. The techniques are identical to those used for cathodically protected steel 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. Potentials more negative than –300 mV can indicate corrosion, current pickup, or that the line is being cathodically protected.[12] If corrosion is found only within a unit pipe section, excavation and repair of the pipe may preclude the use of CP.

Laboratory Phase

This 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 caused by corroding wire, the susceptibility of prestressing wire to HE, and the approximate length of time and potentials to produce HE 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 were evaluated. The maximum CP potential that high-strength prestressing wire can withstand without failure in those environments was determined.[10]

Test Procedure

ASTM A648, Class III prestressing wire specimens from three manufacturers were subjected to no CP and to CP polarization potentials of –850 mV_{CSE} and –1,000 mV_{CSE} as well as cathodic overprotection values of –1,200 mV in a saturated calcium hydroxide ($Ca[OH]_2$) solution for up to 86 months.

Prior to exposure, most of the wire specimens were stressed and maintained at 60% of specified minimum tensile strength, which is the approximate stressed value of the wire in PCCP. A coal tar epoxy coating was applied to the wire specimen surface 1 in. (2.5 cm) above and below the solution level to prevent failure at the air/solution interface.

Specimens were immersed in solutions to simulate the high-alkaline, corrosion-inhibiting environment provided by portland cement or in a hydrochloric acid (HCl) solution (pH 2) to simulate the condition around a severely corroded wire in mortar.

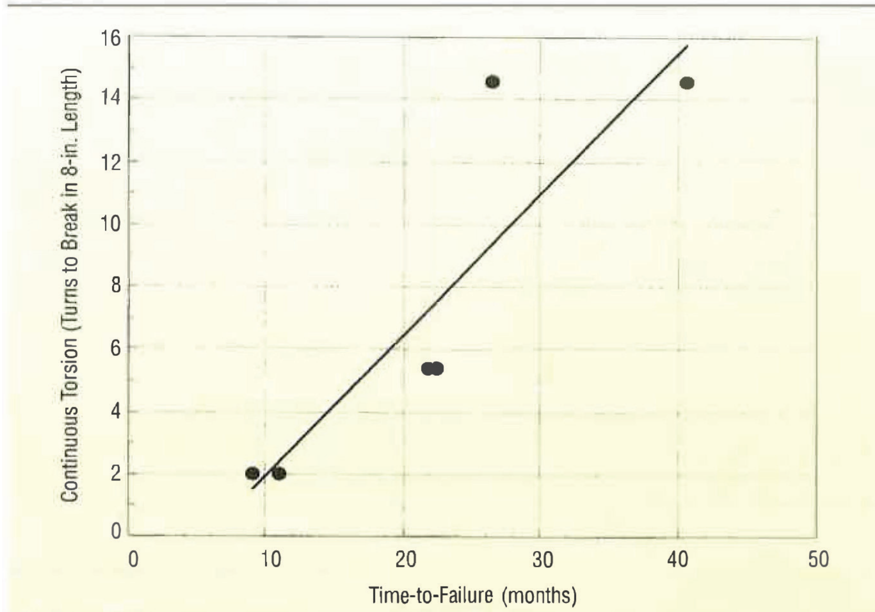

FIGURE 5
Time-to-failure of prestressing wire held at –1,200 mV_{CSE} as a function of continuous torsion.

TABLE 1
Effect of Temperature on 1/4-in. 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-in. length)	15 a 18 a	19 a 15 a 21 a,b	16 a,aj 17 a,b 2 aj	12 a 16 a,b 18 a,b	1 aj 3 aj,c 1 aj,c

a = smooth transverse break; b = inclined break; aj = jagged transverse break; c = a helical crack.

TABLE 2
Continuous Torsion, Reduction of Area, and Tensile Strength of 6-Gage Prestressing Wire Subjected to CP at 3 A/ft² in a $Ca(OH)_2$ Solution for 6 Months

	Continuous Torsion (turns to and type of break)		Reduction of Area (%)		Tensile Strength, ksi (MPa)	
Exposure	Individual	Average	Individual	Average	Individual	Average
CP at 3 A/ft² for 6 months	1 aj 2 aj 2 aj	2	30.4 28.7 31.5	30.2	279 (1,930) 276 (1,900) 280 (1,930)	278 (1,920)
No CP	36 a 28 a 37 b,a,b	34	50.7 50.2 53.0	51.3	278 (1,920) 278 (1,920) 277 (1,910)	278 (1,920)

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

CP of Passive Wire in Simulated Mortar at pH 12.45. At varying time periods, from 3 to 80 months, two 6-gage stressed wire specimens at no CP, and at –850, –1,000, and –1,200 mV_{CSE}, were removed from exposure. Tensile

TABLE 3
Tensile Strength, Reduction of Area, and Hydrogen Content of 6-Gage Prestressing Wire in a HCl Solution at –1,000 mV_{CSE}

Exposure	Tensile Strength, ksi (MPa)	Reduction of Area (%)	Occurrence of Splits	Hydrogen Content (ppm)
None	279 (1,930)	48.4	None	2
	277 (1,910)	51.4	None	3
	282 (1,940)	48.9	None	—
2 weeks corroding	263 (1,810)	49.3	None	2
	282 (1,940)	49.6	None	2
2 weeks corroding PLUS 2 months at –1,000 mV	280 (1,930)	42.7	None	4
	278 (1,920)	45.5	None	—
	273 (1,880)	46.6	None	3
	273 (1,880)	46.9	None	—

TABLE 4
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
–1,000	47.4	48.3	48.1
–1,100	44.5	48.1	46.7
–1,180	40.6	45.0	47.4
–1,260	37.0	46.2	48.0
		Hydrogen content (ppm)	
–1,200	7.4	—	4.1 (7 weeks)

strength properties were immediately determined in accordance with ASTM A648-90a.

Susceptibility of Prestressing Wire to HE. The ductility of prestressing wire after applying high levels of CP were determined using area reduction and continuous torsion in all of the above tests. The ductility of the wire, expressed by turns to break in continuous torsion before CP, was related to the time-to-failure under CP.

The ductility of prestressing wire, after heating the wire to simulate possible wire temperatures during the drawing process, was determined using continuous torsion in accordance with ASTM A648.

CP of Severely Corroded Wire at pH 2. After 2 weeks of immersion in the HCl solution (pH 2) followed by 2 months at –1,000 mV, two 6-gage stressed wire specimens were removed, and their properties were determined in accordance with ASTM A648-90a.

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.

Test Results

CP of Passive Wire in Simulated Mortar at pH 12.45. Figures 2 and 3 show the effects of CP on tensile strength and reduction of area of prestressing wire from two manufacturers maintained at 60% of specified minimum tensile strength in a saturated $Ca(OH)_2$ solution for 3, 6, and 12 months and longer at no CP and at –850, –1,000, and –1,200 mV.

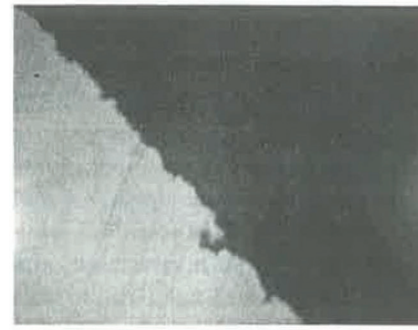

FIGURE 6
Cross section of 6-gage prestressing wire after corroding for 2 weeks in a pH 2 HCl solution followed by 2 months at –1,000 mV_{CSE}. The pits are possible initiation sites for fractures during excessive CP.

The normal-load rate tensile strength was not affected by the level of CP and indicated that the tensile strength cannot be used to determine whether the wire was subjected to excessive CP. The scatter in the tensile strength was typically seen within a coil.

If the slow strain rate test (SSRT) or constant extension rate test (CERT) strength is significantly lower than the normal-rate strength, HE can be considered.

Figure 4 shows the effect of CP on the hydrogen content of the immersed specimens. For plotting purposes, the potentials of the non-cathodically protected but immersed specimens were arbitrarily placed at –200 mV. For comparison purposes, the hydrogen contents of the control specimens determined at 3, 6, and 12 months were plotted at –100 mV even though they were never immersed.

Figure 5 shows time-to-failure of a prestressing wire specimen held at –1,200 mV at 60% of its specified minimum tensile strength. 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 was dependent on the number of turns to break in continuous torsion determined on non-exposed (control) specimens. Embrittlement of the wire occurred. It appeared that wire with higher turns to break in continuous torsion (greater ductility) had a lower susceptibility to HE. This supported the continuous torsion requirement in AWWA C301.

Susceptibility of Prestressing Wire to HE. The quality of the wire, as expressed by the number of turns to break in continuous torsion before exposure, substantially affects its susceptibility to HE and subsequent fracture (Figure 5).

The ductility as expressed by continuous torsion appears to be significantly affected by an increase in wire temperature during the drawing process.[11] Table 1 shows the effect of temperature on continuous torsion. The wire was severely damaged at 375°F (190°C). 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.

Table 2 shows the effect of extremely excessive cathodic current of 3.00 A/ft^2 (32.4 A/m^2) on prestressing wire immersed in a saturated $Ca(OH)_2$ solution for 6 months. The polarization potentials ranged from –1,060 mV_{CSE} to –1,280 mV_{CSE}. Continuous torsion and reduction of area substantially decreased during the 6 months of exposure, which demonstrated the drastic effect that excessive CP can have on the ductility of the prestressing wire.

CP of Severely Corroded Wire at pH 2. Table 3 shows the effect of CP on tensile strength, reduction of area, and hydrogen content of prestressing wire maintained at 60% of its specified minimum tensile strength in a 0.01 M HCl solution for 2 weeks without CP, simulating an acidic condition possible around severely corroded wire, followed by 2 months at –1,000 mV. Four specimens at –1,000 mV did not fail after 24 months of exposure.

Figure 6 shows the cross section of a wire specimen exposed to 2 weeks of corrosion plus 2 months at –1,000 mV. Pits caused by the 2 weeks of corrosion were evident and could be sites for possible fractures to occur while under excessive levels of CP.

CP of Longitudinally Split Wire at pH 2. No failures occurred after 20 months of exposure, indicating that even severely notched prestressing wire located in an acidic environment prior to exposure is not extremely sensitive to HE.

Recovery of Ductility. Table 4 shows the effect of CP on the diffusion of hydrogen from the wire and recovery of ductility as expressed as reduction of area. The loss of ductility, or embrittlement, is reversible. A pipeline that is subjected to excessive CP may be returned to service by turning off or reducing the CP level to allow hydrogen to diffuse from the steel.

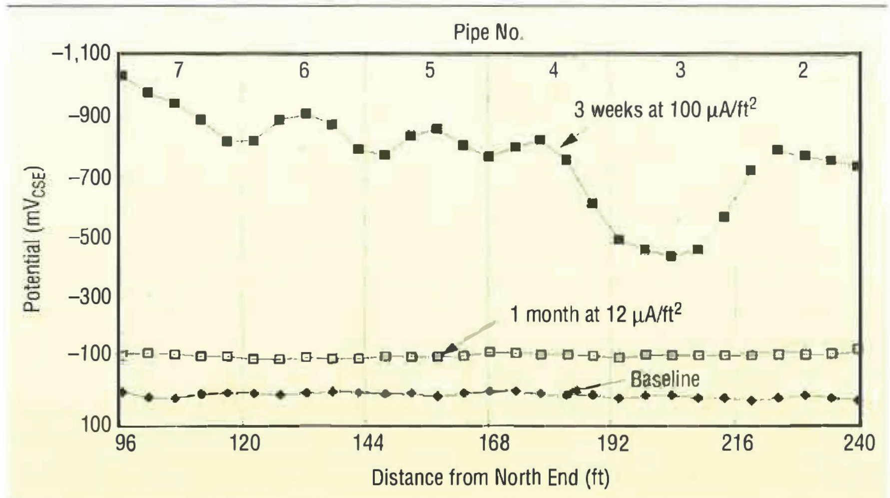

FIGURE 7
Baseline and polarization potentials of PCCP line under CP at 12 µA/ft^2 and 100 µA/ft^2.

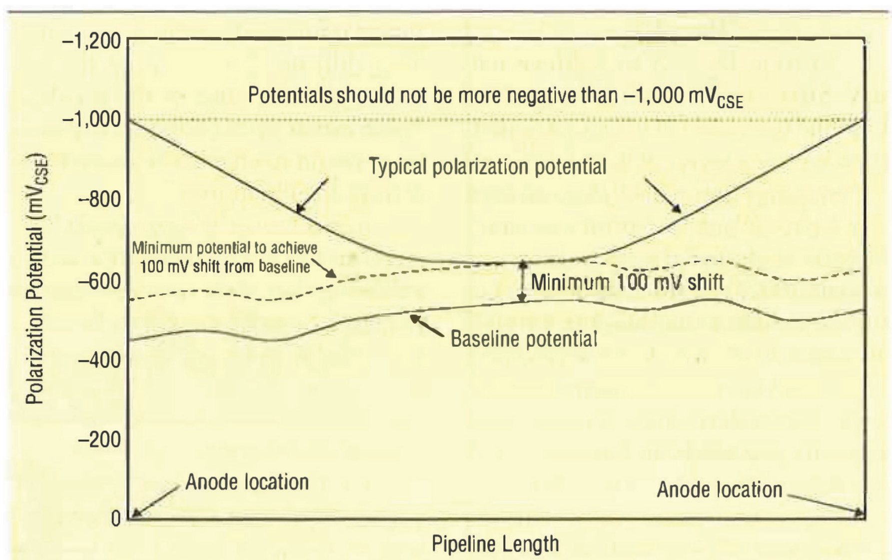

FIGURE 8
Simplified diagram to illustrate the CP design concept of a pipeline to meet the minimum and maximum CP criteria.

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 –1,000 mV_{CSE} while realizing that the actual current density required for other type pipelines will differ.

Test Setup

This project consisted of installing an impressed current CP system on a 48-in. (1.22-m) diameter by 240-ft (73-m) long PCCP line and measuring polarization and depolarization potentials and current of the pipeline during 1 year of system activation. The pipeline consisted of 10 24-ft (7.3-m) long PCCP sections. Each pipe was manufactured with two 1-in. wide shorting straps that were 180 degrees apart to reduce the electrical attenuation along the prestressing wire in each pipe section.

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. Only the joint bonds provided electrical continuity.

Two of the pipe sections were coated with a 0.026-in. (660-µm) thick supplemental coal tar epoxy coating and two of the sections were wrapped in a 0.008-in. (200 µm) thick polyethylene (PE) film. Pinholes were present in both coating systems. Six sections had no additional supplemental protection.

The pipe sections were installed with 6 ft (1.8 m) of cover in an arid environment. Mortared night caps were provided at each end with two access manholes. The native soil at the site was a sandy gravel ranging from 100,000 Ω-cm to 200,000 Ω-cm dry and 16,000 Ω-cm to 30,500 Ω-cm saturated, and a pH range from 7.8 to 8.2. The pipeline was backfilled with sand (13.400 Ω-cm to 63.200 Ω-cm). Provisions were made to allow electrical connection or disconnection between adjacent pipe sections to simulate bonded and unbonded pipelines.

A 4-in. (10-cm) diameter by 45-in. (110-cm) long steel pipe buried 20 ft (6.1 m) perpendicular to the last pipe was used as the anode, to simulate CP systems where anodes are installed close to the pipeline. Gypsum was placed around the anode. A variable power supply was used. A baseline potential survey was taken prior to activating the CP system. Potentials were measured approximately every 5 ft (1.5 m) along the centerline of the pipeline. Current-on and polarization (instant current-off) potentials and current were recorded.

Results

Current Density to Achieve 100 mV Shift and –1,000 mV_{CSE}. The baseline potentials of the six uncoated pipe sections were –0 (CSE) (Figure 7). Since previous work[13] showed that 25 µA/ft² (270 µA/m²) produced a polarization shift of 180 mV during 3 months of CP, the current density on the six sections of uncoated PCCP was adjusted to 12 µA/ft² (130 µA/m²) based on the mortar coating surface area. The polarization (instant current-off) potentials at 3 weeks of CP are shown. The polarization shift was –120 mV. The depolarization shift after 3 weeks of polarization was 100 mV in 4 h and 120 mV after 1 week.

In addition, the average current density required to achieve polarization potentials not < –1,000 mV_{CSE} on the pipe nearest the anode was 100 µA/ft² (1,080 µA/m²). Figure 7 gives the polarization potentials of the pipeline. This indicates that the design current density for PCCP is roughly 100 µA/ft². Within each 24-ft long PCCP section with shorting straps, the most negative potential is in the center of each pipe section, not at the joint.

Current Flow to Prestressing Wire and Cylinder. 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 balance to the cylinder.

Discussion

When serious PCCP pipe corrosion exists, CP can be installed. 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 steel 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 RP0169 allows a 100 mV polarization or depolarization shift. This 100 mV shift also is used as a criterion in RP0290 to protect the steel in atmospherically exposed reinforced concrete structures. This shift needs to occur at the corroding, anodic sites of the pipeline. Polarization shifts of only 20 mV have been found to effectively protect corroding steel in mortar.[7]

In most cases, the pipe joints have a bell and spigot configuration with a rubber gasket. This requires that the joints be bonded for CP to be effective. In the tests performed, embrittlement did not occur at –1,000 mV_{CSE} but signs of embrittlement were evident at –1,100 mV.

CP Design Concept. When applying CP to a PCCP line, the polarization potential should not be more negative than –1,000 mV_{CSE} to prevent HE 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.

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. Then, the corroding areas furthest from the anode bed should polarize at least 100 mV from its corroding potential with potentials that are never more negative than –1,000 mV_{CSE}.

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 –1,000 mV (Figure 8).

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.
- CP is rarely required because of PCCP's inherent corrosion resistance.
- The minimum CP potential shift criterion is 100 mV polarization or depolarization.
- Prestressed wire is susceptible to HE 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 –1,000 mV_{CSE} to avoid HE. More negative potentials can embrittle and split prestressing wire. They also can greatly increase the cost of CP and not improve corrosion protection.
- The ductility of prestressing wire under excessive CP recovered after CP was discontinued, mostly during the first 4 weeks but at least 8 weeks were required for a full recovery.
- CP increases the pH around the prestressing wire in carbonated mortar or around corroding wire to initial uncarbonated or noncorroding levels. Limiting potentials do not need to be adjusted to values more positive than –1,000 mV because of the rapid increase in pH around the wire during CP.
- The continuous torsion test in ASTM A648 is an excellent means to determine the susceptibility of prestressing wire to HE. 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 HE.
- The current from a CP system distributes equally to the prestressing wire and steel cylinder in PCCP.

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Technical Editor's Note: *This is an abbreviated version of CORROSION/98 paper no. 637, presented in San Diego, California. The essential elements of the text have been retained as well as explanatory portions of the original. Details such as those describing laboratory equipment, procedures, and certain findings have been reduced. Case histories of five field applications and results in various environmnents may be obtained by contacting NACE Headquarters at phone: 281/228- 6223 to order a copy of the entire original paper.*

Sylvia C. Hall (now with Sylvia Hall Engineering [SHE]) was a director at Ameron International Corp. She has 35 years of experience in corrosion and corrosion control of concrete pressure pipe. She has conducted extensive research in HE of prestressing wire used in prestressed concrete pipe. She has masters degrees in chemistry and business administration, is a professional engineer (corrosion) in California, and is a NACE-Certified CP Specialist. She is a 38-year member of NACE.

From the Author—Today's Practice

This article was based on 13 years of research following a rupture of a PCCP in 1984 subjected to CP with polarization potentials in the range of –1,150 to –1,250 mV (CSE). Even though HE of high-strength steels was recognized in the corrosion industry, others did not think HE was the cause.

This research led to the development of and the CP criteria in NACE RP0100-2000, "Cathodic Protection of Prestressed Concrete Cylinder Pipelines." The RP was expanded in 2008 to NACE SP0100-2008, "CP to Control External Corrosion of Concrete Pressure Pipelines and Mortar-Coated Steel Pipelines for Water and Waste Water Service" and included additional concrete and steel pressure pipe.

The remaining prestressing wire specimens under exposure mentioned in the CORROSION/98 Paper no. 637 that this article was based continued to be maintained until the author left the company in 2013. The specimens from wire manufacturers "A", "B," and "C" at –1,000 mV (CSE) and stressed at 60% of its minimum specified tensile strength in a simulated mortar environment were cathodically protected at –1,000 mV (CSE) for 23 years without failure.

—Sylvia C. Hall, PE