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CORROSION CONTROL OF PRESTRESSED CONCRETE CYLINDER PIPE

Sylvia C. Hall, PE[1]

Abstract

Recommendations for corrosion control of prestressed concrete cylinder pipe (PCCP) lines are given to ensure that the passivating (corrosion-inhibiting) film is maintained, that the pipeline can be monitored, and that, if necessary, cathodic protection can be applied. Standard recommendations for corrosion control of PCCP are discussed first, followed by special recommendations for PCCP installed in unusually corrosive environments. These environments include acidic, high sulfate-containing, or high chloride-containing soils and waters, stray current interference, and connections to other pipelines. Other less commonly encountered environments include subaqueous installations, long-term atmospheric exposure, and transition from soil or water to air.

Introduction

PCCP is a rigid and durable pressure pipe designed to take optimum advantage of the compressive strength and corrosion-inhibiting property of portland cement concrete and the tensile strength of steel. Most PCCP produced in the United States and Canada is designed and manufactured in accordance with American Water Works Association Standard C301 and C304 (AWWA 1992). It includes a steel cylinder, a rigid concrete core, circumferentially wrapped prestressing wire, and a protective mortar coating. The components of an installed PCCP are identified in Figure 1.

PCCP was first installed in the United States in 1942 (AWWA C301 1992). From 1942 to 1995, 30,700 km (19,100 miles) of PCCP have been installed in North America (Clift 1991; Prosser 1996), principally for the transmission of water for municipal, industrial, and agricultural uses.

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[1]Director, Ameron International Corporation, Engineering Development Center, 8627 South Atlantic Avenue, South Gate, CA 90280

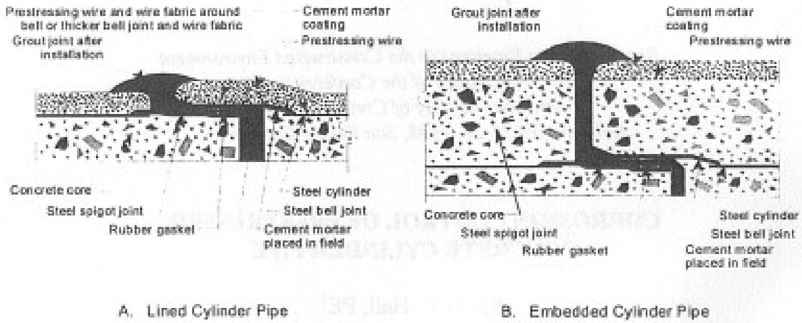

Figure 1. Components of installed PCCP

PCCP is remarkably resistant to physical damage and corrosion under a wide range of environmental conditions. This performance is due in large measure to the effects of circumferential prestressing which places the concrete core in compression. This compression induced in the core makes it possible to design PCCP to withstand the combined effects of internal pressure and external load without exceeding the tensile strength of the concrete core. Experience and extensive testing have shown that this design approach also ensures that the protective cement mortar coating will be visibly crack-free under operating conditions. In addition, corrosion of steel elements in the pipe is prevented by a passivating iron oxide film which quickly forms and is maintained in the highly alkaline concrete core and cement-mortar coating (Scott, 1965; Hausmann, 1964).

Unusual environmental conditions can be recognized and effectively dealt with before damage occurs. These conditions include sulfate or acid attack, high chloride-containing soils and waters, stray current electrolysis, and connections to other pipelines. Other less commonly encountered conditions include subaqueous installations, long-term atmospheric exposure, and transition from soil or water to air.

The recommendations that follow ensure that the passivating film on all steel elements is maintained, that the pipeline can be monitored, and that, if necessary, cathodic protection can be applied. Standard recommendations for corrosion control of PCCP are discussed first, followed by special recommendations for PCCP installed in unusually corrosive environments. The recommendations are summarized in Table 1.

Recommended Corrosion Control Provisions

The following standard corrosion control provisions are recommended as part of the manufacture and installation of all PCCP buried pipelines:

- Provide a steel shorting strap under the prestressing wire
- Apply cement slurry to the core during both prestressing and mortar coating operations

TABLE 1
RECOMMENDATIONS FOR PROTECTION OF PCCP IN CORROSIVE ENVIRONMENTS

Condition	Criteria	Recommendations
Normal exposure	Non-corrosive environments	1, 2, 3 and 4
High sulfate soils/waters	Soils containing more than 0.2% $SO_4^=$ or waters containing more than 2000 ppm $SO4^=$	1, 2, 3, 4 and 5
Acidic soils or waters	Soil pH less than 5.0	1, 2, 3, 4 and 6
High chloride soils/waters	Chloride content in soil or water greater than 350 ppm. As a guideline, soils with resistivities less than 1500 ohm cm should be analyzed for chloride content.	1, 2, 3, 4 and 6
Stray-current interference	Prolonged discharge of direct current picked up from cathodic protection systems or other DC systems	1, 2, 3, 4 and 6 or 1, 2, 3, 4, and 7
Corrosive water	Water with a pH less than 5.5 conveyed or containing chemicals corrosive to concrete	1, 2, 3, 4 and 8
Subaqueous installations	Continuous immersion	1, 2, 3 and 4 or 1, 2, 4, 7 and 9
Atmospheric exposure	Continuous atmospheric exposure for more than 5 years	1*, 2, 10 and 11
Transition from buried to atmospheric exposure		1, 2, 3, 4 and 12
Connections to organically-coated steel pipelines	Buried pipelines	13

*Shorting strap and electrical continuity not required.

Recommendations:

1 = Provide a steel shorting strap under the prestressing wire; apply cement slurry to the core at time of prestressing and mortar coating; apply a 3/4-inch-thick (19 mm) mortar coating over the prestressing wire; make all steel components in the pipe electrically continuous.
2 = Fill interior joint recesses with cement mortar.
3 = Fill exterior joint recesses with cement mortar grout confined in polyethylene-foam-lined grout bands.
4 = Make all pipeline joints electrically continuous with low-resistance bonds; provide test stations to monitor pipe potentials and current flow.
5 = Use portland cement containing not more than 5 percent tricalcium aluminate for all concrete and cement mortar components.
6 = Seal the pipe exterior with a high-build barrier seal coating.
7 = Apply cathodic protection.
8 = Line the pipe with polyvinyl chloride sheet.
9 = Coat steel joint rings with a high-build barrier seal coating applied over an epoxy polyamide primer.
10 = Coat steel joint rings with a high-solids epoxy coating applied over an inorganic zinc primer.
11 = Seal the pipe exterior with an acrylic latex coating; recoat as necessary to maintain coating integrity.
12 = Seal the pipe exterior with a high-build barrier seal coating from 0.9 m (3 ft) below to 0.3 m (1 ft) above the ground surface.
13 = Electrically insulate the connecting pipelines.

- Apply a 19 mm (3/4-inch) thick mortar coating over the prestressing wire
- Electrically bond the joints of installed pipe
- Fill interior joint recesses with cement mortar
- Fill exterior joint recesses with cement mortar grout confined in polyethylene-foam-lined grout bands.

The first four provisions are incorporated during manufacture. The shorting strap is a thin steel band which electrically contacts each wrap of prestressing wire. Its purpose is to reduce the voltage drop in the long prestressing wire if cathodic protection is later applied. Making all steel elements in each pipe electrically continuous is a requirement for both corrosion monitoring and cathodic protection. It is accomplished by welding the prestress anchor assemblies to the steel joint rings during pipe manufacture.

Cement slurry having the consistency of thick cream is applied at time of prestressing and again at time of mortar coating to ensure complete encasement of the prestressing wire in a highly alkaline environment.

Bonding the steel joint rings makes the entire pipeline electrically continuous for monitoring and, if necessary, for cathodic protection. Suggested bonding details are shown in Figure 2 (AWWA 1995).

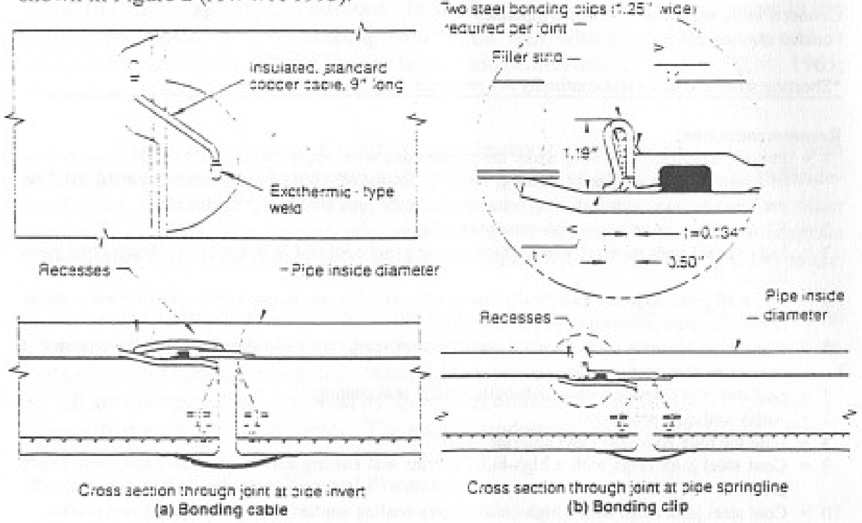

Figure 2. Suggested joint bonding details for PCCP.

Filling the interior and exterior joint recesses with cement mortar prevents corrosion of the joint rings. Cracks which may later occur in the interior joint mortar heal through deposition of calcium carbonate after the pipe is filled with water, a

process often referred to as autogenous healing (Dhir et al 1973; Wagner 1974). Cracks in the exterior joint mortar generally heal by the same process, but additional protection against groundwater infiltration is provided by the polyethylene-foam-lined grout band shown in Figure 3.

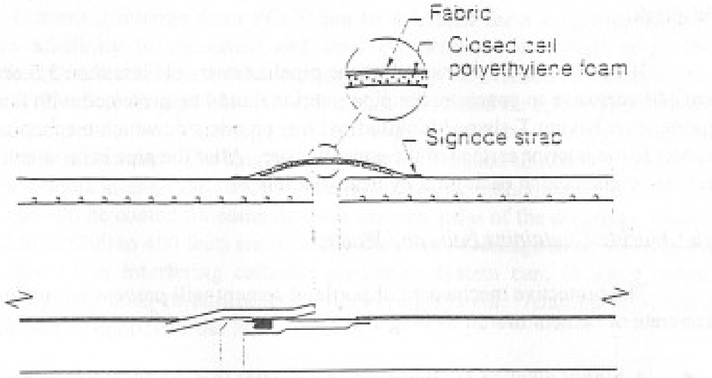

Figure 3. Joint grout band recommended for use on PCCP.

Unusual Environmental Conditions

Unusual environmental conditions can be recognized and effectively dealt with before damage occurs. These conditions include soils and waters which contain high sulfate or chloride contents or are acidic, stray current interference, and connections to other pipelines. Other less commonly encountered conditions include subaqueous installations, long-term atmospheric exposure, and transition from soil or water to air. Criteria and recommendations for these unusual conditions are given in Table 1 and are discussed in greater detail in the sections which follow.

High Sulfate-Containing Soils and Waters

Experience has shown that most soils and waters have little chemical effect on the concrete and cement mortar components of buried pipelines. However, soils or waters with high sulfate content are potentially damaging to the portland cement matrix. To increase resistance to sulfate attack, the use of a portland cement containing not more than 5 percent tricalcium aluminate is recommended for pipe installed in soil containing more than 0.2 percent water-soluble sulfate ion or in waters containing more than 2000 ppm sulfate ion (USBR 1975). While these recommendations have been applied for many years to all types of concrete structures, practically all known incidents of sulfate attack have involved the buildup of exceedingly high sulfate concentrations on partially buried or partially submerged structures. Buried or subaqueous concrete pipelines have proved to be unaffected by this type of attack. For example, sulfate attack does not occur on concrete pipelines submerged in the ocean even though seawater contains approximately 2700 ppm sulfate ion.

Acidic Soils and Waters

When exposed to soils of pH less than 5.0 (Am. Concrete Pipe Assoc. 1980), all exterior pipe surfaces should be sealed with a high-build barrier coating to prevent acid attack.

If water or liquid conveyed by the pipeline has a pH less than 5.5 or contains chemicals corrosive to concrete, the pipe interior should be protected with a polyvinyl chloride sheet having T-shaped longitudinal fins on one side which mechanically lock the sheet to the interior surface of the concrete core. After the pipe is installed, the liner sheets are connected at each joint by heat welding.

High Chloride-Containing Soils and Waters

The protective mechanism of portland cement will prevent corrosion of steel in concrete or cement mortar as long as:

- A highly alkaline environment (pH greater than 11.5) is maintained at steel surfaces, and
- Both chlorides (Cl^-) and oxygen (O_2) are prevented from reaching steel surfaces in quantities sufficient to initiate corrosion cells (Scott 1965; Hausmann 1964, 1967).

In most environments, the above conditions are satisfied for the life of the pipeline, and consequently, corrosion caused by chloride ions seldom occurs. Supplemental protection against corrosion in high chloride soils and waters can be provided by use of a high-build barrier coating applied over the mortar coating (Hall et al 1996). This provision is recommended in soils containing more than 350 ppm chloride ions (Cl^-). A more stringent limit of 150 ppm may be appropriate in soils subject to cyclical wetting and drying, an occurrence which accelerates the buildup of chlorides in the mortar coating.

High-chloride soils have low electrical resistivity. Since soil resistivity can be measured rapidly in the field, it is recommended that a soil resistivity survey be performed to identify soils of potentially high-chloride content along the pipeline right-of-way. As a guideline, soils of resistivity less than 1500 ohmcm should be analyzed for chloride content.

Stray-Current Interference

Buried metallic pipelines may collect and discharge stray currents which originate from nearby cathodically protected pipelines, electric railways, and other sources of direct current. The discharge of such currents from organically coated steel pipelines occurs at pinholes or other flaws in the coating and results in steel pitting at these locations. The effects of current discharge are quite different for steel encased in

concrete or cement mortar. In this case, current discharge is opposed by polarization effects, occurs over large surface areas, and initially consumes alkalinity at steel surfaces rather than the steel itself (Hausmann 1964; Scott 1965; Hall et al 1996).

Current discharge from PCCP can be tolerated for a long time before the protective alkalinity is consumed and steel corrosion occurs (Hall et al 1996). Nevertheless, it is recommended that current discharge be avoided or controlled when recognized. Coating the pipe exterior with a high-build coal tar epoxy greatly reduces both current pickup and discharge and is recommended on new pipelines when interference is anticipated. The length of pipeline to be coated should be determined by a pipeline corrosion engineer. PCCP pipelines crossing cathodically protected steel pipelines should be coated for some distance on both sides of the crossing. Distances of 60 to 120 m (200 to 400 feet) are typically specified. Damage to an existing PCCP pipeline due to an interfering cathodic protection system can, in some cases, be prevented by relocating or adjusting the interfering system. Alternatively, cathodic protection can be applied to the PCCP line.

Connections to Other Pipelines

The potential of steel in concrete normally lies between -50 mV and -250 mV (CSE) which is approximately 300 mV more noble than the potential of bare steel. Consequently, if an uninsulated connection is made between a PCCP line and an organically coated steel pipeline, the steel pipeline may corrode sacrificially, protecting the PCCP line. The problem can be avoided by insulating the connection between the two dissimilar piping materials or by mortar coating the steel pipeline so that the steel in both pipelines is at the same potential.

Subaqueous Installations

In subaqueous pipelines, the preferred method of joint protection is cement mortar inside and out. Where this method of protection is impractical, it may be possible to mortar interior joint recesses and cathodically protect exterior steel joint ring surfaces. To reduce the current required for cathodic protection, it is recommended that the joint rings be coated with a high-build coating applied over an epoxy polyamide primer.

For low-pressure pipelines, typical of many seawater cooling systems, prestressed concrete pipe can be produced without an embedded steel cylinder and with an all-concrete joint which does not require supplemental protection.

Atmospheric Exposure

Application of an acrylic latex seal coat to the pipe exterior is recommended for PCCP continuously exposed to the atmosphere for more than 5 years. In this case, the function of the seal coat is to reduce drying shrinkage in the mortar coating and to prevent loss of coating alkalinity due to reaction between calcium hydroxide in the mortar and carbon dioxide in the atmosphere, a process known as carbonation. Recoating may be necessary every 10 to 15 years to maintain coating effectiveness.

Transition from Soil to Air

PCCP lines extending from below ground to above ground should be protected with an exterior seal coat in the transition zone to prevent the accumulation of soil chemicals by wicking action in mortar coating. Application of a high-build barrier coating is recommended from 0.9 m (3 feet) below to 0.3 m (1 foot) above the ground surface.

Monitoring

Buried pipelines should be monitored periodically to determine pipeline potentials, current flow, and effectiveness of insulated connections. Measurements of pipeline potentials is especially significant because of the unique potential of steel in portland cement environments. As noted earlier, the potential of steel in concrete or cement mortar normally lies between -50 and -250 mV versus a copper-copper sulfate reference electrode (CSE). Pipeline potentials in this range usually indicate that exterior steel surfaces in the pipeline are passivated and protected from corrosion. However, a sudden shift in potential from the apparent baseline of the survey, although still within the -50 to -250 mV range, can also indicate that corrosion is occurring (Hall 1994). Potentials more positive than approximately +50 mV (CSE) are usually indicative of direct current discharge from pipe to soil.

Potentials more negative than approximately -300 mV (CSE) indicate either that steel corrosion is occurring somewhere on the pipeline or that the pipeline is collecting current from a cathodic protection system or some other current source. The occurrence of cathodic interference can be verified by determining the magnitude and direction of current flow along the pipeline. Identification of corrosion activity may require visual inspection of the pipeline at selected locations, supplemented by pipe potential measurements made directly against the mortar coating.

To utilize monitoring procedures effectively, pipe joints in the installed pipeline should be electrically bonded and connections for test leads should be provided at convenient intervals, such as every 300 m (1000 feet) along the pipeline (Carlson 1995; Hall 1994).

Cathodic Protection

Cathodic protection of PCCP pipelines is seldom required and should not be applied indiscriminately. However, the following circumstances may justify the use of cathodic protection:

- ♦ *Stray current electrolysis.* Cathodic protection is required only at sites of current discharge and only at levels sufficient to counter the discharge.
- ♦ *Damaged pipe.* The option of repairing a damaged or defective pipeline should be carefully considered; cathodic protection, if used, is required only at damaged areas.
- ♦ *Bare or organically coated steel.* Corrosion of uninsulated steel appurtenances or pipelines can be prevented by local application of cathodic protection.

Cathodic protection of limited areas is often obtained most economically with galvanic anodes. Impressed current cathodic protection may be suitable if more extensive coverage is required.

There are no universally accepted criteria for cathodic protection of steel in concrete. A commonly used criterion for cathodic protection of bare or organically coated steel is a steel potential of -850 mV (CSE) (RP0169-96 1996). This criterion can be applied to PCCP lines where bare steel is exposed or is no longer passivated in an alkaline environment. Two other criteria for cathodic protection are a minimum negative (cathodic) polarization shift or decay of 100 mV (RP0169-96 1996; RP0290-90 1990). These criteria have been used successfully in the protection of concrete pressure pipelines (Benedict 1989; Hall & Mathew 1995; Hall 1998). The maximum interrupted-current potential should not exceed -1000 mV (CSE) on PCCP to avoid evolution of hydrogen (Scott 1965; Hausmann 1964) and possible embrittlement of the prestressing wire (Hall & Mathew 1995; Hall et al 1996; Hall 1998).

Current density requirements of operating cathodic protection systems of unsealed PCCP lines have been shown to range from 100 to 1000 microampere/m^2 (10 to 100 microampere/ft^2) to achieve the 100 mV minimum shift and -1000 mV (CSE) maximum criteria (Hall 1998). Current density requirements on PCCP lines sealed with a barrier coating have been shown to be approximately 3 to 4 times less than that of unsealed lines (Hall et al 1994; Hall 1998).

Planning

Proper planning early in the design of a PCCP pipeline can prevent corrosion problems. Planning should include a survey to determine soil resistivity, pH, and chloride and sulfate contents along the right-of-way. Locations of parallel and crossing pipelines, cathodic protection and other DC sources, and connections to other pipelines should also be determined. A qualified corrosion engineer should be retained to interpret the information and to recommend corrosion control provisions.

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