FINAL REPORT

PERFORMANCE OF A CONDUCTIVE-PAINT ANODE IN CATHODIC PROTECTION SYSTEMS FOR INLAND CONCRETE BRIDGE PIERS IN VIRGINIA

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16. Abstract

As part of efforts to identify effective and durable anodes for use in cathodic protection of different reinforced concrete members, a water-based conductive paint was tested in two CP systems that were built, one 8 years ago and the other 6 years ago, to protect the concrete piers of twin inland bridges in Virginia. Measurements made at various times of circuit current, voltage, rebar potential, and 4-hour polarization indicated that the CP systems were providing more than sufficient protection to the rebars. Natural paint deterioration (peeling, cracks, stains, etc.) that was observed in the conductive paint ranged from 0% to 0.37% in the older system and 0% to 0.14% in the newer system. Most of the deterioration was located at the exposed ends of the pier caps. Overall, the performance of the conductive paint indicated that (1) earlier prediction by some experts of premature failure of the paint once it is polarized is unwarranted, and (2) barring any extremely rapid paint deterioration in the future, it is a reasonable estimate that the service life of the conductive paint is at least 15 years – especially if minor paint deterioration is touched up as early as possible.

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

As part of efforts to identify effective and durable anodes for use in cathodic protection (CP) of reinforced concrete members, a water-based, electrically conductive paint was evaluated for use as the secondary anode in CP systems for protecting inland concrete piers. In such piers, the concrete areas susceptible to rebar corrosion are not constantly wet as they are in marine environments. The paint was used in two CP systems, one 6 years old and the other 8 years old, that were designed to protect the concrete piers of two pairs of twin bridges in inland Virginia.

Measurements of circuit current, circuit voltage, rebar potential, and 4-hour depolarization indicated that the two CP systems were operating as expected and providing more than sufficient protection to the rebars in the concrete piers. Paint deterioration, such as peeling, cracks, and stains, occurred in both systems. The extent of the deterioration was estimated with the use of a newly developed digital image analysis method, and the largest area of damage was 2.40 percent of the total coated concrete area of a pier protected by the older CP system. Since this unusually large area was restricted to the upstream-side footing of the pier, it was attributed to abrasion and damage caused by timber debris crashing against the footing as the result of recent severe flooding. Other than this area, the natural deterioration in the paint system ranged from only 0 to 0.37 percent. Similar deterioration in the second paint system ranged from only 0 to 0.14 percent.

Most of the paint deterioration in both systems was at the ends of the pier caps, where the concrete was not sheltered from rain by the deck overhang. This suggests that even with inland concrete piers, deterioration of the conductive paint, albeit slow, can occur on any portion of the concrete that becomes wet intermittently, either by rainfall or drainage from the deck. Therefore, extra measures for avoiding this problem must be considered in the design of any CP system that uses the conductive paint as a secondary anode.

Overall, the performance of the paint was better than expected, and its effectiveness can reasonably be expected to last for at least 15 years if minor deterioration is touched up as soon as possible. This type of conductive paint can, therefore, be considered a suitable secondary anode for use in CP of inland concrete piers.

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INTRODUCTION

In the last few years, research related to mitigating the corrosion of steel reinforcement in concrete structures has increased. Such mitigation has included cathodic protection (CP) and electrochemical chloride extraction (ECE).[1-3] There is increased recognition among academics and practicing engineers in the United States and Europe that such electrochemical methods are the only effective and practical solutions for mitigating this costly problem. The alternative is to replace the contaminated concrete. As Uhlig and Revie stated in their widely used textbook *Corrosion and Corrosion Control*: "Cathodic protection is perhaps the most important of all approaches to corrosion control. By means of an externally applied electric current, corrosion is reduced virtually to zero, and a metal surface can be maintained in a corrosive environment without deterioration for an indefinite time."[4]

In simple terms, except for the galvanic mode of CP, ECE and the impressed-current mode of CP are implemented by installing a supplemental anode system on the surface of the concrete structure, followed by applying a DC current between the anode and the rebar network, with the latter serving as the cathode. The difference between these methods is their aims: ECE aims to remove as much chloride ion as possible within a reasonable time, and CP aims to achieve and maintain sufficient cathodic polarization of the reinforcing steel. Therefore, ECE treatment of a concrete structure typically requires 4 to 8 weeks using a DC current ranging from 1.1 to 5.5 A/m^2 (100 to 500 mA/ft^2). The beneficial effects on the reinforcing steel can last for several years. Exactly how long is still being investigated. The latest results from regular monitoring of a portion of a pier in Canada, treated 7 years ago, indicate the steel is still passive, which means that the beneficial effects likely last for at least 7 years (unpublished data). In contrast, CP typically uses DC current on the order of 11 mA/m^2 (1 mA/ft^2) to cathodically polarize the reinforcing steel. As long as this current and the entire electrical system are operating and being maintained properly, the structure will be permanently protected.

The selection of a suitable anode is critical to the durability and, therefore, the effectiveness of any CP system. The search for good anodes for application in CP of concrete bridge decks began at the Virginia Transportation Research Council (VTRC) in the early 1980s.[5-7] Since the requirements for a good anode for inland concrete piers are different from those for concrete decks and piers in marine environments, the search for good anodes for use on inland concrete piers began as early as the mid-1980s.

For CP of inland concrete piers, an anode should have at least the following characteristics: electrically conductive, ability to sustain oxidation without significant physical damage, inexpensive, easy and safe to install or apply, and reasonably easy to maintain. The first effort in this search was a small-scale trial, sponsored by the Federal Highway Administration (FHWA), that involved the use of a sprayable conductive polymer coating and a metallized zinc coating, separately, as secondary anodes on two concrete piers of the eastbound bridge of I-64 over 13th View Street in Norfolk, Virginia.[8] Even though the bridge is on the Atlantic coast of Virginia, the piers were considered inland, because they are on the ground and not surrounded by seawater. The primary anode was platinized niobium copper (Pt-Nb-Cu) wires. The conductive polymer coating appeared to perform satisfactorily for a few years. However, concerns with the potential adverse effects of the organic solvents used in its formulation on construction workers and its long-term appearance made this system unfavorable to potential users. The metallized zinc coating had desirable characteristics. However, it can easily create electrical shorts with tie wires that often extend from just beneath the concrete surface, especially at the underside of pier caps. In addition, because of the chemical properties of zinc, its long-term durability is in question. Lately, health and environmental concerns with zinc, especially in the vapor phase, have warranted the use of containment around construction areas such that the cost has risen considerably.

In 1988, when the 93 hammer-head concrete piers supporting the I-95 bridges over the James River in Richmond, Virginia, needed major rehabilitation, the Virginia Department of Transportation (VDOT) chose to apply CP on at least the pier caps, which would necessitate that only damaged concrete be excavated and replaced. The other option would have necessitated that all concrete contaminated with sufficient chloride to induce steel corrosion, regardless of whether it was sound or damaged, be excavated and replaced. This option has been found to be impractical to implement and would be prohibitively expensive, since most of the contaminated concrete in the pier caps was load bearing and its removal would necessitate expensive temporary shoring of the caps. Based on the experience at Norfolk and a report from the Ontario Ministry of Transportation, it was determined that the most promising anodes available at the time for application on concrete piers were organic solvent-based conductive paints.[8,9] One was selected for use as the secondary anode in the CP system for the 93 concrete pier caps in Richmond.[10]

These conductive paints were basically coatings made electrically conductive by the addition of finely dispersed carbon particles. This type of material has several attractive features: it is relatively low in cost, it can be easily applied on concrete piers with simple tools such as brushes or rollers, it can be easily touched up, and any localized deterioration will not cause a breakdown of an entire CP system. Early observations of the CP system confirmed that this material showed promise as an effective secondary anode for CP of inland concrete piers.

However, these conductive paints contained potentially hazardous organic solvents, such as xylene, propylene glycol, and monoethyl ether, which could easily cause them to become undesirable from the standpoint of the health of construction workers and environmental pollution.

Shortly thereafter, a proprietary water-based conductive paint consisting of a blend of specially treated carbon particles and acrylic resin dispersed in water was introduced as a safer alternative. Independent laboratory and exposure yard testing had shown that it was as durable as the best organic-based conductive paint (see Table 1).[11] However, because testing was limited, there was a concern in some quarters that, under continuous power, the carbon particles might deteriorate too fast, perhaps through oxidation.

Table 1. Properties of the Conductive Paint

Pigment	Specially treated non-graphite carbon
Binder	Acrylic
Color	Black
Carrier (solvent)	Water
Density	Approximately 1.56 g/cc (13 lb/gal)
Solids (by weight)	73%
Solids (by volume)	67%
Viscosity	6,000-10,000 cps (Brookfield RVT)
pH	8.5
Flash point	None
Linear resistance	5.9-7.9 Ω/cm (15-20 Ω/in), point-to-point, at 10 mil dry-film thickness
Recommended thickness	0.254-0.381 mm (10-15 mil)
Application conditions	Air temperature at least 10°C (50°F) Relative humidity less than 80%
Theoretical coverage	26.2 m^2/l at approximately 0.025-mm thick (1,072 ft^2/gal at approximately1 mil)
Actual coverage	2.44 m^2/l (100 ft^2/gal)

Since this material had many of the desirable features of a secondary anode for concrete piers, we decided to investigate its use in CP systems in Virginia for several years to shed light on its service life and, therefore, its life cycle cost. Thus, this paint was tested in a CP system designed to protect the 10 piers of the twin I-81 bridges over Mills Creek, near Mt. Jackson in Shenandoah County, in 1989. It was used again, 3 years later, in another CP system designed to protect the piers of the twin I-81 bridges over the Maury River in Rockbridge County (see Table 2). The concrete piers of all four bridges had damage related to rebar corrosion.

Table 2. CP Systems

CP System	1	2
Location	I-81 over Mills Creek, Mt. Jackson, Shenandoah County	I-81 over Maury River, Rockbridge County
Structure No.	2014 2015	2013 2014
No. piers	10	14
Total concrete area	1,040 m^2	1,385 m^2
Area/pier	104 m^2 (1,120 ft^2)	99 m^2 (1,065 ft^2)
Year installed	1989	1991-1992
System cost	$85,546	$208,527
Unit cost	$82.26/$m^2$ ($7.64/$ft^2$)	$150.56/$m^2$ ($13.99/ ft^2)

CP SYSTEM DESIGN AND CONSTRUCTION

System Design

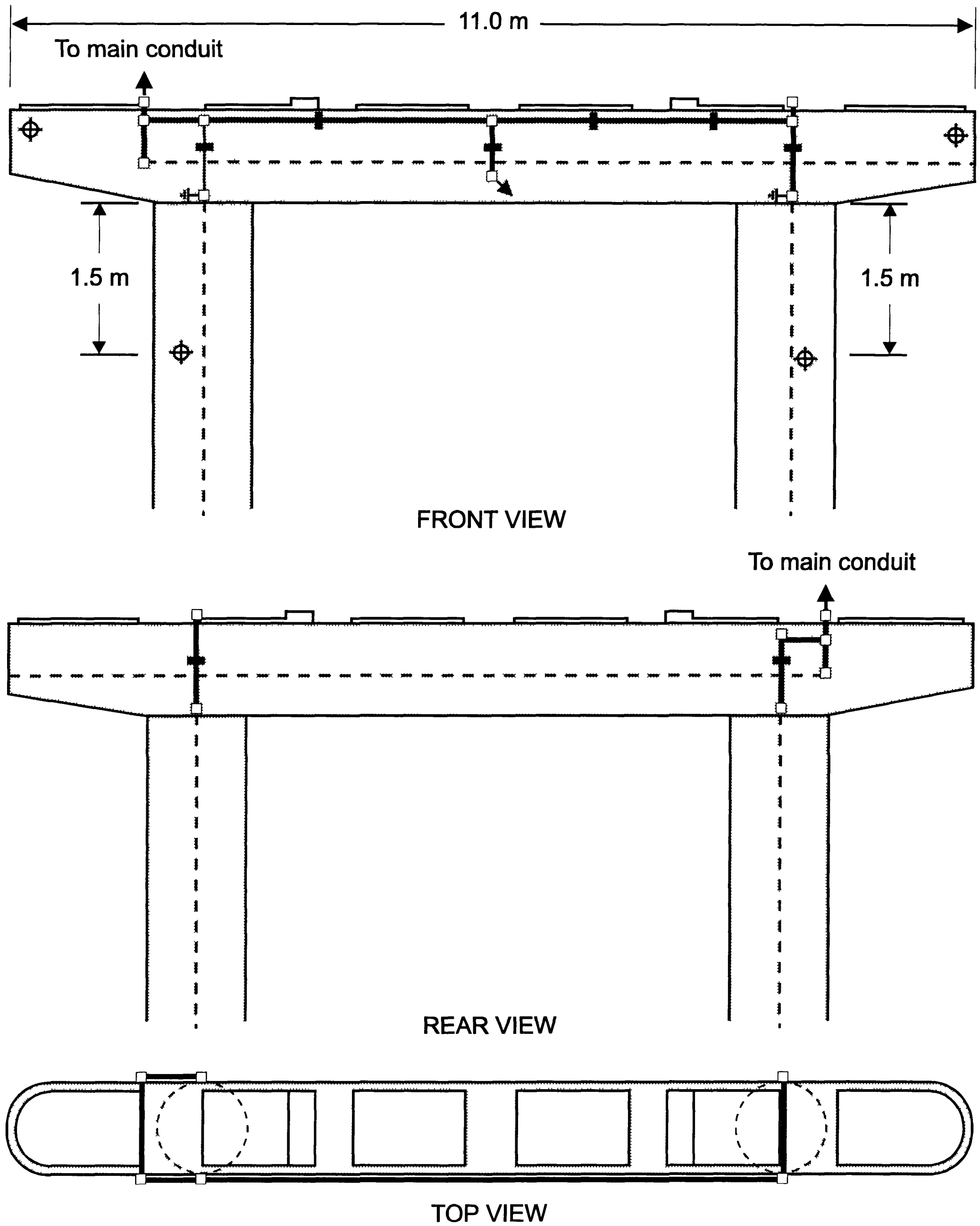
CP System 1 (I-81 Bridges at Mt. Jackson)

As indicated in Table 2, the concrete area to be protected in each of the 10 piers was about 104 m^2 (1,120 ft^2). This dimension allowed the CP system to be designed so that each pier was protected by an independent circuit from a common rectifier-controller (R/C) unit, which would have 10 independent circuits and, therefore, 10 self-regulated and adjustable outputs. In accordance with the geometry of the piers, the system was designed for six Pt-Nb-Cu primary anode wires, 0.79 mm (0.031 in) in diameter, to be installed on each pier at the locations shown in Figure 1. These wires would provide adequate redundancy to prevent complete failure in a circuit should any of them become disconnected.

The paint was applied, with rollers and brushes, over the concrete to a wet thickness of 15 to 20 mil. The coverage over each pier extended from the top of the cap to the bottom portion of each column, stopping at about 0.3 m (1 ft) above the surrounding ground (for columns in the ground) or 1 m (3 ft) above the highest possible waterline (for piers surrounded by water). The dried paint was covered with a light exterior acrylic paint to ensure its durability and reduce the possible distraction to passing motorists.

All six primary anode wires on each pier were then connected to the positive terminal of 1 of the 10 independent circuits in the R/C unit. This unit was specified to accept power from a 220-V AC utility line and operate in a constant-current mode, with a maximum output capacity of 10 A, at 20 V, per circuit. Two system negative (ground) connections to the rebars were provided for each pier, one near each end of the pier cap and near the bottom (Figure 1).

To facilitate long-term monitoring of the effect of CP on the rebars by measuring the potential between the rebar and the concrete, a graphite reference electrode was embedded near



Conductive coating covered with protective coating

- - - - Pt-Nb-Cu anode wires

Test window

Graphite reference electrode

System ground connection

PVC conduit (with conduits & clamps where needed)

Figure 1. Layout of CP System 1

the center of each pier cap. Further, to provide additional areas for potential measurements, four "test windows" (uncoated areas) 7.6-cm (3.0-in) square were provided on each cap. These windows allow measurement of the rebar with a portable $Cu/CuSO_4$ electrode.

CP System 2 (I-81 Bridges Over Maury River)

The layout design used for each of the 14 piers protected by this CP system was different from that used in the first system, simply because of the difference in the pier geometries. As illustrated in Figure 2, six Pt-Nb-Cu primary anode wires, two system ground connections, two graphite reference electrodes, and four test windows were provided for each pier. All were equally divided between the two faces. On each pier, the conductive paint was applied over the entire hammer-head cap and the top 7.2-m (25-ft) portion of the stem to a wet thickness of at least 20 mil. As in System 1, a white exterior latex paint was applied over the dried conductive paint at the rate of 4.9 m^2/l (200 ft^2/gal).

Since the entire system required 14 independent circuits, two separate full-wave, unfiltered rectifiers were used. Each rectifier would had 7 independent circuits, each with a maximum output of 10 A, at 24 V.

Construction of the Systems

The procedures used to construct these CP systems were as follows:

1. Remove damaged concrete. The damaged concrete area was excavated to about 25 mm (1 in) below the rebars to facilitate good bonding between the substrate and the pneumatic concrete (shotcrete) used for patching. Before an excavated area was patched, the corroded rebars were sandblasted in accordance with VDOT specifications.[12] Since using wires to tie the reinforcement together has been found to contribute to establishing electrical continuity between the reinforcing steel, any tie wire damaged during the excavation was replaced.

2. Test for electrical continuity between the rebars in each pier. To ensure that no rebars would be left electrically isolated and, therefore, unprotected by the system, electrical continuity between many rebars in each pier was tested. This test was conducted by exposing some rebars and measuring the DC resistance and voltage difference between different pairs of rebars. Typically, rebars at the ends of the caps and at the top and bottom of columns were tested. In addition, rebars that happened to be conveniently exposed at other locations, due to excavation of damaged concrete, were also tested after corrosion products were cleaned from the rebars. A high-impedance multimeter with minimum resolutions of 0.1 Ω and 0.1 mV was used in these measurements. If the resistance between any two rebars was less than 1 Ω or the voltage difference was less than 1.0 mV, the rebars were considered to be electrically continuous.[13] When a rebar was found to be isolated, it was electrically bonded to a nearby rebar by thermite welding of an insulated copper wire between them.

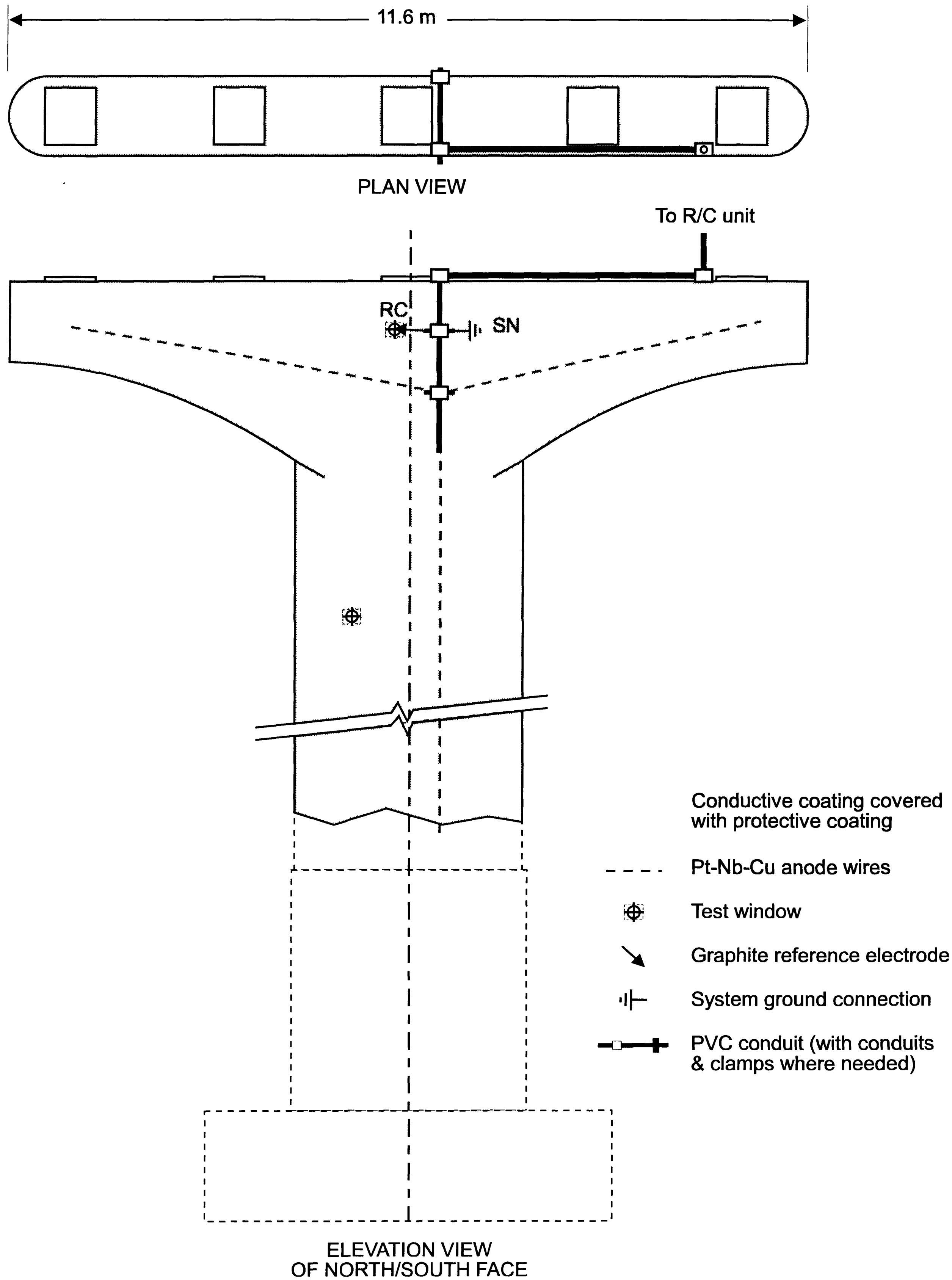


Figure 2. Layout of CP System 2

3. Test for electrical continuity in all metallic appurtenances. Similarly, metallic items, such as drains, anchor bolts, etc., attached to the concrete were tested for electrical continuity with the reinforcement. When necessary, they were bonded to the nearest reinforcement using the procedure described.

4. Install system ground connections and reference electrodes in each pier. On each pier, two system ground connections were established at designated locations, as shown in either Figure 1 or 2. This was performed by locating, with a pachometer, a rebar in a designated location and excavating enough concrete to expose it. The rebar was cleaned and then brazed by exothermic welding to an insulated copper lead wire. The connection was sealed with an epoxy paste to prevent moisture intrusion before the excavation was backfilled with concrete. The lead wire was routed all the way to the negative terminal of one of the output circuits in the R/C unit.

Similarly, graphite reference electrodes were embedded in each pier at specified locations. Procedures for their installations are described elsewhere.[13] After each reference electrode and its corresponding negative connection were installed, the location was backfilled with concrete patching materials. The concrete was allowed to cure before the half-cell potential of that reference electrode and the AC resistance (between the electrode and the ground) were checked to ensure that the reference electrodes were installed properly. If the potential readings fluctuated by more than ± 20 mV in 10 minutes and the AC resistance was greater than 10,000 Ω, the reference electrode was considered faulty and was replaced.

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5. Patch the excavated areas. Excavated areas were patched with pneumatically applied mortar in accordance with VDOT specifications.[12] If an excavated area was large and it was necessary to tie a small piece of steel mesh between the rebars to hold the applied mortar in place, only nongalvanized steel mesh was used. The mesh was installed such that its edges were more than 3.8 cm (1.5 in) below the finished surface.

6. Mask or electrically insulate any exposed metal wire at the concrete surface. In concrete piers, tie wires or chairs, which may be in contact with the rebars, frequently stick out from the bottom side of the pier caps. Such small items were located with a portable holiday detector and then masked with a sealant made of vinyl ester resin. This would prevent the conductive paint from coming into contact with these small wires, during its application, and thereby creating electrical shorts, which would disable a CP circuit.

7. Mask the edges of metallic appurtenances and their surrounding concrete. Another potential cause of electrical shorts in a CP system is the anode coming into contact with any metallic component attached to the concrete, especially when the component is in contact with the reinforcement. To ensure this was avoided, the edges of each metallic component and the surrounding concrete (to 7.5 cm or 3 in) were tightly covered with duct tape before the conductive paint was applied on the concrete. The tape was removed after the paint had dried.

8. Mask concrete at several selected designated locations on the piers. These locations, as shown in Figures 1 and 2, were covered with duct tape to prevent them from being painted over by the conductive paint so that these locations can be used as "windows" for measuring the rebar-to-concrete potential with a portable $Cu/CuSO_4$ half cell.

9. Install Pt-Nb-Cu primary anode wires on each pier. This installation involved taping a Pt-Nb-Cu wire in place with an adhesive mesh tape and then covering it with a conductive paste (see Figure 3). One end of each primary anode wire was then securely connected to an insulated copper lead wire, which in turn was routed through a PVC conduit to the positive terminal of a rectifier output circuit.

10. Apply two coats of the conductive paint. Immediately before application of the conductive paint on a pier, the concrete was thoroughly cleaned by light sandblasting. Then, the paint was applied with rollers and brushes pier to yield a total wet thickness of at least 15 to 20 mil.

11. Apply an overcoating. After the conductive paint had dried, an exterior acrylic paint was applied over it. It is uncertain if this overcoating provides any function other than improving the appearance of the coated piers.

12. Install a PVC conduit system. A system of PVC junction boxes and conduits was installed on the concrete piers and on the entire length of the bridges to route the necessary wiring from the piers to the R/C units at the selected end of the bridges. All critical electrical connections, e.g., connections between primary anode wires, system ground connections,

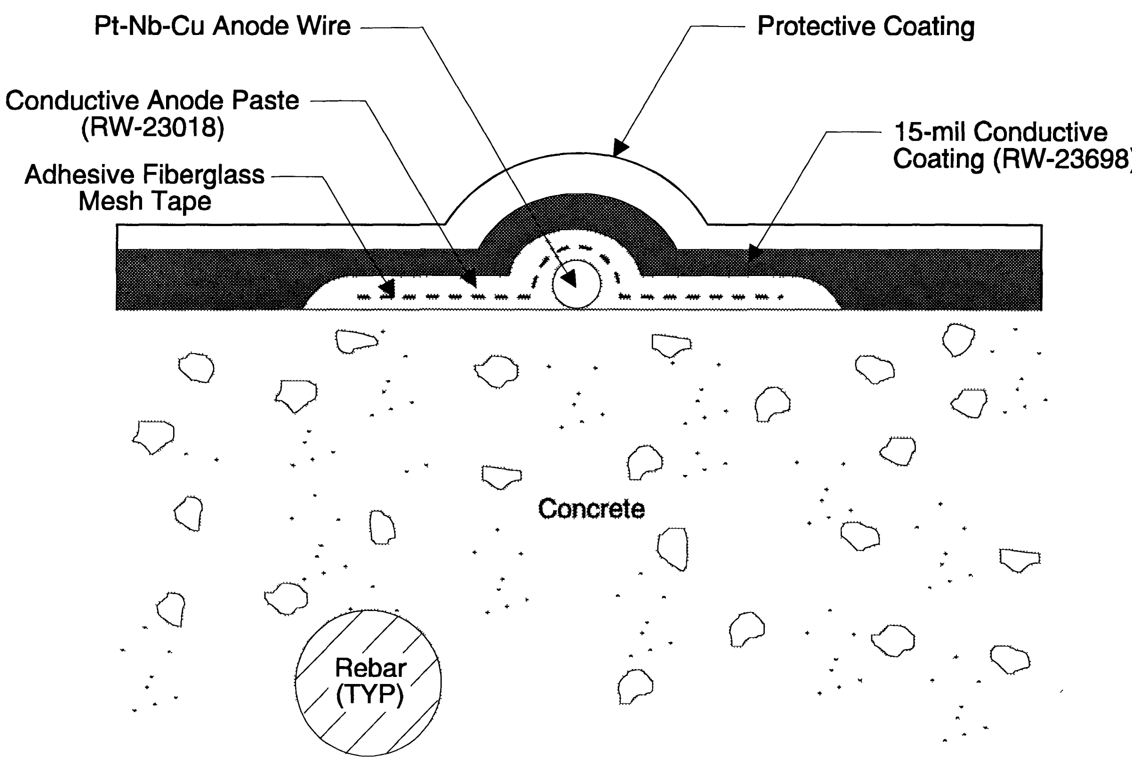

Figure 3. Installation of Anode Wires on Concrete Surface

reference electrodes, and their respective lead wires, were located in junction boxes to allow easy access. The selection of which end of the bridge(s) to locate the R/C unit(s) is often dictated by the location of existing power lines.

13. Inspect the wiring. This inspection was carried out to verify and ensure that all wiring was properly installed and correctly connected to the rectifier(s). Although unthinkable, there had been reports of at least one incidence wherein the contractor had connected the system grounds to the positive terminals and the anodes to the negative terminals of the rectifiers. Any anomaly must be corrected before the system is energized.

14. Activate and adjust the rectifier unit(s). After the rectifier(s) was properly installed and grounded to a ground electrode, it was connected to a 220 VAC electric utility line. Each rectifier was then activated. This was followed by determining the CP current required of each circuit to adequately protect the concrete pier to which it was assigned. For each circuit, this was determined by performing an E-log I analysis, wherein the circuit current output (from the rectifier) is increased incrementally and, at each interval, the IR-drop free potential of the rebar, relative to the embedded reference electrode, is measured. The CP current required from a circuit to protect its pier is the current value, in a E-vs-log I plot, at which oxygen reduction at the cathode begins, which often coincides with the beginning of a linear trend.[14] On the basis of such testing or engineering judgment, whenever it was difficult to determine the linear portion of an E-vs-log I plot, the required current output for each circuit was adjusted accordingly and left to operate in constant-current mode for approximately 30 days.

15. Retest each circuit after approximately 30 days of operation. To ensure that the current output from each circuit was providing sufficient protection or polarization of the rebars, a depolarization test was conducted on each circuit. This test was conducted by interrupting the protective current from a circuit and monitoring the decay of the IR-drop free potential for 4 hours. If the extent of rebar depolarization in 4 hours was at least 100 mV, the protection current provided by the circuit was considered sufficient; otherwise, the current output was adjusted higher and operated at that level for 24 hours before restesting.[13,14] After it was determined that all circuits were providing the sufficient amount of current to protect the rebars, each system was left to operate continuously.

Monitoring the CP Systems

System parameters such as circuit voltage, circuit current, and rebar potential were measured during site visits, which were made as often as possible. For trial purposes, a remote monitoring device was added to System 1 to facilitate checking of the operation of its rectifier system from any remote location equipped with a modem and a PC. Basically, such devices are composed of a modem card, a power supply, and several circuit cards containing signal conversion (i.e., analog-to-digital) and signal conditioning devices. A remote monitoring device is typically not a standard part of a rectifier, and its addition would not interfere in any way with the normal function of a rectifier. The 4-hour depolarization tests, which are relatively more time-consuming, were also performed during some site visits. Electronic advancements since the installation of these CP systems have made it possible to conduct this depolarization test remotely.

RESULTS

Table 2 shows that the unit costs were \$82.26/m^2 (\$7.64/ft^2) and \$150.56/m^2 (\$13.99/ft^2) for System 1 and 2, respectively. Unfortunately, because the bids for both CP systems were in lump sums, no breakdown of the costs can be provided for examination. Although two contractors were involved, it is believed that this factor contributed little, if any, to the large difference between the costs of the two systems. It is more likely that the considerably higher unit cost for installing System 2 was due to the greater height of the piers involved, which were comparatively more difficult to work with.

Not surprisingly, some rebars in a few of the piers were found to be isolated from the rest. To correct this, the isolated rebars were exothermically welded to nearby continuous rebars. For both bridges at Mt. Jackson, all the bearing pins and pads and storm drains (attached to the four piers at the ends of both structures) were also found to be discontinuous; they were also exothermically welded to a wire, which was then connected to the system ground at the junction box above each pier. Because of the relatively high solids content of the conductive paint, 73 percent by weight, its application on the concrete piers with rollers required appreciable effort. Nothing else of note was observed.

Effectiveness of Cathodic Protection

CP System 1

Since it was energized in late November 1989, the operation of System 1 had been followed for close to 6 years. Table 3 provides its initial DC settings (protection current and

Table 3. Initial Rectifier Settings for CP System 1 and Rebar Potentials (as of December 1989)

Circuit	Structure	Pier	Current (A)	Voltage (V)	Potential (V) Static	On
1	2014	1	0.18	3.7	-0.134	-0.478
2	(NBL)	2	0.15	1.8	-0.050	-0.455
3		3	0.10	3.8	-0.056	-0.448
4		4	0.15	4.8	-0.073	-0.522
5		5	0.12	5.1	-0.040	-0.468
6	2015	1	0.26	5.3	-0.101	-0.520
7	(SBL)	2	0.08	4.9	-0.048	-0.595
8		3	0.26	8.5	-0.073	-0.541
9		4	0.10	4.7	-0.056	-0.578
10		5	0.25	6.3	-0.142	-0.765

driving voltage) and the corresponding rebar potentials. In terms of current density, the initial current settings were 0.79 to 2.48 mA/m^2 (0.073 to 0.23 mA/ft^2). With the driving voltage ranging from 1.8 to 8.5 V, the corresponding resistance of these circuits ranged from 12 to 61 Ω, which was relatively high compared to those using metallized zinc coating as the anode.

The behavior of the 10 circuits is illustrated in Figures 4 to 13 for each pier. As the current-vs-time plots show, in general, the R/C unit maintained the current level required of each circuit, except for occasional deviations attributable, perhaps, to short-term, rapid fluctuations in the electrical resistance of the coating and the concrete, particularly during rain.

It is noteworthy that the driving voltage for each circuit increased slowly during the first 1.5 years of operation of the system, then reached a reasonably stabilized level for the last 4 to 5 years. Except for circuit 5, the average driving voltages for the other circuits fluctuated around 9 to 15 V, which is well within 75 percent of the full capacity (20 V) of the rectifier. This behavior is expected when a system is operated galvanostatically, i.e., under constant current. This can be attributed to an increase in the electrical resistance of the concrete, the paint/concrete interface, the steel/concrete interface, or some combination of these factors. The former, in turn, is a consequence of the redistribution of ions in the concrete, including the outward migration of chloride ions. Therefore, the concern that the conductive paint might degrade too much and too soon, after only a few years of being under an electrical charge, is unwarranted. As long as the conductive paint stabilizes and the driving voltage for each circuit remains at about 75 percent, or slightly higher, of its full capacity, the CP system should be fine.

The rebar potentials in all 10 piers shifted, within the first year of operation, toward being more positive before reaching stabilized levels. This unexpected shift may reflect the known sensitivity of graphite electrodes to pH changes it their surroundings, which in this case is expected to occur in the concrete surrounding the rebars when they are cathodically protected. The shift will be toward the desirable higher pH. Another possible explanation is that graphite tends to absorb many species at the more active crystal planes on its surface, and when the right species are present in the concrete, the anodic reaction on the surface of the graphite electrode can be sufficiently poisoned or inhibited, resulting in a positive drift in the potential.

More important, this temporary drift did not hinder depolarization testing of the circuits, which was conducted several times during the first 7 years of operation (see Table 4). As the results of these tests indicated, the mean 4-hour depolarization ranged from 145 to 257 mV, which was higher than the generally accepted NACE criterion of 100-mV depolarization for sufficient CP. In only four tests, each involving a different circuit, did a circuit yield less than 100-mV depolarization. In two, only slight increases in the current settings for the circuits involved were required to obtain the minimum 100-mV depolarization. In the other two cases, wherein the depolarization was only 18 (for circuit 9 on 07/21/92) and 26 (for circuit 7 on 05/02/96), the underlying reason was malfunctioning of the electronic components, which were replaced without much difficulty. These depolarization results confirmed that the system is, in general, providing more than adequate protection to the 10 concrete piers.

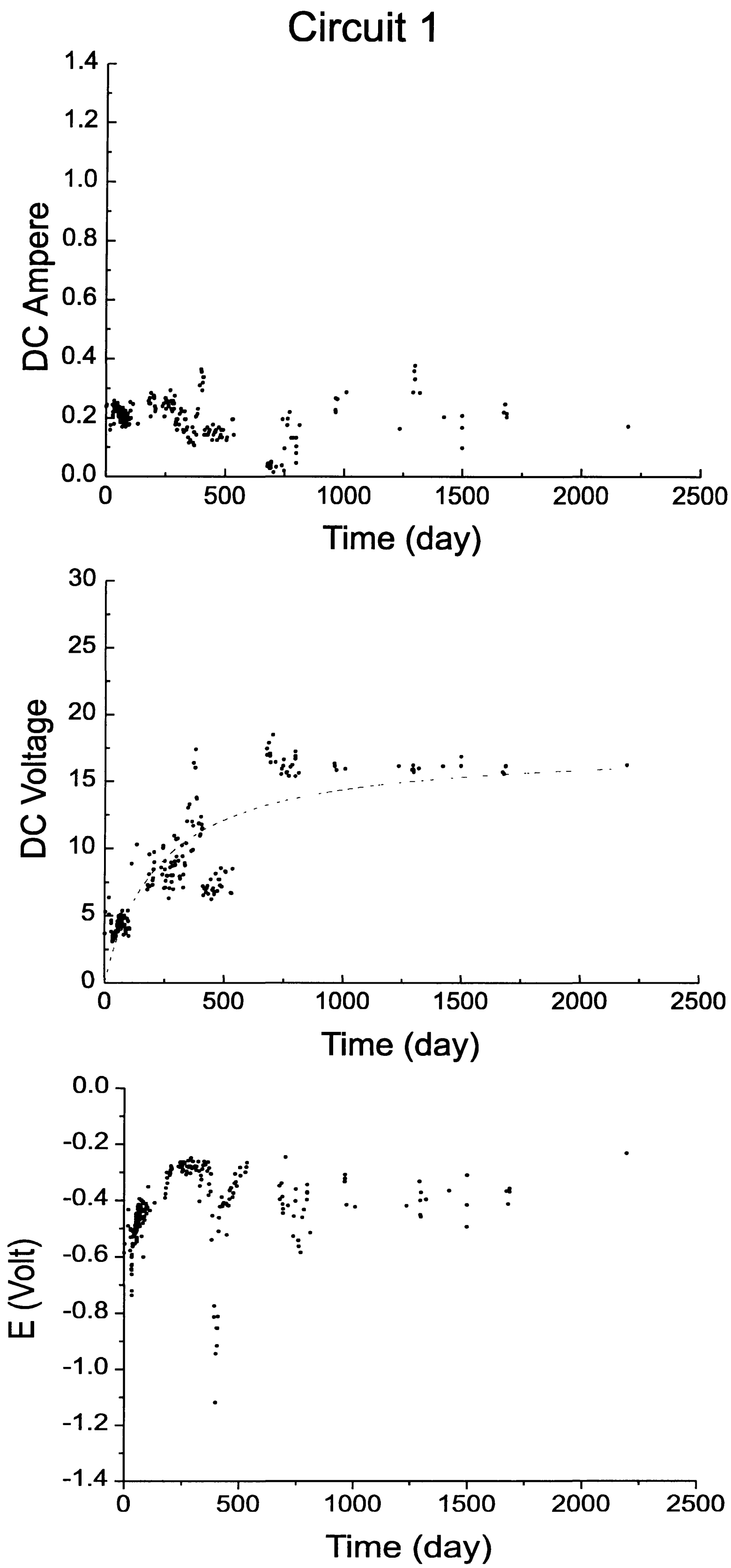

Figure 4. DC Current, Voltage and Rebar Potential for Circuit 1, CP System 1, Since Installation in 1989.

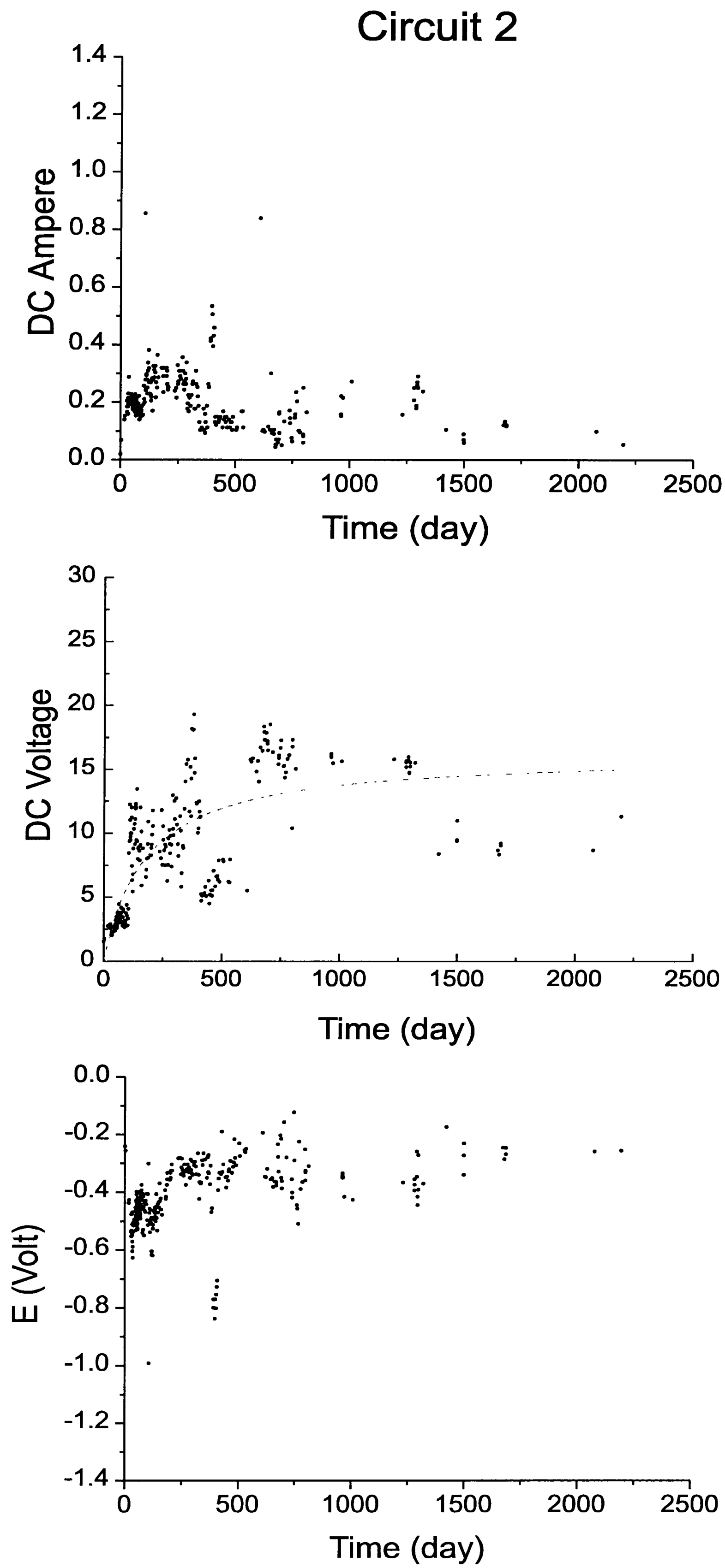

Figure 5. DC Current, Voltage, and Rebar Potential for Circuit 2, CP System 1, Since Installation

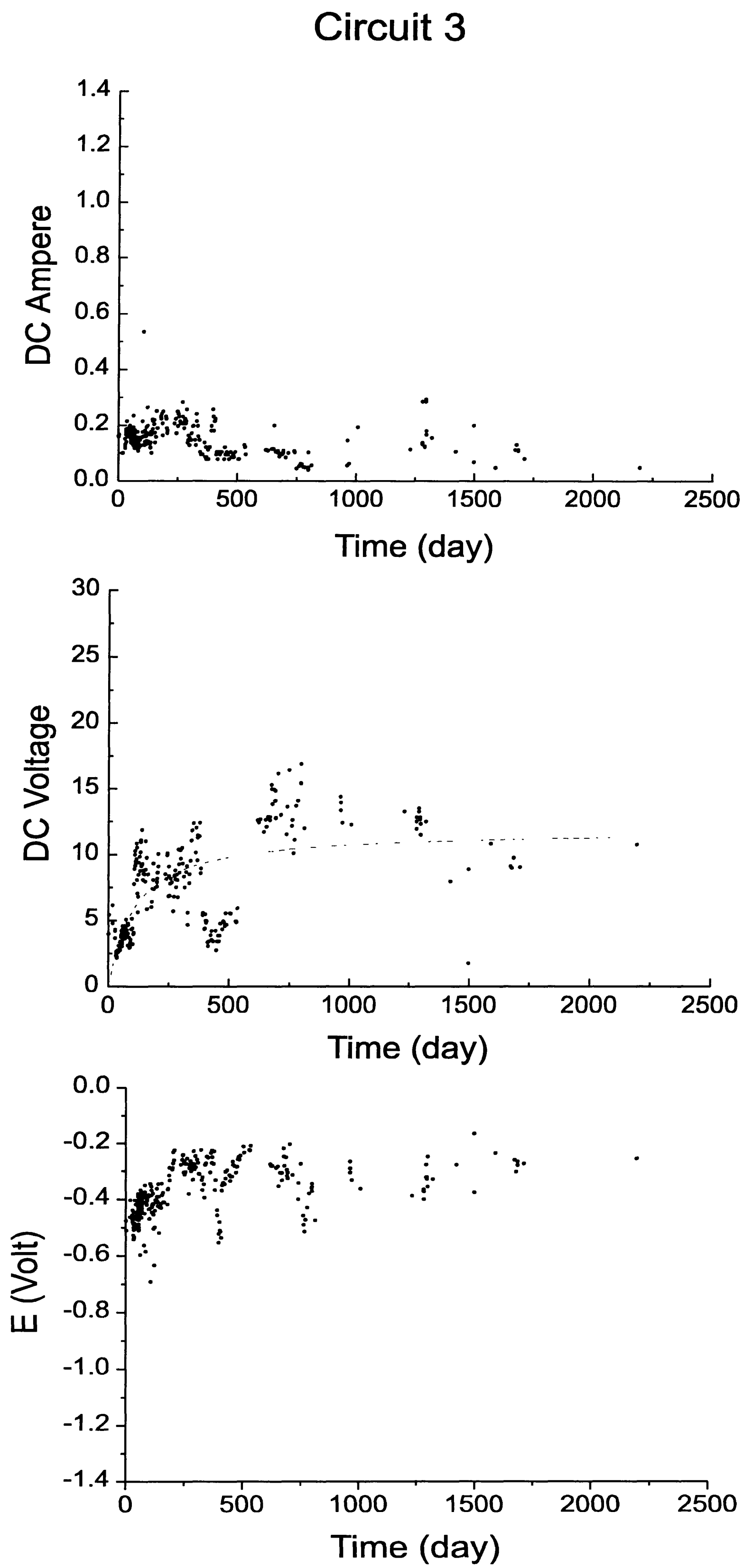

Figure 6. DC Current, Voltage, and Rebar Potential for Circuit 3, CP System 1, Since Installation

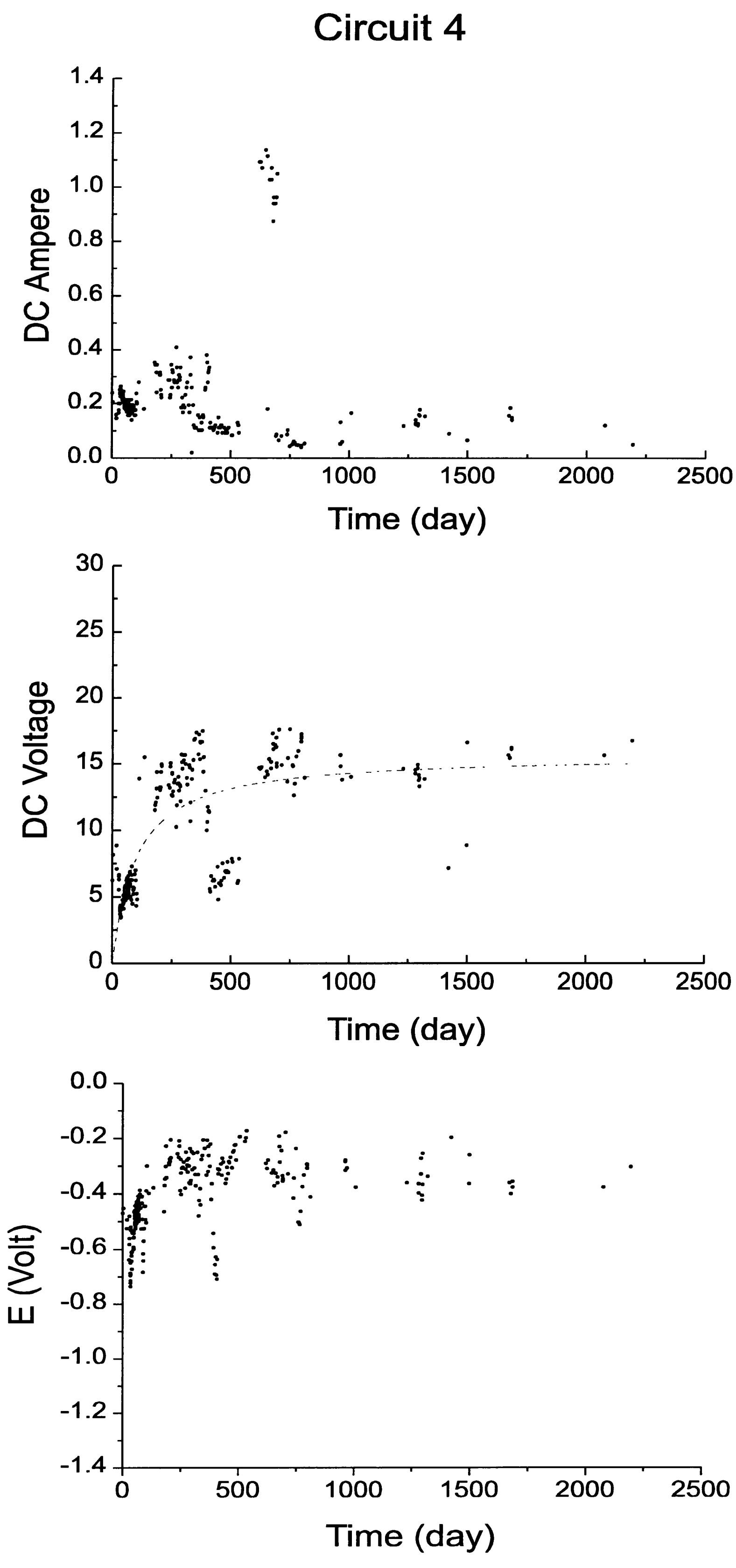

Figure 7. DC Current, Voltage, and Rebar Potential for Circuit 4,CP System 1, Since Installation

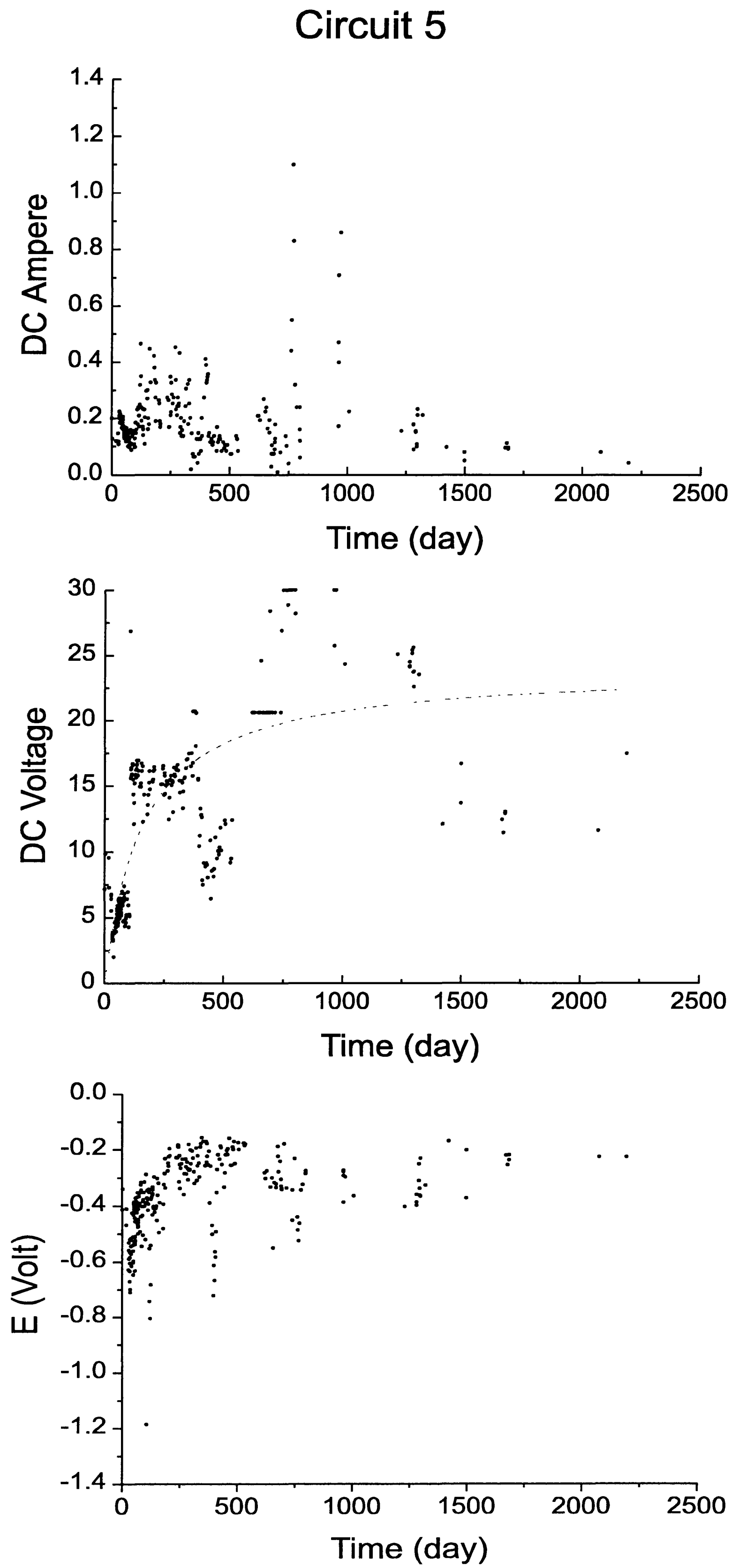

Figure 8. DC Current, Voltage, and Rebar Potential for Circuit 5, CP System 1, Since Installation

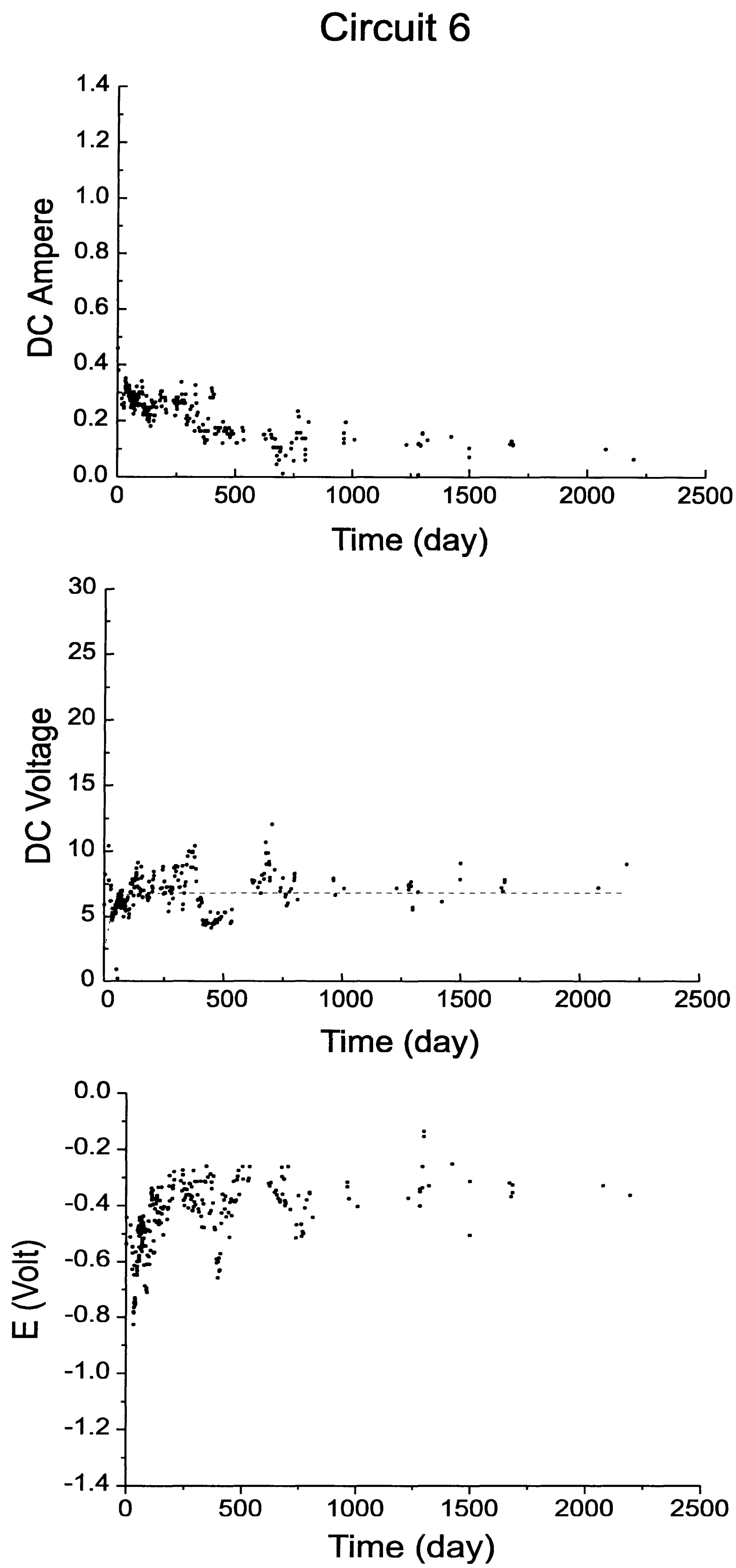

Figure 9. DC Current, Voltage, and Rebar Potential for Circuit 6, CP System 1, Since Installation

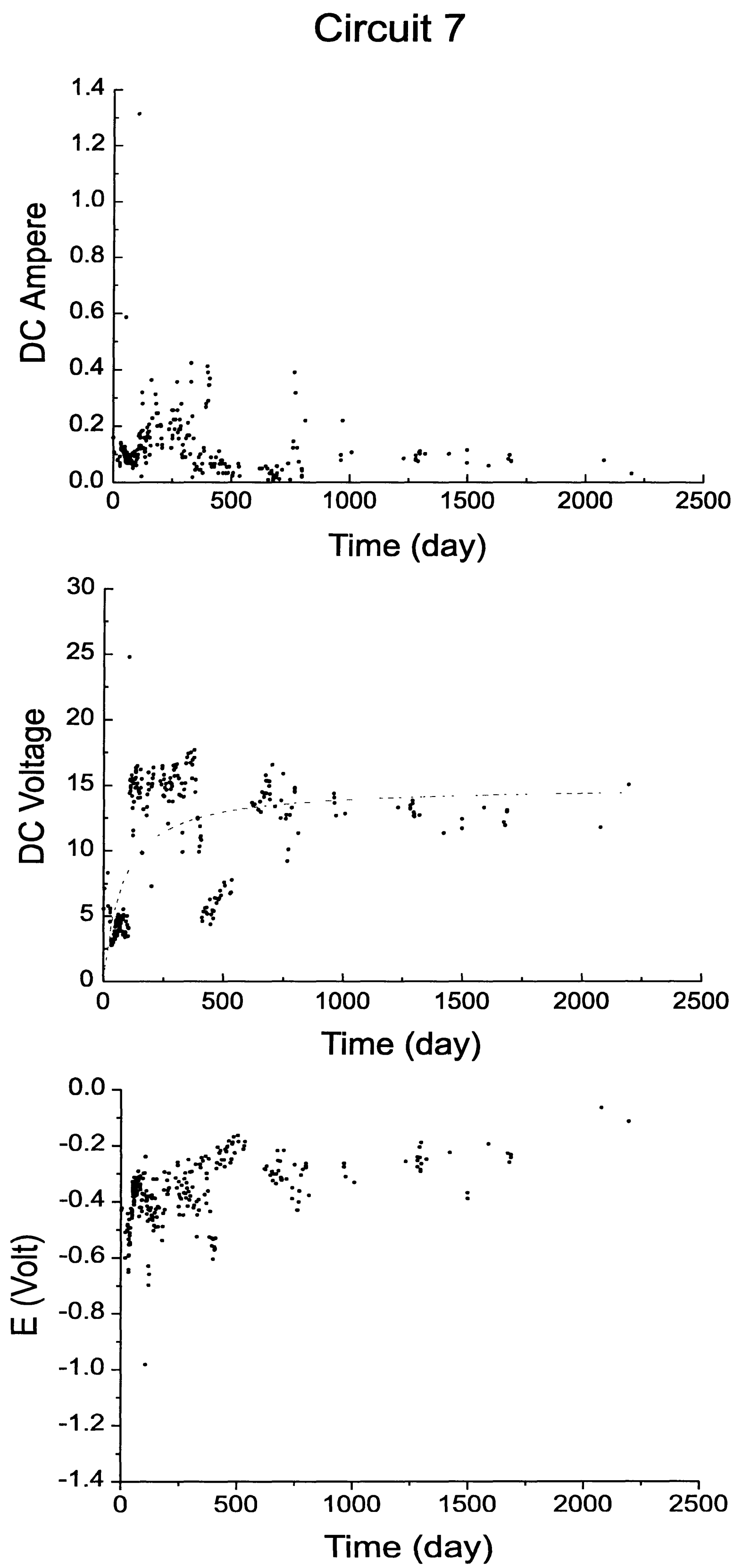

Figure 10. DC Current, Voltage, and Rebar Potential for Circuit 76, CP System 1, Since Installation

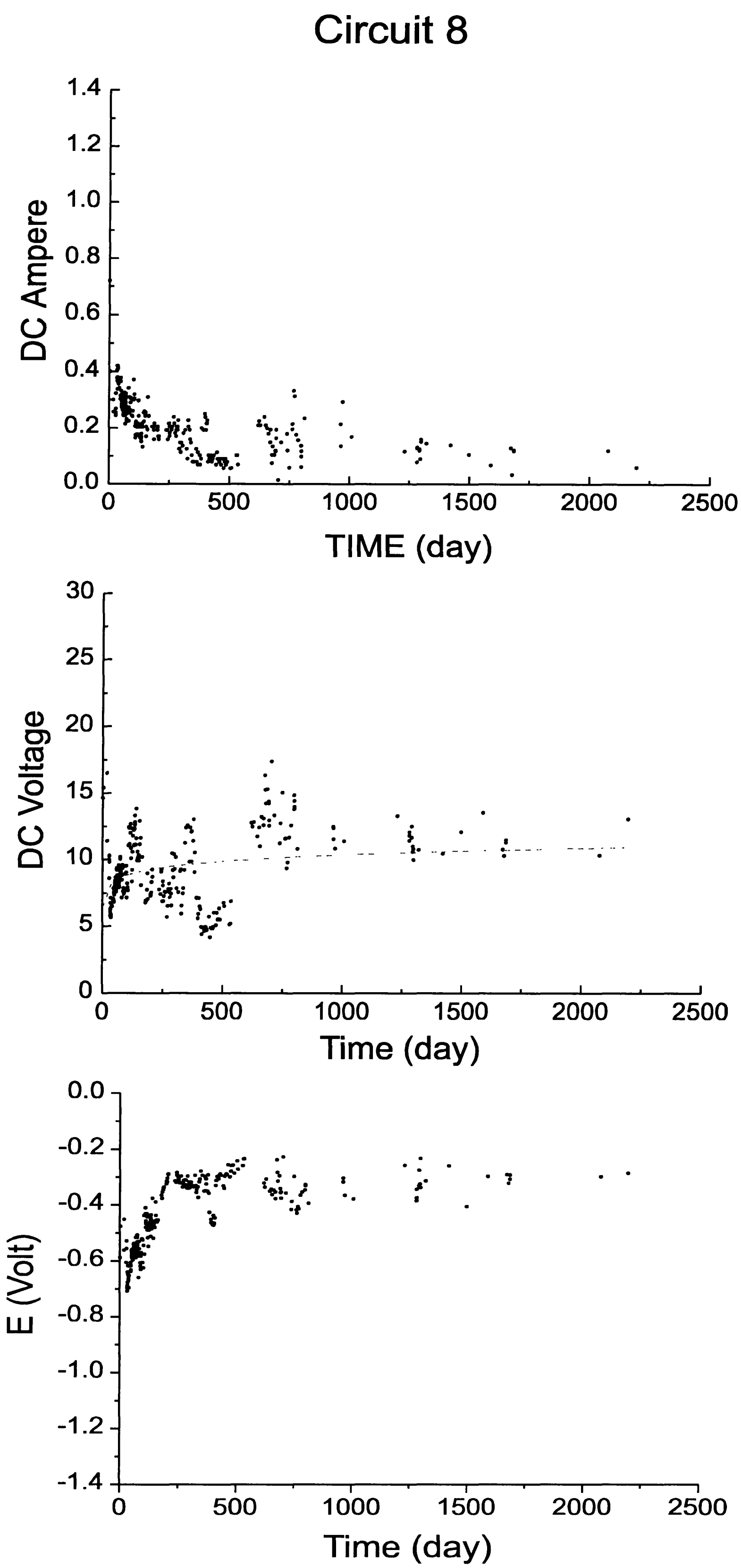

Figure 11. DC Current, Voltage, and Rebar Potential for Circuit 8, CP System 1, Since Installation

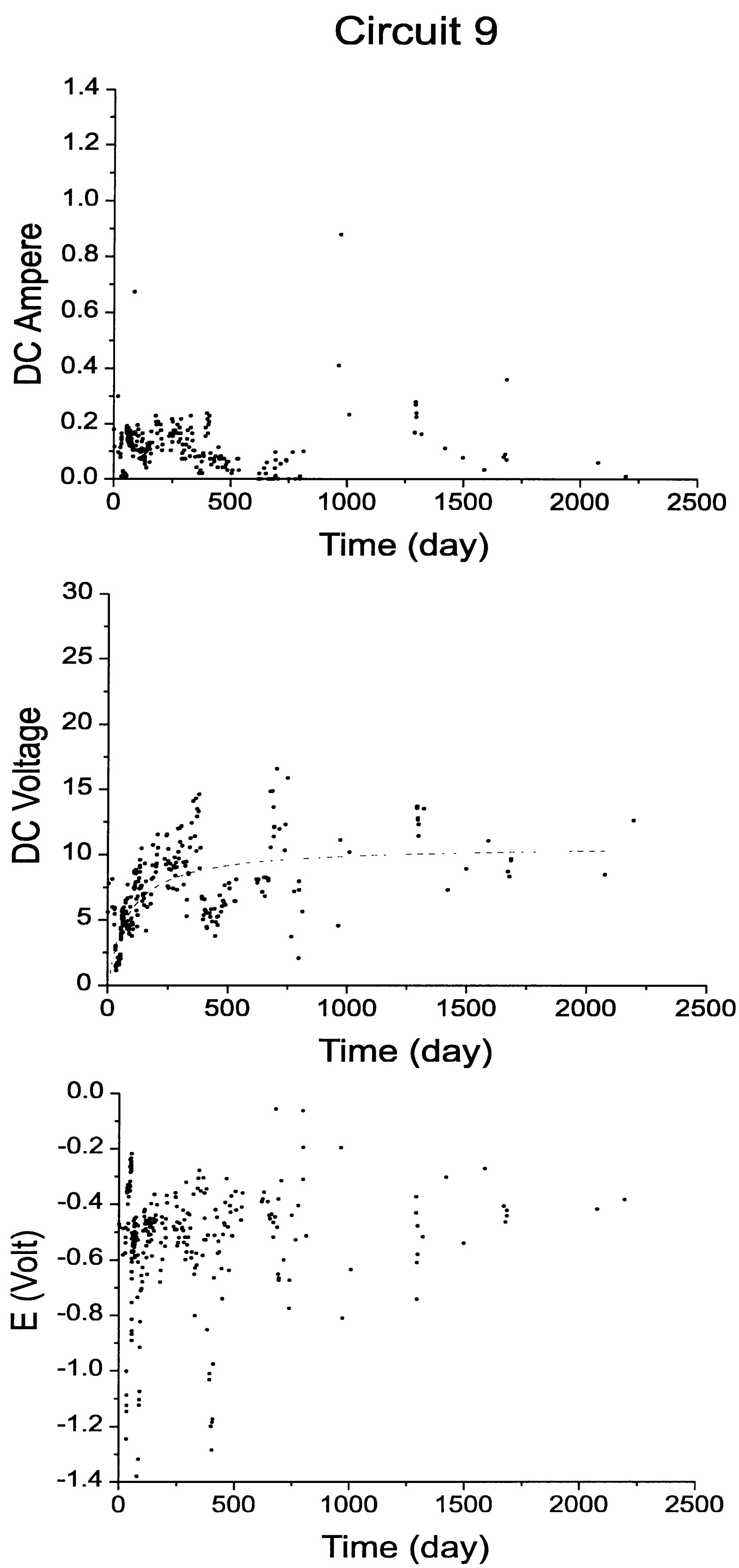

Figure 12. DC Current, Voltage, and Rebar Potential for Circuit 9, CP System 1, Since Installation

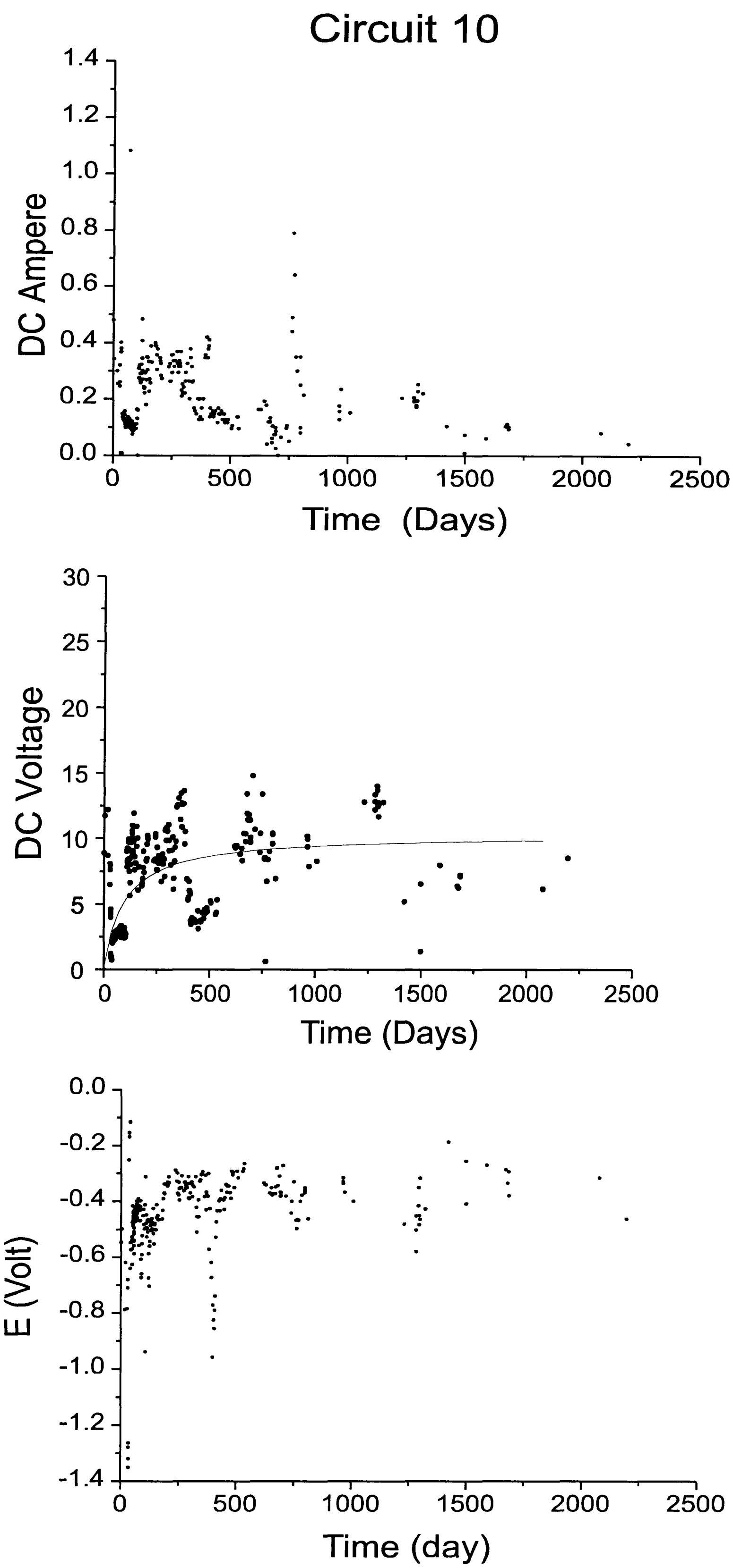

Figure 13. DC Current, Voltage, and Rebar Potential for Circuit 10, CP System 1, Since Installation

Table 4. Depolarization Tests for CP System 1

	4-Hour Depolarization (mV)						
Circuit	**12/19/89**	**05/02/90**	**08/21/90**	**12/05/90**	**07/21/92**	**06/21/93**	**05/02/96**
1	182	126	68	126	153	218	131
2	206	201	166	105	165	192	104
3	236	189	176	147	183	209	137
4	265	194	205	139	186	204	160
5	262	225	135	88	186	249	132
6	248	214	252	172	206	177	190
7	297	209	214	240	191	175	26
8	268	227	181	130	184	189	125
9	319	288	259	123	18	306	186
10	286	179	178	177	131	229	258
Mean	257	205	183	145	160	215	145

Regardless of the real causes, the unexpected temporary positive shifts in the potentials may indicate that a graphite electrode lacks stability and would, therefore, not be an ideal reference electrode for use in long-term monitoring of a CP system.

Current remote monitoring technology allows data to be measured remotely, stored, and downloaded to any remote PC in different spreadsheets. The tedious 4-hour depolarization test can also be performed remotely. In comparison, the remote monitoring device added to System 1 was relatively crude. Nevertheless, the device basically functioned as intended and allowed the CP system to be checked and the operating parameters measured more often than would be possible by site visitations alone, as evident by the amount of data collected (Figures 4 to 13). The device was damaged several times, each necessitating the replacement of a circuit card or a circuit component. It is believed that this damage was caused by lightning-related surges, which can be reduced significantly, if not completely, by providing better safeguards against such surges.

During the 8-year operation of System 1, the following rectifier components became defective at some time: DC fuses, rectifying elements, and, less often, switches and controller cards. Other minor problems, such as loose wire connections to terminals located in the front panel of the R/C unit and the connection between a lead wire and one of the primary wire anodes, also occurred. As a whole, System 1 was operating reasonably well and was providing sufficient protection to the concrete piers.

CP System 2

Tests conducted for continuity between rebars and for resistance between the conductive paint and the system grounds on the piers indicated that System 2 was installed properly. The only exception was the unusually high resistance (70 kΩ) for one of the two graphite reference electrodes on pier 4 of the southbound bridge, the one embedded on the south face, which should have been replaced by the contractor. Although this high resistance did not hinder E-vs-log I and depolarization testing with the electrode, the first depolarization test using the electrode yielded a depolarization of only 36 mV, in contrast to the 232 mV depolarization with the reference electrode embedded on the other face of the same pier. Although the environments surrounding the two electrodes and, therefore, the extent of polarization achieved on the nearby rebars, cannot be expected to be identical, the considerable discrepancy was probably a good indication that the first electrode was either defective or not installed properly.

The initial settings for the system and the rebar potentials following system startup are presented in Table 5. The results of depolarization tests conducted at different times are presented in Table 6. These data indicate large differences between the rebar potentials measured at the north and the south faces of some piers, such as in piers 2 and 6 of the northbound bridge and pier 4 of the southbound bridge. In fact, slightly smaller differences were observed in some other piers.

Further, as Table 6 shows, there were differences in the extent the rebars in these two faces depolarized, especially during the first set of depolarization tests, i.e., those conducted on 09/21/92. In those tests, in 11 of the 14 piers, the extent of the 4-hour depolarization was higher on the north face (cell 1) than on the south face (cell 2). Such difference was also reflected in the later two sets of depolarization tests, although to a slightly lower degree. This apparent effect of the orientation of a vertical concrete structure on the potential readings warrants additional study, since the resulting large variations in potentials for the same structure can make it difficult to set the circuit current so that the possibility of overcharging the conductive paint anode on the faces that are easier to polarize is avoided.

The results from all of the depolarization tests (Table 6) indicated that, except for the inadequate polarization in the south face of some piers on 03/02/95, System 2 was providing adequate CP to the rebars. It must be emphasized that, since in many instances it took actually more than 4 hours for rebars to completely depolarize, the actual polarization of the rebars in those instances was likely to be greater than those observed in 4 hours.

Table 5. Initial Rectifier Settings for CP System 2 and Rebar Potentials (as of 1992)

Structure	Pier	Circuit	Current (A)	Voltage (V)	Potential (mV) Cell 1	Cell 2
2013 (NBL)	1	N1	1.08	7.1	-0.829	-0.400
	2	N2	1.14	7.2	-2.510	-0.428
	3	N3	0.68	7.4	-0.681	-0.398
	4	N4	0.46	3.2	-0.540	-0.722
	5	N5	0.28	2.7	-0.662	-0.553
	6	N6	1.18	8.0	-1.170	-0.255
	7	N7	1.44	8.0	-0.036	-0.536
2014 (SBL)	1	S1	0.3	3.8	-0.241	-0.406
	2	S2	0.4	3.8	-0.726	-0.550
	3	S3	0.2	5.2	-0.554	-0.248
	4	S4	0.3	5.0	-0.939	-0.226
	5	S5	0.4	4.5	-0.307	-0.281
	6	S6	0.2	6.2	-0.372	-0.257
	7	S7	0.2	4.6	-0.276	-0.307

Table 6. Depolarization Tests for CP System 2

Circuit	Cell	4-Hour Depolarization (mV)		
		09/21/92	03/02/95*	08/15/96
N1	1	494	210	240
	2	303	179	153
N2	1	803	599	405
	2	283	115	137
N3	1	373	243	205
	2	211	127	130
N4	1	296	317	256
	2	219	397	184
N5	1	208	292	211
	2	356	109	255
N6	1	552	417	358
	2	159	140	165
N7	1	274	84	126
	2	246	199	178
Mean		341	248	214
S1	1	84	63	133
	2	119	77	148
S2	1	515	160	464
	2	178	92	139
S3	1	254	66	92
	2	77	n.a.	5
S4	1	232	107	185
	2	36	40	72
S5	1	107	134	156
	2	105	47	126
S6	1	181	93	125
	2	104	44	105
S7	1	119	61	104
	2	120	84	127
Mean		159	82	141

*Reference 15.

It also appeared that cell 2 in pier 3 of the southbound bridge may have became defective and should be investigated. This and the extremely high resistance reported earlier for one of the reference electrodes may indicate that System 2, especially its electrical portions, was not installed as well as System 1. In fact, different general construction contractors were involved in the installation of the two systems.

Deterioration of the Conductive Paint

A desirable characteristic of any CP system using conductive paint as the secondary anode is that small and isolated areas of deterioration or damage in the paint, within some limit, do not interfere with the effectiveness of the system. To determine the rate of the deterioration, the paint in both systems was inspected with the aid of a new digital image analysis method for peeling, staining, cracking, etc. This method, which was recently developed for quantitative estimation of the extent of paint or coating damage on structural steel members, is composed of the following procedures: taking photographic slides of both sides of each pier, transforming these analog images of the pier into digital image files (by scanning the slides with a digitizing scanner), and then using a suitable digital image analysis software to estimate the total area of damaged coating on each pier.[16] The paint was also inspected visually.

Table 7 lists the extent of the damage to the paint on each of the 10 piers protected by System 1, which is 8 years old. As indicated, the damage ranged from 0 to 2.50 m^2, or 0 to 2.40 percent, of the total painted area on each pier. In comparison to the damage on most of the piers, the damage of 2.40 percent on pier 3 of the southbound bridge was relatively large and unusual. Since the damage was restricted to the pier footing on the upstream side (Figure 14), it was attributed to abrasion and impact damage caused by recent severe flooding that sent timber debris crashing against the pier. When this unusual damage is excluded from consideration, the damage from natural degradation of the conductive paint system ranged from only 0 to 0.37 percent. It must be noted that most of the damage occurred on the ends of the pier caps (Figure 15), where they are not sheltered from rain by the bridge deck above. This indicates that such areas are more exposed to rain, which may result in more discharge of current in those areas during rain and, therefore, relatively faster degradation of the paint. A consolation is that the concrete in such areas in pier caps is typically considerably less susceptible to rebar corrosion, because it is not directly below deck joints. Nevertheless, this aspect will have to be considered carefully in the design of future CP systems of this type.

The damage to the conductive paint in System 2, which is approximately 6 years old, is listed in Table 8. Damage was observed on only 0 to 0.19 percent of the total painted area on each of the 14 piers. This range of damage is consistent with that in System 1. Likewise, the slightly damaged areas on a few of these 14 piers were located mostly at the ends of the pier caps (Figure 16).

Table 7. Estimated Damage to Conductive-Paint Anode in CP System 1

Structure	Pier	Damaged Coating (m^2)	(%)*
2014 (NBL)	1	0.25	0.24
	2	0.20	0.20
	3	0.04	0.04
	4	0.22	0.21
	5	0.37	0.37
2015 (SBL)	1	0	0
	2	0.28	0.27
	3	2.50	2.40
	4	0	0
	5	0.01	0.01
Mean		0.39	0.37

* Based on total coated area on each pier.

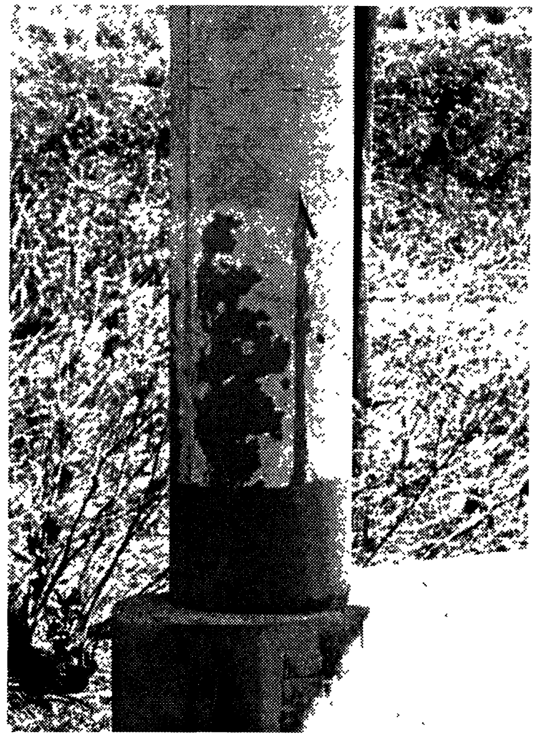

Figure 14. Damage of Conductive-Paint Anode System on Footing of Pier Protected by CP System 1.

Figure 15. Damage of Conductive-Paint Anode System at End of Pier Cap Protected by CP System 1

Table 8. Estimated Damage to Conductive-Paint Anode in CP System 2

Structure	Pier	Damaged Coating (m²)	Damaged Coating (%)*
2013 (NBL)	1	0.02	0.02
	2	0	0
	3	0	0
	4	0	0
	5	0.02	0.02
	6	0.19	0.19
	7	0.05	0.05
2014 (SBL)	1	0	0
	2	0.03	0.03
	3	0	0
	4	0	0
	5	0	0
	6	0	0
	7	0	0
Mean		**0.02**	**0.02**

*Based on total coated area on each pier.

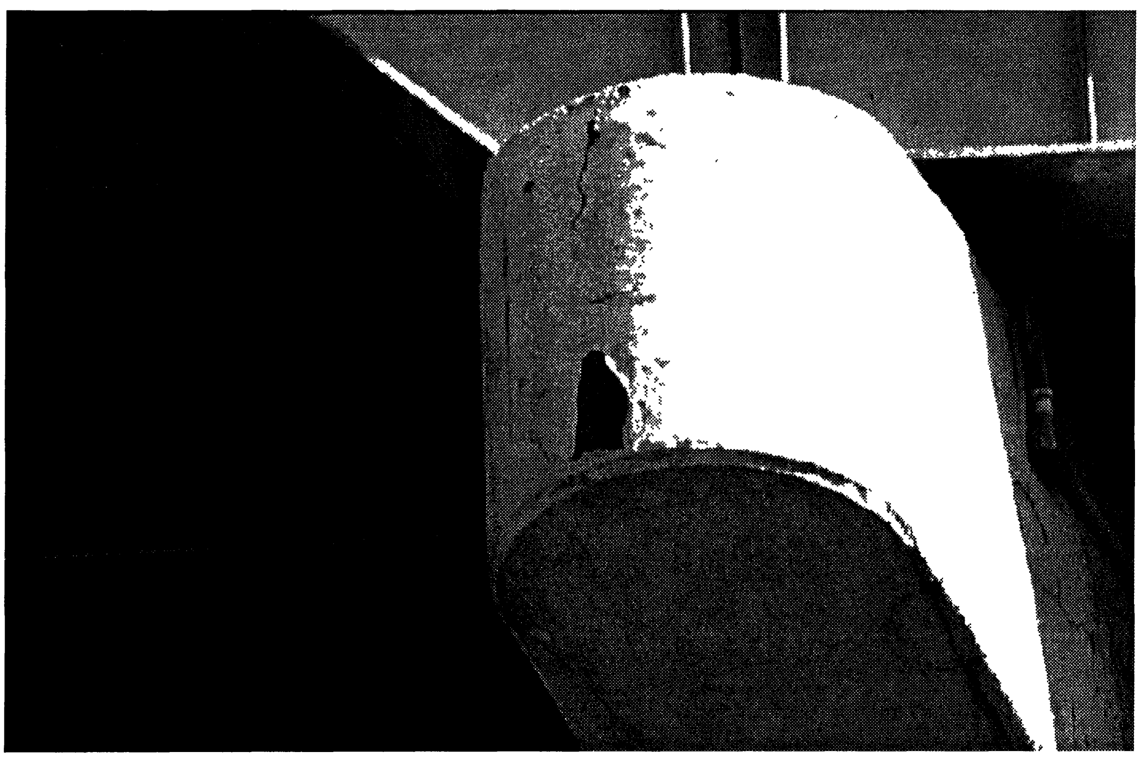

Figure 16. Damage of Conductive-Paint Anode System at End of Pier Cap Protected by CP System 2

In general, the overall condition of the conductive paint in both systems appeared to be very good, as shown in Figures 17 and 18. Therefore, it can be concluded that the conductive-paint anode is holding reasonably well, so far. It must be emphasized, however, that similar good results would likely not be obtained if the conductive paint was used on concrete members that are constantly wet, e.g., concrete piles in marine environments, especially if the paint is applied near the edge of the water. The important key to remember is that no paint or coating will last long when used on a substrate that remains wet all the time; the more frequent the substrate becomes wet, the faster the paint will deteriorate.

Figure 17. View of CP System 1 as of April 1977

Figure 18. View of CP System 2 as of November 1996

It is extremely difficult to predict how long the conductive-paint anode will last in these two CP systems. Since the oldest application is already 8 years old and the existing natural deterioration is relatively minor (no more than 0.37 percent), it is perhaps not unreasonable to expect this anode system to last 15 years, or even more, especially if the existing minor damage is repaired reasonably early by touching up.

CONCLUSIONS

1. In general, the two CP systems, which used a water-based conductive paint as the secondary anode, provide more than sufficient protection to the rebars in the inland concrete piers these systems were designed to protect.

2. As evident in the stabilization of the driving voltages and the minor deterioration of the conductive paint, after as long as 8 years of service, the concern about premature degradation of this type of secondary anode is unnecessary as long as the conductive paint is not used on concrete members that will remain constantly wet.

3. The water-based conductive paint is a suitable alternative secondary anode for application in the CP of concrete bridge piers in locations where the concrete stays dry most of the time. Even with such structures, it is advisable to consider safeguard measures to alleviate the slow deterioration of the paint on portions of the concrete structures that become wet intermittently, including avoiding applying the paint on those portions of the concrete, i.e., stopping the paint application at, say, 0.6 to 1 m (2 to 3 ft) from those portions. It cannot be overemphasized that, just as with any paint, applying conductive paint on structures that remain constantly wet is certain to result in failure.

4. When used in the right locations, it is reasonable to expect the conductive-paint anode to last at least 15 years, especially if efforts are made to touch up any paint damage as early as possible.

5. The relatively primitive remote monitoring unit (by current technological standards) used with the older CP system demonstrated that such equipment is extremely cost-effective and should be incorporated in all new CP systems to eliminate the need for regular visits to a system to determine if it is still operating properly.

6. It appears that graphite reference electrodes may not be suitable for long-term monitoring of CP systems. Consequently, there is an urgent need to search for or develop more stable reference electrodes that can be embedded in concrete.

ACKNOWLEDGMENTS

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