

FINAL REPORT

EFFECTIVENESS OF CATHODIC PROTECTION SPR 345

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16. Abstract The report provides a summary of Oregon's experience with cathodic protection of coastal reinforced concrete bridges. Thermal-sprayed anodes, foil anodes with a conductive adhesive, and carbon painted anodes are effective in distributing current to the steel reinforcement in concrete bridges. A resistive layer develops at the anode-concrete interface with increasing electrochemical age, thereby increasing anode polarization. In impressed current cathodic protection (ICCP) systems this is reflected in a higher circuit resistance. In sacrificial anode cathodic protection (SACP) systems it results in lower current output. Periodic wetting of the anode by rain, fog, and dew is an important factor in reducing anode polarization. Catalyzed thermal-sprayed titanium anodes under ICCP service develop no significant anode polarization with electrochemical age. They perform well in both low and high humidity environments, and exhibit stable long-term performance. Humectants based on LiNO ₃ and LiBr promote more effective performance of new and aged anodes in CP systems than untreated anodes. In SACP tests, LiBr was more effective than LiNO ₃ . In accelerated ICCP, LiNO ₃ was more effective than LiBr. In SACP service, zinc hydrogel anodes produce a stable protection current sufficient to protect reinforcing bar from corrosion. There was practically no effect of changing moisture conditions on current production and no evidence of aging effects in an Oregon DOT field trial.					
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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<u>LENGTH</u>					<u>LENGTH</u>				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
<u>AREA</u>					<u>AREA</u>				
in ²	square inches	645.2	millimeters squared	mm ²	mm ²	millimeters squared	0.0016	square inches	in ²
ft ²	square feet	0.093	meters squared	m ²	m ²	meters squared	10.764	square feet	ft ²
yd ²	square yards	0.836	meters squared	m ²	m ²	meters squared	1.196	square yards	yd ²
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi ²	square miles	2.59	kilometers squared	km ²	km ²	kilometers squared	0.386	square miles	mi ²
<u>VOLUME</u>					<u>VOLUME</u>				
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft ³	cubic feet	0.028	meters cubed	m ³	m ³	meters cubed	35.315	cubic feet	ft ³
yd ³	cubic yards	0.765	meters cubed	m ³	m ³	meters cubed	1.308	cubic yards	yd ³
NOTE: Volumes greater than 1000 L shall be shown in m ³ .									
<u>MASS</u>					<u>MASS</u>				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
<u>TEMPERATURE (exact)</u>					<u>TEMPERATURE (exact)</u>				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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INTRODUCTION

Bridges located in coastal environments and in colder climates where they are exposed to repeat applications of deicing salts suffer many of the same corrosion problems. Salt contamination of concrete causes corrosion of the embedded steel reinforcement. This leads to cracking of the concrete from the expansive forces of the corrosion product. Bridges must eventually be repaired, rehabilitated, or replaced when this occurs.

A 1993 report to the Federal government stated that 44 % of the more than 500,000 bridges in the United States were either structurally deficient or should be posted for weight restrictions (1). Costs for bridge maintenance, rehabilitation, and replacement due to corrosion damage are a necessary but nonproductive use of Department of Transportation (DOT) resources. Safety concerns, disruptions in service, and economic impacts of catastrophic bridge failures are further liabilities for bridge owners and users. Better construction and rehabilitation practices that mitigate these costs and liabilities require understanding the causes of corrosion-related bridge failures, and the complex interplay between the physical, chemical, and mechanical properties of concrete and steel reinforcing bar. Technology is needed to prevent further corrosion damage to existing bridges and to yield a 120+ year bridge service life in new construction.

Cathodic protection is one of the most effective techniques for controlling corrosion damage in existing reinforced concrete bridges (2). More than 500 bridges in North America are currently protected by CP systems (3). Current distribution to the reinforcing bar is a critical factor in the design and effectiveness of these systems. The California Department of Transportation (CALTRANS) pioneered the use of planar consumable thermal-sprayed zinc anodes for optimum current distribution in a CP system installed on the Richmond-San Rafael Bridge (California, USA) in 1983(4).

The Oregon coast is graced by twelve irreplaceable steel-reinforced concrete bridges designed and built by respected bridge engineer Conde B. McCullough in the 1930s. In addition, the Oregon DOT maintains more than 120 coastal bridges, most of which are reinforced concrete structures over 15 m (50 ft) in length. A 1984 report by Oregon DOT (5) raised concerns about the ongoing deterioration of these bridges, rising maintenance and repair costs, and the need to protect Oregon's large investment in coastal bridges.

Since 1988, the Oregon DOT has installed impressed current thermal-sprayed zinc anode CP systems on eight bridges: Cape Creek, Yaquina Bay, Depoe Bay, Big Creek, Cape Perpetua, Rogue River, Ben Jones, and Cummins Creek. Total installed capacity of these systems exceeds 40,000 m² (420,000 ft²), with an average cost for the systems of \$151.50 US/m² (\$14.09 US/ft²) (1997 dollars). Fifty percent of this cost is for installation of the thermal-sprayed zinc anode, the remainder for bridge rehabilitation (6).

Impressed current cathodic protection (ICCP) general installation steps are: 1) the damaged concrete and corrosion on the steel reinforcement is removed, 2) the steel reinforcement is made electrically continuous, 3) the dimensions of the structure are restored with new concrete, 4) an anode,

usually thermal-sprayed zinc, is applied to the surface of the concrete, 5) rectifiers to supply electric current are connected to the steel reinforcement and anode.

When galvanic (sacrificial) cathodic protection (SACP) has been used, an anode, usually thermal-sprayed zinc, is applied to the surface of the concrete leaving exposed rebar, without restoring the original dimensions of the structural element, and without applying an external electric current. This is done to reduce the corrosion rate by sacrificing the zinc and extend the life of the structure until it can be rehabilitated or replaced. Similarly, SACP can be applied to structural elements that have been restored to original dimensions.

The effectiveness of cathodic protection (CP) depends on several factors, such as: temperature, moisture in the concrete, concrete resistivity, condition of the anode, and condition of the anode/concrete interface. GCP has been used effectively in Florida, but its usefulness has not been demonstrated in Oregon, which has much lower average temperatures.

Research on impressed current systems indicates that circuit resistance and electrochemical age (the amount of current passed) can provide a measure of the anode and the anode/concrete interface condition. Oregon collects the current and voltage data that could be used to characterize ICCP and SACP systems. Consequently, the data collected by Oregon DOT could be used to establish the present condition of the ICCP and SACP systems to evaluate system performance and predict remaining service life.

Objectives of the Study

- Increase the value of CP operating data by using it to predict the condition, performance and remaining life of ICCP and SACP anodes.
- Determine the effectiveness of SACP applied to reinforced concrete elements that have been restored to their original dimensions.
- Determine the effectiveness of SACP applied directly on exposed reinforcing steel.

This research will provide a means of assessing the condition of CP anodes and incorporating this information into the Bridge Management System. It will determine whether SACP, a less-expensive method compared to ICCP, is an effective option for corrosion mitigation in Oregon.

Work Plan

Oregon DOT's cathodic protection field data will be collected and analyzed so as to provide estimates of CP system performance, anode performance and remaining anode service life. Polarization and depolarization data will be used to evaluate system performance. Circuit resistance (kohm-m^2) and anode electrochemical age (coulomb/m^2) will be used to determine anode performance and remaining service life.

New field data and bridge core samples will be used to validate the results of previous laboratory testing. Where possible, CP system operating parameters will be correlated with local temperature, precipitation, and relative humidity conditions.

The bridges, CP zones and anode type (Zn, Ti, C) to be considered for this project are given in Table 1 below.

Table 1. Bridges and Zones Considered for This Project.¹

Bridge	ICCP zone	GCP zone	Comments
Yaquina Bay Bridge	TS Zn		arch section: fully repaired structural element
		TS Zn, manually shorted	fully repaired structural element
	C paint		carbon paint anode system to be evaluated; fully repaired structural element
Cape Perpetua Viaduct		TS Zn, shorted	anode applied directly over rebar; requires window and Ag/AgCl reference electrode
		Zn-hydrogel	fully repaired structural element; shorts eliminated
Depoe Bay Bridge	zone 14 TS Ti		fully repaired structural element
		TS Zn, manually shorted	fully repaired structural element
	zone 13 TS Zn		fully repaired structural element

¹ “TS” stands for “thermal-sprayed.”

Table 2 Bridge Details

Bridge	Year energized	Area, m ² (ft ²)	Anode material	Thickness, mm (mils)
Yaquina Bay Bridge – north approach	1986	645 (6910)	C paint	0.50 (20) dft
Yaquina Bay Bridge - arches	1994	18,170 (195,500)	TS Zn	0.57 (22.6)
Yaquina Bay Bridge - south approach	1997	6,041 (65,000)	TS Zn	0.51 (20)
Depoe Bay Bridge	1995	5,940 (63,960)	TS Zn	0.55 (21.7)
Depoe Bay Bridge	1995	280 (3015)	TS Ti	0.10 (4)
Cape Perpetua Viaduct	1997	57 (607)	TS Zn	0.50 (19.7)
Cape Perpetua Viaduct	1997	57 (610)	Zn hydrogel	0.25 (10)

CATHODIC PROTECTION SYSTEMS

ICCP Systems

Yaquina Bay Bridge

The 980 m (3,220 ft) long Yaquina Bay Bridge was built in 1936. It is located about 500 m from the ocean in an open setting fully exposed to the prevailing westerly winds and accompanying salt deposition. The bridge deck is roughly 45 m above the coastal inlet to the Yaquina Bay. Inspections of the Yaquina Bay Bridge and other coastal bridges in the early 1980's demonstrated the need to prevent further corrosion damage to these bridges (Table 3). A carbon anode CP system was contracted for the soffit on the two northernmost approach spans of the Yaquina Bay Bridge in 1984, with installation completed in June 1985. (7-8) A replacement rectifier was installed in 1986. (7-8)

The soffit was rehabilitated and the CP system installed as four zones, each about 160 m² (1700ft²) in area. The primary anode for each zone was platinum-clad niobium wire and the secondary anode was a solvent-based carbon conductive paint. The primary anode was installed using slightly different configurations in each zone to evaluate the influence of primary anode design. These designs have performed satisfactorily with no apparent difference in performance; design 2 involving a fiberglass overlay was simpler to install and less expensive than the other designs.(7-8)

The 645 m² (6900 ft²) soffit area was divided into four zones of about 160 m² (1700 ft²). Solvent-based carbon anode conductive paint was applied using airless equipment in a single application to 35-40 mils wet film thickness, wft (15-20 mils dry film thickness (dft)). Platinum-clad niobium wire primary anode was installed over the carbon anode using 8 inch wide fiberglass screen and conductive paint. Water-based acrylic nonconductive paint was used to topcoat the carbon anode in a single application at 30 mil wft (12 mil dft). The system was energized in constant-current mode by the adjusting current density to meet the 100 mV depolarization criteria.

Four of the concrete approach spans on the south end of the bridge, previously thermal-sprayed (1996) with Zn and protected by ICCP (powered on June 1997), with areas of approximately 465 m² (5000 ft²) were chosen for a two-year humectant field trial. The areas are identified as CP Zones 10, 11, 13, and 14. The ICCP system was powered off in October 1999 and humectants were applied under the decks of two approach spans, CP Zone 13 with one coat of 30-40 wt. % LiNO₃ and CP Zone 11 with two coats of 52-56 wt.% LiBr. CP Zones 10 and 14, approach spans on each side of the treated zones, were left untreated as controls. The ICCP system was powered on the day after the humectants were applied. The total CP current for the CP Zones was: 0.55 A for CP Zone 10, 1.75A for CP Zone 11, 1.45 A for CP Zone 13, and 0.75 A for CP Zone 14. The on voltages and currents for the treated and untreated CP Zones are monitored daily.

Depoe Bay Bridge

The Depoe Bay Bridge in Depoe Bay, OR consists of the original structure built in 1926. Another bridge was built adjacent to the west face in 1939 to widen the bridge. Installation of a cathodic protection system was begun in 1993. A titanium anode was thermal-sprayed to the under deck and beam areas of the southern-most approach span of the bridge built in 1939. The remainder of the bridge was cathodically protected using a thermal-sprayed zinc anode system. The thermal-sprayed titanium anode was applied using the same materials, equipment, and procedures, as used to prepare the slabs for the laboratory experiment. Compressed air was the atomizing gas and the spraying was done manually rather than with the xy-traversing robotic system. Considerable experience was gained from this and the details of that installation have been published (9-10).

The thermal-sprayed titanium anode, zone 14 on the Depoe Bay Bridge, was catalyzed with cobalt nitrate. The catalyst was sprayed onto the titanium anode surface at an application rate of 0.355

L/m² (0.0087 gal/ft²) with 0.0054 A/m² (0.5 mA/ft²) cathodic protection current density flowing between the titanium and the rebar. Further details of this application have been published (9-10). Zone 14 measured 280 m² (3015 ft²) and was operated at a current density of 0.0028 to 0.0038 A/m² (0.26 to 0.35 mA/ft²) and a voltage of 1.4 -1.7 V. The anode was operated approximately 1.4 years after the system was energized when two 5.1 cm (2 in) diameter core samples were taken for purposes of characterizing the titanium-concrete interface. At the time of coring the anode electrochemical age was about 146 kC/m².

SACP Systems

SACP systems are simpler and less costly to install than ICCP systems, and operate immediately and continuously since they require no external power source and rely solely on the galvanic couple between the anodes and rebar. Some state DOT's have applied TS anodes over the exposed rebar to form the couple. While this is the least expensive installation and may be perfectly adequate for short-term service (5-10 years), CP system performance cannot be monitored if the anode is not isolated from the rebar so current output of the anode and depolarization of the rebar can be measured.

Cape Perpetua Viaduct

The Cape Perpetua Half Viaduct is a 27' wide, 76' long, and consists of two span structures carrying the Oregon Coast Highway around the sheer rocky cliff face of Cape Perpetua. The structure was constructed in 1931. Rehabilitation was preferred to replacement due to its location, approximately 200 feet above the ocean on the shear cliff face of Cape Perpetua, which would make replacement both difficult and expensive. The scenic nature of this section of highway and the bridge's location made the likelihood of widening extremely improbable.

Chloride tests showed that the chloride content in the bridge was over 10 times the corrosion

threshold of 0.14% total chlorides by mass of cement. Approximately 25% of the surface area of concrete delaminated or spalled due to corrosion damage. Deterioration of the structure was expected to proceed rapidly due to the extreme chloride levels in the bridge. The structure has no expansion joints and is anchored to the rock cliff of Cape Perpetua, so its ability to withstand a seismic event is as good as the rock cliff to which it is attached.

The FHWA had strong interest in testing the operation of galvanic cathodic protection (GCP) systems in Oregon's moderate climate. Since there was no power source near the Cape Perpetua Half Viaduct, this bridge was chosen for a galvanic (non-impressed current) cathodic protection system as a part of a FHWA demonstration project.

Cape Perpetua has approximately 171 m² (1840 ft²) of surface area on the underside of the deck to which cathodic protection was applied. This area was divided into three zones, approximately 57 m² (614 ft.²) each to test three metallic anodes systems.

Zone 1 had zinc-hydrogel, an adhesive backed zinc foil, applied on completely repaired and restored concrete since a smooth surface was required for good adhesion. After the zinc-hydrogel foil was firmly bonded to the surface, polyurethane caulking was applied to seal the edges of the foil from the weather and the outer surface was painted for cosmetic purposes. The zinc-hydrogel strips were electrically connected to each other by 10 mil (0.254 mm) thick pieces of tinned zinc. The anode terminals consisted of a #10 AWG wire sandwiched between the zinc-hydrogel and the tinned zinc. Zone 1 contains silver-silver chloride and graphite reference cells and is being monitored through depolarization testing. Data is logged from the 57 m² test area.

Thermal-sprayed anodes were applied to the concrete in zones 2 and 3 using the twin-wire arc-spray process. Zone 2 used the thermal-sprayed zinc anode. The concrete was not restored but had

damaged concrete removed. Small areas within zone 2 were excavated where some shear stirrups had debonded. The zinc anode was applied in multiple passes and had a minimum thickness of 0.5 mm (20 mil). The anode terminal was a copper alloy plate for zones 2. The cathode was a rebar that was electrically continuous with all the other rebar. In zone 2, data is logged from 0.09 m² (1 ft²) tests area. The performances of the zone 2 system is being monitoring by comparing the current output of the system over time to that of zone 1.

ANALYSES

Circuit Resistance.

For the ICCP anode, performance in the field was characterized by techniques related to the practical aspects of the anode operation. Anode polarization was characterized by the ICCP system circuit resistance, i.e., the voltage between anode and reinforcing bar divided by current density.

Equation 1:

$$\text{Circuit resistance, ohm} - \text{m}^2 = \frac{\text{volts}}{\left(\frac{\text{current, mA}}{\text{area, }^2} \right)}$$

Concentration polarization of the anode and electrolyte (concrete) resistance, including resistance from minerals formed at the anode-concrete interface from anode dissolution products, were the major sources of system circuit resistance. For the SACP anode, performance in the field was measured by galvanic current density output.

Rebar Depolarization.

Rebar depolarization measurements are made to establish the performance of the anode CP system. Effective CP requires that the anode be polarized sufficiently to inhibit corrosion of the steel. A

common criterion is that the “instant off” potential must be at least 100 mV more negative than the open circuit potential 24 hours later.

The potential of the rebar was monitored using a data acquisition system and computer. Rebar potential measurements were collected at a rate of 10 points/sec when each zone was first depolarized. Additional potential measurements were made at a rate of 1 point/min for 4 to 24 hours after depolarization was begun. The “instant-off” potential was identified as the potential measured approximately 2-3 s after a zone was turned off when a slower rate of potential decay was observed. The depolarized potential was typically taken for 4 to 24 hours.

RESULTS AND DISCUSSION

ICCP anodes

Impressed current cathodic protection systems can involve either a consumable or non-consumable anode. A consumable anode produces metal reaction products that can accumulate at the anode-concrete interface. A non-consumable anode produces no metal reaction products at the anode-concrete interface, but chemical change as the result of acidification do occur at the interface. The current delivered by these systems can be adjusted with a rectifier. The voltage needed to protect a structure is based on the amount of current needed to reduce the rebar corrosion rate to an established standard.

The conductive coating anode ICCP systems on the Oregon coast are typically operated under current control at a current density of 2.2 mA/m² (0.2 mA/ft²) based on anode area (as opposed to rebar area) (17,22,23) . In this paper, the anode performance is expressed in terms of an equivalent circuit resistance (operating voltage divided by current density). Gaps in the graphs are the result of either

missing data or rectifier failure.

Protection of the reinforcing bar was determined by periodic depolarization measurements followed by current density adjustments as necessary to meet the 100 mV depolarization criteria.

Thermal-sprayed planar zinc anode circuit resistance.

The TS Zn anode is consumable, leading to acidification of the anode-concrete interface (with the pH decreasing from 13 to 7), and the formation of Zn minerals that reduced the long-term anode bond strength and increased the CP circuit resistance in ICCP service (11). Moisture at the interface of the anode and concrete had a strong effect on anode performance (19).

Figure 1 shows the circuit resistance of the TS Zn zone 14, located on the south approach to the Yaquina Bay Bridge. Zone 14 is close to the bay and in a moist environment. The TS Zn responded to the seasonal wetting and drying, hence the variations in the circuit resistance. Approximately 4 years after the TS Zn was applied, the circuit resistance averaged 1.5 Kohms-m².

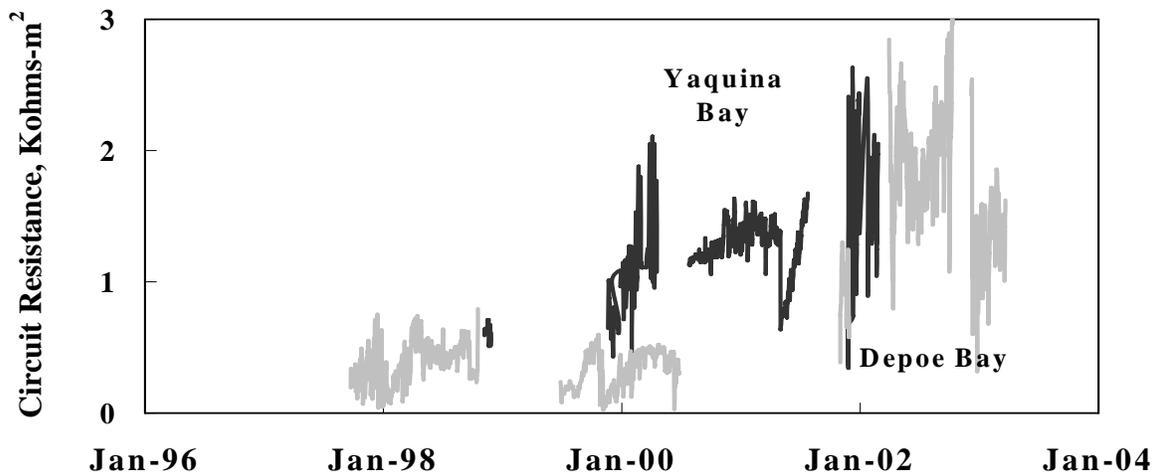


Figure 1 -The anode performance of TS Zn on the Yaquina Bay Bridge, zone 14, and the Depoe Bay Bridge, zone 13, as a function of circuit resistance vs time.

Figure 1 shows the circuit resistance of a TS Zn zone (zone 13) on the Depoe Bay Bridge after 8 years of service. Zone 13 is in a boldly exposed part of the bridge and experiences frequent wetting and drying cycles. These cycles are reflected in variations in the zone circuit resistance.

On all bridges where thermal-sprayed Zn was used as an anode, the circuit resistance increased with increasing electrochemical age.

Cobalt-catalyzed TS titanium anode circuit resistance.

Microanalysis showed the Ti anode had a porous, heterogeneous structure and composition strongly affected by reactions between the molten Ti, the atomizing gas, and air. The anode is non-consumable, and current flow is based on the oxidation of moisture on the anode. This leads to acidification of the anode-concrete interface in ICCP service with the pH decreasing from 13 to 7.

The circuit resistance remained relatively unchanged over the 8 years of service life. Unlike Zn anodes, the Ti anode operation is relatively insensitive to moisture in the environment, remaining stable at relative humidities from 30 to 100%, Figure 2. Evidently the environment provides sufficient moisture to the catalyzed anode surface to maintain the anode reaction.

Conductive carbon paint anode circuit resistance.

In theory, the conductive carbon paint anode is consumable. However, in high-chloride environments such as the Oregon coast, over time these reactions will acidify the interface, lowering the pH to the values that would permit the evolution of chlorine. In this way, the conductive carbon anode behaves in ways similar to the TS Ti anode, supporting anode reactions utilizing reactants originating in the coastal environment.

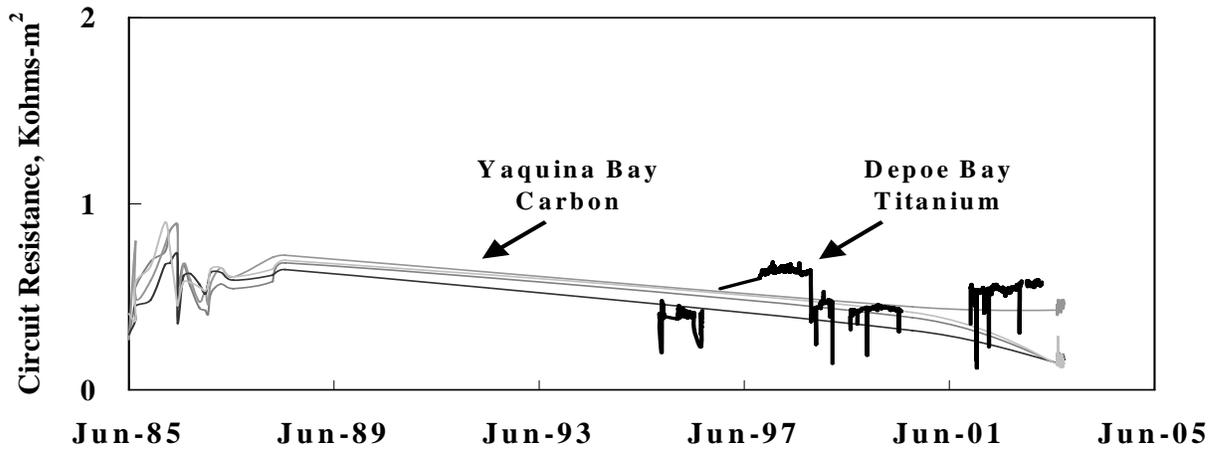


Figure 2 – Anode performance of C and Ti anodes on the Yaquina Bay and Depoe Bay Bridges, respectively, as a function of circuit resistance vs time.

Rectifiers were installed in 1985 and operated in the current-limited mode. The zones were operating at 0.27 to 0.39 mA/ft² (2.8 to 4.1 mA/m²) in 1990 and in 2000 at 0.25 to 0.30 mA/ft² (2.6 to 3.1 mA/m²). The circuit resistance for the four zones decreased slowly from values around 0.7 Kohms-cm² to 0.2 Kohms-cm² over roughly 17 years service, Figure 3. These values are substantially lower than those measured for CP Zn anodes (19,15,11), Figures 1 but similar to that for Ti anodes, Figure 2.

Moisture at the anode-concrete interface had a strong effect on anode performance; drier conditions substantially decreased anode service life based on bond strength (19). Increasing circuit resistance may also be a factor in determining anode service. The anode operating voltages are still reasonably low after up to 11 years service. Some delamination of the anode has been observed at isolated locations over this same period and is thought to be caused by poor surface preparation prior to anode installation and anode thickness substantially greater than specified.

The ICCP circuit resistance for humectant treated zones on the Yaquina Bay Bridge and that of the two adjacent control zones is shown in Figure 3. All of the zones are over land in the approach structure to the bay crossing. Zone 10 is furthest from the bay (about 131 m [430 ft]) and Zone 14 is closest (about 73 m[240 ft]). The humectant-treated zones

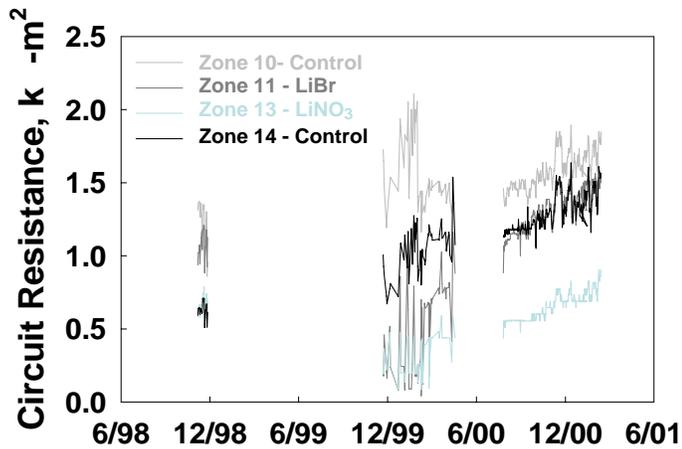


Figure 3. Circuit resistance of controls and humectant-treated zinc anode zones in ICCP service on the Yaquina Bay Bridge (OR).

are physically situated between these two control zones at 94 m[310 ft] (LiNO₃) and 113 m [370 ft] (LiBr). The four zones are sheltered by the bridge deck. The higher circuit resistance of Zone 10 suggests it is the drier of the two control zones. The position of the zones relative to the bay suggests circuit resistance varies inversely with distance to the bay and that, in the absence of humectant, the circuit resistance of the Zones 11 and 13 would lie between Zones 10 and 14. Instead, humectant application substantially reduced the circuit resistance of Zones 11 and 13 compared to the controls.

Rebar depolarization.

Depolarization measurements were made to establish the performance of the conductive carbon anode CP system, using the depolarization standard of 100 mV in 4 hours. For the carbon anode on the north end of the Yaquina Bay Bridge, windows approximately 15 cm (6 in) square were located in each zone and used to measure the potential of the rebar with respect to a copper-copper sulfate (CSE) reference electrode. A CSE reference electrode was installed in each of the four zones on either a beam or the underside of the deck. Depolarization measurements performed on the thermal sprayed zinc anodes on the Yaquina Bay Bridge, Cummins Creek, and Bridge Depoe Bay Bridge and the cobalt-catalyzed TS titanium anode on the Depoe Bay Bridge were made with respect to Ag/AgCl and graphite reference electrodes.

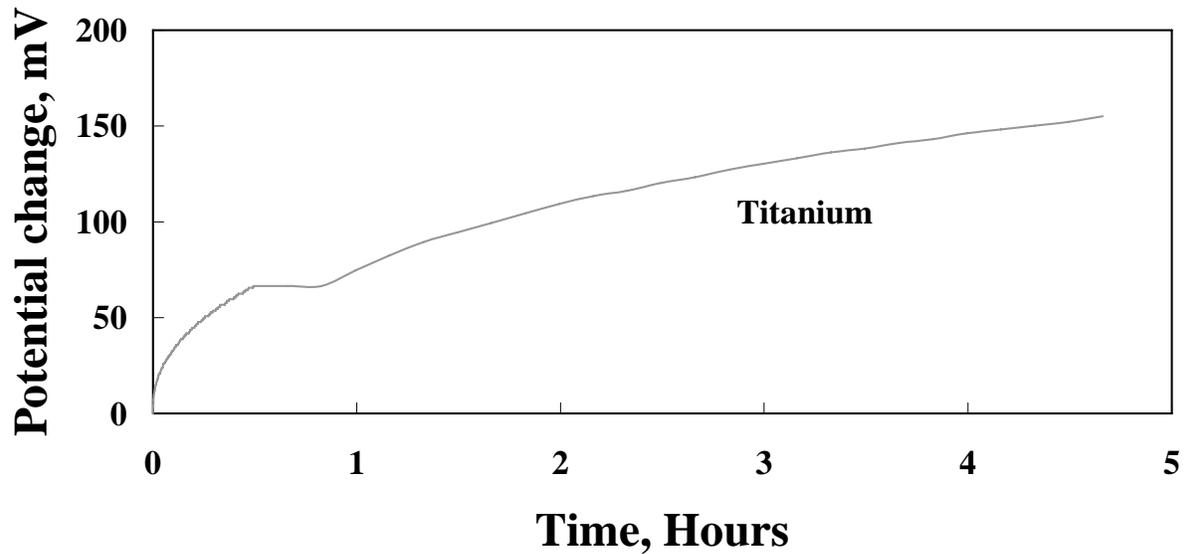


Figure 4 - Depolarization measurements for the titanium anode on the Depoe Bay Bridge.

In the graphs, the potential change is the difference between “instant off” potential and the zone potential at a given time. Depolarization data for the TS Ti anode on the Depoe Bay Bridge is shown in Figure 4. The potential change was greater than 100 mV after 4 hours indicating good protection of the rebar.

Four hour depolarization data for the conductive carbon paint anodes are shown in Figure 5 as a function of service time. Depolarization measurements were taken in 1990 and 2000. The data of Broomfield and Tinnea, (21) taken in 1990, showed that over 80% of the depolarization values exceeded 100 mV after 4 hours, and 92 % exceeded 100 mV after 24 hours. The average instant off potential in 1990 was -387 mV. In 2000, the instant off potential was -380 mV and the depolarization was about 200 mV after 4 hours. Rebar depolarization measurements over the years meet the 100 mV depolarization standard and show the rebar is adequately protected by the conductive carbon paint anode.

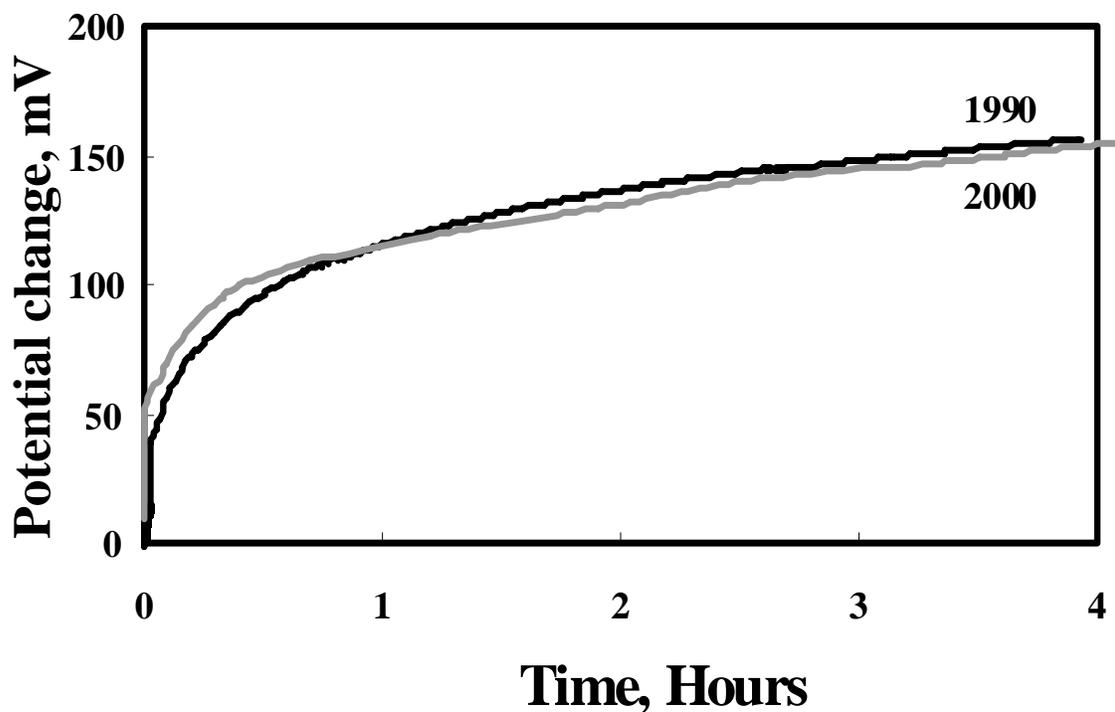


Figure 5 – Depolarization measurements for the solvent-based carbon paint anode on the Yaquina Bay Bridge.

SACP anodes

The SACP anodes were applied to the same standards used for ICCP anodes i.e., active elimination of shorts between anode and rebar. The performance of the SACP anodes was evaluated using the same criteria as for ICCP anodes. Early in the operation of the SACP zones anode current output may be high and it may be necessary to slow the anode reaction. Anode output current typically decreases with time, Figure 6.

TS zinc anode current output.

This is the same type of anode as used in ICCP service. Current output on the Cape Perpetua Viaduct has trended downward over 5 years of service as Zn mineral anode reaction products

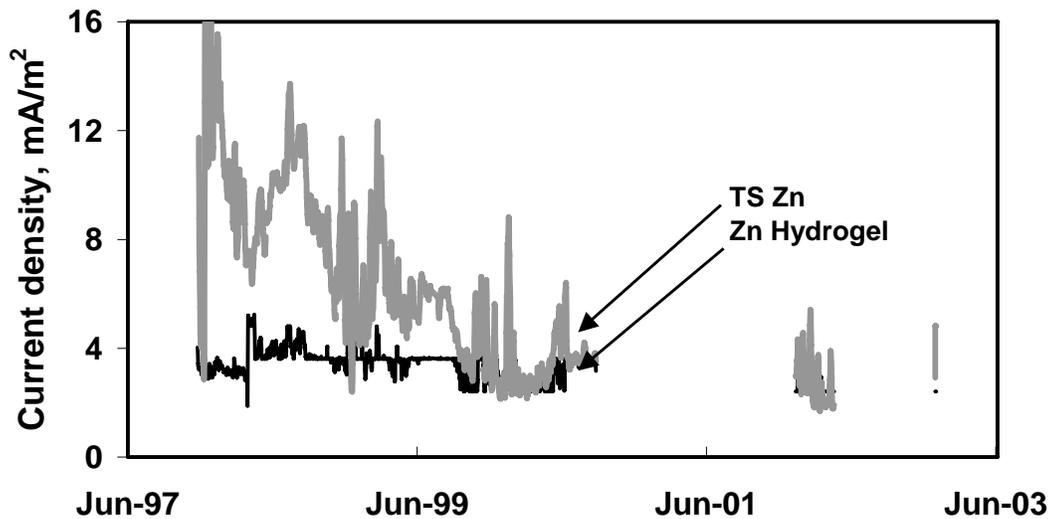


Figure 6 – SACP anode performance of TS Zn and Zn Hydrogel on the Cape Perpetua Viaduct as a function of circuit resistance vs. time.

accumulated at the anode-concrete interface. Current output started at 10-15 mA/m² and decreased to about 2 mA/m² after 6 years, Figure 6.

The initial current output was much higher than necessary and modification of the SACP zone to adjust it downward would greatly extend the service life of the anode. Seasonal variations in current output occurred as a consequence of changing moisture levels at the anode-concrete interface. At 5 years, the SACP current continued to provide adequate protection of the rebar.

Zinc-hydrogel anode current output.

Like the TS Zn, the Zn hydrogel anode is consumable, but the weak sulfonic acid in the adhesive buffers acidity resulting in little change in pH at the anode-concrete interface. Since the adhesive is hygroscopic, conditions that could lead to dehydration of Zn hydroxide produced by the anode reaction are unlikely. Circuit resistance varies little with service and is insensitive to changes in the environment. Current output on the Cape Perpetua Viaduct has remained constant over 6 years at about 3.5 mA/m²,

Figure 6.

Rebar depolarization.

For the Zn-hydrogel anode (Zone 1) on the Cape Perpetua Viaduct, a window were located in the zone and used to measure the potential of the rebar with respect to Ag/AgCl and graphite reference electrodes.

Depolarization measurements for Zn hydrogel anodes are shown in Figure 7 as a function of service time. As in the previous depolarization graphs, the potential change is the difference between instant off and the decaying potential. The rebar depolarization values, after four hours, are consistently above 100 mV, indicating the rebar is adequately protected.

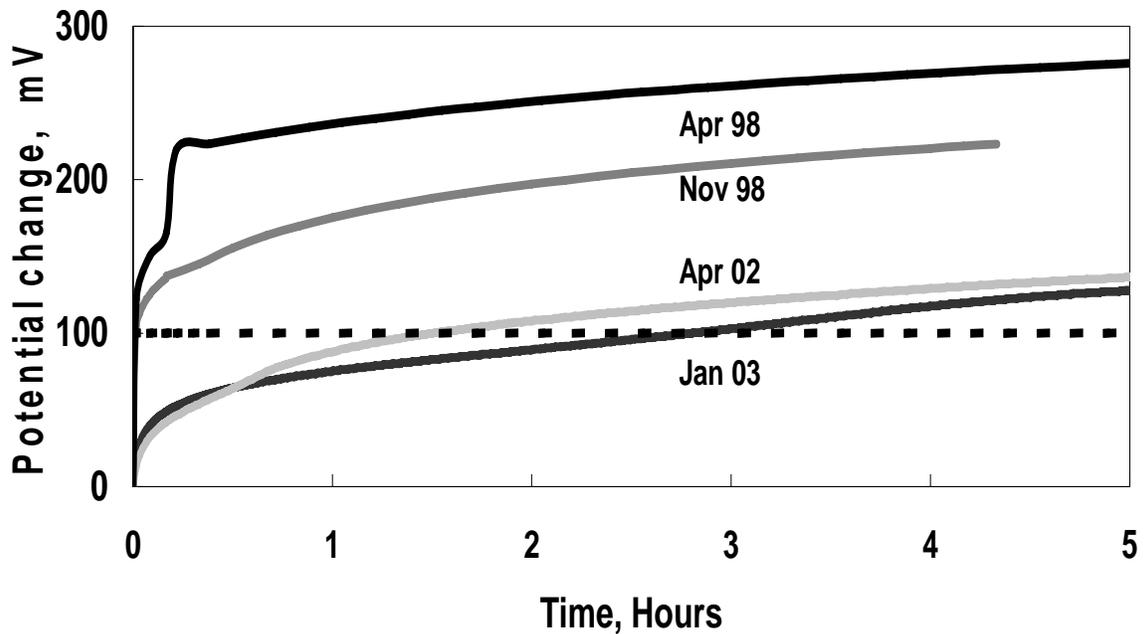


Figure 7 – Depolarization measurements for the Zn hydrogel anode on the Cape Perpetua Viaduct over time.

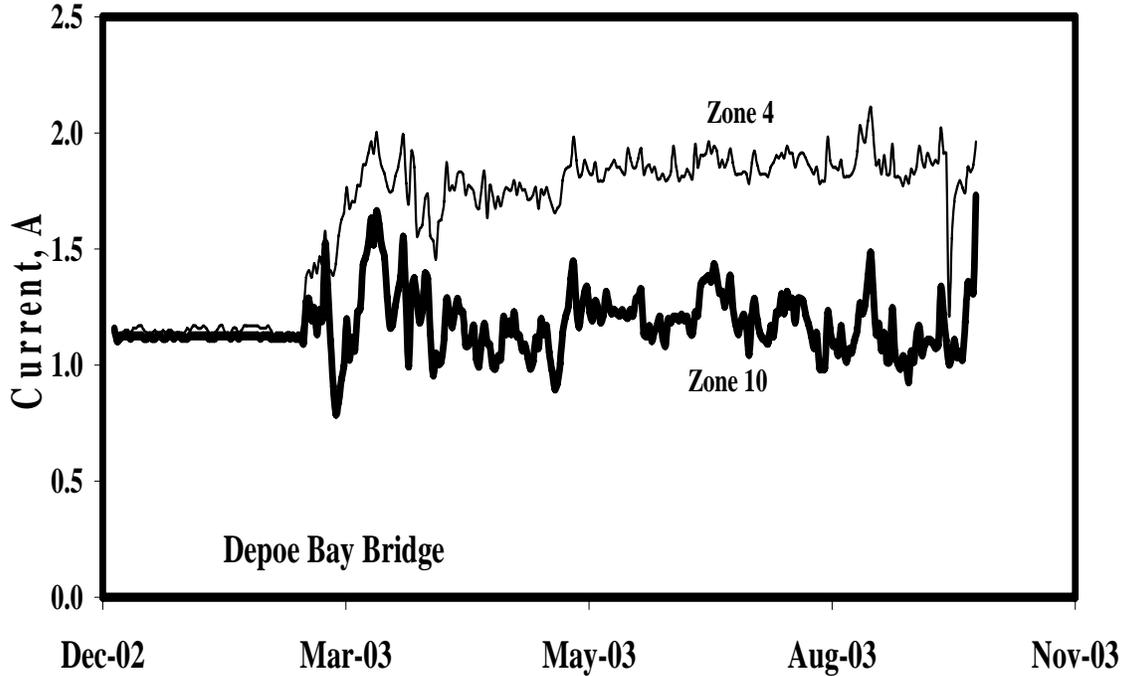


Figure 8 – Performance of CVCP zones on the Depoe Bay Bridge.

CVCP anodes

The performance of the two constant voltage cathodic protection (CVCP) zones on the Depoe Bay Bridge over a 1 year period is shown in Figure 8. A three month period, when the zones were operated in the ICCP mode, precedes CVCP operation. The average current for zone 10 is about the same as when the zone was operated in the ICCP mode. Zone 4 appears to have been set at too high a current. Neither zone exhibits a decline in current during the summer months when pore water in the concrete tends to evaporate, leading to lower conductivity concrete. It is too early to say whether there are any advantages to operating in the CVCP mode other than the apparent simplicity and low cost of the operation.

CONCLUSIONS

Planar anodes are an effective configuration for reducing electrolyte (concrete) resistance and improving current distribution to reinforcing bar in concrete bridges. Thermal-sprayed anodes, foil anodes with a conductive adhesive and carbon painted anodes can achieve these objectives. A resistive layer develops at the anode-concrete interface with increasing electrochemical age, thereby increasing anode polarization. In ICCP systems this is reflected in a higher circuit resistance. In SACP systems it results in lower current output. Periodic wetting of the anode by rain, fog, and dew is an important factor in reducing anode polarization. Bridge structure wetting and drying cycles are reflected in the operation of thermal-sprayed Zn anodes.

Catalyzed thermal-sprayed Ti anodes under ICCP service develop no significant anode polarization with electrochemical age. They perform well in both low and high humidity environments, and exhibit stable long-term performance. The catalyst is located at the anode-concrete interface and appears fairly resistant to leaching by precipitation washing.

Humectants lower the activity of water at the anode-concrete interface and absorb water from the environment into the interface. Both humectants (LiNO_3 and LiBr) promote more effective performance of new and aged anodes in CP systems than untreated anodes. In SACP tests, LiBr was more effective than LiNO_3 . In accelerated ICCP, LiNO_3 was more effective than LiBr . Oxidation of bromide ions to bromine and subsequent loss of humectant at the higher operating voltages sometimes experienced by ICCP systems under drier conditions led to higher circuit resistance.

In SACP service, Zn hydrogel anodes produce a stable protection current sufficient to protect reinforcing bar from corrosion. There was practically no effect of changing environmental conditions

(moisture) on current production and no evidence of aging effects in an Oregon DOT field trial. The Zn hydrogel anodes are readily top-coated to provide visual compatibility with the bridge structure. It is too early to say whether there are any advantages to operating in the CVCP mode.

This report should make it clear that monitoring and interpretation of CP data is equally important to the proper installation and operation of CP systems.

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