

# CORROSION PREVENTION OF OREGON'S REINFORCED COASTAL BRIDGES

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## Abstract

The Oregon Department of Transportation (Oregon DOT) maintains more than 120 coastal bridges; many are reinforced concrete structures over 15 m (50 ft) in length. Twelve of these bridges are historic structures. Oregon DOT is concerned about the ongoing deterioration of these bridges, rising maintenance and repair costs, and the need to protect Oregon's large investment in coastal bridges. Over 80,000 m<sup>2</sup> (850,000 ft<sup>2</sup>) of coastal bridge surface have been repaired and protected from further chloride-induced corrosion damage by using conductive coating anodes. Most of the anode area is thermal-sprayed (TS) Zn. Other anode materials include TS Ti, Zn-hydrogel, and conductive carbon paint. TS Zn anodes are estimated to have a service life exceeding 25 years but exhibit increasing anode polarization with age. Catalyzed TS Ti anodes develop no significant anode polarization and have exhibited stable long-term performance over 8 years of service. Galvanic Zn-hydrogel anodes produce a stable protection current with no evidence of aging effects over 6 years of service. The conductive carbon paint anode operates at a low anode current density and consumption rate with a low rate of acidification at the anode-concrete interface, which has contributed to a stable protection current over 17 years of service.

## 1. Introduction

Cathodic protection (CP) is a commonly used remediation measure to increase the service life of existing reinforced concrete bridges suffering chloride-induced corrosion problems [1]. Thermal-sprayed (TS) metals and alloys are increasingly used as anodes for CP systems operated either galvanically or by impressed current. The Albany Research Center (ARC), in collaboration with the Oregon DOT, has studied the effect of electrochemical aging on the service life of Zn anodes for bridge impressed current cathodic protection (ICCP) systems [2-5]. Sacrificial anode cathodic protection (SACP) systems [7-9] have been tried in Oregon and are less expensive to install and simpler to operate. An understanding of the performance of SACP and ICCP systems is useful for choosing the best anode material for specific applications. Acidification of the anode-concrete interface by anode reaction products may affect the long-term adhesion, operating characteristics, and service life of these anode materials. Accordingly, laboratory and field research are used to characterize the performance of the anodes in ICCP [2-6] and SACP systems [7-9]. This paper describes conductive coating anodes used for cathodic protection on existing reinforced concrete bridges to reduce the cost of chloride-induced corrosion damage.

## 2. Conductive Coating Anodes

The Oregon DOT has been applying conductive coating anodes to coastal bridges for use in ICCP or SACP systems since 1985. Most of the anode area is (TS) Zn [2-5]. Other materials used for anodes are TS Ti [6,9], Zn-hydrogel [7-9], and conductive carbon paint [9-11]. At present, thirteen CP projects have been completed or are in progress on Oregon coastal bridges totaling over 80,000 m<sup>2</sup> (850,000 ft<sup>2</sup>) of conductive coating anode. A partial list is given in Table 1.

**Table 1: Oregon DOT Anode CP Projects using Conductive Anodes**

Bridges	Year	CP	Area m <sup>2</sup> (ft <sup>2</sup> )	Anode material	Thickness mm (mil)
Yaquina Bay	1985	ICCP	645 (6910)	Carbon paint	0.50 (20) dft <sup>1</sup>
Yaquina Bay	1998	ICCP	6,041 (65,000)	TS Zinc	0.38 (15)
Depoe Bay	1995	ICCP	280 (3020)	TS Titanium	0.10 (4)
Depoe Bay	1995	ICCP	405 (4820)	TS Zinc	0.50 (20)
Cape Creek	1992	ICCP	9,530 (102,500)	TS Zinc	0.50 (20)
Cape Perpetua	1997	SACP	57 (607)	TS Zinc	0.50 (20)
Cape Perpetua	1997	SACP	57 (610)	Zn-hydrogel	0.25 (10)

<sup>1</sup>dft - dry film thickness

## 2.1 ICCP anodes

**TS Zn Anodes** TS Zn anodes for ICCP have been installed on five Oregon coastal bridges. The anodes were applied to lightly sand blasted concrete using the twin-wire arc-spray process. High application rates were achieved with 4.8 mm (3/16 inch) diameter wire [5]. The atomizing gas was compressed air at 0.62-0.79 MPa (90-110 psi); spray orientation was normal to the sprayed surface at a distance of 15-23 cm (6-9 inches). Multiple passes in an X-Y pattern were used to build up coating thickness. The fine spray of molten metal created in the electric arc and accelerated to the concrete surface by the atomizing gas forms TS anodes. There the spray is deposited, freezing in place as “splats,” and forming a dense structure with limited porosity. The concrete must be clean and dry before application and the workspace should have a relative humidity of 60% or less [5]. Present Oregon DOT acceptance criteria for TS Zn anodes on coastal RC bridges are: a coating thickness of 0.37 mm (15 mils), and anode bond strength of 0.34 MPa (50 psi). The anodes tested were 0.25-0.5 mm (10-20 mils) thick. The anode color was silver-gray.

**Cobalt-catalyzed TS titanium anode** A cobalt-catalyzed TS Ti anode was installed on one zone on the Depoe Bay Bridge. It was applied in the same way as the Zn anode using the twin-wire arc-spray process, but at a higher voltage [6]. It is somewhat more difficult to apply than Zn because the wire is stiffer, wear rates on the spray gun tips are higher, and stability of the arc is more critical. The TS Ti anode was 0.10-0.15 mm (4-6 mils) in thickness. Despite the reactivity of molten Ti in the atmosphere, the anode contained 88 wt % Ti; present as  $\alpha$ -Ti containing interstitial nitrogen,  $\gamma$ -TiO, and possibly TiN [6]. Nitrogen atomization rather than compressed air atomization produced anodes with more uniform chemistry, less internal cracking, and lower resistivity. A cobalt nitrate-amine complex was applied to the TS Ti as an aqueous solution to catalyze the anode reaction. The catalyzed anode reaction was the breakdown of water to form oxygen. The anode color was gold-brown.

**Conductive carbon paint anode** Oregon DOT installed conductive carbon paint anodes on two of the north approach spans of the Yaquina Bay Bridge in 1985 making these the oldest carbon anodes in CP service in the USA [6-7]. The area protected was divided into four separate zones, each approximately 158 m<sup>2</sup> (1700 ft<sup>2</sup>). The primary anode was a platinum-niobium wire and conductive carbon paint was the secondary anode. The carbon anode covered the bottom of the deck between the beams, the beam sides, and the bottom of the beams. The carbon anode was applied as conductive paint with a wet film thickness of 0.9 - 1 mm (35 - 40 mils) that resulted in a dry film thickness of ~0.5 mm (~20 mils). The dominant anode reactions were the oxidation of both the carbon anode and the chloride ion in the concrete. The carbon anode was top coated with an acrylic paint for cosmetic purposes.

## 2.2 SACP anodes

**TS zinc anode** The TS Zn anode was used on a 57 m<sup>2</sup> (614 ft<sup>2</sup>) SACP zone on the Cape Perpetua Viaduct [7-9]. This is the same anode as is used in ICCP service. The anode had a minimum thickness of 0.5 mm.

**Zinc-hydrogel** The Zn-hydrogel anode was applied, in a field trial to a 57 m<sup>2</sup> (614 ft<sup>2</sup>) SACP zone on the Cape Perpetua Viaduct. The Zn hydrogel anode is a 0.25 mm (10 mil) thick, non-porous Zn foil, backed with a conductive, pressure-sensitive adhesive [7-9]. The adhesive is a hygroscopic acrylate polymer 0.75 mm (30 mil) thick containing sulfonic acid. It is charged with lithium chloride to form an electrolyte at the anode-concrete interface. The anode comes in rolls with a plastic film backing. The backing is removed and the Zn rolled onto the concrete with a hard rubber or wood roller to press the adhesive into the concrete. The edges of the anode are sealed with silicone rubber (or polyurethane) caulking to prevent water from reaching the adhesive and causing it to swell. The hydrogel anode color is a bright silver color. However, after completing the field installation, the hydrogel anode was top-coated with a water-base paint to blend with the bridge appearance.

## 3. Results and Discussion

### 3.1 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 changes occur as the result of acidification 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 rebar corrosion to an established level. The conductive coating anode ICCP systems on the Oregon coast are typically operated under current control at a current density of 2.2 mA/m<sup>2</sup> (0.2 mA/ft<sup>2</sup>) based on anode area (as opposed to rebar area) [7-9].

Past research has shown that TS Zn anodes have a service life exceeding 25 years at the Oregon DOT bridge CP current density of 2.2 mA/m<sup>2</sup> [7-9]. 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 missing data. 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.

### 3.1.1 Circuit Resistance

**TS Zn Anodes** 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 [5]. Moisture at the interface of the anode and concrete had a strong effect on anode performance [3]. Fig. 1 shows the CP system currents and voltages, expressed as a circuit resistance for ICCP zones 11 (black) and 15 (gray) of the Cape Creek Bridge. Zone 11 is on the underside of the bridge deck and remains wet for long periods of time; zone 15 is on the west (ocean) face of bridge columns and experiences extreme wetting-drying cycles. The circuit resistance of these zones responds to seasonal wetting and drying, with the circuit resistance substantially lower during the wet periods, typically November through March on the Oregon coast. In the earlier years, during the drier periods of late spring, summer, and early fall, zone 15 circuit resistance rose to values about twice those of zone 11. From 1996 (5 years after the TS Zn was applied) to 1999, the circuit resistance for both zones averaged about 1.5 Kohms-m<sup>2</sup>. Fig. 2 shows the circuit resistance of the TS Zn zone 14 located on the south approach to the Yaquina Bay Bridge (black). 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-m<sup>2</sup>. Fig. 2 also shows the circuit resistance of a TS Zn zone (zone 13) on the Depoe Bay Bridge after 8 years of service (gray). 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.

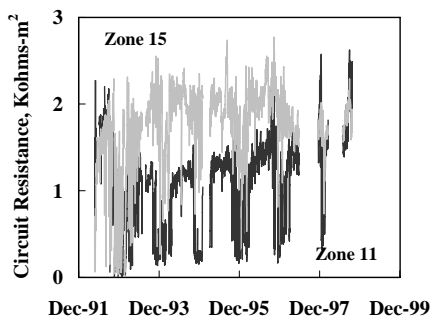


Fig. 1 Anode performance of Zones 11 and 15 on the Cape Creek Bridge expressed as circuit resistance.

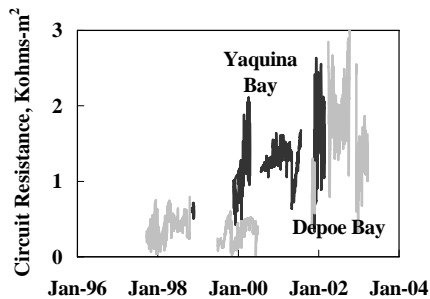


Fig. 2 Anode performance of TS Zn on the Yaquina Bay (black) and Depoe Bay (gray) Bridges.

**Cobalt-catalyzed TS titanium anode** 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, 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, Fig. 3. Unlike Zn anodes, the Ti anode operation is relatively insensitive to moisture in the environment, remaining stable at relative humidities from 30 to 100 %. [6] Evidently the environment provides sufficient moisture to the catalyzed anode surface to maintain the anode reaction.

**Conductive carbon paint anode** In theory, the conductive carbon paint anode is consumable. However, in high-chloride environments such as the Oregon coast acidification of the interface can change the reactions from carbon consumption to chloride oxidation, which produces chlorine gas. 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. Rectifiers were installed in May 1986 and operated in the current-limited mode. The zones were operating at 0.27 to 0.39 mA/ft<sup>2</sup> (2.8 to 4.1 mA/m<sup>2</sup>) in 1990 [1-6], and in 2000 at 0.25 to 0.30 mA/ft<sup>2</sup> (2.6 to 3.1

$\text{mA/m}^2$ ). The circuit resistance for the four zones decreased slowly from values around  $0.7 \text{ k}\Omega\text{-cm}^2$  to  $0.2 \text{ k}\Omega\text{-cm}^2$  after roughly 17 years service, Fig. 3. These values are substantially lower than those measured for CP Zn anodes [2-5] but similar to that for CP Ti anodes (Fig. 3).

### 3.1.2 Rebar Depolarization

Rebar depolarization measurements were made to determine the performance of the conductive coating anode CP systems, by the standard of 100 mV in 4 hours. In the graphs, potential change is the difference between “instant-off” potential and the zone potential. The depolarization data for the TS Ti anode on the Depoe Bay Bridge are shown in Fig. 4. The 100 mV depolarization standard was met. Depolarization data for the conductive carbon paint anodes are also shown in Fig. 4. Depolarization measurements were taken in 1990 and again in 2000. The data of Broomfield and Tinnea, [12] 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 vs CSE. In 2000, the depolarization was about 200 mV vs SCE after 4 hours and the “instant-off” potential was -380 mV vs SCE. 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.

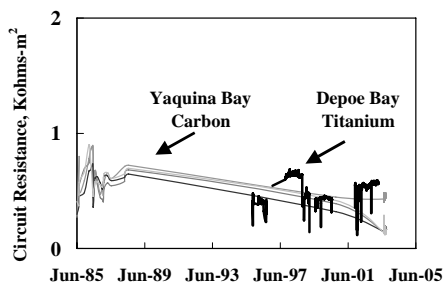


Fig. 3 Anode performance of C and Ti anodes.

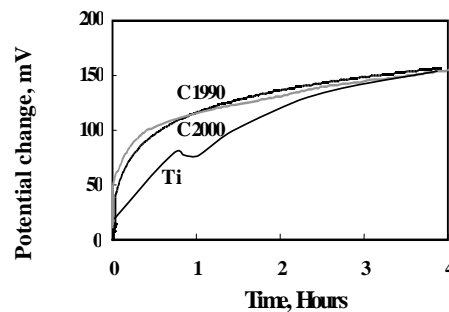


Fig. 4 Depolarization measurements for the C and the Ti anodes.

### 3.2 SACP anodes

SACP systems are simpler and less costly to install than ICCP systems. They require no external power source and rely solely on the galvanic couple between the anode 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 that current output of the anode and depolarization of the rebar can be measured. The SACP anodes were applied to the same standards used for ICCP anodes i.e., elimination of shorts between anode and rebar. Performance of the SACP anodes was evaluated using the same depolarization criteria as for ICCP anodes. Early in the operation of the SACP zones anode current output can be high and it may become necessary to slow the anode reaction. Anode output current typically decreased with time, Fig. 5.

**TS zinc anode** This is the same anode as used in ICCP service. Current output on the Cape Perpetua Viaduct trended downward over 6 years of service as Zn mineral anode reaction products accumulated at the anode-concrete interface. Current output started at  $10\text{-}15 \text{ mA/m}^2$  and decreased to about  $2 \text{ mA/m}^2$ , Fig. 5. The initial current output was much higher than necessary and modification of the SACP zone to adjust it downward would 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 6 years, the SACP current continued to provide adequate protection of the rebar.

**Zinc-hydrogel** 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, Fig. 5. Current output on the Cape Perpetua Viaduct has remained constant over 6 years at about  $3.5 \text{ mA/m}^2$ .

**Rebar Depolarization** Depolarization measurements for Zn hydrogel anodes are shown in Fig. 6 as a function of service time. As in the previous depolarization graphs, the potential change is the difference between “instant-off” and the rebar potential. The rebar depolarization values, after four hours, are consistently above 100 mV standard, indicating the rebar is protected.

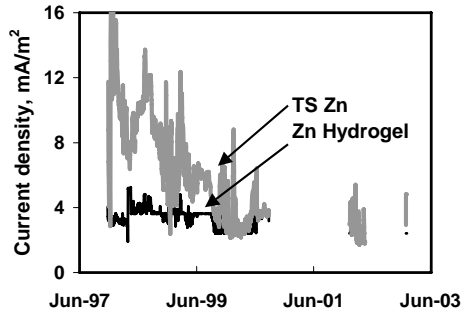


Fig. 5 SACP anode performance of TS Zn and Zn Hydrogel on the Cape Perpetua Viaduct.

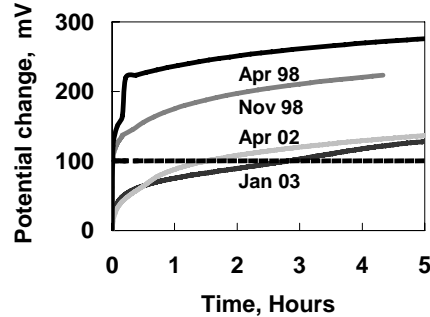


Fig. 6 Depolarization measurements for the Zn hydrogel anode on the Cape Perpetua Viaduct over time.

#### 4. Conclusions

Conductive coating anodes, such as TS and foil anodes can reduce electrolyte (concrete) resistance and improve current distribution to reinforcing bar in concrete bridges. TS Zn anodes develop a resistive layer at the anode-concrete interface with increasing 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 Zn 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. Conductive carbon paint anode performed satisfactorily for over 17 years. Anode current densities and consumption rates were low. Coating bond strengths remained adequate. Rebar depolarization met or exceeded the 100 mV standard.

Catalyzed TS 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 100 mV depolarization standard was met. The catalyst is located at the anode-concrete interface and appears fairly resistant to leaching by precipitation washing. Rebar depolarization met or exceeded the 100 mV standard. 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.

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