STATE OF CALIFORNIA

DEPARTMENT OF TRANSPORTATION

ENGINEERING SERVICE CENTER
OFFICE OF MATERIALS ENGINEERING AND TESTING SERVICES

LONG-TERM MONITORING OF METALLIZED ZINC BRIDGE DECK AND SOFFIT CATHODIC PROTECTION SYSTEMS

Final Report # FHWA/CA/TL-96/06
Caltrans Study # F89TL19

Performed by ..... Testing and Technology Services Branch, Corrosion Technology

Supervised by ..... Douglas M. Parks, P.E.

Principal Investigators ..... Richard A. Carello
Douglas M. Parks, P.E.

Report Prepared By ..... Richard R. Carter, P.E.
Richard A. Carello

PAUL BENSON, Chief
Testing and Technology
Services Branch

DOUGLAS M. PARKS, Chief
Corrosion Technology

ROY BUSHEY, Chief
Office of Materials Engineering
and Testing Services

JOHN WEST
Program Manager
New Technology and Research

REGISTERED PROFESSIONAL ENGINEER
DOUGLAS M. PARKS
No.25696
Exp. 12/31/97
CIVIL
STATE OF CALIFORNIA

TECHNICAL REPORT STANDARD TITLE PAGE

1 Report No.	2 Government Accession No	3 Recipient's Catalog No
FHWA/CA/TL-96/06		

4 Title and Subtitle	5 Report Date
Long-Term Monitoring of Metallized Zinc Bridge Deck and Soffit Cathodic Protection Systems	December 1995
7 Authors R. R. Carter and R. A. Carello	8 Performing Organization Report No 65-631149
9 Performing Organization Name and Address Office of Materials Engineering and Testing Services Corrosion Technology Section California Department of Transportation Sacramento, California 95819	10 Work Unit No 11 Contract or Grant No F89TL19
12 Sponsoring Agency Name and Address California Department of Transportation Sacramento, California 95807	13 Type of Report and Period Covered Final 14 Sponsoring Agency Code

15 Supplementary Notes

A short-term field study of this project was presented in report FHWA/CA/TL-91/05, titled "Cathodic Protection of Reinforced Concrete Bridge Deck and Soffit Using Metallized Zinc" published after 3.6 years of monitoring. This report was performed in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16 Abstract

This report describes the testing and evaluation of two separately installed impressed current metallized zinc cathodic protection (CP) systems: one was applied to the top surface of the deck (deck system) and the other to the soffit surface of the deck (soffit system) of a reinforced concrete bridge that had been contaminated from deicing salt use on the top surface.

Documentation includes a basic description of the CP system installations and 8.5 years of field monitoring to determine the effectiveness and life expectancy of each system. The systems have been operating since November, 1985.

The metallized zinc deck CP system did not provide complete protection for the reinforcing steel based on polarization decay data. This was due, in part, to several years of below average precipitation during the study period, and the application of a slurry seal and chipseal to the bridge deck. The increasing electrical resistance of the system with time and the failure to expeditiously increase the driving voltage to offset these increases also contributed to the low polarization of the reinforcing steel. A life expectancy estimate for this system was not determined due to its ineffective performance.

The current delivered by the metallized zinc soffit CP system did not provide adequate protection for the reinforcing steel based on polarization decay data and delamination surveys. This was due to the high electrical resistance of the soffit concrete caused by low chloride contamination of the soffit concrete. Several years of below average precipitation during the study period also contributed to the increased resistance. A life expectancy estimate for this system was not determined due to its ineffective performance.

17 Key Words	18 Distribution Statement
Reinforced Concrete, Corrosion, Zinc Metallizing, Cathodic Protection, Metallized Zinc Anodes, Bridge Deck Cathodic Protection, Polarization Shift, Impressed Current, Electrical Potential Surveys	No Restriction. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of Pages	22 Price
Unclassified	Unclassified	66	

DS-TL-1242 (Rev. 6/76)

EXECUTIVE SUMMARY

Concrete normally provides excellent corrosion protection for embedded reinforcing steel. However, at some threshold of chloride concentration and given an adequate supply of oxygen and moisture, the embedded steel begins to corrode. Damage to the concrete soon follows in the form of concrete delaminations. Cathodic Protection (CP), the application of a DC current through an electrolyte to protect a corroding metal, is a proven method of halting the corrosion of reinforcing steel in chloride contaminated concrete.

This report describes the testing and evaluation of two separately installed metallized zinc cathodic protection (CP) systems on a reinforced concrete bridge deck that had been contaminated with deicing salts. (Metallizing is a method of spray applying thin layers of molten metal to a substrate.) The deck system uses a grid pattern of metallized zinc strips applied to the top surface of the bridge deck to distribute current through the concrete and a 1 inch (25 mm) AC overlay applied as a wearing course. The soffit system uses a uniform layer of metallized zinc applied to the soffit (underside) of the reinforced concrete bridge deck. Both installations are impressed current systems, requiring external DC power. The deck system was installed by state forces and the soffit system was installed by contract.

Documentation in this report includes a basic description of the CP system installations and the results of 8.5 years of field monitoring to determine the effectiveness and life expectancy of each system. The systems have been operating since November, 1985.

DECK CP SYSTEM:

The metallized zinc deck CP system did not provide complete protection for the reinforcing steel based on the polarization decay data and the criteria established by the National Association of Corrosion Engineers (NACE). During the monitoring period, the polarization decay measurements occasionally met the 100 millivolt NACE requirement, but never at all three anodic measurement locations at once. In addition, most values did not even reach 70 millivolts. Contributing factors were low levels of moisture in the deck concrete due to several years of below average precipitation, the application of a slurry seal and chipseal to the bridge deck and the increase in electrical circuit resistance due to zinc consumption. The application of a slurry seal over the metallized zinc stripes was needed to prevent damage to the zinc stripes by traffic during the lengthy delay between metallizing the stripes and applying the AC overlay caused by construction scheduling problems. The slurry seal would not be required under normal contract installations. The chipseal was accidentally applied to the AC overlay by a maintenance contractor. Both the slurry seal and chipseal reduced the amount of moisture in the concrete which increased the system's electrical circuit resistance. As the zinc metallizing delivers

current through the concrete, the zinc at the zinc/concrete interface oxidizes which increases the electrical resistance of the system. This increasing electrical resistance and the failure to expeditiously increase the driving voltage to offset these increases also contributed to the low polarization of the reinforcing steel.

Inspections determined that the zinc metallizing cracked around almost every primary anode pad inspected on the deck CP system. (The primary anode pads supply electrical current to the metallized stripes.) Alternate methods of installing primary anode pads should be developed if metallized anodes are used on future bridge deck CP systems.

Additional installations of this deck CP system design is not recommended at this time, based on the low polarization decay results. Unless further study concludes that this deck system can consistently be a reliable means of cathodically protecting reinforcing steel, the system should not be used.

Because the deck CP system did not provide complete protection to the reinforcing steel, the life expectancy of the system could not be determined.

SOFFIT CP SYSTEM:

The current delivered by the metallized zinc soffit CP system did not provide adequate protection for the reinforcing steel based on polarization decay data and delamination surveys. Out of the fourteen polarization decay surveys conducted during the monitoring period, the polarization decay exceeded the 100 millivolts requirement only twice. The inadequate protection was largely due to the high electrical resistance of the soffit concrete caused by low chloride contamination of the soffit concrete. Several years of below average precipitation during the study period also contributed to the increased resistance. The soffit CP system should only be used where significant chloride contamination of the concrete occurs on the soffit of a bridge structure such as might be expected at a coastal bridge site.

The installation method for the primary anode pads on the soffit CP system worked well.

As sections of zinc on the soffit surface became disbonded, lower levels of cathodic protection were provided by the CP system and significant quantities of zinc went unused. A thinner application of zinc metallizing is recommended to possibly lessen the amount of disbondment and also to provide a more efficient use of the zinc.

Because the soffit CP system did not provide complete protection to the reinforcing steel, the life expectancy of the system could not be determined.

This study lead to improvements in the metallized zinc substructure CP system (similar to the soffit CP system) used by Caltrans as well as other Transportation Departments in the United States and Canada.

TABLE OF CONTENTS

EXECUTIVE SUMMARY ii

1.0 INTRODUCTION 1

2.0 CONCLUSIONS 2

3.0 RECOMMENDATIONS 4

4.0 IMPLEMENTATION 5

5.0 BRIDGE SITE & CP INSTALLATION DESCRIPTIONS 6

- 5.1 Deck CP System Design (Eastbound Lanes) 8
- 5.2 Soffit CP System Design (Westbound Lanes) 12

6.0 PRELIMINARY SITE TESTS 14

- 6.1 Half-Cell Corrosion Potential Survey 14
- 6.2 Bridge Deck Concrete Cover Survey 14
- 6.3 Chloride Concentration Tests 14
- 6.4 Deck Delamination and Patching Surveys 15

7.0 ZINC ANODE EVALUATION TESTS 16

- 7.1 Zinc Thickness Tests 16
- 7.2 Zinc Bond Strength Tests 16
- 7.3 Zinc Coating Disbondment Surveys 17
- 7.4 Zinc Anode Visual Inspection 17
- 7.5 Zinc Anode Electrical Continuity Tests 17

8.0 CP SYSTEM EVALUATION 20

- 8.1 CP System Operational Parameters 20
- 8.2 Polarization Decay Surveys 20
- 8.3 Concrete Delamination Surveys 21

9.0 RESULTS 23

- 9.1 Half-Cell Corrosion Potential Survey 23
- 9.2 Bridge Deck Concrete Cover Survey 23
- 9.3 Concrete Chloride Concentration Tests 24
- 9.4 Zinc Thickness Tests 24
- 9.5 Zinc Bond Strength Tests 26

9.6 Zinc Coating Disbondment Surveys 26
9.7 Zinc Anode Visual Inspection 27
9.8 Zinc Anode Electrical Continuity Tests 28
9.9 CP System Operational Parameters 29
9.10 Polarization Decay Surveys 36
9.11 Concrete Deck Delamination Surveys 38
10.0 DISCUSSION OF RESULTS 39
10.1 Preliminary Site Tests 39
10.2 Field Installation and Performance 39
10.3 Cathodic Protection Operation and Effectiveness 43
10.4 Life Expectancy 46
11.0 APPENDICES 47
11.1 Guide Specification for Thermally Sprayed Zinc Anode Cathodic Protection System for Bridge Decks 47
11.2 Guide Specification for Thermally Sprayed Zinc Anode Cathodic Protection System for Bridge Substructures 49
12.0 REFERENCES 54

LIST OF FIGURES

Figure	Title	Page
5-1	East Camino Undercrossing	6
5-2	Metallized Bridge Surfaces, East Camino Undercrossing	7
5-3	Deck CP System, Conductive Quadrants	9
5-4	Deck Metallizing Grid Pattern	10
5-5	Metallized Grid Pattern Over Primary Anode Pad	11
5-6	East Camino Undercrossing, Soffit Side	12
7-1	Anode Pad Electrical Continuity and Circuit Resistance Test Circuit	19
7-2	Anode Pad Electrical Continuity Test Circuit	19
9-1	Driving Voltage vs. Time, Deck and Soffit CP Systems	30
9-2	Circuit Resistance vs. Time	31
9-3	CP Current and Monthly Precipitation vs. Time, Deck and Soffit CP Systems	32
9-4	Annual Precipitation vs. Time (Sly Park Weather Station)	33
9-5	Cumulative CP Current vs. Time, Deck and Soffit CP Systems	34
9-6	CP System Quadrant and Bay Identification and Location	35

LIST OF TABLES

Table	Title	Page
5-1	Deck CP System, Conductive Quadrant Surface Areas	8
5-2	Deck CP System, Basic Components	9
5-3	Soffit CP System, Basic Components	13
8-1	Polarization Decay Surveys and "Off" Duration	21
9-1	Half-Cell Corrosion Potential Survey	23
9-2	Measured Concrete Cover Over the Top Mat of Deck Reinforcing Steel	24
9-3	Total Chloride Concentration of Bridge Deck Concrete	25
9-4	Applied Metallized Zinc Thickness	25
9-5	Zinc Bond Strength, Soffit CP System	26
9-6	Zinc Coating Disbondment Survey, Soffit CP System	26
9-7	Zinc Anode Continuity Tests	29
9.8	Current Density, CP Quadrants and Bays	36
9-9	Polarization Decay Results	37
9-10	Deck Delaminated Areas, Deck and Soffit CP Systems	38
9-11	Deck Delaminated Areas, Soffit CP System Only	38

DISCLAIMER

The contents of this report reflect the views of the Office of Materials Engineering and Testing Services which is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION. This report does not constitute a standard, specification, or regulation.

Neither the State of California nor the United States Government endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

ACKNOWLEDGMENTS

The authors wish to acknowledge the following Office of Materials Engineering and Testing Services personnel for their assistance during various phases of the project: Deane Coats, Rob Reis, Tim Kennelly, Angela Giordano, Ken Koebbe, Galen Yeaw, Dawn Becky and Ken Wahl.

In addition, the following individuals were temporarily assigned to the Corrosion Technology Section and provided assistance: Vicki Taylor, Nancy Phipps, Colyn Peterson and Josh Benson.

1.0 INTRODUCTION

Concrete normally provides excellent corrosion protection for embedded reinforcing steel. However, at some threshold of chloride concentration and given an adequate supply of oxygen and moisture, the embedded steel begins to corrode. Damage to the concrete soon follows in the form of concrete delaminations. Cathodic Protection is a proven method of halting the corrosion of reinforcing steel in chloride contaminated concrete.

Caltrans developed a new cathodic protection (CP) system in 1985 for bridge decks using metallized zinc as the distribution anode. Two separate CP systems using the metallized zinc anode were installed on the East Camino Undercrossing (Bridge Number 25-40) near Placerville, California to evaluate the zinc anode's feasibility. The limited data acquired at the completion of the developmental phase of the research period verified that the metallized zinc anode was feasible. However, since only laboratory and short term field data were available, there was not sufficient data to assess the long term viability of this prototype system. The data from the short term field study was presented in a published report following 3.6 years of monitoring (1). The first report discussed the design and installation as well as the results of the 3.6 years of monitoring.

The objective of this project was to determine the long term effectiveness and life expectancy of the two experimental metallized zinc CP systems. These systems were installed on the reinforced concrete bridge deck of the East Camino U.C., which had extensive chloride contamination and corrosion damage due to the application of deicing salts. The deck system was installed on the two eastbound lanes, using a grid of metallized stripes covered by an AC overlay. The soffit system was installed to the bottom (soffit) surface (middle span only) under the two westbound traffic lanes. The soffit metallizing covered the entire soffit surface of the middle span bays.

This report discusses the results of the 8.5 year testing and monitoring period (from November 1985 to April 1994) of these two metallized zinc CP systems. During this time, concrete delamination, zinc coating disbondment and polarization decay surveys were conducted along with zinc thickness, bond strength, and circuit continuity and resistance measurements. Rectifier readings and climatalogical data were also recorded. This data was combined with the data from the initial study to determine the effectiveness of these systems and estimate their life expectancies. In some portions of this report the initial application details as previously reported in the initial study are discussed in order to clarify the details of the two CP systems.

2.0 CONCLUSIONS

The following conclusions are based on 8.5 years of field evaluation (from 1985 to 1994) of two independent metallized zinc cathodic protection (CP) systems. One was applied to the top surface (deck system) of a reinforced concrete bridge deck and the other to the bottom surface (soffit system) of the same bridge deck. The deck system was applied to the eastbound lanes while the soffit system was applied to the middle span under the westbound lanes.

Deck CP System

1. Based on the polarization decay evaluation criteria and the data from Table 9-9, Section 9.10, the metallized zinc deck system did not provide complete protection to the reinforcing steel. Most of the polarization decay values from anodic locations of the bridge deck were well below the 100 millivolt requirement established by the National Association of Corrosion Engineers (NACE). This was due, in part, to the increase in electrical resistance caused by below average precipitation, the application of the slurry seal to temporarily protect the zinc from traffic wear until the AC overlay could be placed, the accidental application of the chipseal nine months after construction, and the consumption and disbondment of the zinc metallized coating. Furthermore, the driving voltage of the system was not increased as high as it should have been to overcome these increases in resistance.

2. The life expectancy of the deck system could not be determined because the system did not provide adequate CP current to the reinforcing steel based on the polarization decay data and criteria. In addition, the levels of consumption and disbondment of the zinc anode could not be used to determine the life expectancy as they do not represent the levels that would have occurred if sufficient CP current had been applied to the reinforcing steel.

3. The installation method used to recess the primary anode pads into the top surface of the concrete bridge deck has lead to cracking of the zinc around the perimeter of the epoxy bonding agent/dielectric shield. This is presumably due to the large difference in coefficients of thermal expansion between the epoxy and concrete and/or the differential movement of the concrete and epoxy due to traffic loading. Extensive cracking around the perimeter of the epoxy interfered with the transfer of CP current from primary anode pads to the zinc distribution anode.

4. There was no discernible difference between the ability of the zinc primary anode pads and the ability of the brass primary anode pads to deliver CP current to the zinc metallized anode.

Soffit CP System

1. Based on polarization decay and deck delamination data, the metallized zinc soffit system did not provide complete protection to the reinforcing steel. This was due largely to the low conductivity of the concrete created by the lack of chlorides and moisture in the soffit side of the bridge deck and the limit on the maximum driving voltage allowed to be imposed on a structure to guard against electrical shock.

2. The life expectancy of the soffit system could not be determined because the system did not provide adequate CP current to the reinforcing steel based on the polarization decay data and criteria. In addition, the levels of consumption and disbondment of the zinc anode could not be used to determine the life expectancy as they do not represent the levels that would have occurred if sufficient CP current had been applied to the reinforcing steel.

3. The installation method used to recess the primary anode pads into the soffit surface of the concrete bridge deck worked well for the soffit CP system, with only minor cracking of the zinc metallizing around the epoxy bonding agent/dielectric shield and primary anode pad on two of the twenty pads. The superior performance of the soffit system anode pad installations compared to those of the deck system is presumably due to their placement on the soffit surface of the deck, where they experienced a smaller thermal range and were less affected by traffic loading.

4. Sections of zinc applied to the overhead (soffit) surfaces became disbonded and provided lower levels of cathodic protection. Thick applications of zinc, which weigh more, combined with the oxidation of the zinc may lead to earlier disbondment than would have occurred with thinner applications and the same level of oxidation.

3.0 RECOMMENDATIONS

1. Based on the data obtained during this study, the metallized zinc deck CP system should not be implemented as a standard corrosion mitigation method at this time. In 1988, a similar system was installed on an I-5 bridge near Redding, California, and is performing well as of this writing. Further study of the Redding installation should be conducted to determine the conditions and requirements necessary for the successful operation of the metallized zinc deck CP system. Unless further study concludes that the deck CP system can consistently be a reliable means of cathodically protecting reinforcing steel, this system should not be used.

2. If the AC overlay on the deck system is removed in the future, a concrete delamination survey should be conducted. The quantity and cause of any delaminations would provide a more complete investigation of the performance of the deck system.

3. The metallized zinc soffit CP system should not be used on low conductivity concrete such as occurred at the East Camino site. More research is needed to better define the level of moisture content and chloride contamination required for successful operation of the metallized zinc soffit CP system.

4. For future deck CP systems that require primary and distribution anodes similar to those used in the metallized zinc system, alternate primary anodes or an alternate method of installing the primary anode pads should be developed.

5. A thinner metallizing application thickness should be considered when metallizing overhead surfaces. A lower weight may lessen the possibility of disbondment, and a larger percentage of the applied zinc would be consumed prior to coating disbondment. This recommendation would result in a more cost effective use of the zinc.

4.0 IMPLEMENTATION

Copies of this report will be sent to Caltrans district and headquarters offices and to the Federal Highway Administration.

Information gained from the initial study of the metallized zinc deck CP system on the East Camino Undercrossing (1) was used in the design and installation of a similar deck system on a bridge near Redding, California (Upper Salt Creek, Bridge Number 6-159L) as part of a comparison study of several deck CP systems. Because the metallized zinc deck CP system did not perform as well as was hoped, and the individual contributions of the slurry seal and chipseal to the ineffectiveness of the system could not be determined, this system should not be implemented at other sites unless results from the Redding installation can justify the long term performance of this system.

Data obtained from the application of the metallized zinc soffit CP system was used to improve the design and installation of a substructure metallized zinc CP system (similar to the soffit system) for the deicing salt contaminated bent cap and columns of the Yuba Pass Bridge (Bridge Number 17-23-R), in Nevada County, California.

Information gained from this study of the soffit system will be used to further define the conditions and requirements necessary for the successful operation of metallized zinc CP systems.

5.0 BRIDGE SITE & CP INSTALLATION DESCRIPTIONS

The East Camino Undercrossing (Bridge Number 24-40) was the first reinforced concrete bridge deck to use a metallized zinc CP system. This structure is located on State Route 50, approximately 6 miles (9.5 km) east of Placerville, California, at an elevation of 3300 feet (1000 m) (Figure 5-1).

Figure 5-1, EAST CAMINO UNDERCROSSING

The structure is an 89 foot (27.4 meter) long, 3 span, reinforced concrete T-beam bridge built in 1964, and has a total deck surface area of approximately 7200 square feet (670 square meters).

Deicing salts are applied to the bridge during the winter season to control ice formation. As a consequence, this structure has a history of corrosion damage with numerous patches used to repair spalled and delaminated concrete. In the 21 years prior to installing the CP systems, 27.4 percent of the total deck area of had been patched due to corrosion induced damage.

The average annual precipitation at the East Camino U.C. (as reported by the Sly Park Weather Station approximately 8 miles away) is approximately 47.9 inches (1.217 meters). The peak monthly average minimum and average maximum temperatures are 36 and 91 °F (3.3 and 32.8 °C) as reported at the Placerville Weater Station.

Two different methods of applying CP current to the bridge deck were used. Both installations were impressed current CP systems. The first system delivered current to the two eastbound lanes, shoulder and median from the metallized top surface of the bridge deck (approximately 3000 ft^2 or 280 m^2 of deck surface). A separate system delivered current to one-half of the westbound lanes (approximately 1400 ft^2 or 130 m^2 of concrete surface) from the metallized bottom (soffit) surface (Figure 5-2). Separate rectifiers were used to supply CP current to each system. All half-cell potentials measurements were made from the top surface of the deck for both the deck and soffit systems.

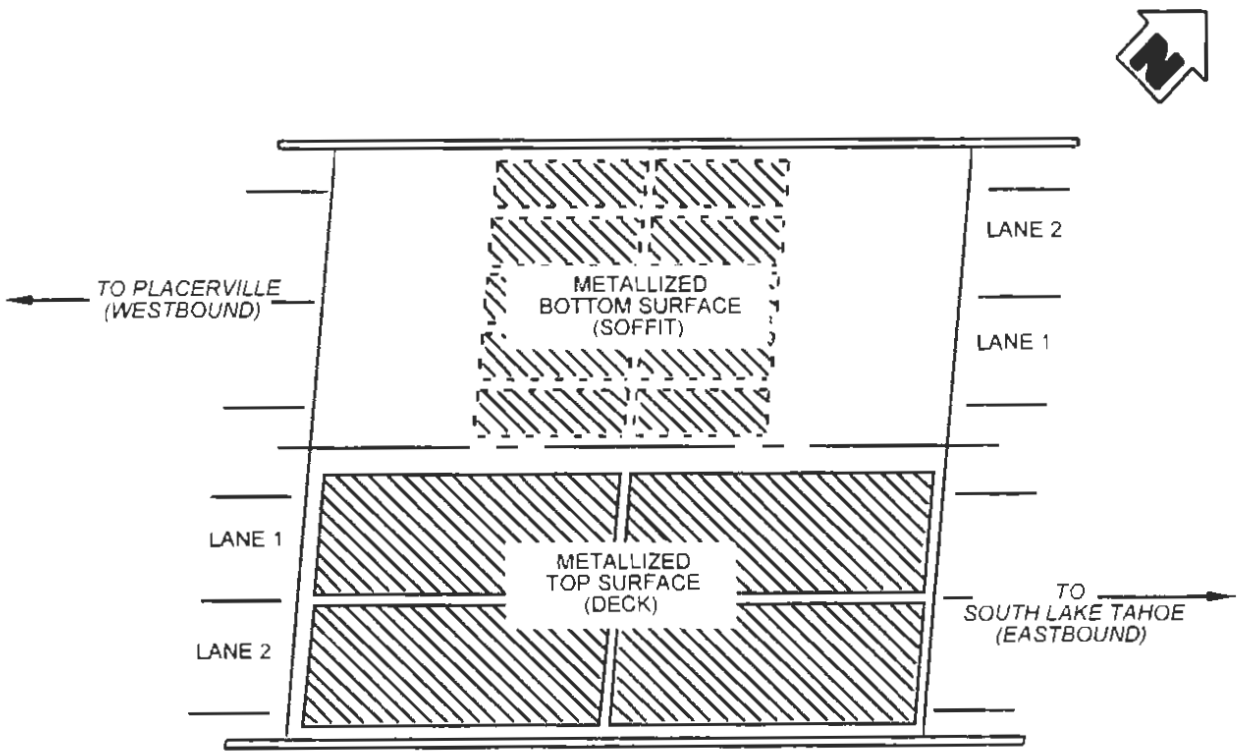


Figure 5-2 METALLIZED BRIDGE SURFACES, EAST CAMINO UNDERCROSSING

The delivery of CP current to the bridge deck reinforcing steel is influenced by the electrical resistance of the concrete and the continuity of the reinforcing steel in the deck. Consequently, for this study, the surface area of reinforcing steel used for current density calculations is the steel mat closest to the current delivery anodes (i.e. the top mat of the deck CP system and the bottom mat for the soffit CP system).

Also, the ratio of the surface area of the reinforcing steel in the top rebar mat to the deck concrete surface is approximately 0.50 to 1 and that for the bottom rebar mat to the soffit concrete area is approximately 0.56 to 1.

5.1 Deck CP System Design (Eastbound Lanes)

In order to more accurately measure current density, the eastbound half of the bridge was divided into four independently wired conductive quadrants, separated by 1 foot (0.3 meters) wide clear areas as shown in Table 5-1 and Figure 5-3.

The basic components of the Deck CP system are given in Table 5-2.

TABLE 5-1
DECK CP SYSTEM
CONDUCTIVE QUADRANT SURFACE AREAS
ft^2 (m^2)

CP QUADRANT	AREA PROTECTED
NW	685 (63.6)
NE	685 (63.6)
SW	785 (72.9)
SE	785 (72.9)
TOTAL	2940 (273.0)

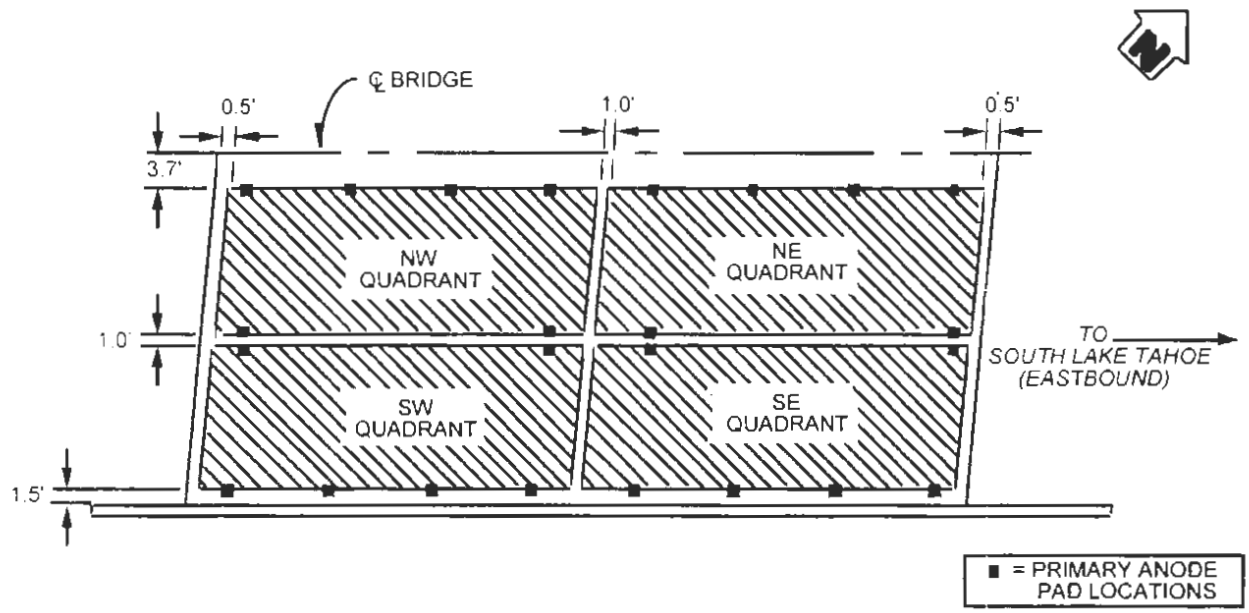


Figure 5-3 DECK CP SYSTEM, CONDUCTIVE QUADRANTS

TABLE 5-2
DECK CP SYSTEM, BASIC COMPONENTS

COMPONENT	DESCRIPTION	INSTALLATION / PURPOSE
Primary Anodes	Four 2" (50 mm) square brass pads and two 2" (50 mm) diameter zinc pads per quadrant.	Epoxied flush with deck, with wires extending through to the underside of the deck.
Distribution Anode	5" (125 mm) wide metallized zinc stripes, spaced transversely on 10" (250 mm) centers with four longitudinal stripes to form grid pattern: stripe design thickness = 0.024" (0.61 mm). Actual applied thickness = 0.030" (0.762 mm) average.	Sprayed by professional metallizers using automated truck mounted arc-spray metallizing equipment that was operated via a wired remote.
Overlay #1	Slurry seal.	Installed to temporarily protect anode until permanent overlay was installed.
Overlay #2	1" (25 mm) Asphalt concrete layer.	Long-term anode protection from traffic wear.
Rectifier	Constant voltage, maximum 24 volts DC, 16 amperes.	Supplies CP current to deck system only; installed below deck in control box.
Rebar Ground Connections	Eight independent ground leads.	Four redundant connections evenly spaced along each rail, cadwelded to rebar mat.

Multiple primary anode pads were used on the deck system since there was limited experience with this method of electrically connecting the metallized zinc distribution anodes (Figure 5-3). The primary anodes were epoxied flush with the deck and the wiring extended through holes cored in the deck beneath the anodes. This installation process is described in detail in the initial report on these systems (1). Both brass and zinc anodes were used to evaluate the ability of these different materials to deliver CP current over an extended period of time.

The metallized zinc was applied in stripes on the deck, with alternating spaces of bare concrete to allow the asphaltic concrete (AC) overlay to bond directly to the concrete deck. All transverse stripes within each quadrant were electrically connected by spraying longitudinal stripes, the length of the structure, across the transverse stripes. These longitudinal stripes were connected within each quadrant and did not bridge any of the 1 foot (0.3 m) wide clear areas between quadrants. The result was a grid pattern of zinc stripes (Figure 5-4). The zinc stripes also transversed each exposed primary anode pad previously placed in the deck surface in order to make the necessary electrical connection to the CP rectifier.

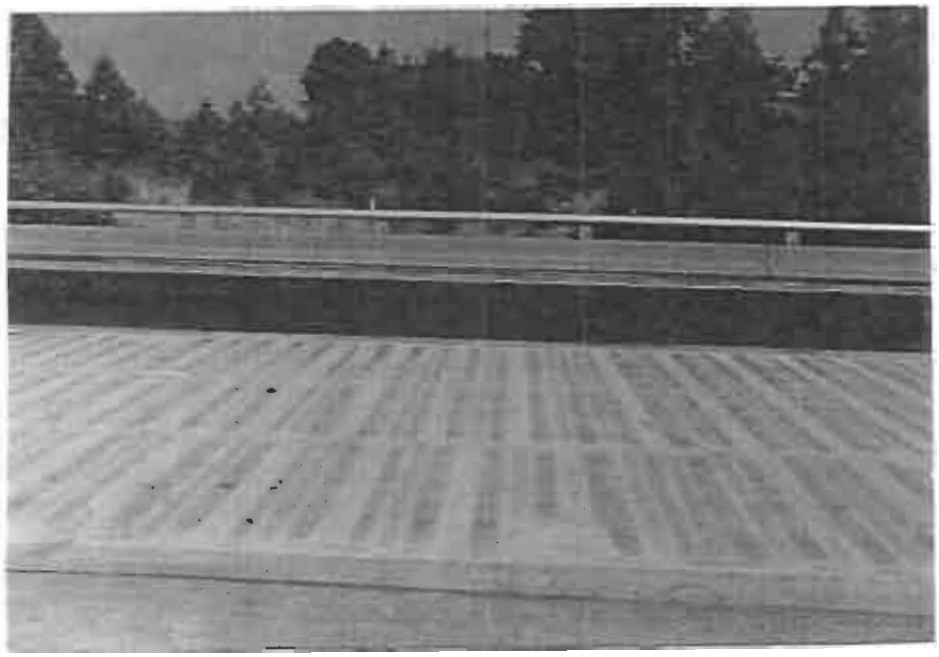


Figure 5-4, DECK METALLIZING GRID PATTERN

An approximately 18 inch square (0.46 meter square) area around each primary anode pad was sprayed with zinc to ensure direct contact between the pad and several of the nearest zinc stripes (Figure 5-5).

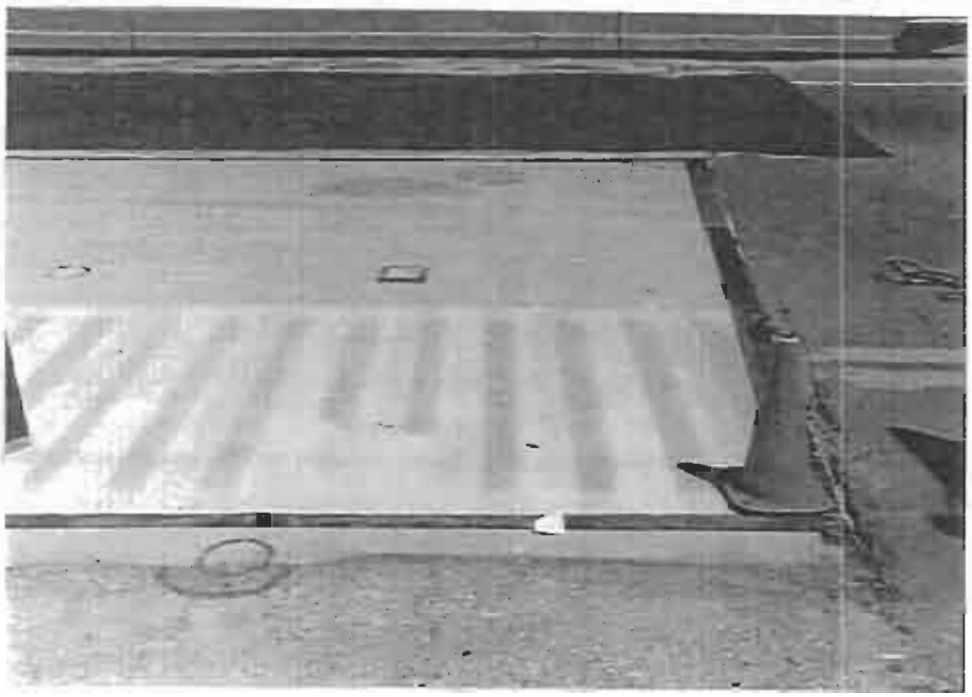


Figure 5-5, METALLIZED GRID PATTERN OVER PRIMARY ANODE PAD

Since the metallized deck coating would be exposed to traffic and snow chain wear if left uncovered, an asphaltic concrete (AC) overlay was applied to protect the zinc from damage. However, since there was an extended time delay between metallizing and the application of this 1 inch (25 mm) AC wearing course, an asphaltic emulsion slurry seal was applied over the metallized area. The slurry seal protected the zinc coating from traffic wear for three months until the AC overlay was applied.

The slurry seal would not be required in future installations since the AC overlay would be applied before the structure is reopened to traffic.

5.2 Soffit CP System Design (Westbound Lanes)

A metallized CP system was also applied to the bottom surface (soffit) of the East Camino bridge deck to determine the ability of this type of installation to provide CP to the top mat of the reinforcing steel. The metallized zinc soffit system was composed of the horizontal surfaces of the ten bays under the number two span of the westbound lanes (Figure 5-6). The bent caps and diaphragms were not metallized. The other two spans (numbers one and three) under the bridge were reserved for future systems as well as serving as control areas for this study.

The anode pads were recessed and epoxied so that their top surface was flush with the surface of the soffit concrete. Since the metallized zinc did not have to be protected, no overlay was applied and the CP wiring was surface mounted. This installation process is described in detail in the initial report on these systems (1).

The basic components of the soffit CP system are given in Table 5-3.

Figure 5-6, EAST CAMINO UNDERCROSSING, SOFFIT SIDE

TABLE 5-3
SOFFIT CP SYSTEM, BASIC COMPONENTS

COMPONENT	DESCRIPTION	INSTALLATION
Primary Anodes	Two 2" (50 mm) square brass pads per bay (10 bays). (One wired for current deliver and one spare per bay.)	Epoxied flush with surface of soffit.
Distribution Anode	Uniform coating of metallized zinc applied to 10 bays in span 2; the 10 bays in span 1 and 3 were not metallized; uniform design thickness 0.015" (0.38 mm). Applied thickness = 0.023" (0.592 mm) average.	Hand held oxygen-acetylene flame spray metallizing equipment.
Rectifier	Constant voltage, max. 50 volts DC, 5 amperes.	Supplies CP current to soffit system only; installed below deck in control box.
Rebar Ground Connections	Uses the same 8 ground leads as the deck CP system.	Four redundant connections evenly spaced along each rail, cadwelded to rebar mat.

6.0 PRELIMINARY SITE TESTS

As presented in the previous report that described these installations (1), field surveys were conducted on the deck prior to applying the CP systems to evaluate the half-cell corrosion potential, concrete cover, chloride concentration and deck delamination.

6.1 Half-Cell Corrosion Potential Survey

A half-cell corrosion potential survey was conducted on the bridge deck in April, 1985, in accordance with ASTM Designation C-876 (2).

The results of the potential survey are presented in Section 9.1.

6.2 Bridge Deck Concrete Cover Survey

At the time the deck half-cell corrosion potential survey was conducted, another survey was conducted to determine the thickness of concrete cover over the deck reinforcing steel mat. The concrete cover was determined using a "James", Model C-4952 "R" meter at 63 locations evenly spaced across the bridge deck.

Results of the concrete cover survey are presented in Section 9.2.

6.3 Chloride Concentration Tests

During the installation of the two CP systems in 1985, the concrete deck was cored and the recovered cores were analyzed to determine chloride concentrations of the deck concrete. Twenty-nine 1 inch (25 mm) diameter full depth cores were taken from primary anode and isolated bar locations. (Forty isolated bar sections of rebar were created in the deck for use as probes, but were not used as part of this study.) Each core was cut into 1 inch (25 mm) long segments. The segments were individually crushed and total chloride concentrations determined in accordance with California Test 404 (3). Results from the individual 1 inch long segments were averaged together in order to display the data in 2 inch increments.

Twenty-one 1-1/2 inch (38 mm) diameter cores were removed from the same general areas of the deck during another testing period in 1993. These cores were also tested for total chloride concentrations using the same procedures used in the 1985 test series.

The results of these tests are presented in Section 9.3.

6.4 Deck Delaminations and Patching Surveys

The entire deck was originally surveyed to determine the existence of previously patched areas as well as existing delaminated areas in June 1984. Additional surveys were later conducted to determine the effectiveness of the system. The delamination surveys relative to the CP system evaluation are discussed in greater detail in Section 8.3, Concrete Delamination Surveys.

The results of these surveys are presented in Section 9.11.

7.0 ZINC ANODE EVALUATION TESTS

Zinc thickness tests, bond strength tests, zinc disbondment surveys, electrical continuity tests and visual inspections were conducted during the study period to evaluate the condition of the metallized zinc anode.

7.1 Zinc Thickness Tests

The metallized zinc stripes of the deck system were applied by spraying three passes of the arc-spray metallizing gun. Since the spray pattern of the gun had a conical shape, the stripes did not have a uniform thickness across their width. In cross section, the stripes were shaped like mounds, having a maximum thickness at the middle and tapering off at each outer edge.

In 1985 and again in 1993, samples were recovered from multiple locations across the width of the stripes. However, in 1993 only a limited number of samples were recoverable and the width of most of the stripes had decreased due to oxidation of the zinc. For this reason, the thickness of the zinc for the 1985 and 1993 samples was compared at the center line of the stripes instead of averaging the thickness across the entire width.

Metallized zinc was applied uniformly (not in a stripe or grid pattern), using an oxygen-acetylene metallizing gun, to the soffit surfaces of the middle ten bays beneath the westbound lanes of the bridge deck. Samples were recovered from each bay prior to applying CP current in 1985 and again in 1993 after 7.5 years of CP application. In this case, the 1985 and 1995 samples could be compared directly because the zinc coating was applied uniformly.

The zinc thickness test results are discussed in Section 9.4.

7.2 Zinc Bond Strength Tests

Bond strength tests were performed on the soffit anode coating prior to applying CP, and after 5 and 7.5 years of CP application. No bond tests were conducted on the deck anode coating due to the AC overlay.

The Elcometer Adhesion Tester, Model 106, Range No. 2 was used to determine the zinc bond strength to the concrete. The method consists of using 0.80 inch (20.3 mm) diameter aluminum "dollies" that are "glued" to the surface of the coating and then pulled off with the tester. The adhesion values include the shear of the coating around the dolly.

No bond tests of the anode coating were performed prior to CP application due to separation failure of the adhesive used to bond the "dollies" to the zinc coating. A different adhesive was successfully used at the 5 year test period (Concresive AEX-1419), and at the 7.5 year test period (Devcon 5-Minute Epoxy Gel, # 14240).

The results of the bond strength tests are presented in Section 9.5.

7.3 Zinc Coating Disbondment Surveys

Disbondment surveys of the zinc anode on the soffit system were performed at the 5 year and 7.5 year time periods. Surveys were not performed on the soffit system immediately after application of the anode. Disbondment surveys could not be conducted on the deck system due to the AC overlay, but spot inspections for disbondment were conducted during the visual inspection (see Section 7.4).

The disbondment surveys were performed by scratching the zinc surface with a thin metal wand to detect "hollow" sounds which would indicate disbonded zinc areas. These areas were outlined and photographed. The outlined areas were scaled off of the photographs and the percentage of delaminated area in each bay was calculated.

The results of the disbondment surveys are presented in Section 9.6.

7.4 Zinc Anode Visual Inspection

A visual inspection was performed on both CP systems after 7.5 years of CP application to determine the overall condition of the anode systems. For the deck system, the inspection involved removing the AC overlay at 20 locations and noting the extent of consumption and disbondment, and the general condition of the anode system at these locations. For the soffit CP system, visual observations were made to determine the consumption of the zinc and the general condition of the anode system. (A description of the zinc disbondment survey from the soffit is covered in Sections 7.3 and the results are presented in Section 9.6.)

The observations made during the April 1993 inspection are presented in Section 9.7.

7.5 Zinc Anode Electrical Continuity Tests

The deck system was designed to provide redundant paths for the CP current by using six primary anode pads well distributed within each quadrant. In addition, the zinc anode coating

was applied to the deck system surface to form a redundant grid pattern of transverse and longitudinal stripes (as discussed in Section 5.1). The zinc anode stripes consume (oxidize to form zinc oxide) as CP current is delivered from the zinc anode through the concrete to the reinforcing steel. This consumption rate is proportional to the rate of current delivery. Differences in the concrete's electrical resistance create areas of high and low current delivery that result in areas of high and low zinc consumption. If the consumption rate is sufficient to consume large enough areas of zinc then isolation between adjacent areas of zinc could occur. Disruptions such as cracks completely across the zinc coating or around the perimeter of primary anodes could also isolate these areas of the system.

The visual inspection prompted the tests for electrical continuity in order to determine the loss of continuity due to the consumption or disruption of the zinc coating between different primary anode pads. Resistance tests were also conducted at the same time to aid in evaluating the condition of the anode system. The electrical circuit in Figure 7-1 was used to measure both voltage drop and circuit resistance between pairs of primary anode pads within the same quadrant. The electrical circuit in Figure 7-2 was used to measure the electrical continuity of the metallized coating between pairs of primary anode pads.

The results of these tests are presented in Section 9.8 and Table 9-7.

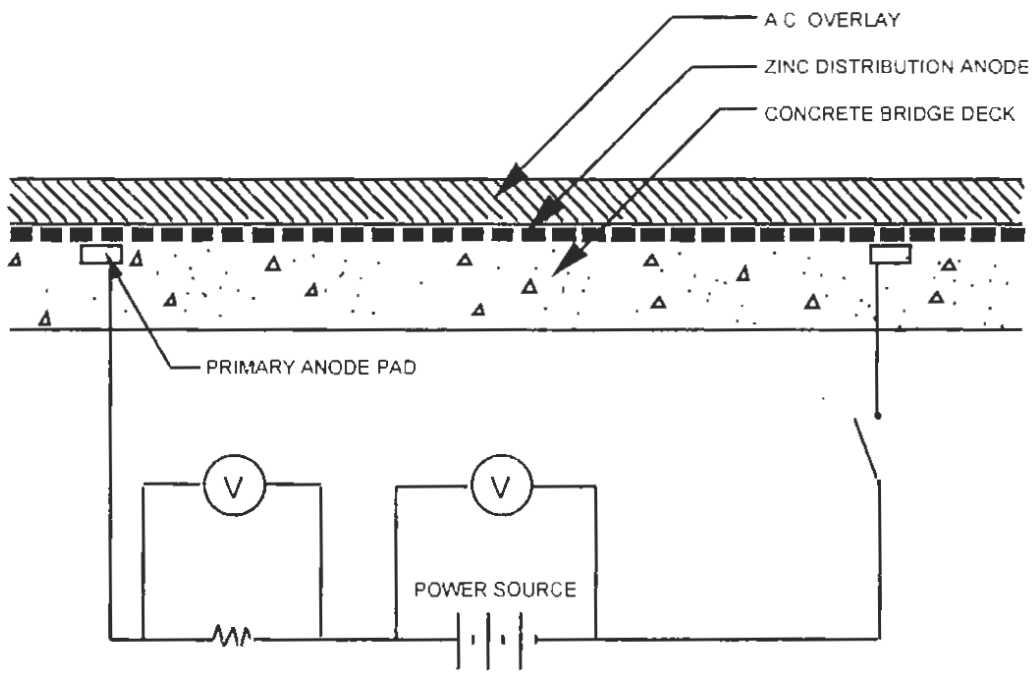


Figure 7-1 ANODE PAD CIRCUIT RESISTANCE TEST CIRCUIT

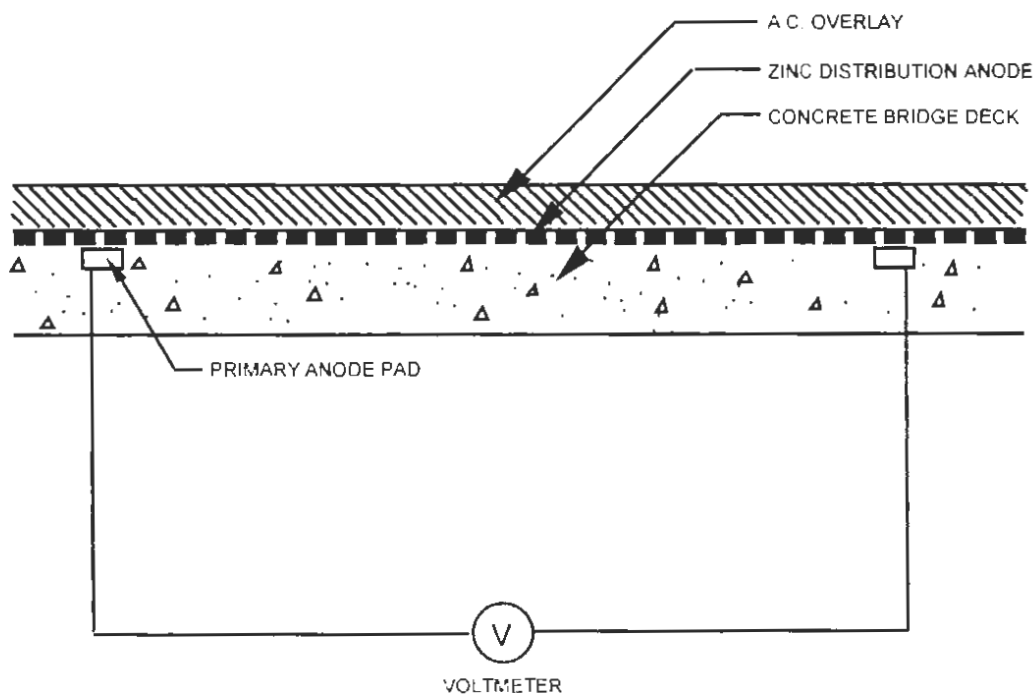


Figure 7-2 ANODE PAD ELECTRICAL CONTINUITY TEST CIRCUIT

8.0 CP SYSTEM EVALUATION

Records documenting the driving voltage, weather, current delivery and density, polarization shifts and deck delaminations were maintained in order to evaluate the operation and effectiveness of the two individual CP systems.

8.1 CP System Operational Parameters

Cathodic protection works by delivering sufficient DC current onto the reinforcing steel to halt its corrosion. The current is controlled by the driving voltage and electrical resistance of the system. Additionally, the zinc anode has a finite life determined by the quantity of zinc and the amount of current discharged from the zinc anode. For these reasons, the driving voltage, resistance, current delivery and current density were recorded to monitor and evaluate the systems. Precipitation was also recorded as changes in moisture concentration in the concrete cause drastic changes in the electrical resistance of the concrete.

Section 9.9 presents the operational variables of the cathodic protection systems along with recorded weather history for the evaluation period.

8.2 Polarization Decay Surveys

A key indicator of the effectiveness of a CP system is the measurement of the electrical potential of the reinforcing steel in the structure. Typical corrosion potential values measured on steel in concrete without CP range from -0.100 to -0.600 volts versus $Cu/CuSO_4$ reference electrodes. Values more negative than -0.350 volts (vs. $Cu/CuSO_4$) generally indicate that active corrosion is occurring (2). When CP current is applied, this potential shifts in a more negative direction and, in general, as more CP current is applied, the shift becomes more negative. The amount of this potential shift (or polarization shift) is an indication of the degree of corrosion protection being achieved.

The "working" criterion used for this study was the achievement of a 0.100 volt polarization shift in a more negative direction occurring in an anodic area over a 4 hour period due to the application of CP current (4). This is the recommended practice of the National Association of Corrosion Engineers (NACE).

An accepted method of determining the polarization shift due to CP current is to measure the depolarization that results from stopping the application of the CP current. This depolarization, or "decay" as it is called, may take a few hours or several days depending on many factors. In

this study, the polarization shift was determined from the polarization decay that occurred during the first one to four hours. Not all surveys were conducted for a full four hour "off" period since access to the structure for extended periods of time was not always possible. A total of 14 polarization decay surveys were conducted during the operational period of the CP systems for this structure.

The number of surveys and length of time of each survey is presented in Table 8-1

TABLE 8-1
POLARIZATION DECAY SURVEYS AND "OFF" DURATION

Total number of surveys	14
Surveys of 1 hour duration	4
Surveys of 2 hour duration	4
Surveys of 4 hour duration	6

Multiple locations across the deck were monitored simultaneously during the instant-off period. These same locations were used for all surveys and were monitored continuously throughout the polarization decay period. Surveys conducted prior to March 1988 used multiple half-cells, a custom made multi-channel voltmeter and a video camera to record the readings. Surveys conducted after March 1988 used multiple half-cells and a Fluke model 1752A multi-channel datalogger.

Section 9.10 presents the results of the polarization decay surveys.

8.3 Concrete Delamination Surveys

Another key indicator of corrosion activity in concrete is concrete delaminations and spalling. As reinforcing steel corrodes, corrosion products build up on the steel's surface. These products occupy a larger volume than the original material so they exert tensile forces on the concrete around them. With sufficient force, the concrete will crack around the reinforcing steel and separate from the rest of the concrete, creating a delamination. If cathodic protection current is reaching the reinforcing steel, it will slow or stop the corrosion process. If the steel is receiving CP current, the quantity of new concrete delaminations should decrease in the areas receiving CP current. Because other factors such as wear and "high steel" contribute to delamination, some delamination of the concrete may be expected to continue.

Concrete delamination and existing patch surveys were conducted on the total surface area of the bridge deck prior to installation of the CP systems. Immediately after the survey, all delaminated areas were patched. The entire deck was then re-surveyed for new delaminations in April 1985, just prior to installing the CP systems. This was the last successful deck delamination survey of the eastbound lanes (deck system). The results of subsequent deck system surveys were deemed unreliable due to the influence of the AC overlay placed over the metallized grid. All delaminations in the westbound lanes (soffit system) were patched in June 1986 and a subsequent delamination survey took place in August 1990. The westbound lanes were again surveyed for new delaminations in May 1993 but it was discovered that an unknown quantity of patching had taken place since the previous survey.

Section 9.11 presents the results of the delamination surveys.

9.0 RESULTS

The results of all testing described in Sections 6.0 (Preliminary Site Tests), 7.0 (Zinc Anode Evaluation Tests), and 8.0 (CP System Evaluation) are presented as follows:

9.1 Half-Cell Corrosion Potential Survey

The results of the April 1985 bridge deck half-cell corrosion potential survey are presented in Table 9-1. The table presents the range of corrosion potentials in percent of total area for both the eastbound and westbound sides of the structure. These results showed that over 54 percent of the total deck area was above the -0.350 volt range (vs. $Cu/CuSO_4$), indicating that active corrosion was probably occurring at the time of the survey.

TABLE 9-1
HALF-CELL CORROSION POTENTIAL SURVEY

LOCATION	Percent of Total Area of Deck vs. Potential ($Cu/CuSO_4$)		
	< 200 mV (%)	200 mV to 350 mV (%)	> 350 mV (%)
Eastbound Lanes	1.7	44.8	53.5
Westbound Lanes	0.1	44.7	55.2
Total Deck	0.9	44.7	54.4

9.2 Bridge Deck Concrete Cover Survey

Table 9-2 presents the results of the survey to determine the thickness of concrete cover over the top mat of the reinforcing steel.

TABLE 9-2
MEASURED CONCRETE COVER OVER THE TOP MAT OF DECK REINFORCING STEEL

Deck Area	Concrete Cover inches (mm)					
	Average		Median		Range	
Eastbound Lanes (Deck System)	2.31	(58.7)	2.25	(57)	1.50 - 3.00	(37- 76)
Westbound Lanes (Soffit System)	2.27	(57.6)	2.25	(57)	2.00 - 2.75	(51 - 70)

Note: Results are based on 63 measured locations evenly spaced across the bridge deck.

9.3 Concrete Chloride Concentration Tests

Table 9-3 presents the results of total chloride concentration testing of the concrete cores removed from the bridge deck during the 1985 and 1993 sampling periods. The results are recorded as chloride concentration versus depth from the top surface of the bridge deck.

9.4 Zinc Thickness Tests

Table 9-4 compares the thickness of zinc samples taken in 1985, prior to initiating the CP current, with those taken in 1993 after 7.5 years of CP application. Due to the extreme consumption of the zinc in many areas, the overlapping of the stripes on the grid, and limited access to the zinc due to the AC overlay, only two reliable samples were recovered from the deck system during the 1993 test period.

TABLE 9-3
TOTAL CHLORIDE CONCENTRATION OF BRIDGE DECK CONCRETE
lb Cl^- /yd^3 (Kg Cl^- /m^3)

Eastbound Lanes (Deck)							
DEPTH (inches)	AVERAGE		MEDIAN		RANGE		Number of samples used
PRIOR TO CP APPLICATION (1985)							
0 - 2	5.7	(3.4)	7.1	(4.2)	1.4 - 9.3	(0.8- 5.5)	13
2 - 4	2.4	(1.4)	2.2	(1.3)	0.8 - 4.8	(0.5- 2.8)	13
4 - 6+	1.3	(0.8)	1.2	(0.7)	0.8 - 2.1	(0.5- 1.2)	13
AFTER 7.5 YEARS OF CP APPLICATION (1993)							
0 - 2	4.1	(2.4)	3.7	(2.2)	0.9-10.3	(0.5- 6.1)	11
2 - 4	1.1	(0.7)	1.1	(0.7)	0.1- 2.1	(0.1- 1.2)	8
4 - 6+	2.3	(1.4)	2.4	(1.4)	1.5- 3.0	(0.9- 1.8)	3

Westbound Lanes (Soffit)							
DEPTH (inches)	AVERAGE		MEDIAN		RANGE		Number of samples used
PRIOR TO CP APPLICATION (1985)							
0 - 2	5.7	(3.4)	5.8	(3.4)	0.4 - 11.0	(0.2- 6.5)	16
2 - 4	1.8	(1.1)	1.3	(0.8)	0.4 - 4.6	(0.2- 2.7)	16
4 - 6+	0.7	(0.4)	0.3	(0.2)	0.1 - 2.6	(0.1-1.5)	16
AFTER 7.5 YEARS OF CP APPLICATION (1993)							
0 - 2	5.4	(3.2)	5.0	(3.0)	3.1- 9.2	(1.8- 5.5)	7
2 - 4	2.9	(1.7)	2.5	(1.5)	2.0- 6.3	(1.2- 3.7)	7
4 - 6+	1.7	(1.0)	1.3	(0.8)	0.4- 3.7	(0.2- 2.2)	8

NOTE: Measurements do not include values biased by patch material or abnormally large pieces of aggregate.

TABLE 9-4
METALLIZED ZINC THICKNESS
Inches x 0.001 (mm)

NUMBER OF SAMPLES	CP SYSTEM	METALLIZED AREA	THICKNESS		
			AVERAGE	MEDIAN	RANGE
PRIOR TO CP APPLICATION					
18	DECK	STRIPES*	30.5 (0.775)	28.0 (0.711)	24.3 - 43.6 (0.617 - 1.107)
10	SOFFIT	BAYS	23.3 (0.592)	23.3 (0.592)	14.7 - 37.2 (0.373 - 0.945)
AFTER 7.5 YEARS OF CP APPLICATION					
2	DECK	STRIPES*	30.5 (0.775)	30.5 (0.775)	29.3 - 32.1 (0.744 - 0.815)
10	SOFFIT	BAYS	23.8 (0.604)	21.0 (0.533)	13.0 - 47.3 (0.330 - 1.201)

* Thickness measured at centerline of stripe.

9.5 Zinc Bond Strength Tests

Table 9-5 presents the results of bond tests performed on the soffit zinc coating before CP was applied, after 5 years, and again after 7.5 years of CP application.

TABLE 9-5
ZINC BOND STRENGTH, SOFFIT CP SYSTEM
psi (MPa)

NUMBER OF DOLLIES	CP DURATION (years)	AVERAGE		MEDIAN		RANGE	
72	0.0	67**	(0.46)	50**	(0.34)	0 - 250**	(0 - 1.72)**
42	5.0	270	(1.86)	250	(1.72)	25 - 600*	(1.72 - 4.14)
60	7.5	248	(1.71)	225	(1.55)	25 - 600*	(1.72 - 4.14)

NOTE: All tensile dollies were placed at locations that were not disbonded.
* The maximum capacity of the bond tester was 600 psi (4.14 MPa), test stopped at this point.
** Bond tests were not taken on-site due to separation of adhesive between the dolly and zinc coating. Subsequent laboratory tests established the presented values as the minimum predictable by the strength of the adhesive used in the on-site testing.

9.6 Zinc Coating Disbondment Surveys

Table 9-6 presents the results of the zinc disbondment survey at the 5 year and 7.5 year test periods.

TABLE 9-6
ZINC COATING DISBONDMENT SURVEY
SOFFIT CP SYSTEM

BAY #	ZINC COATING DISBONDMENT		% INCREASE
	1990 % of surface area	1993 % of surface area	from 1990 to 1993
F	8.8	14.4	64
G	8.8	17.9	103
H	35.0	43.6	25
I	7.0	25.3	261
J	13.9	29.2	110
K	6.8	16.9	149
L	13.1	29.8	127
M	0.5	15.7	3040
N	40.9	80.5	97
O	36.0	58.7	63
AVERAGE, EXCLUDING BAY M *	18.9%	35.1%	86%

* Bay M has been excluded due to a short circuit as described in Section 9.9, Current Delivered.

9.7 Zinc Anode Visual Inspection

In April, 1993, a visual inspection was performed on the deck and soffit CP systems to evaluate their performance. At twenty locations on the deck, approximately 1 square foot (0.9 m^2) of AC overlay was carefully removed. The anode system was then inspected for the extent of consumption and disbondment, and the overall condition of the anode system. Nine locations exposed zinc stripes, and eleven exposed primary anode pads. The soffit system was inspected for consumption and the overall condition of the anode system. Disbondment of the soffit system is covered in Sections 7.3 and 9.6.

Deck Stripes: Eight of the nine stripes appeared to have delivered CP current, evidenced by the consumption of the zinc and the presence of zinc oxide. The metallized zinc at the one remaining stripe location appeared shiny, with no zinc oxide present, indicating little consumption. A test between a nearby primary anode pad and the stripe showed no electrical continuity indicating the pad was no longer supplying current to the zinc strip grid.

Three stripes had extensive consumption, leaving only small pieces of the original zinc stripe. The consumption was extensive enough to create an electrical discontinuity between any remaining zinc in that area and a nearby primary anode pad. Three more of the stripes showed varying degrees of moderate consumption, but appeared to have enough zinc to provide some cathodic protection to the structure. Moderate consumption locations had larger amounts of zinc oxide, but the zinc was largely intact with little or no zinc perforation due to consumption. The last three showed low levels of consumption, with no perforations and only a small amount of zinc oxide. These three locations included the one discontinuous stripe mentioned earlier.

Because the zinc consumption occurs at the zinc-concrete interface, low levels of consumption can easily disbond the zinc from the concrete. For this reason, the extent of disbondment was greater than the extent of consumption. Four of the stripes had extensive disbondment (visually estimated at greater that 50% of the zinc area), including the three locations that were almost completely consumed. Four of the remaining five had moderate levels of disbondment (estimated at 25% to 50%). One had low levels of disbondment (less than 25%).

Deck Anode Pads: All eleven of the pad locations appeared to have delivered CP current, evidenced by the consumption and disbondment of the zinc and the presence of zinc oxide around the outside of the epoxy. It was also observed that the zinc directly contacting the pad and epoxied areas surrounding the pads showed no consumption and was well bonded at all

eleven locations. This indicated there was a good bond and electrical contact between the zinc and pad, and that the epoxy was acting as a good insulator between the zinc and the concrete.

Eight of the eleven primary anode pad locations had cracks in the zinc around the perimeter of the epoxy used to install the pads. Two locations had consumed all the zinc around the epoxy so it is unclear if these locations had ever cracked. No record was made regarding the presence or absence of cracks around the remaining pad that had been exposed.

Three of the primary anode pad locations had such extensive consumption outside the epoxy area of the pad that they were either isolated, or nearly isolated from the rest of the anode system. Seven locations showed moderate levels of consumption. One location showed low levels of consumption.

Seven of the eleven pad locations exhibited extensive disbondment of the zinc area outside the epoxied section (greater than 50%). (Three of these include the locations where the zinc was almost completely consumed.) Four locations had moderate levels of disbondment, while none of the zinc around the pad locations exhibited low levels of disbondment.

Soffit Zinc Coating: In general, the disbonded areas had large quantities of zinc oxide while the well bonded areas had little. There were however, some instances of disbonded areas with very little zinc oxide. The authors believe this resulted from disbondment of the zinc prior to or shortly after the application of the CP current. The air gap in these areas precluded any further delivery of CP current and thus no zinc oxide developed.

Most of the bays had small (approximately 1/4", 6 mm) areas of oxidation that perforated all the way through the zinc. These spots numbered in the hundreds and were found in both the bonded and disbonded areas.

Soffit Anode Pads: Two of the twenty primary anode pads on the soffit system had traces of corrosion. One had a small amount of zinc oxide along one edge of the pad, while the other had traces of oxide along a short length of the epoxied area's perimeter. This is a dramatic difference from what occurred on the deck system anode pads.

9.8 Zinc Anode Electrical Continuity Tests

Table 9-7 presents the results of the anode continuity tests of the deck CP system conducted after 8.5 years of CP operation. This table shows the number of pads in each quadrant that are still

maintaining direct metallic contact with the zinc stripe grid system and the number that are not. It is worth noting that the resistance between a few of the pads that had not maintained direct metallic contact were rather low (less than 3 ohms), indicating that low resistance ionic paths were still allowing current delivery to the zinc grid system.

TABLE 9-7
ZINC ANODE CONTINUITY TESTS

QUADRANT	Number of pads with direct metallic contact between the pad and the metallized zinc stripe grid system	Number of pads without direct metallic contact between the pad and the metallized zinc stripe grid system
NORTHEAST	2	4*
SOUTHEAST	3	3
NORTHWEST	2	4
SOUTHWEST	2	4

*NOTE: In April 1993, samples were taken for analysis from the zinc stripes of the deck system. This sampling resulted in a complete electrical isolation of one primary anode pad in the northeast quadrant.

9.9 CP System Operational Parameters

In November 1985, the CP systems were activated and CP current was applied using the deck and soffit CP systems of the bridge.

Driving Voltage: The driving voltage of the deck system was initially set at 3.0 volts (nominal) while the driving voltage of the soffit system was set at 26 volts (nominal). A graph showing the variation in the driving voltage versus time throughout the duration of this study is given in Figure 9-1.

The driving voltage was increased in January 1986 to 5 volts on the deck system and to 40 volts on the soffit system in order to maintain the start-up design current density criteria of 2 mA/ft^2 (10.8 mA/m^2) of steel surface area. This was achieved on the deck CP system, but the current density of the soffit CP system increased only to 1.2 mA/ft^2 (12.92 mA/m^2).

In June 1986, for safety reasons, the driving voltage of the soffit CP system was reduced to a nominal voltage of 30 volts to reduce hazards associated with contacting the exposed metal

coating. The deck CP system was not altered at this time and remained set at the nominal 5 volts.

The deck system continued at the January 1986 setting of 5 volts and was increased to 9 volts in January 1988 and again to 14 volts in April, 1991 in an attempt to keep up with the increasing circuit resistance of the system. During this time, the soffit CP system was maintained at the 30 volt setting.

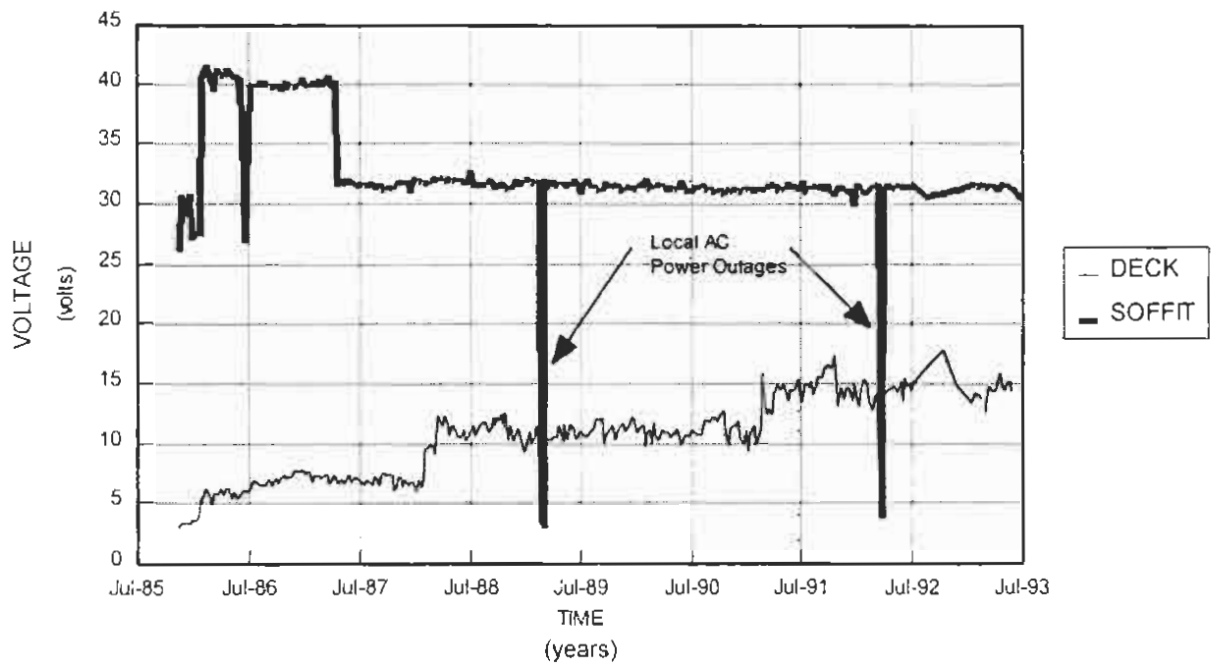


Figure 9-1, DRIVING VOLTAGE VS TIME, DECK AND SOFFIT CP SYSTEMS

Moisture Affects: As shown in Figure 9-2, seasonal climatological changes affect the electrical resistance of the concrete. As expected, the CP current flow was higher (the electrical resistance lower) during the wet periods as shown in Figure 9-3. The current dropped off during the warm, dry summer as the concrete dried. A higher driving voltage was necessary on the soffit CP system to overcome the high electrical resistance of the dry concrete surface.

One of the requirements for the continued delivery of CP current is adequate moisture in the concrete. Six consecutive drier than normal weather years immediately following the start-up of

the CP systems had a negative impact on their operation. Figure 9-4 presents the annual precipitation occurring during the test period of this project.

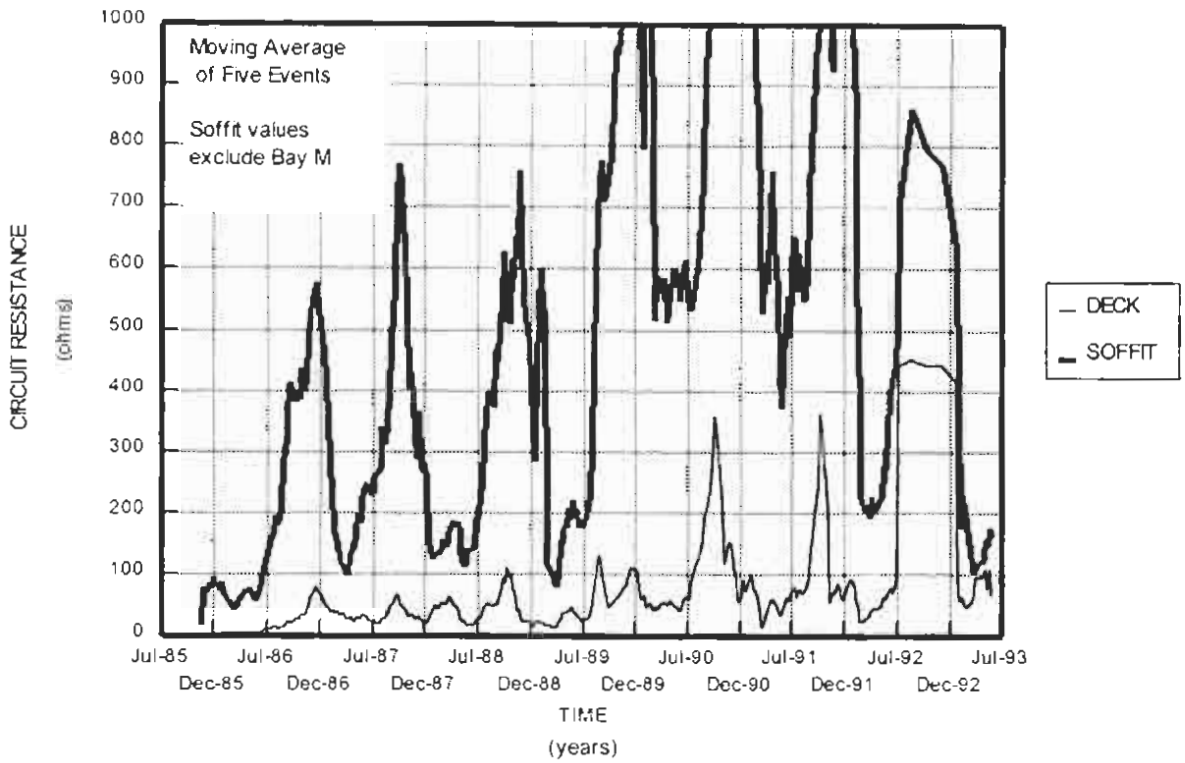
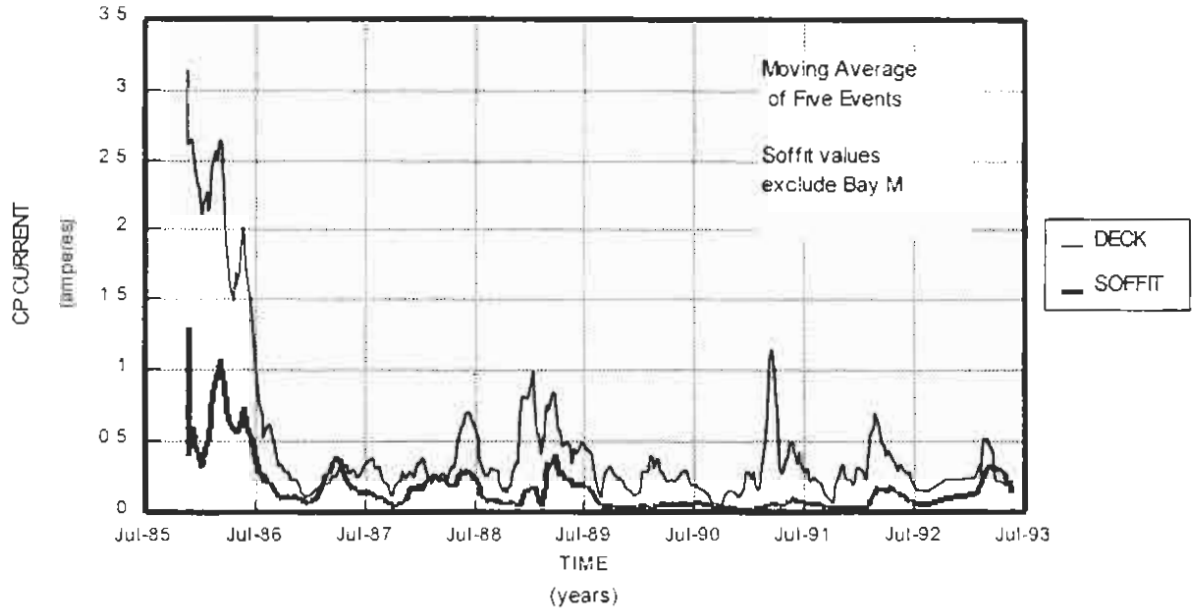


Figure 9-2, CIRCUIT RESISTANCE VS TIME



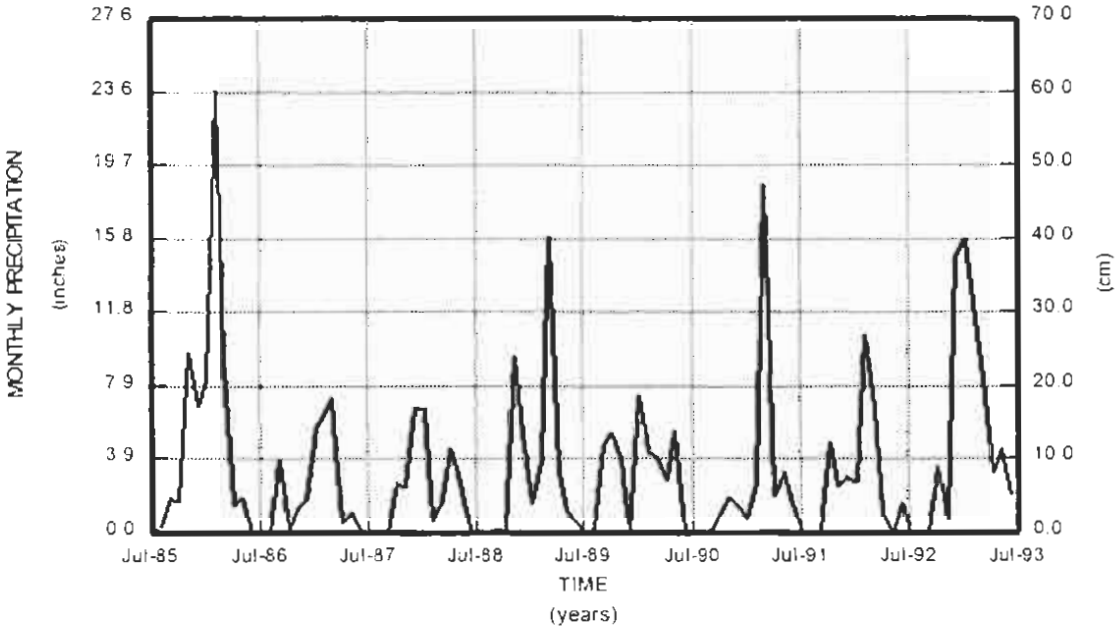


Figure 9-3, CP CURRENT & MONTHLY PRECIPITATION VS TIME, DECK AND SOFFIT CP SYSTEMS

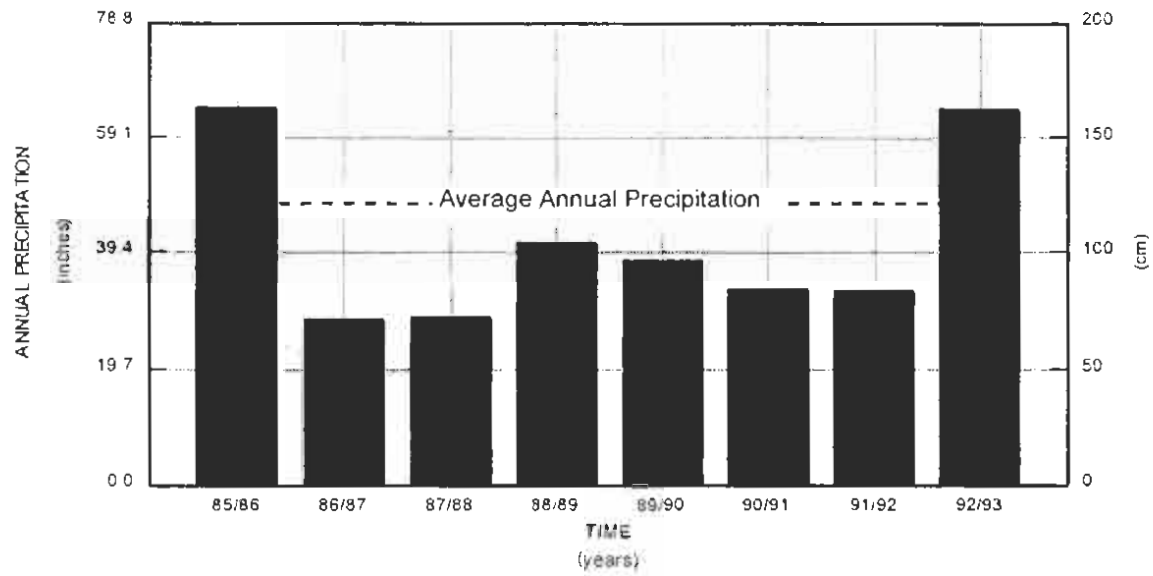


Figure 9-4, ANNUAL PRECIPITATION VS TIME (SLY PARK WEATHER STATION)

Current Delivered: The capacity of the metallized zinc coating to discharge CP current is directly related to the amount of zinc metal applied and the consumption rate of the zinc. The theoretical maximum amount of CP current that could be delivered to each system was calculated using the consumption rate of zinc of 366 Ah/lb (807 Ah/Kg), the amount of zinc applied, and an estimated 50% current delivery efficiency of the coating (5). The cumulative current delivered for both systems is shown in Figure 9-5. Additionally, as presented in this report, consumption of metallized zinc at the bonded surface between the zinc and concrete will result in a gradual buildup of oxides which will result in an increased circuit resistance. This buildup must be compensated for by increasing the driving voltage of the CP system.

The total CP current delivered during the first 7.5 years of CP operation reported by this study was approximately 29800 Ah for the deck system and 41700 Ah for the soffit system. The vast majority (31318 Ah) of the soffit system current was delivered through Bay M. The remaining 10382 Ah are from the other nine bays. The explanation for the large current delivery in Bay M is discussed later.

The CP systems on the East Camino U.C. were initialized to deliver a maximum current density of 2 mA/ft^2 (21.5 mA/m^2) of reinforcing steel area during the wet periods and lesser current densities when the concrete was drier. In practice, the current densities, measured bimonthly

from start-up (November 1985) until May 1993, varied seasonally from 0.01 to 2.79 mA/ft^2 (0.11 to 30.03 mA/m^2) for the deck system and between 0.08 to 2.71 mA/ft^2 (0.86 to 29.17 mA/m^2) for the soffit system. The average current density supplied was 0.32 mA/ft^2 (3.44 mA/m^2) of steel for the deck CP system and 0.25 mA/ft^2 (2.69 mA/m^2) of steel (excluding Bay M) for the soffit CP system.

Each CP system was divided into quadrants or bays as described earlier. Figure 9-6 identifies the individual quadrants and bays (those areas providing CP current) relative to the deck area of the structure.

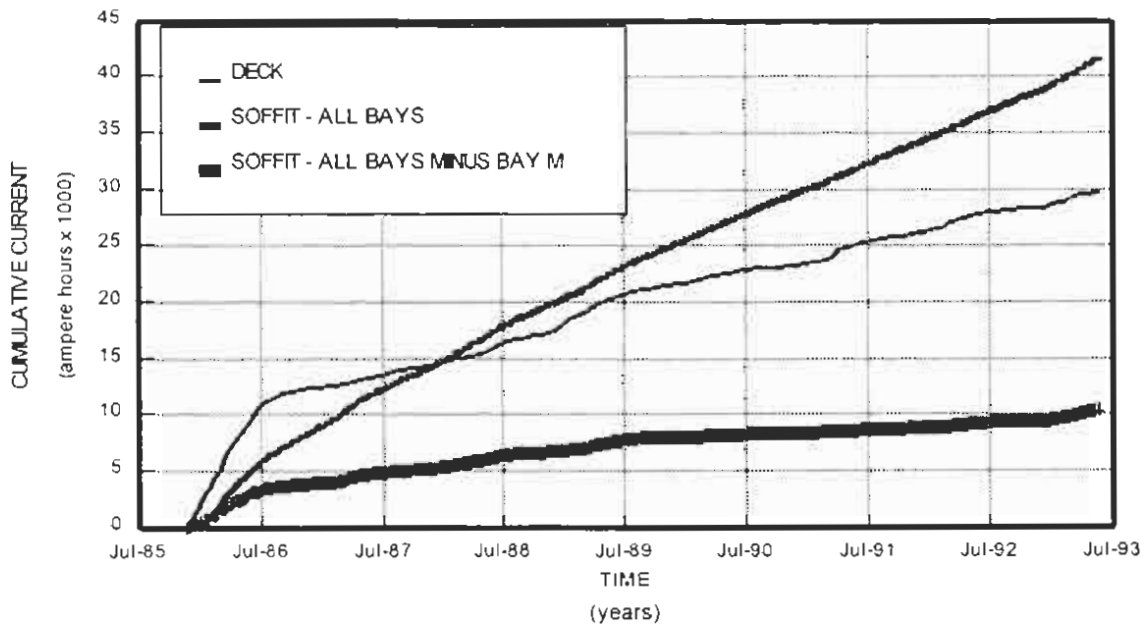


Figure 9-5, CUMULATIVE CP CURRENT VS TIME DECK AND SOFFIT CP SYSTEMS

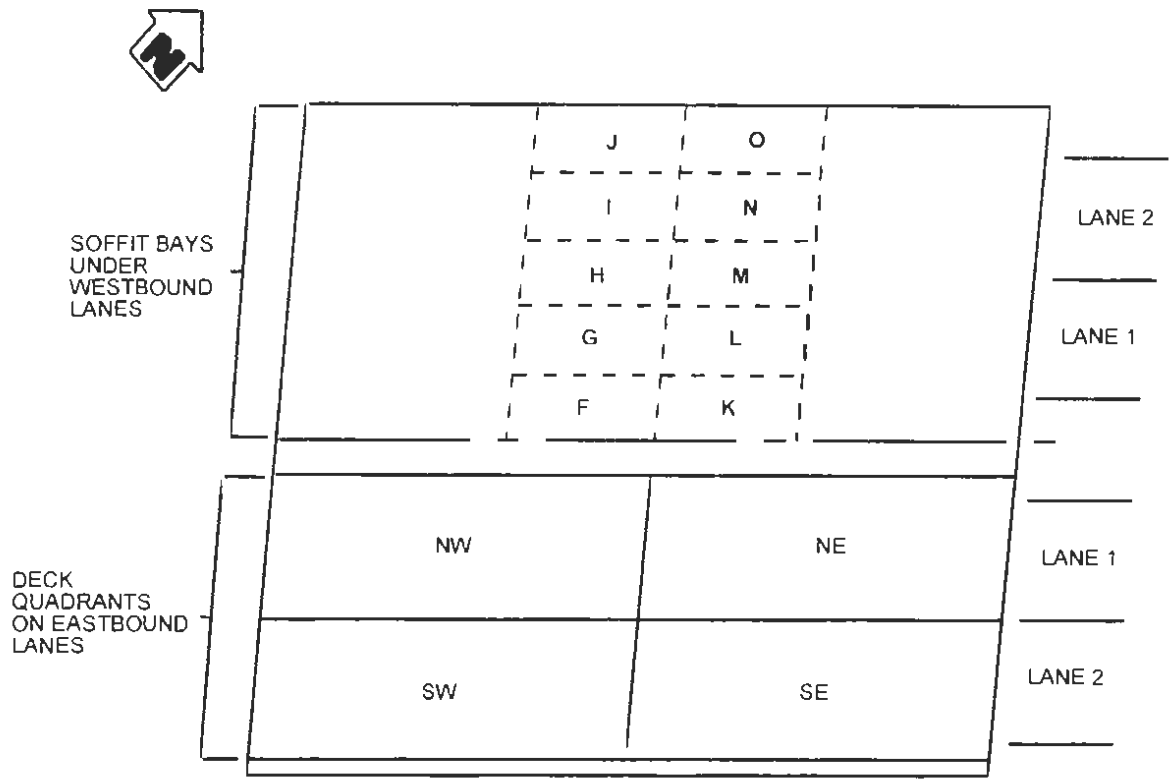


Figure 9-6 CP SYSTEM QUADRANT AND BAY IDENTIFICATION AND LOCATION

Since the quadrants and bays of these systems were independently wired, current flow to each could be monitored separately. Table 9-8 presents the average current density delivered during the first 7.5 years of CP operation to each area protected on the structure.

Bay M of the soffit CP system has been calculated separately because the final data was biased by the extremely high current flows to that bay. There may be a near short circuit between the zinc coating and the reinforcing steel in Bay M caused by thin cover or a rebar tie wire close to the surface. This near short was not detected prior to energizing the soffit CP system.

TABLE 9-8
CURRENT DENSITY, CP QUADRANTS AND BAYS
(NOV. '85 - MAY '93)
mA/ft^2 of steel (mA/m^2 of steel)

LOCATION	AVERAGE		RANGE	
NW Quadrant	0.55	(5.92)	0.020 - 3.25	(0.22 - 34.98)
NE Quadrant	0.24	(2.58)	0.010 - 2.97	(0.11 - 31.97)
SW Quadrant	0.20	(2.15)	0.001 - 2.57	(0.01 - 27.66)
SE Quadrant	0.35	(3.77)	0.010 - 3.93	(0.11 - 42.30)
Combined Quadrants	0.32	(3.44)	0.010 - 2.79	(0.11 - 30.03)*
Bay F	0.08	(0.86)	0.001 - 0.58	(0.11 - 6.24)
Bay G	0.18	(1.94)	0.010 - 1.56	(0.11 - 16.79)
Bay H	0.41	(4.41)	0.010 - 6.06	(0.11 - 65.23)
Bay I	0.31	(3.34)	0.020 - 2.99	(0.22 - 32.19)
Bay J	0.23	(2.48)	0.010 - 1.68	(0.11 - 18.08)
Bay K	0.09	(0.97)	0.001 - 1.25	(0.01 - 13.46)
Bay L	0.12	(1.29)	0.001 - 1.33	(0.01 - 14.32)
Bay M**	6.19	(66.63)	0.570 - 7.90	(6.14 - 85.47)
Bay N	0.47	(5.06)	0.004 - 6.62	(0.04 - 71.26)
Bay O	0.37	(3.98)	0.010 - 2.64	(0.11 - 28.42)
Combined Bays*	0.83	(8.93)	0.080 - 2.71*	(0.86 - 29.17)*
Combined Bays Excluding Bay M	0.25	(2.69)	not available	

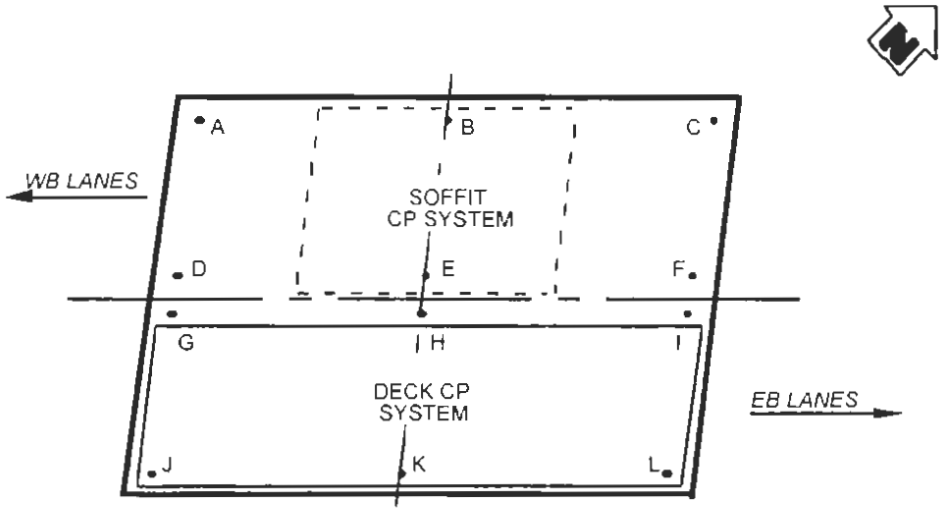
* Based on total current and total steel area of each system at time of measurement. For this reason, the range of current densities for the combined areas is not equal to the extremes for the individual areas.

** See discussion, previous page.

9.10 Polarization Decay Surveys

The polarization decay results from fourteen polarization decay surveys of 1 hour or more duration are presented for eight half-cell locations in Table 9-9. (Access to the structure for sufficient time to perform 4 hour depolarization decay measurements was not always possible.) Values of 80 millivolts or more from the 1 and 2 hour depolarization decay surveys were considered likely to reach 100 millivolts in 4 hours.

TABLE 9-9
POLARIZATION DECAY RESULTS



BRIDGE LOCATION MAP OF DATA COLLECTION POINTS AND AREAS OF CP APPLICATION

NOMINAL DRIVING VOLTAGE		INSTANT OFF SURVEY	CP OFF DURATION	POSITIVE POLARIZATION DECAY AT DATA COLLECTION POINTS (mV)								CURRENT DENSITY (mA/ft2)	
SOFFIT	DECK	DATES	(hrs)	B	E	G	H	I	J	K	L	SOFFIT	DECK
26	3	11/19/85	1	43	172	83	150	90	80	68	64	1.86	2.13
		11/22/85	1	42	180	79	81	82	64	43	45	0.57	1.77
		12/17/85	1	31	124	81	86	73	91	46	48	0.29	2.18
		01/22/86	1	33	136	70	91	69	57	29	30	0.41	0.95
40		02/26/86	2	55	157	77	95	63	87	64	66	1.45	1.90
		8-2-86 Chipseal applied to bridge deck 10-2-86 Chipseal removed from Westbound lanes (Soffit System)											
	5	04/08/87	2	102	102	24	18	35	32	3	19	0.49	0.11
30		10/30/87	2	14	109	27	42	67	16	12	16	0.10	0.15
		01/28/88	2	96	106	7	31	27	37	11	13	0.38	0.10
	9	01/12/89	4	9	120	60	60	63	**	**	43	0.13	0.25
		04/18/89	4	50	107	46	31	41	100	19	6	0.23	0.16
		04/02/91	4	-9	79	93	70	54	24	85	-18	0.09	0.33
	14	01/29/92	4	-8	72	19	44	34	-20	-10	-8	0.03	0.07
		02/21/92	4	13	102	77	62	116	**	**	63	0.31	0.79
		04/20/93	4	15	NR	NR	NR	NR	-8	-24	-12	0.24	0.05
In an anodic location?*			---	Y	N	N	N	N	Y	Y	Y	---	---

* Is the data collection point in an anodic area? (based on original corrosion potential survey taken prior to cathodic protection, using $Cu/CuSO_4$ half-cells)
Y = area more negative than -350 mV. N = area less negative than -200 mV

** Data invalid due to water leaks in half-cell ports

NR Data not recovered

9.11 Concrete Deck Delamination Surveys

Table 9-10 presents the delaminations as a percent of the deck area for both the eastbound and westbound lanes of the structure. Table 9-11 presents the quantity of delaminations as a percent of the deck area directly above the CP and non-CP areas of the soffit system (westbound lanes).

TABLE 9-10
DECK DELAMINATED AREAS
DECK AND SOFFIT CP SYSTEMS

SURVEY DATE	DESCRIPTION OF AREAS	PERCENT OF EASTBOUND DECK DELAMINATED (DECK SYSTEM)	PERCENT OF WESTBOUND DECK DELAMINATED (SOFFIT SYSTEM)	PERCENT OF TOTAL DECK DELAMINATED
JUNE 1984	Previously Patched	7.2	11.1	9.2
	Existing Delaminations	7.3	20.9	14.1
APRIL 1985	New Delaminations Since June 1984	6.4	1.8	4.1
AUGUST 1990	New Delaminations Since Repairs in June 1986	NR	19.6	NR
TOTAL DELAMINATIONS		20.9*	53.2	NR

NR Not recorded (Eastbound deck covered with AC overlay)
* Value is the total for the eastbound (deck system) lanes through April 1985.

TABLE 9-11
DECK DELAMINATED AREAS
SOFFIT CP SYSTEM ONLY

SURVEY DATE	DESCRIPTION OF AREA	PERCENT OF DECK DELAMINATED OVER CP AREA	PERCENT OF DECK DELAMINATED OVER NON-CP AREA
JUNE 1984	Existing Patches and Delaminations	33.4	30.6
APRIL 1985	New Delaminations Since June 1984	2.2	1.3
AUGUST 1990	New Delaminations Since Repairs in June 1986	17.7	19.6

NOTE: The soffit CP system began operation in November 1985.

10.0 DISCUSSION OF RESULTS

This report has presented the results of two independent CP systems applied to different areas of the same bridge deck using metallized zinc as the distribution anodes. Both systems were applied to stop the corrosion of a salt-contaminated reinforced concrete bridge deck. The CP current of one system was applied from the top surface of the deck (deck system), while the current of the other CP system was applied from the soffit, or bottom surface (soffit system), of the same bridge deck. The deck system was applied to the eastbound lanes while the soffit system was applied to the middle span of the westbound lanes.

10.1 Preliminary Site Tests

Preliminary site tests confirmed that extensive corrosion of the reinforcing steel had resulted from successive years of deicing salt application to the top surface of the bridge deck.

The corrosion potential survey found corrosion activity in over half the bridge deck as indicated by potential measurements in excess of -0.350 volts versus $Cu/CuSO_4$. Analysis of the concrete cores removed from the bridge deck showed average chloride concentrations at the level of the rebar to be in excess of 1.4 pounds chloride ion per cubic yard (0.83 kg/m^3) of concrete (see Tables 9-2 and 9-3). This value is generally considered to be the approximate threshold limit for rebar corrosion (6).

The history of delamination and spalling on the deck also supports the existence of extensive corrosion activity. Bridge records indicate spalling began about 7 years after the bridge was constructed. In the 21 year period just prior to installing the CP systems, approximately one quarter of the surface area of the deck had been patched due to corrosion induced delaminations.

10.2 Field Installation and Performance

The two methods of applying cathodic protection to the bridge deck, the deck system and soffit system, were chosen for this study so that installation performance and operational effectiveness could be compared.

<u>Deck CP System:</u>
The deck system had the advantage of delivering CP current through the most electrically conductive region of the concrete due to the high chloride content of the deck surface.

The main disadvantage of the deck system was the need to protect the zinc metallizing from traffic wear. The deck system was designed with an AC overlay as the only protection from traffic wear. The deck system was installed by state employees, except for the zinc metallizing. Unfortunately, due to scheduling conflicts, the state maintenance crew was not able to place the AC overlay shortly after the metallizing was completed. Because the bridge could not remain closed during the delay period, a slurry seal was applied over the zinc to protect it from traffic wear until the AC overlay could be placed. Under normal contract installations the slurry seal would not have been necessary as the AC overlay would have been applied before the bridge was opened to traffic. The slurry seal reduced the moisture content of the concrete which increased the electrical resistance of the system. In addition, the AC overlay hindered the evaluation of the anode system and the ability to detect concrete delaminations.

On the deck CP system, continued electrical contact between the primary anode pads and the zinc coating was an initial concern because the pads were inaccessible for inspection beneath the AC overlay. As a precaution, six primary distribution anode pads were placed and wired within each of the four quadrants on the deck. Two zinc and four brass primary anode pads were used in each quadrant to compare the performance of the two metals.

The visual inspection and tests for electrical continuity of the primary anode pads revealed that these initial concerns were justified. The visual inspection of the deck system, conducted after 7.5 years of CP application, showed varying levels of zinc consumption at the inspection locations and cracking of the zinc around the primary anode pads. At some stripe inspection locations, the zinc stripes had almost completely oxidized, leaving only discontinuous fragments of zinc. If oxidation occurred in enough locations, the grid system could have large isolated regions where no current was being delivered. To determine the actual extent of the isolated areas, if any existed, would have required the removal of the entire AC overlay. As this was beyond the scope of this project, the existence and extent of any large isolated areas was not determined. At two primary anode pad locations, the zinc had completely oxidized around the entire perimeter of the epoxy used to mount the pads. This condition electrically isolated these pads. The deck inspection also revealed that at almost all other pad inspection locations, cracks and gaps developed in the zinc around the perimeter of the epoxy. As a result of this visual inspection, electrical continuity tests were conducted to determine how many primary anode pads were affected. The electrical continuity tests, conducted a year after the visual inspection, disclosed electrical discontinuity or complete isolation at 15 of the 24 primary anode pads as shown in Table 9-7, Section 9.8. (See Figure 7-2, Section 7.5 for the test circuit.) The high

prevalence of zinc cracking around the inspected anode pads is believed to be the main cause of the discontinuity between the primary anode pads.

The authors believe the zinc cracking around the perimeter of the epoxy is due to the difference in coefficients of thermal expansion between the epoxy and the concrete and/or the differential movement between the epoxy and concrete due to traffic loading. No tests were conducted to confirm these theories. Similar pad installations were used on the soffit system of this bridge and on the vertical face of the columns of the Richmond San Rafael Bridge without significant cracking. The horizontal orientation of the pads, their placement below the AC overlay, and the mountain climate may have created more severe temperature extremes for the deck installation than for the soffit installation or the coastal Richmond San Rafael Bridge site. In addition, the deck system primary anodes were wired through cored holes behind the pads. Both the soffit system and the Richmond San Rafael Bridge installations used surface mounted wiring that did not require cored holes behind the pads. It is also possible that these cored holes contributed to the cracking. An alternate method of mounting the primary anode pads or contacting the metallizing substance should be developed before this type of distribution anode is used in a deck application again.

As of March 1994, there was no discernible difference in the delivery of CP current between either the zinc or brass primary anode pads used in the deck system.

In the process of delivering CP current, the metallized zinc was consumed (oxidized to form zinc oxide) at the zinc concrete interface. As mentioned in Section 9.7, Visual Inspection, most of the zinc inspection locations on the deck system showed moderate to extensive consumption and disbondment of the zinc. The zinc oxide powder is obviously much less conductive than pure metallic zinc. Furthermore, as a powder, the zinc oxide reduced the bond between the zinc and concrete, and contributed to disbondment. Over time, both the consumption and disbondment increased the circuit resistance of the deck CP system. These conditions had a negative impact on the effectiveness of the system.

Soffit CP System:

There were obvious advantages to applying CP from the bottom surface, or soffit, of the deck. The soffit CP system was easier to install for a number of reasons: holes in the deck were not required to place the surface mounted primary anode pads; the use of a uniform coating eliminated most of the layout and masking required to install the grid for the deck system; and the electrical wiring could be easily surface mounted and routed to the rectifier and control

cabinet. The absence of an overlay also made inspection and any necessary repairs easier. In addition, minimal traffic control was required since the system was being installed over a secondary road. Lane closures were not needed due to the limited traffic on the secondary road. Traffic was diverted around the work area by two flag-persons. This traffic control method also resulted in less worker exposure to the hazards of freeway traffic.

For this project, the disadvantage of applying CP from the soffit was in overcoming the high electrical resistance of this concrete surface to deliver an adequate amount of CP current to the reinforcing steel. It was understood at the onset that the top surface of the deck had been exposed to salt while the soffit had not, and for that reason, the soffit surface would be less conductive.

Zinc disbondment surveys performed on the soffit CP system at 5 and 7.5 years revealed 18.9% and 35.1% zinc disbondment respectively, as shown in Table 9-6, Section 9.6. The disbondment was usually accompanied by large quantities of zinc oxide at the interface between the zinc and the concrete. However, some of the samples removed from disbonded areas showed little or no zinc oxide. It is believed that these areas disbonded just prior to or shortly after initiating CP current due to internal stresses built up in the zinc during the metallizing process. This type of stressing and disbondment was observed during the initial installation of the deck CP system stripes when thicker coatings of zinc were applied too quickly. These stresses could have pulled the zinc away from the concrete surface and resulted in little or no CP current being delivered from the zinc at these areas.

Because the zinc is applied to the underside of the deck, gravity probably plays some role in its disbondment. All of the disbonded sections had relatively thick sections of zinc metal left compared to the amount of zinc oxide. Using thinner applications of zinc metallizing would reduce the weight and may delay some disbondment while still providing a sufficient quantity of zinc for the system to operate efficiently. A thinner zinc application would also reduce the application time and material costs of the soffit system.

Bond tests were performed on the zinc coating to determine the adhesion of the zinc to the concrete. After 5 years of cathodic protection, the average bond strength was 270 psi (1.86 MPa). Two and a half years later, the average bond strength measured 248 psi (1.71 MPa). Because the sampling method did not include disbonded areas, the results are biased and thus higher than would be expected from random sampling.

An inspection of the primary anode pads was completed after 7.5 years of cathodic protection. The pads in the soffit CP system were in excellent condition, with only two of the twenty showing evidence of cracking and zinc consumption, as described in Section 9.7, Zinc Anode Visual Inspection.

In an attempt to determine the ideal zinc metallizing thickness based on the consumption rate and the resistance of the zinc oxide, samples of zinc were taken from both systems at 0 and 7.5 years. Unfortunately, the thickness measurements varied tremendously and attempts to determine a consumption rate were inconclusive due to the variability of the metallizing thickness and the small number of samples. The thickness of the professionally applied hand flame spray metallizing samples taken from the soffit system after 7.5 years varied from 0.013 to 0.047 inches (0.33 to 1.20 mm). The difference between these values is over twice the design thickness of 0.015 inches (0.38 mm).

10.3 Cathodic Protection Operation and Effectiveness

During the 8.5 year study period, the operation of both CP systems varied due to the following variables: changes in precipitation; the effects of the slurry seal and chipseal; the changes in driving voltage; the increased resistance and disbondment resulting from the zinc consumption; and the non-homogeneous state of the concrete due to differences in chloride contamination and multiple patches which influenced the uniform delivery of CP current to the deck.

Deck CP System:

Based on the evaluation criteria of achieving a 100 millivolt polarization decay at an anodic location over a four hour period, the deck CP system did not provide complete protection to the reinforcing steel. Polarization decay measurements from anodic locations determined from the original corrosion potential survey (data collection points J, K, and L in Table 9-9, Section 9.10) were occasionally considered to have met the 100 millivolt requirement. (Values of 80 millivolts or greater from the 1 and 2 hour duration decays were considered likely to reach 100 millivolts in 4 hours.) Unfortunately, the polarization requirement was never met at all three anodic measurement locations at the same time. The poor response to cathodic protection was due, in part, to the resistance of the concrete and to the failure to maintain a sufficient driving voltage.

Originally, the nominal driving voltage for the deck CP system was set at 3 volts. It was adjusted to 5 volts shortly after initialization, in an attempt to achieve the 100 millivolt polarization decay recommended by NACE (4). After the first polarization decay results determined that 5 volts

was too low, the voltage was not immediately increased so that the other variables (moisture content, temperature, etc.) affecting the system could be analyzed. Since it was a drought year, it was thought that changes such as an increase in rain might significantly increase the polarization. After the chipseal was applied, the voltage was still not changed and several more polarization decay surveys were performed to determine the affect of the chipseal on the system. Due to the low polarization decay, the driving voltage was increased to 9 and later 14 volts in an attempt to offset the increased resistance of the system. Both times the increases were insufficient to generate a consistent 100 millivolt decay. It is difficult to assess the ultimate capability of this system since a rigorous attempt to achieve the 100 millivolt polarization decay was not made.

Several factors contributed to the high circuit resistance for the deck CP system. These included the moisture dependency of the concrete, the application of the slurry seal and chipseal, and the zinc consumption and disbondment.

Since six of the eight study years received below normal precipitation, the effect of the precipitation on the operation of the CP systems is shown by the wide range of current values in Figures 9-2 and 9-3, Section 9.9. These ranges reflect the seasonal variation and moisture dependency of the systems. The lower current delivery values and higher circuit resistances were recorded during the dry periods. As moisture increased, higher current delivery and lower resistance were measured.

The slurry seal was originally applied over the zinc grid and deck to protect the zinc from traffic wear until the AC overlay could be applied. Research has shown that a slurry seal reduces the water permeability of a pavement to very low values (7) further reducing the amount of moisture in the deck.

The inadvertent application of the chipseal in August 1986, about 9 months after the CP systems were energized, also reduced the amount of moisture reaching the eastbound lanes of the concrete deck. The one hour duration polarization decay values of surveys taken from the anodic regions during the first three months of operation ranged from 29 to 91 millivolts with an average of about 59. Eight months after the chipseal was applied to the deck, the measurements ranged from 3 to 32 millivolts with an average value of about 18 millivolts.

The disbondment and consumption of the zinc discussed in Section 10.2 also added to the resistance of the system.

The slurry seal and chipseal made it difficult to differentiate between their effects and those due to precipitation and the AC overlay. A similar system was installed near Redding, California without the use of a slurry seal. but with a lower level of chloride contamination. (A chipseal was accidentally applied there too.) The Redding site has been performing well since its installation in 1988 (8).

The high electrical resistance of the deck CP system required greater driving voltages than were supplied. This limited the ability of the system to regularly achieve the 100 millivolt polarization decay criteria used to judge the effectiveness of the system.

Because corroding reinforcing steel leads to concrete delamination and spalling, delamination surveys can be good indicators of continued corrosion if observed over an extended time period. Unfortunately, the extent of any concrete delamination and spalling on the deck system which may have resulted from the lack of polarization could not be determined due to the presence of the AC overlay. From the available data gathered however, the deck system does not appear to be providing adequate protection to the reinforcing steel. Unless further research can confirm more conclusively that the slurry seal and chipseal are responsible for the deck system's low polarization decay measurements, the deck metallized zinc CP system should not be implemented on other structures for corrosion protection of reinforcing steel.

Soffit CP System:

Based on the NACE evaluation criteria of a 100 millivolt polarization decay at an anodic location over a four hour period, the soffit CP system has not provided complete protection to the reinforcing steel either. The polarization decay data in Table 9-9, Section 9.10 points this out. The data from location B was used to characterize the soffit CP system. This location is in an anodic region (based on the original corrosion potential survey of the deck). Polarization decay measurements from this location were considered to have met the 100 millivolt requirement only twice. (Values of 80 millivolts or greater from the 1 and 2 hour duration decays were considered likely to reach 100 millivolts in 4 hours.) The other twelve polarization decay measurements fell well below the 100 millivolts required.

Low levels of chlorides and moisture content contributed to the high circuit resistance of the soffit CP system. The deck was contaminated with deicing salts from the top surface, with very little contamination occurring on the bottom surface. As a result, the conductivity of the soffit concrete was significantly lower than the top concrete. In addition, several drought years created low moisture content conditions in the concrete and added to the high resistance problem. The

conductivity of the concrete is moisture dependent as shown in Figures 9-2 and 9-3, Section 9.9. From these graphs, it can be seen that the current delivery rises sharply after large amounts of precipitation and is cyclical with the seasons. Concrete with higher levels of moisture content and chloride contamination would be more conductive. A higher conductivity concrete would allow more CP current to be applied to the reinforcing steel at a given driving voltage. Initial studies of metallized zinc CP systems applied to the soffit and substructures of bridges in marine environments in Florida, where chloride and moisture levels are high, have shown adequate cathodic protection of the reinforcing steel (9, 10).

The disbondment and consumption of the zinc discussed in Section 10.2 also contributed to the increased resistance of the soffit system.

For safety reasons, the driving voltage was limited to 30 volts (nominal). This limit on the driving voltage prevented higher currents from being delivered through the concrete. These higher currents would have provided more protection to the reinforcing steel.

Deck delamination and spalling can also be an indicator of the effectiveness of cathodic protection. Data in Table 9-10, Section 9.11, shows that the deck continued to deteriorate, as was expected based on the low polarization decay values. However, the soffit CP system appears to have provided a small amount of protection to the reinforcing steel based on the deck delamination data in Table 9-11, Section 9.11. In the 1984 and the 1985 surveys, a larger percentage of the delaminations were found over the area where the CP system would later be installed compared to the non-CP areas. The 1990 survey found that after CP, a lower percentage of delaminations occurred over the CP area compared to the non-CP area. Although the differences are small and other factor such as the amount of patching should be considered, this suggests that the CP system slightly lowered the rate of corrosion over the CP area.

Although the soffit CP system may have slightly slowed the deterioration of the structure over the CP area, it did not stop it. The limit on the driving voltage, combined with the high circuit resistance of the uncontaminated soffit concrete, limited the ability of the soffit system to halt the corrosion of the reinforcing steel.

10.4 Life Expectancy

Because the metallized zinc anode consumes as it delivers CP current, the useful life of these CP systems are governed by the amount of current delivered by the zinc and the consumption and

disbondment of the zinc. Based on the visual inspection of the anode, it is obvious that these systems are progressing toward the end their "useful" lives. Unfortunately, neither the deck system nor the soffit system provided adequate CP current to consistently protect the reinforcing steel based on the NACE four-hour polarization decay criteria (4). Because of their inadequate performance, an accurate determination of the life expectancy of these individual systems is not practical or possible.

11.0 APPENDICES

After the initial evaluation of the deck system, the original specifications used at the East Camino Undercrossing were modified and a similar installation was installed on an I-5 bridge near Redding, California (8). The basic specifications as used at the Redding site are provided below for anyone considering further work on this type of CP system. The reader is cautioned that the final evaluation of the metallized zinc deck CP system at Redding is not complete. Experience gained from the application and performance of the soffit CP system anode coating led to further development of the substructure metallized zinc CP system. SHRP has published "Cathodic Protection of Concrete Bridges: A Manual of Practice" (11) which contains a tentative guide specification for substructure metallized zinc CP systems. Because the East Camino U.C. soffit system in essentially a substructure application applied to the underside of the deck, the SHRP substructure specification is reprinted below.

11.1 Guide Specification for Thermally Sprayed Zinc Anode Cathodic Protection System For Bridge Decks

METALLIZING CONCRETE. This work shall consist of preparing bridge deck, metallizing concrete, electrical connectors, and asphalt concrete in accordance with details shown on the plans as specified in the California DOT Standard Specifications, these special provisions, and as directed by the Engineer.

PREPARE CONCRETE DECK SURFACE. Preparing concrete deck surface shall consist of abrasive blast cleaning concrete deck surfaces, including exposed surfaces of brass pads (anode pads), to remove remaining asphalt concrete, oil, dust, laitance and other foreign material adhering to bridge deck, as shown on the plans.

Immediately prior to placement of overlay, the entire deck area shall be further cleaned by compressed air blasting to remove loose dust and chips.

If the surface to receive the overlay becomes contaminated, as determined by the Engineer, or if the traffic as allowed over the surface, the areas shall be recleaned by abrasive blast cleaning.

All materials which are removed shall become the property of the Contractor and shall be disposed of outside the highway right of way in accordance with the provisions in Section 7-1.13, "Disposal of Material Outside the Highway Right of Way" of the California DOT Standard Specifications.

ELECTRICAL CONNECTORS. Brass pads (2" x 2" x 3/8" thick) will be State-furnished as provided for under "Materials" of these special provisions.

Portion of bridge deck shall be removed as required for brass pad installation in accordance with the details shown on the plans.

Brass pads shall be installed prior to metallizing the deck.

Epoxy adhesive (bedding) shall be electrically non-conductive and of such viscosity as to support the brass pads in place without "flow" until the epoxy hardens. Epoxy shall be "Concresive AEX 1419" as manufactured by Master Builders or equal.

After abrasive blast cleaning and before metallizing the concrete surface, the Contractor shall provide access to the cleaned area for the Engineer to conduct electrical continuity testing to locate discontinuities in the electrical insulating characteristics of the concrete cover over the deck reinforcement.

If discontinuities (caused by tie wire or other metal extending too close to the concrete surface or voids in concrete) are detected, the metal shall be removed and the area patched as directed by the Engineer. Removal of metal and patching of resulting holes will be paid as extra work as provided in Section 4-1.03D "Extra Work," of the California DOT Standard Specifications.

METALLIZING CONCRETE. Metallizing concrete shall consist of applying zinc with wire fed type conventional thermal spray equipment.

Zinc wire shall be 99.9 percent pure. The contractor shall furnish a signed certification by the manufacturer of the purity of the zinc wire and a list of impurities with quantity of each.

The concrete surface shall be dry and dust free when the zinc is applied.

Zinc shall be applied to the concrete at a uniform rate. The quantity of zinc to be sprayed shall be 75 pounds per 100 square feet of bridge deck surface area.

Metallizing concrete shall be applied in uniform continuous 6-inch wide stripes spaced at 12-inch on centers on the transverse direction and a total of four 6-inch wide uniform continuous metallizing stripes on the longitudinal direction with a stripe traversing a row of brass pads as shown on the plans.

Metallizing shall be stopped when wind or other atmospheric conditions prevent the collection of waste as specified herein or adversely affect the metallizing process as determined by the Engineer.

Good housekeeping shall be practiced during metallizing operations. Waste products and dust shall not be blown off. Precautions in the metallizing operations shall be in accordance with all applicable occupational safety and health standards, rules, regulations, and orders established by the State of California. Workmen shall use personal protective equipment including respirators and appropriate clothing. Respirators shall conform to ANSI Standard: Z 88.2.

All reasonable precautions shall be exercised to prevent the discharge of any hazardous waste material onto the ground. Hazardous waste material shall consist of residue from the metallizing process. Curtains, drapes, or other methods, approved in advance by the Engineer, shall be used to contain hazardous waste material.

No "on ground" temporary storage of hazardous waste material will be permitted.

Hazardous waste material shall be stored in leak proof bins and shall be handled in such a manner that no spillage will occur.

Disposing of hazardous waste material shall be performed in accordance with all applicable Federal, State and local laws.

Laws which govern this work include but are not necessarily limited to:

1. Health and Safety Code, Division 20, Chapter 6.5 (Hazardous Waste Control Act).

2. Title 22; California Administrative Code, Chapter 30 (Minimum Standards for Management of Hazardous and Extremely Hazardous Materials).

3. Title 8, California Administrative Code.

It shall be the responsibility of the Contractor to verify with the operator of a disposal site whether the material will be accepted for disposal. This material shall only be hauled by a registered hazardous waste hauler using correct manifesting procedures and vehicles displaying current certification of compliance.

11.2 Guide Specification for Thermally Sprayed Zinc Anode Cathodic Protection System for Bridge Substructures.

Reprinted from SHRP report S-372, "Cathodic Protection of Concrete Bridges: A Manual of Practice" (11)

657. THERMALLY SPRAYED ZINC ANODE CATHODIC PROTECTION SYSTEM

657.10 DESCRIPTION: This cathodic protection system consists of a primary anode connection of titanium strips or brass plates and a high purity zinc coating which may be covered with a decorative or protective coating. The optimum design current limits have not yet been identified, but it is recommended the design does not exceed 2 mA/ft^2 of concrete surface.

657.20 MATERIALS

657.21 PRIMARY ANODE CONNECTION: Primary anode connection to the zinc coating shall be made of titanium strips or brass plates. These shall be fixed to the concrete surface with an insulating bed of epoxy prior to spraying the zinc coating.

657.21.01 The titanium strips shall be made of solid ASTM A 265 Grade I titanium. The titanium strips are typically 0.50" thick by 0.040" wide and 6.0" long.

657.21.02 Brass plates shall be made from brass conforming to UNS number C21000 or C22000 as specified in ASTM Standard B 36. The Contractor shall submit a mill certificate verifying compliance with ASTM Standard B 36 to the Engineer. The brass plates are typically 2 1/2" in diameter and 1/8" thick. The bolts shall be a 1/4"-20 UNC x 1" of brass. One bolt shall be affixed perpendicular to the plate by brazing with a silver alloy filler material conforming to procedures in the AWS "Brazing Manual".

657.21.03 Epoxy adhesive for attaching primary connections to concrete shall be Concresive AEX 1419 as manufactured by Adhesive Engineering Co., DP-420 by 3M Co., or an approved equal.

657.22 ZINC ANODE: The anode material consists of pure (99.9%) zinc coating which may be overcoated. The Contractor shall have an independent laboratory certify the purity of all zinc wire to be used on the project and list the percentage of each impurity. The physical properties of the zinc are similar to those of a conductive coating, being only a light weight addition to the reinforced concrete. The zinc is applied by arc or flame spray to the external concrete surface to a thickness of approximately 10 to 20 mils. Zinc is not suitable for wearing surfaces. The durability of zinc coating is minimal on wet surfaces were corrosion of the zinc will occur. An overcoat in this case will increase the life of the anode.

657.30 DESIGN AND CONSTRUCTION REQUIREMENTS

657.31 SURFACE PREPARATION

657.31.01 DELAMINATED CONCRETE: All delaminated concrete shall be removed prior to installation of the anode system. Concrete shall be reinstated to its original profile using cementitious materials. Surface treatments shall not be applied.

657.31.02 PREVIOUS PATCHES: All patches exceeding 2 sq. ft. in area repair materials with a volume resistivity of more than 50,000 ohm-cm as determined by AASHTO T-277 shall be removed prior to installation of the cathodic protection system. Concrete shall be reinstated to its original profile using cementitious materials. surface treatments shall not be applied.

657.31.03 REINFORCEMENT: Reinforcement exposed after the removal of concrete shall have all loose rust or scale removed. All replacement bars must be spliced to the remaining reinforcing bars to ensure electrical continuity.

657.31.04 EPOXY INFECTED AREAS: All epoxy injected areas exceeding 2 sq. ft. in area must be removed.

657.31.05 FERROUS COMPONENTS AT SURFACE: Any tying wires, nails, chairs or other ferrous components visible on the surface of the concrete shall be cut back or covered with cementitious patch material to insure not less than 1/4" cover from the surface. Deliberately exposed ferrous components shall be masked.

657.31.06 EMBEDDED MONITORS: All embedded monitors shall be installed prior to installation of anode materials.

657.31.07 MASKING: Cathodic protection anode materials shall not make direct contact to any ferrous component of the concrete substructure. All ancillary steel or deliberately exposed reinforcing steel must be masked before anode application. Areas of concrete to be used for future surface half-cell potential measurements can be achieved by simple masking tape.

657.31.08 PATCHING: Concrete shall be reinstated to its original profile using cementitious materials. Surface treatments and curing membranes shall not be applied. In general, patching shall be done sufficiently in advance to the anode installation so that the patch material fully cures.

657.31.09 SCARIFICATION: The concrete surface should be scarified as required for satisfactory bonding of the anode components. The surface should be cleaned and abraded by dry grit blasting or other approved techniques.

657.32 THERMALLY SPRAYED ZINC CONSTRUCTION REQUIREMENTS

657.32.01 The Contractor shall prepare the concrete and primary connection surfaces for zinc anode application by abrasive blasting these surfaces to remove all surface contaminants.

657.32.02 The Contractor shall apply the zinc anode before the surfaces can become re-contaminated.

657.32.03 There shall be a minimum of 0.25 inch of concrete cover between the anode and the reinforcing steel. Where less than 0.25 inch of cover exists, a non conductive polymer or masking shall be installed between the anode and reinforcing steel.

657.32.04 All foreign material shall be cleaned from the concrete surface prior to placing anode materials in a manner approved by the Engineer.

657.32.05 Titanium strips or brass plates shall be used as the primary anode connections. These connection shall be fixed onto the concrete surface with an insulating bed of epoxy prior to coating. A minimum of two anode connections shall be designed for each zone.

657.32.05.01 The primary connection shall be mechanically connected to a #10 AWG size which will terminate at the rectifier/controller.

657.32.06 The zinc anode shall be thermally sprayed using flame or arc spray techniques per the specified thickness. Typically 10 to 20 mil thickness is designed. The Contractor shall allow a minimum of one hour between installation and energization.

657.32.07 The Contractor shall submit the manufacturer's zinc spraying equipment specification and recommended operational procedures for the Engineer's review. Approval shall be made by successful demonstration in a trial area.

657.32.07.01 Bond strength and thickness uniformity must be demonstrated during the application using a hand controlled spray gun. Feed wire rate, spray distance, rate and path of travel, overlaps distances and time between successive overlap and number of overlaps shall be established and maintained through out the project by the Contractor.

657.32.08 Short Circuit Testing: During the application of the zinc coating, electrical shorting of the zinc to any metallic member of the substructure that is electrically continuous to the reinforcing steel can be immediately detected. One detection plan which has been successful consists of monitoring the DC voltage between the zinc coating and the reinforcement steel. Expected voltage will range from 100 to 500 mV. A sharp drop in voltage is a definite indication of a short. The Contractor shall submit a detection plan to the Engineer for approval. All shorts identified shall be immediately located and corrected to eliminate the short prior to continuing the zinc application.

657.32.09 Visual Inspection: The zinc anode shall be visually inspected using a lens with a magnification of 10. To be acceptable, the coating shall have uniform appearance and follow the form of the concrete surface. The coating shall not contain any lumps, blisters, coarse texture or loosely adhering particles, nor shall it contain any cracks, pinholes, or chips which expose the concrete substrate.

657.32.10 Adhesion Testing: Adhesion test shall be conducted using aluminum or steel test discs. These discs shall be cemented to the test area and after curing the test discs shall be pulled from the test area with a calibrated pull off tester as specified by the Engineer. To be acceptable, the adhesion strength shall be greater than 150 psi.. Adhesion test areas shall be recoated with zinc to the specified thickness after scraping any loose or delaminated zinc caused by the adhesion test.

657.32.11 Thickness Testing: Thickness measurements shall be performed for each zone. Measurement locations and frequency shall be determined by the Engineer. The zinc coating thickness at each location shall be ± 2 mils of the specified thickness.

657.32.12 A platform which provides efficient and safe access for workers, supervisors and inspectors to all work areas shall be provided by the Contractor. This platform shall be enclosed

by a structure with heating and ventilation system which provides for operational efficiency, occupational health and safety and environmental conditions which promote high zinc to concrete bond strength and protection of the external environment from contamination by noxious materials. The ventilation system which filters and recirculates enclosure air shall be designed to prevent dusts, vapors and gases in the enclosure from accumulating in concentrations which are explosive or otherwise hazardous to personnel.

657.32.13 The Contractor shall provide a plan for collecting and safely disposing of all project wastes in accordance with environmental regulations. Waste includes scrap metal, concrete and concrete dust, blasting material and zinc dust .

12.0 REFERENCES

1. Carello, R.A., Parks, D.M., "Cathodic Protection of Reinforced Concrete Bridge Deck and Soffit Using Metallized Zinc," FHWA/CA/TL-91/05, November 1992, California Department of Transportation, Sacramento, CA.

2. ASTM, Annual Book of ASTM Standards, ASTM Designation C-876, Standard Test Method for "Half-cell Potentials of Uncoated Reinforcing Steel in Concrete", ASTM, Philadelphia, PA, 1985.

3. California Department of Transportation, "California Testing Manual, Testing and Control Procedures", California Test 404, 1986, California Department of Transportation, Division of New Technology, Materials and Research, Sacramento, CA.

4. NACE Standard Recommended Practice, "Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures," NACE Standard RP0290-90, April 1990, Item No. 53072, National Association of Corrosion Engineers, Houston, TX.

5. Carello, R.A., Parks, D.M. and Apostolos, J.A., "Development, Testing and Field Application of Metallized Cathodic Protection Coatings on Reinforced Concrete Substructures," FHWA/CA/TL-89/04, May 1989, California Department of Transportation, Sacramento, CA.

6. Ferragut, T.R. and Jackson, D.R., "Cathodic Protection of Reinforced Concrete Bridge Decks," FHWA Demonstration Project Number 34, Oct. 1986, FHWA, Washington, DC.

7. Zube, E., "Studies on Water Permeability of Asphalt Concrete Pavements", California Division of Highways, transactions from the Fourth Annual Highway Conference, March 1961.

8. Carello, R.A., Kennelly, T. B., Parks, D.M., "Installation and Operational Comparison of Five Bridge Deck Cathodic Protection Systems," Federal Study Number F87SD26, Currently Unpublished, California Department of Transportation, Sacramento, CA.

9. Florida Department of Transportation, "Sacrificial Anode Cathodic Protection of Steel Reinforced Concrete Bridge Components," Experimental Project No. FL 91-01, March 1994, Florida Department of Transportation, Gainesville, FL.

10. Kessler, R. J., Powers. R. G., "Zinc Metallizing for Galvinic Cathodic Protection of Steel Reinforced Concrete in a Marine Environment," Paper number 324 Nace Corrosion 90 Conference, April 1990, National Association of Corrosion Engineers, Houston, TX.

11. Bennett, J. E., et al, "Cathodic Protection of Concrete Bridges: A Manual of Practice", SHRP-S-372, December 1993, National Research Council, Washington, DC., Appendix B, pp 34-37.