



PB97-124887



U.S. Department  
of Transportation  
**Federal Highway  
Administration**

Publication No. FHWA-RD-96-073  
December 1996

---

# Galvanic Cathodic Protection of Reinforced Concrete Bridge Members Using Sacrificial Anodes Attached by Conductive Adhesives

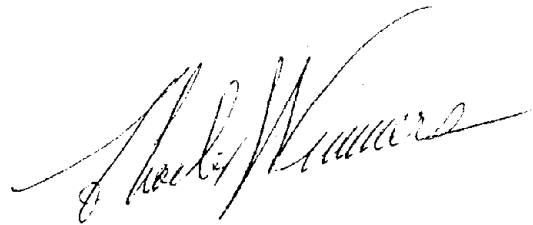
---

Research and Development  
Turner-Fairbank Highway Research Center  
6300 Georgetown Pike  
McLean, Virginia 22101-2296

## FOREWORD

This report documents a study to develop and demonstrate a galvanic cathodic protection system for concrete bridge structures using sacrificial anodes attached by conductive hydrogel adhesives. This Interim Report describes laboratory studies to identify the optimal anode and hydrogel compositions, followed by a field installation on a marine structure to demonstrate feasibility of the system. Performance of the field installations will be evaluated following a 2½-year monitoring period.

This report will be of interest to bridge engineers and maintainers of reinforced concrete structures. The investigation will also be of interest to owners, inspectors, design firms, and construction contractors who are involved with concrete bridges.




Charles J. Nemmers, P.E.  
Director, Office of Engineering  
Research and Development

## NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

1. Report No. FHWA-RD-96-073		2		 PB97-124887		3. Recipient's Catalog No.	
4. Title and Subtitle GALVANIC CATHODIC PROTECTION OF REINFORCED CONCRETE BRIDGE MEMBERS USING SACRIFICIAL ANODES ATTACHED BY CONDUCTIVE ADHESIVES						5. Report Date December 1996	
7. Author(s) J.E. Bennett and T.J. Schue				6. Performing Organization Code			
9. Performing Organization Name and Address ELTECH Research Corporation 625 East Street Fairport Harbor, OH 44077				8. Performing Organization Report No.			
12. Sponsoring Agency Name and Address Office of Engineering R&D Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296				10. Work Unit No. (TRAIS) 3D4b		11. Contract or Grant No. DTFH61-92-C-00051	
15. Supplementary Notes Contracting Officer's Technical Representative (COTR): Y.P. Virmani, HNR-10				13. Type of Report and Period Covered Interim Report October 1992 - September 1995			
16. Abstract  This is the interim report in a study to investigate the feasibility of using galvanic cathodic protection (CP) of reinforced concrete bridge members using sacrificial anodes attached by conductive adhesives. Galvanic CP systems have recognized advantages of simplicity and the potential to operate with little or no maintenance for the life of the system. But galvanic systems have been used relatively little. Applications have so far been limited to the seawater splash and tidal zone where concrete is moist and most conductive, and where the anode surface is periodically wetted. In this study, a new galvanic CP system is being investigated in which sacrificial anodes are attached to the concrete surface with ionically conductive adhesives called hydrogels.  Laboratory studies first demonstrated that aluminum and aluminum alloys were unsuitable as anodes in contact with hydrogel adhesives. Aluminum and its alloys exhibited either unstable passive behavior or low anode working potential. Zinc was then selected as the sacrificial anode for installation on field validation trials. Commercially available hydrogel adhesives also proved to be unsatisfactory for CP systems, but further study resulted in the development of a hydrogel with adequate performance and life expectancies.  About 1000 ft <sup>2</sup> (100 m <sup>2</sup> ) of zinc/hydrogel composite was installed on the pilings, pile caps, and double-tee beams of a fishing pier in Ft. Pierce, Florida. The system was relatively easy to install, and performance over the first 4 months of operation has been good.  Additional field trials on the Long Key Bridge in Florida and other structures are planned. Field trials will be monitored for 2½ years, and the performance of the systems will be evaluated.				14. Sponsoring Agency Code			
17. Key Words Corrosion, Cathodic Protection, Anodes, Bridges, Concrete, Sacrificial Anodes, Hydrogel, Galvanic Cathodic Protection				18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.			
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 46		22. Price	

# SI\* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>					<b>LENGTH</b>				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
<b>AREA</b>					<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>	mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>	m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	square meters	m <sup>2</sup>	m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>	km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>					<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>	m <sup>3</sup>	cubic meters	35.71	cubic feet	ft <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>	m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>					<b>MASS</b>				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
<b>TEMPERATURE (exact)</b>					<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
<b>ILLUMINATION</b>					<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>	cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>					<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

\* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

## TABLE OF CONTENTS

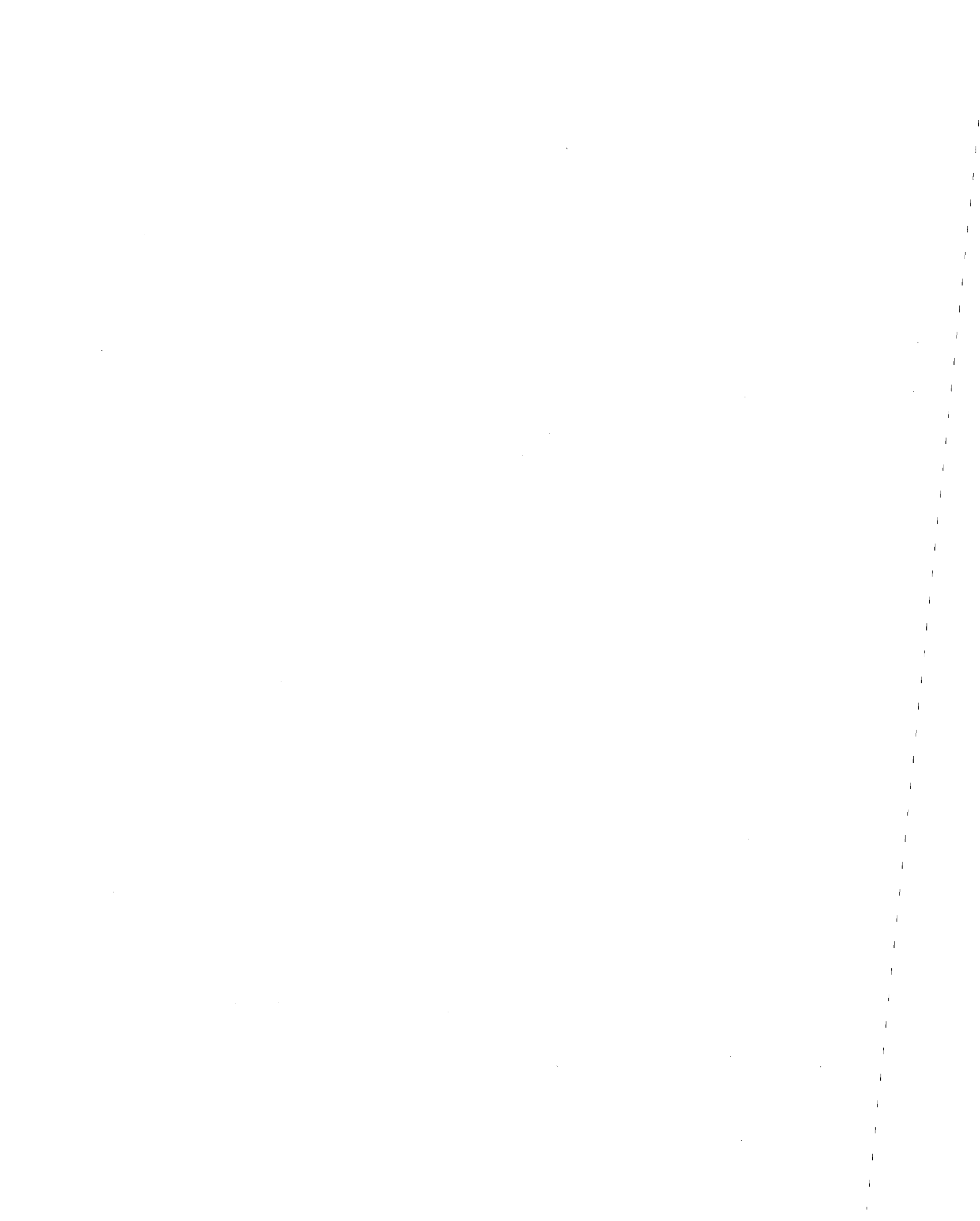
	<u>Page</u>
<b>CHAPTER 1. INTRODUCTION</b> .....	1
PROBLEM STATEMENT .....	1
OBJECTIVES .....	1
SUMMARY OF RESEARCH APPROACH.....	1
<b>CHAPTER 2. TECHNOLOGY REVIEW</b> .....	5
IMPRESSED CURRENT CATHODIC PROTECTION .....	5
GALVANIC CURRENT CATHODIC PROTECTION .....	6
OTHER STUDIES IN PROGRESS.....	7
SUMMARY .....	8
<b>CHAPTER 3. LABORATORY SCREENING OF ANODES AND ADHESIVES</b> .....	9
SCREENING OF ANODES .....	9
Background .....	9
Test Procedure.....	10
Testing of Anode Candidates.....	11
SCREENING OF HYDROGEL ADHESIVES .....	14
Background .....	14
Test Procedure.....	15
Testing of Hydrogel Adhesives .....	17
TESTING OF OTHER CONFIGURATIONS.....	21
SUMMARY .....	22
<b>CHAPTER 4. INSTALLATION OF FIELD TRIALS</b> .....	23
STRUCTURE SELECTION.....	23
SYSTEM DESIGN.....	24
INSTALLATION.....	27
ENERGIZING.....	31
SUMMARY .....	31
<b>CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS</b> .....	33
CONCLUSIONS .....	33
RECOMMENDATIONS .....	33
<b>APPENDIX. POLARIZATION DATA FOR OTHER     ALUMINUM ALLOY/RG-63B HYDROGEL COMPOSITES</b> .....	35
<b>REFERENCES</b> .....	39

## LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1.	Cell for the testing of anode materials. ....	10
2.	Polarization data for pure zinc/RG-63B hydrogel composite.....	12
3.	Polarization data for pure aluminum/RG-63B hydrogel composite. ....	12
4.	Polarization data for 0.1 percent indium, 0.05 percent gallium-aluminum alloy/RG-63B hydrogel composite. ....	13
5.	Polarization data for 0.5 percent magnesium, 0.07 percent tin-aluminum alloy/RG-63B hydrogel composite. ....	13
6.	Specimen used for accelerated testing of hydrogel adhesives.....	15
7.	Cell voltage versus equivalent life for medical hydrogel adhesives. ....	18
8.	Cell voltage versus equivalent life for CP hydrogel adhesives. ....	20
9.	Galvanic current versus time for medical hydrogel adhesives. ....	20
10.	Plan view of west end of Ft. Pierce fishing pier. ....	24
11.	Layout of zinc/hydrogel on piling.....	25
12.	Layout of zinc/hydrogel on pile cap of bent #2.....	25
13.	Layout of zinc/hydrogel on pile caps of bents #4 and #6.....	26
14.	Layout of zinc/hydrogel on pile cap of bent #5.....	26
15.	Layout of zinc/hydrogel on beams #4 and #5.....	27
16.	Cleaning of concrete surface prior to installation of zinc/hydrogel. ....	29
17.	Zinc/hydrogel installed on bent #2 pile cap prior to painting.....	30
18.	Completed zinc/hydrogel system installed on pilings and pile cap.....	30

## LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
1.	Properties of Sacrificial Anode Materials.....	2
2.	Aluminum Alloys Tested as Anode Materials.....	10
3.	Properties of Promeon RG-60 Series Hydrogels.....	14
4.	Proportions and Mixture Properties for Ohio DOT Class C Concrete.....	16
5.	pH and Resistivity of Medical Hydrogel Adhesives.....	17
6.	Accelerated Testing of Medical Hydrogel Adhesives.....	17
7.	pH and Resistivity of Hydrogel Adhesives Developed for CP.....	19
8.	Accelerated Testing of Hydrogel Adhesives Developed for CP.....	19
9.	Concrete, Anode, and Steel Areas for Members of Phase I Installation.....	27
10.	Results of Potential Survey on Members of Fishing Pier.....	28
11.	Current Densities for Ft. Pierce CP System.....	31





## CHAPTER 1. INTRODUCTION

### PROBLEM STATEMENT

In a 1991 report to Congress, the Federal Highway Administration (FHWA) reported that of the nation's 577,000 bridges, 226,000 (39 percent of the total) were deficient, and 134,000 (23 percent of the total) were classified as structurally deficient.<sup>(1)</sup> Structurally deficient bridges are those that are restricted to light vehicles only, or that require immediate rehabilitation to remain open. The damage on most of these bridges is caused by corrosion of the steel reinforcement. The United States Department of Transportation has estimated that \$90.9 billion will be needed to repair the damage on these existing bridges.<sup>(2)</sup> Today, the nation's bridges continue to deteriorate at an alarming rate.

The conventional means of repair—removing the delaminated concrete and filling the spalled area with a patch material—is, in many cases, inadequate. Deterioration of the concrete around the patched area is usually accelerated due to increased corrosion of the reinforcing steel, and patching becomes a never-ending process. Low-permeability overlays, when properly constructed, have been found to extend life, but reinforcement corrosion continues beneath the overlays because of salt-contaminated concrete left in place.<sup>(3)</sup>

Cathodic protection (CP) has been proven to be an effective means of stopping the corrosion of steel in concrete,<sup>(4)</sup> and over the past 20 years, State highway agencies have installed more than 300 impressed current cathodic protection (ICCP) systems on highway structures around the country.<sup>(5)</sup> A recent survey has found that although 80 percent of the installed CP systems were still functional, several problems had been encountered. Most of these problems occurred as a result of the relative complexity of impressed current CP systems and the lack of a mechanism for proper servicing and maintenance.<sup>(5)</sup> Galvanic cathodic protection systems, which use sacrificial anodes, have recognized advantages of simplicity and reliability, but have been used very little for reinforced concrete structures due to unavailability of functional systems. Additional research and development is needed before galvanic CP systems can be used with confidence on highway bridge members.

### OBJECTIVES

The objectives of this study were: (1) to study and develop sacrificial anode and conductive adhesive materials in terms of their ability to provide galvanic protection to reinforced concrete structures, (2) to optimize an anode/adhesive composite to provide galvanic current to reduce the corrosion of steel in concrete, and (3) to install the most promising system on a highway structure and to evaluate its performance over a 3-year monitoring period.

### SUMMARY OF RESEARCH APPROACH

A technology review was first conducted to identify available sacrificial anode candidates. These included aluminum, zinc, and aluminum and zinc alloys. The most promising

metals and alloys were then tested in combination with conductive adhesives. Emphasis was placed on aluminum and aluminum alloys. Aluminum is a particularly attractive candidate, as shown by the following table:

Table 1. Properties of Sacrificial Anode Materials.

<i>Anode</i>	<i>Theoretical Energy Efficiency (A-hr/lb)</i>	<i>Current Efficiency (percent)</i>	<i>Practical Energy Efficiency (A-hr/lb)</i>	<i>Thickness (mil/yr) Consumed*</i>	<i>Material Cost (\$/ft<sup>2</sup>)**</i>	<i>Working Potential V vs. SCE</i>
<b>Zinc</b>	372	95	353	1.0	\$0.18	-1.03
<b>Aluminum</b>	1352	95	1285	0.7	\$0.06	-1.03
<b>Magnesium</b>	1000	50	500	2.9	\$0.38	-1.53

1 A-hr/lb = 2.2 A-hr/kg

1 mil/yr = 0.025 mm/yr

\$1/ft<sup>2</sup> = \$10.7/m<sup>2</sup>

\* Based on a current density of 1.5 mA/ft<sup>2</sup> (0.14 mA/m<sup>2</sup>).

\*\* Based on costs in *Chemical Marketing Reporter*, March 1992, Zn = \$0.48/lb, Al = \$0.58/lb, and Mg = \$1.43/lb (\$1/lb = \$2.2/kg).

Aluminum was identified as an attractive candidate, particularly in terms of its availability, ease of handling, and cost. An aluminum anode designed to deliver a given amount of energy could be 30 percent thinner, 74 percent lighter, and 65 percent less expensive than zinc. In practical terms, however, the high potential and energy efficiency of aluminum are often not realized due to the formation of a passive oxide film at the metal surface. Therefore, it is usually necessary to modify the nature of that oxide film in order to achieve the performance required of a sacrificial anode in galvanic cathodic protection systems.

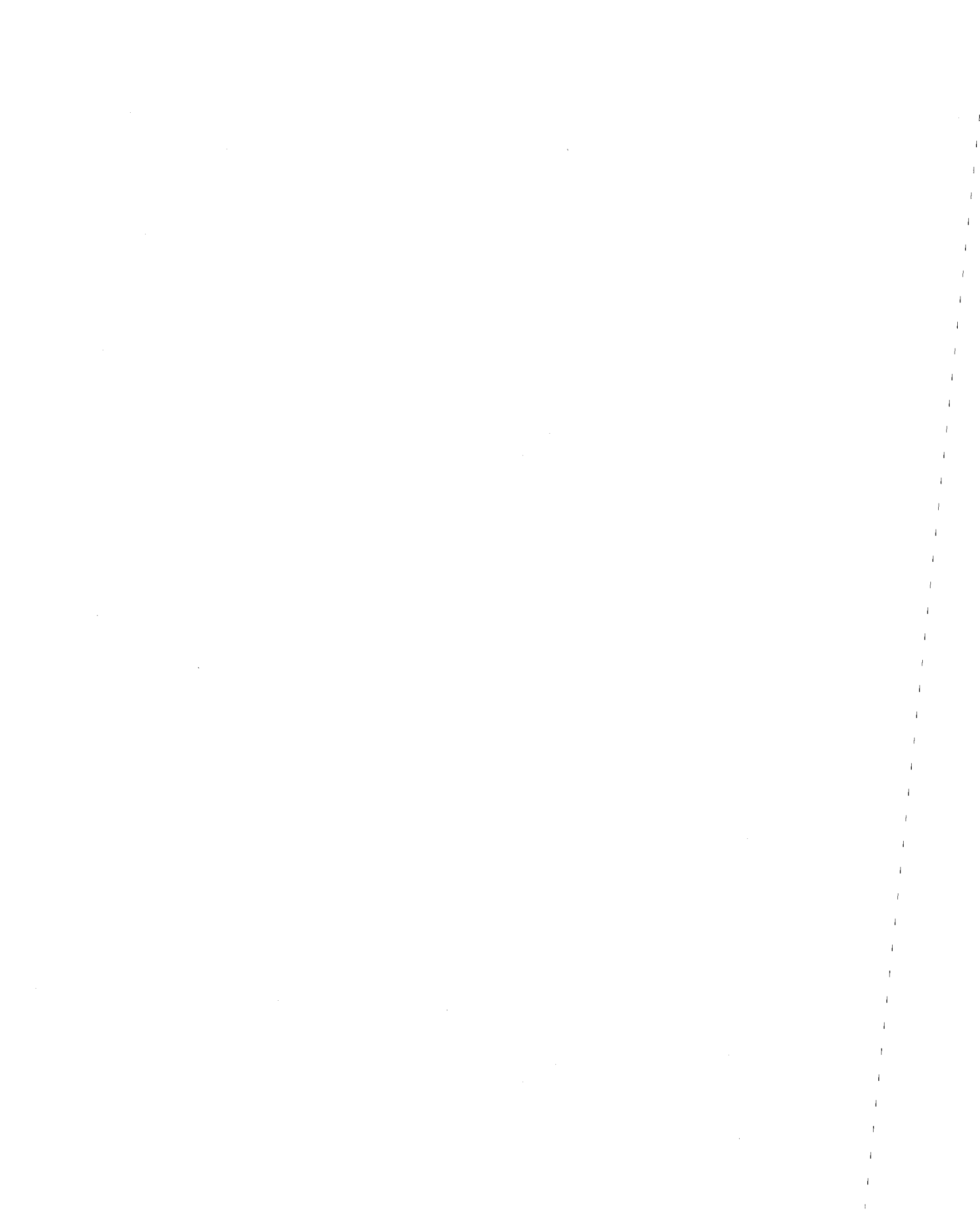
One approach to modify the electrochemistry of aluminum is to alloy the metal with low concentrations of other elements. Much of the development of such alloys has been empirical in nature. Previous studies have found that elements such as mercury, gallium, tin, indium, bismuth, and zinc alloyed with aluminum significantly improved coulombic efficiency. Ternary alloys, such as aluminum-zinc-mercury, aluminum-zinc-indium, and aluminum-zinc-tin, were particularly attractive. In this study, several key alloys were obtained and tested in combination with an available medical hydrogel as a conductive adhesive. Pure zinc was also tested as a sacrificial anode in combination with the hydrogel adhesive.

The ionically conductive adhesives used in this study were coagulated colloids known as hydrogels. These hydrogels are a type of polyelectrolyte generally based on acrylic-sulfonamide copolymers. Since hydrogels are hydrophilic, they retain absorbed water and remain conductive even in relatively low-humidity environments. Several variations of hydrogel adhesives are available for medical purposes, and these were tested for their ability to function together with sacrificial anodes. Also, the chemistry of the hydrogel adhesives was modified in a development program to provide improved properties for best performance of galvanic CP systems.

After having identified the best anode from the laboratory study of sacrificial metals and alloys and the best conductive adhesive from the study and development of hydrogels, the best anode/hydrogel combination was then subjected to further testing on reinforced concrete test slabs.

Finally, the anode/hydrogel combination system showing the most promise was installed on pilings, caps, and beams of a field structure in Ft. Pierce, Florida. Additional field trials on the Long Key Bridge in the Florida Keys and other structures are planned.

This Interim Report describes the results of the technology review, laboratory screening tests, test yard results, and the initial field trial installation. A description of the other planned field trial installations, together with 3-year monitoring results, will be included in a Final Report to be issued at a later date.



## CHAPTER 2. TECHNOLOGY REVIEW

### IMPRESSED CURRENT CATHODIC PROTECTION

Impressed current cathodic protection (ICCP) has been demonstrated to effectively mitigate the corrosion of reinforcing steel in chloride-contaminated concrete. This has been verified in both laboratory tests and studies conducted on field structures.<sup>(6-10)</sup> As noted in the Introduction, a recent survey determined that of the 300 ICCP systems installed on bridge structures in this country, about 80 percent were functional.<sup>(5)</sup> Most of the problems encountered were related to the rectifier used to impress current and the lack of a program for proper servicing and maintenance of the installed ICCP system.

ICCP was first put into practice by the California Department of Transportation on the Sly Park Road Bridge in June 1973.<sup>(7)</sup> This first system used a conductive coke-asphalt overlay as the cathodic protection anode. Since those early days, ICCP has evolved through several generations of systems. Each generation improved the functionality and reliability of protection, or provided a system uniquely suited for a particular structure or environment. Slotted CP systems were developed and are still used for structures with load limitations or lack of head room. Catalyzed titanium mesh anodes with concrete encapsulation were developed next, and these remain the most commonly used anodes for protection of bridge decks. Conductive paints and mastics were used as surface-applied anodes on non-traffic-bearing areas. Other types of inert anode systems investigated included conductive portland cement concrete, conductive polyethylene wire, conductive ceramics, and conductive rubber. Each of these anode types is intended to be inert, in which case the electrochemical reaction that occurs at the anode surface does not involve the anode as a reactant.

Zinc has recently been developed as an anode for use on highway substructures. Although zinc is traditionally used as a galvanic anode, the majority of its use as an anode on concrete structures has been in impressed CP systems, where a power supply was used to provide driving voltage. Zinc anodes were first studied for use on concrete structures in the early 1980's by California Department of Transportation (Caltrans) researchers. The results of their study of 15 different painted and metallized coatings indicated that flame-sprayed zinc offered the best combination of cost-effectiveness, performance, and coating consumption rate. The process of zinc metallizing was first applied to concrete in the field on a pier of the Richmond-San Raphael Bridge located in San Francisco Bay.<sup>(14)</sup> A recent survey<sup>(15)</sup> has identified 22 systems in 7 States and 2 countries using the metallized zinc anode on more than 500,000 ft<sup>2</sup> (46,000 m<sup>2</sup>) of concrete surface. In the majority of these installations, zinc is used as the anode in an ICCP system with an external power supply. The largest of these installations are on historic bridges along the Oregon coast, where metallized zinc has been applied to three bridges totaling 393,000 ft<sup>2</sup> (33,700 m<sup>2</sup>) of concrete surface area.

Metallized zinc has been very satisfactory as an anode in ICCP systems on concrete, and all of these systems are reported to be working as intended. A major disadvantage of the zinc anode is that it is not inert and it is slowly consumed, both as a result of the intended reaction and

undesired self-corrosion. Since the metallized zinc anode can only be applied up to about 20 mils (0.5 mm) thick, the expected life of these systems is limited to about 10 to 15 years. This anode life cycle can result in a significant addition to the life-cycle cost of the CP system, particularly on structures where substructure access is difficult.

Other disadvantages of the metallized zinc anode include safety and environmental concerns related to zinc fumes and dust. If personnel are exposed to the zinc fumes, a sickness known as "zinc fume fever" can result. The zinc dust is also toxic to aquatic life. These concerns have prompted agencies to construct enclosures for the zinc metallizing operations. Waste materials are collected for disposal and air-fed respirators are provided for workers within the enclosures. These precautions have led to increased costs, and zinc containment has become the most expensive component of the installation. The metallizing process itself remains a complex procedure requiring highly skilled operators. Other problems associated with the use of a zinc anode in an ICCP system include electrical shorting to the steel and bond strength of sprayed zinc to the concrete substrate.

## GALVANIC CURRENT CATHODIC PROTECTION

Since zinc, aluminum, and magnesium have very negative natural electrode potentials,<sup>(16)</sup> these metals may be used as sacrificial anodes in galvanic current cathodic protection. In this case, the difference in potential between the anode and the reinforcing steel is used to create a battery effect, and protective current will flow when the anode and steel are electrically connected. The anode will oxidize and the steel potential will be driven more cathodic, toward that of the anode.

Metallized zinc has been used galvanically (without the installation of an external power supply) on eight structures in Florida, totaling about 160,000 ft<sup>2</sup> (14,800 m<sup>2</sup>) of concrete surface area. Most of these systems were installed by the Florida Department of Transportation (DOT) by removing the delaminated and loose concrete, cleaning the steel, and metallizing the zinc anode directly over the exposed rebar and surrounding concrete.<sup>(17,18)</sup> No effort was made to replace the failed concrete. This type of installation provides simplicity and a good electrical connection to the reinforcement, but can only be used where there is no structural or esthetic need to restore the original concrete surface. This type of system was investigated in detail in a joint study by the Florida DOT and the University of South Florida.<sup>(19)</sup> The results supported the use of a metallized galvanic anode for such locations as the splash and tidal zone of marine bridge substructures, where high relative humidities and periodic wetting of the surface were prevalent. But the results also demonstrate that the metallized zinc anode was not capable of maintaining an adequate flow of galvanic current without periodic wetting of the surface. Experience with other systems has also shown that the metallized zinc anode, unless periodically wetted, is not capable of maintaining an adequate galvanic current for protection of steel in concrete. The importance of surface wetting is not fully understood for these systems, but it is most likely related to the contact resistance between the anode and concrete.

In addition to the inability of galvanic systems to deliver adequate current without surface wetting, metallized zinc anodes used galvanically also have the same safety, environmental, and cost concerns as discussed above for impressed current systems using metallized zinc anodes.

The Florida DOT has also used perforated zinc sheet anodes that were applied to the surface of square concrete pilings in the splash and tidal zone.<sup>(20)</sup> The anodes were held in place by a wood-plastic composite support, which also helped to retain water. Interim results indicated that the steel within the pilings was being adequately protected from corrosion, and that the predicted lifetime of the anodes was between 5 and 15 years. Again, periodic wetting was found to be necessary to maintain an adequate flow of CP current. It is unlikely that such a system would function satisfactorily outside of the seawater splash and tidal zone.

Aluminum sacrificial anodes have been used as part of a galvanic CP system applied to pilings in Lake Maracaibo, Venezuela.<sup>(21)</sup> The anodes were fastened to concrete pilings and then embedded in porous mortar containing chloride. Results indicated that the system was protecting the reinforcement after 3 years without cracking of the mortar overlay.

The use of sacrificial anodes for cathodic protection of a bridge deck was first investigated as part of a National Cooperative Highway Research Program (NCHRP)-sponsored research program.<sup>(22)</sup> Small-scale testing indicated that both zinc and magnesium were promising materials for use as sacrificial anodes in galvanic CP systems. A follow-up study to this research was conducted on a bridge deck in Bloomington, Illinois.<sup>(23)</sup> Two different anode configurations were used: (1) a perforated zinc sheet, and (2) zinc alloy ribbons embedded in grooves cut into the concrete surface. Both of these configurations were found to adequately protect the steel from corrosion. Galvanic current supplied by the zinc sheet anodes varied from more than 3.0 mA/ft<sup>2</sup> (32 mA/m<sup>2</sup>) of rebar surface during the summer months to about 1.0 mA/ft<sup>2</sup> (10.8 mA/m<sup>2</sup>) in the spring and fall. Current was measured at 1.5 mA/ft<sup>2</sup> (16.8 mA/m<sup>2</sup>) after 12 years of operation.

## OTHER STUDIES IN PROGRESS

The FHWA is presently funding three studies to investigate the use of sacrificial anodes for use on reinforced concrete bridge members. A contractor is investigating improvements to metallized anodes that may enhance their ability to function in a galvanic mode. Efforts have focused on the development of an alloy composition that will maintain a high operating potential over a longer period of time without periodic wetting. A field demonstration of an improved alloy is planned.

A contract has also been awarded to develop and demonstrate the use of sacrificial anodes for cathodic protection of reinforced concrete bridge decks, and an Interim Report has been issued.<sup>(24)</sup> In this study, both zinc and aluminum anodes were found to deliver adequate CP current when embedded in free-draining concrete overlays, but potential durability problems and high anode consumption rates preclude the use of these overlays until additional development can be carried out. Aluminum anodes also showed good current delivery when embedded in

normal-weight or lightweight concrete, and a field trial of this system on a bridge deck has been recommended.

Zinc/hydrogel CP systems have also been installed on four condominium balconies in Florida in the fall of 1994. These trials were privately funded by a major company. The performance of these trials is reported to be favorable after 1 year of operation.

## SUMMARY

Both impressed current cathodic protection (ICCP) and galvanic cathodic protection systems have been shown to prevent the corrosion of steel in concrete. ICCP systems have been broadly used, having been installed on more than 300 bridge structures in the United States. Although ICCP systems have been generally successful, some failures have occurred as a result of system complexity and the lack of regular servicing and maintenance. Galvanic CP systems are simpler and have the potential to operate with little or no maintenance for the life of the system, but galvanic systems have been used relatively little. Application of galvanic systems have so far been limited to the seawater splash and tidal zone where concrete is moist and conductive, and where the anode surface is periodically wetted.

Most of the galvanic systems installed to date consist of a metallized zinc anode that is sprayed directly onto the concrete surface. This type of anode requires periodic wetting of the anode surface to maintain adequate current when used galvanically. Other concerns include safety, environment, and cost. A need exists for a simpler and more acceptable means of application of sacrificial metals to concrete structures, but little work has been done.



## CHAPTER 3. LABORATORY SCREENING OF ANODES AND ADHESIVES

### SCREENING OF ANODES

#### Background

A galvanic (also known as a sacrificial) anode may be described as a metal that operates at a very electronegative potential with respect to corroding steel, and will therefore discharge current through the electrolyte (in this case, concrete) to the steel. In order to perform this function, the anode material must meet the following general requirements:<sup>(25)</sup>

1. The potential difference between the anode and the corroding steel must be large enough to overcome the anode-cathode cells on the corroding structure. In the case of a concrete electrolyte, which is very resistive, the potential difference must also be large enough to overcome the resistive component of the electrolyte (IR-drop). It is therefore important that the working potential of the anode be, and remain, as negative as possible.
2. The anode must have sufficient electrical energy to permit reasonably long life with a practical consumption of anode material.
3. The anode must operate with good efficiency, that is, a high percentage of the energy content of the anode must be available for useful cathodic protection current output. The balance of the energy that is consumed in self-corrosion of the anode itself should be very small.

Three anode materials—zinc, aluminum, and magnesium (and alloys of these)—are usually considered candidates for sacrificial anodes. Of these three, we did not consider magnesium to be a viable candidate. Although magnesium has the highest theoretical working potential of the three (-1.6 V versus copper sulfate electrode), it also suffers from a high rate of self-corrosion, particularly at low current density. Also, the cost of magnesium is usually high.

Zinc is a common choice as a material for sacrificial anodes. It has a good current efficiency and relatively low cost. Small amounts of aluminum and cadmium are sometimes added to prevent the zinc from becoming “passive” and ceasing to discharge useful amounts of protective current. Because of the relative success of metallized zinc anodes on concrete, pure zinc was considered the standard against which other anode materials were judged.

Most of the work done on anode materials was conducted on aluminum alloys. As noted in the Introduction, aluminum alloys have the potential to be 30 percent thinner, 74 percent lighter, and 65 percent less expensive than zinc. This is largely due to its very high energy efficiency, about 1285 A-hr/lb (2830 A-hr/kg), and a relatively high working potential, about -1.10 V versus copper sulfate electrode (CSE). In order to maintain that working potential, aluminum must usually be alloyed with small amounts of other elements in order to prevent the

anode from becoming passive. Aluminum alloy anodes have recently been developed for use in high energy and high power density aluminum-air batteries. This application is similar to cathodic protection of steel in concrete because of the requirement of maintaining a very negative working potential in a high-pH environment. Most of the aluminum alloys tested in this contract were developed for use as anodes in aluminum-air batteries. Those tested include:

Table 2. Aluminum Alloys Tested as Anode Materials.

1.	99.999% pure aluminum
2.	aluminum + 0.1% indium, 0.05% gallium
3.	aluminum + 0.5% magnesium, 0.07% tin
4.	aluminum + 0.04% indium, 0.07% tin
5.	aluminum + 0.5% calcium, 0.07% tin
6.	aluminum + 0.07% gallium, 0.025% indium, 0.015% tin
7.	aluminum + 0.5% magnesium, 0.04% gallium, 0.015% indium, 0.006% tin
8.	aluminum + 0.1% magnesium, 0.1% manganese, 0.1% indium (heat treated)
9.	aluminum + 0.1% magnesium, 0.1% manganese, 0.1% indium (cold pressed)

Test Procedure

It was first necessary to develop a test cell and a test procedure to analyze alloys for this application. Since the performance of the alloy was dependent on its environment, it was decided to test the anode directly in contact with the hydrogel adhesive. The configuration of the test cell is shown in figure 1.

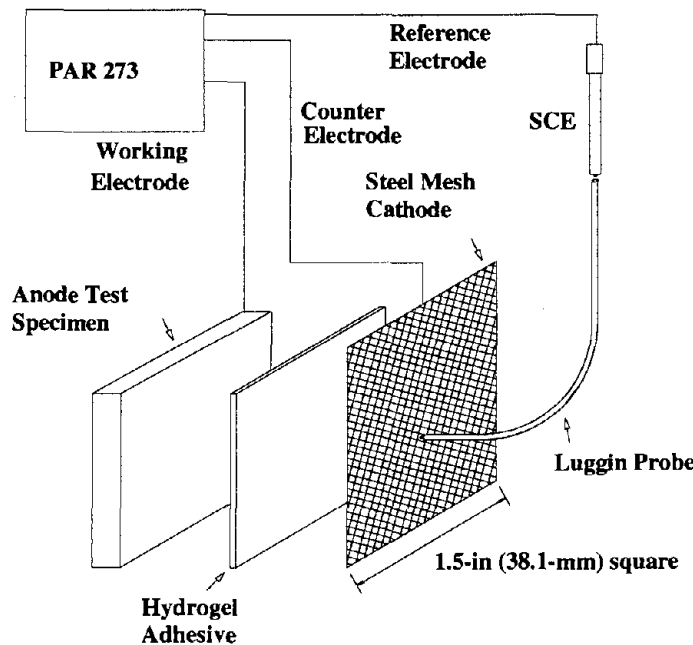


Figure 1. Cell for the testing of anode materials.

The anode test specimen was laminated to hydrogel adhesive, which was in turn placed in contact with a steel mesh cathode. A Luggin probe placed between the strands of mesh allowed the working potential of the anode to be measured versus a stable reference electrode. The working, counter, and reference electrodes were connected to a Princeton Applied Research Model 273 potentiostat.

It was essential that the test procedure reveal the working potential of the test specimen and its ability to pass current through the hydrogel without passivation. After investigating several possible techniques, a current-step chronopotentiometry method was found to be appropriate and reproducible. In this procedure, a constant anodic current was imposed on the anode specimen for 20 minutes, and working potentials were periodically recorded. After 20 minutes, the current was increased and working potentials were again recorded. The constant current steps were varied from 0.01 to 100 mA/ft<sup>2</sup> (0.1 to 1000 mA/m<sup>2</sup>) for each anode evaluation. A complete test required about 12 hours to complete. In cases where passivation was occurring, a steady-state working potential was not reached in the 20 minutes allotted, and equilibrium was not achieved. All anode specimens were first tested in contact with Promeon RG-63B hydrogel. Even though improved hydrogel formulations were being developed throughout this phase of the contract, it was considered important to have a standard adhesive in order to determine the relative performance of various anode specimens.

#### Testing of Anode Candidates

The polarization data for pure zinc are shown in figure 2. Zinc in contact with hydrogel adhesive had a working potential at very low current densities of -1.08 V versus a saturated calomel reference electrode (SCE). This agrees favorably with published data (see table 1). The working potential was also stable, and the anode showed no tendency to passivate. As the current steps were slowly increased, the zinc anode polarized only slightly. At a current density of 1.0 mA/ft<sup>2</sup> (10 mA/m<sup>2</sup>), a practical current density for an anode in the field, the working potential was still -1.07 V vs. SCE. Even at 100 mA/ft<sup>2</sup> (1000 mA/m<sup>2</sup>), a current density far in excess of that experienced on actual structures, the zinc anode had polarized to only -0.92 V vs. SCE. At all levels of current tested, the working potential of the zinc anode was stable and showed no tendency to passivate.

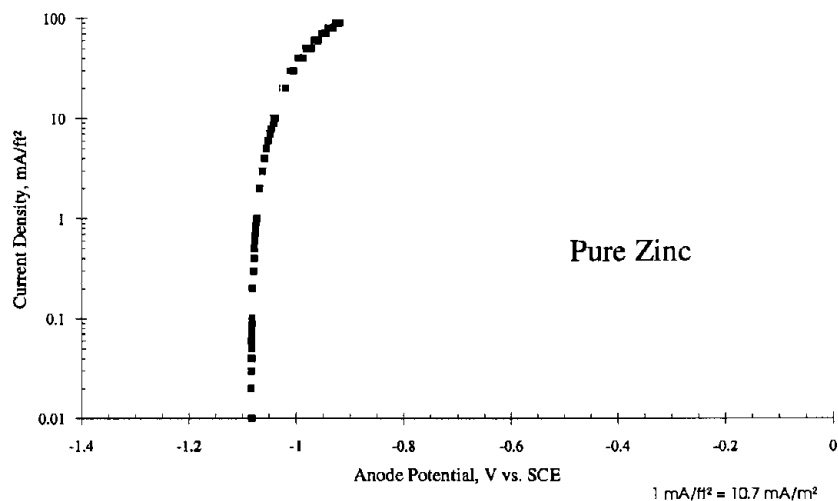


Figure 2. Polarization data for pure zinc/RG-63B hydrogel composite.

The polarization data for 99.999 percent pure aluminum are shown in figure 3. In this case, aluminum in contact with hydrogel adhesive did not possess a desirable potential at very low current. Anode potential was only -0.80 V at 0.01 mA/ft<sup>2</sup> (0.1 mA/m<sup>2</sup>). This does not compare favorably with the published value of working potential for aluminum anodes (see table 1). Anode working potential at low current density appeared stable, even though not very electronegative. As current was increased during the test, the working potential of the anode became unstable, indicating a tendency to passivate. This can be seen in figure 3 by the broad range of potentials recorded at a given current density. By the time the practical current density of 1.0 mA/ft<sup>2</sup> (10 mA/m<sup>2</sup>) had been reached, the anode potential was ranging freely from -0.52 to -0.72 V vs. SCE. The anode potential appeared to remain stable for up to 2 hours, but would then exhibit erratic passive behavior. Pure aluminum is clearly an unacceptable candidate as an anode in contact with hydrogel adhesive.

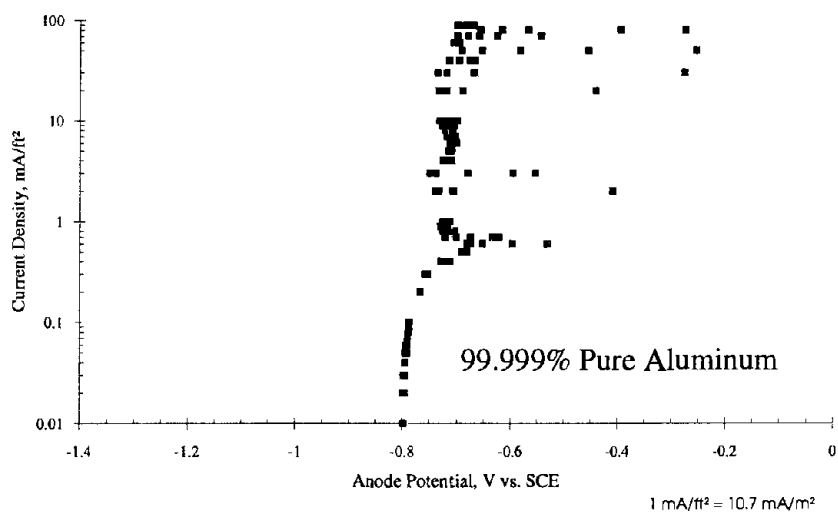


Figure 3. Polarization data for pure aluminum/RG-63B hydrogel composite.

Other aluminum alloys tested showed different behavior, depending on the alloying elements and the fabrication practice used. Two examples are shown in figures 4 and 5, while the polarization behavior of other aluminum alloys tested are shown in the Appendix.

The polarization data for an aluminum alloy containing 0.1 percent indium and 0.05 percent gallium are shown in figure 4. The working potential of the anode is very favorable, about -1.20 V vs. SCE at low current densities. The very negative potential of this anode would result in a maximum amount of delivery of protective current. But the anode potential is also unstable, varying as much as 200 mV during the 20-minute current step. This instability is likely to become even more pronounced over longer periods of time. This is characteristic of passive behavior, and this alloy is therefore regarded as unsuitable for this application.

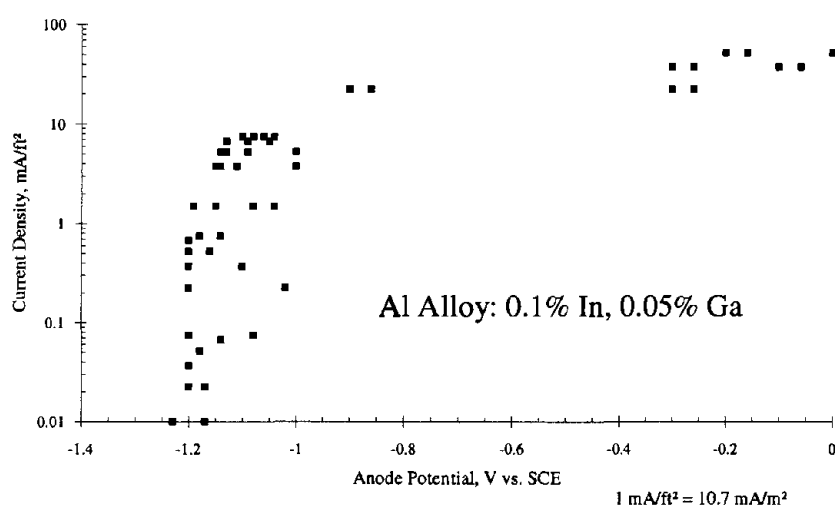


Figure 4. Polarization data for 0.1 percent indium, 0.05 percent gallium-aluminum alloy/RG-63B hydrogel composite.

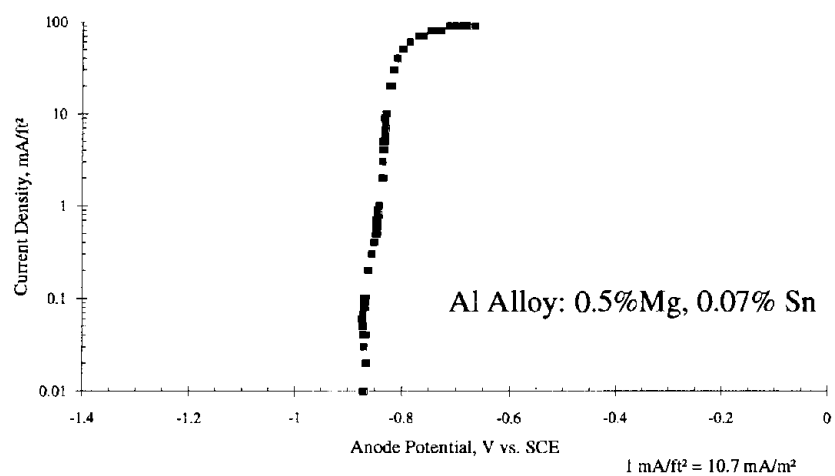


Figure 5. Polarization data for 0.5 percent magnesium, 0.07 percent tin-aluminum alloy/RG-63B hydrogel composite.

Figure 5 shows polarization data for an aluminum alloy that exhibits no tendency to passivate when used as an anode in contact with hydrogel adhesive. Anode working potentials remained stable at all levels of current tested. Unfortunately, anode potentials were not favorable, beginning at -0.87 V at low current and diminishing to -0.82 V at a current density of 1.0 mA/ft<sup>2</sup> (10 mA/m<sup>2</sup>). This alloy was also determined to be unacceptable for this application.

In order to deliver adequate protective current, it was considered necessary that the anode maintain a stable working potential more negative than -1.0 V at a current density of 1.0 mA/ft<sup>2</sup> (10 mA/m<sup>2</sup>). Neither pure aluminum nor any of the aluminum alloys tested met this goal when operated as an anode in contact with hydrogel adhesive. The alloys either failed to demonstrate adequate working potential or exhibited unpredictable passive behavior. Following this work, it was concluded that the best anode material for use in contact with hydrogel adhesive was pure zinc.

## SCREENING OF HYDROGEL ADHESIVES

### Background

The hydrogel adhesives used in this study were coagulated colloids based on acrylic-sulfonamide copolymers. Since these hydrogels are hydrophilic, they retain absorbed water and remain ionically conductive, even in low-humidity environments. Hydrogel adhesives are presently used to adhere electrodes to skin for a variety of medical applications, including patient monitoring, transcutaneous nerve and muscle stimulation, and electrocautery grounding. They are compliant, mechanically strong, and have a very aggressive tack. The resistivity of hydrogel adhesives are typically in the range of 1000 to 4000 ohm-cm, about the same as chloride contaminated concrete. List prices for medical applications are about \$2.00/ft<sup>2</sup> (\$20/m<sup>2</sup>) in large quantity. The vast majority of hydrogel is sold for medical applications by Promeon, a Division of Medtronic, Inc. in Minneapolis, Minnesota. 3M Company is also a supplier to this market with its own hydrogel adhesives. The properties of the medical hydrogels available from Promeon are given in table 3.

Table 3. Properties of Promeon RG-60 Series Hydrogels.

	<i>RG-62D</i>	<i>RG-62X</i>	<i>RG-63L</i>	<i>RG-63B</i>	<i>RG-63G</i>	<i>RG-63X</i>
<b>Primary Application</b>	Stimulating, Disposable	Stimulating, Reusable	Sensing, Disposable	Sensing, Disposable	Sensing, Reusable	Sensing, Reusable
<b>Resistivity, (ohm-cm)</b>	2500 max.	2500 max.	1500 max.	1500 max.	1500 max.	1500 max.
<b>Adhesive Tack</b>	Moderate	Strong	Weak	Moderate	Moderate	Strong
<b>Dryout Resistance</b>	High	Low	High	High	Moderate	Low

Hydrogels had been briefly explored for the purpose of applying anodes to concrete for cathodic protection. In the late 1980's, Raychem Corporation introduced the concept of a flat, carbon-loaded polyethylene wire, which was fastened to the concrete with hydrogel. One field

trial was installed on a pier of the Oregon Inlet Bridge at Cape Hatteras, North Carolina. This trial was regarded as unsuccessful. Hydrogels also became of interest to ELTECH Research Corporation in the 1980's as a possible means of adhering inert anodes to a concrete surface. At that time, research was limited to catalyzed titanium anodes. For the cases of both carbon-based and titanium-based anodes, the long-term stability of the hydrogel adhesive was not satisfactory since the hydrogel formulations do not tolerate the reaction products of an inert anode—namely, acid, chlorine, and oxygen gas. It was learned in 1990 that the reaction products of a sacrificial zinc anode were compatible with the hydrogel adhesives.

### Test Procedure

Two types of tests were conducted for the purpose of screening hydrogel adhesives: a galvanic test and an accelerated impressed current test. The specimens for both of these tests were constructed in the same way. The design used for the accelerated impressed current test is shown in figure 6. Concrete blocks were prepared 10 in long x 3 in wide x 5 in deep (25.4 cm x 7.6 cm x 12.7 cm). The blocks contained two bars of #4 (1.27 cm dia.) reinforcing steel. Concrete was cast in two layers, with the top layer containing 6 lb/yd<sup>3</sup> [3.5 kg/m<sup>3</sup>] (0.16 percent by weight of concrete) of admixed chloride ion, and the bottom layer containing no chloride addition. The chloride-contaminated layer surrounded the top bar of reinforcement. The sides of the blocks were coated with a non-conductive urethane sealant to prevent transport of moisture laterally. The zinc/hydrogel composite was typically placed on the top face of the concrete, which was prepared by light sandblasting. The perimeter of the composite was sealed with urethane caulking to prevent the hydrogel from exchanging water with the atmosphere.

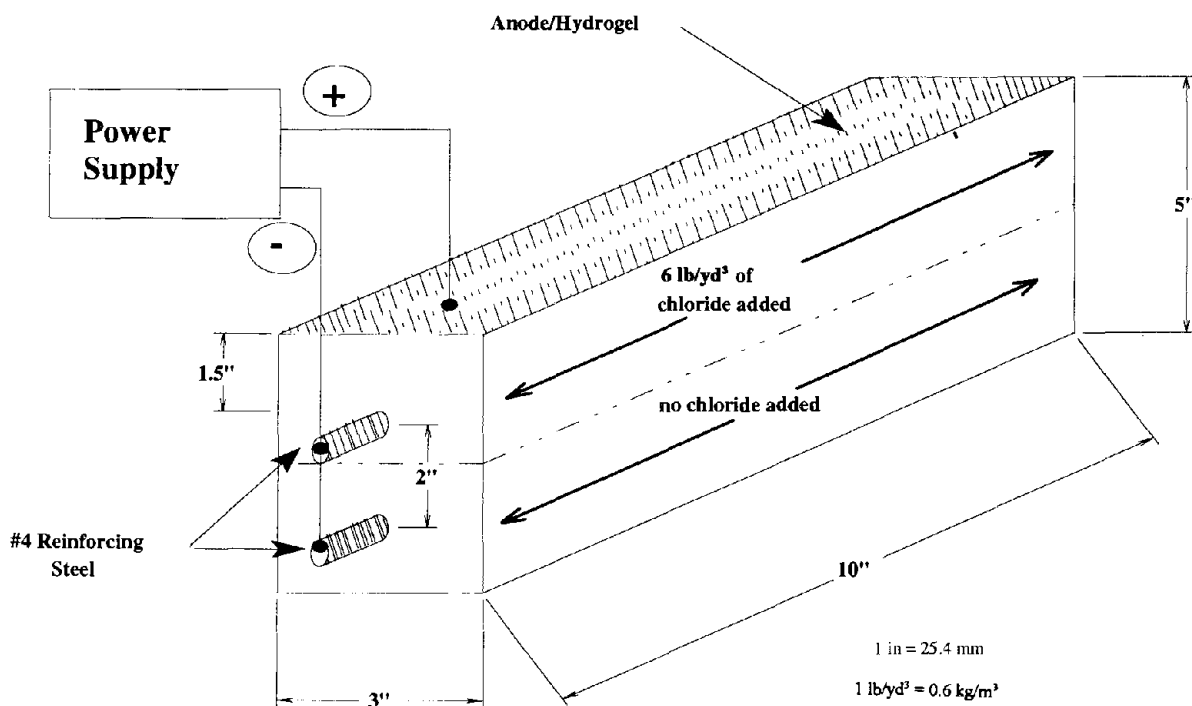


Figure 6. Specimen used for accelerated testing of hydrogel adhesives.

The concrete used for these specimens conformed to the Ohio Department of Transportation (DOT) specifications for Class C concrete. This is typical of concrete used for bridge construction in Ohio. The specifications for this concrete have the concrete mixture properties and proportions shown in table 4.

Table 4. Proportions and Mixture Properties for Ohio DOT Class C Concrete.

<u>Concrete Constituent</u>	<u>lb/yd<sup>3</sup></u>	<u>kg/m<sup>3</sup></u>
Type I LA Portland Cement	612	363
Fine Aggregate	1310	777
Coarse Aggregate	1662	986
Water	306	182
Air-Entraining Admixture	1 oz/100 lb	0.65 mL/kg
Slump = 2-1/4 in (5.5 cm)		
Air Content = 6.0%		
Water-Cement Ratio = 0.50		
Theoretical Unit Weight = 144.1 lb/ft <sup>3</sup> (2308 kg/m <sup>3</sup> )		

A power supply was connected to the specimen for accelerated testing as shown in figure 6. The negative terminal of the power supply was connected to both bars of reinforcing steel, and the positive terminal was connected to the zinc anode. A constant current of 3.125 mA, equal to a current density of 15 mA/ft<sup>2</sup> (160 mA/m<sup>2</sup>) of concrete surface, was impressed on the specimen. This accelerated the amount of charge received by the specimen by a factor of about 15 over normal field service. In this way, a total charge equivalent to 10 years of normal service could be impressed on the specimen in about 8 months. Power supply voltage was monitored periodically, and was used as a criterion for failure of the specimen. Power supply voltage at first was typically low, less than 2 V, but increased rapidly near the end of the test. Tests were continued until cell voltage reached 50 V, but hydrogel was regarded as failed at a cell voltage in excess of about 10 V.

The specimens used for the galvanic tests were identical in construction to those used for accelerated testing, but no power supply was used. Instead, the reinforcing bars were connected directly to the zinc through a 10-ohm resistor, and current was monitored by measuring the voltage drop across the resistor. A surge of current was typically observed at first, with current slowly decreasing throughout the test. Since this test was not accelerated, failure was usually not identified over the duration of the test, but differences in hydrogel performance were often apparent. A higher delivery of current over a longer period of time was desirable.

Specimens for both accelerated and galvanic tests were placed in a chamber maintained at a relative humidity of 80 to 85 percent throughout the test.



Following completion of the tests, specimens were dismantled for observation and autopsy. Visual observations were recorded and, in some cases, the hydrogel was returned to the supplier for failure analysis.

### Testing of Hydrogel Adhesives

The only hydrogel adhesives available for testing early in the contract were those listed in table 3. These were adhesives developed for medical applications. As hydrogel adhesives were received, they were tested for pH and resistivity. The results of those tests for the medical adhesives are given in table 5.

Table 5. pH and Resistivity of Medical Hydrogel Adhesives.

<u>Hydrogel Adhesive</u>	<u>pH</u>	<u>Resistivity, ohm-cm</u>
RG-63B	4.2	6800
RG-63L	3.8	840
RG-63X	3.0	1000
RG-42	7.8	1400
MSX-1160	5.4	2200
3M Red Dot	5.3	1050

These adhesives were tested by both the galvanic method and the accelerated impressed current method described above. Inadequate contact between the zinc/hydrogel composite and the base concrete was at first a problem. This problem was caused by the very uneven surface of the concrete specimens and by the various thicknesses of the hydrogels. As the contract progressed, better contact was achieved between the hydrogel and concrete. This improvement accounts, in part, for the performance differences seen in table 6, which shows the results of accelerated testing of the medical hydrogels.

Table 6. Accelerated Testing of Medical Hydrogel Adhesives.

<u>Hydrogel Adhesive</u>	<u>Life, days</u>	<u>Life, A-hr/ft<sup>2</sup></u>	<u>Comments</u>
RG-63B	35	12.6	poor contact, blue color after testing
RG-63B	90	32.4	blue color after testing
RG-63B	117	42.1	
RG-63L	29	10.4	poor contact
RG-63L	139	50.0	good contact, gel dry after test
RG-63X	18	6.5	poor contact, gel white after test
RG-42	10	3.6	poor contact
RG-42	153	55.1	
MSX-1160	18	6.5	
3M Red Dot	53	19.1	
3M Red Dot	45	16.2	very thick sample

$$1 \text{ A-hr/ft}^2 = 10.7 \text{ A-hr/m}^2$$

Cell voltage was monitored during the accelerated test at a current density of 15 mA/ft<sup>2</sup> (160.5 mA/m<sup>2</sup>), and voltage was plotted versus equivalent life for a system operated at 1.0 mA/ft<sup>2</sup> (10.7 mA/m<sup>2</sup>). A graph of the data for a few representative samples of medical hydrogels is shown in figure 7. This is a useful depiction since it shows the expected lifetime of the hydrogel in field application.

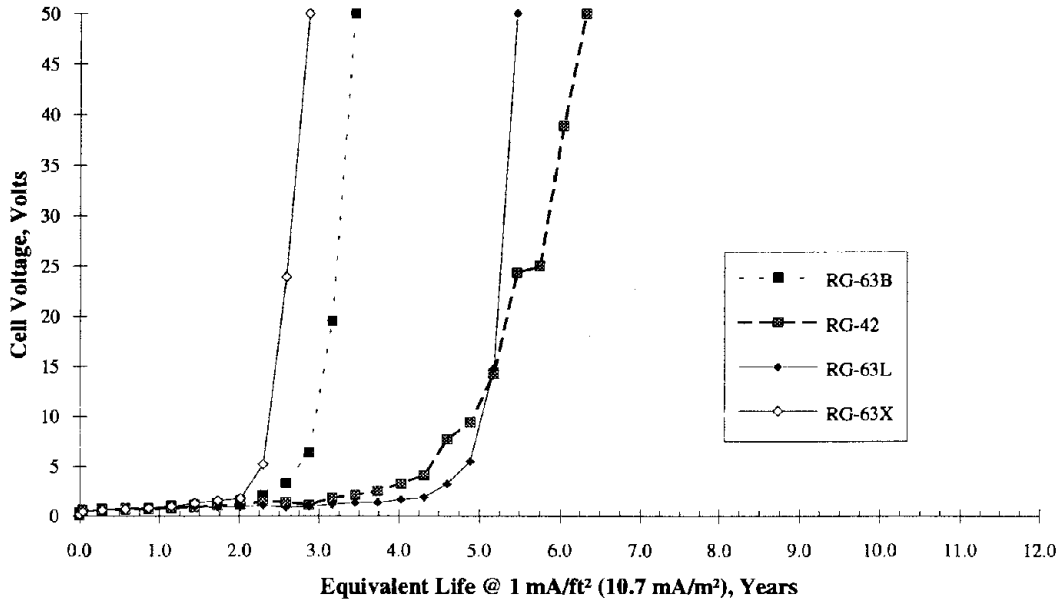


Figure 7. Cell voltage versus equivalent life for medical hydrogel adhesives.

The goal for the life of the hydrogel was set at 87.6 A-hr/ft<sup>2</sup> (943 A-hr/m<sup>2</sup>), which represents the total charge of a CP system operating at 1.0 mA/ft<sup>2</sup> (10.7 mA/m<sup>2</sup>) for a period of 10 years. To achieve this charge would take an operating period of 243 days in the accelerated test. As seen by the data presented in table 6, the best medical hydrogel RG-42 was able to achieve only slightly more than 60 percent of this goal. It was clear that the hydrogel adhesives developed for medical applications were not adequate for use in cathodic protection systems.

During this contract, 3M Company became interested in the market potential of hydrogel adhesives for the application of cathodic protection to concrete structures, and began a development program to improve adhesives for this use. The pH and resistivity values for the hydrogels developed under this program are given in table 7, and the performance of these hydrogels is given in table 8.

Table 7. pH and Resistivity of Hydrogel Adhesives Developed for CP.

<u>Hydrogel Adhesive</u>	<u>pH</u>	<u>Resistivity, ohm-cm</u>
9102	3.7	277 x 10 <sup>3</sup>
9103	3.5	238 x 10 <sup>3</sup>
9104	2.0	386 x 10 <sup>3</sup>
2993-1	2.8	4698 x 10 <sup>3</sup>
2993-2	3.0	584 x 10 <sup>3</sup>
2993-3	2.8	23,435 x 10 <sup>3</sup>
2993-4	3.0	36,100 x 10 <sup>3</sup>
3M-1	4.1	720
3M-2	11.0	630
3M-3	10.3	400

Table 8. Accelerated Testing of Hydrogel Adhesives Developed for CP.

<u>Hydrogel Adhesive</u>	<u>Life, days</u>	<u>Life, A-hr/ft<sup>2</sup></u>	<u>Comments</u>
9102	7	2.5	high resistance
9103	7	2.5	high resistance
9104	2	0.7	high resistance
3M-1	111	40.0	
3M-2	181	65.2	
3M-3	294	105.8	life goal achieved

$$1 \text{ A-hr/ft}^2 = 10.7 \text{ A-hr/m}^2$$

During these tests, it became apparent that a low pH was detrimental to the lifetime of the hydrogel adhesive. A hydrogel with low pH developed bubbles, both at the zinc/hydrogel interface and at the concrete/hydrogel interface, which tended to increase resistance and decrease the amount of area free to take part in the galvanic reaction. The hydrogel known as 3M-3 was the first adhesive to achieve the necessary lifetime in accelerated life testing. The total charge of 105.8 A-hr/ft<sup>2</sup> (1137 A-hr/m<sup>2</sup>) achieved by 3M-3 is equivalent to a life of 12 years at a current density of 1.0 mA/ft<sup>2</sup> (10.7 mA/m<sup>2</sup>). Hydrogel 3M-3 also retained excellent adhesion throughout the accelerated test.

Cell voltage was monitored during these tests and a graph of voltage versus equivalent life is presented in figure 8.

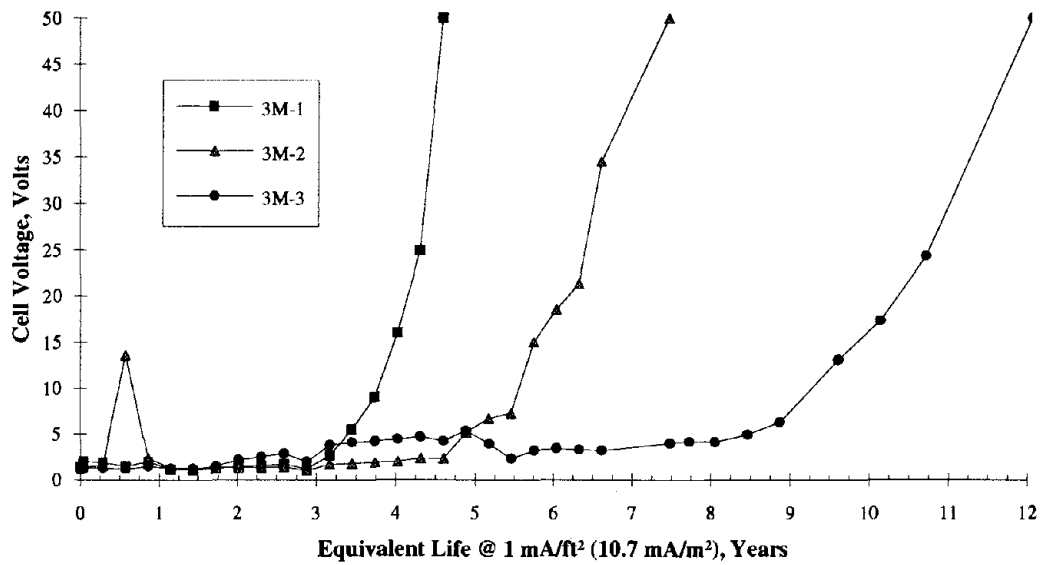


Figure 8. Cell voltage versus equivalent life for CP hydrogel adhesives.

Galvanic tests were also conducted on most of the hydrogel samples described above. In galvanic mode, the zinc/hydrogel composite delivered an initial surge of current, normally from 4 to 8 mA/ft<sup>2</sup> (43 to 86 mA/m<sup>2</sup>). Galvanic current decreased with time and, for all composites tested, current was down to 2 mA/ft<sup>2</sup> (21 mA/m<sup>2</sup>) after about 100 days of operation. Current was monitored during the test, and a graph of current density versus time is shown in figure 9.

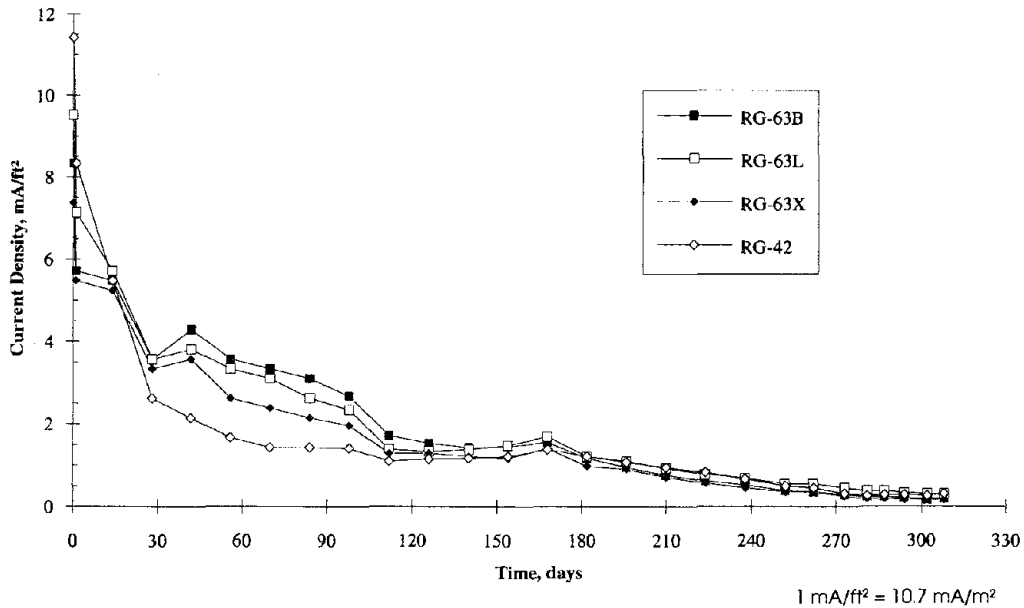


Figure 9. Galvanic current versus time for medical hydrogel adhesives.

Although some differences could be seen between hydrogels in the galvanic test, the test did not appear to be very useful. No practical conclusions could be drawn from the results of this test. The galvanic tests were therefore discontinued, and the hydrogels developed late in the program were not tested galvanically.

## TESTING OF OTHER CONFIGURATIONS

Although most of the testing done in the laboratory phase of this contract was conducted using a simple zinc/hydrogel composite, a few other innovative configurations were investigated in an effort to improve hydrogel lifetime and current delivery.

Despite the apparent problems of aluminum alloys in contact with hydrogel, one long-term galvanic test was conducted with 0.1 percent indium, 0.05 percent gallium-aluminum alloy using RG-63B hydrogel. This alloy demonstrated the most negative anode potential, while showing little tendency to passivate at low current densities (see figure 4). The test started at a current density of  $5.7 \text{ mA/ft}^2$  ( $61.3 \text{ mA/m}^2$ ), similar to that of tests conducted with zinc. But current density dropped rapidly to  $0.5 \text{ mA/ft}^2$  ( $5.4 \text{ mA/m}^2$ ) after only 56 days of operation. The specimen was then removed from operation and dismantled for autopsy. The corrosion products of the aluminum alloy were found to be so voluminous that they pushed the anode away from the concrete and resulted in loss of adhesion. The corrosion products of aluminum do not appear to be compatible with the hydrogel adhesive. No other long-term tests were conducted with aluminum or aluminum alloy anodes.

It was speculated that an increase in surface area of the anode would result in higher current delivery and possibly longer system life. In order to test this theory, zinc was thermally sprayed onto a plastic substrate, then removed by peeling off the zinc. This produced a porous zinc foil with very high surface area. When operated in sacrificial mode together with RG-42 hydrogel, this high surface area zinc foil started at  $5.6 \text{ mA/ft}^2$  ( $60 \text{ mA/m}^2$ ), typical of start-up current recorded for solid zinc foil. But as time progressed, current remained at a higher level than that measured for solid zinc. After 260 days, current density had dropped to only  $2.4 \text{ mA/ft}^2$  ( $26 \text{ mA/m}^2$ ), higher than for any other specimen.

Although the results of the test above using thermally sprayed zinc foil are interesting, the configuration is not practical, since zinc foil prepared by thermal spray is much too expensive. Tests were then conducted using zinc particles embedded in the hydrogel in an effort to achieve a high surface area anode. In the first test, a zinc mesh current distributor was placed on a concrete block fitted with RG-63B hydrogel adhesive. Zinc particles (30 mesh) were then sprinkled over the void in the mesh and pressed into the hydrogel at  $200 \text{ lbf/in}^2$  ( $1379 \text{ kPa}$ ). In another configuration, zinc particles were sprinkled over the hydrogel adhesive, then covered with solid zinc foil. The composite was then compressed at  $500 \text{ lbf/in}^2$  ( $3400 \text{ kPa}$ ) to embed the zinc particles into the hydrogel. Both of these composites failed after 2 to 4 weeks in the accelerated current test. Following the test, an autopsy revealed that the adhesive had become dry, followed by loss of adhesion. No further tests were conducted on high surface area zinc configurations.

Since it was anticipated that a field trial of the zinc/hydrogel CP system would be installed on a marine structure, a test was conducted to evaluate the ability of the hydrogel to tolerate direct contact with seawater. One face of a concrete specimen was fitted with a zinc anode and 3M-3 hydrogel, while a second face of the specimen was fitted with hydrogel alone (without an anode). The specimen was then partially immersed in solution containing 28 gm/L NaCl so that both hydrogel samples were half immersed. The zinc/hydrogel composite was operated sacrificially, and was initially operated at a current density of 10 mA/ft<sup>2</sup> (107 mA/m<sup>2</sup>). After two weeks of operation, the zinc hydrogel was still operating at the same current density, but had lost dimensional stability. The bare hydrogel had completely peeled from the concrete surface, and the hydrogel under the zinc anode was swelling badly. It was concluded that any hydrogel installed on a marine structure must be protected from direct contact with seawater.

## SUMMARY

As a result of this laboratory testing, it was concluded that aluminum alloys were not suitable for use as anodes in contact with hydrogel adhesives. The best anode tested was pure zinc, which was used in field trials. Medical hydrogels were also not suitable as anode adhesives because they have a projected lifetime that is too short for cost-effective CP systems. However, a hydrogel adhesive known as 3M-3, which was developed specifically for use with galvanic CP systems, does have an adequate projected lifetime of 12 years. The hydrogel must be protected from direct exposure to water and seawater during this time.

## CHAPTER 4. INSTALLATION OF FIELD TRIALS

### STRUCTURE SELECTION

Selection of a structure for field trial of the zinc/hydrogel CP system was conducted in late 1994. It was necessary to find a structure that was contaminated with chloride and exhibited corrosion of the reinforcing steel. It was also necessary to find a structure in which the concrete was relatively conductive, such as a marine structure in a tropical or subtropical climate. It was desirable to select a structure that did not need extensive concrete rehabilitation. Other considerations were ease of access and the cooperation of the local department of transportation (DOT).

The Florida DOT was very helpful in identifying two qualified structures. The first was a fishing pier in Ft. Pierce, Florida. Several members of the pier were showing visible signs of corrosion, such as concrete cracking and staining, yet concrete damage was not extensive. The pier was scheduled for rehabilitation in late 1995 or early 1996, which presented the possibility of installing CP on both repaired and unrepaired members. The pier also offered the prospect of installation on three different types of members: precast conventionally reinforced pilings, cast-in-place pile caps, and double-tee precast beams with prestressed steel. One of the most attractive features of the pier in Ft. Pierce was its ease of access. The walkway of the pier was only 10 ft (3 m) above mean high tide, and it was well protected from storms and wave action. It had no vehicle traffic, so traffic control was not an issue. The interest and cooperation of the Florida DOT was another factor that led to the selection of this structure.

The second structure chosen for a field trial was the Long Key Bridge in the Florida Keys. In this case, the zinc/hydrogel composite will be used to cathodically protect precast V-piers that rest on footers about 5 ft (1.5 m) above high tide. The V-piers rest on neoprene bearing pads that are scheduled for replacement in the near future. The bottom of the V-pier measures about 30 in (76 cm) square and contains a double mat of reinforcing steel with several 180-degree bends. The concrete cover in this area is inadequate, particularly for the bent portions of the reinforcement, and the steel is experiencing significant corrosion. The Florida DOT had already decided to place zinc on top of the neoprene bearing pad and use the conductive hydrogel to bond the zinc to the bottom of the V-pier. In this way, the hydrogel adhesive will enhance contact and maximize the flow of protective current. Zinc/hydrogel will be used on two piers showing early deterioration and two piers showing no deterioration. Since this work is being specified and contracted by the Florida DOT, the involvement with this installation will be limited to consultation, monitoring, and reporting.

At the time of this writing, the system at Long Key has not yet been installed, and so will not be discussed further in this report. Installation and energizing of the CP system at Long Key will be described in a final report to be issued at a later date.

## SYSTEM DESIGN

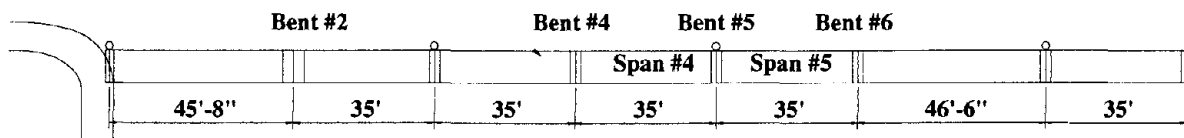
Based on the results of the laboratory phase of this study, it was decided to use the hydrogel adhesive known as 3M-3 for the field trials. The exact composition and processing details for this hydrogel are the proprietary information of the 3M Company. At this time, the maximum width of the hydrogel is about 9 in (23 cm), due to the limited capability of the supplier. The thickness of the hydrogel supplied for the field trials was approximately 30 mil (0.76 mm).

The anode used for the field trials was 99.5 percent pure zinc. A zinc thickness of 10 mil (0.25 mm) was used to ensure a reasonable life for supplying necessary current to the structure. A constant current density of 1 mA/ft<sup>2</sup> (10.7 mA/m<sup>2</sup>) will consume about 1 mil (0.025 mm) of zinc per year. The zinc was ordered in a 9-in (23-cm) width to match the available width of the hydrogel.

Based on the laboratory studies, it was considered necessary to prevent wetting of the hydrogel with either water or seawater. The edges of the zinc/hydrogel composite were therefore sealed with polyurethane caulking compound to prevent ingress of water. Pilings were also sealed by application of custom Retrowrap pile jackets manufactured by NICC, LTD. The CP system was painted with XL-70 Bridgecoat, color 36622 light gray, for esthetic reasons. This paint is used by the Florida DOT over galvanized steel.

Since the fishing pier in Ft. Pierce was scheduled for rehabilitation, it offered a unique opportunity to install a trial system on new, repaired, and unrepaired members. A plan was adopted to install this field trial in two phases. In Phase I, which took place in the spring and summer of 1995, a zinc/hydrogel CP system was installed on three different types of unrepaired members: pilings, pile caps, and beams. In Phase II, expected to take place in late 1995 or early 1996, zinc/hydrogel CP will be installed on repaired and new members. This plan will enable the contractor to take advantage of lessons learned during Phase I, as well as possible material improvements, to improve the Phase II installation.

A plan view of the west end of the Ft. Pierce fishing pier is shown in figure 10. In the Phase I installation, zinc/hydrogel was installed on the four pilings of bent #2; pile caps of bents #2, #4, #5, and #6; and beams of spans #4 and #5. The layout of the zinc/hydrogel on each type of member is shown in figures 11 through 15.



**Anode Placed on: Caps of Bents #2, #4, #5, and #6  
Spans #4 and #5  
Four Piles of Bent #2**

1 ft = 0.305 m  
1 in = 25.4 mm

Figure 10. Plan view of west end of Ft. Pierce fishing pier.



**Piles of Bent #2W**

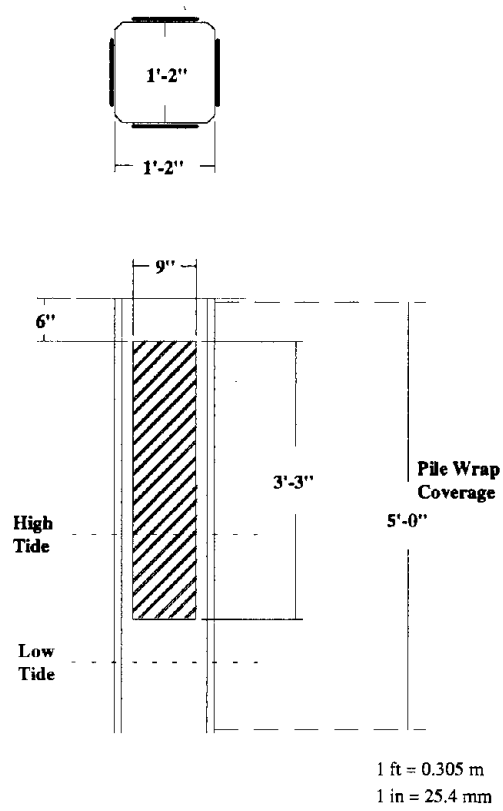
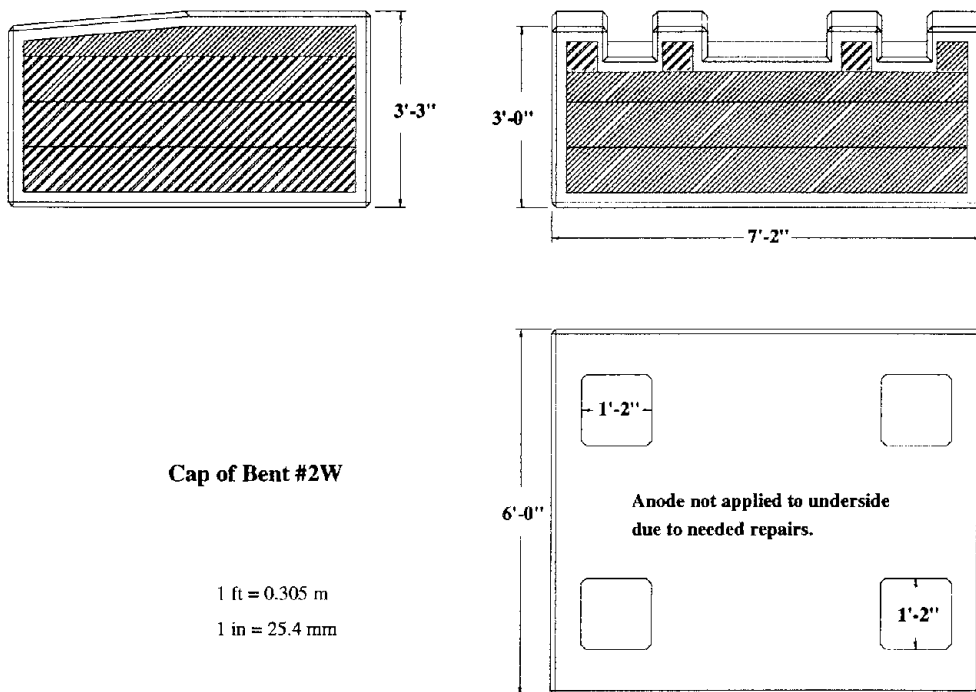
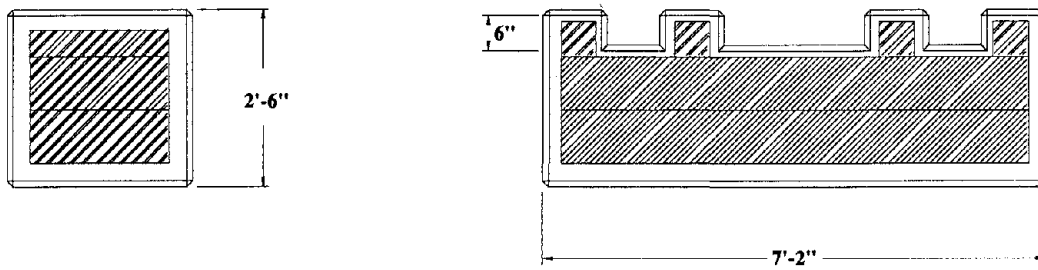


Figure 11. Layout of zinc/hydrogel on piling.



**Cap of Bent #2W**

Figure 12. Layout of zinc/hydrogel on pile cap of bent #2.



**Caps of Bents #4W & #6W**

1 ft = 0.305 m  
 1 in = 25.4 mm

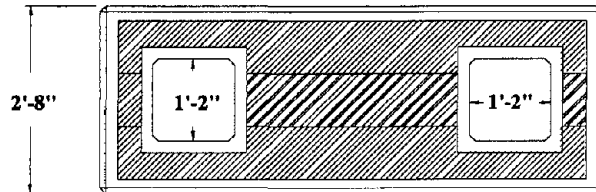
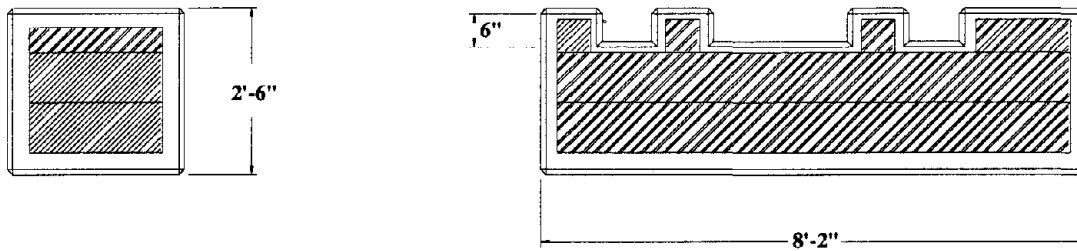


Figure 13. Layout of zinc/hydrogel on pile caps of bents #4 and #6.



**Cap of Bent #5W**

1 ft = 0.305 m  
 1 in = 25.4 mm

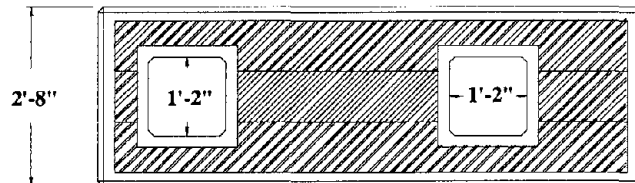


Figure 14. Layout of zinc/hydrogel on pile cap of bent #5.

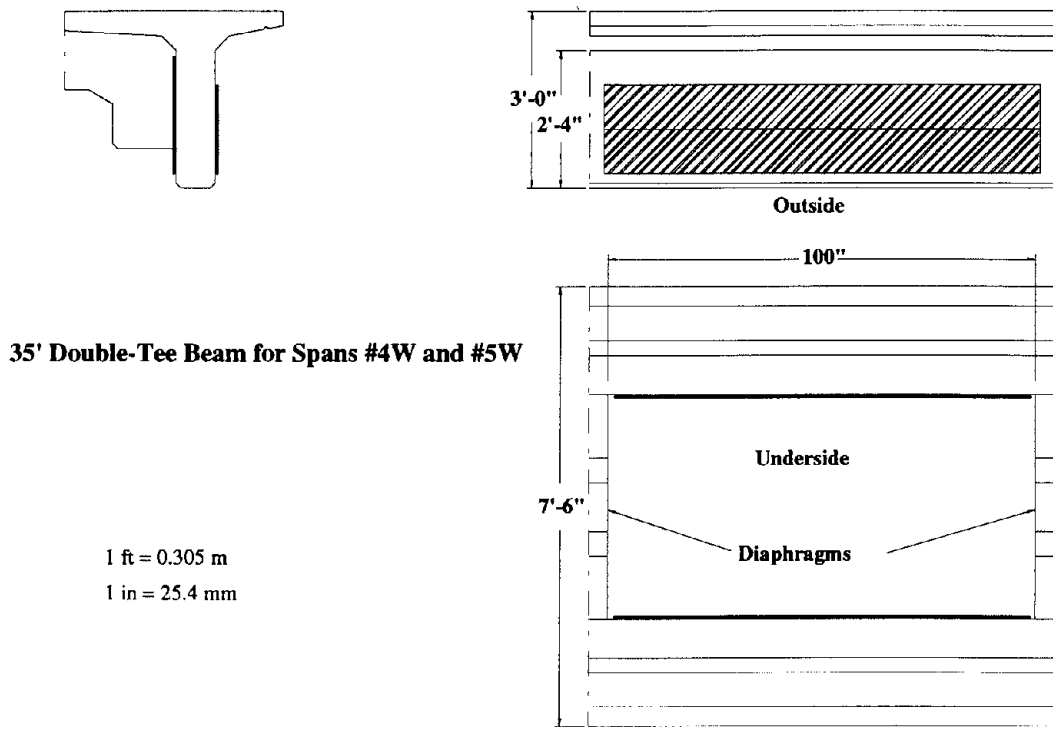


Figure 15. Layout of zinc/hydrogel on beams #4 and #5.

The concrete, anode, and steel areas for each member are given in table 9. As can be seen in the table, all members of this structure are lightly reinforced.

Table 9. Concrete, Anode, and Steel Areas for Members of Phase I Installation.

Zone	Concrete Area, ft <sup>2</sup>	Anode Area, ft <sup>2</sup>	Steel Area, ft <sup>2</sup>
Bent #2 Piles	60.7	39.0	21.6
Bent #2 Cap	79.5	60.6	33.4
Bent #4 Cap	62.5	40.0	28.0
Bent #5 Cap	70.2	46.2	30.3
Bent #6 Cap	62.5	40.0	28.0
Span #4 Beam	306	256	138
Span #5 Beam	306	256	138

1 ft<sup>2</sup> = 0.093 m<sup>2</sup>

## INSTALLATION

Installation of the zinc/hydrogel galvanic CP system on the pilings of bent #2; pile caps of bents #2, #4, #5, and #6; and beam #4 was done on April 24 to 28 and May 8 to 12, 1995. Installation on beam #5 was completed on September 13 to 15, 1995.

A potential survey was first conducted on all members scheduled for installation of CP. The results of the potential survey are summarized in table 10. Of the 80 potentials taken on the pilings of bent #2, 68 were more negative than -350 mV versus CSE, indicating the presence of very strong corrosion. Potentials taken on the pile caps indicated the presence of moderate corrosion activity, while those taken on the beams indicated little or no corrosion activity.

Table 10. Results of Potential Survey on Members of Fishing Pier.

	% of Readings Indicating <u>No Corrosion</u>	% of Readings Indicating <u>Uncertainty</u>	% of Readings Indicating <u>Active Corrosion</u>
Pilings:	0%	15%	85%
Pile Caps:	27%	59%	13%
Beams:	99%	1%	0%

Electrical continuity between rebars was found to be good within each member, and no continuity bonding was necessary. Even the north and south sides of the double-tee beams were found to be continuous. Two of the pilings of bent #2 were found to be continuous with the pile cap, while two other pilings were found to be isolated. A single negative connection was made to each member by removing concrete down to the rebar and spot-welding three steel wires to the rebar. The concrete was then patched around the negative connection, and an electrical junction box was mounted directly over the wires protruding from the concrete.

Silver/silver chloride reference electrodes were embedded in a piling of bent #2, the pile cap of bent #4, and in beam #6 in most corrosive areas of those members. Reference electrodes were installed in areas of sound concrete, with the reference electrode tip adjacent to the reinforcing steel. An effort was made not to disturb the concrete around the rebars being measured. The reference electrodes were backfilled with mortar and the reference wires were routed to the junction box on that member.

The first step for the anode installation was to clean all surfaces scheduled to receive cathodic protection. Barnacles and other marine growth were physically scraped from the pilings. All surfaces were then cleaned by water/steam-blasting with hot water at 5000 lbf/in<sup>2</sup> (34.5 MPa) and 225 °F (107 °C). Hot water flow rate was 5.5 gal/min (20.8 L/min). Cleaning of bent #2 pilings and pile cap is shown in figure 16.

Zinc/hydrogel was provided to the site in the form of a composite with 10 mil (0.25 mm) of zinc laminated to 30 mil (0.76 mm) of hydrogel adhesive, which was covered on the opposite face by a thin backing paper. The zinc/hydrogel was cut into pieces to fit the members of the pier prior to arrival at the site. Application to the concrete was made by peeling the backing paper from the composite, then pressing the adhesive onto the concrete surface. Contact was improved by placing a block of wood on the zinc and striking the wood with a hammer.



Figure 16. Cleaning of concrete surface prior to installation of zinc/hydrogel.

After attaching the composite to the concrete, the anode electrical connections were made. Adjacent strips of zinc were soldered together using a 2-in (5.1-cm) square of tinned zinc. Where zinc strips were not adjacent, such as around the beveled corners of the pile caps, connection was made by soldering to a stranded copper wire. After all surfaces of the zinc anode had been made electrically continuous, a primary anode lead wire was routed to the junction box on that member. The anode lead wire was then connected to one end of a 0.1-ohm resistor, and the opposite end of the resistor was connected to the steel via the negative lead wire. Current measurements were made by measuring the voltage drop across the resistor.

The edges of each zinc strip were then sealed with polyurethane caulking using a pneumatic caulking gun. The zinc was cleaned of caulking, hydrogel, and other contaminants by rubbing with isopropyl alcohol, and the entire member was painted with gray XL-70 Bridgecote solvent-based paint. Figures 17 and 18 show the installed zinc/hydrogel system on bent #2 before and after painting.



Figure 17. Zinc/hydrogel installed on bent #2 pile cap prior to painting.

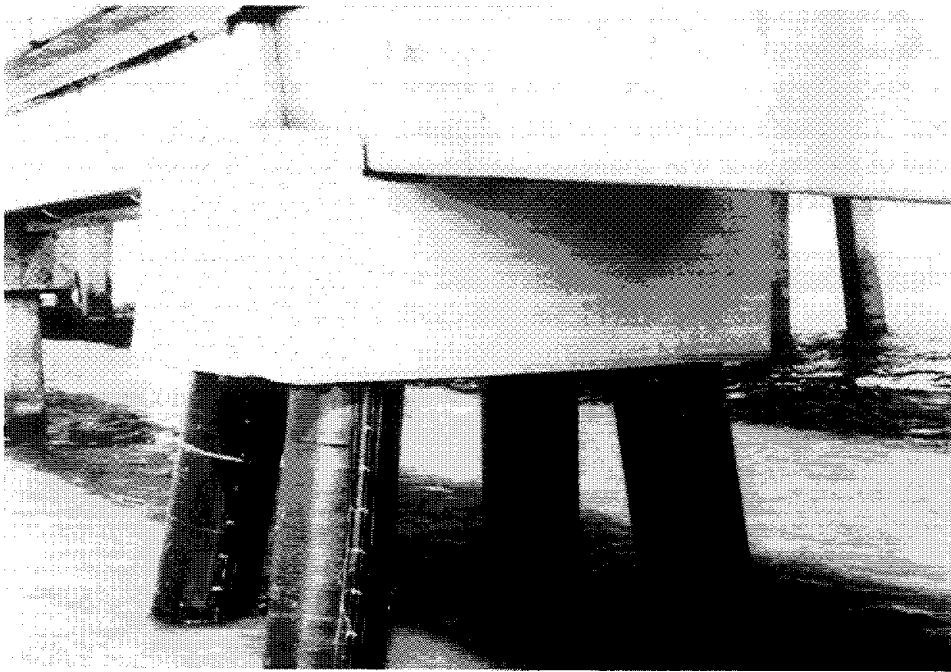


Figure 18. Completed zinc/hydrogel system installed on pilings and pile cap.

## ENERGIZING

The members of the Phase I zinc/hydrogel CP system installed at Ft. Pierce, Florida were energized on May 11, 1995, except for beam #5, which was energized September 15, 1995. Table 11 shows current densities for all zones of the system on three different dates. Current densities are reported as both milliamperes per square foot (mA/ft<sup>2</sup>) of anode and mA/ft<sup>2</sup> of steel. Current at start-up was measured after the initial surge of current had decreased and a state of equilibrium had apparently been reached.

Table 11. Current Densities for Ft. Pierce CP System.

	5/12/95 mA/ft <sup>2</sup> anode	5/12/95 mA/ft <sup>2</sup> steel	7/31/95 mA/ft <sup>2</sup> anode	7/31/95 mA/ft <sup>2</sup> steel	9/15/95 mA/ft <sup>2</sup> anode	9/15/95 mA/ft <sup>2</sup> steel
Bent #2 Pilings	2.08	3.75	1.56	2.82	1.03	1.85
Bent #2 Pile Cap	0.78	1.41	0.96	1.74	0.66	1.20
Bent #4 Pile Cap	1.40	2.00	1.20	1.71	0.75	1.07
Bent #5 Pile Cap	1.17	1.78	1.21	1.85	1.21	1.85
Bent #6 Pile Cap	1.12	1.61	1.02	1.46	0.72	1.62
Beam #4	0.67	1.25	0.73	1.36	0.59	1.09
Beam #5	-----	-----	-----	-----	0.88	1.62

$$1 \text{ mA/ft}^2 = 10.7 \text{ mA/m}^2$$

As shown by table 11, current flow has been good over the first 4 months of operation. Although total current delivery has dropped slightly, in no case had the current decreased below 1 mA/ft<sup>2</sup> (10.7 mA/m<sup>2</sup>) of steel.

At last observation, the system looked good and showed no signs of anode disbondment. The only damage was caused by vandalism, where one junction box had been ripped off and about 4 in (10.1 cm) of one strip of zinc had been peeled off. This was easily repaired on September 15, 1995 during the end of the Phase I installation.

## SUMMARY

Two structures were selected for field installation of the zinc/hydrogel galvanic CP system: a fishing pier in Ft. Pierce, Florida and V-piers of the Long Key Bridge in the Florida Keys. About 1000 ft<sup>2</sup> (93 m<sup>2</sup>) of 10-mil (0.25-mm) pure zinc/30-mil (0.76-mm) hydrogel were installed on the fishing pier in May and September of 1995. Protected members of the pier

include pilings, pile caps, and beams. The zinc/hydrogel was caulked to prevent exchange of water with the environment, and the installed system was painted for esthetic purposes. The appearance of the finished system was very good.

The system was energized in May and September 1995 as installation was completed on individual members. Current delivery was good and had not decreased below  $1 \text{ mA/ft}^2$  ( $10.7 \text{ mA/m}^2$ ) of steel on any member over the first 4 months of operation.

The Phase II installation of zinc/hydrogel at Ft. Pierce and the Long Key installation are expected to take place early in 1996.



## CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

### CONCLUSIONS

- Aluminum and aluminum alloys were unsuitable for use as CP anodes in contact with hydrogel adhesives. Aluminum alloys exhibited either unstable passive behavior or low anode working potential. The corrosion products of aluminum were also voluminous and difficult to accommodate.
- Pure zinc was the best anode tested for use as a CP anode in contact with hydrogel. Its working potential was a stable -1.07 V versus SCE at current densities typical of those used for cathodic protection of reinforced concrete.
- A hydrogel adhesive was developed that met technical targets of conductivity, adhesive tack, and lifetime. This proprietary adhesive, known as 3M-3, tolerated a total charge of 105.8 A-hr/ft<sup>2</sup> (1140 A-hr/m<sup>2</sup>) in accelerated testing. This charge is equivalent to about 12 years of operation for a system operating at typical cathodic protection current densities. Hydrogel adhesives available for medical applications are not satisfactory for CP of reinforced concrete structures.
- Hydrogel adhesives must be prevented from direct contact with water or seawater. This may be accomplished by caulking the edge of the zinc/hydrogel composite to prevent exchange with the environment.
- About 1000 ft<sup>2</sup> (100 m<sup>2</sup>) of zinc/hydrogel were installed on a fishing pier in Ft. Pierce, Florida during May and September of 1995. The system was applied to pilings, pile caps, and double-tee beams. The installation was relatively easy, and was done without the services of a separate installation contractor.
- The CP system installed on the Ft. Pierce fishing pier was energized without difficulty. Start-up current averaged 1.92 mA/ft<sup>2</sup> (20.7 mA/m<sup>2</sup>) of steel. After 4 months of operation, current densities remain high, averaging 1.45 mA/ft<sup>2</sup> (15.6 mA/m<sup>2</sup>) of steel. Adhesion of the zinc remains high and appearance of the system is good.

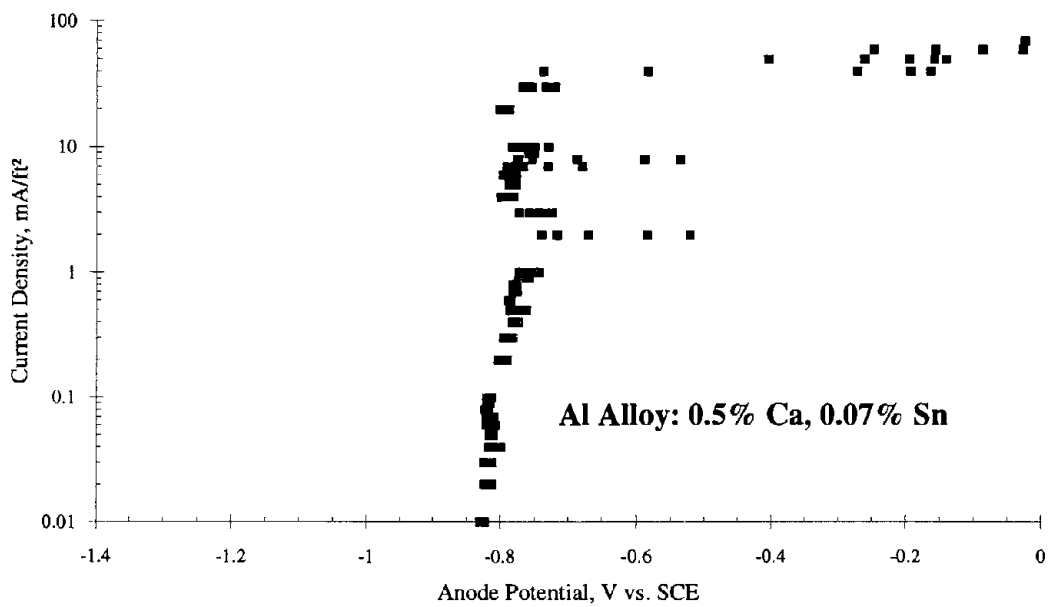
### RECOMMENDATIONS

- Complete the installation of zinc/hydrogel on the fishing pier at Ft. Pierce (Phase II) and on the V-piers of the Long Key Bridge.
- Monitor the performance of these zinc/hydrogel field trials for at least 3 years. Monitoring should be extended if performance is promising.

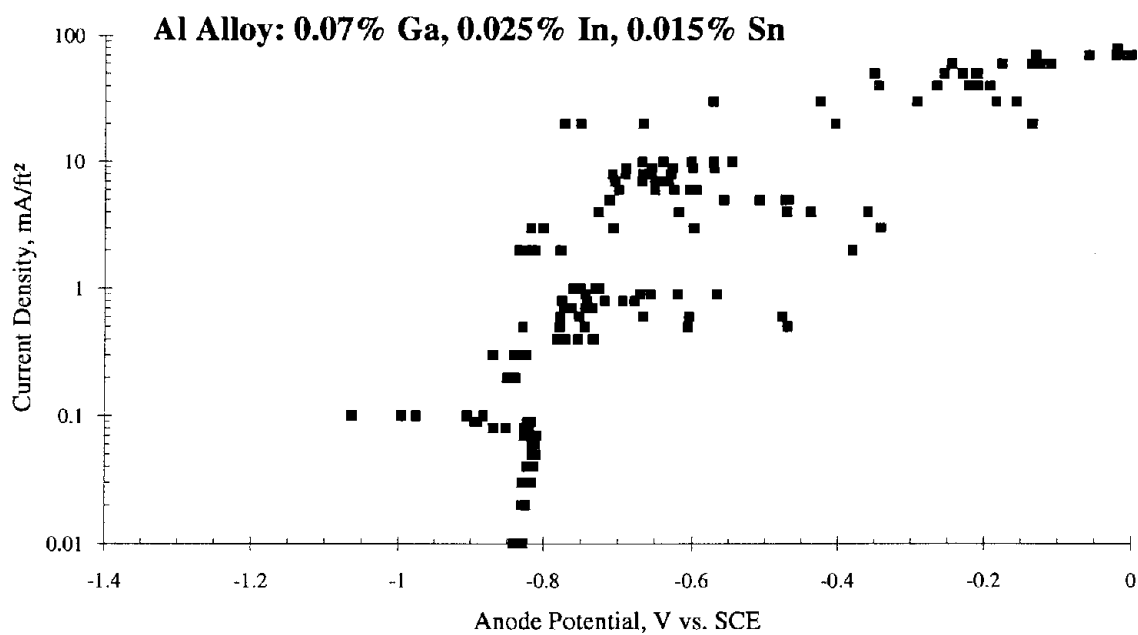


## APPENDIX

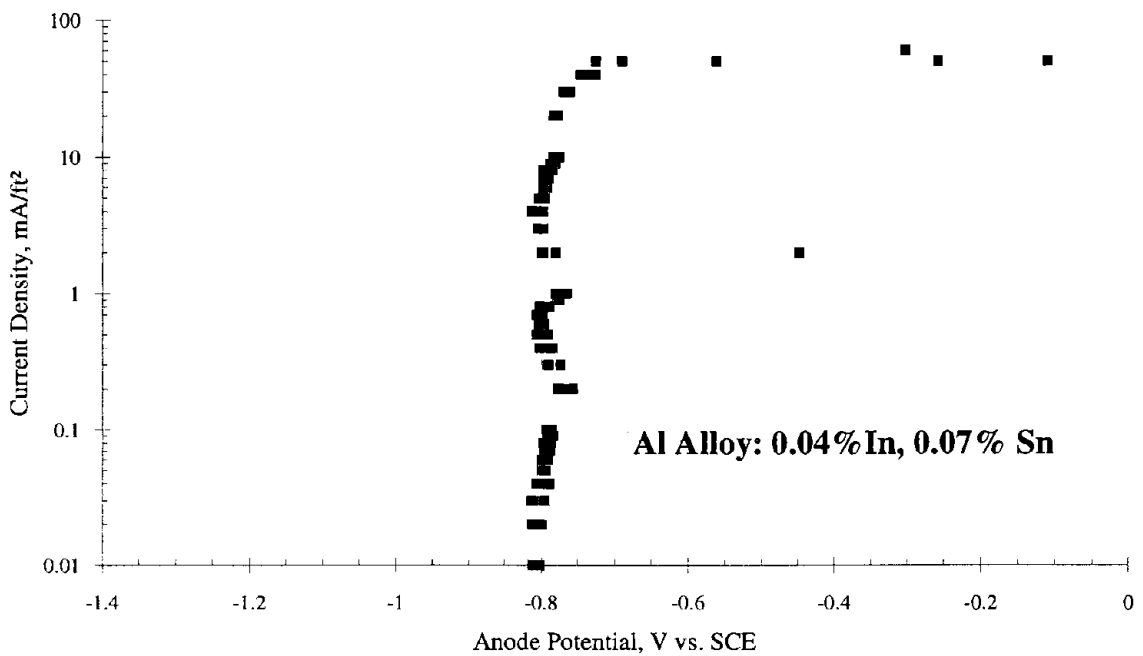
### POLARIZATION DATA FOR OTHER ALUMINUM ALLOY/RG-63B HYDROGEL COMPOSITES



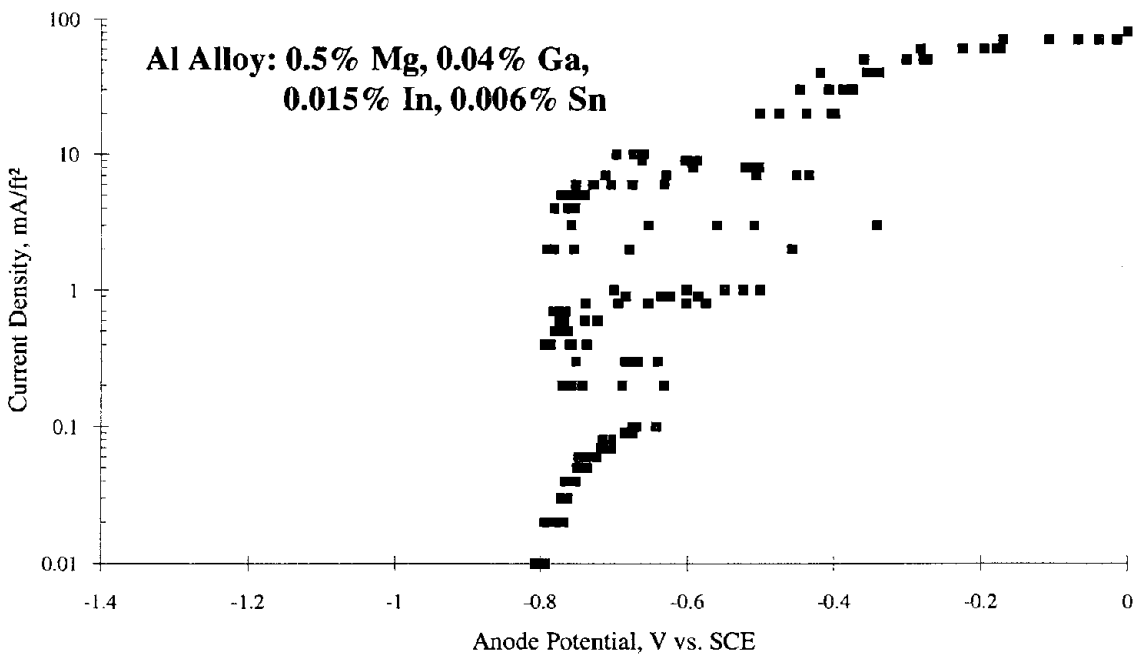
$$1 \text{ mA/ft}^2 = 10.7 \text{ mA/m}^2$$



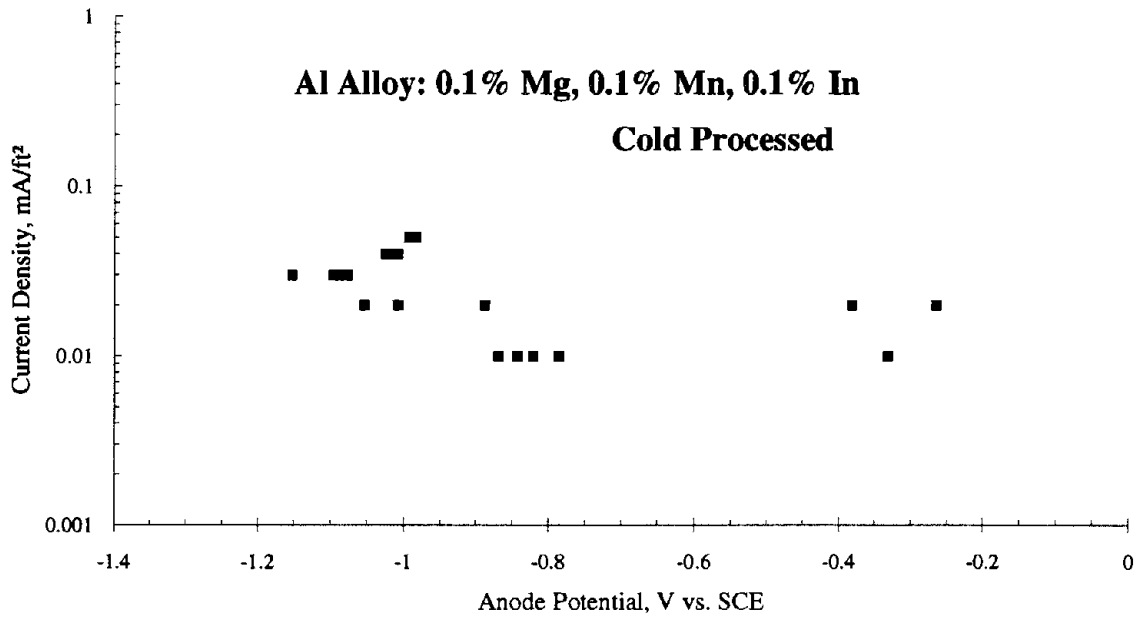
$$1 \text{ mA/ft}^2 = 10.7 \text{ mA/m}^2$$



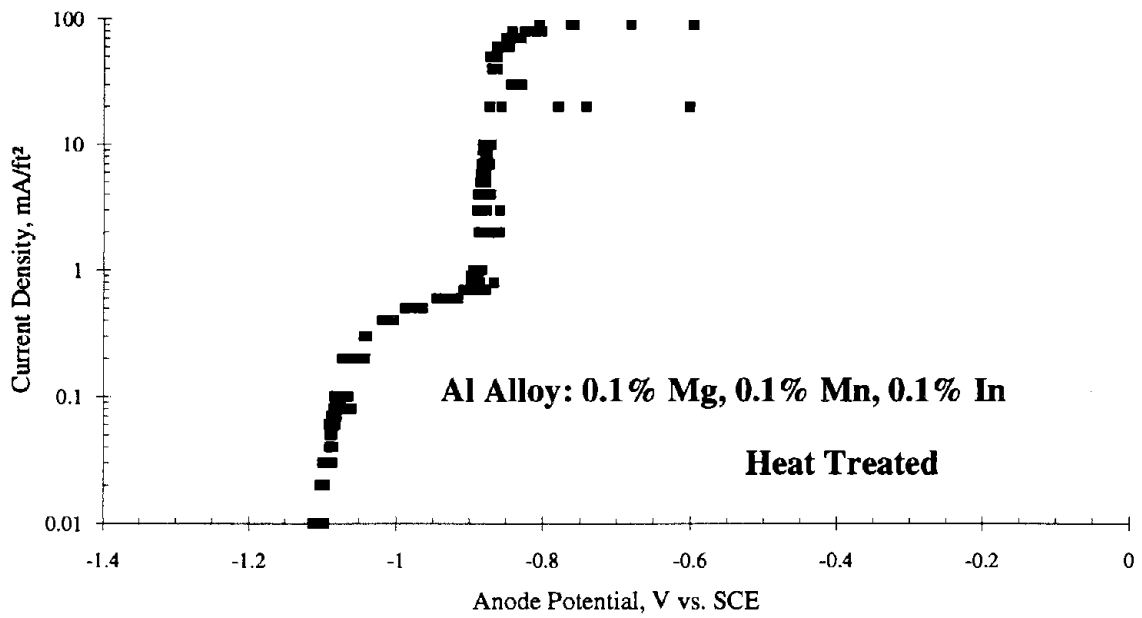
1 mA/ft<sup>2</sup> = 10.7 mA/m<sup>2</sup>



1 mA/ft<sup>2</sup> = 10.7 mA/m<sup>2</sup>



1 mA/ft<sup>2</sup> = 10.7 mA/m<sup>2</sup>



1 mA/ft<sup>2</sup> = 10.7 mA/m<sup>2</sup>



## REFERENCES

1. Federal Highway Administration, *1991 Report to Congress*, Washington, D.C., June 1991.
2. Federal Highway Administration, *1991 Status of the Nation's Highways and Bridges: Conditions, Performance and Capital Investment Requirements*, Washington, D.C., July 2, 1991.
3. Clear, K.C. and Virmani, Y.P., "Research Update: Methods and Materials," Presented at the National Association of Corrosion Engineers Conference: Solving Rebar Corrosion Problems in Concrete. September 1982.
4. Bennett, J.E., Bushman, J.B., and Clear, K.C., *Cathodic Protection of Reinforced Concrete Bridge Elements: A State-of-the-Art Report*, Report No. SHRP-S-337, Strategic Highway Research Program, Washington, D.C., 1993.
5. Clear, K.C., "Chlorides at the Threshold - Comments and Data," American Concrete Institute Convention Debate, Anaheim, California.
6. Bartholomew, J., Bennett, J.E., Hartt, W.H., Lankard, D.R., Sagues, A.A., Savinell, R., and Turk, T., *Control Criteria and Materials Performance Studies for Cathodic Protection of Reinforced Concrete*, Report No. SHRP-S-670, Strategic Highway Research Program, Washington, D.C., 1993.
7. Stratfull, R.F., "Eleven Years of Success for Coke Breeze CP Pavement," Paper No. 12, Conference on Cathodic Protection of Reinforced Concrete Bridge Decks, 1985.
8. Stratfull, R.F., "Knowledge and Needs in the Field of Impressed Current Cathodic Protection: System Control and Monitoring," Presented at the FHWA Federally Coordinated Research Program of Highway Research and Development, December 1979.
9. Fromm, H.J., "Cathodic Protection of Concrete Bridge Decks - Three Years of Successful Application to an Ontario Bridge Deck," Transportation Research Board Annual Meeting, Washington, D.C., January 1980.
10. Perenchio, W.E., Landgren, J.R., Clear, K.C., and West, R.E., *Cathodic Protection of Concrete Bridge Decks*, Final Report, NCHRP 12-19B, National Cooperative Highway Research Program, May 1985.
11. U.S. Patent No. 4,506,485, March 1985.
12. Apostolos, J.A., "Cathodic Protection of Reinforced Concrete Using Metallized Coatings and Conductive Paints," Paper Presented at the Transportation Research Board Annual Meeting, Washington, D.C., January 1984.

13. Apostolos, J.A., Parks, D.M., and Carello, R.A., "Cathodic Protection Using Metallized Zinc," CORROSION/87, Paper No. 137, National Association of Corrosion Engineers, March 1987.
14. *Roads and Bridges*, June 1986, pp. 57-64.
15. Lankard, D.A. and Bennett, J.E., *Repair of Reinforced Concrete Piers*, Final Report, SBIR Contract No. N47408-94-C-7406, Small Business Innovation Research Program.
16. Pourbaix, M., *Atlas of Electrochemical Equilibria in Aqueous Solutions*, National Association of Corrosion Engineers, Houston, Texas, 1974.
17. Flynn, L., "Metallizing Protects Rebar from Corrosion," *Roads and Bridges*, Vol. 29, No. 8, August 1991, pp. 58-59.
18. Kestler, R.J. and Powers, R.G., "Zinc Metallizing for Galvanic Cathodic Protection of Steel Reinforced Concrete in a Marine Environment," CORROSION/90, Paper No. 324, National Association of Corrosion Engineers, Houston, Texas, 1990.
19. Powers, R.G. and Sagues, A.A., *Sprayed Zinc Galvanic Anodes for Concrete Marine Bridge Substructures*, Report No. SHRP-S-405, Strategic Highway Research Program, Washington, D.C., 1994.
20. Kestler, R.J., Lasa, I.R., and Powers, R.G., "Cathodic Protection Using Scrap and Recycled Materials," *Materials Performance*, Vol. 30, No. 6, June 1991, pp. 29-31.
21. DeRincon, O.T., Carruyo, A.R., Romero, D., and Cuica, E., "Evaluation of the Effects of Oxidation Products of Aluminum Sacrificial Anodes in Reinforced Concrete Structures," *Corrosion*, Vol. 48, No. 11, November 1992, pp. 960-967.
22. Vrable, J.B., *Cathodic Protection of Reinforced Concrete Bridge Decks - Laboratory Phase*, NCHRP Report No. 180, National Cooperative Highway Research Program, 1977.
23. Whiting, D. and Stark, D., *Cathodic Protection of Reinforced Concrete Bridge Decks - Field Evaluation*, NCHRP Report No. 234, National Cooperative Highway Research Program, 1981.
24. Whiting, D., Nagi, M., and Broomfield, J.P., *Evaluations of Sacrificial Anodes for Cathodic Protection of Reinforced Concrete Bridge Decks*, Publication No. FHWA-RD-95-041, Federal Highway Administration, Washington, D.C., May 1995.
25. *Corrosion Basics*, National Association of Corrosion Engineers, Houston, Texas, 1984, p. 181.