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

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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 Final Report describes laboratory studies to identify the optimal anode and hydrogel compositions, followed by field installations on three structures to demonstrate feasibility of the system. Field installations were evaluated after monitoring for periods up to 3½ years.

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.

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Director, Office of Infrastructure
Research and Development

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16. Abstract

This is the final 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 applications 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. In this study, a new galvanic CP system was investigated in which sacrificial anodes were 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. Zinc attached by hydrogel adhesive was selected as the sacrificial anode for installation on field validation trials. Studies also resulted in the development of a hydrogel adhesive with adequate performance and life expectancy.

Three field trials were installed and monitored under this contract. About 1000 ft^2 ($93m^2$) of zinc/hydrogel was installed on the pilings, pile caps, and double-tee beams of a fishing pier in Ft. Pierce, Florida. Although electrical contact was disrupted on one of the beams, most of the system performed well and met the 100 mV potential decay criterion after 32 months of operation. Zinc/hydrogel anodes installed on the bearing pads of V-piers of the Long Key Bridge also performed well, generally meeting accepted CP criteria. A more recent installation of 700 ft^2 ($65m^2$) on the Cape Perpetua half-viaduct in Oregon has performed well for 1 year, providing about 0.3 mA/ft^2 ($3.2\ mA/m^2$) and easily achieving CP criteria.

The zinc/hydrogel anode was easy to install, fix and has performed generally well for all three trials conducted under this contract.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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* 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)

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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.(1) 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 U.S. Department of Transportation has estimated that $90.9 billion will be needed to repair the damage on these existing bridges.(2) 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 because of 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.(3)

Cathodic protection (CP) has been proven to be an effective means of stopping the corrosion of steel in concrete,(4) 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.(5) 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 ICCP systems and the lack of a mechanism for proper servicing and maintenance.(5) Galvanic CP systems, which use sacrificial anodes, have recognized advantages of simplicity and reliability, but have seldom been used for reinforced concrete structures because functional systems are unavailable. 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.

Anode	*Theoretical Energy Efficiency (A-hr/lb)*	*Current Efficiency (percent)*	*Practical Energy Efficiency (A-hr/lb)*	*Thickness (mil/yr) Consumed**	*Material Cost ($/ft²)***	*Working Potential V vs. SCE*
Zinc	372	95	353	1.0	$0.18	-1.03
Aluminum	1352	95	1285	0.7	$0.06	-1.03
Magnesium	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^2 = $10.7/m^2
* Based on a current density of 1.5 mA/ft^2 (0.14 mA/m^2).
** 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 because of 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 CP 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 the laboratory phase of 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 identifying 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. Results of laboratory and test slab studies conducted under this contract are presented in detail in an Interim Report published in 1996.(6)

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 the Cape Perpetua half-viaduct near Yachats, Oregon, were also conducted.

This Final Report describes the results of the technology review, laboratory screening tests, test yard results, and three field trial installations. Present cost and installation status of the product developed by this contract are also presented.

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.(7-11) 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.(5) 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.(8) This first system used a conductive coke-asphalt overlay as the CP 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, including 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.(12) Although zinc is traditionally used as a galvanic anode, it is also used as an anode on concrete structures 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.(13) 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.(14) A recent survey(15) has identified 22 systems in 7 States and 2 countries using the metallized zinc anode on more than 500,000 ft^2 (46,000 m^2) of concrete surface. In about half of these installations, zinc was 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^2 (33,700 m^2) 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 20 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. These concerns have prompted some 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 an expensive component of the installation.

GALVANIC CURRENT CATHODIC PROTECTION

Since zinc, aluminum, and magnesium have very negative natural electrode potentials,(16) 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^2 (14,800 m^2) 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.(17,18) 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.(19) 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 demonstrated that the metallized zinc anode was not capable of maintaining an adequate flow of galvanic current without periodic wetting of the surface.

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.(20) 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.(21) 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.(22) 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.(23) 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^2 (32 mA/m^2) of reinforcing steel bar surface during the summer months to about 1.0 mA/ft^2 (10.8 mA/m^2) in the spring and fall. Current was measured at 1.5 mA/ft^2 (16.8 mA/m^2) after 12 years of operation.

Concurrent with this study, the FHWA funded two other contracts to investigate the use of sacrificial anodes for use on reinforced concrete bridge members. Under one of these contracts, evaluations were carried out on a series of anode materials, including aluminum, magnesium, and zinc alloys.(24) Following the laboratory phase of this study, reinforced concrete test slabs were produced for evaluation of the candidate anode materials, which were overlaid with normal structural concrete, structural lightweight concrete, free-draining concrete, and free-draining latex-modified concrete. On the basis of laboratory and test slab data, a field trial was conducted using aluminum anodes overlaid with high air content, chloride-laden mortar to activate the anode. The concrete wearing course suffered distress during the first year of operation, and significant problems were also encountered with the anode system itself. Further installation of such systems was not recommended.

Under another contract, an aluminum alloy was identified that provided adequate cathodic protection to steel embedded in concrete over a range of temperature and humidity conditions as might be expected on bridge structures.(25) Two pilings of the Brian Patton Bridge, which is located between Eastpoint and St. George Island in Florida, were sprayed with an aluminum alloy consisting of 80 percent aluminum, 20 percent zinc, and 0.2 percent indium. Two other piles of the bridge were sprayed with pure zinc as controls. Testing during 2 years of operation and final on-site testing indicated that the aluminum alloy was capable of providing a better degree of cathodic protection to the embedded steel than pure zinc.

OTHER STUDIES IN PROGRESS

In another study, chemical treatment of metallized zinc coatings is being researched to enhance the flow of protective current.(26,27) Candidate chemicals were chosen for their ability to maintain moisture at the anode-concrete interface and to maintain the zinc in an electrochemically active state. The most effective chemicals were able to increase galvanic current by a factor of 2-15, depending on relative humidity and chloride contamination of the concrete.

SUMMARY

Both ICCP and galvanic CP systems have been shown to prevent the corrosion of steel in concrete. ICCP systems have been broadly used, and have 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 has 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 has been generally successful, but requires periodic wetting of the anode surface to maintain adequate current when used galvanically. Promising developments include an aluminum-zinc-indium alloy and chemical treatment of metallized zinc anodes. Both of these developments, as well as the product of this contract, increase the flow of galvanic current to embedded steel and are expected to make simple galvanic CP systems more viable for use on reinforced concrete bridge members.

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. To perform this function, the anode material must meet the following general requirements:(25)

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, magnesium was not considered to be a viable candidate. Although magnesium has the highest theoretical working potential of the three [-1.6 V versus copper sulfate electrode (CSE)], it suffers from a high rate of self-corrosion, particularly at low current density. Also, the cost of magnesium is relatively 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 CSE. To maintain that working potential, aluminum must usually be alloyed with small amounts of other elements 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. The alloys that were tested are listed in table 2.

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.

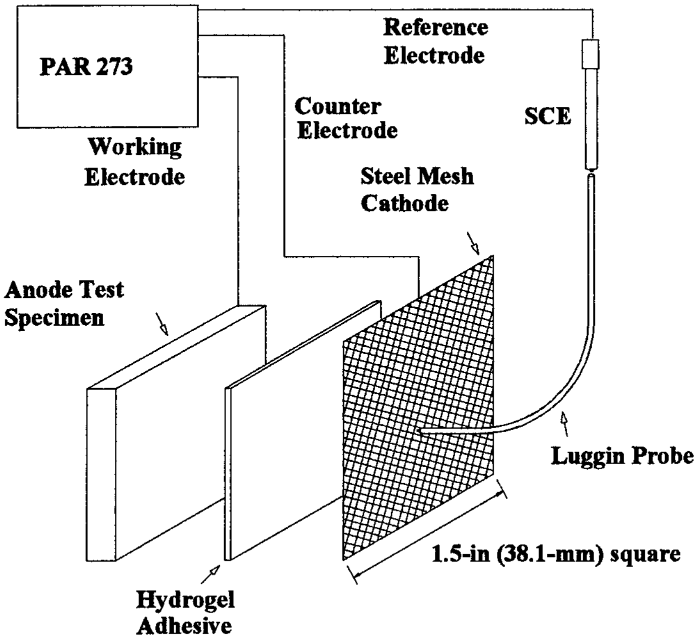


Figure 1. Cell for the testing of anode materials.

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^2 (0.1 to 1000 mA/m^2) 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^2 (10 mA/m^2), a practical current density for an anode in the field, the working potential was still -1.07 V versus SCE. Even at 100 mA/ft^2 (1000 mA/m^2), a current density far in excess of that experienced on actual structures, the zinc anode had polarized to only -0.92 V versus SCE. At all levels of current tested, the working potential of the zinc anode was stable and showed no tendency to passivate.

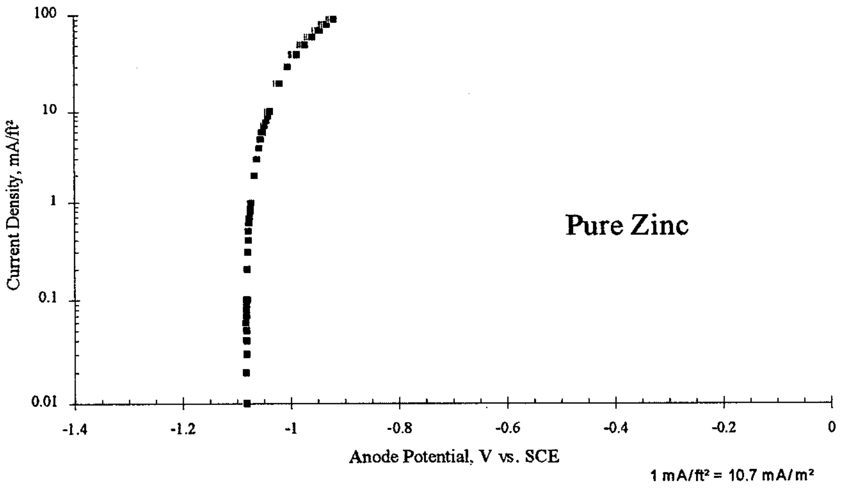


Figure 2. Polarization data for pure zinc/RG-63B hydrogel composite.

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^2 (0.1 mA/m^2). 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^2 (10 mA/m^2) had been reached, the anode potential was ranging freely from -0.52 to -0.72 V versus 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.

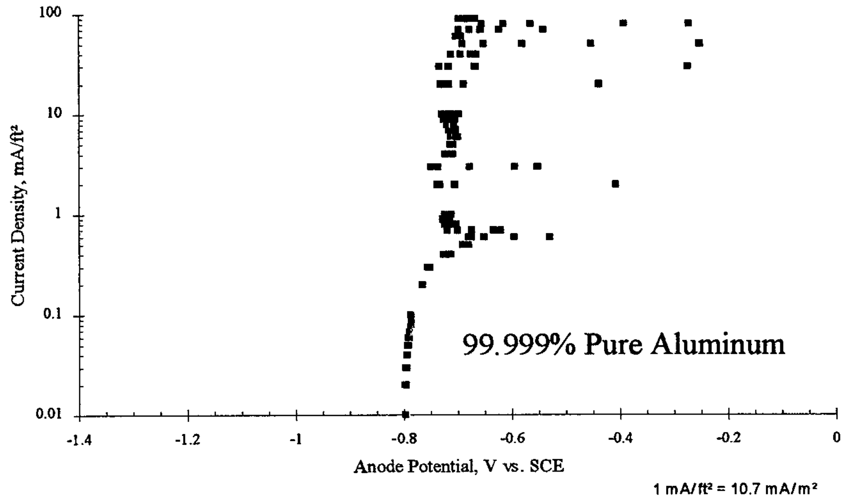


Figure 3. Polarization data for pure aluminum/RG-63B hydrogel composite.

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; the polarization behavior of other aluminum alloys tested is presented in the Interim Report.(6)

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 versus 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.

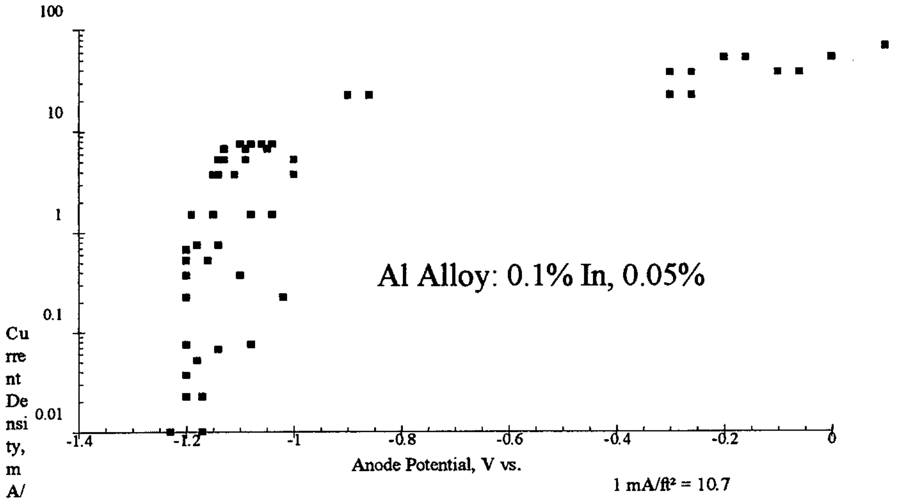


Figure 4. Polarization data for 0.1 percent indium, 0.05 percent gallium-aluminum alloy/RG-63B hydrogel composite.

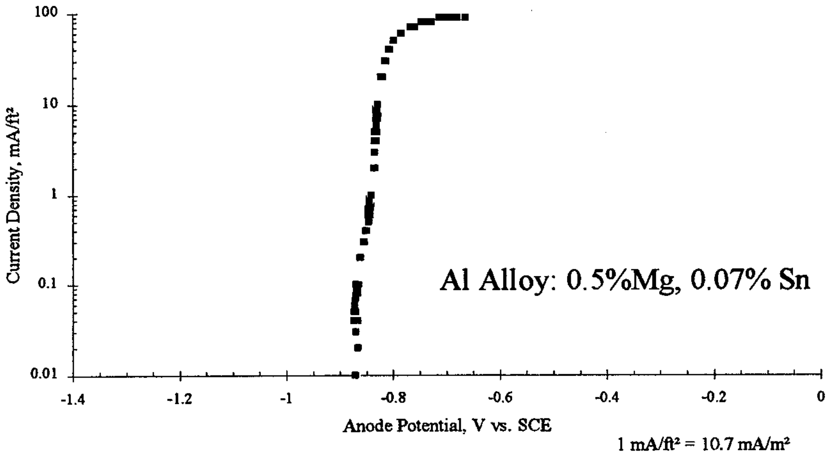


Figure 5. Polarization data for 0.5 percent magnesium, 0.07 percent tin-aluminum alloy/RG-63B hydrogel composite.

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^2 (10 mA/m^2). This alloy was also determined to be unacceptable for this application.

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^2 (10 mA/m^2). 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^2 (\$20/m^2) 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 another supplier of hydrogel adhesives to this market. The properties of the medical hydrogels available from Promeon are given in table 3.

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

	RG-62D	*RG-62X*	*RG-63L*	*RG-63B*	*RG-63G*	*RG-63X*
Primary Application	Stimulating, Disposable	Stimulating, Reusable	Sensing, Disposable	Sensing, Disposable	Sensing, Reusable	Sensing, Reusable
Resistivity, (ohm-cm)	2500 max.	2500 max.	1500 max.	1500 max.	1500 max.	1500 max.
Adhesive Tack	Moderate	Strong	Weak	Moderate	Moderate	Strong
Dryout Resistance	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 more 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 10 in long x 3 in wide x 5 in deep (25.4 cm x 7.6 cm x 12.7 cm) were prepared. 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^3 (3.5 kg/m^3) (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.

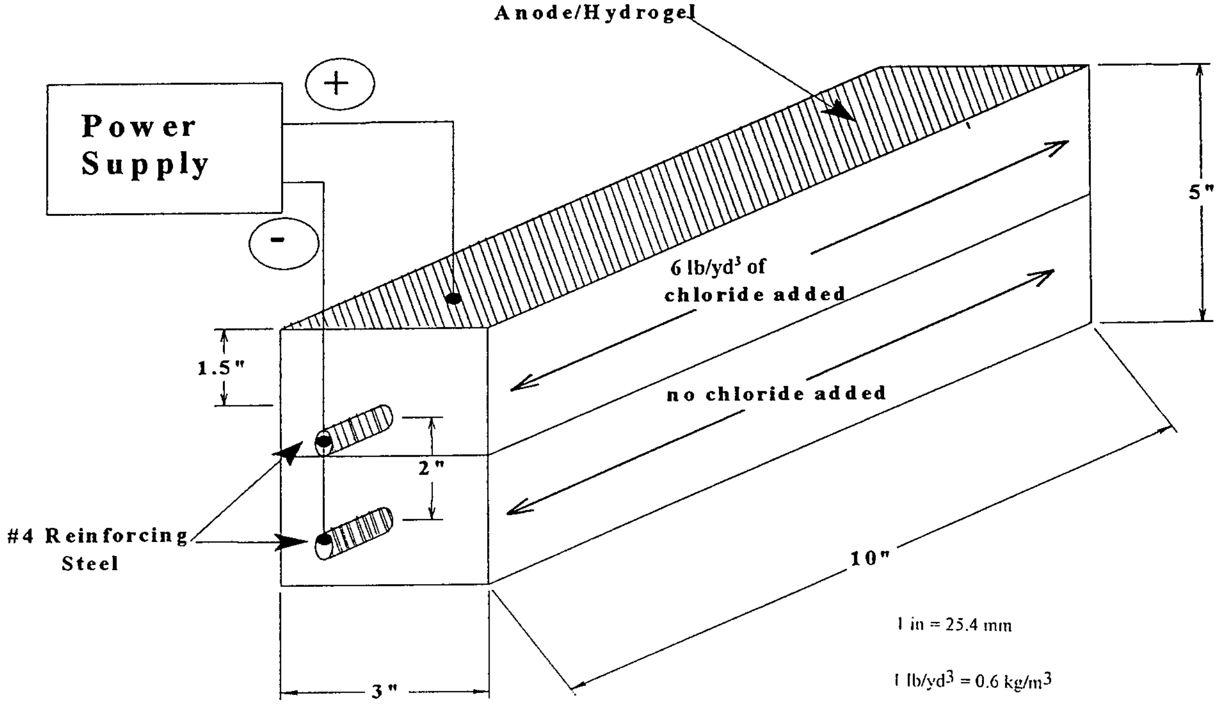


Figure 6. Specimen used for accelerated testing of hydrogel adhesives.

The concrete used for these specimens conformed to the Ohio 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.

Concrete Constituent	lb/yd^3	kg/m^3
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^3 (2308 kg/m^3)

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^2 (160 mA/m^2) 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. The galvanic tests were not as useful as the accelerated tests, and galvanic testing was eventually discontinued. Results of the early galvanic tests are presented in the Interim Report.(6)

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.

Hydrogel Adhesive	pH	Resistivity, ohm-cm
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.

Hydrogel Adhesive	Life, days	Life, A-hr/ft^2	Comments
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 A-hr/ft^2 = 10.7 A-hr/m^2

Cell voltage was monitored during the accelerated test at a current density of 15 mA/ft^2 (160.5 mA/m^2), and voltage was plotted versus equivalent life for a system operated at 1.0 mA/ft^2 (10.7 mA/m^2). 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.

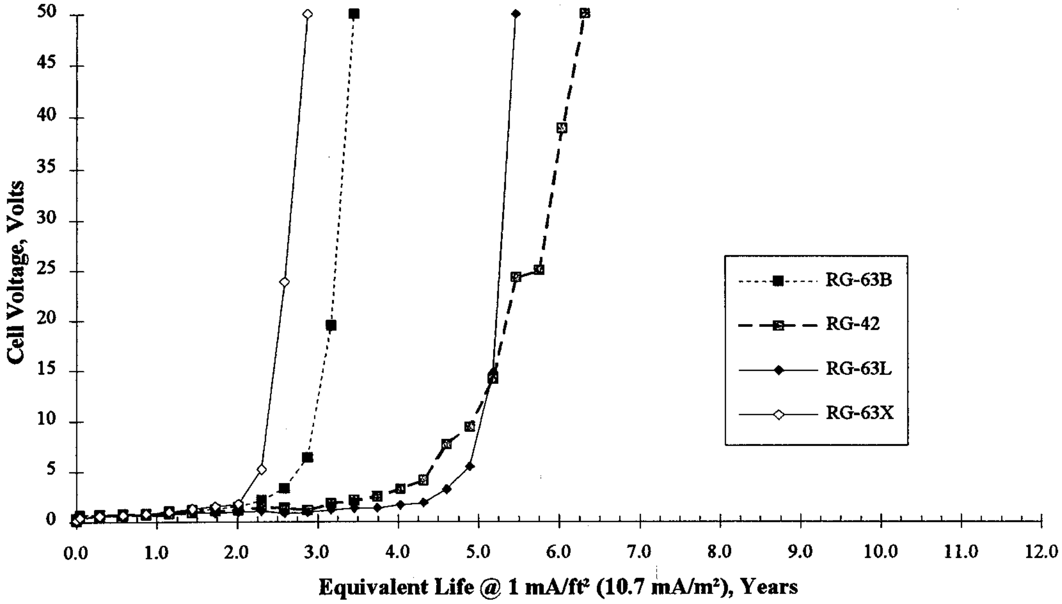


Figure 7. Cell voltage versus equivalent life for medical hydrogel adhesives.

The goal for the life of the hydrogel was set at 87.6 A-hr/ft^2 (943 A-hr/m^2), which represents the total charge of a CP system operating at 1.0 mA/ft^2 (10.7 mA/m^2) 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 CP 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 Cathodic Protection.

Hydrogel Adhesive	pH	Resistivity, ohm-cm
9102	3.7	277×10^3
9103	3.5	238×10^3
9104	2.0	386×10^3
2993-1	2.8	4698×10^3
2993-2	3.0	584×10^3
2993-3	2.8	$23{,}435 \times 10^3$
2993-4	3.0	$36{,}100 \times 10^3$
3M-1	4.1	720
3M-2	11.0	630
3M-3	10.3	400

Table 8. Accelerated Testing of Hydrogel Adhesives Developed for Cathodic Protection.

Hydrogel Adhesive	Life, days	Life, A-hr/ft^2	Comments
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 A-hr/ft^2 = 10.7 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^2 (1137 A-hr/m^2) achieved by 3M-3 is equivalent to a life of 12 years at a current density of 1.0 mA/ft^2 (10.7 mA/m^2). 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.

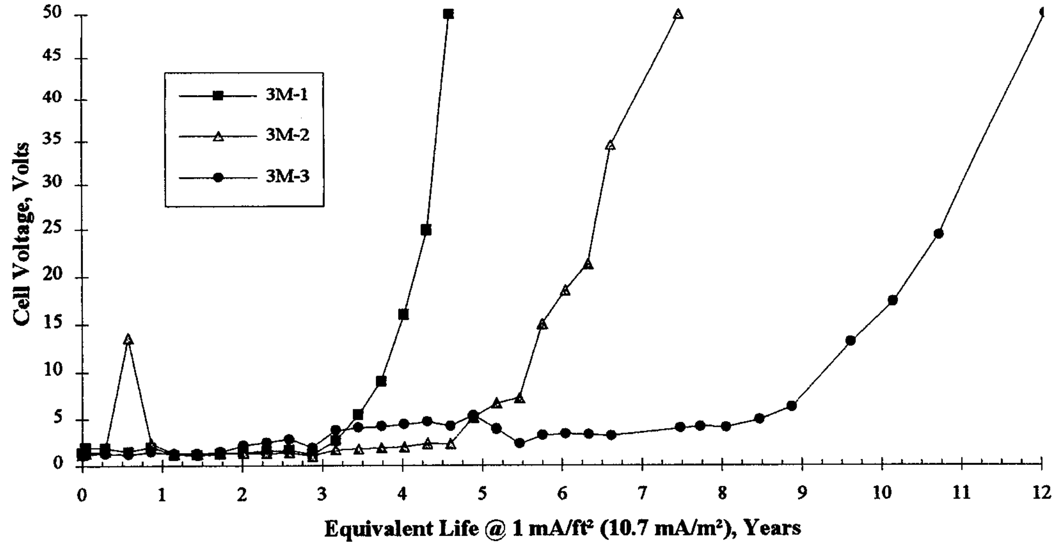


Figure 8. Cell voltage versus equivalent life for CP hydrogel adhesives.

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. These included testing of selected aluminum alloys on test slabs and testing of high surface area zinc configurations. The results of these tests are described in detail in the Interim Report.(6)

Since it was anticipated that a field trial of the zinc/hydrogel CP system would be installed on a marine structure, a test was also conducted to evaluate the ability of the hydrogel to tolerate direct contact with seawater. A specimen fitted with a zinc anode and 3M-3 hydrogel was partially immersed in solution containing 28 gm/L NaCl. After 2 weeks of operation in galvanic mode, the zinc hydrogel was still operating at a consistent 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. This hydrogel must be protected from direct exposure to water and seawater during operation.

CHAPTER 4. INSTALLATION AND OPERATION OF FIELD TRIALS

FT. PIERCE FISHING PIER

Structure Selection

Selection of a structure for the first 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. Finally, 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 DOT.

The Florida DOT was 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.

System Design

On the basis of 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 the time of this installation, the maximum width of the hydrogel was about 9 in (23 cm) because of 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 Ft. Pierce field trial was 99.5 percent pure zinc from LaSalle Rolling Mills. A zinc thickness of 10 mil (0.25 mm) was used to ensure a reasonable life while supplying necessary current to the structure. A constant current density of 1 mA/ft^2 (10.7 mA/m^2) 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.

On the basis of 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.

A plan view of the west end of the Ft. Pierce fishing pier is shown in figure 9. 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 10 through 14.

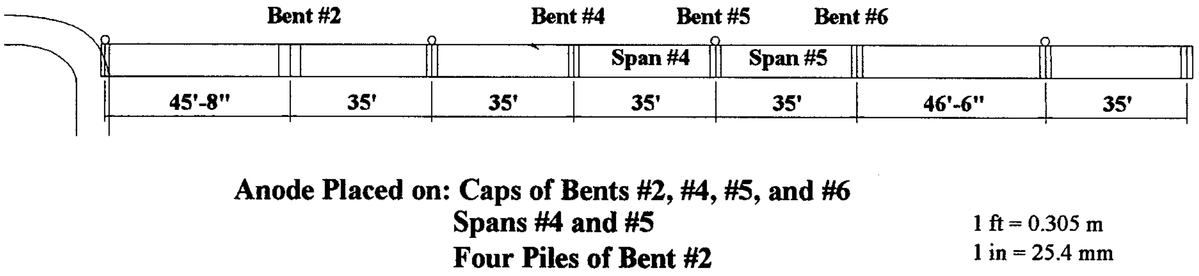


Figure 9. Plan view of west end of Ft. Pierce fishing pier.

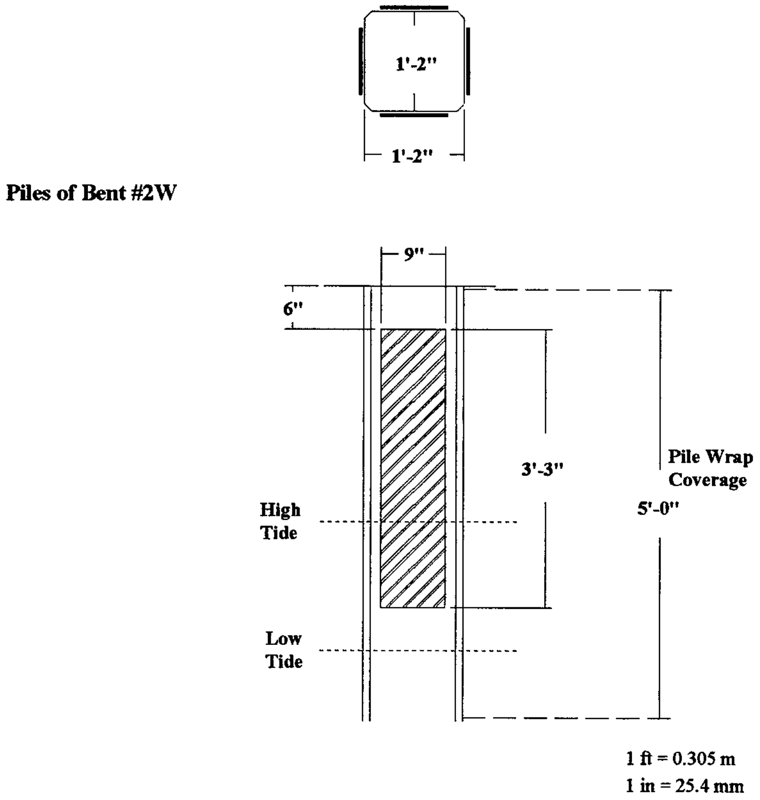
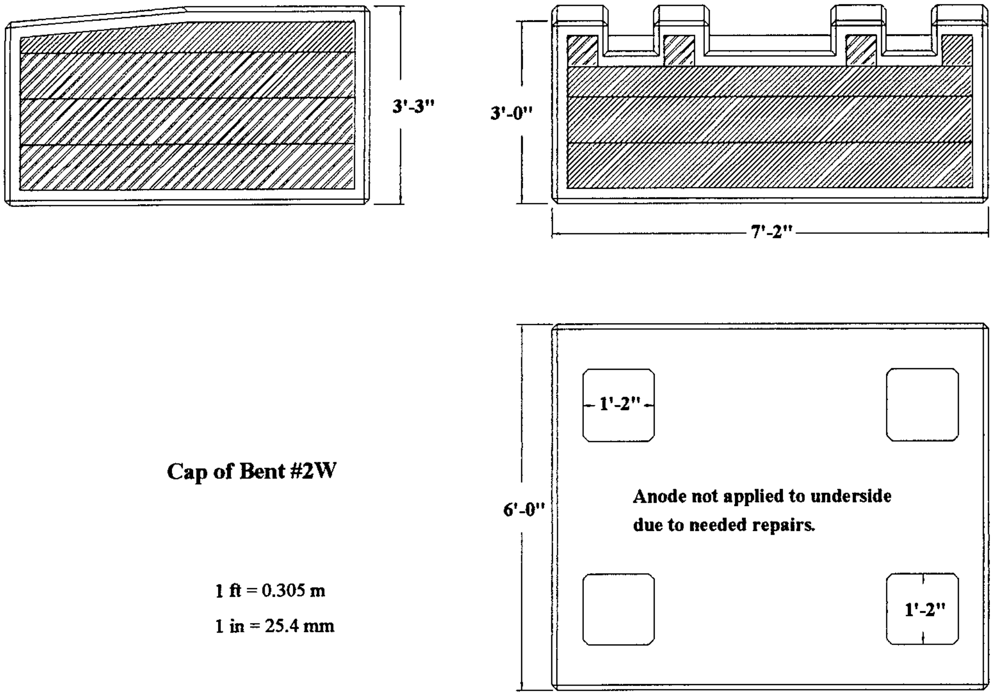


Figure 10. Layout of zinc/hydrogel on piling.

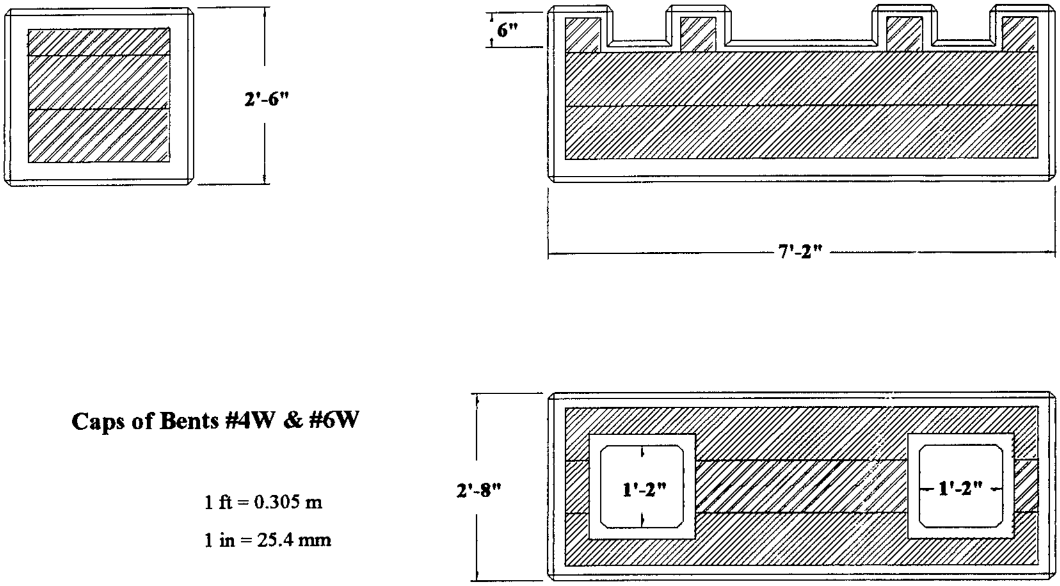


Cap of Bent #2W

Anode not applied to underside due to needed repairs.

1 ft = 0.305 m
1 in = 25.4 mm

Figure 11. 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 12. Layout of zinc/hydrogel on pile caps of bents #4 and #6.

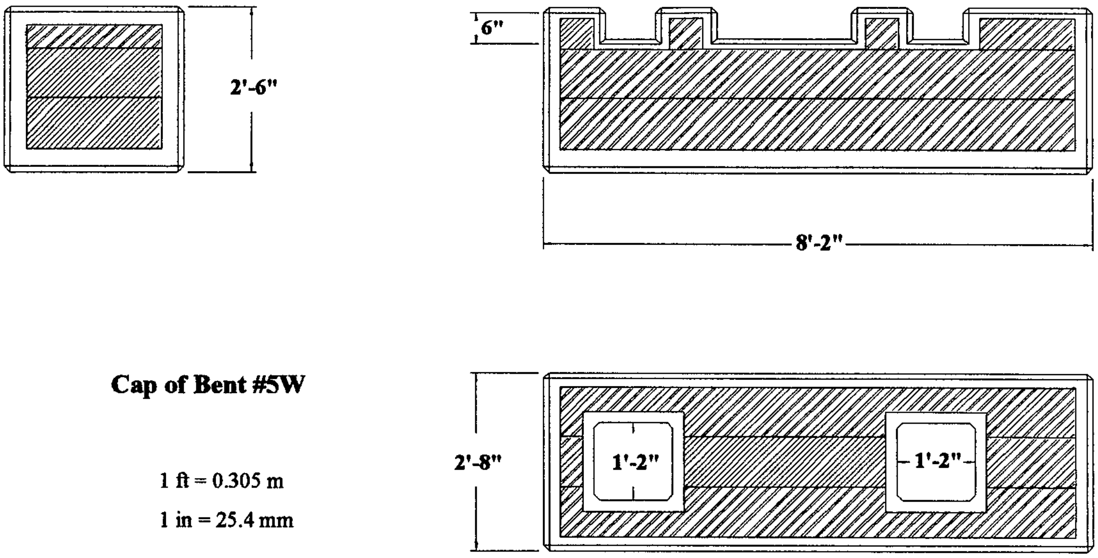


Figure 13. Layout of zinc/hydrogel on pile cap of bent #5.

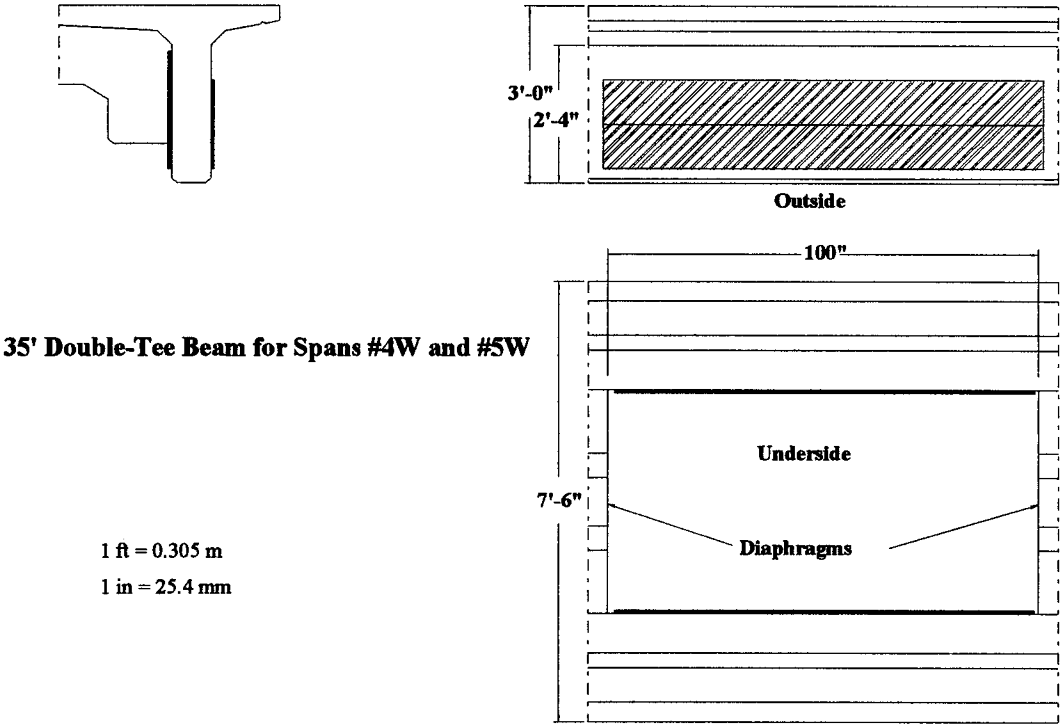


Figure 14. Layout of zinc/hydrogel on beams #4 and #5.

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 at Ft. Pierce.

Zone	Concrete Area, ft^2	Anode Area, ft^2	Steel Area, ft^2
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^2 = 0.093 m^2

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 from April 24 to 28 and May 8 to 12, 1995. Installation on beam #5 was completed from 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 No Corrosion	% of Readings Indicating Uncertainty	% of Readings Indicating Active Corrosion
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^2 (34.5 MPa) and 225 ^{o}F (107 ^{o}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 15.

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 15. 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 16 and 17 show the installed zinc/hydrogel system on bent #2 before and after painting.

Figure 16. Zinc/hydrogel installed on bent #2 pile cap prior to painting.

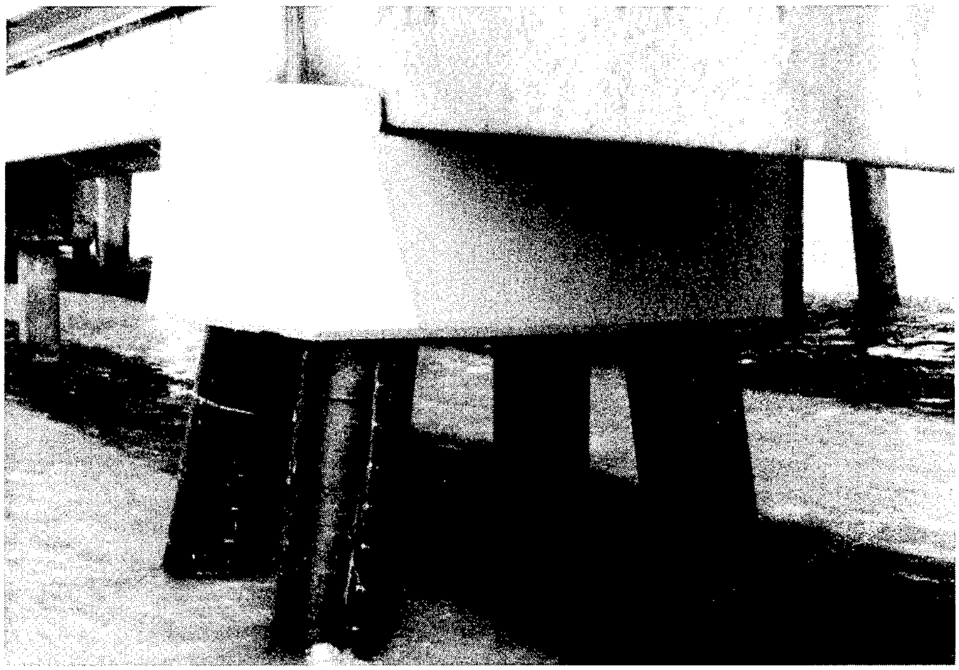


Figure 17. Completed zinc/hydrogel system installed on pilings and pile cap.

Energizing

The members of the 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 shortly after energizing. Current densities are reported as both milliampere per square foot (mA/ft^2) of anode and mA/ft^2 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.

As shown by table 11, current flow was good during initial operation. Although total current delivery dropped slightly, in no case had the current decreased below 1 mA/ft^2 (10.7 mA/m^2) of steel during the first 4 months of operation. Current was especially high for the pilings, which remain wet and conductive because of tide and wave fluctuations.

Operation of the CP system installed at Ft. Pierce was monitored for a period of 31 months. It was first intended to install a remote monitoring unit (RMU), which would automatically monitor both current flow and reference cell potentials and could be remotely accessed by cellular telephone. But this plan was plagued by a series of problems. At first, as a result of construction in progress on the fishing pier, there was no power available for the RMU. When power was finally restored, the RMU and all necessary wiring were installed in November 1996. Even then, power was only available at night for lighting so the RMU could be accessed

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

	5/12/95 mA/ft^2 anode	*5/12/95 mA/ft^2 steel*	*7/31/95 mA/ft^2 anode*	*7/31/95 mA/ft^2 steel*	*9/15/95 mA/ft^2 anode*	*9/15/95 mA/ft^2 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 mA/ft^2 = 10.7 mA/m^2

only at night by cellular phone. Thereafter followed a long series of antenna and battery problems that rendered the RMU essentially useless. Monitoring was therefore conducted manually during a series of scheduled site visits.

Long-Term Operation

Figure 18 shows galvanic current flow to the pile caps for the monitoring period of 31 months. Current density on the caps was high at start-up, and slowly decreased over the first 6 months of operation to about 0.3 mA/ft^2 of steel, which was maintained over the balance of the monitoring period.

Figure 19 shows galvanic current flow to the pilings and the beams. Current density on the pilings was also high at start-up, decreasing slightly over the first few months of operation. But current equilibrated at a relatively high level on the pilings, probably as a result of frequent wetting and higher conductivity. Current density on the pilings averaged about 1.7 mA/ft^2 of steel, higher than necessary to meet CP criteria. Current density on the beams also started out at a high level, but quickly declined to very low values. Current density on beam #4 declined to about 0.15 mA/ft^2 of steel, whereas the current density on beam #5 declined to nearly zero after only 9 months. These low currents were attributed in part to low moisture content and low conductivity, a result of sheltered location and distance above the water. It was also discovered that a loss of electrical continuity had occurred, causing most of the CP system on beam #5 to become inoperative. One attempt to restore continuity on beam #5 was unsuccessful.

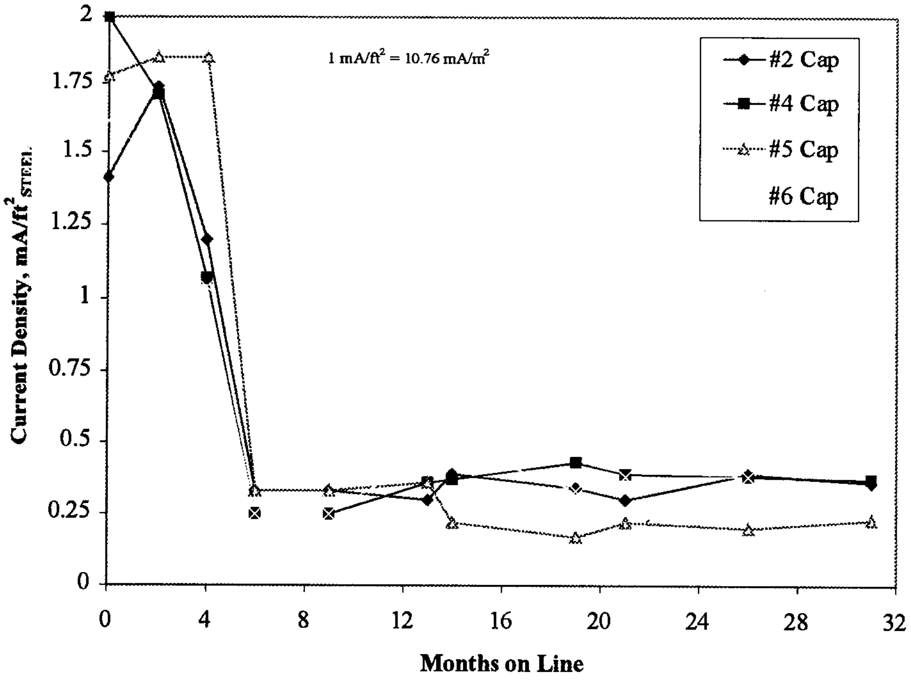


Figure 18. Galvanic current to the pile caps at Ft. Pierce.

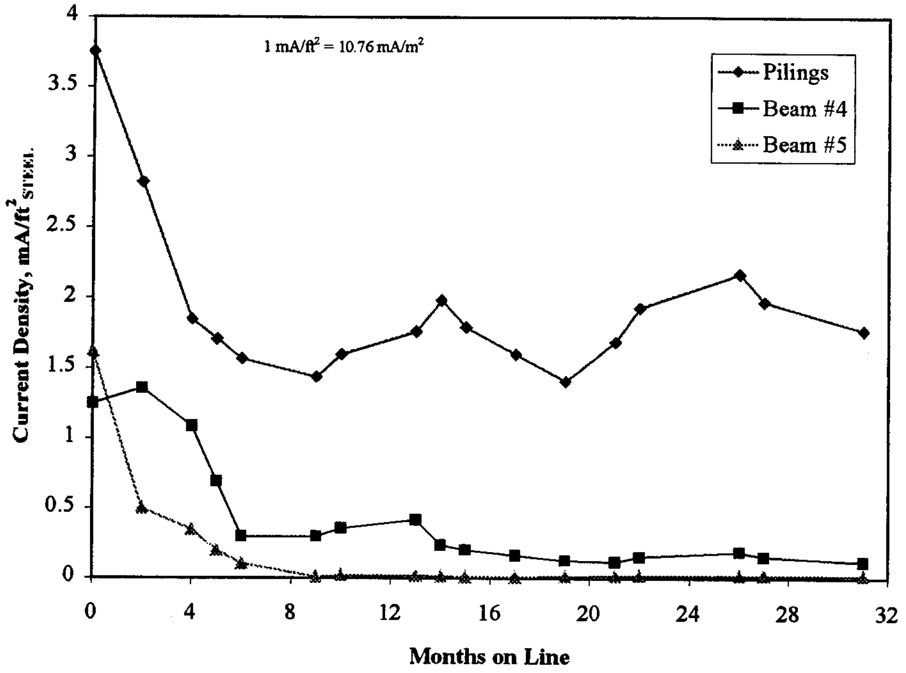


Figure 19. Galvanic current to the pilings and beams at Ft. Pierce.

Potential decay tests were conducted at five different times during the monitoring period, and the results of these tests are shown in table 12. All values shown were recorded after a 4-hour decay period unless otherwise noted.

Table 12. 4-Hour Potential Decay Tests at Ft. Pierce.

	2/6/96	*6/16/96*	*2/3/98*	*7/18/98*	*12/10/98*
Pilings, (embedded reference)	151 mV	106 mV	90 mV (292 mV)	90 mV (216 mV)	102 mV
#2 Cap, (portable reference)			196 mV		198 mV
#4 Cap, (embedded reference)	99 mV	128 mV	68 mV	88 mV	-39 mV
#4 Cap, (portable reference)			217 mV		-289 mV
#5 Cap, (portable reference)	97 mV		178 mV		108 mV
#6 Cap, (portable reference)	137 mV		56 mV*		16 mV*
Beam #4, (portable reference)	148 mV		259 mV		227 mV
Beam #5, (embedded reference)	111 mV	107 mV	39 mV	48 mV	35 mV
Beam #5, (portable reference)	79 mV		270 mV**		267 mV**

(   ) denotes potential after a 24-hour decay period.
* slow decay from concrete saturation.
** at only one location near power connection.

As shown in table 12, 4-hour potential decay values were modest for the pilings despite the relatively high current densities. This was a result of the water-saturated condition of the pilings, and 24-hour potential decay values were much higher (average 254 mV). Also, the instant-off potentials on the pilings were very negative, indicating a good degree of protection. It is likely that the pilings were overprotected throughout the monitoring period. This condition has no adverse effects other than rapid consumption of the zinc anode.

Potential decay values on the pile caps were generally good, near or more than 100 mV, but with two notable exceptions. Four-hour potential decay values were low on #6 cap following construction on the pier in late 1996. The beams above #6 cap were not properly leveled, which caused water to pond and drain through a construction joint directly on top of the cap. This resulted in #6 cap remaining in an almost constant state of saturation, which in turn caused a slow rate of potential decay. Current-off potentials during this period were more negative than -900 mV, indicating a high degree of protection despite the very slow potential decay. Also, a negative potential decay was recorded for #4 cap during the final site visit even though current-off potentials were quite negative. There is no obvious explanation for this behavior.

Potential decay values were good for beam #4 despite relatively low current density. Potential decay values were inadequate for beam #5 as measured using the embedded reference electrodes. This is likely related to the loss of electrical continuity for this member discussed above. Potential decay values taken near the power feed using a portable reference electrode were good.

The zinc/hydrogel CP system at Ft. Pierce looked generally good at the conclusion of the monitoring period, although a slight dark stain had permeated through the topcoat at some of the zinc foil joints. The system was subjected to some vandalism during the first year of operation when a junction box and about 4 in (10.1 cm) of zinc were peeled from #5 Cap, but this was easily repaired during the next site visit. A piece of zinc foil was removed during the final visit for inspection. It was noted that the bond strength of the adhesive had decreased, and that the hydrogel had hardened and turned partly white, apparently a result of loading by zinc corrosion products. This condition had not interrupted the flow of protective current over 3 years of operation.

LONG KEY BRIDGE

Structure Selection and Design

The second structure chosen for a field trial was the Long Key Bridge in the Florida Keys. In this case, the zinc/hydrogel composite was used to cathodically protect precast V-piers that rest on footers about 5 ft (1.5 m) above high tide. The V-piers are separated from the footer by neoprene bearing pads. The bottom of the V-pier measured about 27 in (70 cm) square and contained a double mat of reinforcing steel with several 180-degree bends. The bearing pad and exposed reinforcing steel of the V-pier at Long Key are shown in figure 20. The concrete cover in this area was inadequate, particularly for the bent portions of the reinforcement, and the steel was experiencing significant corrosion. The Florida DOT 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 could enhance contact and maximize the flow of protective current. Zinc/hydrogel was used on two piers showing early deterioration and two piers showing no deterioration. Since this work was specified and contracted by the Florida DOT, involvement with this contract was limited to consultation, monitoring, and reporting.

Installation and Operation

Installation of zinc/hydrogel on the V-piers of the Long Key Bridge was completed early in 1996, and the CP system was energized on February 28, 1996. Figure 21 shows the galvanic current flow provided by the zinc/hydrogel on five V-piers over a monitoring period of up to

27 months. As at Ft. Pierce, the galvanic current started high and then slowly decreased to about 0.5 to 0.8 mA/ft^2 (5.4 to 8.6 mA/m^2). The results of potential decay tests taken during the monitoring period are shown in table 13. As shown by the table, potential decay was good at Long Key, rarely dropping below the 100 mV potential decay criterion.

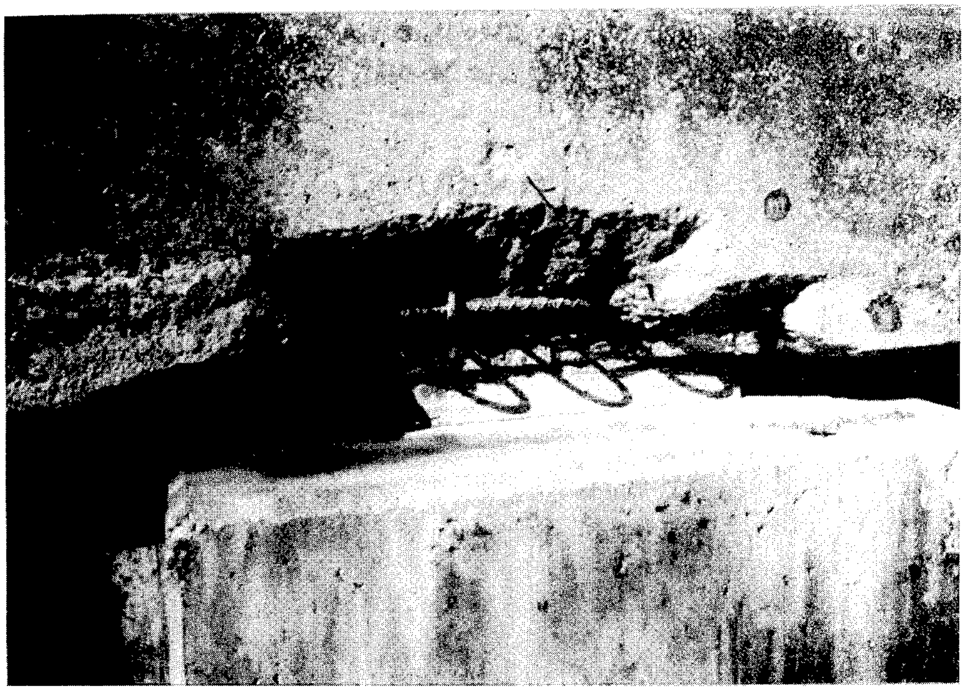


Figure 20. Bearing pad and reinforcement of the V-pier at Long Key.

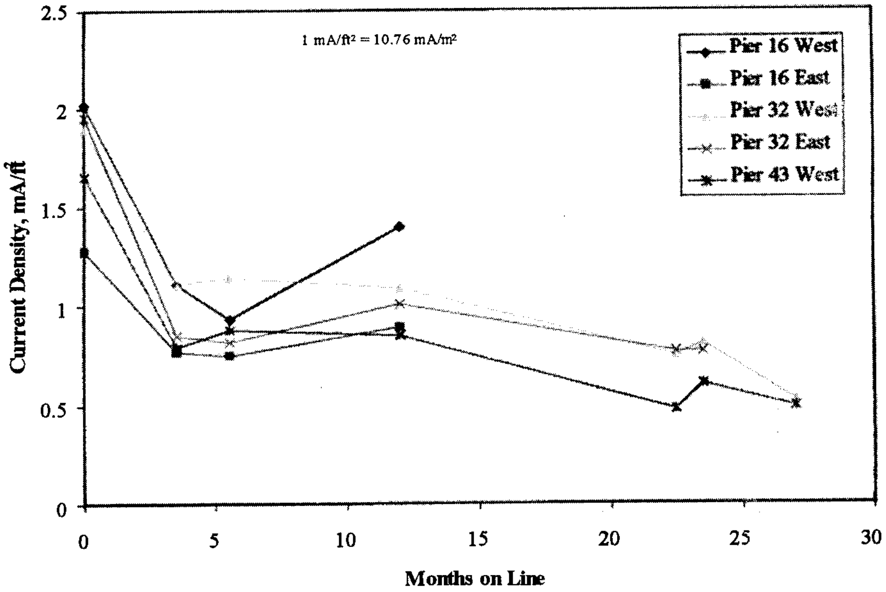


Figure 21. Galvanic current to the V-piers at Long Key.

Table 13. Potential Decay Tests at Long Key.

Time on Line Months	Pier 16 West	Pier 16 East	Pier 32 West	Pier 32 East	Pier 43 West
3½	125**	218*	149*	95*	166*
5½	74	150*	239	137	151
12	88	140*	194	122	138
22½			180	74	110
23½			229	162	169
27			100		175**

Potential decay in mV over 4 to 7 hr, unless otherwise noted.

* 10 min potential decay in mV.

** 16-24 hr potential decay in mV.

A problem encountered late in 1997 led to the hasty removal of zinc from Pier 16 at Long Key. During an inspection it was noticed that this pier had slipped laterally about 9 in (23 cm) on its bearing pad. This slippage, which may have been facilitated by the gelatinous hydrogel adhesive, was considered hazardous and the zinc/hydrogel was quickly removed and replaced by zinc mesh. Zinc/hydrogel was left on the remaining piers since no other slippage was apparent, and monitoring continued on those piers through the summer of 1998. Performance of the remaining zinc/hydrogel at Long Key was still satisfactory at the conclusion of this contract.

Another installation of zinc/hydrogel was placed on Pier 28 at Long Key on April 20, 1998. In this case, the zinc/hydrogel was placed on the vertical faces of the pier immediately above the bearing pad. It was hoped that galvanic current from the anode applied in this way would be sufficient to protect the steel in the pad. Unfortunately, the hurricane that hit the Florida Keys in the summer of 1998 removed the zinc/hydrogel from Pier 28, probably because the edges of the anode were not sealed to prevent water ingress.

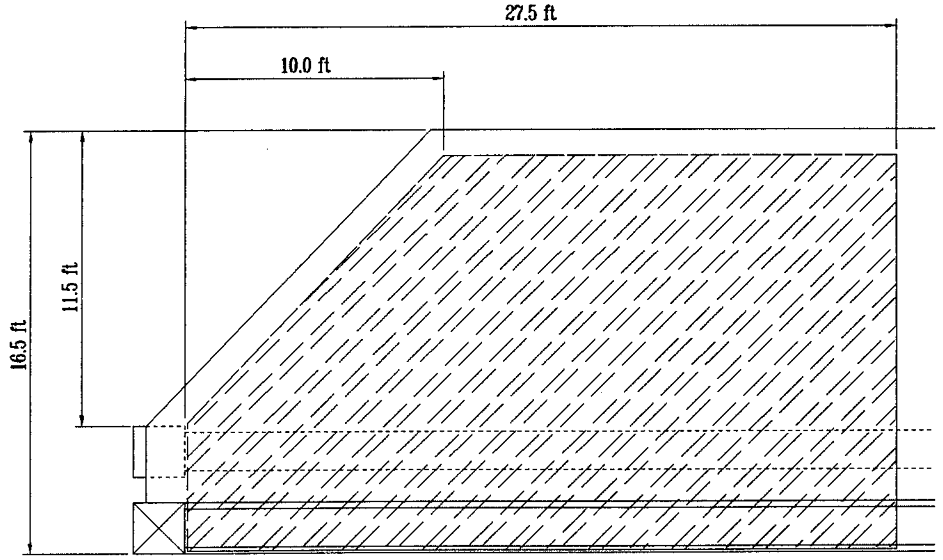
CAPE PERPETUA HALF-VIADUCT

Structure Selection and Design

The Cape Perpetua half-viaduct was selected for installation of three galvanic CP systems. The three systems included pure metallized zinc, aluminum-zinc-indium alloy, and zinc/hydrogel. The purpose of the project was to provide a direct comparison of the performance of these three systems under identical operating conditions. The portion of the structure receiving zinc/hydrogel was funded under this contract. Funding for the other two CP systems was provided by the Office of Technology Application, FHWA, under Demonstration Project 84. The Cape Perpetua half-viaduct is located about 2 miles south of Yachats, Oregon, on US Route 101. The western side of the viaduct is exposed to wind off the Pacific Ocean, and chloride ions from the marine environment had penetrated the concrete and accumulated in sufficient concentration to cause corrosion of the reinforcing steel. There were areas of the bottom of the deck, beam, and bent surfaces of the viaduct that were spalled and delaminated because of corrosion. Beneath the viaduct was a vertical drop of nearly 300 ft (90 m) to the ocean, making access difficult.

The viaduct was divided into three approximately equal areas for installation of the three galvanic systems. The area to receive zinc/hydrogel was the northern-most section and included deck soffit, beam, curb soffit, and curb face surfaces. The total surface area of concrete to receive zinc/hydrogel was approximately 648 ft^2 (61 m^2). About 20 percent of this surface area was spalled or delaminated because of corrosion of the reinforcing steel.

A plan view of the portion of the half-viaduct where zinc/hydrogel was installed is shown in figure 22, and figure 23 shows a strip of zinc/hydrogel being installed on the curb soffit. The zinc/hydrogel anode was connected through a resistor of known value to the reinforcing steel to permit testing of polarization development/decay. Two reference electrodes, one silver-silver chloride and one graphite, were permanently installed in the zinc/hydrogel zone to facilitate potential decay testing. The galvanic current provided by the anode was passed through a resistor to allow measurement of the protective current provided to the steel, and a battery powered RMU was installed to monitor the flow of current and reference electrode potentials.



1 ft = 0.95 m

Figure 22. Plan view of the zinc/hydrogel zone at Cape Perpetua.

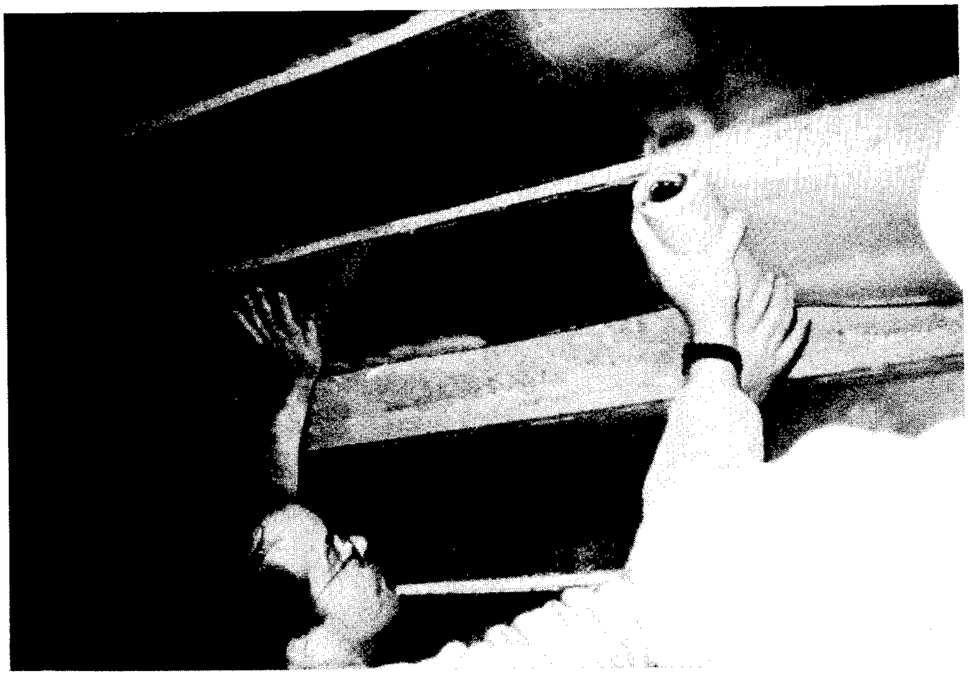


Figure 23. Zinc/hydrogel being installed on the curb soffit at Cape Perpetua.

The other two anodes installed at Cape Perpetua, metallized zinc and aluminum-zinc-indium alloy, were both directly connected to the reinforcing steel. A 1.0 ft^2 (0.93 m^2) window was isolated to allow for the measurement of galvanic current. The current to each window was passed through a measuring resistor, and the measurement was recorded by the RMU. No embedded reference electrodes were installed in the metallized zinc or aluminum alloy zones.

Installation and Operation

Prior to installation of the zinc/hydrogel anode, all spalls and delaminations were repaired, and surface imperfections were ground smooth to receive the anode. Zinc/hydrogel was installed at Cape Perpetua on October 27-30, 1997. The 648 ft^2 (61 m^2) of anode was installed by three men in about 1½ days. The edges of the anode strips were sealed with polyurethane caulking, and the anode was painted only on the outside curb soffit and curb faces that were subject to weathering.

All three CP systems at Cape Perpetua were energized on January 1, 1998. The flow of galvanic current for the three anode systems is shown in figure 24. Fourth-order polynomial trendlines have been aded to provide a smooth representation of the data. Current for all three anodes was initially gauged by measuring the voltage drop across a 0.75-ohm resistor. But this procedure was inappropriate for the zinc/hydrogel zone, where current was being measured on the entire 648 ft^2 (61 m^2) rather than a small test window. In that case the resistance of the circuit was less than 2.0 Ω and the 0.75-Ω resistor presented too great an impediment to current flow. This was recognized, and the measuring resistor was changed to 0.01 Ω in early April 1998. This change is recognized by an increase in current flow shown in figure 24. The flow of current at Cape Perpetua appeared to decline less from start-up than that at Ft. Pierce, and was more influenced by seasonal change. It is also interesting to note that the highest galvanic current at Cape Perpetua was provided by the metallized zinc anode, followed by zinc/hydrogel, and the lowest current was provided by the aluminum alloy anode.

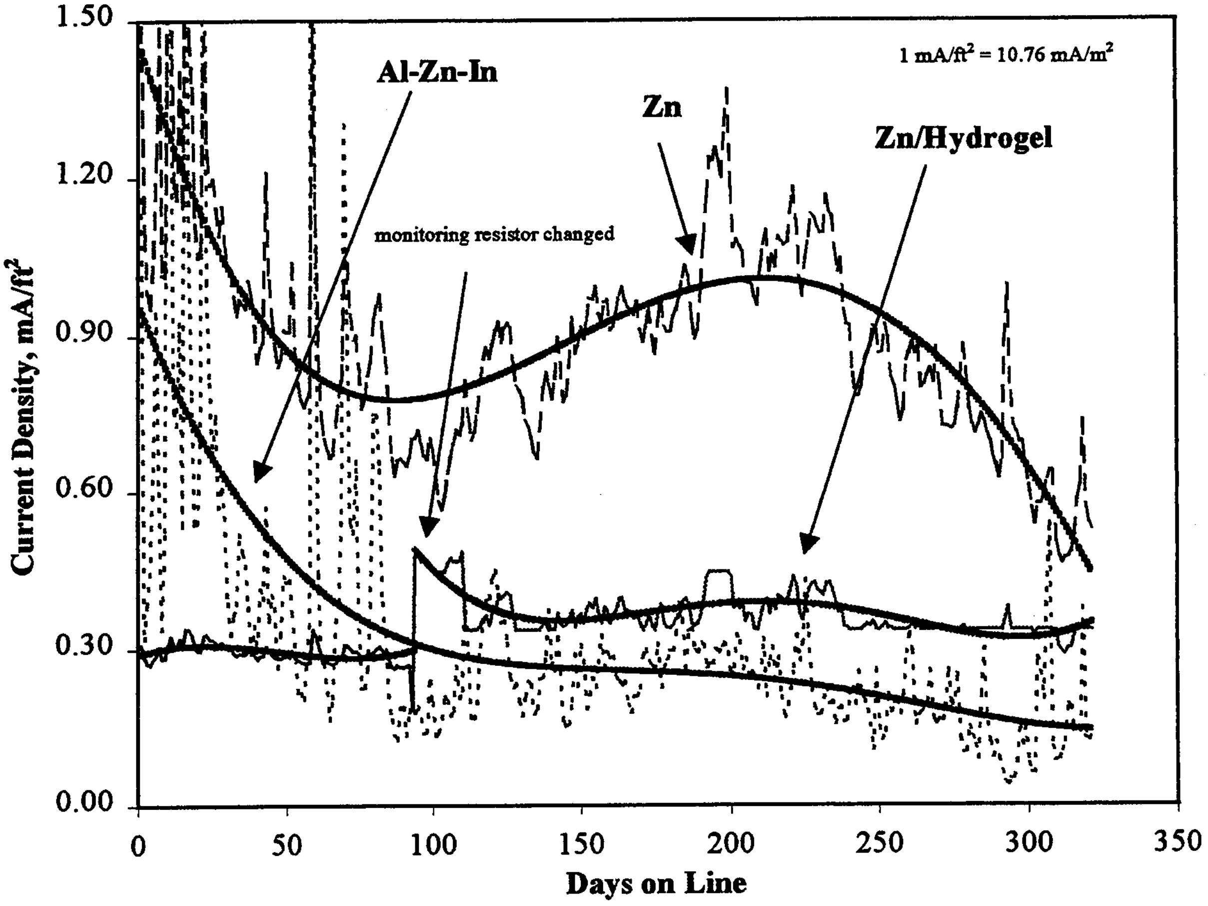


Figure 24. Galvanic current provided by three CP systems at Cape Perpetua.

Potential decay was conducted on the zinc/hydrogel zone in April and again in November as shown in table 14. As shown in the table, all recorded potential decays were well in excess of the 100-mV criterion.

Table 14. Potential Decay Tests of Zinc/Hydrogel Zone at Cape Perpetua.

	April 21, 1998		November 19, 1998
	4-hr decay	16-hr decay	4-hr decay
Ag/AgCl Reference	270 mV	305 mV	225 mV
Graphite Reference	246 mV	276 mV	189 mV

At the time of the last site visit, the zinc/hydrogel installed at Cape Perpetua looked very good. The bond of the hydrogel adhesive was very aggressive and there appeared to be very little non-Faradaic corrosion of the zinc foil.

CHAPTER 5. PRESENT COMMERCIAL STATUS

The zinc/hydrogel anode developed under this contract is presently marketed commercially under the name "4727 Anode." As of February 1999, the 4727 Anode had been installed on 9 bridges, 5 parking structures, and 9 condominiums, representing a total of about 108,000 ft^2 (10,000 m^2) of concrete surface area. The zinc/hydrogel anode has found special interest for users who prefer the simplicity and reliability of galvanic CP systems. Ease of installation and lesser requirements for long-term monitoring and maintenance have been its greatest assesets.

The cost of installation for this type of anode varies greatly with circumstances, such as condition of the concrete and difficulty of access, but the anode together with all ancillary CP components can generally be installed for \$8-\$12 per square foot (\$85-130 per square meter). To this must be added the cost of the topcoat, if needed.

CHAPTER 6. CONCLUSIONS

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^2 (1140 A-hr/m^2) in accelerated testing. This charge is equivalent to about 12 years of operation for a system operating at typical CP current densities. Hydrogel adhesives available for medical applications are not satisfactory for cathodic protection 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^2 (100 m^2) of zinc/hydrogel was 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^2 (20.7 mA/m^2) of steel. After 6 months of operation current densities on the pile caps declined to about 0.30 mA/ft^2 (3.2 mA/m^2) of steel, which was maintained throughout the 31-month monitoring period. This was generally sufficient to polarize the steel about 100 mV. Current on the pilings remained high.

- Zinc/hydrogel CP systems were also installed on the Long Key Bridge in Florida and the Cape Perpetua half-viaduct in Oregon. In both cases installation of the anode was relatively easy, and operation of the system was satisfactory during initial operation.

- After 31 months of operation at Ft. Pierce, the hydrogel adhesive had become somewhat hard and had lost tack, but this condition did not interrupt the flow of protective current during the monitoring period of this contract. The useful lifetime of the zinc/hydrogel anode is not yet established by experience in the field.

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