
Field Evaluation of a New Aluminum Alloy as a Sacrificial Anode for Steel Embedded in Concrete

PUBLICATION NO. FHWA-RD-98-058

APRIL 1998



U.S. Department of Transportation
Federal Highway Administration

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



1. REPORT NO. FHWA-RD-98-058		2. GOVERNMENT ACCESSION NO.		3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE FIELD EVALUATION OF A NEW ALUMINUM ALLOY AS A SACRIFICIAL ANODE FOR STEEL EMBEDDED IN CONCRETE			5. REPORT DATE April 1998		
			6. PERFORMING ORGANIZATION CODE		
			8. PERFORMING ORGANIZATION REPORT NO.		
7. AUTHOR(S) M. Funahashi and W.T. Young		9. PERFORMING ORGANIZATION NAME AND ADDRESS Corpro Companies, Inc. 610 Brandywine Parkway West Chester, PA 19380			
12. SPONSORING AGENCY NAME AND ADDRESS Office of Engineering Research and Development Federal Highway Administration, HNR-10 6300 Georgetown Pike McLean, VA 22101-2296		10. WORK UNIT NO. (TRAIS) 3D4b			
		11. CONTRACT OR GRANT NO. DTFH61-92-C-00079			
		13. TYPE OF REPORT AND PERIOD COVERED Final Report April 1995 - October 1997			
15. SUPPLEMENTARY NOTES Contracting Officer's Technical Representative (COTR): Y.P. Virmani, HNR-10 Subcontractors involved in the development of new alloys were Sumitomo Metal Mining Co. and Drexel University Materials Engineering Department, Dr. Alan Lawley. The assistance of Mr. Rodney Powers and his personnel of the Florida Department of Transportation is acknowledged.		14. SPONSORING AGENCY CODE			
		16. ABSTRACT <p>This is the final report for a study to evaluate the use of sacrificial cathodic protection for reinforced and prestressed concrete bridge members. Cathodic protection (CP) using impressed current is an accepted and common method used to provide corrosion protection to steel in concrete. Sacrificial cathodic protection, however, is relatively easy to apply, does not require that the anode be electrically isolated from the steel, and does not require an external power supply. In the past, attempts to apply sacrificial anode CP to bridge structures have met with limited success because conventional sacrificial anode alloys operate at a low fixed potential and the conductivity of concrete often does not permit satisfactory current output. The Florida Department of Transportation (DOT) has applied arc-sprayed zinc to several bridges in the marine environment. This study examined the performance of existing sacrificial alloys in different environments for sacrificial CP, and developed new sacrificial alloys for protecting steel in concrete. The study consisted of both laboratory and field tasks. The first task consisted of tests to identify suitable environments for sacrificial alloys. In this task, an alloy consisting of aluminum, zinc, and indium 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. In the laboratory tests, the aluminum alloy outperformed pure zinc. The field task was designed to evaluate the alloy on a real bridge structure for a period of 2 yr. The bridge selected was the Bryant Patton Bridge, which is located between Eastpoint and St. George Island in Florida. This bridge has experienced significant corrosion problems with its substructure, and has been the subject of evaluations of thermally sprayed zinc and zinc compression jacket anodes by Florida DOT. Two bents were selected for the current tests. One bent consisted of four piles. Two of these piles were sprayed with the aluminum alloy, which consisted of 80 percent aluminum, 20 percent zinc, and 0.2 percent indium. The other two piles were sprayed with pure zinc. The piles were instrumented to measure anode current, rebar potential, rebar probe current, and structure depolarization. The other bent also consisted of four piles. Two of these piles were coated with the aluminum alloy, and one pile was coated with pure zinc. The piles on the second bent were not instrumented. Testing during the 2 yr of operation and final on-site testing indicate that the aluminum alloy is capable of providing a better degree of cathodic protection to the embedded steel than pure zinc.</p>			
17. KEY WORDS Cathodic Protection, Corrosion, Prestressed Concrete, Concrete, Pre-Tensioned Concrete, Cathodic Protection, Bridges, Sacrificial Anodes		18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.			
19. SECURITY CLASSIF. (OF THIS REPORT) Unclassified	20. SECURITY CLASSIF. (OF THIS PAGE) Unclassified	21. NO. OF PAGES 65	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
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
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

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

* 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>Section</u>	<u>Page</u>
INTRODUCTION	1
CHAPTER 1. OVERVIEW OF PREVIOUS WORK	5
Effect of Environment.....	5
Testing of Existing Sacrificial CP Systems	6
Laboratory Evaluation of Existing Alloys	6
Laboratory Development of New Alloys.....	7
Conclusions from Laboratory Evaluations	7
CHAPTER 2. ALLOY APPLICATION TO BRIDGE.....	9
CHAPTER 3. GALVANIC ANODE PERFORMANCE	19
Remote Monitoring.....	19
Field Examination.....	25
Visual Condition.....	25
Electrical Measurements	36
Adhesion	49
Anode Consumption	49
CONCLUSIONS.....	55
RECOMMENDATIONS	55
REFERENCES	57

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Location of the Bryant Patton Bridge and the piles used to test the sacrificial anodes.....	9
2	General layout of island-side piles (test location #1).....	11
3	General view of mainland-side piles (test location #2).....	13
4	General view of Bryant Patton Bridge from St. George Island - view toward north.	14
5	Application of aluminum alloy using arc-spray equipment (test location #1).	14
6	View of cathode connection at piles 1 to 4.	15
7	Schematic diagram of connections to piles.....	15
8	Details of reference electrode and rebar probe construction.....	16
9	Completed island-side piles 1 yr after installation (test location #1)	16
10	Terminal board inside data acquisition unit.....	17
11	Schematic of data acquisition system	20
12	Sacrificial anode current density on steel, 8/30/95 to 10/9/95.....	21
13	Depolarization curves, 10/24/95	23
14	General view of the mainland-side pile bent (test location #2), May 1996	27
15	View of north and west faces of pile #1-1, May 1996.....	28
16	View of north and west faces of pile #1-2, May 1996.....	28
17	Pile #1-3, north and east faces, May 1996.....	29
18	Pile #1-4, north and east faces, May 1996	29

List of Figures
(continued)

<u>Figure</u>		<u>Page</u>
19	General view of island-side pile bent (test location #1) on June 9, 1997	30
20	View of north and east faces of pile #2-5, June 1997	32
21	View of south face of pile #2-5, June 1997	32
22	View of north and east faces of pile #2-6, June 1997	33
23	View of north and west faces of pile #2-6, June 1997	33
24	View of north face of pile #2-6, June 1997.....	34
25	View of north and east faces of pile #2-7, June 1997	34
26	View of west face of pile #2-7, June 1997.....	35
27	View of south and east faces of pile #2-7, June 1997.....	35
28	Galvanic anode current density (on steel) and driving voltage, June 10, 1997	38
29	Comparison of instant-off and static cathode potentials with position on pile, June 11, 1997	38
30	Instant-off anode potentials, pile #1-1	39
31	Static anode potentials, pile #1-1	39
32	Instant-off anode potentials, pile #1-2	40
33	Static anode potentials, pile #1-2	40
34	Instant-off anode potentials, pile #1-3	41
35	Static anode potentials, pile #1-3	41
36	Instant-off anode potentials, pile #1-4	42
37	Static anode potentials, pile #1-4	42

List of Figures
(continued)

<u>Figure</u>		<u>Page</u>
38	Mixed anode-cathode potentials, piles on mainland side, June 10 to 11, 1997	43
39	Depolarization to embedded reference, final data, pile #1-1	45
40	Cathode depolarization on pile surface, final data, pile #1-1	45
41	Depolarization to embedded reference, final data, pile #1-2	46
42	Cathode depolarization on pile surface, final data, pile #1-2	46
43	Depolarization to embedded reference, final data, pile #1-3	47
44	Cathode depolarization on pile surface, final data, pile #1-3	47
45	Depolarization to embedded reference, final data, pile #1-4	48
46	Cathode depolarization on pile surface, final data, pile #1-4	48
47	SEM image of a cross-section through the concrete core from pile #1-1 south face, 100X	51
48	SEM image of a cross-section through the concrete core from pile #1-2 south face, 100X	52
49	SEM image of a cross-section through the concrete core from pile #1-2 north face, 100X	52
50	SEM image of a cross-section through the concrete core from pile #1-3 west face, 100X	53

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Initial corrosion potentials at selected test points on the piles at test location #1.....	10
2	Initial anode data for piles #1-1 to #1-4.....	19
3	Summary of current and depolarization values observed at test location #1	24
4	Condition of the test piles at May 15, 1996, inspection.....	26
5	Condition of the test piles at June 9 to 11, 1997, inspection	31
6	Test locations for potentials on piles #1-1 to #1-4.....	37
7	Summary of depolarization values to embedded reference electrode, piles #1-1, 1-2, 1-3, and 1-4.....	44
8	Adhesion test results	49
9	Estimates of anode life on the basis of estimated thickness lost.....	54

INTRODUCTION

Many structures have been built to support our nation's highway system in the last several decades. Since the late 1960's, the infrastructure has been facing major problems regarding significant corrosion of conventional reinforcing steel. Both conventional and prestressed reinforced concrete bridges, which once were thought to be virtually maintenance-free, are deteriorating as a result of extensive use of deicing salt. In addition, numerous reinforced and prestressed concrete structures located in marine environments also are experiencing corrosion caused by seawater or chloride-laden air. Maintenance costs for concrete structures that are exposed to such corrosive environments have become large expenditures for many owners.

To extend the service lives of existing structures, various protection methods have been evaluated. In the late 1970's, the Federal Highway Administration (FHWA) expended considerable effort to assess the effectiveness of various repair methods as applied primarily to reinforced concrete bridge decks. The conclusion was that "only cathodic protection (CP), either alone or in combination with other repair methods, is capable of completely stopping the corrosion of the reinforcing steel in chloride-contaminated concrete."⁽¹⁾ Recently, the FHWA encouraged states to protect existing bridges before they reach the stage where replacement is necessary. The FHWA strongly suggested that CP systems should be used more frequently as a cost-effective means to extend the useful life of chloride-contaminated bridges.⁽²⁾

Since the first impressed current CP system was installed on a bridge deck in California in 1973, the technology has advanced significantly. The majority of CP systems for reinforced concrete structures are of the impressed current type. With impressed current CP, an external direct current (dc) power supply, or rectifier, is used to force cathodic protection current from the anode through the concrete to the reinforcing steel.

The sacrificial CP system does not require a rectifier because the source of the (dc) current is the anode. All metals have their own oxidation potential (emf) in a particular environment. When two different metals are electrically connected to each other, and both are embedded or immersed in an electrolyte (e.g., water, soil, and concrete), a galvanic cell is established.⁽³⁾ As a result, electrical current flows naturally from the more active (anodic) metal to the less active (cathodic) metal through the electrolyte. When the potentials of two metals in a galvanic cell are greatly different, more current is generated. Therefore, when a metal or an alloy is more anodic than steel embedded in concrete, the more active metal or alloy can be used as a sacrificial anode.

Sacrificial metals commonly used for CP in soil and seawater environments are zinc, aluminum, magnesium, and their alloys. The potential difference of the sacrificial anode with respect to steel is dependent upon the surrounding environment. The effectiveness of an anode is not only determined by the potential of the anode, but also by the magnitude of its anodic polarization. Polarization is the change in the effective potential of the anode (or cathode) resulting from current between the anode and the cathode. The essential requirement for an anode is that it be able to provide adequate current density to polarize the steel sufficiently where the steel will either not corrode at all, or will corrode at an acceptable rate in a cost-effective manner.

Important considerations in selecting an anode are:

- Material composition.
- Potential (oxidation).
- Current output.
- Anode efficiency.
- Polarization characteristics with time.

The external factors that have to be taken into consideration in relation to anode performance are:

1. Surface area of steel requiring protection.
2. Electrolyte:
 - Chemical composition.
 - Temperature.
 - Electrical resistivity (moisture content).
 - pH.
3. Electrical contact of the anode with the electrolyte.

Thus, the performance of a sacrificial anode is a complex interaction between the electrochemical properties of the anode and the environmental factors affecting it.

In 1977, two types of galvanic cathodic protection systems were installed and tested in Illinois by the Portland Cement Association under the National Cooperative Highway Research Program (NCHRP).(4,5) Sacrificial alloys used in this study were zinc ribbon and perforated zinc sheet. The zinc ribbon was placed in saw-cut slots in the bridge deck. The perforated zinc sheet was placed on the concrete deck surface and covered with an open-graded asphalt. Environmental factors, such as temperature, moisture, and salt content, appeared to play an important role in the functioning of the above field-applied systems. The CP systems were not very successful because of the poor distribution of CP current to the rebars and the relatively high cost of the systems. This limited success in sacrificial (galvanic) anode cathodic protection systems prevented further development even though they had inherent simplicity and low maintenance costs. Thus, in the last two decades, much of the work on application of CP to reinforced concrete structures has centered on impressed current techniques.

The Florida Department of Transportation (DOT) has studied the concept of using a thermally sprayed zinc coating as a sacrificial anode for atmospherically exposed concrete bridge components in marine environments. Using the concrete metallizing technique developed by the California Department of Transportation (Caltrans), zinc was applied and tested as a sacrificial anode for bridge substructures in 1983.(6,7) In addition, detailed laboratory tests were conducted on the sprayed zinc sacrificial anode. The results indicated that the cathodic protection current produced by the zinc anodes decreased with time in areas of dryer concrete above the splash zone. However, anodes installed in the splash zone of marine structures appeared to perform well. Thus, the use of thermally sprayed zinc is somewhat limited to moist concrete.

To develop a new sacrificial anode material for sacrificial cathodic protection of reinforced and prestressed concrete substructures of bridges, an intensive research and development program evolved. The program consisted of four tasks:

1. Study the effect of the environment on sacrificial anode CP.
2. Study existing sacrificial anodes applied to reinforced concrete structures in the field.
3. Evaluate suitable materials for their use as sacrificial anodes and determine the limitations of those materials.
4. Develop and test new sacrificial anode materials by thermally spraying them on concrete specimens.

A sprayed-type sacrificial anode is most suitable for bridge substructures. Bridge substructures consist of vertical and overhead surfaces, as well as irregularly shaped concrete surfaces. In addition, since many substructures are highly visible, the sacrificial anode must not only work properly, it may also have to satisfy aesthetic requirements.(8)

To spray metal onto concrete field structures, two techniques (flame spray and arc spray) are generally used.(9) The flame-spray process uses a hand-held gun. A single zinc wire is fed through the back of the gun using an air-driven motor inside the gun and is melted by the mix of oxygen and acetylene gases. The resultant molten metal is propelled out of the gun nozzle by compressed air.

The arc-spray process is basically similar, but uses high-voltage direct current (dc) arc to melt the wire instead of a combustible gas flame. Two metal wires of the alloy being deposited are fed to the spray gun through a power supply unit through hoses to the gun, along with high-pressure air. Each wire is charged with a high dc voltage which causes an arc at the tip of the gun where the wires join. At the tip of the arc-spray gun, the arc melts the wires. At the same time, a jet of compressed air passes through the arc and sprays the molten metal onto the concrete surface as a coating.

As the initial part of the study sponsored by the FHWA, a laboratory and field program was conducted to evaluate the performance of pure zinc as a galvanic anode material, to identify the environmental factors affecting galvanic anode alloys, and to develop an alloy or alloys capable of providing sacrificial CP under both wet and dry concrete conditions. The results of the laboratory portion of that study were presented in FHWA Report No. FHWA-RD-96-171, titled *Development of a New Sacrificial Cathodic Protection System for Steel Embedded in Concrete*. The results of that study identified an alloy of aluminum, zinc, and indium that provided adequate CP under wet or dry, and hot or cold conditions.

The second part of the study involved the application of the alloy to a corroding reinforced/ prestressed concrete bridge, and monitoring of that system for 2 yr to evaluate the performance of the alloy under real field conditions. The alloy was applied to several piles on the Byant

Patton Bridge in Florida. The alloy's performance was compared to that of pure zinc, which was applied to the same bridge. This final report of the study presents results of the field tests on the aluminum-zinc-indium alloy.

CHAPTER 1

OVERVIEW OF PREVIOUS WORK

A sacrificial zinc anode cathodic protection (CP) system used in 1977 to protect a reinforced concrete deck was unsuccessful due to poor CP current distribution and high costs. This prevented further development even though sacrificial systems have inherent simplicity and low maintenance cost. The Florida Department of Transportation (DOT) has studied the concept of using a thermally sprayed zinc coating as a sacrificial anode for atmospherically exposed concrete bridge substructure components in marine environments. CP data analysis indicated that the use of thermally sprayed zinc was somewhat successful for moist concrete. However, the reduction in pH at the anode-to-concrete interface made the anode passive, and a lack of moisture at the interface between the zinc and concrete reduces the activity of the zinc.

An intensive research and development program was funded by FHWA to develop a new sacrificial anode material for reinforced and prestressed concrete substructures of bridges. This work was detailed in FHWA Report FHWA-RD-96-171, titled *Development of a New Sacrificial Cathodic Protection System for Steel Embedded in Concrete*, and dated June 1997. This chapter presents a brief overview of that work.

Effect of Environment

Since bridge members are exposed to many different environments, even on a single bridge, tests were devised to monitor the performance of zinc under various environments. Cement mortar test blocks were constructed containing embedded cathode wires and plates. The wires acted as corrosion sensors. Pure zinc was applied by thermal spraying to one surface and this sprayed zinc anode was connected to the embedded cathodes. The blocks were constructed in such a way that a portion of the wire was exposed to chloride-contaminated mortar, while most of the wire was embedded in chloride-free mortar, thus creating a strong galvanic corrosion cell. The blocks were exposed in sheltered and non-sheltered vertical positions in north, south, east, and west directions in northern marine, southern marine, and northern semi-rural environments. Blocks also were exposed to seawater splash, partial seawater immersion, humid seawater atmosphere, controlled laboratory temperatures of 60 to 80 °F (15 to 27 °C) and relative humidity (40 to 60 percent) with and without salt water spray, and continuous 100 relative humidity (RH).

Those wires exposed to chloride-free cement mortar in the slots and those wires not exposed to water spray during the test did not show corrosion. The zinc anode prevented the initiation of corrosion on some of the wires that were exposed to moisture and chlorides; however, the condition of the plate cathodes also provided interesting information. The corrosion potentials of the steel plates embedded in the blocks with CP were more noble than the plates in the blocks without CP, and less corrosion was observed on these plates. The open circuit potentials of the anode indicated passivation of the zinc on many blocks. The zinc anodes at all of the test sites showed a range in potentials, except the northern marine site where all of the zinc passivated. In spite of the passive potentials observed on the zinc anodes, the corrosion of the steel was reduced when compared with the control blocks without CP.

Testing of Existing Sacrificial CP Systems

Florida DOT had applied metallized zinc to several bridges in the Keys as a sacrificial CP system to protect the embedded reinforcing that had begun to corrode. Tests were conducted on the Bahia Honda and Niles Channel bridges to determine the effectiveness of the CP system. The piles of Niles Channel Bridge contain epoxy-coated reinforcing steel, while the piles of the Bahia Honda Bridge contain bare reinforcing steel. The zinc coating had been applied to the concrete surface and to directly exposed reinforcing steel after the epoxy coating was removed by sandblasting. Rebar probes embedded in the piles and isolated “windows” in the anode had been provided to allow monitoring. Testing included the following: rebar probe (cathode) current measurements, anode (CP) current measurements, instant-off anode potential measurements, instant-off rebar probes (cathode) potential measurements, depolarization tests for zinc windows, depolarization tests for rebar probes, static potential measurements for windows and rebar probes, zinc coating adhesion strength, pH measurements at the concrete/zinc interface, anode-to-concrete surface analysis, and resistance measurements.

Current density to the rebar probes and anodic current density from the anode windows decreased as the height above the waterline increased. The depolarization tests indicated that the rebar probes that were located up to 5 ft from the high tide line met the “100 mV depolarization” criterion regardless of the low CP current densities received by the probes; however, the amount of depolarization decreased with increasing distance from the water. The static potentials of the rebar probes that were embedded in the column, including the probes that had not been connected to the zinc anode, indicated passive potentials. It was suspected that the cement mortar used to embed the rebar probes did not contain chlorides. If the rebar probes were not corroding, the amount of CP current received and the magnitude of depolarization on the probes would not be representative of the corroding reinforcing steel in the concrete. Thus, it was difficult to determine the effectiveness of the sacrificial anode CP system on the basis of data collected from the installed rebar probes. However, the amount of CP current received from the zinc appeared to be sufficient up to 2.5 ft above the water line.

Laboratory Evaluation of Existing Alloys

Fifteen different types of sacrificial alloys were tested on fabricated mortar specimens. In addition to conventional anode materials, two binary aluminum alloys with magnesium, two binary aluminum alloys with zinc, two binary zinc alloy with aluminum, and two tertiary aluminum alloys were selected for evaluation. The alloys were applied to mortar test blocks by either thermal spray or by embedding plates of the alloy in mortar on one side of the block. The mortar contained chlorides and the anodes were connected to embedded steel cathodes. The blocks were exposed in an environmental chamber to 40, 70, or 90 °F (4, 21, or 32 °C), and 40, 70, or 90 percent relative humidity at each temperature. After 10 days of test, depolarization tests were run on the steel and the anode of each mortar specimen to determine the CP effectiveness and the anode performance.

Generally, the anodes produced more current at higher temperatures and higher relative humidity levels. The aluminum alloys performed better than the zinc alloys and maintained relatively high static potentials even under the low temperature and low humidity conditions. The zinc-based anodes generally exhibited passivation after a time. All of the alloys showed a decrease in current output and potential as the pH of the environment decreased; however, the Al-55Zn alloy showed the least decrease in current. The decrease in current was most pronounced below a pH of about 12.

Laboratory Development of New Alloys

Since aluminum-zinc alloys provided the best current output in the previous tests, these were selected for further development. To improve the performance in lower pH (<12) concrete pore solution, various amounts of indium were added to the aluminum-zinc alloys. The optimum amounts of indium were based on the results obtained by potentiodynamic polarization, potential and electrical capacity measurements in simulated concrete pore solution. Further tests evaluated the electrochemical performance of the alloys in simulated concrete pore solutions at various pH levels by purging the solution with carbon dioxide. In addition to the aluminum-zinc-indium alloys, the electrochemical effect of titanium and zirconium also were evaluated. The alloys were subjected to testing at various temperatures and relative humidity levels in an environmental chamber.

Three alloys consisting of aluminum, zinc, and indium were selected from the electrochemical tests and were produced in wire form to be metallized onto mortar test blocks for testing under various temperature and relative humidity conditions. All three new alloys out performed pure zinc and pure aluminum anodes in all of the environments tested. Passive potentials were measured on the steel embedded in some of the chloride-contaminated mortar blocks at the end of the depolarization tests. This tendency was more noticeable on the steel plates that had received higher current densities during the early portion of the testing. Applications of low current density by the new anode alloys depolarized the steel more than 100 mV in the dry environment (40 percent RH) and low temperature. The Al-20Zn-0.2In alloy appeared to perform the best because it had the smallest anode polarization and maintained relatively active static potentials in all the environments.

Conclusions from Laboratory Evaluations

1. The performance of sprayed zinc as a sacrificial anode on concrete is greatly influenced by the presence of moisture at the anode-concrete interface. The zinc anodes that were exposed to moderately corrosive environments appeared to perform well for a relatively short period of time. The zinc anodes that were exposed to highly corrosive environments, such as direct seawater exposure areas, could reduce the corrosion rate of steel; however, the zinc anode could not completely prevent the corrosion of the steel embedded in concrete.
2. The sprayed zinc sacrificial anode installed on field structures appeared to produce moderate amounts of CP current in the areas where concrete resistivity is relatively low because of high moisture levels.

3. The current output from pure zinc and aluminum, as well as commercial sacrificial alloys, significantly decreased at low pH values. The cause of current reduction in the 15 anode materials that were initially selected for testing appears to be the result of the reduction in pH at the anode-to-concrete interface, caused by corrosion products or carbonation of the concrete.
4. The Al-Zn-In alloys developed as sacrificial anode alloys produced sufficient current to cathodically protect steel embedded in chloride-contaminated mortar specimens in the laboratory.
5. The new aluminum alloy sacrificial anodes were superior to pure zinc at various temperature and relative humidity conditions on concrete, and in lower pH (<12) simulated concrete pore solution.
6. If a sacrificial anode can produce sufficient CP current to steel embedded in chloride contaminated concrete for a relatively short period of time, the sacrificial anode current appears to result in the passivation of the steel by removing chlorides from the immediate vicinity of the steel. As a result, a low galvanic (CP) current density is adequate to maintain the cathodic polarization of steel.
7. The new aluminum alloy, applied by the arc- or flame-spray process, was readily applied to concrete and penetrated well into concrete pores, resulting in strong adhesion to the concrete surface.

Because of the ability of the Al-Zn-In alloys to provide adequate CP under conditions where pure zinc lost effectiveness in laboratory tests, it was decided to identify a bridge for field application, and apply the aluminum-20 percent zinc-0.2 percent indium alloy to a portion of that structure. The remainder of this report describes that testing.

CHAPTER 2

ALLOY APPLICATION TO BRIDGE

The laboratory work presented in this report shows that the aluminum-zinc-indium alloys developed under this program provide suitable CP to steel embedded in concrete. The objectives of the project called for this technology to be applied to a bridge structure. Specifically, plans called for installation of the anode material to the substructure of a corroding bridge, and monitoring the performance of the anode for the remainder of the contract period.

The anode was applied with Florida DOT's assistance to selected prestressed concrete piles of the Bryant Patton Bridge, located between Eastpoint and St. George Island in Florida. This location is on the Gulf of Mexico coast between Tallahassee and Panama City. Figure 1 shows the location of the bridge and the test piles.

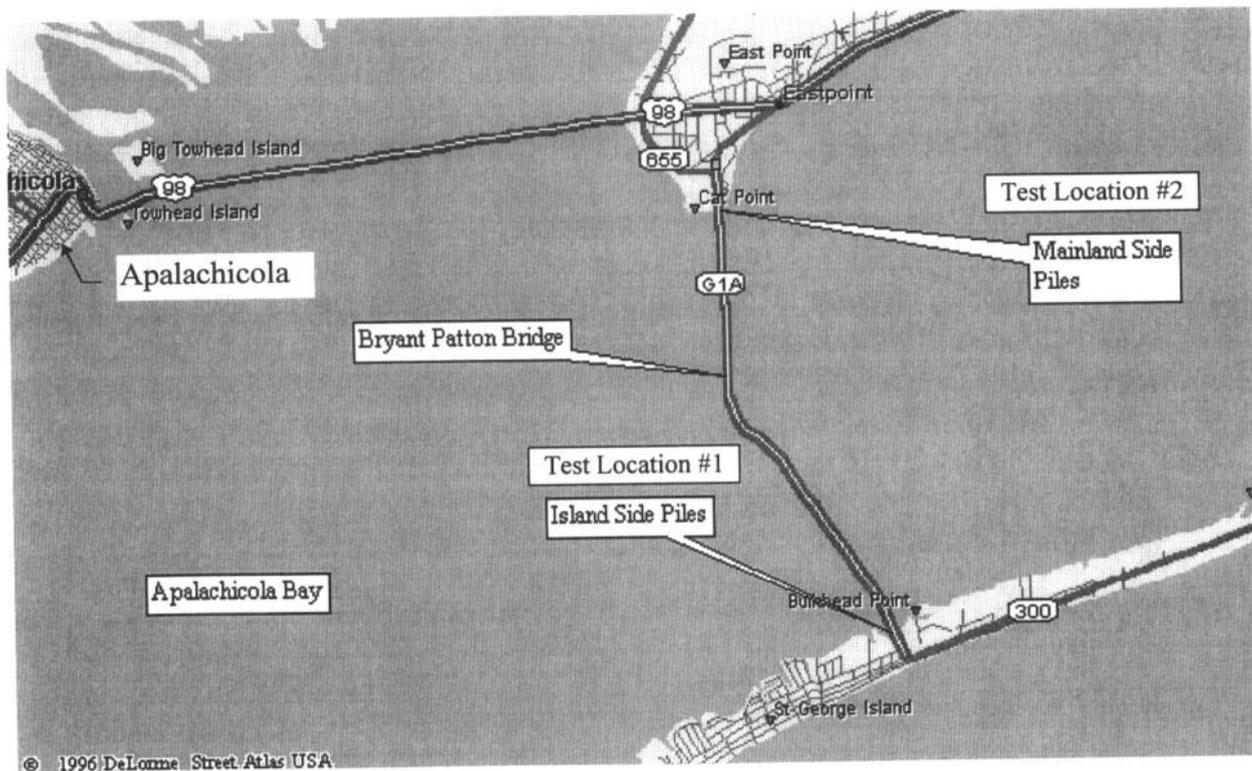


Figure 1. Location of the Bryant Patton Bridge and the piles used to test the sacrificial anodes.

This bridge was selected in collaboration with the Florida DOT. This bridge was about 40 yr old at the time this test program was begun. It is supported by prestressed concrete piles, many of which have suffered corrosion damage. Several piles had deteriorated to the point where supplemental support piles had to be installed. This bridge is the subject of development work by the Florida DOT that includes the installation of a pure zinc metallized anode in atmospheric corrosion zones and zinc expanded metal anode compression panels in splash zones.

Two bents were selected for testing the Al-Zn-In anode. One bent consisting of four piles was selected on the island side of the bridge (bent no. 2, test location #1). One bent consisting of four piles (only three were used for this test) was selected on the mainland side of the bridge (bent no. 129, test location #2), as shown in figure 1. The piles contain 20 stranded longitudinal prestressing tendons at a depth of about 2 in from the surface. The area of steel embedded in each pile was calculated to be 23.2 ft² (2.2 m²). The lower portions of the piles at test location #1 were immersed in seawater. The concrete surface area coated with the anode at test location #1 was 40 ft² (3.7 m²) per pile. The piles at test location #1 also were fitted with reference electrodes, rebar probes, remote monitoring, and control facilities to generate depolarization data remotely from Corpro's West Chester, PA, office.

The lower portions of the piles at test location #2 were in direct contact with seawater during high tide and were exposed during low tide. The concrete surface area coated at test location #2 was also 40 ft² (3.7 m²) per pile. The anodes at test location #2 were connected directly to the embedded reinforcing with no provision for remote monitoring. Figures 2 and 3 show the general layout of the coated piles. Figure 4 shows the bridge looking north and the island-side piles (test location #1). This photograph was taken during the application work and shows the scaffolding in place.

No visible signs of corrosion or distress were present on any of the selected piles. Prior to applying the anode materials, corrosion potentials were taken at selected locations on two piles at test location #1 to confirm that corrosion was taking place. These data were taken on the south face of each pile, and each data point was taken at 1-ft intervals from the top to the bottom of the pile. Table 1 presents the corrosion potential data, which show that the embedded steel reinforcing was corroding.

Table 1. Initial corrosion potentials at selected test points on the piles at test location #1.

Pile*	Location	Average Potential, mV CSE**	Range mV CSE
#1-1	Island side, outside pile	-379	-313 to -434
#1-2	Island side, inside pile	-411	-274 to -543

* Same numbering system as used throughout report (test location # - Pile #)

** CSE = copper-copper sulfate reference electrode

Corrosion Restoration Technologies, Inc., Jupiter, FL, was contracted to prepare the piles and apply the anode. Prior to applying the anode, the contractor blast-cleaned the piles using sand to remove any carbonated concrete and loose material, to expose some aggregate, and to provide a sound surface for the metal coating to adhere.

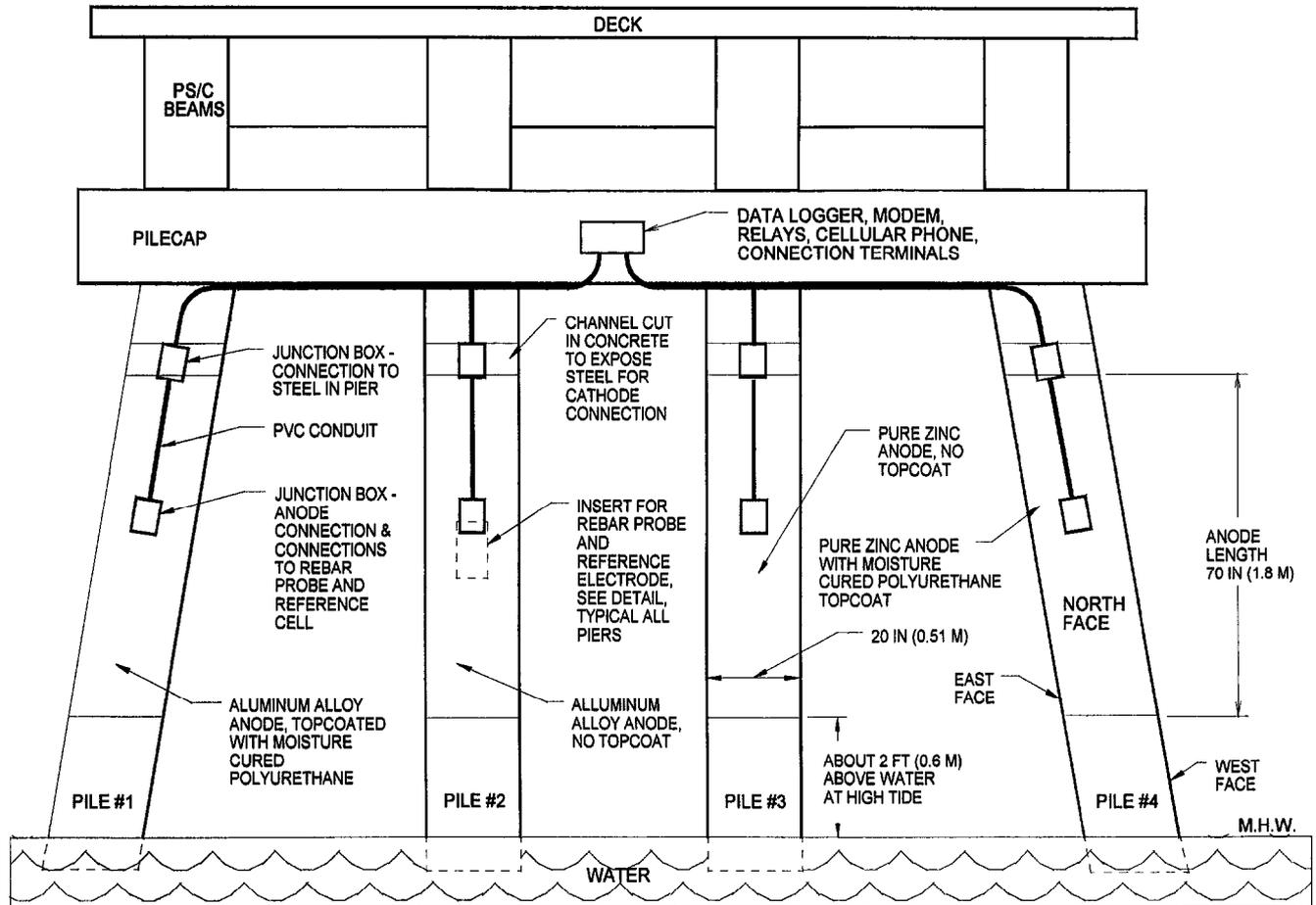


Figure 2. General layout of island-side piles (test location #1).
(view south toward St. George Island)

Two of the piles at test location #1 were coated with the aluminum alloy. In addition, two piles at this bent were coated with zinc for comparative purposes. Piles #1-1 and #1-2 were coated with the aluminum alloy and piles #1-3 and #1-4 were coated with pure zinc. Piles #2-5 and #2-6 on the bent at test location #2 were coated with the aluminum alloy, and pile #2-7 was coated with pure zinc. The zinc used for piles #1-3, #1-4, and #2-7 was 100 percent pure zinc supplied as 1/8-in- (0.3175-cm-) diameter wire. The nominal composition of the aluminum alloy was 80 percent aluminum, 20 percent zinc, 0.2 percent indium, and it was manufactured in the Sumitomo Metal Mining Co. laboratory for this project. Note that pile #2-7 also had a zinc anode mesh compression jacket applied at the base by Florida DOT.

The aluminum alloy was applied using both arc-spray and flame-spray equipment. The contractor first used an Eagle Arc 600 spray gun to spray a 1/8-in- (3.18-mm-) diameter wire. Figure 5 shows the anode application using this device. However, the contractor encountered some problems in applying the anode. Laboratory tests showed that the anode material can be thermally sprayed, either by arc or by flame spray; however, the amount of available manufactured wire and the contracted time at the bridge did not allow this method to be used.

Therefore, most of the wire had to be applied using oxygen-acetylene flame-spray equipment. The north and east faces of piles #1-1 and #1-2 were sprayed using the arc-spray technique. The south and west faces of piles #1-1 and #1-2 were sprayed using the flame-spray technique. The anodes for piles #2-5, 2-6, and 2-7 were applied using flame-spray technique. The target thickness was 12 mils (305 μm) for the aluminum alloy and 20 mils (508 μm) for the pure zinc (this is the thickness of zinc used by Florida DOT).

During application of the anode metal to piles #1-1 to #1-4, tests were conducted to ensure that the anode was electrically isolated from the embedded reinforcing, in order to monitor: the current to the steel reinforcing, current to an embedded rebar probe, reference electrode potential to the structure, and depolarization of the structure. This procedure would not normally be needed with a sacrificial anode installation, but was needed for purposes of this project. No attempt to keep the anode isolated from the embedded steel was made in piles #2-5 to #2-7.

Piles #1-1 and #1-4 were topcoated with a moisture-cured polyurethane (Wasser High-Tech Coatings, Inc., Kent, WA, "Wasser MC-Ferrox-A"), while the other two piles were not topcoated. The objective of topcoating the anode was to determine if this would improve the resistance of the anode to atmospheric corrosion. The detrimental effects of a coating on anode performance also were of interest. The south and east faces of piles #2-5 and #2-6 also were coated with a barrier coating. Pile #2-5 was coated with a moisture-cured polyurethane and pile #2-6 was coated with a water-based latex coating (Sherwin-Williams A-100).

In piles #1-1 to #1-4, the cathode connection for the island-side piles was made by connecting a cable to the diagonal reinforcing wire wrapped around the prestressing tendons. Cutting a channel around the top of the pile to expose the diagonal wire and vertical prestressing tendons accessed this wire. The cathode cable was then brazed to the wire and the back of the cavity was sprayed with zinc to ensure the electrical continuity of each of the tendons. The cavity was then filled with an epoxy mastic. Figures 6 and 7 show the connection. The cavity was then filled with epoxy mastic, and the cathode cable routed to the data logger junction box. In piles #2-5 to #2-8 the anode was electrically connected directly to the prestressing tendons by continuously spraying inside the cavity with the zinc and aluminum-zinc alloy. The cavity was then filled with epoxy mastic (this is the normal manner in which Florida DOT connects the zinc anodes to the reinforcing).

The anode connection for the aluminum alloy consisted of a perforated alloy plate attached to the pile with a stud and epoxy. A reference electrode consisting of a chloridized silver element and a current pick-up rebar probe, both embedded in chloride-contaminated mortar [15 lb/yd³ (9 kg/m³)], were embedded in the pile at the depth of the prestressing tendons. Figure 7 shows the details of the connections of each of these components. Figure 8 shows the details of the reference electrode and the rebar probe construction. The reference probe was intended to act as a reliable reference for depolarization measurements but not as a standard reference.

Environmental Data Systems, Inc., designed a data remote acquisition system. This data acquisition unit (DAU) was designed to allow the current path to be opened to permit

measurement of depolarization potentials. The DAU could be addressed through a cellular phone system mounted on the pile cap (see figure 2). Thus the data could be monitored and downloaded for analysis from Corrpro's office. Figure 9 shows the completed installation (1 yr after installation) and figure 10 shows the interior of the DAU.

The anodes were activated on July 14, 1995. The DAU was activated on August 30, 1995.

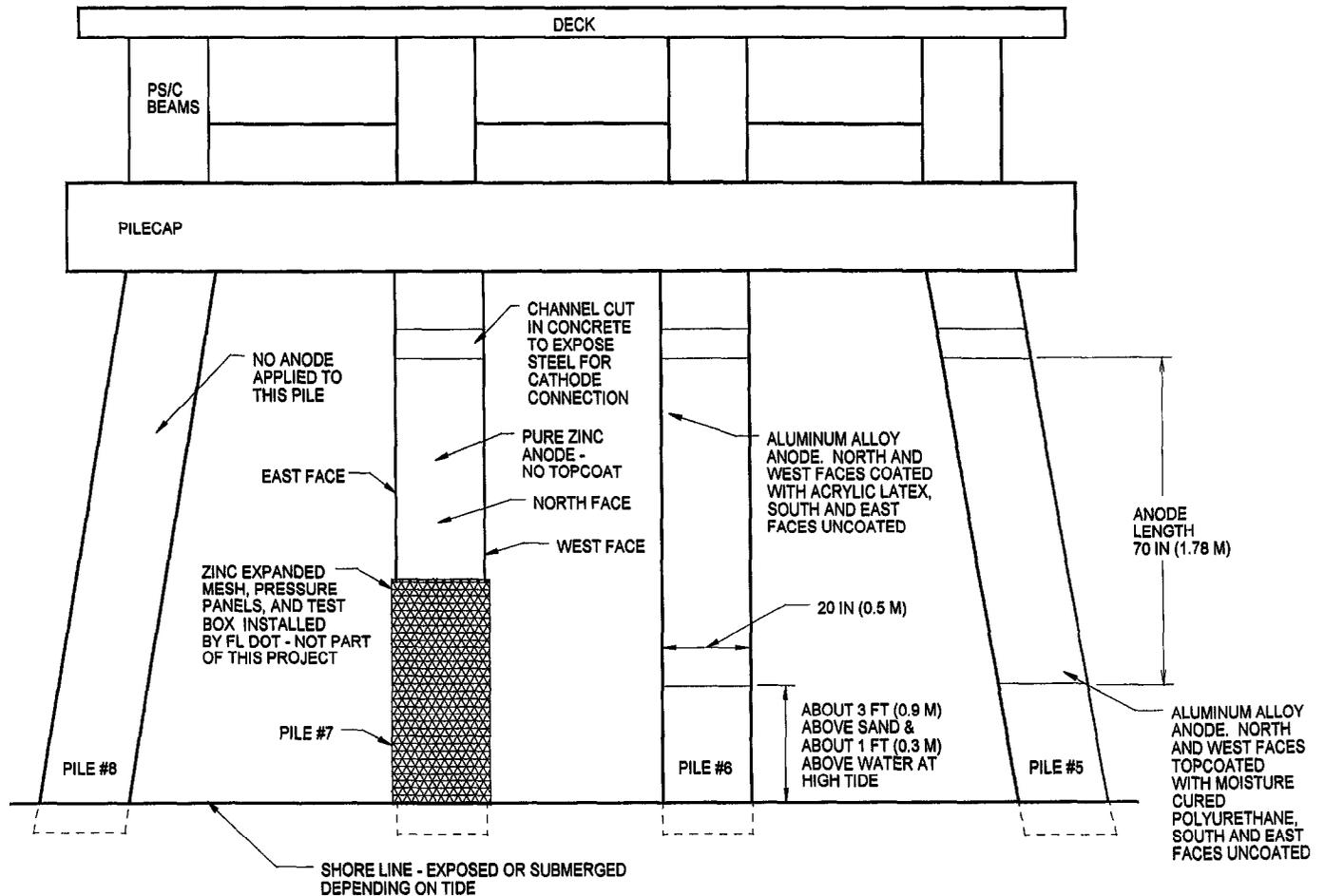


Figure 3. General view of mainland-side piles (test location #2).
(view south toward St. George Island)

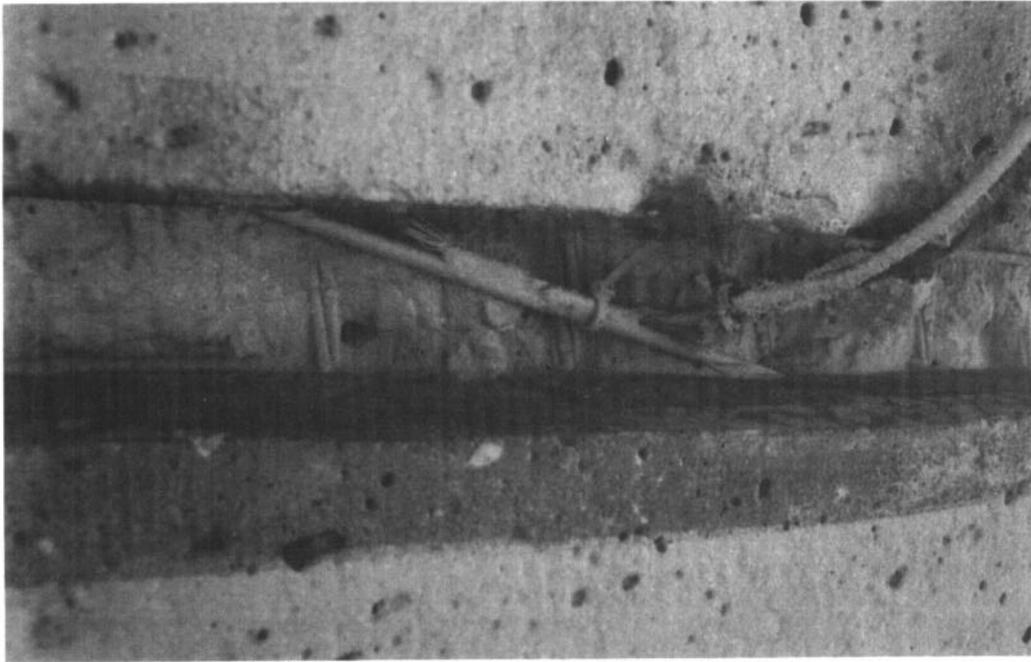


Figure 6. View of cathode connection at piles 1 to 4.

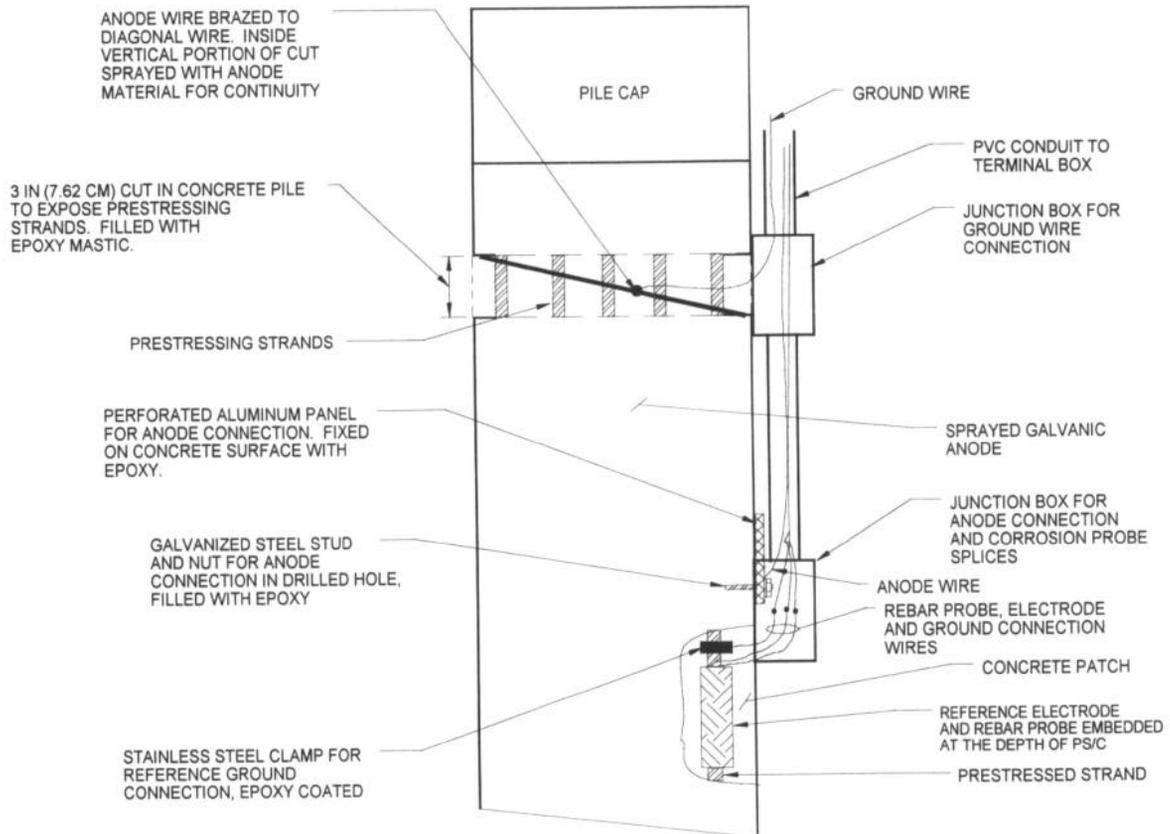


Figure 7. Schematic diagram of connections to piles.



Figure 4. General view of Bryant Patton Bridge from St. George Island - view toward north.
(island-side piles are on the left)



Figure 5. Application of aluminum alloy using arc-spray equipment (test location #1).

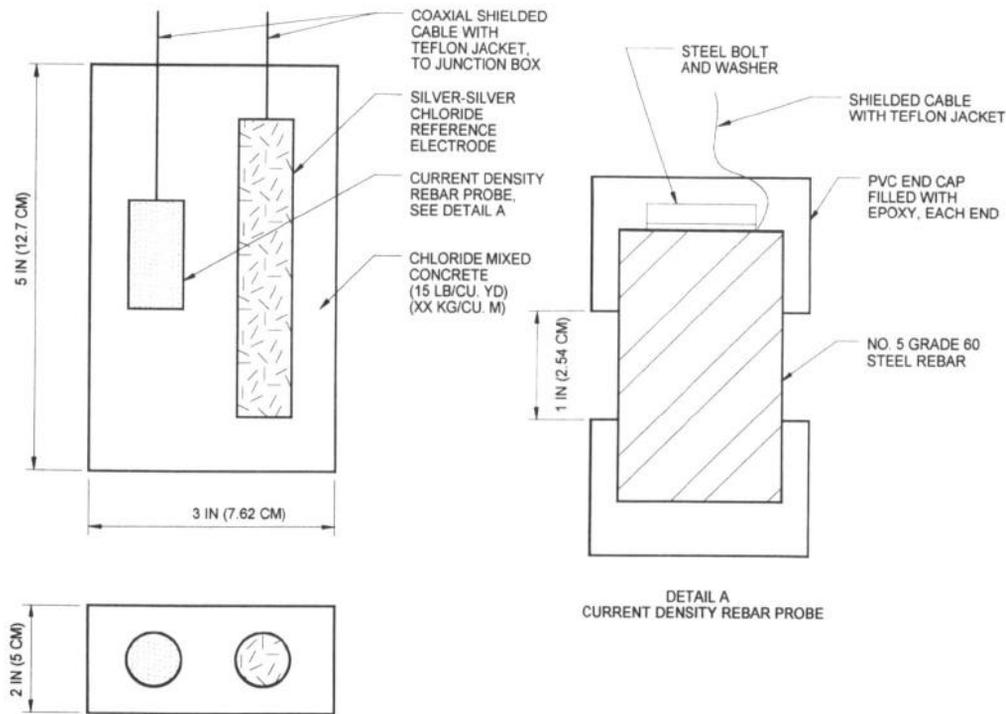


Figure 8. Details of reference electrode and rebar probe construction.

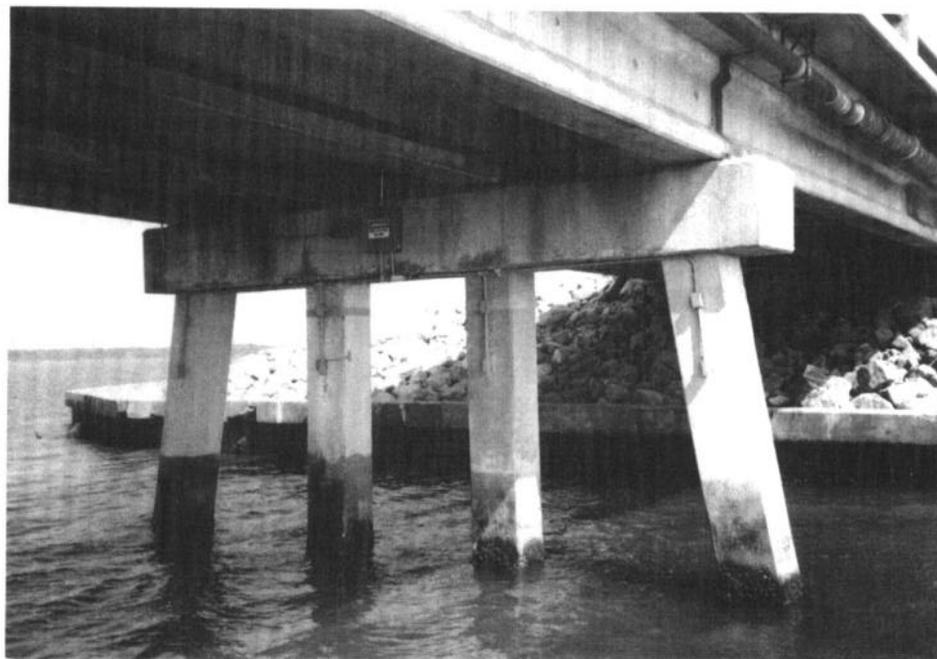


Figure 9. Completed island-side piles 1 yr after installation (test location #1).
(the data acquisition unit is the gray box mounted on the pile cap)

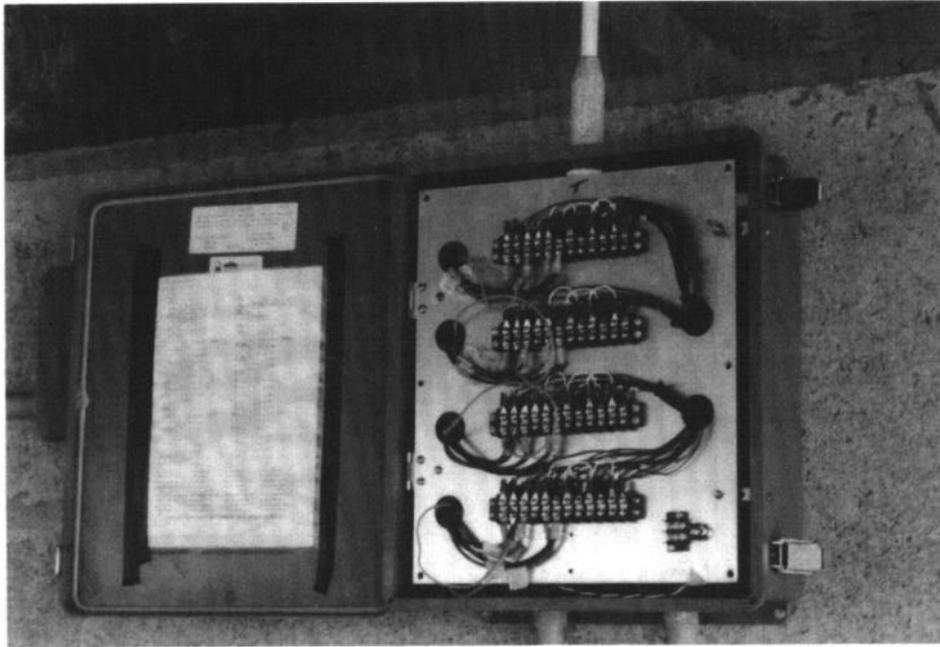


Figure 10. Terminal board inside data acquisition unit.

CHAPTER 3

GALVANIC ANODE PERFORMANCE

Monitoring of the galvanic anode performance at test location #1 was accomplished primarily through monitoring of current, potential, rebar probe current, and depolarization data acquired using a data logger that was accessed through a cellular telephone and modem. Test location #2 could only be monitored during field visits since those piles were not instrumented. The principal investigators made three field visits to the site after the anodes were installed. One visit occurred on May 15, 1996, the second was in November 1996 to supervise repairs to pile #1-2, and the last was at the end of the test period on June 9 to 11, 1997.

The sacrificial anode trials were begun in July 1995. Table 2 shows initial data for the anodes at test location #1 before and immediately after connecting the anode and cathode. The potential data were taken at five locations on each pile at test location #1.

Table 2. Initial anode data for piles #1-1 to #1-4.

Pile	Average Current, mA/ft ² (mA/m ²) (1)	Average Open-Circuit Potential, Anode, mV CSE (2)	Anode Open-Circuit Potential Range, mV CSE (2)
1	1.2 (12.9)	-1033	-1000 to -1095
2	1.9 (20.4)	-1077	-1020 to -1180
3	0.6 (6.5)	-784	-780 to -827
4	0.57 (6.1)	-718	-603 to -858

(1) Current density on steel after 10 min connection time

(2) Measured before connecting the anode to the structure

The data acquisition unit (DAU) was activated in August 1995, and all of the operating data, except the final data, were acquired through the DAU.

Remote Monitoring

The remote monitoring system was designed to permit measurement of anode-to-cathode current, anode-to-rebar probe current, and cathode potential. The system also was designed to allow the anode-to-cathode current to be interrupted remotely so that depolarization data could be taken. Figure 11 shows a schematic diagram of the data monitoring system.

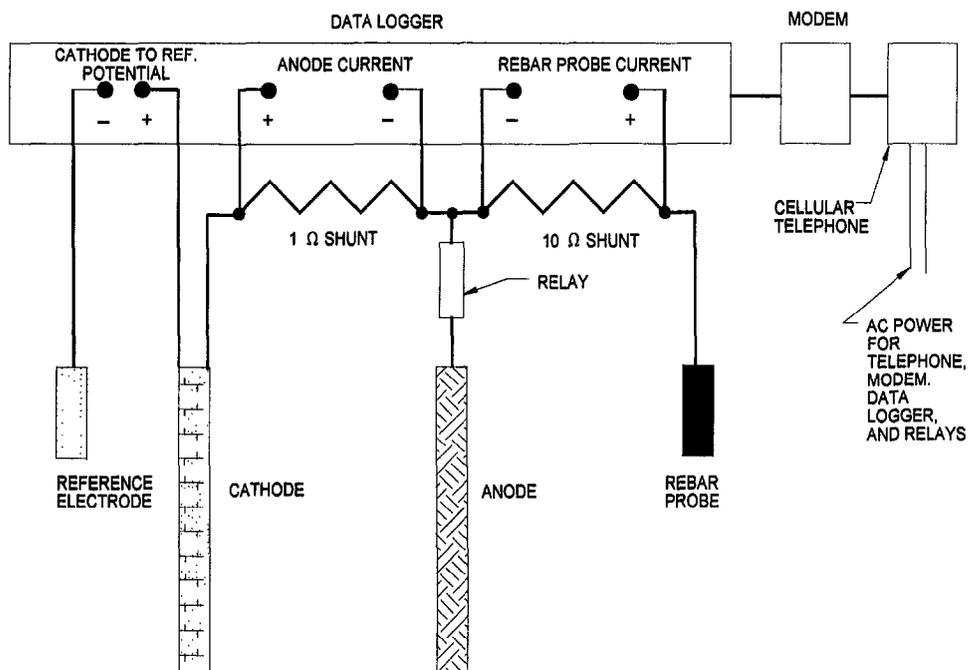


Figure 11. Schematic of data acquisition system.

The original intent was to obtain current, voltage, and depolarization data monthly. Damage to the data logger, primarily due to storms, occurred several times, which necessitated repairs to the system and resulted in some data loss during the 2 yr exposure. The location of the data logger made it prone to water immersion and wave action during storms, and power outages were not uncommon. The following discussion presents the data.

Table 3 summarizes the data derived from the data logger for the 2-yr test period. Figure 12 shows a representative anode current pattern (based on the steel surface area), this chart having been obtained at the beginning of the test, from the 43rd to the 85th day of operation (the period ending 10/9/95). The coated and uncoated anodes performed similarly throughout the whole 2-yr test period, so no differentiation is made between the coated and uncoated piles in this report.

The data logger was not active until after the system had been active for about a month and a half, but a gradual decline in current is seen for both anodes until about the 73rd day when the current started to rise, particularly that from the zinc anode. On about the 80th day, the current of all the anodes peaked. This corresponds to the date Hurricane Opal struck the Florida coast. There is a gap of about 24 h at the time of the hurricane, possibly caused by a power outage. After the hurricane, the current declined slowly, because of retained moisture in the concrete from the storm. The initial current rise before the hurricane was probably caused by moisture from rough seas and rain. Prior to the hurricane, the current density on the steel (steel surface area per pier = 23 ft²) from the aluminum alloy anodes was about 1 mA/ft² (10.76 mA/m²) and about 0.3 mA/ft² (3.23 mA/m²) from the zinc anodes. Note the fluctuation in current with time, resulting from temperature and humidity changes of the environment from hour to hour and day to day.

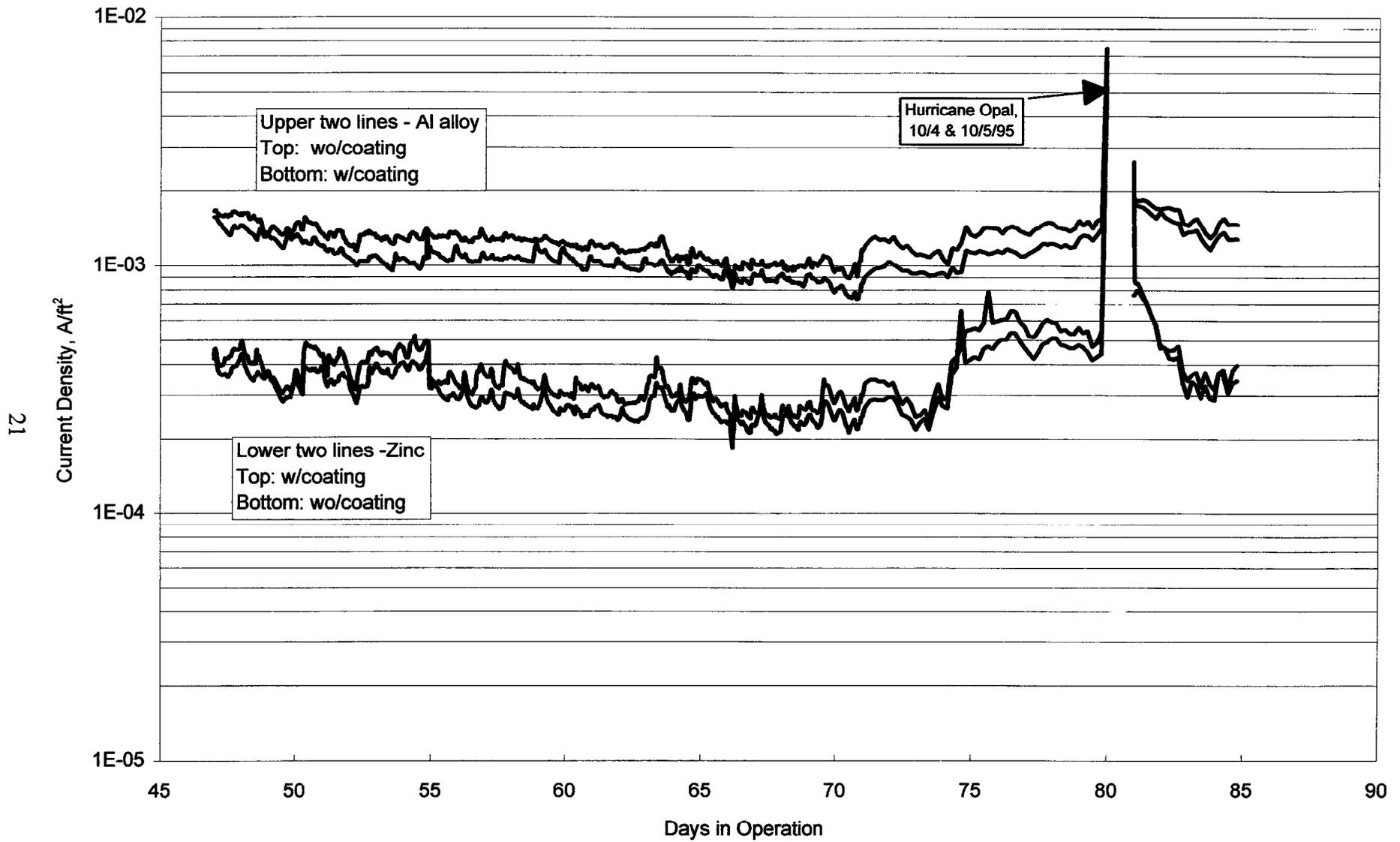


Figure 12. Sacrificial anode current density on steel, 8/30/95 to 10/9/95.

Rebar probe current density also was measured for the piles at test location #1. Current was generally from the anode to the rebar probe, although there was considerable fluctuation, including some negative currents. We suspect that the rebar probe, being embedded in high-chloride-containing concrete, was anodic to many areas of the reinforcing steel in the pier. Current could have been discharging from the rebar probe to the steel in the pier. The rebar probe current showed considerable variation throughout the test, including both positive and negative values that could not be correlated to changes in anode current output. Since the rebar probe currents are, in our opinion, being influenced by galvanic current not associated with the CP system, we will not present these data.

The reference cell potential for the four piles at test location #1 were measured. The original corrosion potentials on the piles ranged between 0.274 and 0.543 v (CSE). The curves show the mixed cell potentials of the cathode and anode to silver-silver chloride reference electrodes embedded in each pier. Reference cell potentials of the piers with the aluminum alloy anodes are generally higher (more negative) than those with zinc anodes, as would be expected from the higher current. Since the meaning of these potentials is difficult to interpret without depolarization data, it will not be presented in this report since the depolarization data are more meaningful.

The current density on piles #1-1 and #1-2 (aluminum alloy) from the 85th day to the 96th day (period ending October 25, 1996) remained at about 1 mA/ft² (10.76 mA/m²). The current on piles #1-3 and #1-4 (pure zinc) stayed about 0.3 mA/ft² (3.23 mA/m²) until about the 86th day when the current from pile #1-3 dropped considerably (a dip in the current on the other piles also occurred). We do not know the reason for the drastic variations in current on the zinc coated pile. Figure 13 shows the first depolarization curve. Depolarizing potentials were recorded for at least 4 h. Piles #1-1 and #1-2 displayed 250 to 300 mV depolarization after less than 2 h. Pile #1-3 displayed about 60 mV total depolarization and pile #1-4 displayed about 110 mV total depolarization. This depolarization curve is typical of those measured. Depolarization details are given in table 3.

The data logger did not record data from the 117th day to the 178th day, probably due to a power surge, and the data logger was not back on-line until the 178th day. For piles #1-1 and #1-2, the current ranged from 0.5 to 1 mA/ft² (5.4 to 10.76 mA/m²). For piles #1-3 and #1-4, the current ranged from about 0.1 to 0.3 mA/ft² (1 to 3.2 mA/m²), with the high values for both anodes occurring at the end of the period. Depolarization of piles #1-1 and #1-2 on the 181st day of operation (January 16, 1996) was about 200 mV and that for piles #1-3 and #1-4 about 50 mV.

Considerable current fluctuation was observed on all of the anodes from about the 185th day through the 264th day of operation (period ending April 17, 1996). Some of this fluctuation was associated with daily temperature and humidity changes, but the majority was caused by sea activity. Current from the aluminum anodes on piles #1-1 and #1-2 seemed to generally stay within the 0.3 to 1 mA/ft² (3.23 to 10.76 mA/m²) range. Current on piles #1-3 and #1-4 (zinc anodes) decreased and generally stayed within the 0.05 to 0.2 mA/ft² (0.54 to 2.15 mA/m²) range.

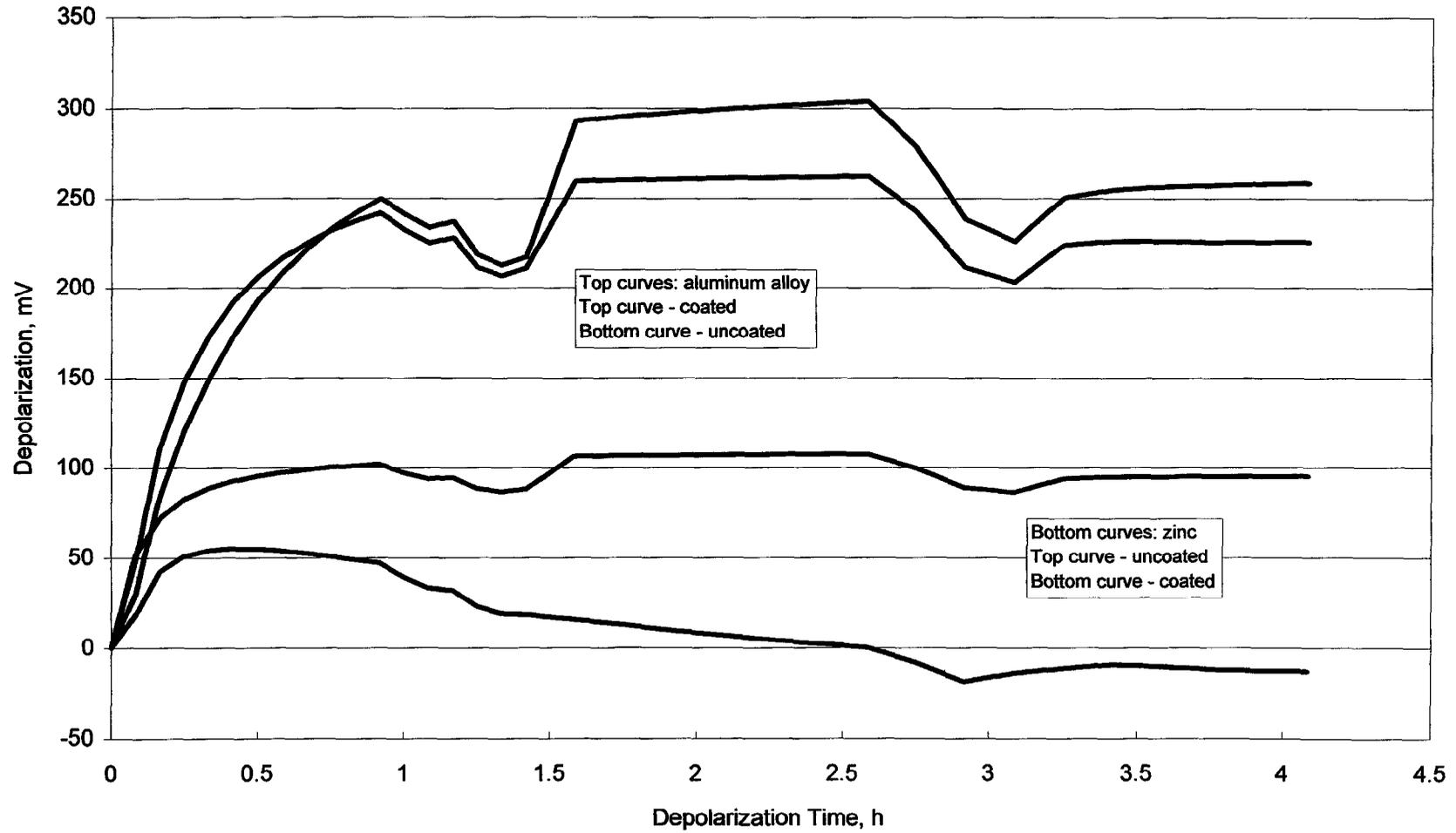


Figure 13. Depolarization curves, 10/24/95.

Current from the aluminum anodes was consistently above that of the zinc anodes. The exception occurred on pile #1-2 starting about the 245th day, when the current fell drastically. Since there seemed to be instability in the data, it was apparent that one of the connections in the circuit was failing.

Table 3. Summary of current and depolarization values observed at test location #1.

Test Period Ending	Current Density Range (on steel)				Cathode Depolarization, mV		Notes
	Aluminum Alloy		Zinc		Aluminum Alloy	Zinc	
	mA/ft ²	mA/m ²	mA/ft ²	mA/m ²			
10/9/95	0.8-1.7	8.6-18.3	0.3	3.23	Data not taken		
10/25/95	0.75-1.7	8.1-18.3	0.3	3.23	250-300	60-110	
1/16/96	0.5-1	2.8-12.9	0.1-0.3	1-3.2	200	50	
2/15/96	0.3-1	3.23-10.8	0.06-0.4	0.65-4.3	90-100	25-30	
3/19/96	0.25-1.2	2.7-12.9	0.04-0.32	0.38-3.4	175-200	60-80	
4/17/96	0.26-1.2	2.8-12.9	0.07-0.4	0.75-4.3	9 - 82	25-30	1
5/13/96	0.4-0.8	4.3-8.6	0.09-0.3	0.97-3.2	0 - 43	23	1, 2
5/15/96	0.5-1	5.4-10.8	0.15	1.6	Data not taken		3
6/20/96	0.4-0.85	4.3-9.1	0.1-0.2	1.1-2.2	26	18-24	2
7/16/96	0.45-1	4.8-10.8	0.16-0.4	1.7-4.3	17	24	2
8/20/96	0.35-1	3.8-10.8	0.16-0.3	1.7-3.2	25	12	2
9/23/96	0.2-1	2.2-10.8	0.1-0.38	1.1-4.1	22	15	2
10/18/96	0.2-1	2.2-10.8	0.13-0.4	1.4-4.3	Data not taken		
1/12/97	0.7-3	7.5-32.3	0.2-0.4	2.2-4.3	5	20	2, 4

- (1) Connection failed on pile #1-2; range given is for pile #1-1.
- (2) Following restoration of connection to pile #1-2; anode disbonded and lost at the reference electrode location on piles #1-1 and #1-2 causing low depolarization values.
- (3) Field data following restoration of connection at #1-2
- (4) Lost connection in pile #1-1 anode circuit. High current value is pile #1-2 after recoating of the north and east faces.

The connection between the anode and pile #1-2 was found to have broken, and was repaired on May 15, 1996. The current on pile #1-2 returned to its previous range, as seen in table 3. The current from the anodes on the four piles continued at the same general levels and environmental fluctuations until October 18, 1996, when another storm struck and disabled the data logger. The current from all four anodes increased steadily due to the increased moisture from the storm, until the data logger stopped functioning on October 18th.

Despite the good current values observed on piles #1-1 and #1-2, the depolarization values remained disappointingly low from April 1996 on. The inspection trip in May 1996 revealed the reason for this, which was the disbonding of the aluminum alloy anode from the face of the concrete patch where the reference electrode was placed. This anode was placed over relatively

fresh concrete, so the bond was not as good as it was to the remainder of the concrete. The result was that the rebar in the vicinity of the reference electrode was not receiving enough current to polarize the steel reinforcing, although current density to the remainder of the pile should have been sufficient to maintain depolarization values similar to those observed prior to May 1996. Field tests conducted in April 1997 (to be discussed) confirm that this was the case.

The field inspection in May 1996 revealed another problem with the adhesion of the aluminum alloy coating on pile #1-2. The alloy was applied by two methods. The north and east faces of piles #1-1 and #1-2 were coated using the arc spray method, and the south and west faces were coated using the flame-spray method. As previously stated, some difficulties were encountered applying the anode using the arc-spray. The alloy that was applied using arc spray might have been applied too thinly since the disbondment was on the north face of pile #1-2 that had been sprayed using arc spray. The two sides of the pile that were coated using flame spray (south and west faces) were in good condition, and the piles at test location #2 also were in good condition. To continue the test with an adequate coating, the old alloy was removed from the north and east faces of pile #1-2 in November 1996, and replaced with new aluminum alloy coating. The current output of this anode returned to substantial level, as shown in the January 12, 1997, data in Table 3. A connection in the anode circuit for pile #1-1 was later lost. Whether or not this meant that current to the pile was reduced or the measuring circuit was defective is not known.

The data logger was repaired following the October 1996 storm, but the ability to measure depolarization was not restored. Troubles with the data logger continued despite repairs, and no further data were available from the data logger past January 1997. After the last storm, both the data logger and cellular telephone were damaged beyond repair. Florida DOT moved the junction box containing the data logger from its position on the pile bent to the bridge abutment on St. George Island. The data logger was removed and the electrical connections were made directly between the anode and cathode.

Field Examination

The piles were inspected on May 15, 1996, and for the last time on June 9 to 11, 1997. During the last inspection, visual observations, current, potential, depolarization, anode adhesion, surface pH, and anode-to-cathode resistance data were taken. Detailed potential and depolarization data were only possible at test location #1. Core samples also were taken at test location #1, both for detailed evaluation of the anode-to-concrete interface and to estimate the service life of the anode.

Visual Condition

At the May 1996 inspection, the condition of all the anodes was good. Conditions were dry at the time of the inspection. Figure 9 shows a general view of test location #1, and Figure 14 shows a general view of test location #2 in May 1996. Table 4 presents a summary of the observations at each of the piles. Figures 15 to 18 show photographs of the condition of some of the piles.

The last inspection was conducted on June 9 to 11, 1997. Figure 19 shows the general condition of the pile bent at the time of this inspection. Note in the photograph the wave action and the wetness at the bottom of pile #1-2 (second from right). Table 5 summarizes the observations of the anodes at that time. The concrete was moist on all piles because of wave action and recent rain.

Table 4. Condition of the test piles at May 15, 1996, inspection.

Pile	Anode	Comments	Figure
1-1	Alum. alloy	Anode completely disbonded from area around reference cell on north face. Topcoat flaking on north and west faces. No topcoat disbondment on south face.	15
1-2	Alum. alloy	Heavy oxidation on the north face and disbondment. Anode well bonded on south, east, and west faces with some minor flaking in local areas. Some white corrosion products on surface. Anode connection repaired. Anode completely disbonded from area around reference cell on north face.	16
1-3	Zinc	White corrosion products on east face. No oxidation products on south or west faces except at bottom. No delamination of anode.	17
1-4	Zinc	No delamination of anode. Some white corrosion products in localized areas on all faces. Corrosion products at bottom of anode.	18
2-5	Alum. alloy	No visible delamination. Localized areas with white corrosion products.	
2-6	Alum. alloy	Small areas, $\approx 1/2$ -in ² (2 cm ²) on south, north, and west faces at aggregate blistered with white corrosion deposits underneath. Coating has some white corrosion product showing through. Coating not protecting as well as that on #2-5.	
2-7	Zinc	No surface coated. Some white corrosion products on west, east, and south faces. No delamination.	



Figure 14. General view of the mainland-side pile bent (test location #2), May 1996.
(pile #2-5 is on the far right)



Figure 15. View of north and west faces of pile #1-1, May 1996.
(note loss of anode material below center junction box on north
face)

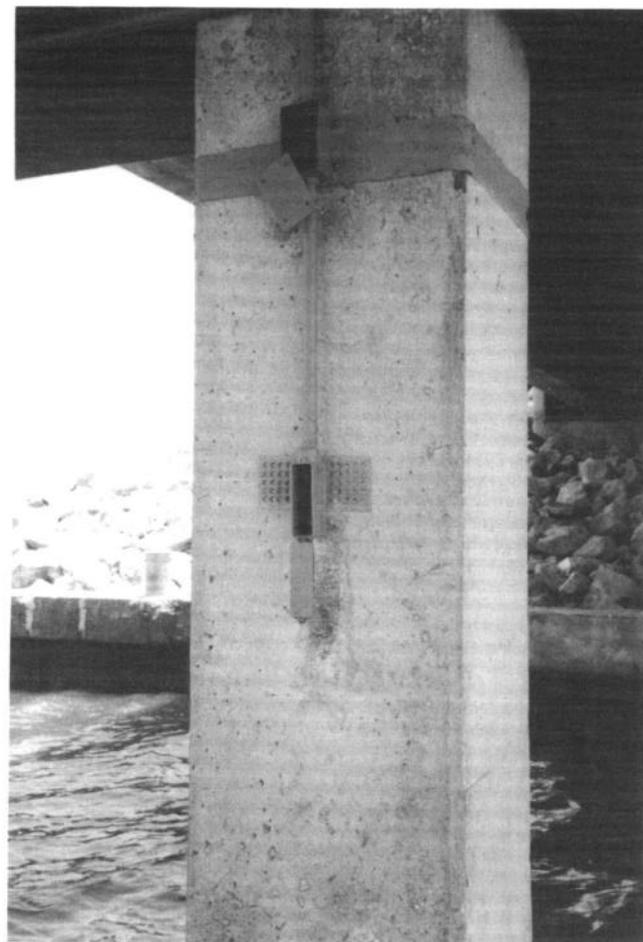


Figure 16. View of north and west faces of pile #1-2, May 1996.
(note anode material loss below center junction box on north face)



Figure 17. Pile #1-3, north and east faces, May 1996. (note white corrosion products on surface, particularly near base)

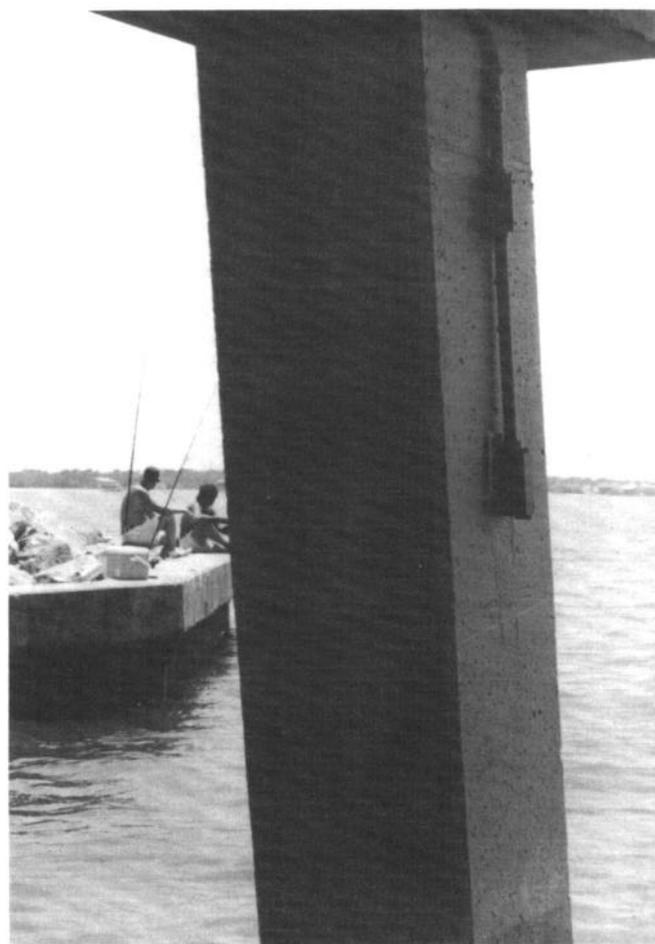


Figure 18. Pile #1-4, north and east faces, May 1996.



Figure 19. General view of island-side pile bent (test location #1) on June 9, 1997. (View is looking north, with aluminum alloy coated piles on right and zinc coated piles on left. Note wave action and wetness of pile #1-2.)

Table 5. Condition of the test piles at June 9 to 11, 1997, inspection.

Pile	Anode	Comments	Figure
1-1	Alum. alloy	North face - excellent condition, some white corrosion products, no delamination. West face - topcoat almost gone from surface. South face - concrete very porous, anode in good condition, no delamination. East face - coating intact.	
1-2	Alum. alloy	North face - corrosion products on whole surface with disbondment in local areas at aggregate. West face - about 1/2 surface covered with white corrosion products, spotty areas of disbondment at aggregate, no other disbondment. South face - same.	
1-3	Zinc	North face - corrosion products on about 95 percent of surface, no disbondment. West face - good condition, corrosion products on lower right corner and along bottom 3 to 4 in (7.6 to 10.2 cm) of coating and along cut near top; otherwise, corrosion free, no delamination.	
1-4	Zinc	North face - concrete very porous on north face, no disbondment. East face - topcoat is eroding. West face - anode kept disbonding during core cutting. South face - concrete very porous, topcoat seems intact, no delamination of anode.	
2-5	Alum. alloy	White corrosion products on uncoated surfaces. North face - small areas of localized disbondment at aggregate. East face intact. Similar condition to May 1996 inspection. No other disbondment. South face - concrete very porous with some localized areas where coating disbonded from anode, corrosion products on anode surface. West face same as south face.	20, 21
2-6	Alum. alloy	North face - several areas with delamination about 1 in (2.54 cm) dia., delamination and depletion in lower left corner, small areas of delamination at aggregate. West face - depletion in lower left and lower right corners, localized areas of delamination at aggregate. South face - concrete very porous, most of topcoat is gone, corrosion products on anode, anode depleting under topcoat. East face - Topcoat gone in upper portions, anode depleting	22, 23 24
2-7	Zinc	North face - concrete very porous, no delamination, no corrosion products. West face - some corrosion products, no delamination. South face - concrete very porous, corrosion products, especially around junction box, some localized disbondment at aggregate. East face - heavy corrosion products on lower portion, no delamination.	25, 26 27

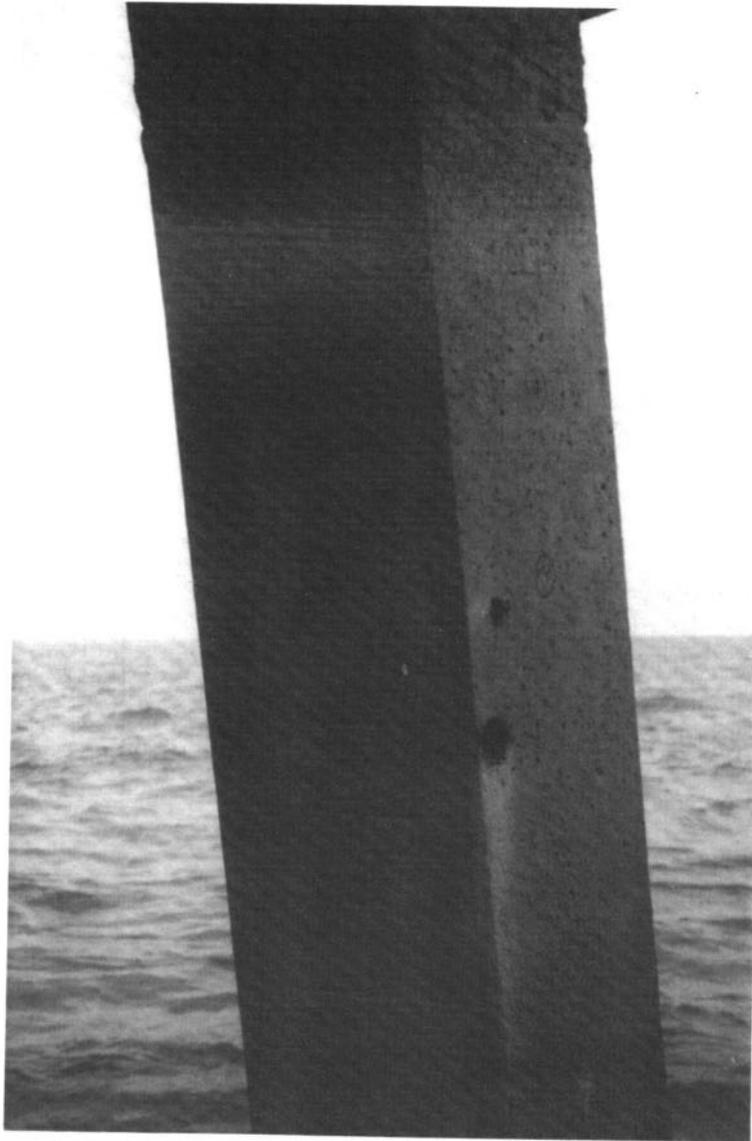


Figure 20. View of north and east faces of pile #2-5, June 1997.
(Note wetness at bottom of pile because of wave action)

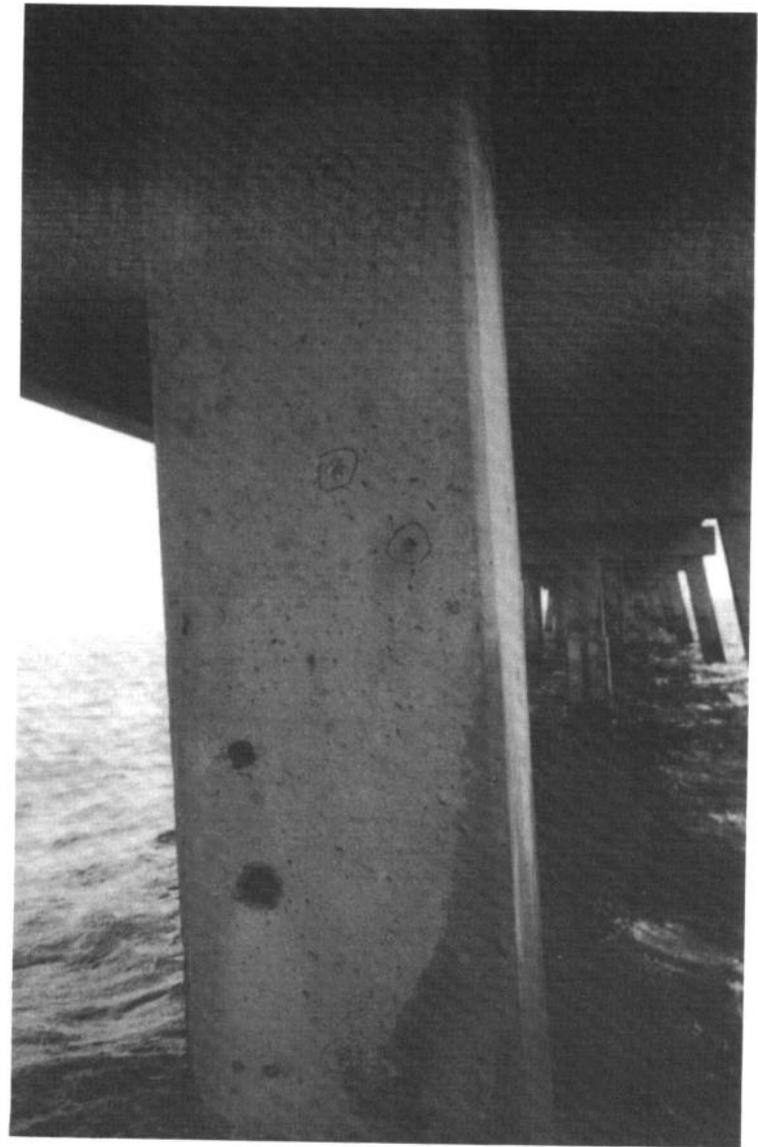


Figure 21. View of south face of pile #2-5, June 1997.
(Note porosity of concrete and small delaminated area)

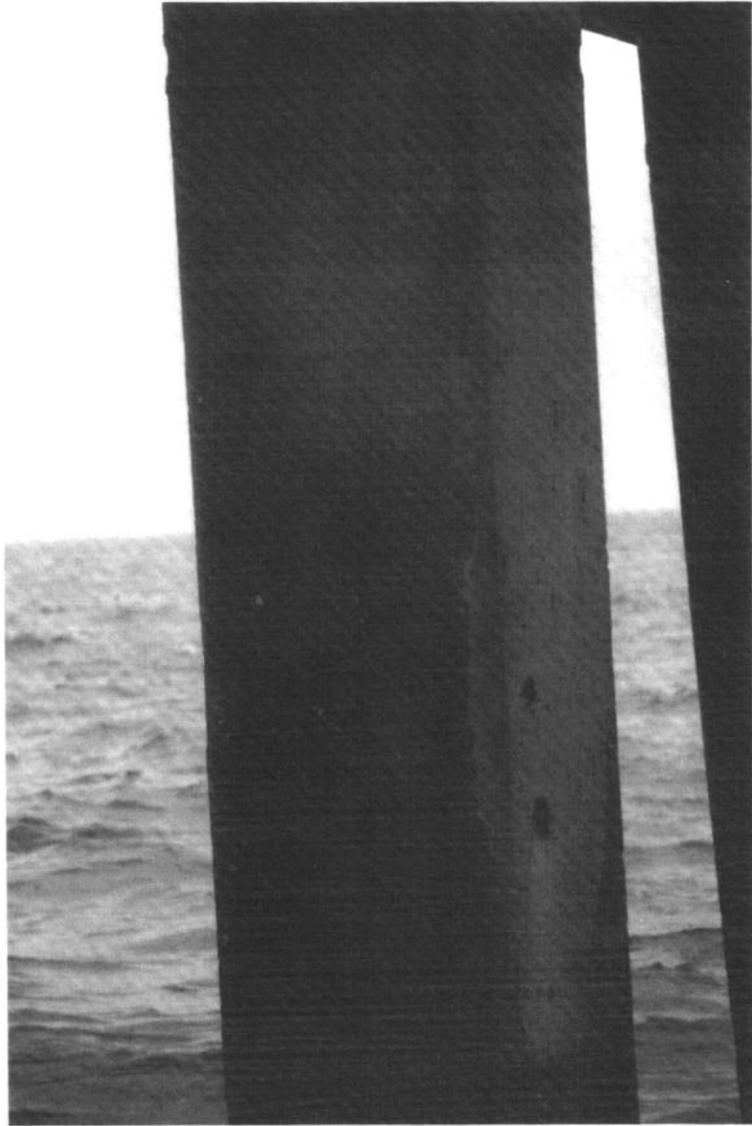


Figure 22. View of north and east faces of pile #2-6, June 1997.
(Note wetness of bottom of pile from wave action)

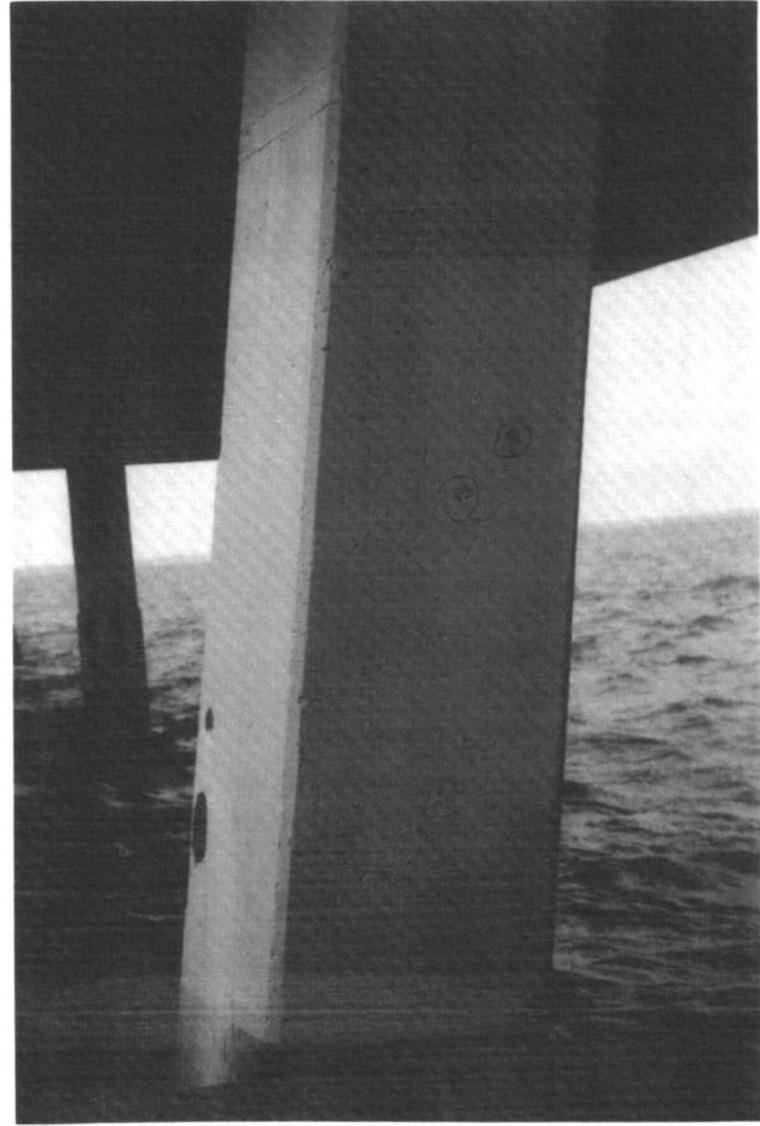


Figure 23. View of north and west faces of pile #2-6, June 1997.
(Note localized areas of disbondment at aggregate and adhesion dollies)



Figure 24. View of north face of pile #2-6, June 1997.
(Close up of disbonding at aggregate)



Figure 25. View of north and east faces of pile #2-7, June 1997.
(note adhesion dollies)



Figure 26. View of west face of pile #2-7, June 1997.

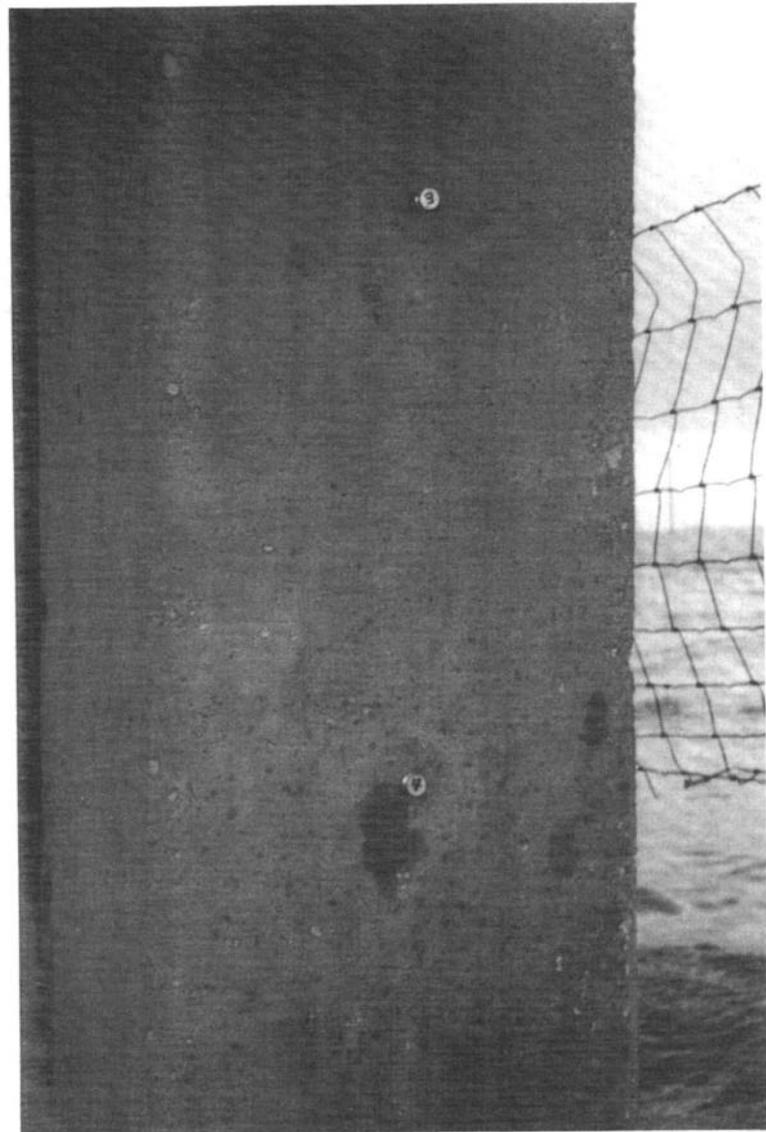


Figure 27. View of south and east faces of pile #2-7, June 1997.
(South face, note localized disbondment at aggregate, junction
box is for FL DOT splash zone anode test)

Electrical Measurements

In addition to the visual inspections, the current between the anode and reinforcing, anode and cathode potentials, and depolarization measurements were taken during the June 1997 inspection. These detailed measurements were only possible at test location #1. Mixed potential measurements were taken at test location #2. This section presents the results of that testing. The resistance between the anode and cathode at test location #1 was measured and found to be: #1-1: 19 ohms, #1-3: 13 ohms, #1-2: 10.5 ohms, and #1-4: 12 ohms.

Current

The current and instant-off driving voltage between the anode and pile (measured immediately after disconnecting the circuit) reinforcing for each of the piles at test location #1 were measured at the junction box. Figure 28 graphically shows the current and driving voltage. Both the current and driving voltages on the aluminum alloy-coated piles were larger than those on the zinc-coated piles.

Potential

To obtain accurate and detailed potential and depolarization data on each pile, data were taken on the pile itself, rather than using only the embedded reference electrode. Individual measurements were taken at several locations. Contact to the concrete was obtained by chipping away about 1 in² (6.45 cm²) of the anode to expose fresh concrete. A small amount of conductive gel provided the electrolytic contact between the copper-copper sulfate reference electrode (CSE) and concrete. A digital meter with 10 M Ω resistance was used to take the potential data. Table 6 shows the terminal designations and positions used in the figures.

Figure 29 shows instant-off and static potentials (16 h after the anode was disconnected) at the top, mid-length, and bottom of the south face of piles #1-1 through #1-4. Generally, the instant-off values were more active toward the bottom of the anode. This makes sense, because this area has more moisture from wave action. The instant-off potentials of the aluminum alloy-coated piles (#1-1 and #1-2) were more negative than those of the zinc-coated piles (#1-3 and #1-4) — an exception was pile #1-1 at the bottom. The static cathode potentials at the bottom of the piles with the aluminum alloy anodes were less negative than those of the zinc-coated piles. This means that some degree of passivity was restored on piles #1-1 and #1-2. This observation agrees with the observations made during the laboratory phase of the project where passive potentials developed on test blocks with continued use of sacrificial CP.

Instant-off and static potential measurements for each of the anodes were taken at piles #1-1, #1-2, #1-3, and #1-4 (see Table 6). Figures 30 through 37 show these data graphically. The first two bars in each graph represent instant-off potentials at the mid-point of the anode, while the last four bars represent instant-off potentials starting from the top of the anode and progressing toward the water. The instant-off potentials for the aluminum alloy anodes were higher than those of the zinc anodes. Except for pile #1-1, the instant-off potentials of each anode tended to increase (become more active) toward the bottom of the anode where the concrete was wetter.

The instant-off potentials of the aluminum alloy anodes ranged from -744 to -1036 mV (CSE) and those of the zinc anodes ranged from -158 to -836 mV, with the higher values occurring at the bottom of the anode. The static potentials of the aluminum alloy anodes also were higher than those of the zinc, ranging from -708 to -1084 mV compared with -495 to -768 mV for the zinc anode. Again, the more active potentials occurred at the bottom of the anode.

Table 6. Test locations for potentials on piles #1-1 to #1-4.

Pile	Face	Cathode Terminal	Anode Terminal	Location (All measurements taken at middle of column width unless noted otherwise)
1	North	Ec-n	Ea-n	mid-point of anode
1	West	Ec-w	Ea-w	mid-point of anode
1	South	Ec-t'	Ea-t'	3 in (7.6 cm) above channel cut
1	South	Ec-t	Ea-t	6 in (15.2 cm) below channel
1	South	Ec-m	Ea-m	mid-point of anode on column
1	South	Ec-b	Ea-b	6 in (15.2 cm) above bottom of anode
2	North	Ec-n	Ea-n	mid-point of anode about 3 in (7.6 cm) from east edge in core hole 2-in (3-cm) deep
2	East	Ec-m	Ea-e	mid-point of anode
2	South	Ec-t'	Ea-t'	1 in (2.54 cm) above channel cut
2	South	Ec-t	Ea-t	6 in (15.2 cm) below channel cut in concrete
2	South	Ec-m	Ea-m	mid-point of anode on column
2	South	Ec-b	Ea-b	4 in (10.2 cm) above bottom of anode
3	North	Ec-n	Ea-n	mid-point of anode
3	West	Ec-w	Ea-w	mid-point of anode
3	South	Ec-t'	Ea-t'	4 in (10.2 cm) above channel cut
3	South	Ec-t	Ea-t	6 in (15.2 cm) below channel
3	South	Ec-m	Ea-m	mid-point of anode on column
3	South	Ec-b	Ea-b	4 in (10.2 cm) above bottom of anode
4	North	Ec-n	Ea-n	mid-point of anode
4	West	Ec-w	Ea-w	mid-point of anode
4	South	Ec-t'	Ea-t'	4 in (10.2 cm) above channel cut
4	South	Ec-t	Ea-t	4 in (10.2 cm) below channel cut
4	South	Ec-m	Ea-m	mid-point of anode on column
4	South	Ec-b	Ea-b	4 in (10.2 cm) above bottom of anode

Mixed anode-cathode potentials were taken on the mainland-side (test location #2) pile bent. The potentials were taken in the same manner as those at test location #1, but at random locations. The test points were located about mid-length of the anode, and data were taken on each face. Figure 38 presents the high, low, and average potential at each pile. There is a large variation in potentials, although the zinc anode (pile #2-7) does have a wider range and lower average. The active potentials were measured at locations where the concrete was obviously wet and the more noble potentials were measured in drier locations.

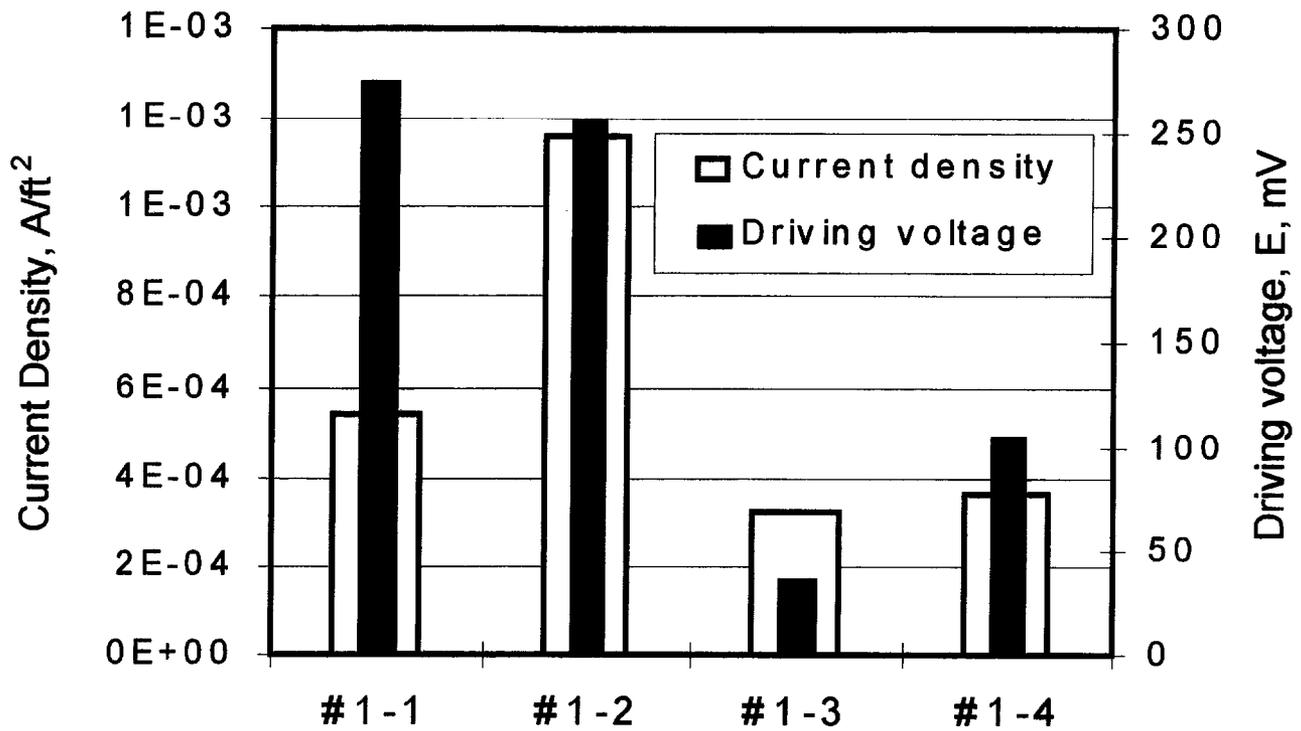


Figure 28. Galvanic anode current density (on steel) and driving voltage, June 10, 1997.

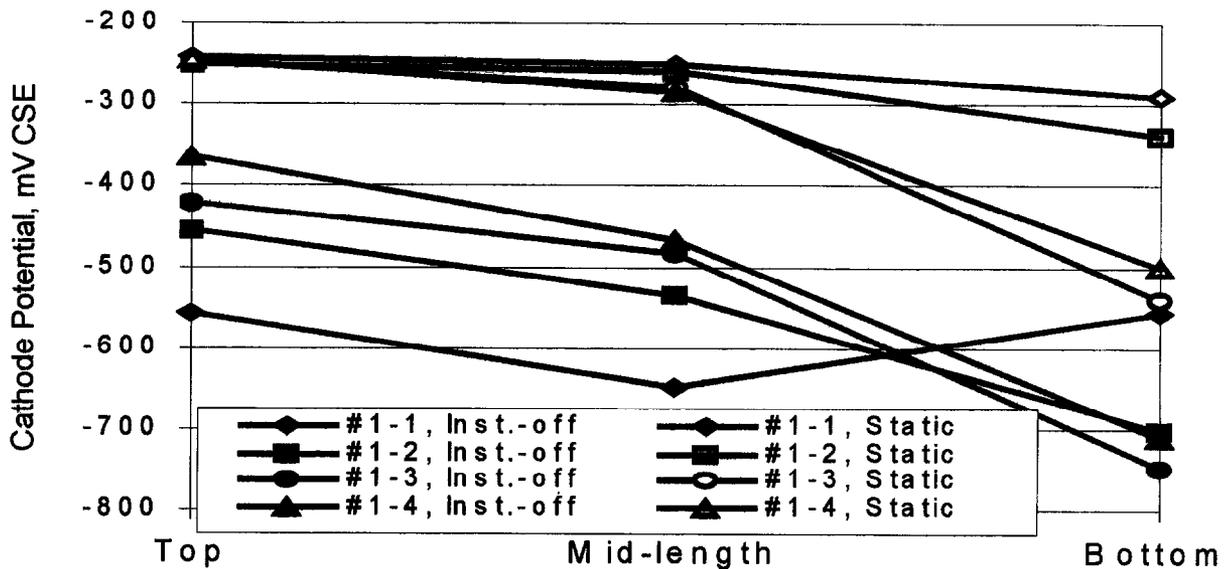


Figure 29. Comparison of instant-off and static cathode potentials with position on pile, June 11, 1997.

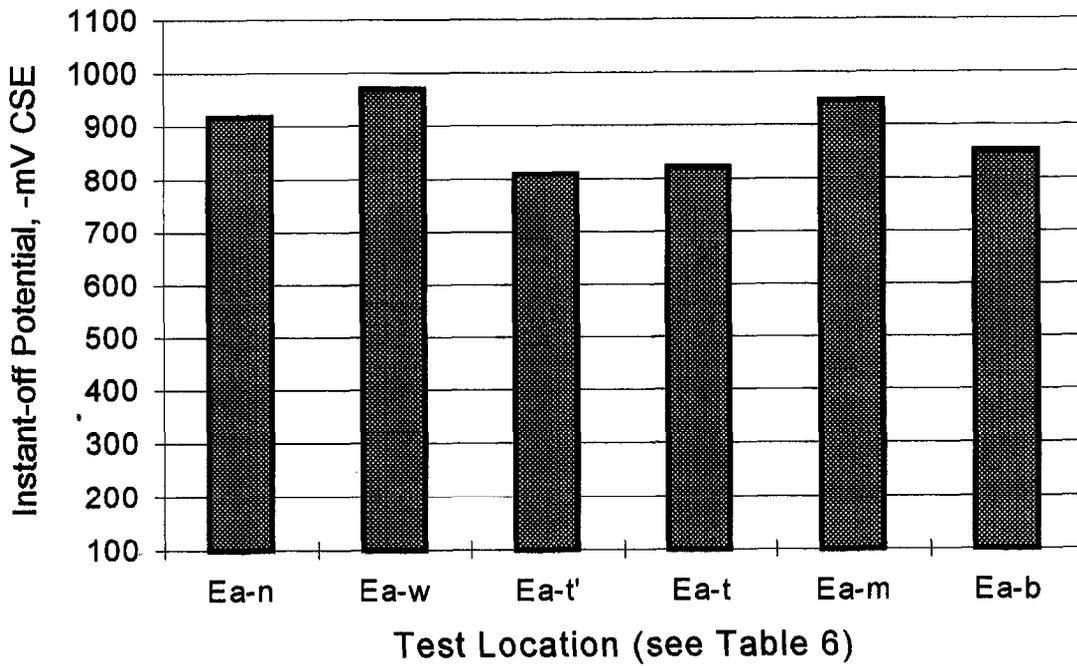


Figure 30. Instant-off anode potentials, pile #1-1.

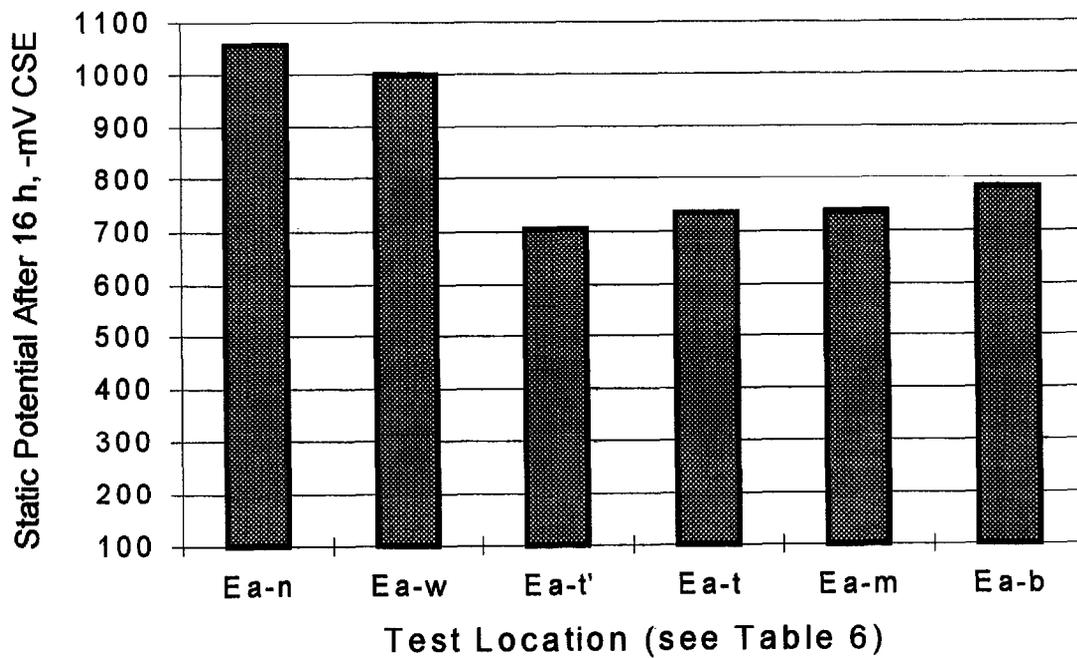


Figure 31. Static anode potentials, pile #1-1.

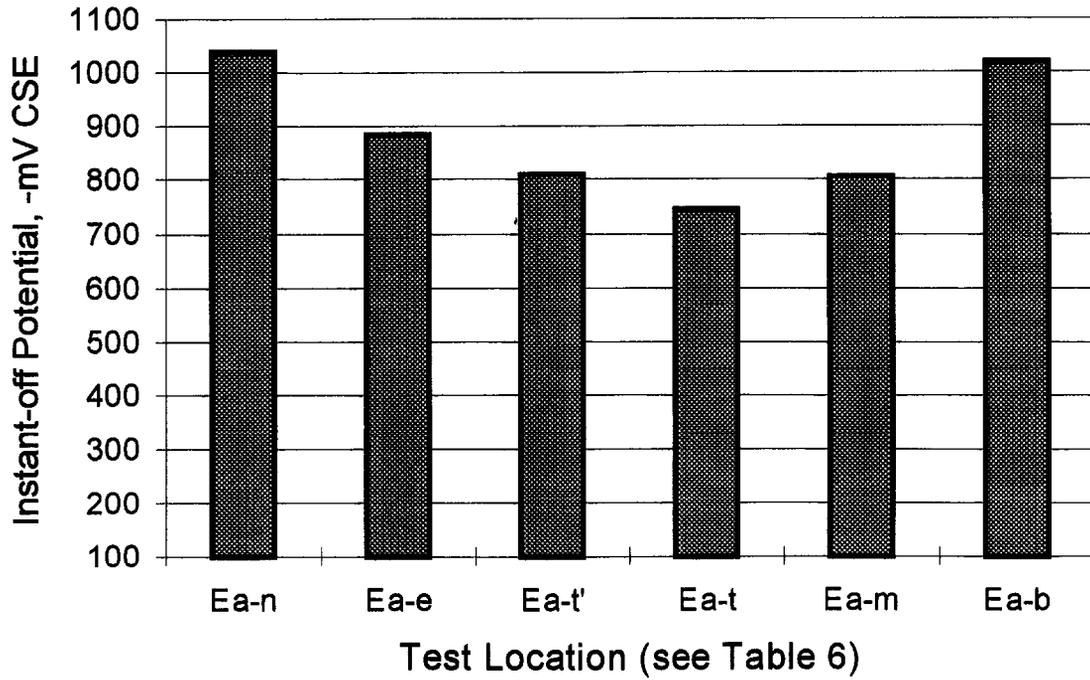


Figure 32. Instant-off anode potentials, pile #1-2.

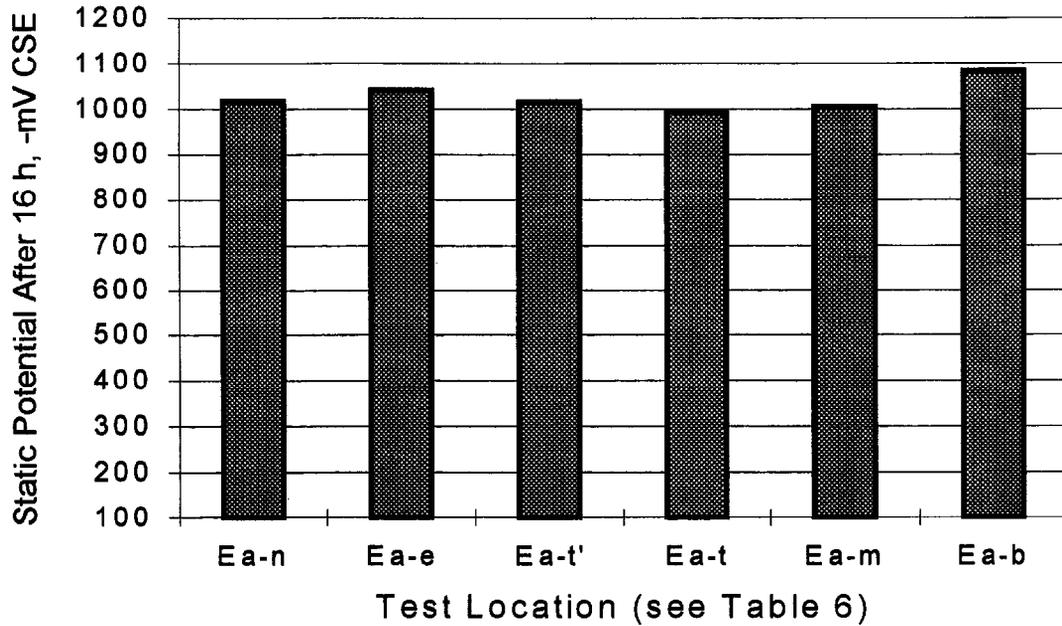


Figure 33. Static anode potentials, pile #1-2.

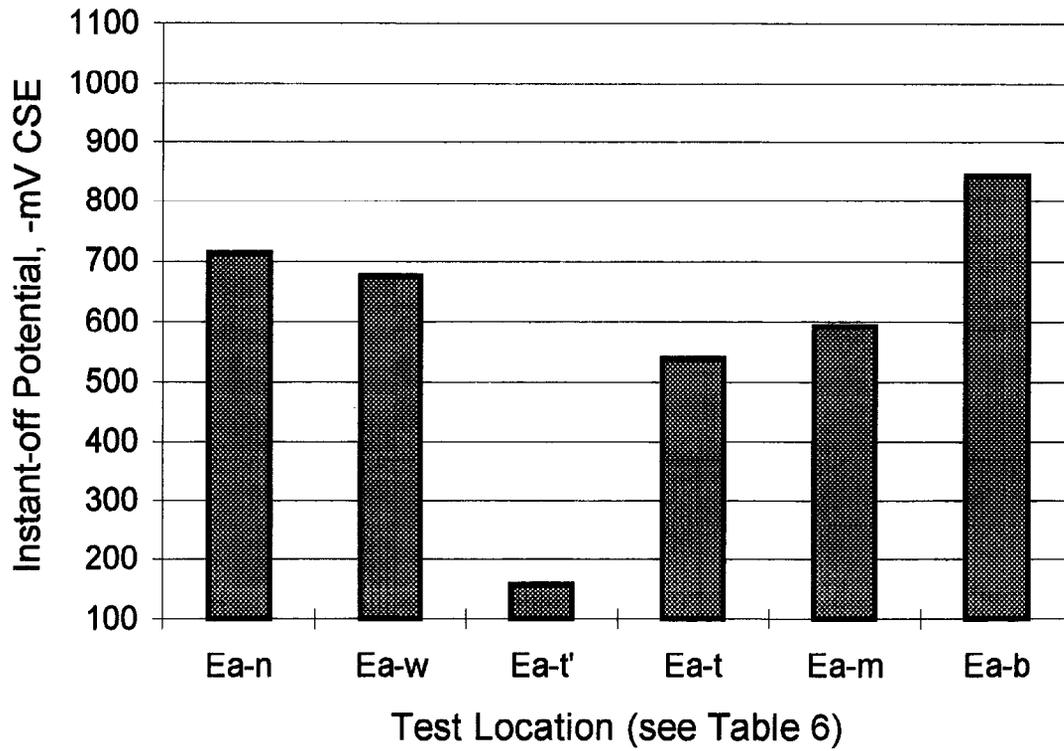


Figure 34. Instant-off anode potentials, pile #1-3.

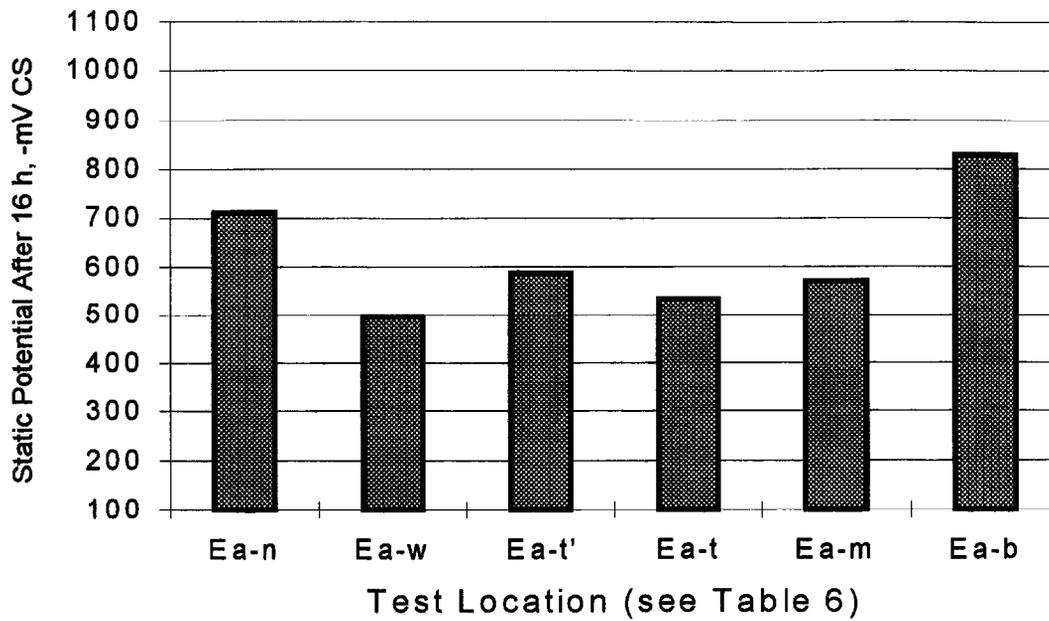


Figure 35. Static anode potentials, pile #1-3.

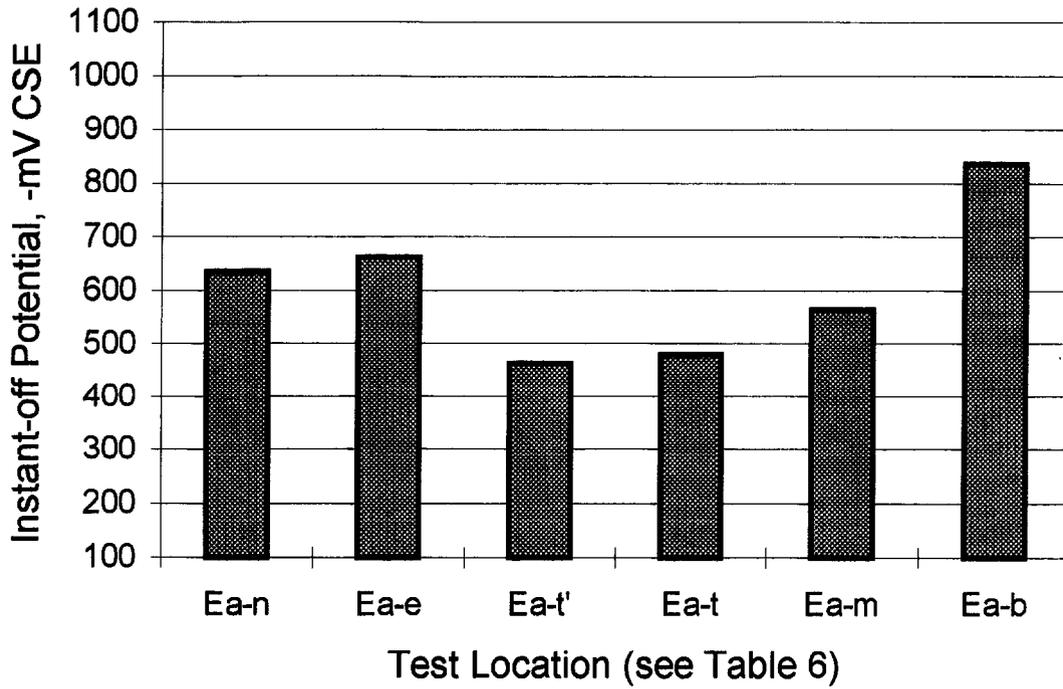


Figure 36. Instant-off anode potentials, pile #1-4.

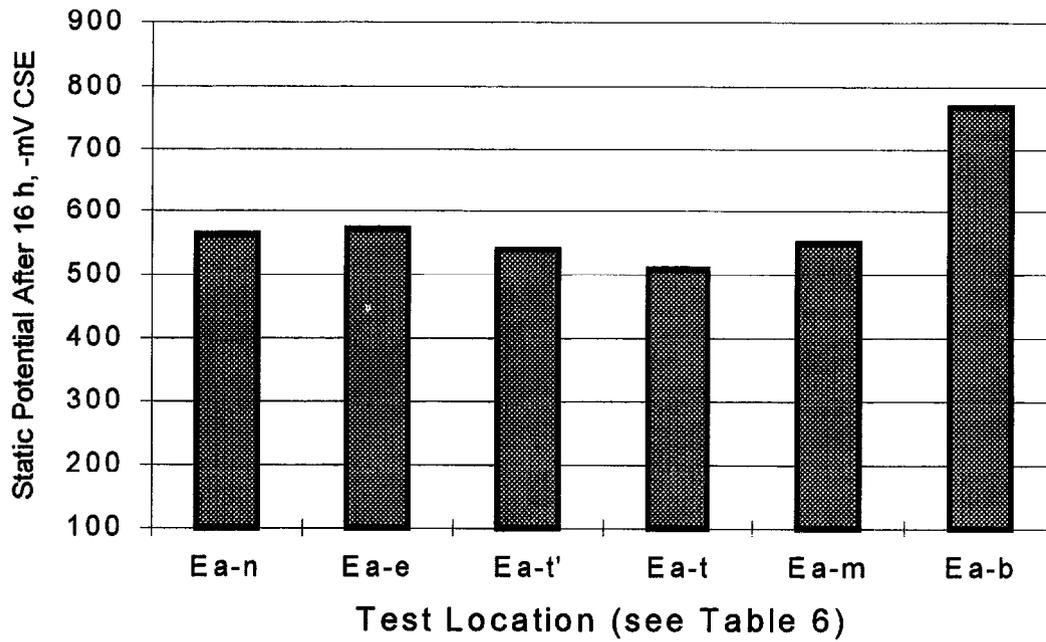


Figure 37. Static anode potentials, pile #1-4.

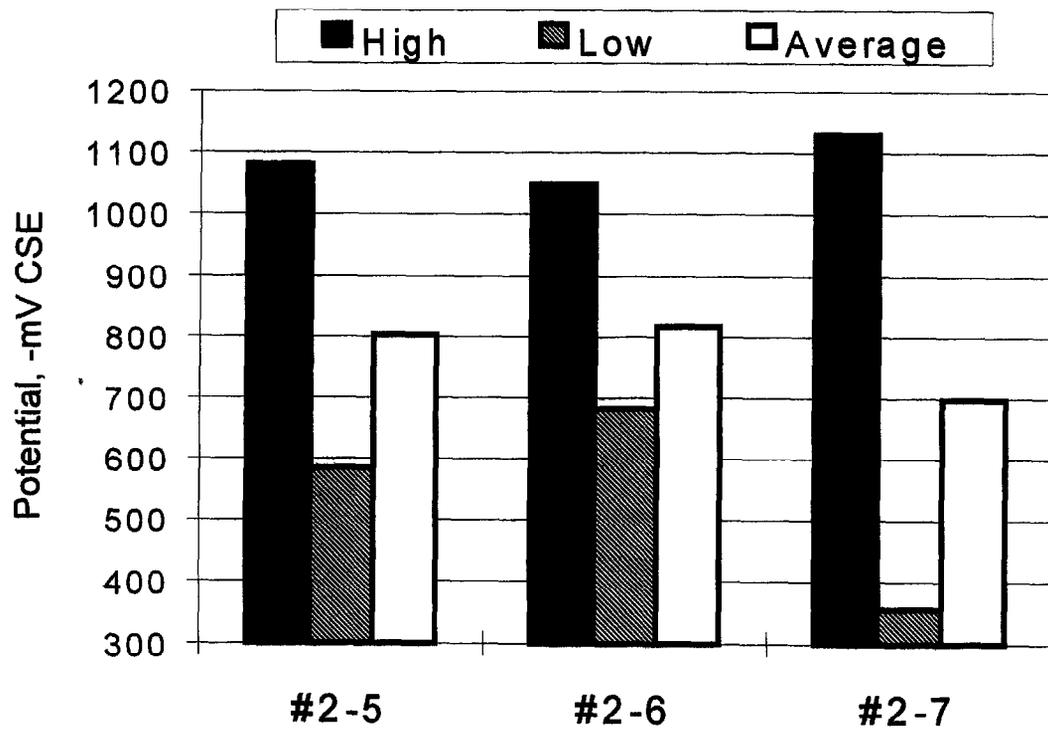


Figure 38. Mixed anode-cathode potentials, piles on mainland side, June 10 to 11, 1997.

Depolarization

Depolarization measurements were taken at piles #1-1 through #1-4. Depolarization curves were obtained of both the anode and cathode versus the embedded silver-silver chloride reference electrode from instant-off up to 16 h from opening the circuit. Depolarization of the cathodes, based on instant-off less static potentials after 16 h, were taken to each of the test points directly on the piles, using the potential measuring technique previously described (see Table 6). Figures 39 through 46 present these data. Table 7 summarizes the depolarization data from the embedded reference electrodes (Figures 39, 41, 43, and 45).

Table 7. Summary of depolarization values to embedded reference electrode, piles #1-1, 1-2, 1-3, and 1-4.

Pile	Depolarization after 4 h, mV		Depolarization, after 16 h, mV	
	Anode	Cathode	Anode	Cathode
1-1	151	290	176	290
1-2	133	301	170	318
1-3	83	60	107	82
1-4	135	82	153	97

Figures 40, 42, 44, and 46 show the depolarization data obtained directly on the concrete surfaces of the piles using a surface reference electrode. Depolarization values for the cathodes on the aluminum alloy-coated piles ranged from 219 to 447 mV and those for the zinc-coated piles ranged from 77 to 336 mV. The depolarization values for the aluminum alloy-coated piles are generally higher than those for the zinc-coated piles. The values of depolarization tended to increase toward the bottom of the anode, as might be expected, although the bottom reading on piles #1-1 and #1-2 did not follow this trend.

The wet conditions existing at the time of the June tests resulted in higher current levels and correspondingly higher depolarization levels for all of the anodes. The depolarization values measured during the test with the surface electrode generally met the CP criterion of 100 mV, but the depolarization values measured with the embedded reference electrode only met the criteria on piles #1-1 and #1-2. The instant-off potentials of the surface electrode measurements tended to be more active (even allowing for the normal difference between silver-silver chloride and copper-copper sulfate reference electrodes). The instant-off potentials for the embedded reference cells averaged 412 mV for the aluminum alloy and 299 mV for the zinc anodes. The instant-off potentials for the surface reference cells averaged 611 mV for the aluminum alloy and 533 mV for the zinc anodes.

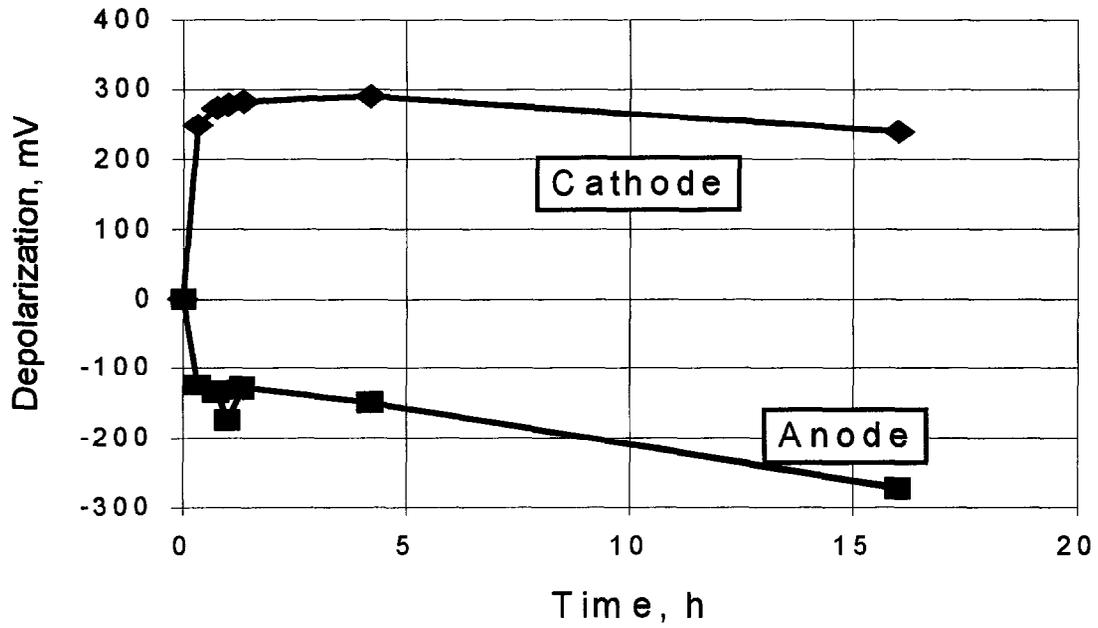


Figure 39. Depolarization to embedded reference, final data, pile #1-1.

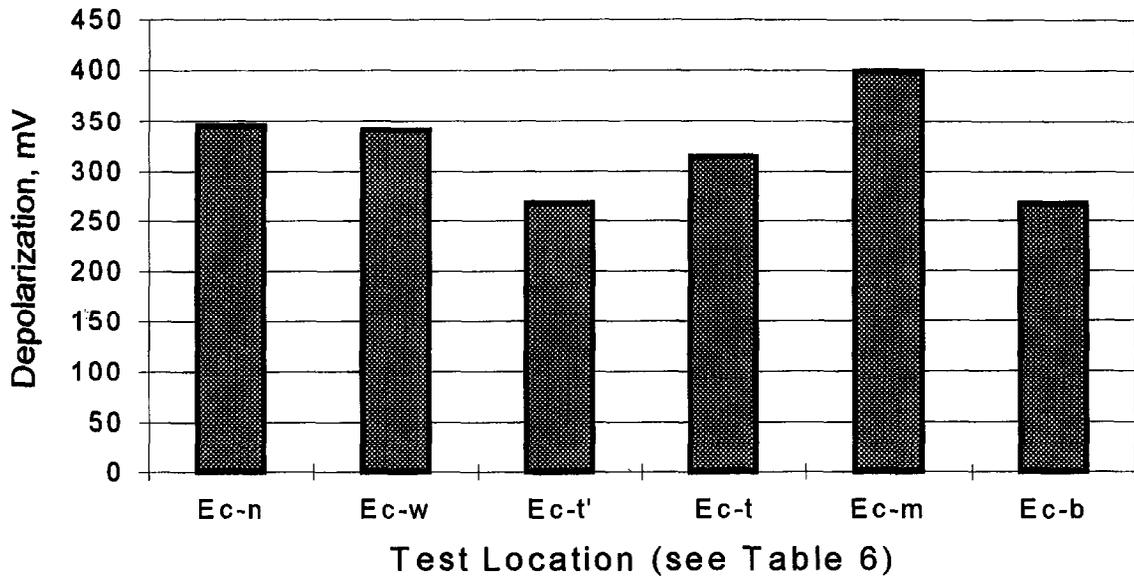


Figure 40. Cathode depolarization on pile surface, final data, pile #1-1

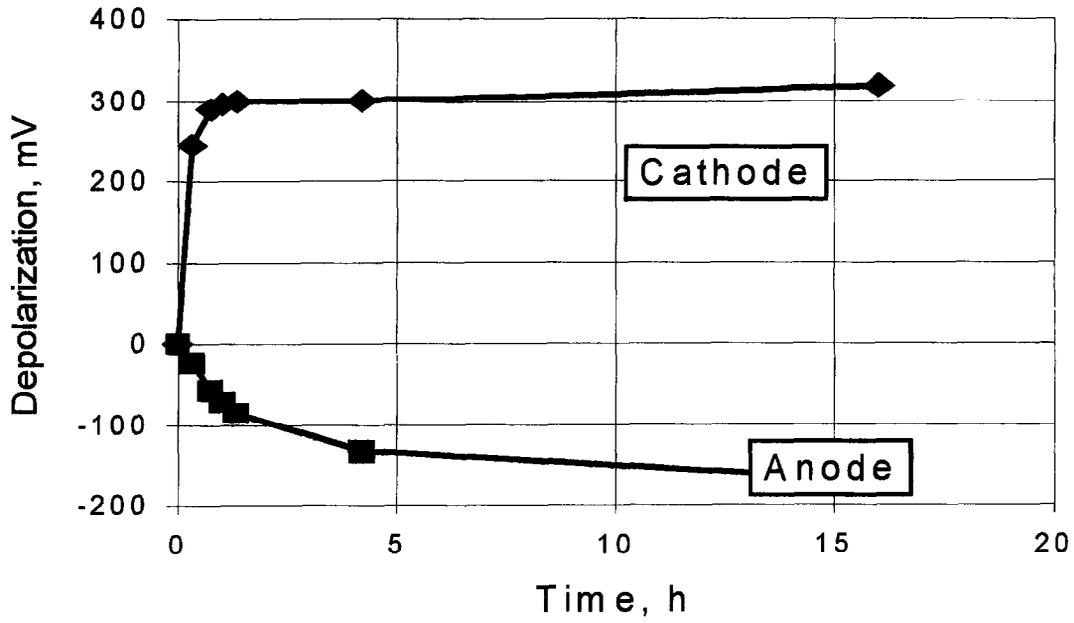


Figure 41. Depolarization to embedded reference, final data, pile #1-2

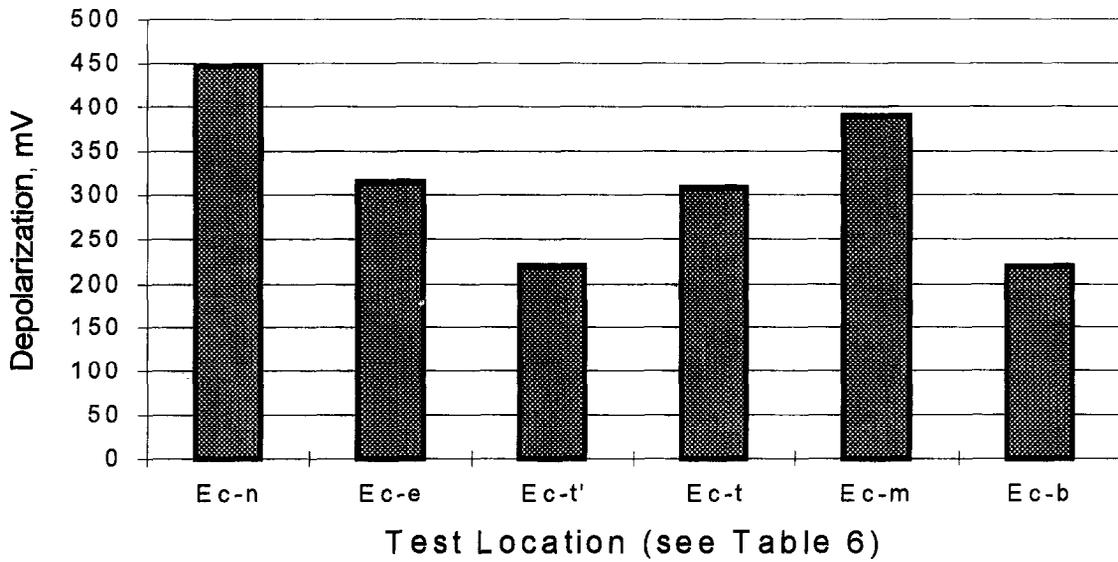


Figure 42. Cathode depolarization on pile surface, final data, pile #1-2.

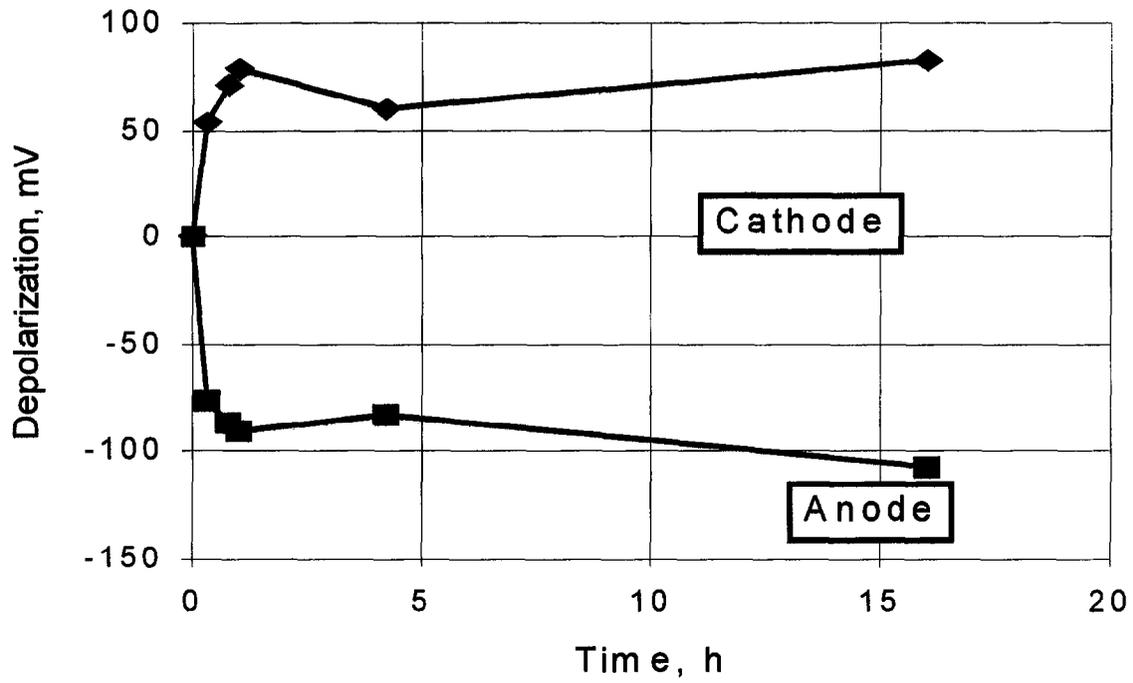


Figure 43. Depolarization to embedded reference, final data, pile #1-3.

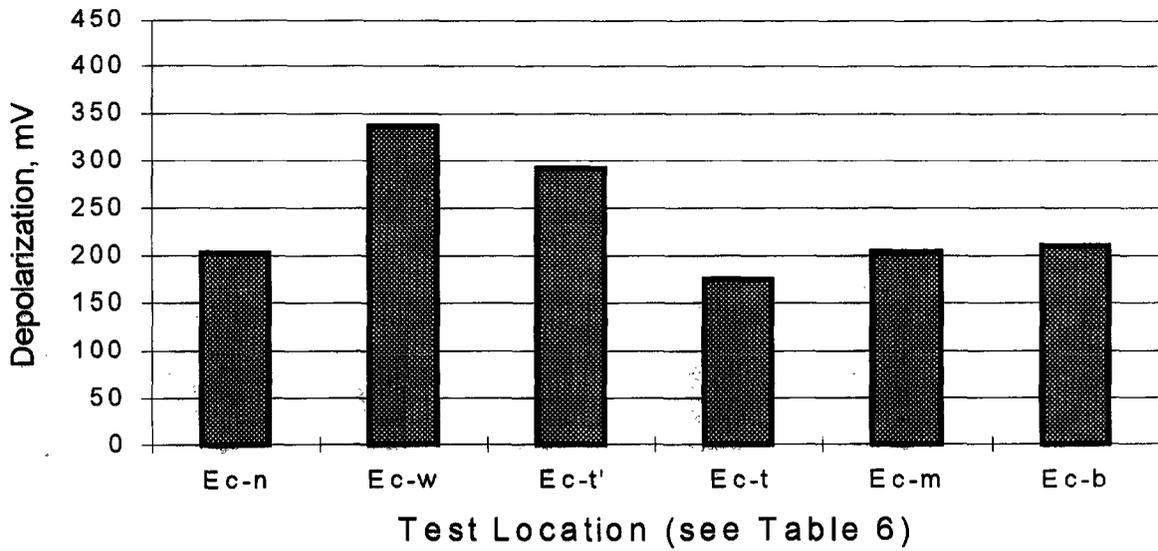


Figure 44. Cathode depolarization on pile surface, final data, pile #1-3.

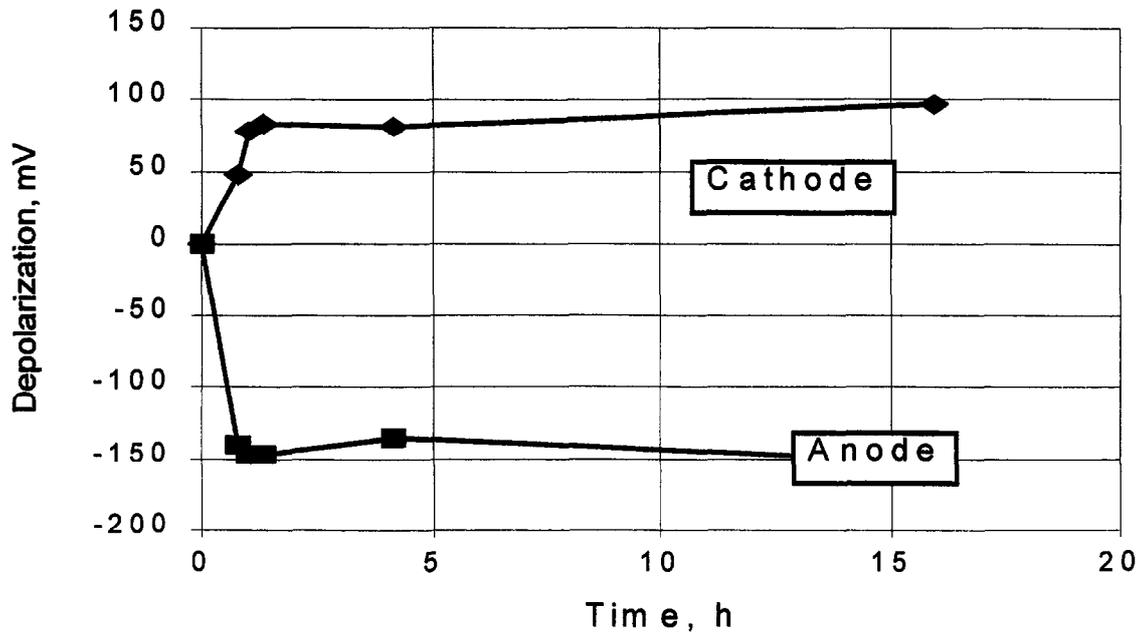


Figure 45. Depolarization to embedded reference, final data, pile #1-4.

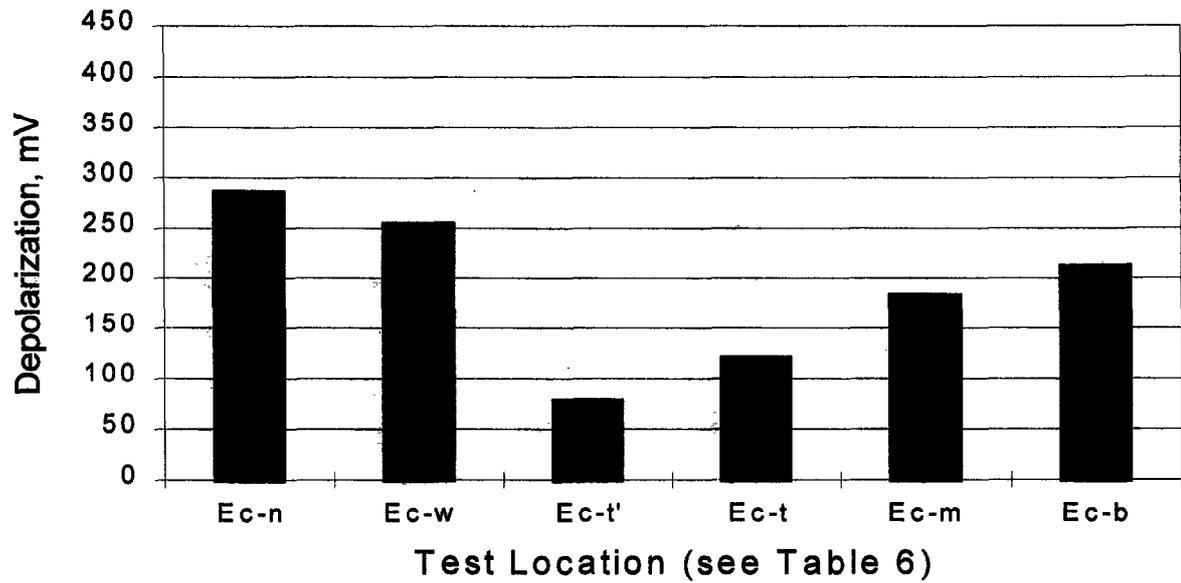


Figure 46. Cathode depolarization on pile surface, final data, pile #1-4.

Adhesion

Adhesion tests using an Elcometer pull-off tester were conducted on each of the seven piles during the June 1997 tests. The anode surface was cleaned with a non-metallic pad before adhering the dolly. Immediately after pulling the adhesion dolly, the pH of the concrete surface was measured using pH paper and demineralized water. Table 8 presents the adhesion test results.

Table 8. Adhesion test results.

File	Location	Adhesion, kg/cm ²	pH	Comments
1-1	mid-length, S face, W face	25, 18	7, 8	Aluminum alloy anode. 1st broke in concrete, others broke at interface
1-2	mid-length N face	5	6-7	Aluminum alloy anode. Broke at interface, adhesion failure on other dollies
1-3	12 in (30.5 cm) from bottom, W and E face, S face	25, 20	9, 7-8, 11	Zinc anode. Broke in concrete
1-4	N face, E face, S face (all mid-length)	23, 25, 20	8-9, 9, 9-10	Zinc anode. Broke at interface
2-5	N face, E face	19, 20	6-7	Aluminum alloy anode. Broke at interface
2-6	W face, mid-length	20, 21	8, 9	Aluminum alloy anode. Broke at interface
2-7	N face, mid-length	19, 20, 12, 19, 20	7-8, 8-9, 7	Zinc anode. 1st broke in concrete, others broke at interface

The adhesion test results are generally similar for both anode coatings, with the adhesion at about 20 kg/cm² (284 lb/in²). The pH of the interface also showed a decrease from the normally expected alkaline pH of concrete.

Anode Consumption

Core samples were removed from each of the piles at test location #1. The cores were subjected to scanning electron microscopy (SEM), energy dispersive x-ray (EDXA), and wavelength dispersive spectroscopy (WDS) analyses to characterize the interface. Two cores were taken from pile #1-1 (north and south faces) and two cores were taken from pile #1-2 (north and south faces).

Some of the adhesion dollies with adhered concrete or corrosion products from test location #2 were analyzed using SEM and EDXA. Three distinct layers were found: The first layer was the

corrosion product on the outer surface of the anode (that surface exposed to the atmosphere), the middle layer was the anode metal itself, and the inner layer was the corrosion product between the anode and concrete. Figures 47 through 50 show backscatter electron images of the cross-sections of the core samples removed from test location #1. The elemental analyses show that the outer and inner faces of each anode metal contain the base metal (and major alloying elements, if present) plus oxygen, which is consistent for corrosion products. In addition, sulfur, silicon, calcium, magnesium, and chlorine also are present in varying minor amounts. None of the elements found are unexpected.

One of the primary reasons for analyzing the cores from test location #1 and the adhesion dollies from test location #2 was to estimate the life of the anode. Anode consumption was estimated using the cross-sections of the cores and adhesion dollies and measuring the thickness of the coating. This estimate of anode consumption assumed that the consumption rate remains the same throughout the life of the anode. The thickness showed considerable variation for each of the coatings, and showed that the target thickness of 12 mils (305 μm) for the aluminum alloy and 20 mils (508 μm) for the zinc were not uniformly met. For the purposes of this estimate, the remaining thickness plus the corrosion product thickness at the concrete-anode interface was used to estimate the original thickness. There are errors involved in estimating the original thickness this way. First, the corrosion product layer is thicker than the amount of metal lost. The other error in using this method is that the amounts of metal depleted and coating thickness vary from location to location. Table 10 presents the data used and estimated life. Since the thicknesses were not consistent, the last column in table 10 shows the estimated life based on a consistent 12-mil (305- μm) coating thickness. Keeping in mind the errors associated with this analysis, the time to total consumption of the coatings varies from 8 to 48 yr, with an average of 22 yr.

The time to total consumption of the anodes also was calculated by estimating the current over the 2 yr of operation (ignoring any short periods of downtime, and assuming that consumption rate was uniform throughout the test period), and estimating metal loss on the basis of known consumption rates for zinc and aluminum. The consumption rate of the aluminum alloy is not known with precision, but estimates based on laboratory work by our subcontractor indicate that the consumption rate is similar to the aluminum-zinc-indium alloy bulk anode used in other cathodic protection applications.¹ The life calculations are based on the following:

Zinc density:	440 lb/ft ³ (7.05 g/cm ³)
Zinc consumption rate:	25 lb/A-y (11.3 kg/A-y)
Zinc current range:	0.11 to 0.325 mA/ft ² (1.18-3.49 A/m ²)
Aluminum alloy density:	202.3 lb/ft ³ (3.24 g/cm ³)
Galvalum III consumption rate:	7.62 lb/A-y (3.46 kg/A-y)
Aluminum alloy current range:	0.41 to 1.26 mA/ft ² (4.41-13.56 A/m ²)

¹ Such as Galvalum III, Dow Chemical Co., 3 percent zinc, 0.015 percent indium, 0.1 percent silicon, rem. aluminum, 8.4-7.4 lb/amp-y (3.8-3.4 kg/amp-y).

The results of the analysis using theoretical consumption rates yield a time to total consumption for the zinc anode to be 54 to 160 yr, and that for the aluminum alloy anode to be 21 to 65 yr at a thickness of 12 mils (305 μm). The lower values correspond to the higher current outputs, and appear to correspond reasonably well to the estimates based on remaining metal thickness. While these numbers indicate that the zinc anodes might have a long life expectancy, another factor to be considered is that the low current output of the zinc anode did not result in full cathodic protection for the rebar except in moist concrete (where the current output and consumption rates are higher). Also, some of the anode will deplete due to external atmospheric corrosion and non-galvanic corrosion at the anode-to-concrete interface. These factors were not considered in this analysis. The efficiency (amount of metal useful for cathodic protection - not including atmospheric corrosion losses) of zinc and aluminum anodes in underground or submerged cathodic protection systems is 95 percent.² The efficiencies of zinc and aluminum in atmospheric CP applications on concrete are not as well defined. Additional work is needed to establish the life expectancy of sacrificial anode systems.

The time to consumption estimates assume that all of the anode metal is usable, and do not necessarily indicate the life of the CP system. In reality, the life of the galvanic anode CP system will be lower than that estimated from purely theoretical considerations. Not all of the metal is usable as an anode. Some areas will deplete faster than others, because some areas of the structure will be wetter or physically closer to rebar than others, resulting in locally higher current densities. As these areas of anode become depleted, the effectiveness of the system is reduced, and the system will need to be renewed.

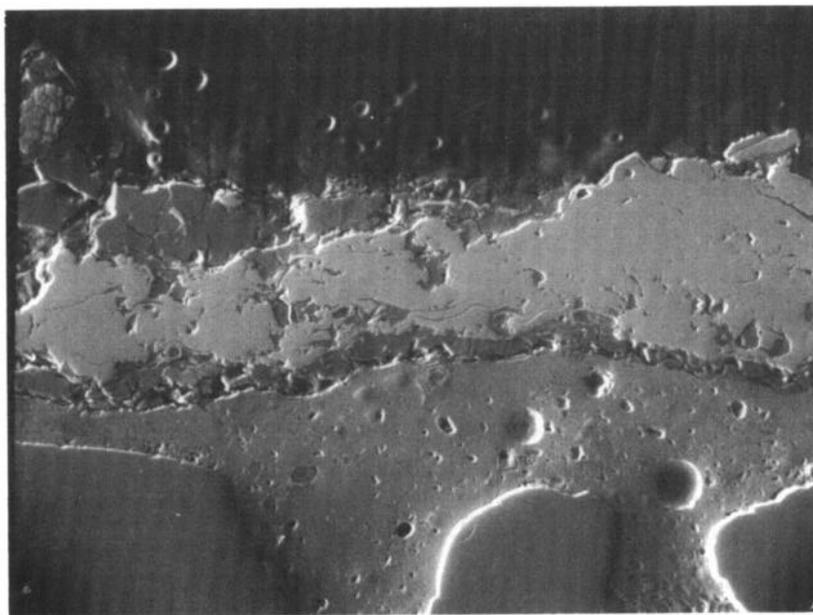


Figure 47. SEM image of a cross-section through the concrete core from pile #1-1 south face, 100X. (aluminum alloy anode had been active for 2 yr, concrete is at the bottom)

² Shreir, L.L., *Corrosion*, Vol. 2, Corrosion Control, 2nd Ed., Newnes-Butterworths, Toronto, 1976

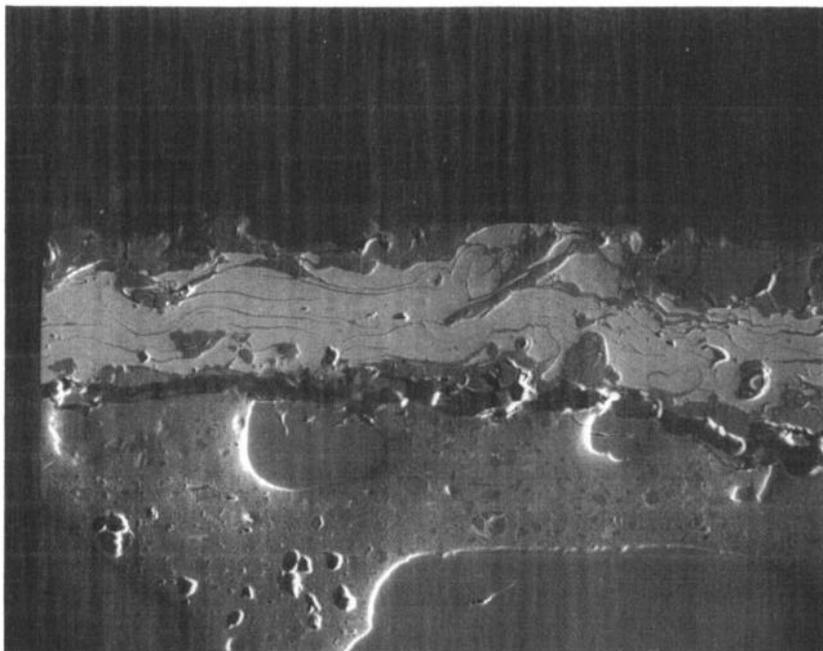


Figure 48. SEM image of a cross-section through the concrete core from pile #1-2 south face, 100X. (aluminum alloy anode had been active for 2 yr, concrete is at the bottom of the photograph)

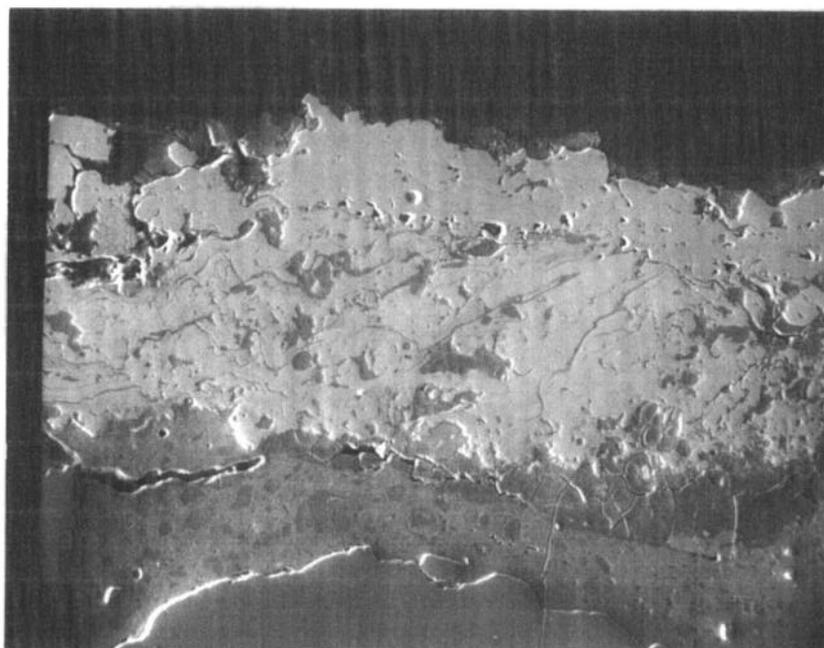


Figure 49. SEM image of a cross-section through the concrete core from pile #1-2 north face, 100X. (aluminum alloy anode had been active for 1 yr, concrete is at the bottom of the photograph)

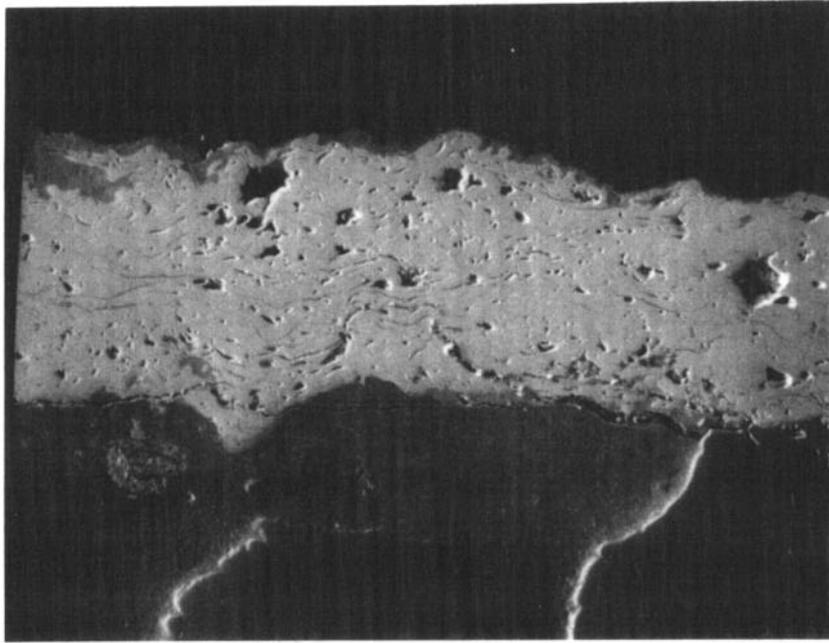


Figure 50. SEM image of a cross-section through the concrete core from pile #1-3 west face, 100X. (zinc anode had been active for 2 yr, concrete is at the bottom of the photograph)

Table 9. Estimates of anode life on the basis of estimated thickness lost.

Pile	Estimate of Remaining Coating Thickness		Years Operation	Corrosion Product Thickness at Concrete		Estimate of Original Coating Thickness		Average Corrosion Rate		Estimated Life, y	
	mils ⁽¹⁾	μm		mil ⁽¹⁾	μm	mil ⁽¹⁾	μm	mils/yr	μm/yr	Ave. mils	12 mils (305 μm)
1-1	4-10	101-254	2	1	25.4	5-11	127-279	0.5	12.7	16	24
1-2	5-7	127-177	2	2-3	51-76	6-9	153-229	0.5	12.7	15	8
1-2	12-17	381-431	1	1-1.5	25.4-38	15-18	381-457	1.5	25	11	24
1-3	10-15	254-330	2	0-0.5	0-12.7	10-16	254-406	0.25	6.4	51	48
1-4	No Data										
2-5	7	177	2	ND ⁽²⁾		9	229	1	25.4	9	12
2-6	9	228	2	ND		10	254	0.5	12.7	20	24
2-7	12	306	2	ND		14	356	1	25.4	14	12

(1) 1 mil = 0.001 in (0.00254 cm)

(2) ND = No Data

CONCLUSIONS

1. The aluminum-zinc-indium alloy anode provided higher current than the zinc anode. Indeed, the current output of the aluminum alloy might be more than necessary for a warm marine climate, such as Florida.
2. The current output of both anode materials fluctuated with changes in relative humidity, temperature, and wetness of the concrete.
3. The high level of current from the aluminum alloy anode resulted in higher levels of cathode depolarization than the zinc anode. The depolarization achieved by the aluminum alloy anode exceeded 100 mV during the 2-yr test period.
4. The zinc did not discharge enough current to provide depolarization levels sufficient to meet cathodic protection criterion of 100 mV, except in wet areas and when wet conditions existed.
5. The aluminum alloy anode continued to adhere well to the piles during the 2-yr test period, and exhibited adhesion values the same as those of the zinc anodes after 2 yr.
6. Both anodes can be expected to provide a reasonable life expectancy — above 15 yr at 12 mils (305 μm) thickness.
7. Topcoating of the aluminum alloy anode is not necessary, and might result in disbondment of the coating from corrosion products on the outside face of the anode.

RECOMMENDATIONS

1. Conduct research into varying the composition of the aluminum-zinc-indium alloy to meet the needs of a variety of climates.
2. Evaluate the life expectancy of the aluminum-zinc-indium alloy through laboratory testing and by monitoring field installations using the alloy as a sacrificial anode.
3. Periodically monitor both pile bents of the Bryant Patton Bridge having the zinc and aluminum alloy anodes to develop long-term performance data of the anodes. The anodes were left operating at the conclusion of the June 1997 tests.

REFERENCES

1. Federal Highway Administration, U.S. Memorandum, "Bridge Deck Deterioration: A 1981 Perspective," Office of Research, Washington, D.C., Dec. 1981.
2. Federal Highway Administration, U.S. Memorandum, "FHWA Position on Cathodic Protection Systems Revisited," Office of the Administrator, Washington, D.C., May 24, 1994.
3. W. Shreir, *Corrosion*, Volume 2, Newnes-Butterworths, Boston, 1976.
4. J.L. Saner, *Zinc Anodes to Control Bridge Deck Deterioration*, Illinois Department of Transportation, Report No. FHWA-IL-77-PR-69, December 1977.
5. D. Whiting and D. Stark, *Galvanic Cathodic Protection for Reinforced Concrete Bridge Decks - Field Evaluation*, NCHRP Report 234, June 1981.
6. J.A. Apostolos, "Cathodic Protection of Reinforced Concrete Using Metallized Coatings and Conductive Paints," *Transportation Research Record* 962, TRB, Washington, DC, 1984, pp. 22-29.
7. A.A. Sagues and R.G. Powers, *Sprayed Zinc Galvanic Anodes for Concrete Marine Bridge Substructures*, Report No. SHRP-S-405, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.
8. R.A. Carello, D.M. Parks and J.A. Apostolos, *Development, Testing and Field Application of Metallized Cathodic Protection Coatings on Reinforced Concrete Substructures*, Report No. FHWA/CA/TL-89/04, Caltrans, May 1989.
9. J.A. Apostolos, D.M. Parks, and R.A. Carello, "Cathodic Protection of Reinforced Concrete Using Metallized Zinc," *Materials Performance*, NACE, Houston, TX, Dec. 1987, pp. 22 - 28.