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Further Improvements in Cathodic Protection

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FOREWORD

This report presents the findings of a field research study in which the performance of seven cathodic protection systems were evaluated. The findings will be of interest to engineers and administrators responsible for the design, implementation and adjustment of cathodic protection systems on bridges located in areas subject to deicing salt use and ocean salt environments.

The cathodic protection systems were monitored and data collected on a continuous basis for approximately 2 years after initial energization. The research effort also assesses embedded monitors, rectifier control and cathodic protection criteria for bridges.

This report concludes the FHWA Research Study "Further Improvements in Cathodic Protection." Installation of the various cathodic protection systems are described in detail in Interim Report No. FHWA/RD-87/062 dated June, 1987.

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16. Abstract

The performance of seven cathodic protection systems installed on two mild steel reinforced concrete bridges was assessed. One bridge is located in a marine environment and the other is located in a northern climatic region. Critical review of embedded silver/silver chloride reference cells and macrocell rebar probes was made. Constant voltage and constant current control for cathodic protection systems were monitored and results are described. Test procedures and actual field data to establish cathodic protection criteria for bridge structures are discussed.

The effectiveness of an improved coke-asphalt cathodic protection system for bridge decks was laboratory tested and discussed.

This report is the conclusion of this research study. Details on the installation of the various cathodic protection systems are described in the Interim Report No. FHWA/RD-87/062 dated June 1987.

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Cathodic Protection, Corrosion, Bridge Structures, Cathodic Protection Anode Systems, Cathodic Protection Criteria, Cathodic Protection Monitor Instrumentation, E Log I/Depolarization Testing

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METRIC CONVERSION FACTORS

Approximate Conversions U.S. Customary to Metric Measures

LENGTH

1 inch = 2.5 centimeters
1 foot = 30 centimeters
1 yard = 0.9 meters
1 mile = 1.6 kilometers

AREA

1 square inch = 6.5 square centimeters
1 square foot = 0.09 square meters
1 square yard = 0.6 square meters
1 square mile = 2.6 square kilometers
1 acre = 0.4 hectares

MASS (weight)

1 ounce = 28 grams
1 pound = 0.45 kilograms
1 short ton (2000 lb) = 0.9 tonnes

VOLUME

1 teaspoon = 5 milliliters
1 tablespoon = 15 milliliters
1 fluid ounce = 30 milliliters
1 cup = 0.24 liters
1 pint = 0.47 liters
1 quart = 0.95 liters
1 gallon = 3.8 liters
1 cubic foot = 0.03 cubic meters
1 cubic yard = 0.76 cubic meters

TEMPERATURE (exact)

$^{O}F = 5/9 (^{O}F-32) ^{O}C$

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INTRODUCTION

The final task of this research study was to evaluate the performance of seven cathodic protection systems installed on two reinforced concrete bridges in different environments. Every aspect of implementing these cathodic protection systems, including the condition survey, design preparation, material selection, installation and equipment is discussed in the interim report of this research project. (Report No. FHWA/RD-87/062).

One bridge is in a southern marine environment. A schematic diagram of the cathodic protection system is shown in figure 1. The bridge is divided into three zones, each having a different cathodic protection anode system. The deck, Zone 1, has a rigid conductive polymer concrete (CPC) in slots anode system. The East pier, Zone 2, has a zinc arc-spray anode system and the West pier, Zone 3, has a specially formulated conductive polymer spray anode system.

The second bridge is in a northern climate. A schematic diagram of the cathodic protection system is shown in figure 2. The bridge is divided into four zones, each having a different cathodic protection anode system. Raychem's Ferex 100, a flexible polymeric material, with a latex modified concrete (LMC) overlay was installed on the West Bound Lane (WBL) of the deck, Zone 1. Eltech's Elgard 210, titanium wire mesh with catalytic coating, with a LMC overlay was installed on the East Bound Lanes (EBL) of the deck, Zone 2. The sidewalk system, Zone 3, consists of Elgard 210 anode with modified HCR Thorotop overlay. Eltech's Elgard's 150 anode mesh was embedded in the modified HCR Thorotop coating for the bridge piers, Zone 4.

Silver-silver chloride (Ag/AgCl) reference cells and macrocell rebar probes were installed into the bridge structures. A rectifier/controller capable of monitoring "IR Drop Free" reference cell potential and controlling constant current or constant voltage, powered each system.

A monitor program was established to evaluate the effectiveness of the cathodic protection system in voltage or current control and to determine acceptance criteria for cathodic protection. Various criteria have been proposed for determining the effectiveness of cathodic protection. E Log I (chapter 1, figure 3), 100 mV polarization decay, concrete surface current density and rebar surface current density methods were evaluated during this research project. Pertinent data (appendix A; figures 4 to 24) was collected on a bi-monthly basis to include voltage, current, "Instant Off" reference cell potential, macrocell rebar probe current and ambient temperatures.

Detailed tests were performed at approximately 6-month intervals. The testing included visual inspection, delamination sounding, electrical resistance measurements between various components of the cathodic protection system, depolarization testing (appendix B; figures 25 to 56), E Log I testing (appendix C; figures 57 to 116) and corrosion current measurements of the macrocell rebar probes.

In addition, the findings of a substudy to define and test the effectiveness of an improved coke-asphalt cathodic protection system for bridge decks is included in appendix D of this report.

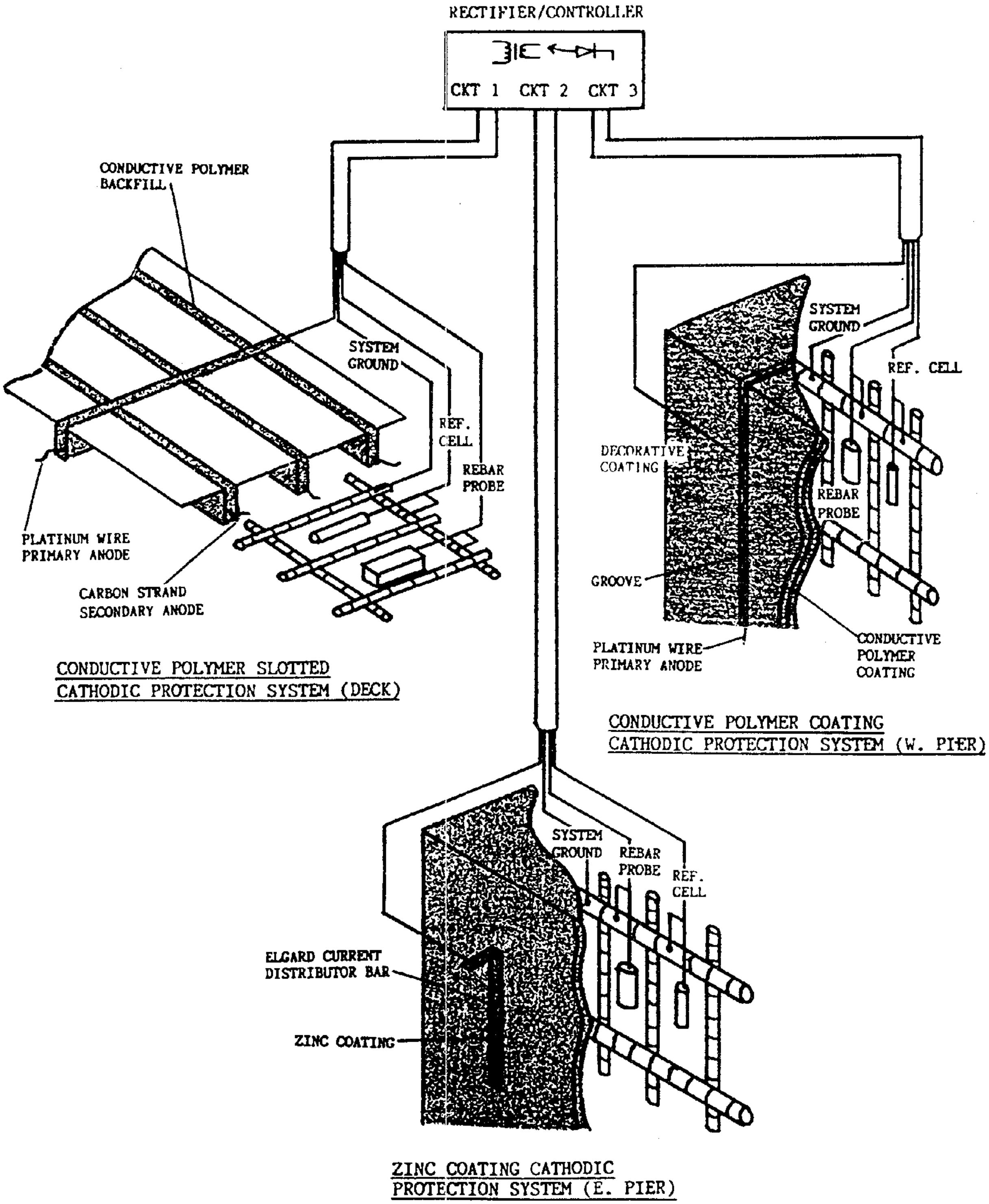


Figure 1. Cathodic protection schematic diagram for marine environment bridge, Norfolk, Virginia.

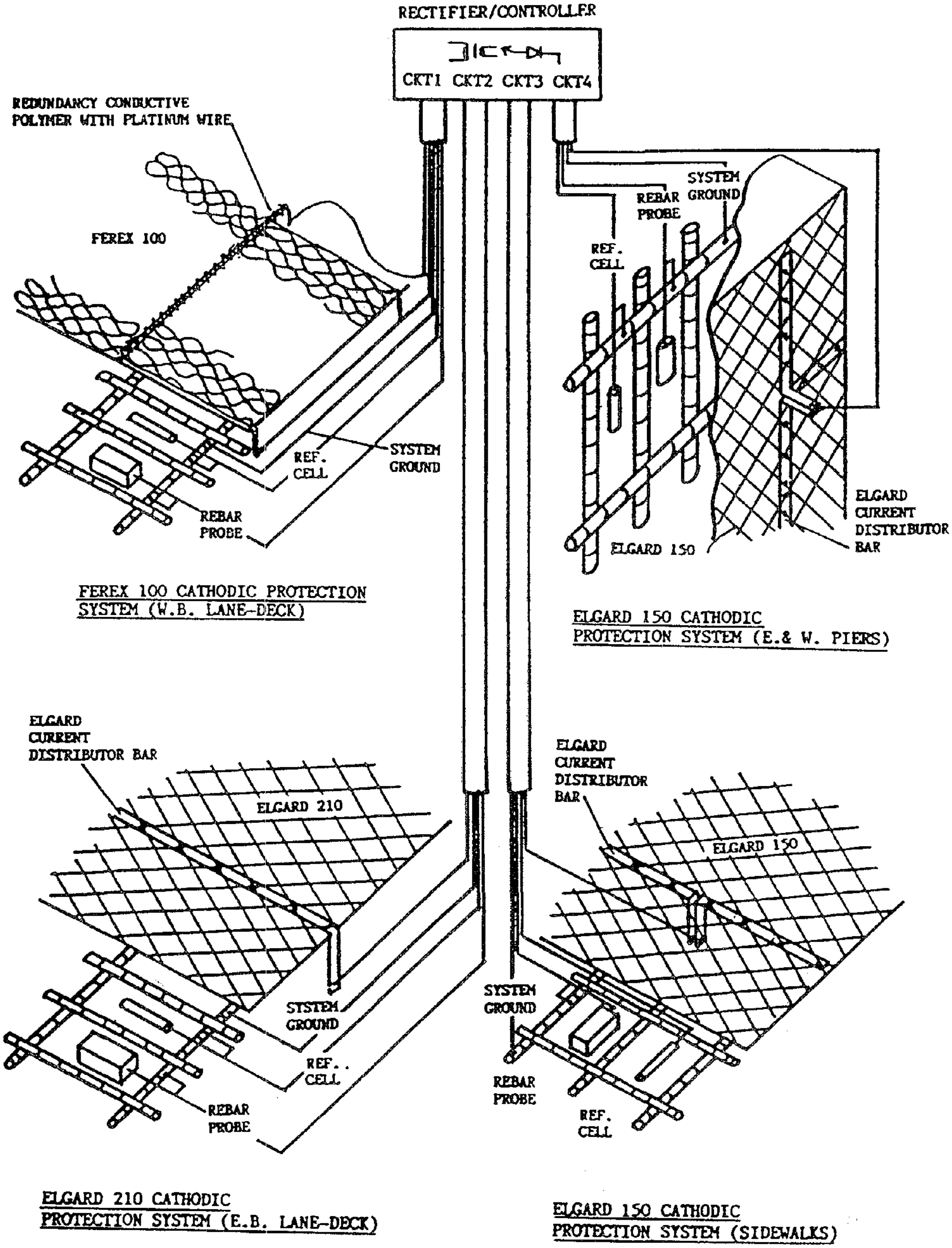


Figure 2. Cathodic protection schematic diagram for northern climate bridge, Cincinnati, Ohio.

CHAPTER 1 DETAILED EVALUATIONS

A detailed evaluation of the cathodic protection systems at approximately 6-month intervals from activation was performed. The evaluation included the following:

- Visual inspection.
- Delamination study.
- Electrical resistance measurements.
- Macrocell rebar probe current measurements.
- Depolarization testing
- E Log I testing.

TEST PROCEDURE

Visual Inspection

Physical condition of the bridge structure components and the cathodic protection systems were examined by a visual survey.

Delamination/Disbondment Study

A delamination/disbondment study was conducted across the top deck, sidewalks and lower portions of the piers using visual observation, chain drag and hammer pounding methods.

Electrical Resistance Measurements

Electrical resistance measurements were taken between the various components of the cathodic protection system. The measurements were obtained using a Nilsson Model 400 AC impedance meter connected to the component lead wires at each of the rectifier.

Macrocell Rebar Probes Current Measurements

Each macrocell rebar probe voltage and polarity was measured at the rectifier test station across a precision shunt resistor (10 ohm, 1 percent accuracy) using a Miller Model LC-4 voltmeter. The positive lead of the meter was connected to the macrocell rebar probe and the negative lead to the reinforcing steel ground. The direction and magnitude of current across the shunt was recorded. By monitoring the electrical current flow produced by electrochemical reactions on the macrocell rebar probe and the surrounding reinforcing steel, whether the macrocell rebar probe is an anode (corroding) or cathode (non-corroding) is determined. When the electrical current direction is from the reinforcing steel to the macrocell rebar probe, the macrocell rebar probe is anodic. When the electrical current flow is from the macrocell rebar to the reinforcing steel, it is cathodic. There is a high probability that all other anode cells in the reinforcing steel will be eliminated if the macrocell rebar probe current is reversed during the application of cathodic protection.

Depolarization Testing

100 mV of polarization decay after interruption of applied protection current is a proposed cathodic protection polarization criterion by The National Association of Corrosion Engineers (NACE) for steel in water or soil. NACE Unit Committee T3K, "Corrosion and Other Deterioration Phenomena Associated with Concrete", is currently evaluating the use of this criterion (as well as other criteria) for steel in concrete. The considered criterion requires that the half cell potential depolarizes at least 100 mV more positive from the "Instant Off" potential of the reinforcing steel when the cathodic protection current is first turned off. This depolarization shift should occur in a reasonable time period which is generally accepted to be 4 hours maximum. Permanent embedded Ag/AgCl reference cells and portable copper-copper sulfate reference cells placed on the concrete in conjunction with automatic potential data logging computers were used for this testing.

E Log I Testing

E Log I testing is another criterion under considerations by the NACE Unit Committee T3K. E Log I testing was performed using permanent embedded Ag/AgCl reference cells for each system. IR drop free potential measurements were made utilizing the automatic circuits in the rectifier unit. The protection currents were increased at approximately 2 to

3 minute intervals. "Instant Off" reference cell potentials were recorded at the end of each current increment time period.

The purpose for performing E Log I tests is to determine the amount of current required to protect the reinforcing steel against further corrosion. According to theory, as increments of current are applied to a structure, oxidizing and reduction reactions occur on the steel surface. When the reduction reaction dominates, a plot of the applied current versus the polarized structure potentials on a semi-log graph gives a straight line called Tafel behavior. The polarized potential at the beginning of the Tafel segment is the value which indicated adequate cathodic protection. Using the above theory, the required cathodic protection current is graphically found for each structure. Figure 3 shows a classic E Log I curve identifying all the corrosion and cathodic protection parameters. The interpretation of the linear portion of the curve and the break is subjective to individual opinion. Therefore, to obtain the best fit straight line of the Tafel slope, a linear regression technique using a computer was adapted. This computerized method enables evaluation of all possible linear portions of the graph to determine the most linear portion of the curve. The linear regression program then calculates the Tafel slope (Bc), Corrosion current (I-corr), Corrosion potential (E-corr), Cathodic protection current (I-protect), Cathodic protection potential (E-protect), Standard deviation of potential estimate (standard error), Closeness of fit of the estimated data to actual data (R^2) and number of observations used. Based on the results, the best Tafel slope is chosen and the E Log I graphs were generated.

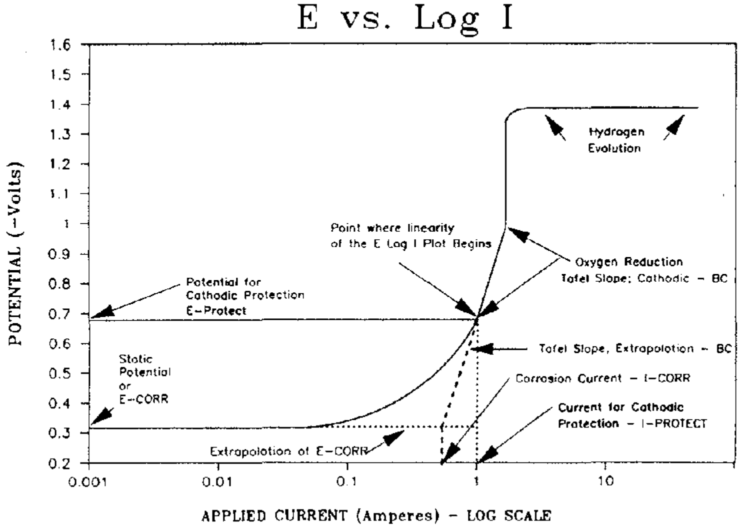


Figure 3. Classic E Log I curve.

RESULTS AND ANALYSIS OF CATHODIC PROTECTION SYSTEMS IN MARINE ENVIRONMENT

Visual Inspection

Zone 1, Deck (Slot System with Conductive Polymer)

Discoloring of the concrete was observed at high current discharge areas. These areas were; at the end of the slots, at stress cracks and at the boundary of concrete patches. Discoloring of the concrete at some locations is attributed to acid formation at select locations. Aside from the appearance of a striped surface, the deck was found in good condition throughout the 23-month evaluation.

Zone 2, East Pier (Zinc Spray System)

General appearance of the pier was in good condition throughout the 23-month evaluation. Streaks of dirt from the leaking deck joint were observed. The appearance of the zinc coating was darker after the first 6 months but has remained relatively constant since that time. After 9 months at one of the small areas where the zinc coating was isolated from the anode system (short to rebar), a rust stain formed but no apparent damage was ever observed. At two locations on the bottom of the pier cap, rust stains and cracks were observed at 16 months. At 23 months these areas spalled, exposing the bottom of rebar chairs.

Zone 3, West Pier (Conductive Polymer Spray System)

As in the case of the east pier, dirt streaks from a leaking deck joint were observed. Discoloration of the decorative overcoat was found at the lower end of the columns (near the end of all the primary anode platinum wires). Dot size rust stains were also observed over the entire pier at the 9-month evaluation. At 16 months the conductive polymer was found blistered at two locations. The blisters were less than 1-in (2.5 cm) diameter each. In addition, five rust stains were found at the bottom of the pier cap and the overall number of dot size rust stains increased. At 23 months, at least up to a dozen 1-in (2.5 cm) diameter conductive polymer blisters were found scattered throughout the columns.

In addition, two of the six platinum wire ends had extensive conductive polymer blistering. In general the rust staining on the underside of the pier cap increased but the amount of dot size rust appeared the same. The decorative overcoat appeared darker (black shadowing) with time.

Delamination/Disbondment Study

Zone 1, Deck (Slot System with Conductive Polymer)

At 9 months, a very small area of concrete disbondment, approximately 1 in^2 (6.5 cm^2) was found near an anode slot at a repair patch boundary. It was readily spalled by tapping. Based on discoloration and porous appearance of the spall, it is considered that anode acid attack of the cement paste and freeze-thaw deterioration led to the disbondment. No other delamination or disbondment was found during the 23-month evaluation.

Zone 2, East Pier (Zinc Spray System)

Two delaminations of about 2-in (5 cm) diameter each were observed on the bottom of the pier cap. Some electrical discontinuity was found on the chairs of the pier cap during the design study. No attempt to electrically bond these chairs was made during the installation. It is suspected that these delaminations were from rebar chairs which were not electrically continuous to the cathodic protection system. No disbondment of the zinc coating was detected during the 23-month evaluation.

Zone 3, West Pier (Conductive Polymer Spray System)

The west pier may also have some discontinuous rebar chairs in the pier cap. Where rust colored areas were observed, the concrete did not spall, as it did on the east pier cap. It is suspected that in time this concrete will also spall. Scattered disbondment areas of the conductive polymer were reported in the visual inspection section of this chapter. No disbondment of the decorative overcoat to the conductive polymer was detected during the 23-month evaluation.

Electrical Resistance Measurements

Table 1 documents the resistance measurements obtained at initial energization through 23 months of continuous activation. The anode to system ground circuit resistance increased for all zones at 9 months as expected and again at 16 months. This was a 79 percent increase for Zone 1, 174 percent increase for Zone 2 and 200 percent increase for Zone 3. At 23 months the circuit resistance was less than at 16 months, but was higher than recorded 1 year previous (2.3% increase for Zone 1, 22% increase for Zone 2 and 5.7% increase for Zone 3). Many factors can contribute to the increase in resistance such as concrete temperatures, moisture concentration, anode/concrete bond and anode consumption. Of course, the life of the cathodic protection system will be dependent on the anode/concrete bond and anode consumption rate. It is noted that the resistance cycles with season changes after the initial evaluation. Therefore, excluding the initial resistance measurements the average circuit resistance is 1 ohm for Zone 1, 1.3 ohms for Zone 2 and 5.3 ohms for Zone 3. The reference cell and rebar probe resistance measurements are discussed in detail in chapter 4. It should be noted that all resistance measurements were within design consideration throughout the 23-month evaluation.

Table 1.

Electrical resistance measurements for marine environment bridge, Norfolk, Virginia.

Components	Resistance (ohms) 8-86 (Initial Energization)	4-87 (9 Months)	11-87 (16 Months)	5-88 (23 Months)
Anode - System Ground				
Zone 1 (Deck - Slotted System)	0.67	0.88	1.20	0.90
Zone 2 (E. pier - Zinc coating system)	0.59	0.98	1.60	1.20
Zone 3 (W. pier - Conductive polymer spray system)	2.20	4.40	6.60	4.65

Table 1. (continued)

Electrical resistance measurements for marine environment bridge, Norfolk, Virginia.

Components	Resistance (ohms) 8-86 (Initial Energization)	 4-87 (9 Months)	 11-87 (16 Months)	 5-88 (23 Months)
Reference Cell - Reference Cell Ground				
Zone 1, Reference Cell 1	170	460	530	2200
Zone 1, Reference Cell 2	200	670	1000	1100
Zone 2, Reference Cell 1	270	700	980	1200
Zone 2, Reference Cell 2	240	400	500	590
Zone 3, Reference Cell 1	410	900	1150	1200
Zone 3, Reference Cell 2	200	670	2100	9300
Rebar Probe - Rebar Probe Ground				
Zone 1, Rebar Probe 1	125	230	340	350
Zone 1, Rebar Probe 2	120	250	400	385
Zone 2, Rebar Probe 1	330	660	880	820
Zone 2, Rebar Probe 2	410	900	1400	1400
Zone 3, Rebar Probe 1	520	1200	1500	1600
Zone 3, Rebar Probe 2	235	500	560	650

Macrocell Rebar Probe Current Measurements

Initial current and polarity did show that all macrocell rebar probes were anodic to the surrounding reinforcing steel prior to applying cathodic protection current. After 16 months of cathodic protection operation, not all macrocell rebar probes returned to an anodic state. The corrosion current density and the rectifier current which reversed the polarity of each macrocell rebar probe are shown in table 2. As shown by the corrosion current densities, all rebar probes were more powerful corrosion cells at the initial energization. With continuous cathodic protection current applied over time, with only a few exceptions, less rectifier current was required to protect the macrocell rebar probe. A detailed discussion on the macrocell rebar probe is in chapter 4. After 23 months the rectifier current required to reverse the macrocell rebar probes did not agree with the protective current requirement defined from the E Log I testing, however the difference was greatly reduced.

Table 2.

Corrosion current density and rectifier current to reverse macrocell rebar probes for marine environment bridge, Norfolk, Virginia.

Location	Rectifier Current to Reverse (Amps)				Corrosion Current Density of Rebar Probe (mA/ft^2)			
	8-86 (Initial)	**4-87 (9 Mo)**	**11-87 (16 Mo)**	**5-88 (23 Mo)**	**8-86 (initial)**	**4-87 (9 Mo)**	**11-87 (16 Mo)**	**5-88 (23 Mo)**
Zone 1 (Deck)								
Rebar Probe (E. Span)	8.44	4.20	2.0	1.9	17.8	6.4	4.6	3.1
Rebar Probe (M. Span)	4.00	3.60	0.90	0.85	17.4	9.9	3.2	2.0
Zone 2 (E. Pier)								
Rebar Probe (Pier Cap)	1.35	0.20	0.60	0.33	7.8	1.2	3.9	2.8
Rebar Probe (Column)	0.30	0.07	n/a[1]	n/a[1]	10.1	0.7	n/a[1]	n/a[1]
Zone 3 (W. Pier)								
Rebar Probe (Pier Cap)	2.20	0.25	0.20	0.7	7.4	1.0	0.5	0.02
Rebar Probe (Column)	0.50	0.15	0.42	0.28	6.1	1.5	3.8	3.6

[1] n/a = Not applicable since the rebar probe was not anodic.

Depolarization Testing

The depolarization test results are summarized in table 3 (a graphic presentation of all data collected is shown in appendix B; figures 25 to 41). In addition to the two embedded reference cells in the deck (Zone 1), six locations were selected for portable reference cell monitoring. The location of the portable cell test sites are as follows: Portable cell #1 was positioned at a patched area boundary on the east span of the south shoulder, portable cell #2 was positioned the furthest distance from the primary anodes on the east span of the south shoulder, portable cell #3 was near a primary anode on the middle span of the south shoulder, portable cell #4 was positioned the furthest distance from the primary anode on the middle span of the south shoulder, portable cell #5 was positioned near a primary anode on the west span of the south shoulder, and portable cell #6 was positioned the furthest distance from the primary anodes on the west span of the south shoulder. In addition to the two embedded reference cells for each pier system, test locations (windows) were made on the columns during the installation and were used for portable cell tests. Two portable cell test sites for the East pier (Zone 2) and four portable cell test sites for the West pier (Zone 3) were used during the evaluation.

Table 3.

Depolarization test data summary on embedded and portable reference cells for marine environment bridge, Norfolk, Virginia.

Zone/RC#	4 Hours Depolarization Potential Shift (mV)						
	Initial[1]	Constant Current Setting	9 Months	Constant Current Setting	16 Months	Constant Voltage Setting	23 Months
1/RC 1	126	5.5 A	226	3.5 A	290	8.0 V	201
1/RC 2	103		226		180		127
1/Port RC 1	N/Reading		194		301		130
1/Port RC 2	N/Reading		154		161		N/Reading
1/Port RC 3	N/Reading		214		307		177
1/Port RC 4	N/Reading		272		252		166
1/Port RC 5	N/Reading		225		198		N/Reading
1/Port RC 6	N/Reading		225		323		160
2/RC 1	121	0.7 A	314	0.4 A	214	7.0 V	165
2/RC 2	196		344		315		171
2/Port RC 1	170		142		193		118
2/Port RC 2	152		N/Reading		N/Reading		181

Table 3. (continued)

**Depolarization test data summary on embedded
and portable reference cells for
marine environment bridge,
Norfolk, Virginia.**

Zone/RC#	4 Hours Depolarization Potential Shift (mV)						
	Initial[1]	Constant Current Setting	9 Months	Constant Current Setting	16 Months	Constant Voltage Setting	23 Months
3/RC 1	128 mV	0.7 A	180	0.4 A	170	7.0 V	147
3/RC 2	156 mV		212		201		153
3/Port RC 1	243 mV		232		269		180
3/Port RC 2	222 mV		307		237		148
3/Port RC 3	175 mV		245		235		148
3/Port RC 4	125 mV		227		22		146

[1] **After 1 hour, 15 minutes**

As shown in table 3, the 100 mV potential shift criterion was exceeded on all systems at the 9-month test period. The rectifier was initially set in constant current control based on the results of the initial E Log I test. At the 16-month evaluation all but two locations (one portable cell test site on each of the piers) met the 100 mV potential shift criteria. It is noted that the protection current was reduced at the 9-month test period based on the results of the depolarization and E Log I tests. At 16 months the rectifier controller was adjusted for constant voltage operation. The set voltage was determined by review and analysis of bi-monthly data (appendix A; figures 4 to 12). At the 23-month evaluation test, all reference cell monitors again exceeded the 100 mV shift criterion.

E Log I Testing

Results of the E Log I tests are summarized in table 4 (actual E Log I plots with computed corrosion and cathodic protection data are shown in appendix C; figures 57 to 80).

Table 4.

E Log I test data summary on embedded reference cells for marine environment bridge, Norfolk, Virginia.

	BC (mV/decade)				ICORR (mA)				ECORR (−mV)			
Month	8	4	11	5	8	4	11	5	8	4	11	5
Year	86	87	87R	88	86	87	87R	88	86	87	87R	88
Zone/RC#												
1/1	176	192	405	307	2021	1077	765	480	370	338	83	115
1/2	248	190	283	186	2045	1324	572	375	382	307	86	117
2/1	295	903	502	485	349	276	171	117	258	216	187	193
2/2	241	856	422	413	46	251	115	118	181	134	25	36
3/1	192	773	407	370	138	290	202	157	205	111	96	103
3/2	266	593	280	287	183	247	122	116	346	207	208	203

	IPRO (mA)				EPRO (−mV)				IPRO (%)			
Month	8	4	11	5	8	4	11	5	8	4	11	5
Year	86	87	87R	88	86	87	87R	88	86	87	87R	88
Zone/RC#												
1/1	5123	3499	2372	2098	444	437	282	311	100	68	46	41
1/2	5124	3699	2121	2098	481	392	247	256	100	72	41	41
2/1	675	374	310	320	342	334	317	405	100	55	46	113
2/2	474	374	290	250	426	283	194	170	100	79	61	53
3/1	524	374	470	310	316	196	246	212	100	71	90	59
3/2	725	405	270	270	505	334	305	308	100	56	37	37

Note: R equals repeat test

With only one exception, current requirement for cathodic protection decreased with the application of continuous protective current. This is typical of cathodic protection systems for steel structures in other corrosive environments.

With one exception, the E Log I tests were performed the day after the depolarization test. The exception was during the 11-87 visit (16-month evaluation). The first E Log I test was conducted after only 6 hours of depolarization. The results were questioned by the researchers, so the rectifiers were turned off and the test was repeated the following day. As shown in table 5, the results of the two tests are very different. The computed I-pro and measured E-corr were less after the rebars depolarized for a longer time period.

Table 5.

Computed corrosion and cathodic protection data for E Log I tests performed within 24 hours of each other.

	BC (mV/decade)		ICORR (mA)		ECORR (−mV)		IPRO (mA)		EPRO (−mV)	
ZONE/RC#	FIRST TEST	REPEAT TEST	FIRST TEST	REPEAT TEST	FIRST TEST	REPEAT TEST	FIRST TEST	REPEAT TEST	FIRST TEST	REPEAT TEST
1/1	339	405	678	765	158	83	3499	2372	399	282
1/2	179	283	429	572	150	86	2800	2121	212	247
2/1	428	502	186	171	244	187	385	310	379	317
2/2	355	422	76	115	66	25	370	290	122	194
3/1	347	407	197	202	134	96	485	470	270	246
3/2	276	280	148	122	234	208	485	270	387	305

Conclusions

Zone 1, Deck (Slot System with Conductive Polymer concrete)

This system provided effective corrosion control to the reinforcing steel of the bridge deck. The system circuit resistance averaged 1 ohms. Minor discoloring of the concrete around the slots was visible at suspected high current discharge areas. Aside from the slot appearance, the deck was found in good condition throughout the research study. The life of this system is dependent on the length of time it takes to damage the concrete at the high current discharge areas.

Zone 2, East Pier (Zinc spray System)

This system provided effective corrosion control to the reinforcing steel of the bridge piers. The system circuit resistance averaged 1.3 ohms. The zinc color darkened with age. As a surface type cathodic protection system, the anode is exposed which may limit its useful life. However the pier and zinc coating were found in good condition throughout the research study.

Zone 3, West Pier (Conductive Polymer Spray)

This system provided effective corrosion control to the reinforcing steel of the bridge pier. The system circuit resistance averaged 5.3 ohms. Scattered small disbondment areas of the conductive polymer were observed. Dot sized rust colored stains also appeared over the entire pier. The decorative overcoat appeared to darken with age. As the disbondment areas increase, the life of the system will be affected.

Reversal of macrocell rebar probes is not a criteria for determining cathodic protection current requirements.

E Log I and 100 mV depolarization criteria do not agree on steel reinforced concrete bridge structures in marine environments.

RESULTS AND ANALYSIS OF CATHODIC PROTECTION SYSTEMS IN NORTHERN CLIMATE

Visual Inspection

Zone 1, WBL Deck (Ferex 100 Anode with LMC Overlay)

General appearance of the west bound lane was in good condition throughout the 18-month evaluation. During the 18-month evaluation, approximately 2-in (5 cm) of Ferex strand was found exposed at about the center of the zone. The concrete cover over the top of the strand was less that .25 in (0.6 cm). A small concrete pop-out exposed the top surface of the strand. Two small transverse cracks less than 5-in (12.5 cm) long each were also found at 18 months.

Zone 2, EBL Deck (Elgard 210 With LMC Overlay)

At the 6-month evaluation, several cracks were observed toward the south end of the zone. At 12 months, the cracking at the south end was more predominant and cracks were observed at half a dozen other locations. At 18 months, more cracks and wider cracks were found, but the locations remained the same. For the most part the cracks were in the transverse direction. Except for cracks, the general appearance of the east bound lane was in good condition.

Zone 3, Sidewalk (Elgard 210 with Modified Thorotop HCR Coating)

Transverse cracks were observed on both sidewalks at the 6-month evaluation. The cracks appeared more numerous at the 18-month evaluation, but locations appeared the same. At 12 months, and more predominant at 18 months, ends of the anode mesh were observed at the curb edge of the concrete surface and at the edge of the Thorotop cover at the pavement. A white ring had developed around the anode wire followed by a brown colored ring. It was also observed that the wire was exposed at other locations without the discoloration which was not detected during the post installation and 6-month evaluation.

Zone 4 Piers (Elgard 150 with Modified Thorotop HCR Coating)

General appearance of the piers was good throughout the 18-month evaluation. A water stain under one of the junction boxes and a small 1-in (2.5 cm) diameter spall of thorotop coating at the corner of one column was observed. The anode wire was found exposed in a few locations at the bottom of the columns, but discoloration around the anode was as obvious as those on the sidewalk.

Delamination/Disbondment Study

Zone 1, WBL Deck (Ferex 100 with LMC Overlay)

No delamination/disbondment was found on the west bound lane throughout the 18-month evaluation.

Zone 2, EBL Deck (Elgard 210 with LCM Overlay)

Two delaminations were detected at 6 months and a total of five at 12 months. During the 18-month evaluation the number of delaminations increased to 24. Many of the delaminations were less that 1 ft^2 (0.09 m^2) of area. The two largest delaminations initially detected had developed to 12 ft^2 (1.08 m^2) and 24 ft^2 (2.16 m^2) of area. In most cases, cracks were observed on the delamination. To determine if the delamination was caused by a corroding rebar, a missed delamination during patching, a bad patch, or de-bonding of the LMC overlay, cores were taken after the 18-month evaluation. A crack between the LMC overlay and the original deck surface was found in each core.

Zone 3, Sidewalks (Elgard 210 with Modified Thorotop Coating)

On the sidewalks, delaminations were noted during the 6-month evaluation. These delaminations increased and some combined to form larger delaminations. During the 18-month evaluation, 14 delaminations were located. From cores taken on the sidewalk, the concrete was found cracked at the rebar. Based on the amount of corrosion product and the color (red/brown rust), it appears these are areas where the delamination were not detected and repaired before the installation of the cathodic protection system.

Zone 4, Piers (Elgard 150 with Modified Thorotop Coating)

With the exception of the small concrete spall identified in the visual inspection portion of this section, no delamination or disbondment was found on the piers throughout the 18-month evaluation.

Electrical Resistance Measurements

Table 6 documents the resistance measurements obtained at initial energization through 18 months of continuous activation. The anode to system ground resistance decreased for Zones 1 and 2 and increased for Zones 3 and 4 at the 6-month evaluation. It is believed that the cold temperatures during the initial testing (January) and hot temperatures at 6 months (July) influenced these measurements as it is more typical to see cathodic protection systems increase in resistance after installation. Review of the bimonthly rectifier output data (appendix A) did show an increase in resistance on all zones in the first 3 months after energization. A comparison of system resistance at the 6-month and 18-month evaluation (summertime monitoring period) revealed an increase in resistance of 33 percent for Zone 1, 2 percent for Zone 2, 33 percent for Zone 3 and 1045 percent for Zone 4. It is noted that Zone 4 anode to system ground resistance continuously increased from 2.3 ohms to 110 ohms in 18 months. Zones 1, 2 and 3 cycled with higher resistance measured in the winter than in the summer which is expected. Reference cell and rebar probe resistance measurements are discussed in more detail in chapter 4. It is noted that some of the reference cell circuits were extremely high resistance in the winter and were not considered useable during the evaluation time period. The rebar probe resistance was comparable to the measurements found in the marine environment rebar probes.

Table 6.

Electrical resistance measurements for northern climate bridge, Cincinnati, Ohio.

Components	Resistance (ohms) 1-87 (Initial Energization)	7-87 (6 Months)	12-87 (12 Months)	6-88 (18 Months)
Anode - System Ground				
Zone 1 (Ferex 100 & Platinum Wire)	0.49	0.24	1.3	0.32
Zone 1 (Ferex 100)	0.57	0.35	1.45	0.40
Zone 1 (Platinum wire)	0.52	0.26	1.45	0.30
Zone 2	0.50	0.42	0.62	0.43
Zone 3 (North & South Sidewalks)	0.70	1.2	3.40	1.60
Zone 3 (North Sidewalk)	1.35	2.0	6.90	3.00
Zone 3 (South Sidewalk)	1.70	2.5	6.70	3.20
Zone 4 (East & West Piers)	2.3	9.6	50.0	110.0
Zone 4 (East Pier)	5.2	20.0	290.0	280.0
Zone 4 (West Pier)	3.9	18.5	170.0	175.0
Reference Cell - Reference Cell Ground				
Zone 1, Reference Cell A	5500	4200	35K	8.6K
Zone 1, Reference Cell B	1300	20000	76K	22K
Zone 1, Reference Cell C	105	100	4.6K	2.4K
Zone 2, Reference Cell A	605	220	5.7K	3.7K
Zone 2, Reference Cell B	140	5200	2.5K	15K
Zone 2, Reference Cell C	310	100	310	670
Zone 3, Reference Cell A	610	3100	32K	19K
Zone 3, Reference Cell B	310	31500	180K	68K
Zone 4, Reference Cell A	490	3100	200K	7K
Zone 4, Reference Cell B	670	10000	170K	8.5K
Rebar Probe - Rebar Probe Ground				
Zone 1, Rebar Probe 1	560	330	1.1K	380
Zone 1, Rebar Probe 2	430	240	640	250
Zone 2, Rebar Probe 3	415	300	620	320
Zone 2, Rebar Probe 4	350	250	670	290
Zone 3, Rebar Probe 5	310	240	600	260
Zone 3, Rebar Probe 6	330	290	670	290
Zone 4, Rebar Probe 7	650	415	1.1K	420
Zone 4, Rebar Probe 8	650	380	1.0K	430

Macrocell Rebar Probe Current Measurements

Initial current and polarity did show that all macrocell rebar probes were anodic to the surrounding reinforcing steel prior to applying cathodic protection current. After 12 months, not all macrocell rebar probes returned to an anodic condition. The corrosion current density and the rectifier current which reversed the polarity of the macrocell rebar probe are shown in table 7. Interpretation of the macrocell rebar probe currents measured on this bridge are difficult as no clear-cut results developed. In general the corrosion current was higher in the summer than winter months. The rebar probes in the pier became cathodic or very near cathodic within 1 year of system energization. As shown in table 7, the pier macrocell rebar probes were extremely anodic at first, but very low rectifier current was required to reverse them. It is suspected that climate conditions and the dense concrete cover affected the performance of the cells. Throughout the evaluation tests, the cathodic protection systems were able to reverse all the macrocell rebar probes, however, the rectifier output was not always adjusted to accomplish this. A more detailed discussion on the performance of the macrocell rebar probe can be found in chapter 4.

Table 7.

Corrosion current density and rectifier current to reverse macrocell rebar probes for northern climate bridge, Cincinnati, Ohio.

Location	Rectifier Current to Reverse (amps)				Corrosion Current Density of Rebar Probe (mA/ft^2)			
	1-87 (Initial)	7-87 (6 Mos)	12-87 (12 Mos)	6-88 (18 Mos)	1-87 (Initial)	7-87 (6 Mos)	12-87 (12 Mos)	6-88 (18 Mos)
Zone 1 (West Bound Lane)								
Rebar Probe 1	0.30	2.05	0.70	1.80	0.74	4.51	1.29	2.27
Rebar Probe 2	1.00	3.10	1.45	2.50	3.12	9.91	2.2	5.00
Zone 2 (East Bound Lane)								
Rebar Probe 3	1.60	4.00	1.50	1.80	1.00	1.43	0.72	0.76
Rebar Probe 4	1.00	N/A[1]	N/A[1]	N/A[1]	0.71	0.00	0.00	0.00

Table 7. (continued)

Corrosion current density and rectifier current to reverse macrocell rebar probes for northern climate bridge, Cincinnati, Ohio.

Location	Rectifier Current to Reverse (amps) 1-87 (Initial)	7-87 (6 Mos)	12-87 (12 Mos)	6-88 (18 Mos)	Corrosion Current Density of Rebar Probe (mA/ft^2) 1-87 (Initial)	7-87 (6 Mos)	12-87 (12 Mos)	6-88 (18 Mos)
Zone 3 (Sidewalks)								
Rebar Probe 5 (North)	0.35	0.22	0.00	0.35	2.25	0.78	0.00	2.30
Rebar Probe 6 (South)	0.29	0.32	0.30	0.75	1.83	0.89	3.95	5.73
Zone 4 (Piers)								
Rebar Probe 7 (West)	0.12	0.25	N/A[1]	N/A[1]	4.49	6.83	0.00	0.00
Rebar Probe 8 (East)	0.16	0.27	N/A[1]	N/A[1]	4.56	3.17	0.00	0.00

[1] N/A: Not applicable since the rebar probe was not anodic

Depolarization Testing

A summary of all depolarization test results is shown in table 8 (a graphic presentation of all data collected is shown in appendix B; figures 42 to 56). Only embedded reference cells were used during this testing. For the deck systems, Zone 1 reference cell C and Zone 2 reference cell B are installed at the bottom rebar mat, while all others are located at the top rebar mat.

All zones met and typically exceeded the 100 mV depolarization shift criteria with the exception of zone 2. Based on interpretation of the initial test data, 3.0 amps of protective current was selected for both Zones 1 and 2 which are very similar size zones except for anode material. 100 mV depolarization was not achieved during the initial testing nor was it achieved after 6 months of continuous protection current for Zone 2. From initial to 6 months, Zone 1 reference cell potentials increased an average 189 percent where as Zone 2 increased an average 42 percent. Based on the 6 month evaluation, Zone 2 current was increased to 3.4 amps and all other zone currents were reduced. It is noted that the response from the bottom mat reference cells indicated good current pick-up from the two deck cathodic protection systems. At the 12-month test period, all reference cell depolarization test results exceeded the 100 mV shift criterion. At 12 months the rectifier controller was adjusted for constant voltage operation. The set voltage was determined by review and analysis of bi-monthly data (appendix A; figures 13 to 24). At the 18-month evaluation test, all reference cell monitors exceeded the 100 mV shift criterion.

Table 8.

Depolarization test data summary on embedded reference cells for northern climate bridge, Cincinnati, Ohio.

Zone/RC Letter	4 Hours Depolarization Potential Shift (mV)						
	Initial	Constant Current Setting	6 Months	Constant Current Setting	12 Months	Constant Voltage Setting	18 Months
1/RC A	109	3.0 A	N/Reading	2.5 A	229	6.2 V	209
1/RC B	127		N/Reading		207		227
1/RC C	101		N/Reading		218		155
2/RC A	59	3.0 A	72	3.4 A	230	4.3 V	127
2/RC B	66		101		214		142
2/RC C	50		76		190		180
3/RC A	193	1.5 A	336	1.1 A	252	7.1 V	312
3/RC B	177		407		218		222
4/RC A	941	1.7 A	812	0.6 A	326	14.0 V	318
4/RC B	903		841		599		380

E Log I Testing

Results of the E Log I tests are summarized in table 9 (actual E Log I plots with computed corrosion and cathodic protection data are shown in appendix C; figures 81 to 116). Unlike the marine environment bridge system, the northern climate system did not show a decrease in amount of protection current needed after 18 months of continuous protection. It is noted that in the beginning, this bridge was in a more severe environment and at a higher level of corrosion activity than the marine environment bridge. No E Log I tests were performed on the bridge piers after the 6-month evaluation due to the very high circuit resistance of that system.

Table 9.

E Log I test data summary on embedded reference cells for northern climate bridge, Cincinnati, Ohio.

	BC(mV/decade)				ICORR (mA)				ECORR (−mV)			
Month	1	7	12	6	1	7	12	6	1	7	12	6
Year	87	87	87	88	87	87	87	88	87	87	87	88
Zone/RC#												
1/A	312	242	390	350	2002	1165	391	1195	309	245	247	201
1/B	416	336	353	254	1032	1006	692	1473	386	175	209	171
1/C	322	349	326	247	1032	1033	608	1514	390	115	173	174
2/A	339	185	197	155	1251	1735	1234	1331	282	286	264	253
2/B	403	231	269	239	1067	1433	1125	1423	208	209	214	182
2/C	307	194	151	196	1276	2114	1517	1805	127	(−17)	366	68
3/A	532	505	981	772	844	444	345	864	319	164	251	266
3/B	697	666	1488	814	672	504	408	1178	282	167	413	518
4/A	822	1253	*	*	233	242	*	*	128	(−3)	*	*
4/B	975	1076	*	*	394	216	*	*	144	105	*	*

	IPRO (mA)				EPRO(−mV)				IPRO (%)			
Month	1	7	12	6	1	7	12	6	1	7	12	6
Year	87	87	87	88	87	87	87	88	87	87	87	88
Zone/RC#												
1/A	4974	2574	1849	4099	473	328	510	389	100	52	37	82
1/B	3024	2124	1749	3699	536	284	351	273	100	70	42	122
1/C	2874	2424	1849	3699	528	244	331	268	100	84	64	129
2/A	3324	3474	3698	3299	426	342	358	314	100	105	111	101
2/B	2874	2724	3699	3499	381	274	353	276	100	95	129	122
2/C	3474	3324	3699	3699	261	21	424	129	100	96	107	107
3/A	1849	1080	875	3098	500	359	648	695	100	58	53	168
3/B	1949	1080	875	2898	604	387	909	816	100	55	45	149
4/A	1449	640	*	*	780	525	*	*	100	56	*	*
4/B	1849	600	*	*	799	583	*	*	100	32	*	*

Note: * No E log I Test, too high circuit resistance

CPC/Platinum Wire Redundancy Loop for Zone 1 System

A platinum wire embedded in a conductive polymer concrete (CPC) strip was installed on the Zone 1 system to provide electrical redundancy. Electrical redundancy within the anode network is considered a plus in cathodic protection system design. It will provide a projected longer system life, as it is another current path through the anode network, if the need arises. It will also improve the current distribution as it reduces voltage drop within the anode electrical network. This research study was not intended to quantify voltage drop nor was it to qualify electrical redundancy. It was, however, to determine if a CPC/platinum wire design would provide electrical redundancy to a flexible polymer anode.

To monitor the redundancy design, separate lead wires from the platinum wire and Ferex 100 strand were brought into the rectifier. As shown in table 10, the connection between the rigid CPC and flexible polymer strand has remained constant throughout the research project. E Log I tests were performed at various times during the research with similar results using either the platinum or Ferex strand lead. Current through the leads was measured at the evaluation periods and is shown in table 11. Initially the difference of current through the leads was only 3 percent, but this changed and remained relatively constant at 36 percent after that. The CPC/platinum wire lead carried more current throughout the entire research project.

Table 10.

Electrical resistance measurements for CPC/platinum wire redundancy to Ferex 100 strand.

Components	Resistance (ohms)			
	1-87 (Initial)	7-87 (6 Months)	12-87 (12 Months)	6-88 (18 Months)
Anode Lead - System Ground				
Ferex 100 & CPC/Platinum	0.49	0.24	1.3	0.32
Ferex 100 Only	0.57	0.35	1.45	0.40
CPC/Platinum Only	0.52	0.26	1.45	0.30

Table 11.

Electrical current flow through
CPC/platinum wire and
Ferex 100 strand.

Components	Current (Amp)			
	1-87 (Initial)	7-87 (6 Months)	12-87 (12 Months)	6-88 (18 Months)
Anode Lead				
Ferex 100 & CPC/Platinum	3.0	3.0	2.17	4.0
Ferex 100 Only	1.46	0.96	0.69	1.2
CPC/Platinum Only	1.54	2.04	1.48	2.8

Conclusions

Zone 1, WBL Deck (Ferex 100 with LMC Overlay)

The system provided effective corrosion control to the reinforcing steel of the bridge deck. The CPC/platinum wire design did provide effective electrical redundancy to the flexible polymeric anode and will provide a longer system life. The system circuit resistance averaged 0.62 ohms. An exposed anode strand suggests the anode will rise during the overlaying process, therefore it should be carefully tacked down on the deck surface during installation. The deck was found in good condition throughout the research study.

Zone 2, EBL Deck (Elgard 210 with LMC Overlay)

The system provided effective corrosion control of the reinforcing steel of the bridge deck. The system circuit resistance averaged 0.5 ohms. Disbondment of the LMC overlay was found and continued to increase throughout the research study. It is suspected that the bond slurry and application procedure, which was different from the WBL construction, initially affected bond strength and freeze-thaw conditions increased the disbonded area.

Zone 3, Sidewalks (Elgard 210 with Modified HCR Thorotop Coating).

Based on the cathodic protection criteria, effective corrosion control was provided to the reinforcing steel of the bridge sidewalks. The system circuit resistance averaged 2.0 ohms. Surface cracks and delamination of the sidewalk was found very early in the research study. It is suspected that all the delaminations were not detected and repaired during the construction. The discoloring found around the exposed anode wire needs study. Further research on the sidewalks system is suggested.

Zone 4, Piers (Elgard 150 with Modified HCR Thorotop Coating)

Based on cathodic protection criteria, the system provided effective corrosion control of the reinforcing steel of the bridge piers. However, the resistance (Average 57.0 ohms) of this system was very high for cathodic protection systems. The macrocell rebar probes stopped providing corrosion current after 1 year in service. It is suspected that the modified HCR coating is influencing the corrosion process and affecting the cathodic protection system by increasing the concrete resistivity. The piers on this bridge are never exposed to direct rain, but only area humidity. This system cannot be recommended for bridge piers at this time. As with the sidewalk system, further research is suggested. The appearance of the pier was in very good condition throughout the research study.

All Systems

Time to depolarize a cathodic protected structures prior to performing E Log I test should be studied. Reversal of macrocell rebar probes is not a criterion for determining cathodic protection current requirements.

E Log I and 100 mV depolarization criteria do not agree on steel reinforced concrete bridge structures subject to deicing chemicals.

CHAPTER 2 CATHODIC PROTECTION USING CURRENT CONTROL

The following presents an analysis and evaluation of the cathodic protection data obtained when under constant DC current control. All zones of the marine environment and northern climate cathodic protection systems were initially energized for continuous operation for at least 12 months using the constant current control mode of the rectifiers. To determine operating set current, E Log I test results were analyzed.

CATHODIC PROTECTION SYSTEMS IN MARINE ENVIRONMENT

Three cathodic protection systems were energized in Norfolk, Virginia under the constant current control of the rectifier from August 1, 1986 through November 16, 1988. The total monitor period for constant current control on the marine environment bridge systems was approximately 16 months (this data is graphically shown in appendix A; figures 4 to 12). System DC voltage, DC current, "Instant Off" reference cell potential, rebar probe current and ambient temperature measurements were recorded bi-monthly during the entire monitor period.

Current fluctuation was reported between November 18, 1986 and March 18, 1987 for Zone 1 and for Zone 2, between January 18, 1986 and April 14, 1987 and between October, 1987 and November, 1987 for Zone 2. No current fluctuations were ever recorded for Zone 3. The current fluctuation periods were not considered in the evaluation of current control for cathodic protection systems. Corrective measures were taken throughout the research project to maintain proper rectifier control. The fluctuations in current were either attributed to controller malfunction or voltage limitation.

As shown in table 12, the current output was reduced for all systems at 9 months into the monitor program. This is further discussed in chapter 5 of this report.

Table 12.

Constant current settings for marine environment.

	Current (Amp)		
	Deck (Zone 1) Slotted System With Conductive Polymer	**E. Pier (Zone 2) Zinc System**	**W. Pier (Zone 3) Polymer Spray System**
Initial Energization to 9 months	5.5	0.7	0.6
9 months to 16 months	3.5	0.4	0.4

A pattern was determined in the rectifier voltage of systems 1 and 3. The rectifier voltage for these zones increased as ambient temperature decreased. Therefore, a higher voltage requirement was found during the winter months. This was expected as it is known that the resistance of concrete varies inversely to change in temperature. Zone 2, however, did not show as well a defined pattern. Table 13 shows the average voltage and standard deviation needed to maintain the constant current setting. It is noted that the voltage was more constant with the zinc spray system (Zone 2) than the conductive polymer systems (Zone 1 and Zone 3).

Table 13.

Voltage to maintain constant current for marine environment.

Zone	**Initial to 9 Months**		**9 Months to 16 Months**	
	AVG (Voltage)	**Standard Deviation**	**AVG (Voltage)**	**Standard Deviation**
Zone 1	9.1	2.18	5.4	2.58
Zone 2	4.36	1.29	4.87	1.32
Zone 3	7.73	2.59	4.70	1.88

In warmer temperatures, the macrocell rebar probes had the tendency to drift less cathodic with continuous cathodic protection constant current application. This applied for all six macrocell rebar probes for all three systems. This suggests higher temperatures will produce more powerful corrosion cells. It is understood, if all things are equal, when temperature increases, the resistance of the concrete decreases which yields a more corrosive environment for the reinforcing steel.

When current was held constant, "Instant Off" potentials from the embedded reference cells were monitored. In summary, the pattern that developed suggests "Instant Off" reference cell changes are inversely related to temperature changes. Stability of all types of embedded reference cells used in concrete is a very controversial subject in the cathodic protection community. Because all cathodic protection criteria are based on reference cell potential measurements, continued evaluation of their performance is critical. One definite pattern observed on the Ag/AgCl embedded reference cell is that both cells in a zone followed like patterns with temperature variations. Another pattern developed suggests that insufficient protective current was provided at higher temperatures. It is known that reference cell potential measurements are proportional to corrosion activity (more negative potential = higher corrosion rate). It is also known that higher temperatures result in higher corrosion activity just as more powerful rebar probe corrosion cells were found during warmer months. Therefore, with corrosion potential increase added to the polarization potential from application of cathodic protection current, the result should have been a higher "Instant Off" potential measurement. However, at warmer temperatures, the "Instant Off" potential measured was less, which indicates reduction in polarization potential achieved by the cathodic protection current. The effect of change in concrete electrolyte resistance to the "Instant Off" reference potential during energized cathodic protection systems needs further investigation.

CATHODIC PROTECTION SYSTEMS IN NORTHERN CLIMATE

Four cathodic protection systems were energized under the constant current control of the rectifier in Cincinnati, Ohio from January 9, 1987 through December 15, 1987. The total monitor period for constant current control on the northern climate bridge systems was approximately 12 months (this data is graphically shown in appendix A; figures 13 to 24). System DC voltage, DC current, "Instant Off" potential, rebar probe current and ambient temperature measurements were recorded bi-monthly during the monitor period.

Current fluctuation was reported for Zone 1 between March 24, 1987 to April 7, 1987 and also from June 17, 1987 to September 8, 1987. The current controls for Zones 2 and 3 were constant throughout the entire monitor period. Very erratic current control was reported for Zone 4 from initial energization up to August 9, 1987 and after that, current control was not erratic but was not constant due to rectifier voltage limitations. Corrective measures were taken throughout the research project to maintain proper rectifier control. The fluctuations in current were either attributed to controller malfunction or voltage limitation. The current fluctuation periods were not considered in the evaluation of constant current control for cathodic protection systems.

Table 14.

Constant current settings for northern environment.

	Current (Amp)			
	Zone 1 West Bound Ferex 100 Anode	**Zone 2 East Bound Elgard 210 Anode**	**Zone 3 Sidewalk Elgard 210 Anode**	**Zone 4 Piers Elgard 150 Anode**
Initial Energization to 6 months	2.0	3.0	1.6	2.0
6 Months to 12 months	2.5	3.4	1.1	0.6

As shown in table 14, the current output was increased for Zones 1 and 2 and decreased for Zone 3 at 6 months into the monitor program. Zone 4 circuit resistance increased beyond design consideration and current output was controlled by the rectifier voltage limit.

Table 15 shows the average voltage and standard deviation needed to maintain the constant current setting. Zone 1 voltage was higher during the winter months much the same as was found in Zones 1 and 3 of the marine environment bridge. Zone 2 voltage was relatively constant providing only small voltage changes vs. temperature or season. Zone 3 was the same anode system as Zone 2 but embedded in a different concrete mix design. Voltage variations for Zone 3 were over twice the magnitude of Zone 2. Zone 4 will not be discussed here because, for most of the monitor period, constant current control could not be maintained.

Table 15.

Voltage to maintain constant current for northern climate.

Zone	**Initial to 6 Months**		**6 Months to 12 Months**	
	AVG (Voltage)	**Standard Deviation**	**AVG (Voltage)**	**Standard Deviation**
Zone 1	7.01	5.07	3.93	1.90
Zone 2	2.74	0.26	3.42	0.47
Zone 3	3.79	0.70	4.57	1.03
Zone 4[1]	N/A	N/A	N/A	N/A

[1] Zone 4 did not maintain constant current for most of monitor program.

As shown in the marine environment bridge, with increasing temperature, the rebar probe had the tendency to drift less cathodic or more anodic with continuous cathodic protection current application. With few exceptions all rebar probes showed less variation with temperature changes and for the most part remained cathodic throughout the monitor period.

As previously discussed, interpretation of "Instant Off" potential measurements needs further investigation. For the most part, the reference cells in the northern climate follow the same pattern found for the marine environment cells (i.e. when temperature increases, reference cell potential decreases and vice versa).

CONCLUSIONS

Based on the evaluation of all data, similar patterns developed on the marine environment and northern climate bridge deck and substructure cathodic protection systems using constant current control. These patterns are defined as follows:

(a) In all systems the constant current control did not provide the same level of protection throughout the season changes.

(b) Voltage variation to maintain constant current control is higher for carbon-base anode systems than metal- base anode systems.

(c) "Instant Off" potential measurements obtained from embedded Ag/AgCl reference cells follow similar patterns to each other.

CHAPTER 3 CATHODIC PROTECTION USING VOLTAGE CONTROL

The following presents an analysis and evaluation of the data obtained during the monitoring period when the cathodic protection systems were under constant DC voltage control. All zones of the marine environment and northern climate cathodic protection systems were energized for continuous operation for approximately the last 6 months of the study using the constant voltage mode of the rectifiers. To determine operating voltage, the bi-monthly data (appendix A) was analyzed as depolarization data (appendix B) and E Log I data (appendix C) alone did not provide the voltage criteria for continuous operation.

CATHODIC PROTECTION SYSTEMS IN MARINE ENVIRONMENT

Three cathodic protection systems were energized under the constant voltage control of the rectifier from November 17, 1987 to May 1, 1988. The monitoring period was approximately 6 months (this data is graphically shown in appendix A; figures 4 to 12). System DC voltage, DC current, "Instant Off" reference cell potential, macrocell rebar probe corrosion current, and ambient temperature measurements were recorded bi-monthly during the monitor period.

Minor voltage fluctuations were recorded for all zones' circuits. The current, on the other hand, changed with anode to rebar circuit resistance in accordance with Ohm's Law. The voltage settings are shown in table 16. Also shown in table 16 is the current limit set to protect the anode/concrete interface from excessive current.

As expected, it was found that an increase in temperature induced an increase in circuit current (and vice versa). The short time period of monitoring this type of control did not allow for all seasons changes, but lower current output would be expected during the winter months. Zone 1 average current was 2.8 amps with a standard deviation of 0.92. Zone 2 average current was 0.27 amps with a standard deviation of 0.14. Zone 3 average current was 0.32 amps with a standard deviation of 0.13.

In warmer temperatures, the macrocell rebar probes had the tendency to drift more cathodic with constant voltage control. This is opposite of what was found during constant current control.

Table 16.

Constant voltage settings for marine environment bridge, Norfolk, Virginia.

	Voltage Set (V)			Current Limit Set (A)		
	Initial	To	6 Mo.	Initial	To	6 Mo.
Deck (Zone 1) Slotted System		8.0			6.0	
E. Pier (Zone 2) Zinc System		7.0			0.85	
W. Pier (Zone 3) Polymer Spray System		7.0			0.85	

When voltage was held constant, "Instant Off" potentials of the embedded reference cells were monitored. The reference cell potentials had the tendency to increase with increasing temperatures and current (and vice versa). This is opposite of what was found during constant current control.

Behavior of both embedded monitors for this structure suggest that constant voltage may provide better levels of protection with environment changes. More data is required to be collected at constant voltage control before making any definite conclusions regarding constant current control versus constant voltage control rectifiers.

CATHODIC PROTECTION SYSTEMS IN NORTHERN CLIMATE

Four cathodic protection systems were energized under the constant voltage control of the rectifier from December 16, 1987 to June 1, 1988. The total monitoring period was approximately 6 months (this data is graphically shown in appendix A; figures 13 to 24). System DC voltage, DC current, "Instant Off" potentials, rebar probe corrosion current, and ambient temperature measurements were recorded bi-monthly during the monitor period.

Although in voltage control, circuits 1, 2, and 3 showed voltage fluctuation during the same time period. It was noted that during the 6-month monitoring, the fluctuations for all three circuits occurred only at high temperatures when the circuits went into current limit control. This reflects that the rectifier/controller is behaving as designed.

The voltage settings and maximum current limits are shown in table 17.

Table 17.

Constant voltage settings for northern climate bridge, Cincinnati, Ohio.

	Voltage Set (V)	Current Limit (A)
Zone 1 (West Bound) Ferex 100	6.2	4.1
Zone 2 (East Bound) Elgard 210	4.3	4.1
Zone 3 (Sidewalk) Elgard 210	7.1	2.2
Zone 4 (Piers) Elgard 150	14.0	2.4

At the end of the monitor period, Zone 1 average current was 2.23 amps with a standard deviation of 1.39. Zone 2 average current was 3.29 amps with a standard deviation of 0.72. Zone 3 average current was 2.07 amps with a standard deviation of 0.73, and Zone 4 average current was 0.16 amps with a standard deviation of 0.07.

The macrocell rebar probes had the tendency to drift more cathodic with increasing temperature. The same pattern was observed for the macrocell rebar probes of the marine environment bridge structure in constant voltage control.

Without taking into account the periods when the circuits reached current limits (i.e. not in voltage control), the "Instant Off" reference cell potentials were analyzed. In summary, the pattern that developed suggested "Instant Off" reference cell potential change is directly related to temperature changes (i.e. temperature increase yields reference cell potential increase and vice versa). This pattern was also observed for the reference cell potentials in the marine structure under constant voltage control.

CONCLUSIONS

Based on the analysis of the systems bi-monthly monitoring data, of the marine environment and northern climate bridge structures, the following conclusions can be derived.

(a) The embedded monitors (macrocell rebar probes and reference cells) for both structures under constant voltage control showed similar behavior. The data analysis suggest that all systems have appeared to achieve better levels of protection under constant voltage control. An additional monitoring period is recommended to verify this conclusion and for future consideration of rectifier control.

(b) To determine voltage setting for constant voltage control, historical system operational data is suggested.

(c) For both structures, the metal-base anode system shows less current variation during voltage control than the carbon base-anode system.

(d) Unlike the northern climate structure, the marine environment structure did not reach current limits with change in temperature. The northern bridge is exposed to much wider temperature ranges and is in a more severe corrosion environment.

CHAPTER 4 EMBEDDED MONITORS

To test and monitor the cathodic protection system, macrocell rebar probes and Ag/AgCl reference cells were embedded in each cathodic protection zone of both the marine environment and northern climate bridges.

The macrocell rebar probes placed in the bridge deck and sidewalk zones consist of a 6 in (15 cm)-long No. 5 deformed rebar encased in a 2 1/2 in-(6.25 cm) by 2 1/2 in-(6.25 cm) by 8-in (20 cm) concrete beam. The concrete beam contains a chloride concentration of 15 lb/yd^3 (8.9 kg/m^3) of concrete. The Ag/AgCl reference cells placed in the bridge deck and sidewalk zones consists of a 4-in (10 cm)-long high purity Ag/AgCl coated element embedded in a 1-in (2.5 cm)-diameter by 8-in (20 cm)-long cloth bag containing a 15 percent chloride rich plaster mix. The macrocell rebar probes located in the bridge piers consist of a 3-in (7.5 cm)-long No. 5 deformed rebar encased in a 2-in (5 cm)-diameter concrete cylinder 4 1/2-in (11.25 cm)-long. Each concrete cylinder contained a chloride concentration of 15 lb/yd^3 (8.9 kg/yd^3) of concrete. The Ag/AgCl reference cells in the bridge piers consist of the same materials as the reference cells in the bridge decks but the silver element is 2 in (5 cm) long and the cloth bag is 3/4 in (1.9 cm) diameter by 4 in (10 cm) long.

Circuit resistances were monitored throughout the research project. All resistance measurements were obtained using a Nilsson 400 AC resistance meter connected to the lead wires terminated at the rectifier. Reference cell corrosion potential measurements were obtained using a Miller LC-4 potential meter connected to the lead wires at the rectifier. Macrocell rebar probe corrosion current measurements were obtained by calculating the current from the potential measured across a 10 ohm precision resistor wired between the rebar probe and structure rebar at the rectifier. The results are analyzed in this chapter.

MARINE ENVIRONMENT MONITORS

Embedded Ag/AgCl Reference Cells

Evaluation of Resistance Measurements

Table 18 shows resistance measurements obtained on the reference cell circuits at four different times during the research project.

Table 18.

Reference cell circuit resistance measurements for marine environment bridge, Norfolk, Virginia.

Location				**Resistance (ohms)**			
Zone/ Reference Cell	**Initial**	**After Approx 9 Months**	**% Change Initial to 9 Months**	**After approx 16 Months**	**% Change 9 Months to 16 Months**	**After Approx 23 Months**	**% Change 16 to 23 Months**
Z1, RC 1	170	460	171%	530	15%	2200	315%
Z1, RC 2	200	670	235%	1000	49%	1100	10%
Z2, RC 1	270	700	159%	980	40%	1200	23%
Z2, RC 2	240	400	67%	500	25%	590	18%
Z3, RC 1	410	900	120%	1150	28%	1200	4%
Z3, RC 2	200	670	235%	2100	213%	9300	343%
AVERAGE			165%		62%		119%

As shown in table 18, and as expected, reference cell resistance increased substantially after initial testing. This increase is attributed to curing of the concrete patch and reference cell backfill. From this initial change, it was expected that the reference cell circuit resistance would stabilize and vary only due to moisture concentration and temperature change around the cell. This was not the case for the reference cell as their resistance continued to increase throughout the 23-month monitoring period. Although the reference cell resistance continued to increase, all cells were considered operational throughout the research project.

Evaluation of "Natural" Potential Measurements

The reference cell corrosion potential (E-corr) data accumulated with time and under continuous cathodic protection application is shown in table 19.

Table 19.

Reference cell natural corrosion potential for marine environment bridge, Norfolk, Virginia.

Location		Potential (mV)				
Zone	Reference Cell	Initial	9 Months	16 Months	23 Months	Overall Change (%)
1	1	-370	-338	-83	-115	68.9%
	2	-383	-307	-86	-177	53.7%
2	1	-258	-216	-187	-193	25.2%
	2	-181	-134	-25	-36	80.1%
3	1	-205	-111	-25	-103	49.8%
	2	-346	-207	-208	-203	41.3%
					Average Decrease:	53.2%

The corrosion potential of the reference cells decreased from their initial values. This behavior is well expected and proves the effectiveness of the systems in mitigating reinforcing steel corrosion.

Macrocell Rebar Probes

Evaluation of Resistance Measurements

Table 20 shows the resistance measurements obtained on the rebar probe circuits at four different times during the research project. An average increase of 109 percent in resistance for the first 9 months was found. Over the period between 9 months and 16 months, only a 39 percent increase in resistance was measured and this dropped to only a 3 percent increase between 16 months and 23 months. The initial resistance increase is due to the curing of the concrete patch around the rebar probe. The circuit resistance appears to be very stable during the last 6 months of this research project.

Table 20.

Rebar probe circuit resistance measurements for marine environment bridge, Norfolk, Virginia.

Location	Resistance (ohms)						
Zone/ Rebar Probe	Initial	After Approx 9 Months	% Change Initial to 9 Months	After Approx 16 Months	% Change 9 Months to 16 Months	After Approx 23 Months	% Change 16 to 23 Months
Z1, RP 1	125	230	84%	340	46%	350	3%
Z1, RP 2	120	250	108%	400	60%	385	-4%
Z2, RP 1	330	660	100%	880	33%	820	-7%
Z2, RP 2	410	900	120%	1400	56%	1400	0%
Z3, RP 1	520	1200	131%	1500	25%	1600	7%
Z3, RP 2	235	500	113%	560	12%	650	16%
AVERAGE			109%		39%		3%

Evaluation of "Natural" Corrosion Current Measurements

Natural corrosion current of the macrocell rebar probes is considered to be the current measured the day following depolarization testing. Negative values reflect anodic macrocells whereas positive values reflect cathodic macrocells. The data collected is shown in table 21.

The natural corrosion current (with cathodic protection turned "off" for 24 hours) of all the macrocell rebar probes decreased with time and under continuous cathodic protection application. Macrocell rebar probe No. 2 of Zone 2 changed polarity and became cathodic. It is assumed that the chemical property of the macrocell rebar probes have changed due to chloride migration from the chloride rich concrete beam to the chloride free concrete patch surrounding it. The reason may be the continuous application of cathodic protection current and/or the natural laws of equilibrium.

Table 21.

Rebar probe natural corrosion current for marine environment bridge, Norfolk, Virginia.

Location		Current (mA)				
Zone	**Rebar Probe**	**Initial**	**9 Months**	**16 Months**	**23 Months**	**Overall Change (%)**
1	1	-1.496	-0.536	-0.385	-0.258	82.8%
	2	-1.461	-0.826	-0.266	-0.163	88.8%
2	1	-0.337	-0.051	-0.157	-0.144	66.2%
	2	-0.433	-0.028	+0.004	+0.010	97.7%
3	1	-0.318	-0.041	-0.022	-0.009	97.2%
	2	-0.263	-0.064	-0.162	-0.122	53.6%
					Average Decrease:	81.1%

NORTHERN CLIMATE MONITORS

Embedded Ag/AgCl Reference Cells

Evaluation of Resistance Measurements

Table 22 shows the resistance measurements obtained on the reference cell circuits at four different times during the research project. After 6 months, it was found that 40 percent of the reference cells showed a decrease in resistance. This might be attributed to the higher temperature in August when the readings were taken versus the initial readings in the cold temperature of January. The other reference cells (60 percent) showed a sharp increase in resistance as was expected. At the end of 1 year, and again in winter, a severe resistance increase was found for all reference cells. This increase may be attributed to possible damaging effects of freeze-thaw cycles, extreme cold, defective reference cells, or improper installation. It is also noted that 50 percent of the reference cells at that time were considered inadequate for operation. After 18 months (in summer), a noticeable reduction in reference cell circuit resistance was measured (an average decrease of 561 percent). At 18 months only reference cell B in Zone 3 was considered too high a resistance for proper operation.

Table 22.

Reference cell circuit resistance measurements for northern climate bridge, Cincinnati, Ohio.

Location	Resistance (ohms)						
Zone/ Reference Cell	Initial	After Approx 6 Months	% Change Initial to 6 Months	After Approx 12 Months	% Change 6 Months to 12 Months	After Approx 18 Months	% Change 12 to 18 Months
Z1, RC A	5.5 K	4.2 K	24%	35 K	733%	8.6 K	-75%
Z1, RC B	1.3 K	20 K	1439%	76 K	280%	22 K	-71%
Z1, RC C	105	100	-5%	4.6 K	4500%	2.4 K	-48%
Z2, RC A	605	220	-64%	5.7 K	2491%	3.7 K	-35%
Z2, RC B	140	5.2 K	3614%	2.5 K	-52%	15 K	500%
Z2, RC C	310	100	-68%	310	210%	670	116%
Z3, RC A	616	2.1 K	409%	32 K	932%	19 K	-41%
Z3, RC B	310	31.5 K	10061%	180 K	471%	68 K	-62%
Z4, RC A	490	3.1 K	533%	200 K	6352%	7 K	-97%
Z4, RC B	670	10 K	1393%	170 K	1600%	8.5 K	-95%

Evaluation of "Natural" Corrosion Potential Measurements

Table 23 documents the change of the corrosion potential (E-corr) of the reference cells with time and continuous system operation as computed from E Log I test data.

In general, the corrosion potential of the reference cells (except cell 3 B) decreased from their initial values with continuous system operation, an expected behavior that proves the cathodic protection systems were operating as intended.

Table 23.

Reference cell natural corrosion potential for northern climate bridge, Cincinnati, Ohio.

Location		Potential (mV)				
Zone	Reference Cell	Initial	6 Months	12 Months	18 Months	Overall Change (%)
1	A	-309	-245	-247	-201	35.1%
	B	-386	-175	-209	-171	55.7%
	C	-390	-115	-173	-174	55.4%
2	A	-282	-286	-264	-253	10.3%
	B	-208	-209	-214	-182	12.5%
	C	-127	-117	-366	-68	46.5%
3	A	-315	-164	-251	-266	15.6%
	B	-277	-167	-413	-518	(Increase 87.0%)
4	A	-177	+3	N/A[1]	N/A[1]	N/A[1]
	B	-127	-105	N/A[1]	N/A[1]	N/A[1]
					Average Decrease:	18.0%

[1] N/A Due to High Reference Cell Circuit Resistance

Macrocell Rebar Probes

Evaluation of Resistance Measurements

Table 24 shows that all resistance measurements obtained 6 months after energization were lower than the initial resistance readings. The drastic change in temperature between initial energization (January) and the 6-month evaluation reading (August) is believed to be the cause. As expected, a sharp increase in resistance was measured at 12 months with an average increase of 161 percent from the previous 6-month measurements. Overall, an increase in resistance of 64.4 percent was measured for the first year. At 18 months (summertime) the resistance decreased an average of 58 percent from the 12-month (wintertime) measurements and was within 8 percent of the resistance recorded the previous summer.

Table 24.

Rebar probe circuit resistance measurements for northern climate bridge, Cincinnati, Ohio.

Location	Resistance (ohms)						
Zone/ Rebar Probe	Initial	After Approx 6 Months	% Change Initial to 6 Months	After Approx 12 Months	% Change 9 Months to 12 Months	After Approx 18 Months	% Change 12 to 18 Months
Z1, RP 1	560	330	-41.1%	1100	233.3%	380	-66%
Z1, RP 2	430	240	-44.2%	640	166.7%	250	-61%
Z2, RP 3	415	300	-27.7%	620	106.7%	320	-48%
Z2, RP 4	350	250	-28.6%	670	168.0%	290	-57%
Z3, RP 5	310	240	-22.6%	600	150.0%	260	-57%
Z3, RP 6	330	290	-12.1%	670	131.0%	290	-57%
Z4, RP 7	650	415	-36.2%	1100	165.1%	420	-62%
Z4, RP 8	650	380	-41.5%	1100	163.2%	430	-57%

Evaluation of "Natural" Corrosion Current Measurements

Natural corrosion current is considered to be the corrosion current of the macrocell rebar probe measured the day following depolarization testing. Negative values reflect anodic macrocells whereas positive values reflect cathodic macrocells. The data collected is shown in table 25.

The macrocell rebar probe corrosion current varied with time and continuous cathodic protection application. This can be attributed to severe weather variations and/or possible changes in the chemical properties of the macrocell rebar probes. Macrocell rebar probe Nos. 1, 2, and 3 (Deck) performed more as expected as their trend was to decrease in corrosion current. Macrocell rebar probe No. 4 (Deck) and Nos. 7 and 8 (Pier) became cathodic or very near cathodic and could no longer be evaluated as a corrosion cell. Macrocell rebar probe Nos. 5 and 6 (Sidewalk) initially showed a decrease in corrosion current and then a substantial increase.

Table 25.

Rebar probe natural corrosion current for northern climate bridge, Cincinnati, Ohio.

Location		Current (mA)				
Zone	Rebar Probe	Initial	6 Months	12 Months	18 Months	% Change From 6 Mo To 18 Mo (%)
1	1	-0.0666	-0.410	-0.116	-0.206	49.8%
	2	-0.281	-0.900	-0.198	-0.453	49.7%
2	3	-0.0890	-0.130	-0.065	-0.069	46.9%
	4	-0.0639	+0.010	+0.029	+0.007	N/A
3	5	-0.203	-0.070	+0.008	-0.216	(Increase 208.6%)
	6	-0.165	-0.080	-0.356	-0.517	(Increase 546.3%)
4	7	-0.404	-0.280	0.00	0.00	N/A
	8	-0.410	-0.130	-0.007	-0.006	95.4%

CONCLUSIONS

Very different resistances were measured embedded monitors in the marine environment and northern climate bridge structures. These differences may be attributed to the following factors.

(a) Temperature at time of installation.
(b) Amount of temperature variation between monitor periods.
(c) Dense concrete overlay systems vs. systems with no concrete overlays or cover.

In general, the corrosion current (with the cathodic protection turned "off" for 1 day), of the macrocell rebar probes and the corrosion potential of the embedded reference cells in both structures decreased in time with continuous cathodic protection applied. However, exceptions were found on the northern climate bridge which may be attributed to the factors listed above.

To properly test and evaluate cathodic protection systems, the reference cell potential is of paramount importance. The Ag/AgCl embedded reference cells used were not considered operational during freezing conditions.

The macrocell rebar probe is a good embedded reference for monitoring protection current distribution. In time, however, the magnitude of the natural macrocorrosion cell is reduced. In addition, if the cathodic protection current or nature causes the rebar probe to become permanently cathodic, it no longer can be used for measuring "current reversal" to establish system operating parameters.

CHAPTER 5 CRITERIA FOR CATHODIC PROTECTION OF STEEL REINFORCEMENT IN CONCRETE BRIDGE DECKS AND SUBSTRUCTURES

Various criteria have been proposed for determining the effectiveness of cathodic protection in controlling corrosion on steel embedments within concrete bridge decks and substructures. Among the methods used to establish the current density criteria to be used for each zone or structure are the following:

(1) E Log I method.
(2) 100 mV polarization decay method.
(3) Statistical distribution potential analysis method.
(4) Fixed current density per square foot of embedded steel surface area method.
(5) Fixed current density per square foot of concrete surface area method.

Criteria (1) and (2) above were essentially adopted from criteria which are used on underground ferrous metal structures. The subject of the validity of each of these methods has been very controversial. Nevertheless at the 1988 annual conference of the (NACE), T3K-2 Task Group assigned to preparing a standard Recommended Practice for "Cathodic Protection of Reinforcing Steel in Concrete Structures" adopted, by unanimous vote, the first three of the above criteria. This proposed recommended practice has been forwarded to the NACE Unit Committee T3K for review and comment.

Of the 3 proposed NACE criteria, only the first 2 have been widely practiced by various corrosion engineers for energizing and testing cathodic protection systems installed on steel reinforced concrete bridge decks and substructures. The third method had not been widely used and was not evaluated in this study. Data obtained during criteria testing for both bridges through the duration of this study is provided in tables 26 and 27.

TABLE 26.

Criteria testing & operational data for marine environment bridge, Norfolk, Virginia.

	Deck Zone 1	Pier Zone 2	Pier Zone 3
POST INSTALLATION AND ACTIVATION			
E Log I Test, Iprotect avg/Percent variation (mA)/(%)	5124/0	575/17/5	625/16.2
E Log I Test, Rectifier Voltage for Iprotect (V)	6.4	1.4	4.2
Concrete Surface Current Density (mA/ft^2)	0.94	0.68	0.74
Rebar Surface Current Density (mA/ft^2)	1.09	1.39	1.5
*Depolarization Test avg/Percent variation (mV)/(%)	115/8.0	159/23.9	142/9.9
Constant Current setting at end of evaluation (mA)	5500	0700	0700

*4 Hour Depolarization Shift after 1 day constant current

9 MONTH EVALUATION			
*Depolarization Test avg/Percent variation (mV)/(%)	226/4.4	329/4.6	196/8.2
E Log I Test, Iprotect avg/Percent variation (mA)/(%)	3599/2.8	374/0	390/4.1
E Log I Test, Rectifier Voltage for Iprotect (V)	4.1	1.1	3.2
Concrete Surface Current Density (mA/ft^2)	0.66	0.44	0.46
Rebar Surface Current Density (mA/ft^2)	0.76	0.90	0.94
Constant Current setting at end of evaluation (mA)	3500	400	400

*4 Hour Depolarization Shift after 9 months of constant current set at activation evaluation testing.

16 MONTH EVALUATION			
*Depolarization Test avg/Percent variation (mV)/(%)	235/23.4	265/19.2	186/8.6
E Log I Test, Iprotect avg/Percent variation (mA)/(%)	2247/5.6	300/3.3	370/27.0
E Log I Test, Rectifier Voltage for Iprotect (V)	4.1	4.8	5.5
Concrete Surface Current Density (mA/ft^2)	0.41	0.35	0.44
Rebar Surface Current Density (mA/ft^2)	0.48	0.72	0.89
Constant Voltage setting at end of evaluation (V)	8.0	7.0	7.0

*4 Hour Depolarization Shift after 7 months of constant current set at 9-month evaluation.

23 MONTH EVALUATION			
*Depolarization Test avg/Percent variation (mV)/(%)	164/22.6	168/1.8	150/2.0
E Log I Test, Iprotect avg/% variation (mA)/(%)	2098/0	285/12.3	290/6.9
E Log I Test, Rectifier Voltage for Iprotect (V)	2.8	2.0	3.2
Concrete Surface Current Density (mA/ft^2)	0.38	0.34	0.34
Rebar Surface Current Density (mA/ft^2)	0.44	0.67	0.67
Constant Voltage setting at end of evaluation (V)	8.0	7.0	7.0

*4 Hour Depolarization Shift after 7 months of constant voltage set at 16-month evaluation.

Table 27.

Criteria testing & operational data for northern climate bridge, Cincinnati, Ohio.

	Deck Zone 1	Deck Zone 2	Sidewalk Zone 3	Pier Zone 4
POST INSTALLATION AND ACTIVATION				
E Log I Test, Iprotect avg/Percent variation (mA)/(%)	3624/29.0	3224/9.3	1899/2.6	1649/12.1
E Log I Test, Rectifier Voltage for Iprotect (V)	7.4	2.2	3.8	7.6
Concrete Surface Current Density (mA/ft^2)	1.37	1.22	1.32	0.64
Rebar Surface Current Density (mA/ft^2)	1.63	1.45	1.45	1.10
*Depolarization Test avg/Percent variation (mV)/(%)	112/8.9	58/10.3	185/4.3	922/2.1
Constant Current setting at end of evaluation (mA)	3000	3000	1500	1700
*4 Hour Depolarization Shift after 1 day constant current.				
6 MONTH EVALUATION				
*Depolarization Test avg/Percent variation (mV)/(%)	321/2.8	83/18.1	372/9.7	872/1.7
E Log I Test, Iprotect avg/Percent variation (mA)/(%)	2374/14.7	3174/11.8	1080/0	640/0
E Log I Test, Rectifier Voltage for Iprotect (V)	1.0	2.4	2.0	6.7
Concrete Surface Current Density (mA/ft^2)	0.90	1.20	0.75	0.25
Rebar Surface Current Density (mA/ft^2)	1.07	1.43	0.82	0.43
Constant Current setting at end of evaluation (mA)	2500	3400	1100	600
*4 Hour Depolarization Shift after 6 months of constant current set at activation evaluation testing.				
12 MONTH EVALUATION				
*Depolarization Test avg/Percent variation (mV)/(%)	218/3.2	211/6.6	235/7.2	463/29.6
E Log I Test, Iprotect avg/Percent variation (mA)/(%)	1816/2.8	3699/0	875/0	N/A^1
E Log I Test, Rectifier Voltage for Iprotect (V)	6.3	4.3	6.6	N/A^1
Concrete Surface Current Density (mA/ft^2)	0.69	1.40	0.61	N/A^1
Rebar Surface Current Density (mA/ft^2)	0.82	1.67	0.67	N/A^1
Constant Voltage setting at end of evaluation (V)	6.2	4.3	7.1	14.0(max)
*4 Hour Depolarization Shift after 6 months of constant current set at 6-month evaluation.				
16 MONTH EVALUATION				
*Depolarization Test avg/Percent variation (mV)/(%)	197/14.2	150/10	267/16.9	349/8.9
E Log I Test, Iprotect avg/Percent variation (mA)/(%)	3832/5.2	3499/2.9	2998/3.3	N/A^1
E Log I Test, Rectifier Voltage for Iprotect (V)	2.3	2.6	5.6	N/A^1
Concrete Surface Current Density (mA/ft^2)	1.45	1.33	2.08	N/A^1
Rebar Surface Current Density (mA/ft^2)	1.73	1.581	2.29	N/A^1
Constant Voltage setting at end of evaluation (V)	6.2	4.3	7.1	14.0(max)

*Depolarization Test after 6 months of constant voltage set at 12-month evaluation.

^{1}N/A No E Log I Test performed during evaluation period.

E LOG I METHOD

In the textbook "Corrosion and Cathodic Protection of Steel Reinforced Concrete Bridge Decks", prepared for the Federal Highway Administration (FHWA-IP-88-007), a discussion of the E Log I testing method is presented. The cathodic polarization process on the surface of the steel reinforcing can be determined from a plot of polarized potential vs. logarithm of applied current. From this plot several of the pertinent corrosion parameters can be graphically determined as previously shown in chapter 1, figure 3. At low values of applied current, the polarized potential does not change much from the original corrosion potential (commonly referred to as the "static potential" or "E-corr"). As the current density is increased, the polarized potential begins to gradually increase to point at which a linear relationship between the polarized potential and the logarithm of applied current exists. From this plot, the current required for cathodic protection, I-protect, and the theoretical corrosion current, I-corr, can be extrapolated. The potential at which cathodic protection is achieved, E-protect is extrapolated from the tangent point of the I-protect extension line to the potential plot. For the start-up of a cathodic protection system, this data establishes an initial DC current (I-protect) and a polarized potential (E-protect) to use in future monitoring.

As a minimum, an E Log I plot should be done at each embedded reference cell. Additional plots using a portable reference cell should be conducted using the data from a potential contour plot to indicate anodic and cathodic areas. If used for monitoring surveys, the E Log I plot requires complete depolarization of the steel reinforcing. Comparison of initial plots to those obtain after significant system operation are useful to determine if the electrochemical activity on the bridge has altered. Increases in values for I-corr and I-protect would indicate an increase in corrosion activity. Conversely, if the penetration of additional deicing salts is slowed by the application of an overlay or of a sealer or if the cathodic protection removes the chloride ion away from the surface of the reinforcing steel, the current required (I-protect) and corrosion current, (I-corr) will be reduced.

Polarization plots of E Log I measurements require more equipment and expertise to obtain than needed for the 100 mV polarization decay criteria. In addition to a reference cell and high impedance voltmeter, oscilloscope or computer, a variable DC power source is required. If provided with appropriate control circuitry, the installed DC rectifier can be used as the power source. Often the DC current required to obtain a full plot is several times I-protect.

Several researchers have theorized that it is quite likely the above criteria may not be applicable since the development of Tafel behavior is dependent upon the cathodic polarization process being that of activation polarization (oxygen reduction at the cathode) rather than concentration polarization (oxygen diffusion controlled polarization at the cathode). The NACE Task Force acknowledged that either process may tend to dominate during the E Log I testing of a steel reinforced concrete structures. On the other hand, it was concluded that it did not matter which polarization process was involved as long as a linear segment was generated by the plot of potential values vs. the logarithm of the applied cathodic current. Simply stated, as long as either process or a combination of the both processes were involved which result in linear cathodic polarization behavior, corrosion control will have been achieved and the current required for cathodic protection will be established by the point at which the initiation of this linear behavior occurs. Thus NACE deleted the reference to Tafel behavior and simply substituted the words "linear behavior" to determine the initial point in which cathodic protection is achieved on a given structure. As with any of the criteria, the above criterion should be achieved at all locations on the steel surfaces within the concrete structures. To authenticate this, it is a generally accepted practice to conduct E Log I tests both at the areas where the most active corrosion is occurring and at areas where the steel reinforcement is most concentrated (with respect to the relative surface areas) and most deeply embedded within the concrete. If effective cathodic protection can be achieved at these locations, it is reasonable to presume that cathodic protection has been achieved at all other locations within the area being tested.

To determine the segment of the E Log I plot which is truly linear, a number of corrosion engineers have adopted the use of linear regression analysis methods. Comparison of the actual field data measured vs. the calculated straight line approximation established by the linear regression analysis is performed. The prime measurement of the comparative linearity is the coefficient of determination (R^2). It is generally agreed that at least a .98 coefficient is required over at least 10 observation points for linearity to be assured. Of course, the higher the value of the coefficient of determination (a value of 1.0 is a perfect straight line) and the greater the number of observations used in analysis, the greater the assurance that a truly linear segment in the E Log I test has been achieved. Of additional value is the "Y" estimate error which is the vertical deviation of the measured data from the calculated linear regression line. Greater deviation values indicate reduced linearity but only if the value is relatively large compared to the absolute value of the "Y" measurements.

The statistical data analysis information obtained from the E Log I tests performed on both bridges is provided in table 28. The average number of data points used in each linear regression analysis was 17 with a standard deviation of plus or minus 5.9. This is significantly greater than the minimum value of 10 data points. Also, additional data confirmation is provided by the extremely high average coefficient of determination of 0.998 with a standard deviation of only 0.002. The average standard error of the "Y" estimate is also very low at 1.793 mV when compared to the potentials being measured which were typically in the range of 300 to 800 mV.

The prime advantage of the E Log I test is that it enables the corrosion engineer to perform tests before the system has been operated for any period of time to establish the initial current level at which the system should be set. The test method is also used at any later time as long as the system has been turned off (typically for 1 or 2 days) to assure that it has depolarized back to its free corrosion potential. Thus, the technique can be used to determine both the initial operating current density requirements on the steel reinforcing and to determine whether a reduction or increase in operating current density is applicable at any future time in order to maintain effective corrosion control.

100 MILLIVOLT POLARIZATION DECAY METHOD

In accordance with the NACE proposed Recommended Practice T-3K-2 which was adopted unanimously in 1988 by the committee preparing the standard, the following description is provided for this test methodology: "The reinforcing steel, and any other metal embedments that are to be protected shall be polarized by a minimum cathodic shift of 100 mV. This polarization is to be determined by interrupting the protective current and monitoring the decay of the reinforcement potential measured to a stable reference electrode. When the current is interrupted, an immediate voltage shift will

Table 28.

E Log I statistical data.

(All Data Sorted in Descending Order)

Data Count	Standard Error Of "Y" Estimate (in mV)	Coefficient of Determination (R Squared)	No. of Data Pts. Used
1	9.86443	0.99976	33
2	8.50113	0.99971	28
3	5.83708	0.99970	28
4	5.78246	0.99968	28
5	3.91616	0.99967	27
6	3.91263	0.99966	27
7	3.46997	0.99956	26
8	3.43652	0.99955	26
9	3.40908	0.99952	24
10	2.49044	0.99930	23
11	2.41797	0.99920	22
12	2.35689	0.99910	22
13	2.17865	0.99910	22
14	2.16005	0.99909	22
15	2.05262	0.99906	22
16	1.95068	0.99900	12
17	1.83599	0.99900	20
18	1.83221	0.99899	20
19	1.65021	0.99887	20
20	1.64137	0.99887	20
21	1.52821	0.99885	20
22	1.50427	0.99876	10
23	1.46386	0.99877	19
24	1.32261	0.99867	18
25	1.23911	0.99865	17
26	1.23709	0.99860	17
27	1.23349	0.99853	17
28	1.23319	0.99851	17
29	1.23207	0.99845	16
30	1.22957	0.99841	16
31	1.20405	0.99841	15
32	1.18426	0.99840	15
33	1.18382	0.99836	15
34	1.17571	0.99829	15
35	1.15200	0.99827	14
36	1.14987	0.99826	14
37	1.13428	0.99815	14
38	1.10110	0.99811	14
39	1.09102	0.99797	14
40	0.96883	0.99791	13
41	0.96224	0.99781	13
42	0.93821	0.99775	13
43	0.92003	0.99770	13
44	0.90283	0.99765	13
45	0.88264	0.99750	13
46	0.85244	0.99748	12
47	0.84630	0.99747	12
48	0.81117	0.99733	12
49	0.74849	0.99732	11
50	0.74191	0.99684	11
51	0.69627	0.99662	11
52	0.68859	0.99623	11
53	0.66781	0.99517	10
54	0.63351	0.99512	10
55	0.54511	0.99408	10
56	0.47431	0.99308	10
57	0.45409	0.99243	10
58	0.42741	0.99238	10
59	0.37505	0.99187	9
60	0.26388	0.98650	9

Statistical Evaluation of
E Log I Analysis Data

Average No. of Data Pts. Used: 17.050
Std. Deviation of Data Pts. Used: 5.861
Average of "Y" Estimate Error: 1.818
Std. Deviation of "Y" Estimate: 1.793
Average Coefficient of Determ. (R-squared): 0.998
Std. Deviation of Coefficient of Determ: 0.002

occur. This shift is the result of eliminating the "IR drop" and is not to be included in the polarization measurements. The potential of the steel immediately after that shift shall be used at the initial reading from which to measure polarization decay. The total polarization decay equals the initial steel potential subtracted from the steels final potential. Typically, this criteria should be met within four hours".

The fundamental limitation for the use of this criterion is that it can only be used after the cathodic protection has been operating for some reasonable time period. It can not be used for establishing the initial current density at which the cathodic protection will be set to operate. Thus, it is more typically used to confirm that cathodic protection was effective at any later point in time when the system is being retested. If 100 mV of decay is achieved within the 4-hour time limit, it is presumed that protection was being maintained at the current setting (or current density) of the cathodic protection system prior to running the depolarization test. The question always exists as to what to do if the polarization decay is higher than 100 mV (e.g. 300 or even 400 mV of decay within a 4-hour time period). If the decay is considered to be to great, the methodology does not indicate what the current density value should be reduced to in order to maintain effective corrosion control without excessive polarization.

Of even greater concern is the actual polarization decay data (appendix B), measured during this study. For the two bridges evaluated in this study, the E Log I test data (appendix C) and macrocell polarization reversal data contained in chapter 1 indicate that the current densities at which the systems were operated were reasonable for achieving effective but not excessive cathodic protection. The polarization decay data contained in table 29 shows that the average of all decays measured was 236 mV with a standard deviation of 164 mV. The average decay is considerably higher than the 100 mV decay required by the criterion. Further, the very large range of 72 to 400 mV for one standard deviation raises serious doubts as to the applicability of this criterion at least for the two structures evaluated in this study.

Table 29.

Polarization decay data in millivolts.
(Excerpted from tables 3 & 8)

Data in Descending Order

941	326	290	227	218	196	177	158	127	101
903	323	272	227	214	194	177	155	127	76
841	318	252	226	214	193	175	154	126	72
812	315	252	226	214	193	171	152	125	66
599	314	245	225	212	190	170	142	121	59
407	312	243	225	209	181	166	142	118	50
380	307	232	222	207	180	165	130	109	
344	307	230	222	201	180	161	128	103	
336	301	229	218	198	180	160	127	101	

No. of Observations: 87
Average of All Values: 236 mV
Std. Deviation of All Values: 164 mV
Range of Values for 1 Std. Dev.: 72 to 400 mV

FIXED CURRENT DENSITY PER SQUARE FOOT OF CONCRETE SURFACE AREA METHOD

Several firms who manufacture cathodic protection system components for steel reinforced concrete structures have proposed that the cathodic protection can be provided by simply adjusting the system to a fixed current density per square foot of concrete surface area. While this method is quite simple to apply, there can be significant variation in the steel reinforcing surface area to the concrete surface area especially if both decks and substructures are considered. Since the cathodic protection current density required for protection is fundamentally dependent upon the rebar surface area contained within the concrete, simply picking a current density based on concrete surface area alone is not valid. To apply such a criterion, it would be essential to first evaluate the relative surface area of the rebar for each portion of the structure where different reinforcing bars schedules are used. Thus, if a current density method is to be used, directly applying a fixed density based on the rebar surface area rather than the concrete surface area would be more effective.

Table 30.

Concrete surface current density in mA/ft^2.
(Excerpted from tables 26 & 27)

Data In Descending Order

2.08
1.45
1.40
1.37
1.33
1.32
1.22
1.20
0.94
0.90
0.75
0.74
0.69
0.68
0.66
0.64
0.61
0.46
0.44
0.44
0.41
0.38
0.35
0.34
0.34
0.25

No. of Observations: 26
Average of All Values: 0.8227 mA/ft^2
Std. Deviation of All Values: 0.4555 mA/ft^2
Range of Values for 1 Std. Dev.: 0.3672 to 1.2782 mA/ft^2

All the concrete surface current densities required for the two structures evaluated in this project are shown in table 30. The concrete surface current density required for cathodic protection ranged from a minimum of 0.25 mA/ft^2 (2.5 mA/m^2) of concrete to a maximum of 2.08 mA/ft^2 (20.8 mA/m^2) of concrete. The average concrete surface area current density was 0.83 mA/ft^2 (8.3 mA/m^2) with a standard deviation of 0.46 mA/ft^2 (4.6 mA/m^2). With this wide range of values, the applicability of a fixed current density per square foot of concrete surface area is invalid for either of these structures.

FIXED CURRENT DENSITY PER SQUARE FOOT OF EMBEDDED STEEL SURFACE AREA METHOD

Again, some manufacturers have suggested that use of a single current density value for a per square foot steel reinforcing unit in concrete is generally applicable to all concrete structures. This method is also relatively simple to apply, however, it does not take into consideration the widely varying current density requirements which occur on steel and concrete. This variation in cathodic protection current density is impacted by the variation in concrete chemistry, porosity, temperature, oxygen content, chloride concentration, vibration, and moisture content.

Table 31.

Rebar surface current density in mA/ft^2. (Excerpted from tables 26 & 27)

Data In Descending Order

2.29
1.73
1.67
1.63
1.58
1.50
1.45
1.45
1.43
1.39
1.10
1.09
1.07
0.94
0.90
0.89
0.82
0.76
0.72
0.67
0.67
0.67
0.67
0.48
0.44
0.43

No. of Observation: 26
Average of all Values: 1.0996 mA/ft^2
Std. Deviation of All Values: 0.4640 mA/ft^2
Range of Values for 1 Std. Dev.: 0.6356 to 1.5636 mA/ft^2

Table 31 provides the operating rebar surface area current densities used for effecting cathodic protection on the two bridge structures. The current density required ranged from a maximum of 2.29 mA/ft^2 (23 mA/m^2) of steel reinforcing to a minimum of 0.43 mA/ft^2 (4.3 mA/m^2). The average current density for all values was 1.1 mA/ft^2 (11 mA/m^2) of steel reinforcing with a standard deviation of .464 mA/ft^2 (4.6 mA/m^2). For the two structures studied, application of a single fixed current density would simply not have provided effective corrosion control for these bridges.

CONCLUSIONS

Based on the data and testing conducted on the two bridges evaluated for 2 years, the following can be concluded:

(1) The E Log I test method appears to provide a realistic method of determining the operating current required for cathodic protection both during initial starting and later reevaluation of the system(s) requirements.

(2) Use of the polarization decay of 100 mV method may have resulted in under protection in most areas of both structures. Further, there was

widely varying decay values both for different areas of each structure and at each system test interval. A detailed controlled research study may be required to determine the magnitude of polarization decay necessary to protect a corroding reinforced concrete structure.

(3) Based on the large variation in current density required (plus or minus approximately 50 percent of the average of all values for one standard deviation in the data), neither concrete surface or rebar surface fixed current density methods appear to be applicable for establishing effective corrosion control of steel reinforced concrete structures.

APPENDIX A

BI-MONTHLY CATHODIC PROTECTION DATA

System voltage, current, "Instant Off" reference cell potential, macrocell rebar probe current and ambient temperature measurements collected for 23 months on three cathodic protection systems on a marine environment bridge and 18 months on four cathodic protection systems on a northern climate bridge.

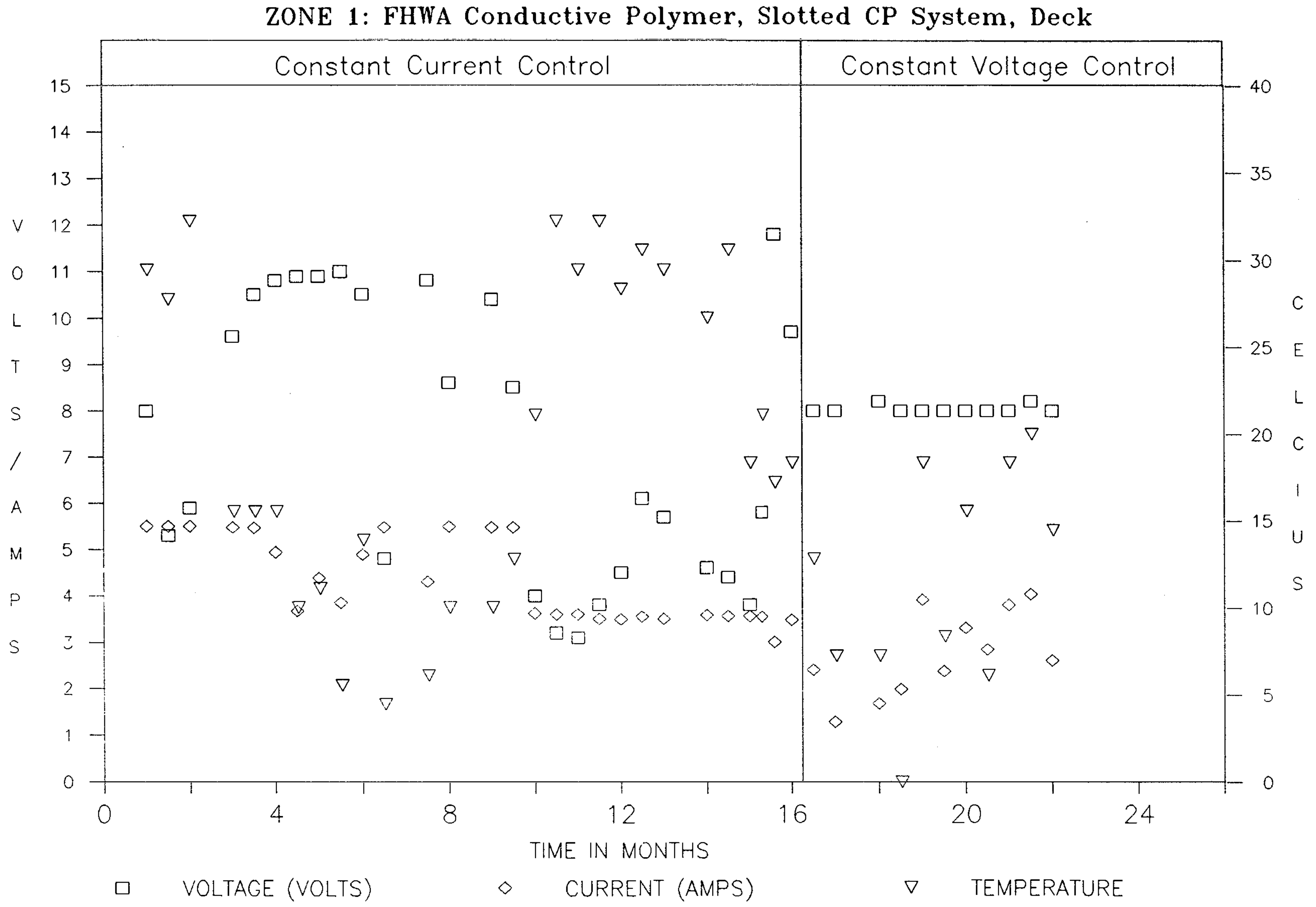


Figure 4. System voltage, current and temperature monitor data for Zone 1, marine environment bridge, Norfolk, Virginia.

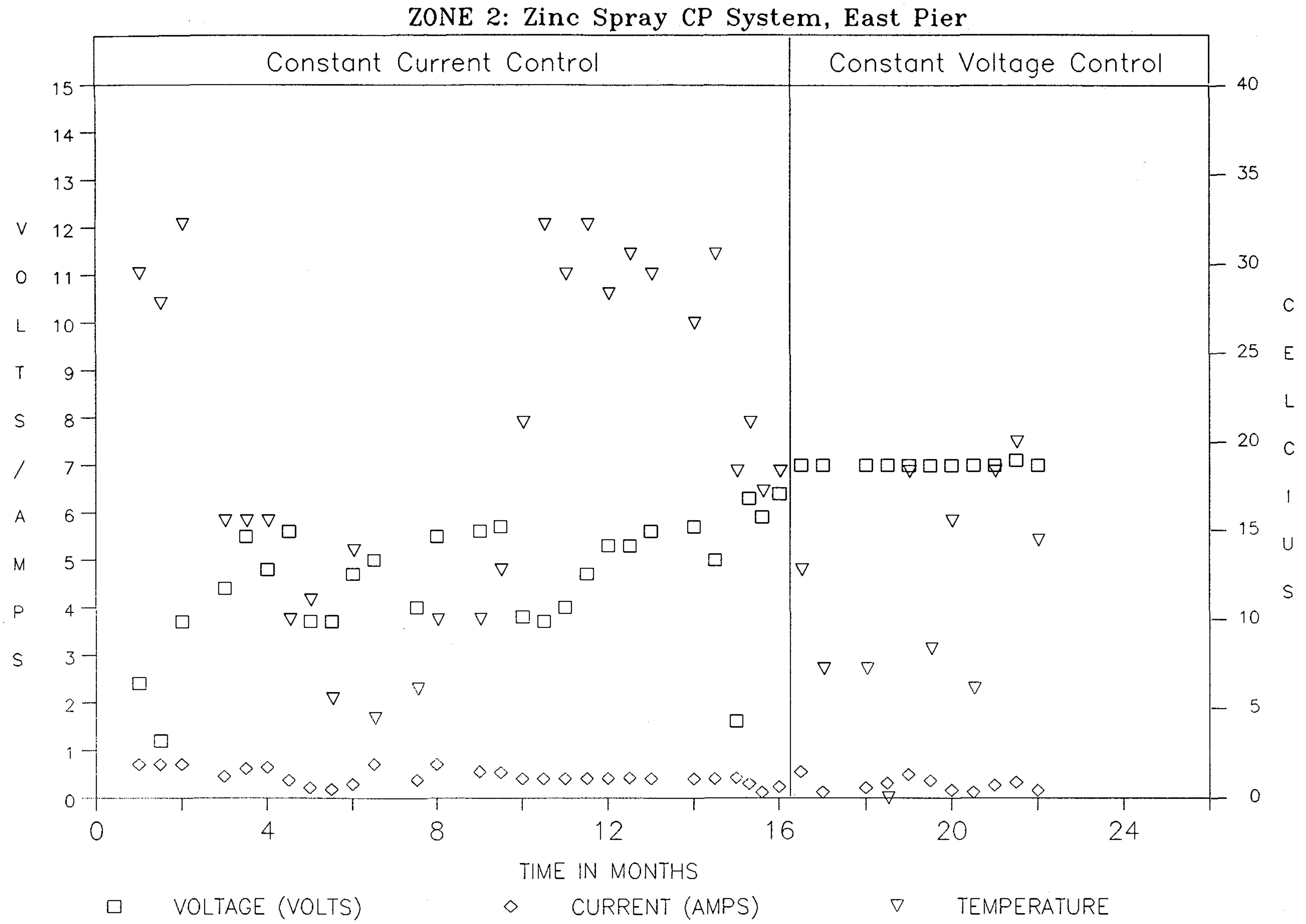


Figure 5. System voltage, current and temperature monitor data for Zone 2, marine environment bridge, Norfolk, Virginia.

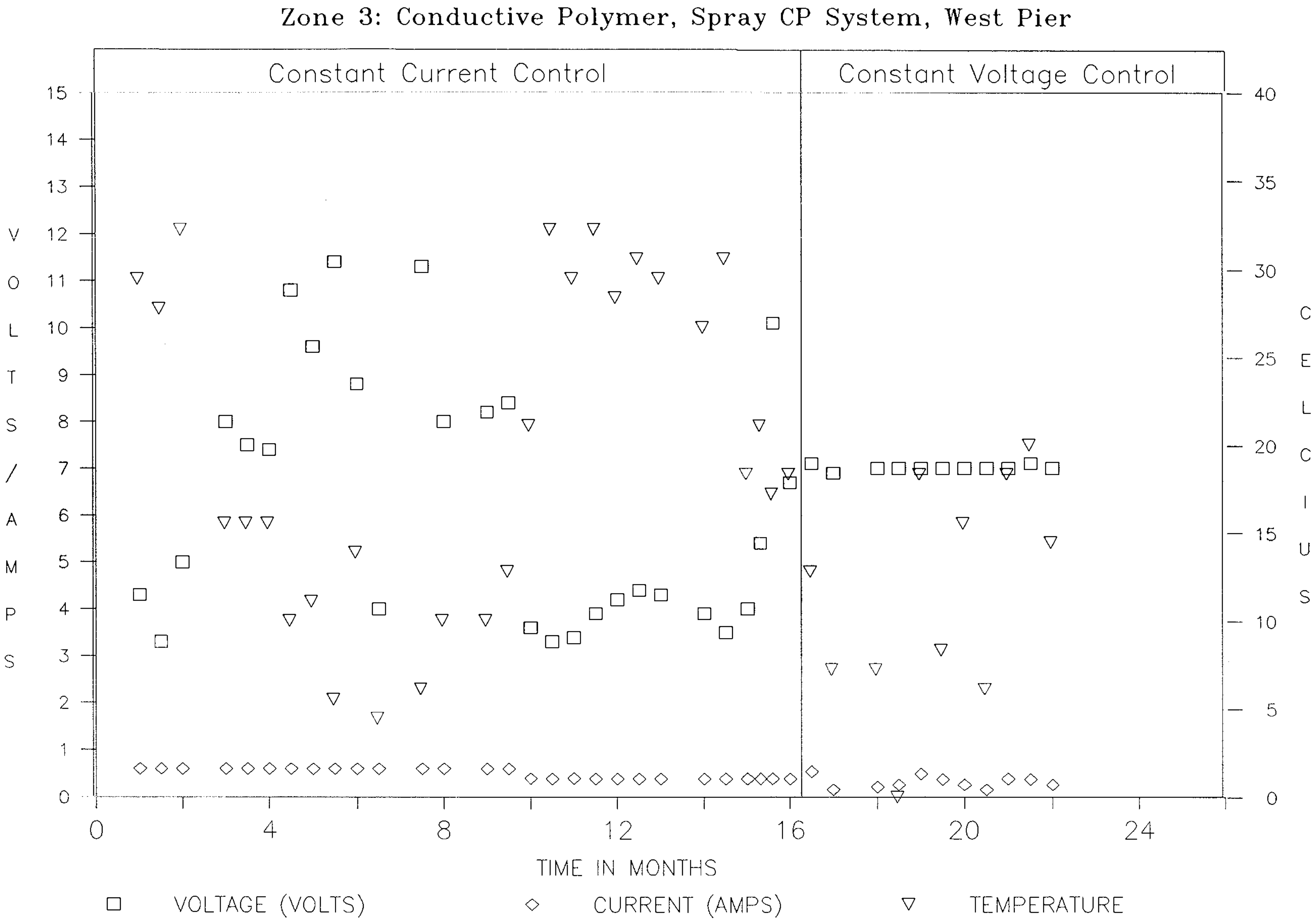


Figure 6. System voltage, current and temperature monitor data for Zone 3, marine environment bridge, Norfolk, Virginia.

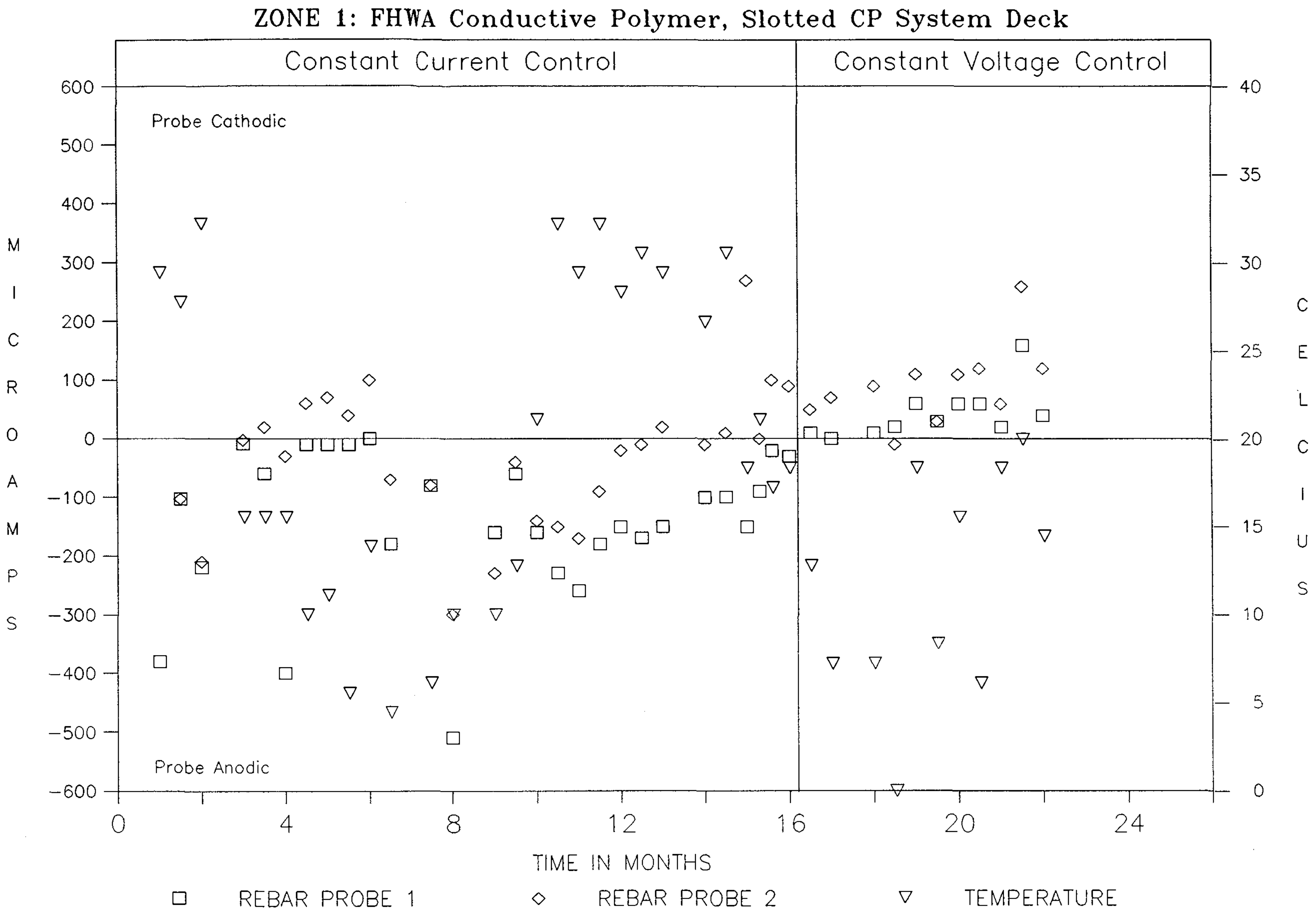


Figure 7. Rebar probe current and ambient temperature monitor data for Zone 1, marine environment bridge, Norfolk, Virginia.

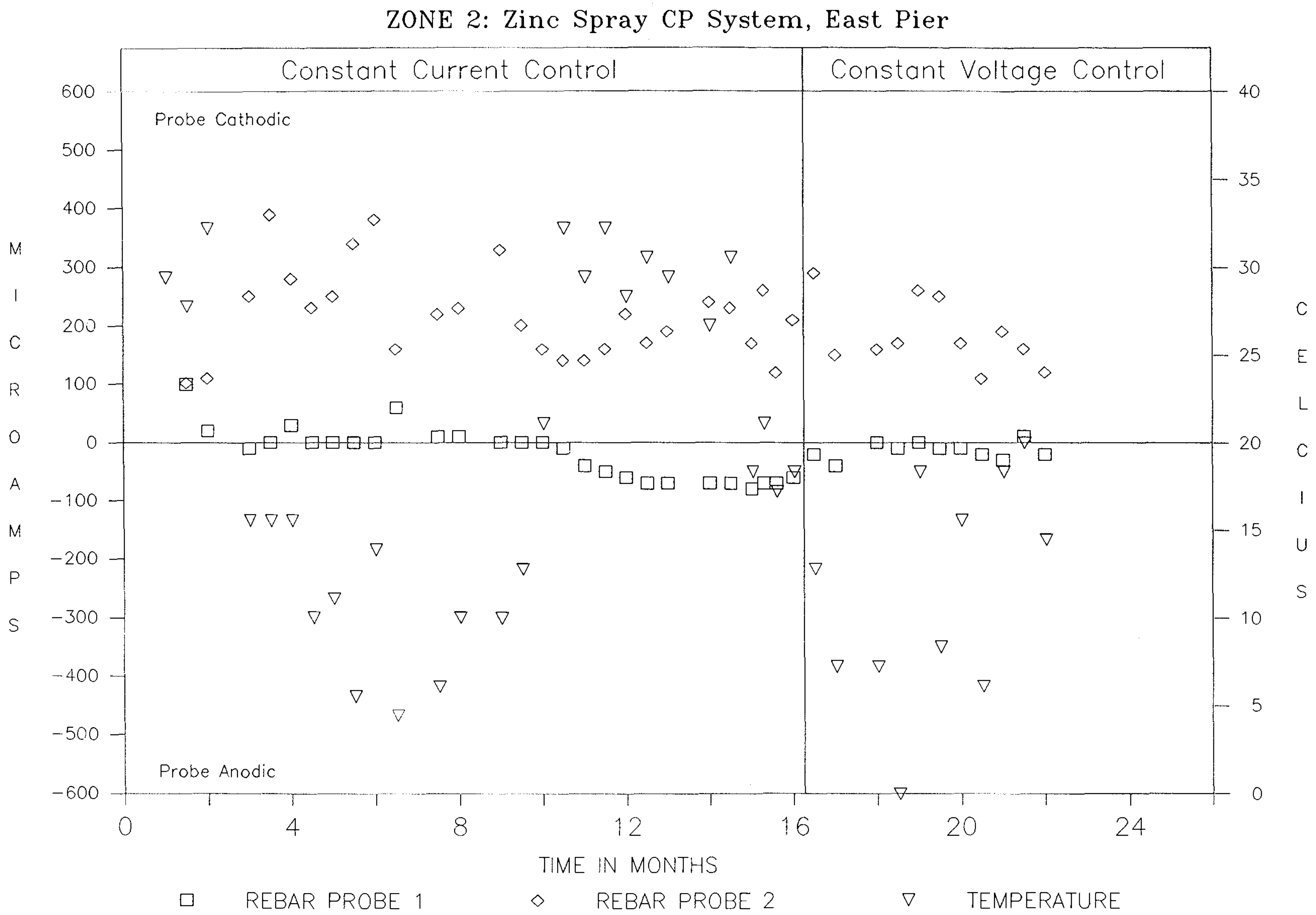


Figure 8. Rebar probe current and ambient temperature monitor data for Zone 2, marine environment bridge, Norfolk, Virginia.

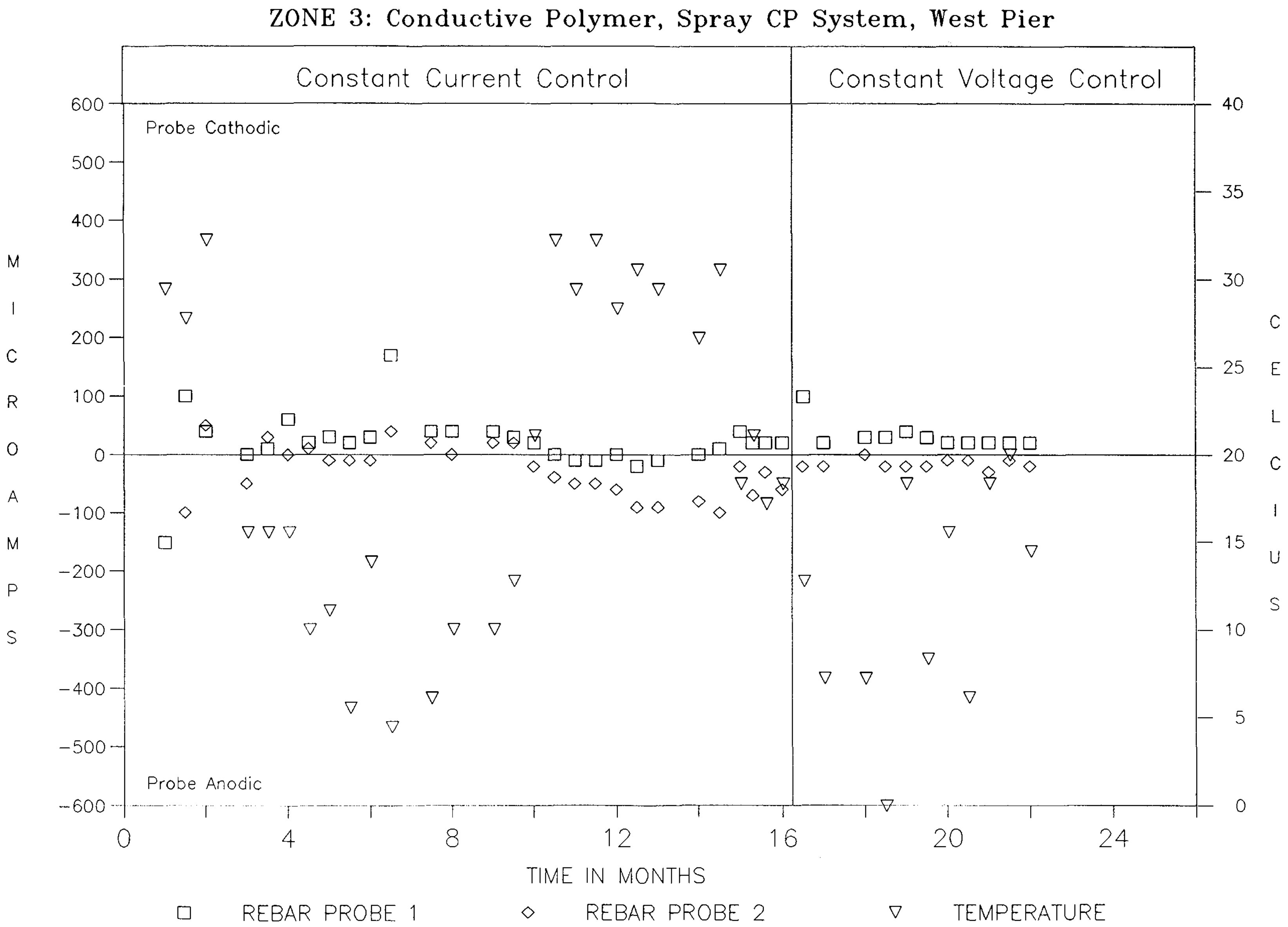


Figure 9. Rebar probe current and ambient temperature monitor data for Zone 3, marine environment bridge, Norfolk, Virginia.

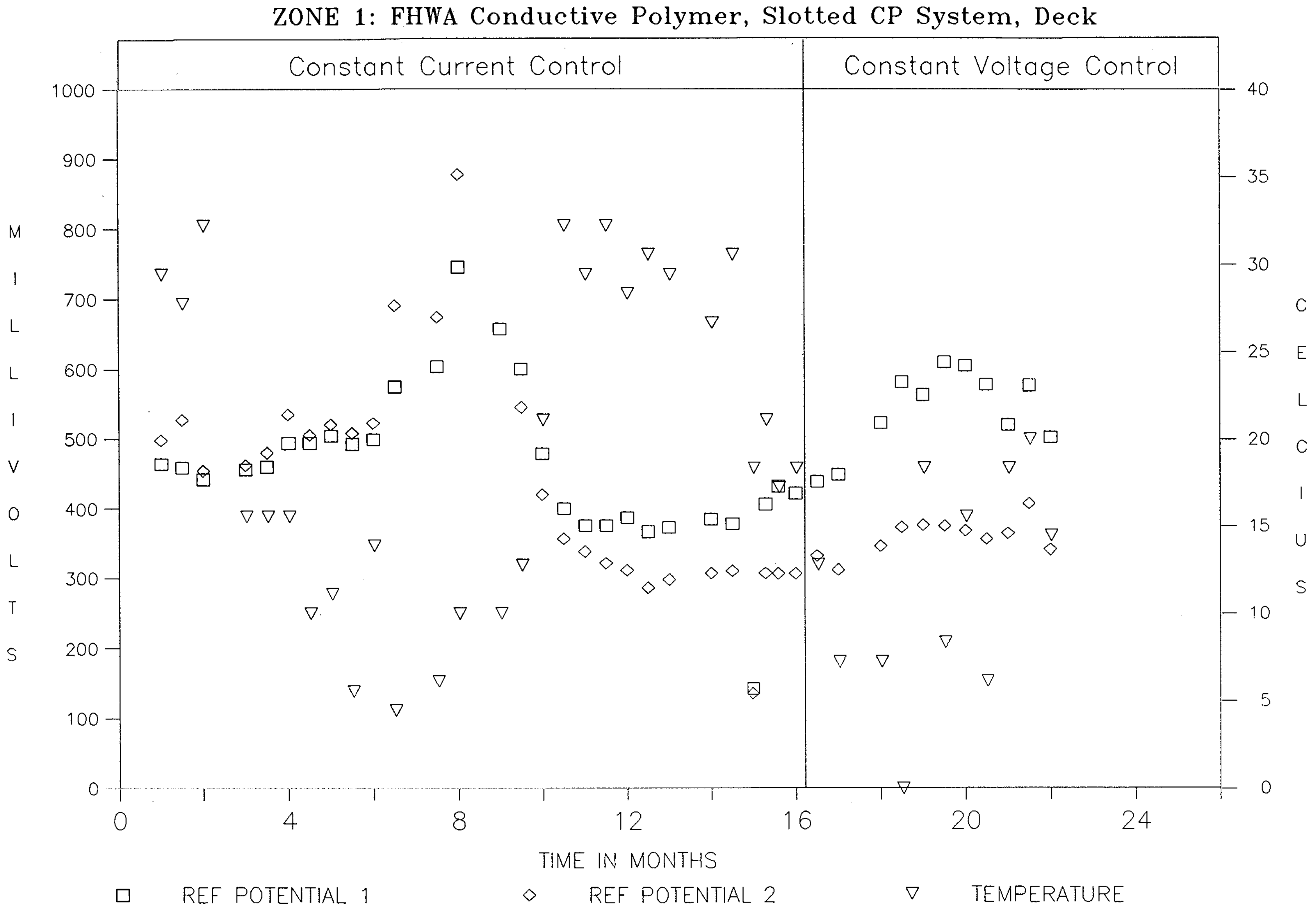
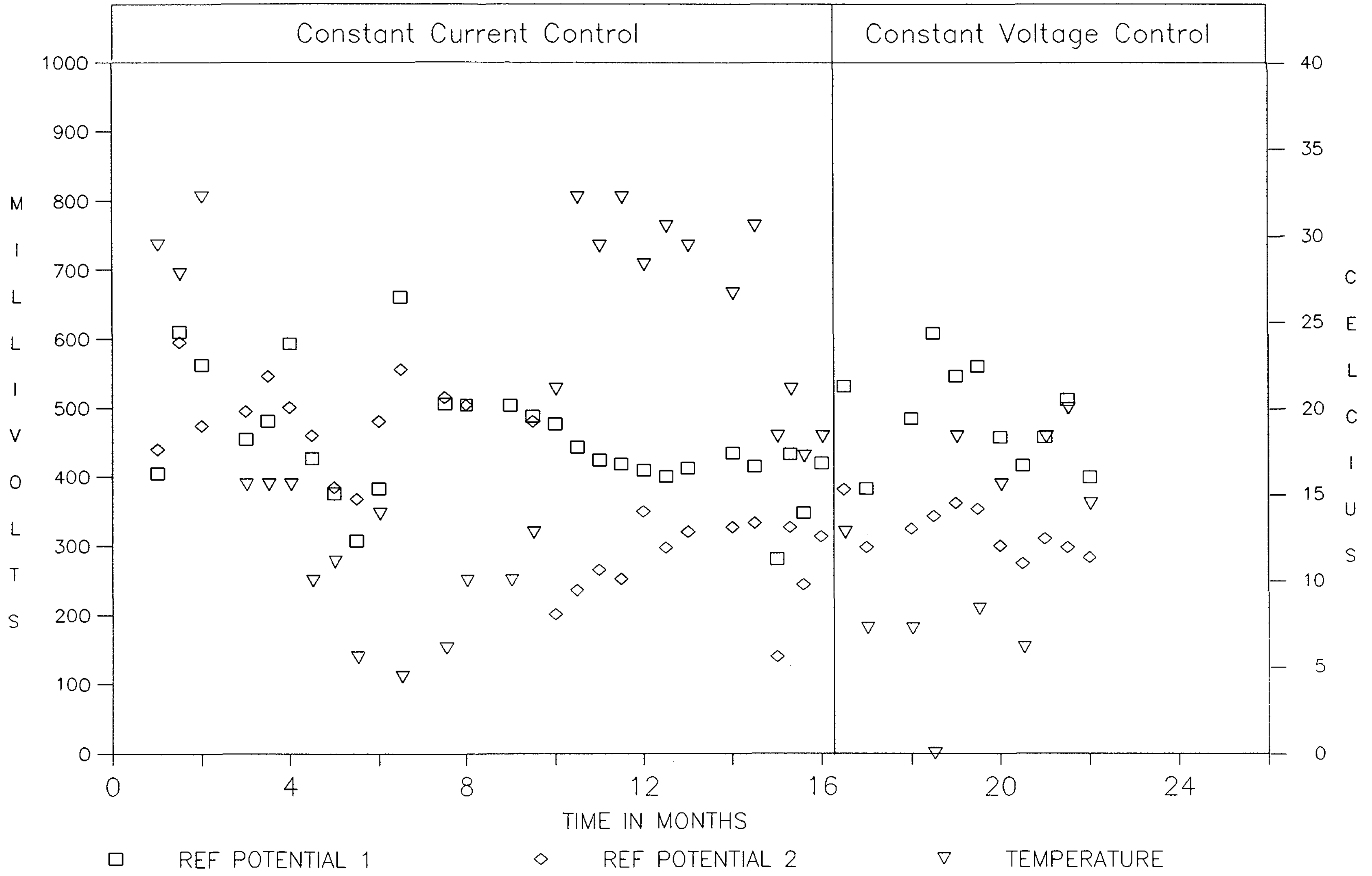


Figure 10. Instant off reference cell potential and ambient temperature monitor data for Zone 1, marine environment bridge, Norfolk, Virginia.



Zone 2: Zinc Spray CP System, East Pier

Figure 11. Instant off reference cell potential and ambient temperature monitor data for Zone 2, marine environment bridge, Norfolk, Virginia.

ZONE 3: Conductive Polymer, Spray CP System, West Pier

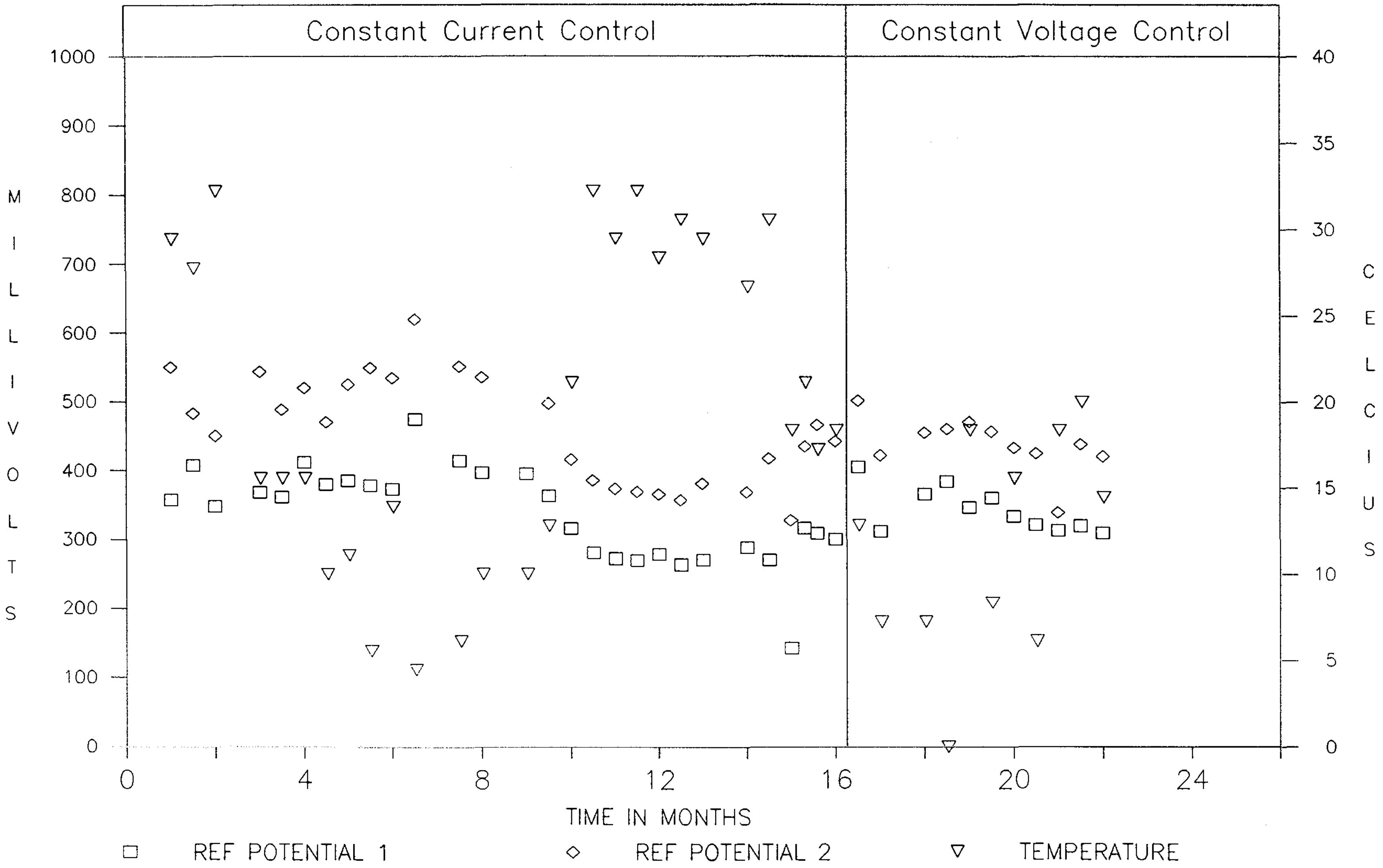


Figure 12. Instant off reference cell potential and ambient temperature monitor data for Zone 3, marine environment bridge, Norfolk, Virginia.

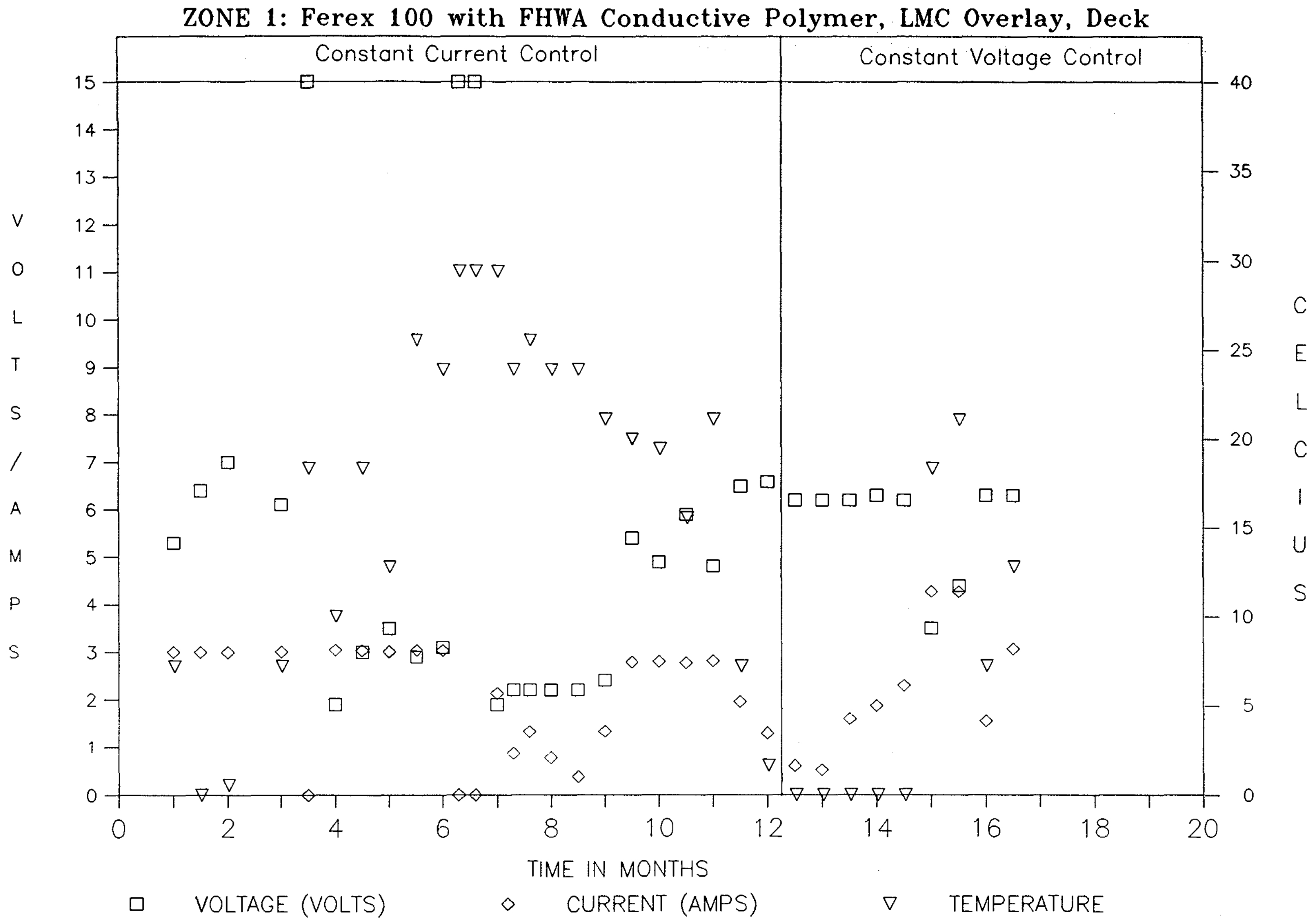


Figure 13. System voltage, current and temperature monitor data for Zone 1, northern climate environment, Cincinnati, Ohio.

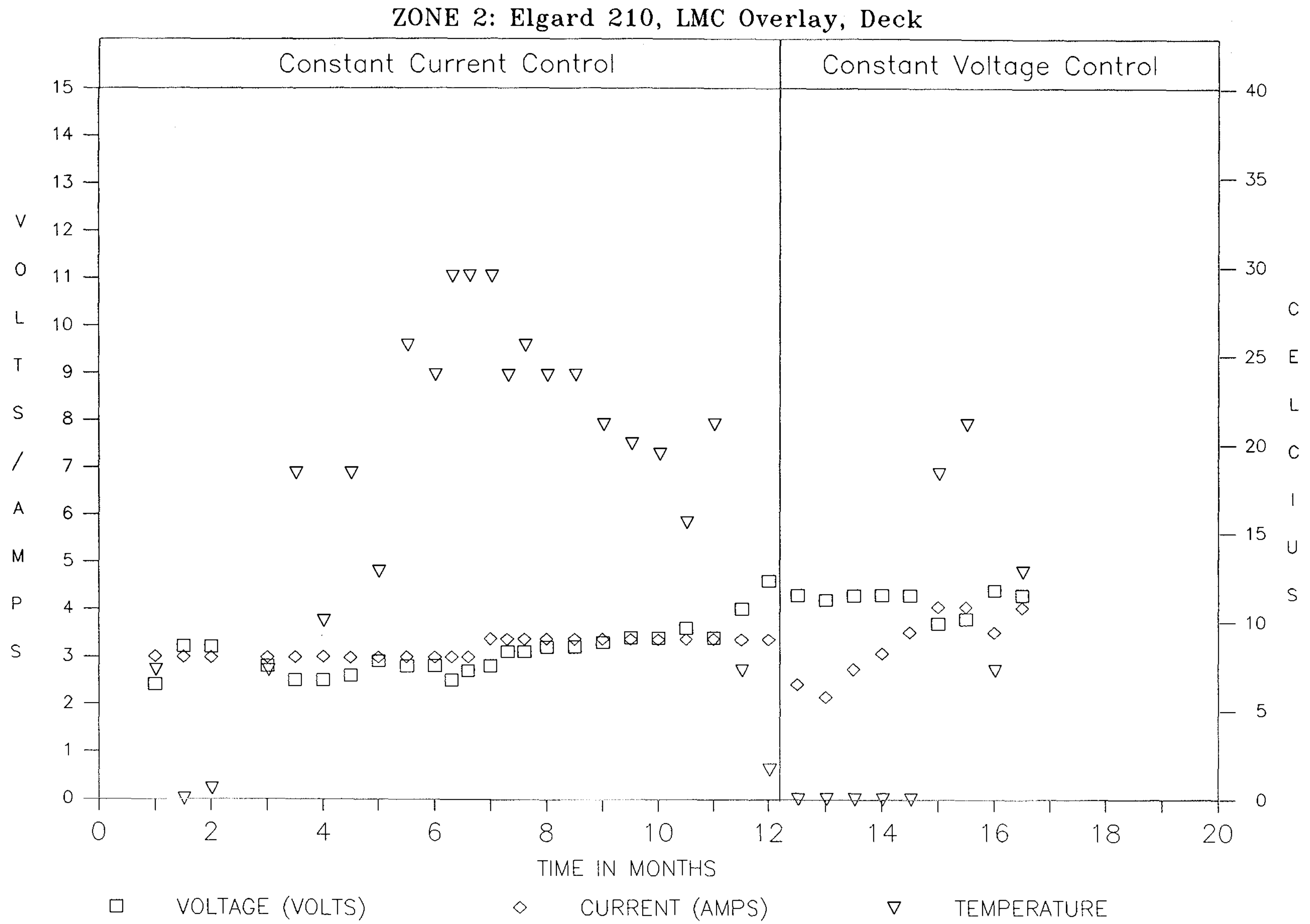


Figure 14. System voltage, current and temperature monitor data for Zone 2, northern climate environment, Cincinnati, Ohio.

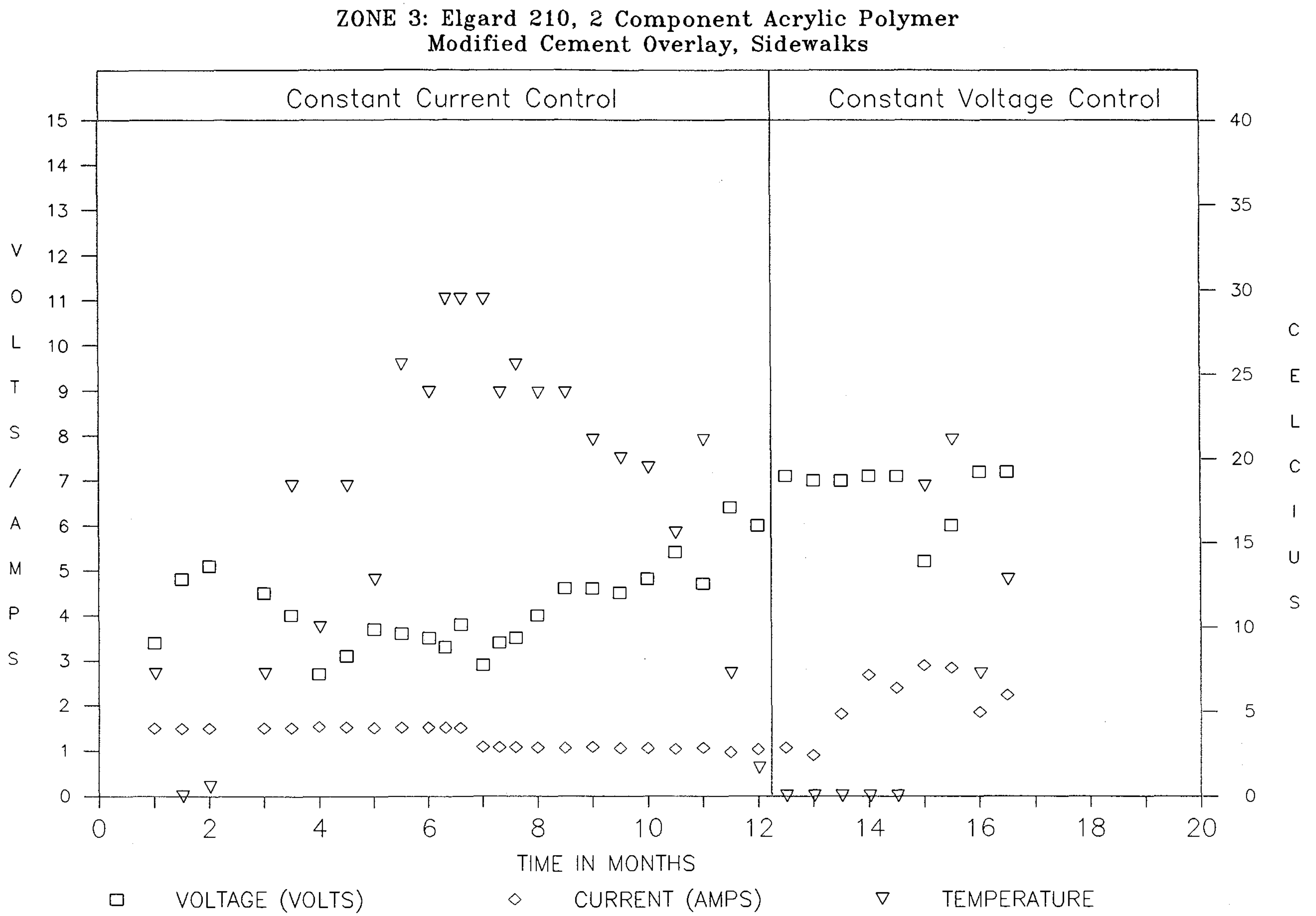


Figure 15. System voltage, current and temperature monitor data for Zone 3, northern climate environment, Cincinnati, Ohio.

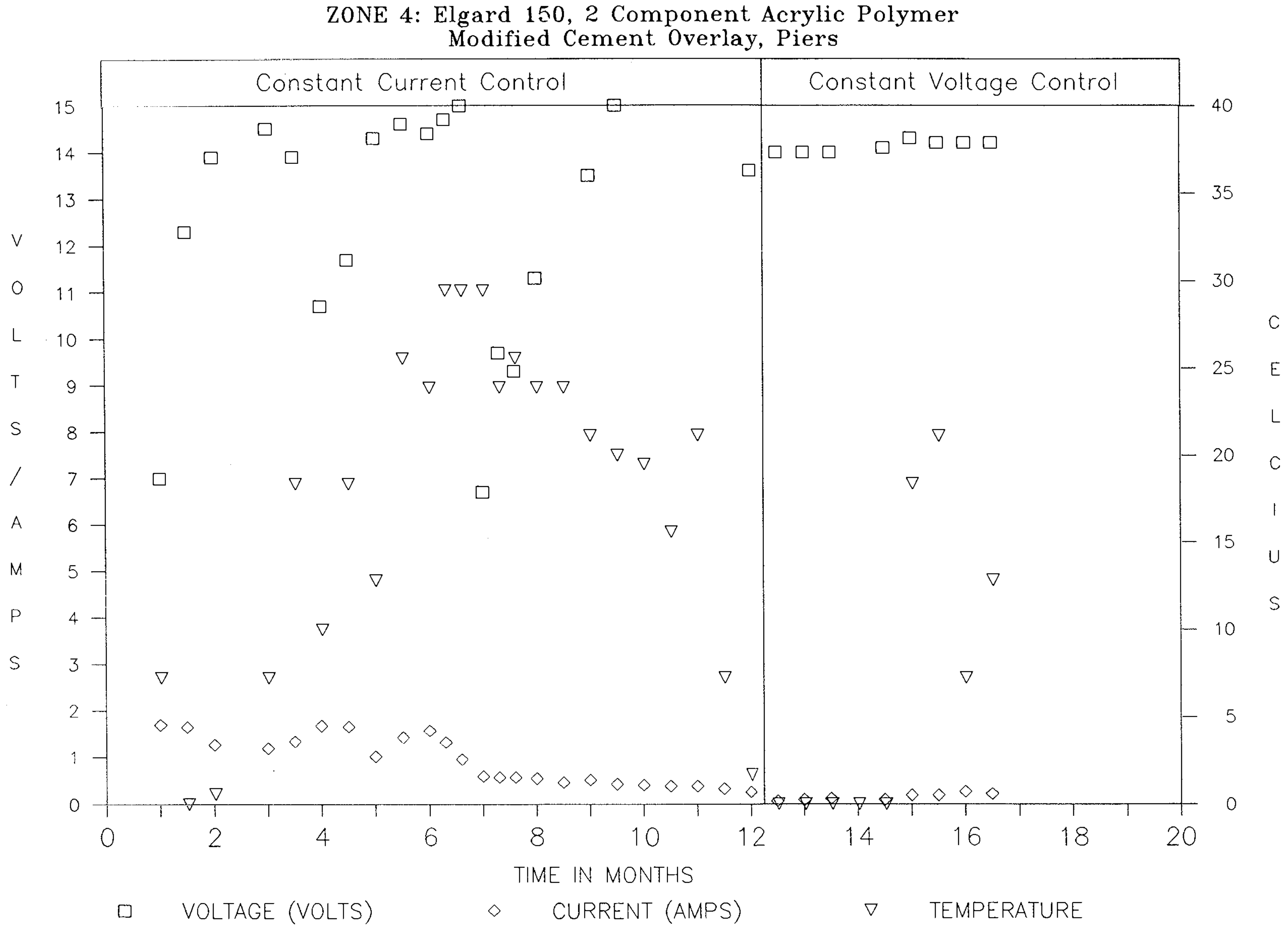


Figure 16. System voltage, current and temperature monitor data for Zone 4, northern climate environment, Cincinnati, Ohio.

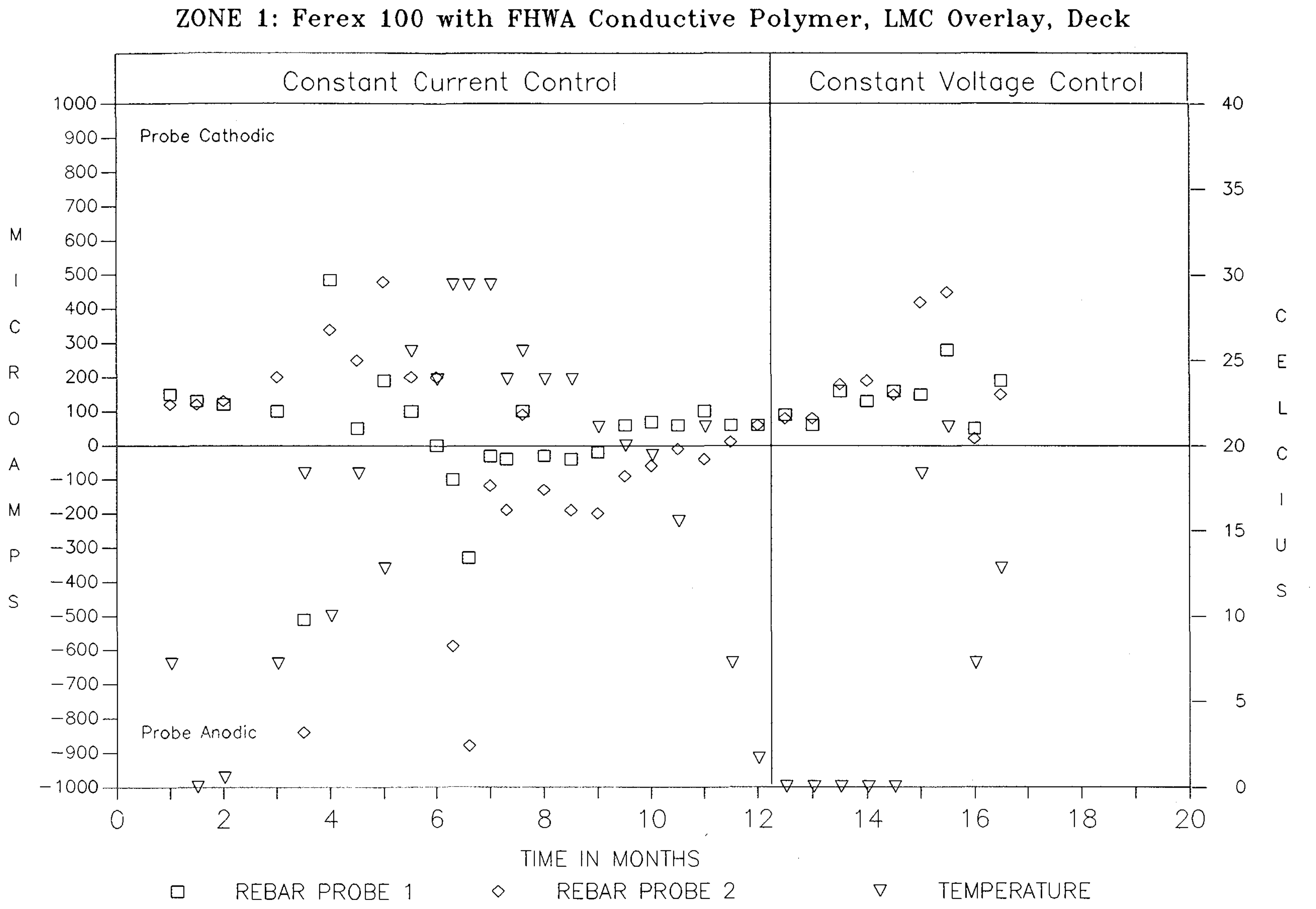

ZONE 1: Ferex 100 with FHWA Conductive Polymer, LMC Overlay, Deck

Figure 17. Rebar probe current and ambient temperature monitor data for Zone 1, northern climate environment, Cincinnati, Ohio.

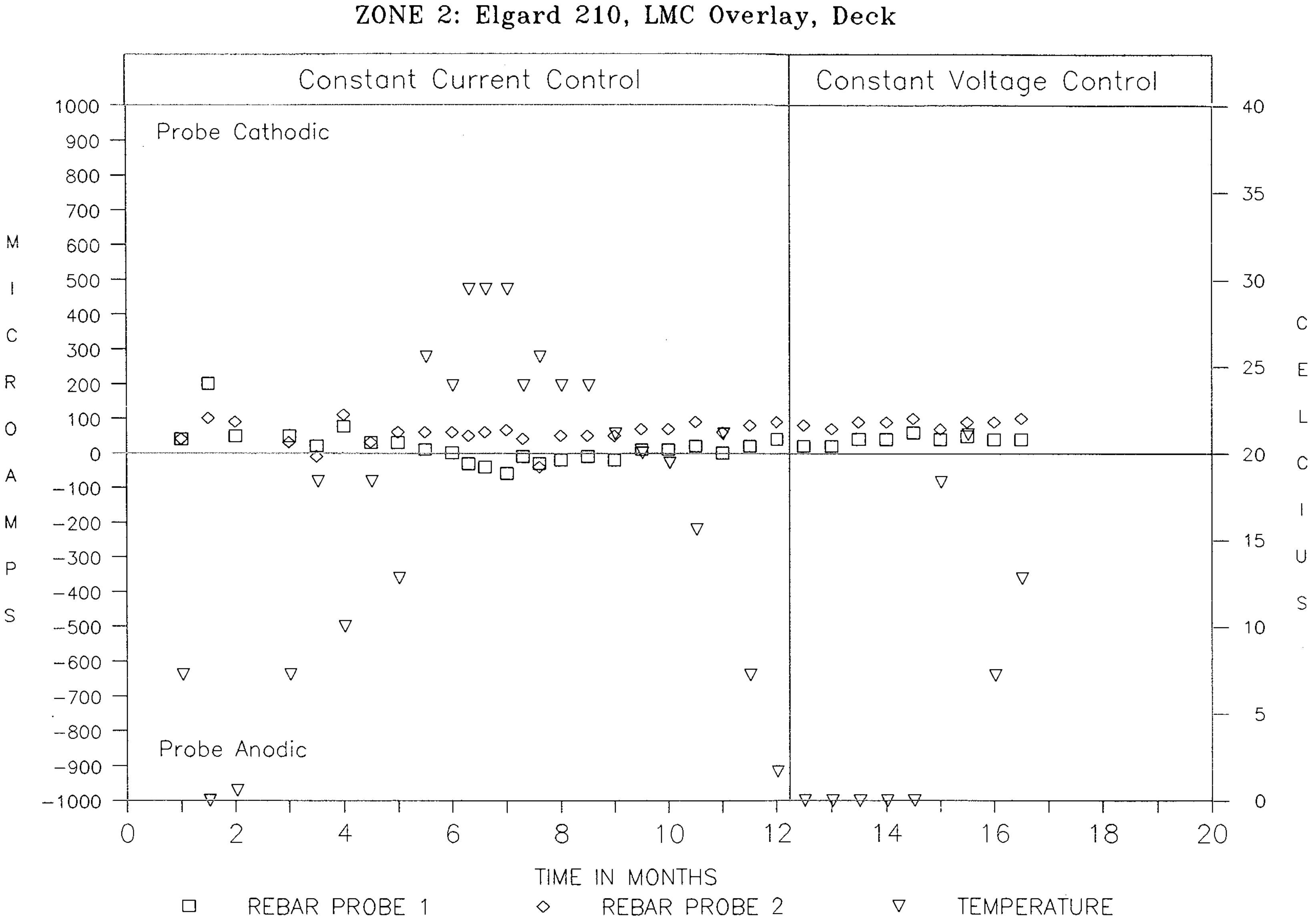


Figure 18. Rebar probe current and ambient temperature monitor data for Zone 2, northern climate environment, Cincinnati, Ohio.

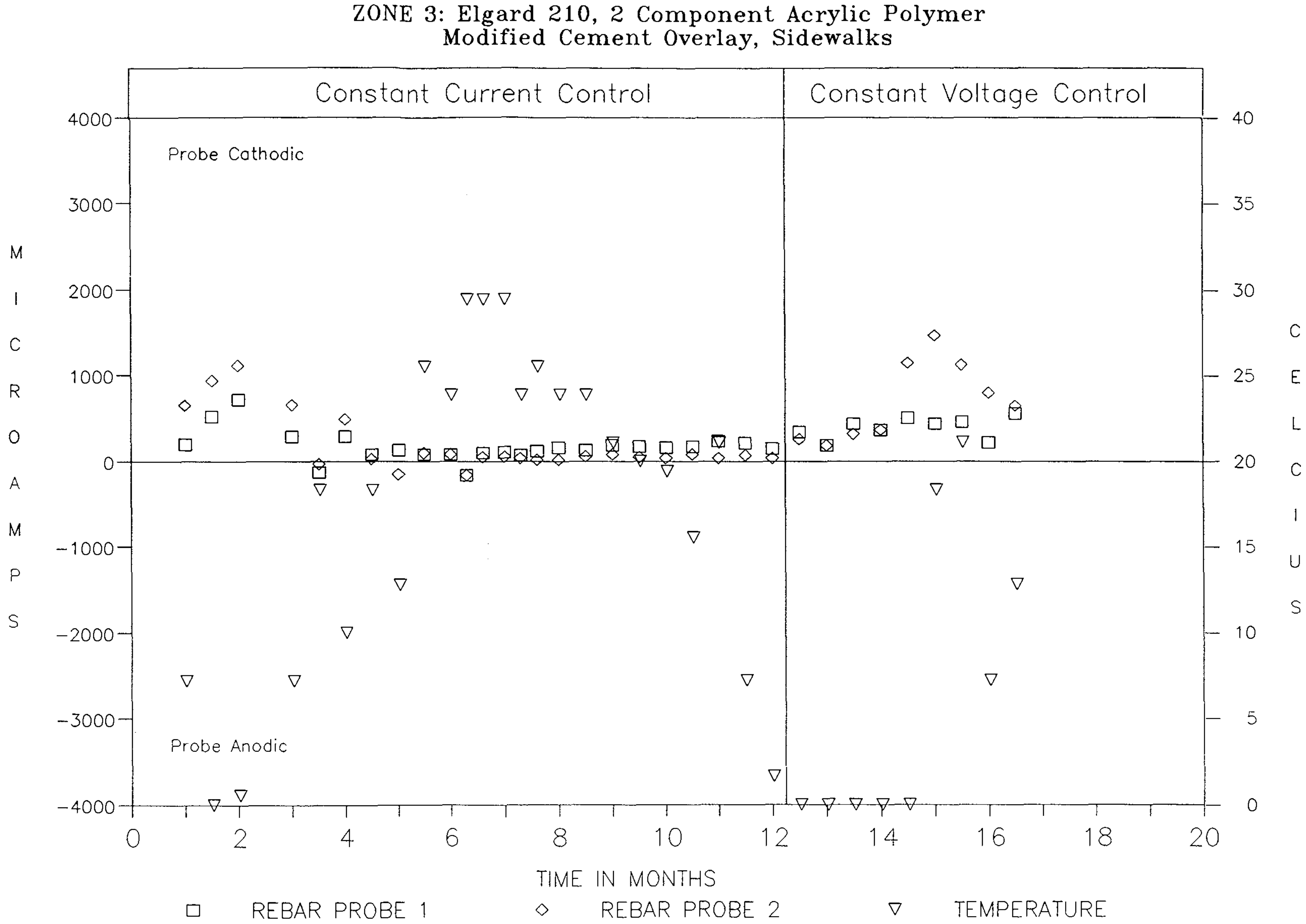


Figure 19. Rebar probe current and ambient temperature monitor data for Zone 3, northern climate environment, Cincinnati, Ohio.

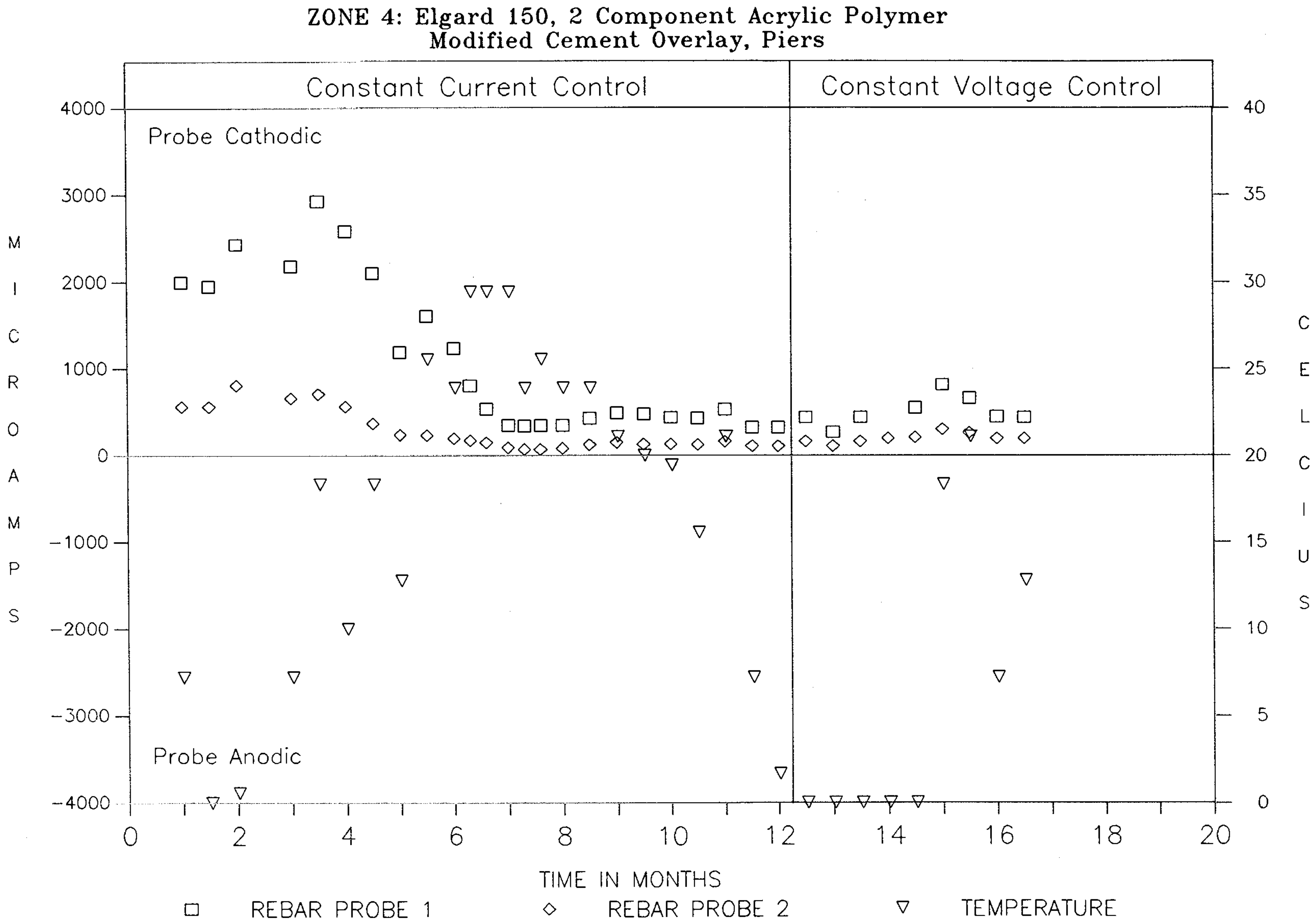


Figure 20. Rebar probe current and ambient temperature monitor data for Zone 4, northern climate environment, Cincinnati, Ohio.

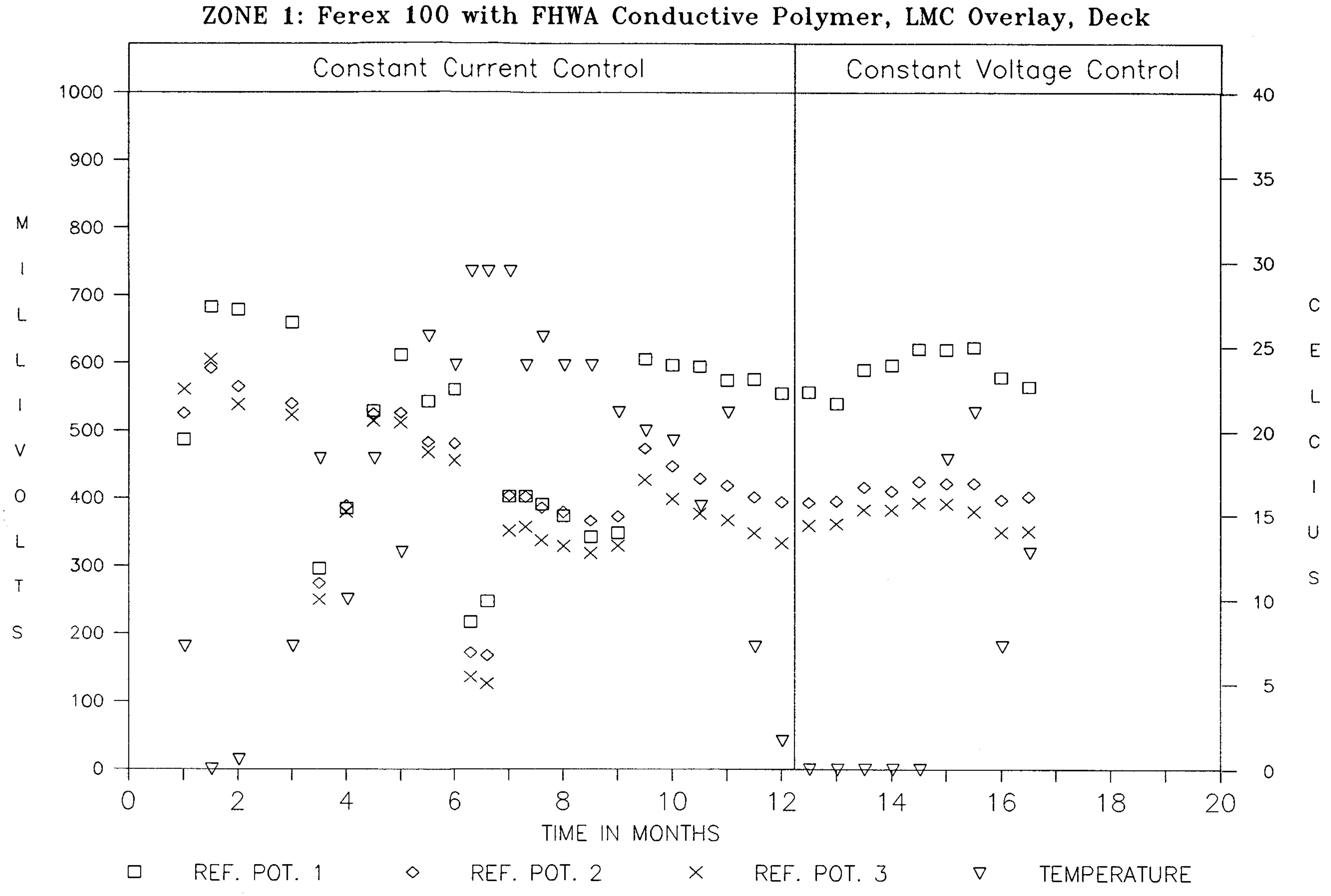


Figure 21. Instant off reference cell potential and ambient temperature monitor data for Zone 1, northern climate environment, Cincinnati, Ohio.

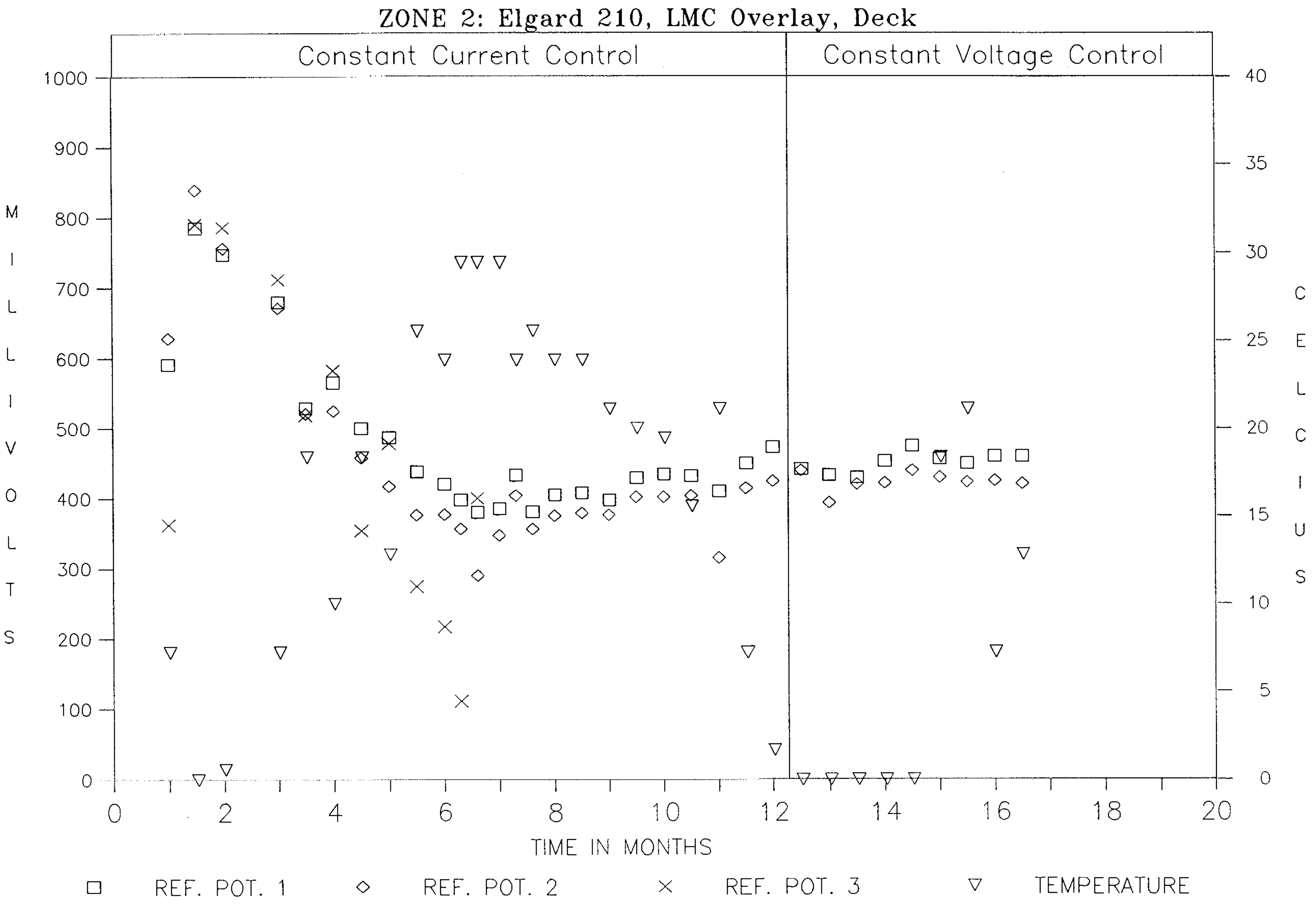


Figure 22. Instant off reference cell potential and ambient temperature monitor data for Zone 2, northern climate environment, Cincinnati, Ohio.

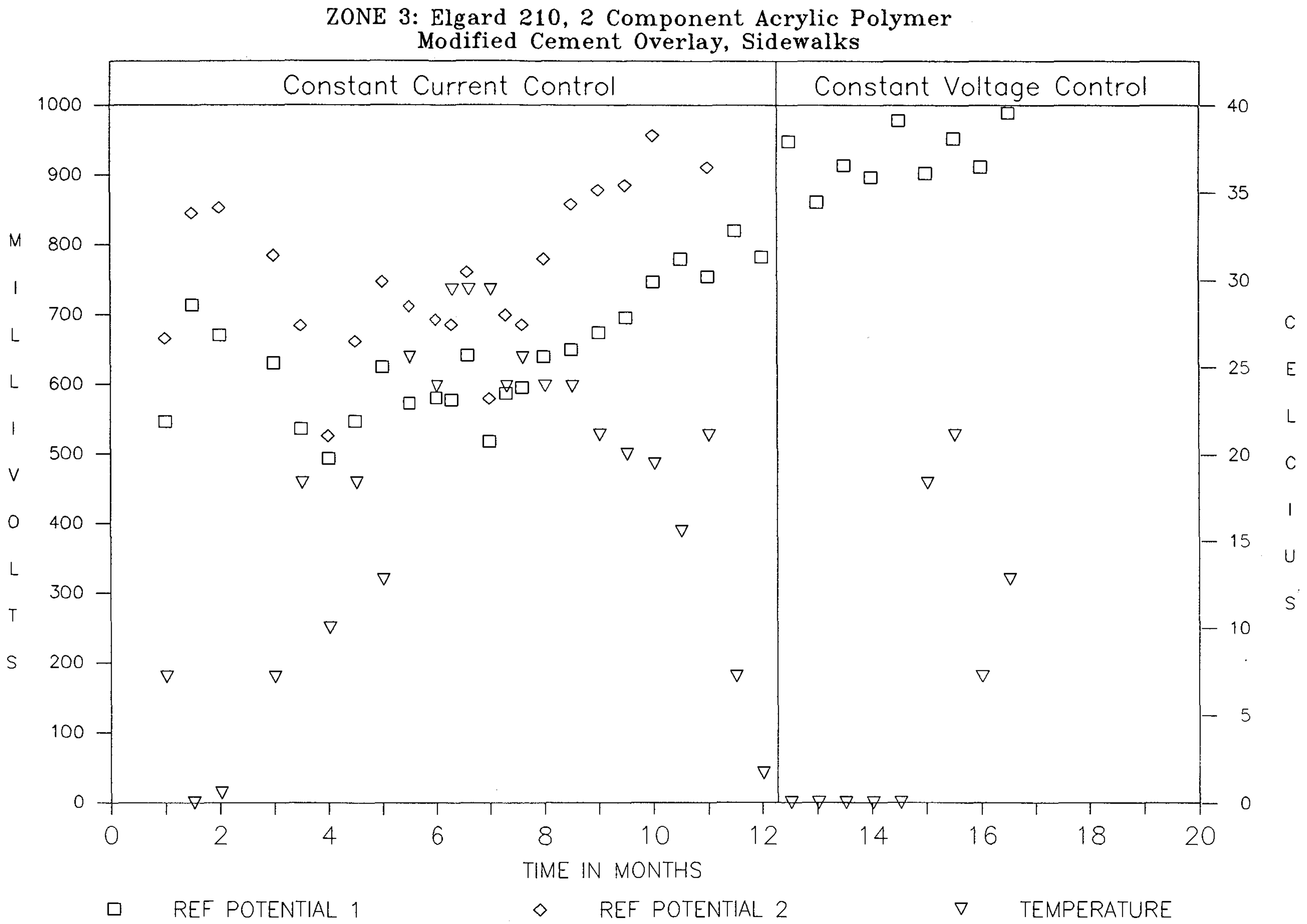


Figure 23. Instant off reference cell potential and ambient temperature monitor data for Zone 3, northern climate environment, Cincinnati, Ohio.

ZONE 4: Elgard 150, 2 Component Acrylic Polymer
Modified Cement Overlay, Piers

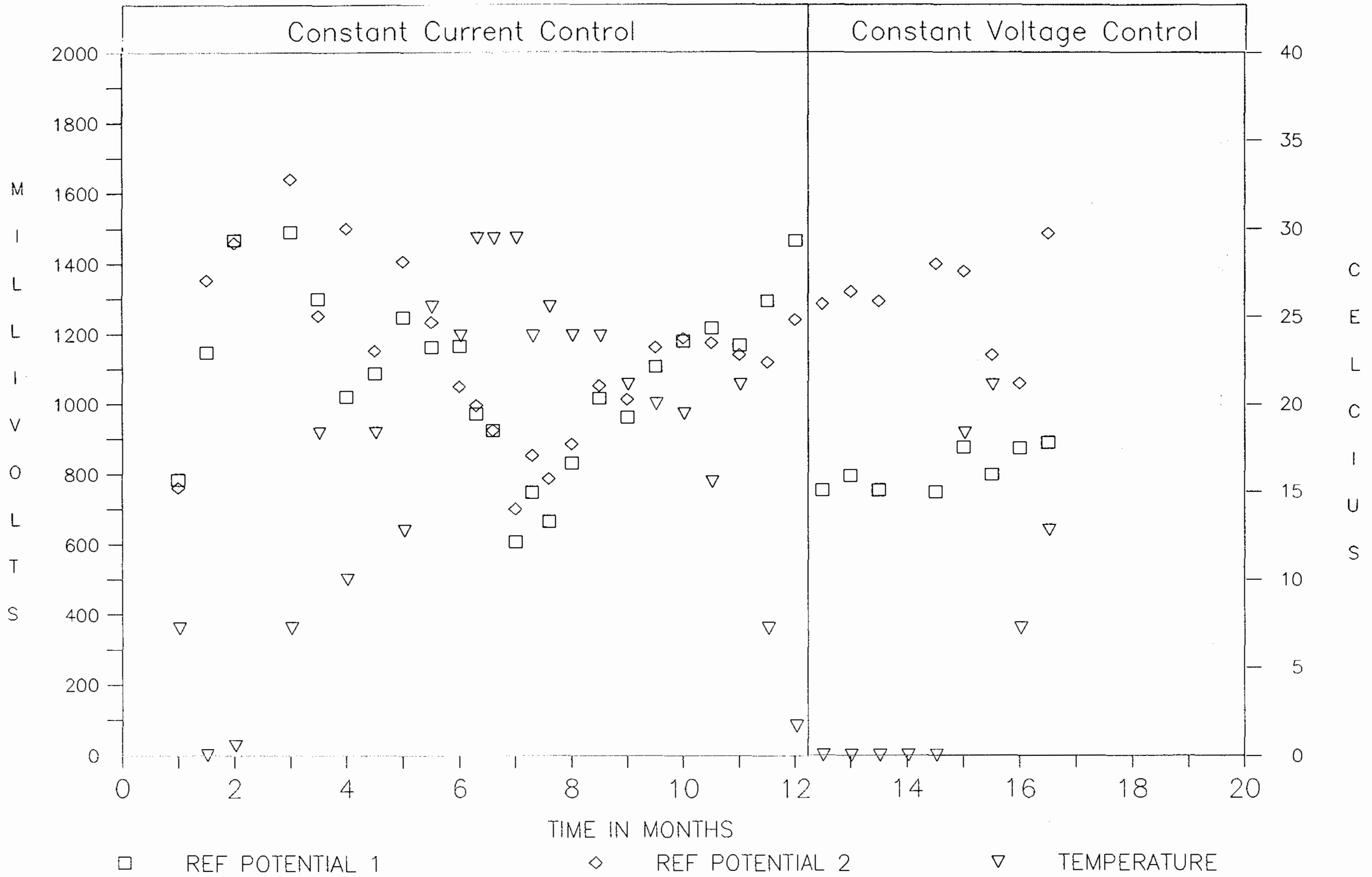


Figure 24. Instant off reference cell potential and ambient temperature monitor data for Zone 4, northern climate environment, Cincinnati, Ohio.

APPENDIX B

CATHODIC PROTECTION DEPOLARIZATION GRAPHS

Reference cell depolarization potential obtained at four different evaluation periods on three cathodic protection systems on a marine environment bridge and four cathodic protection systems on a northern climate bridge.

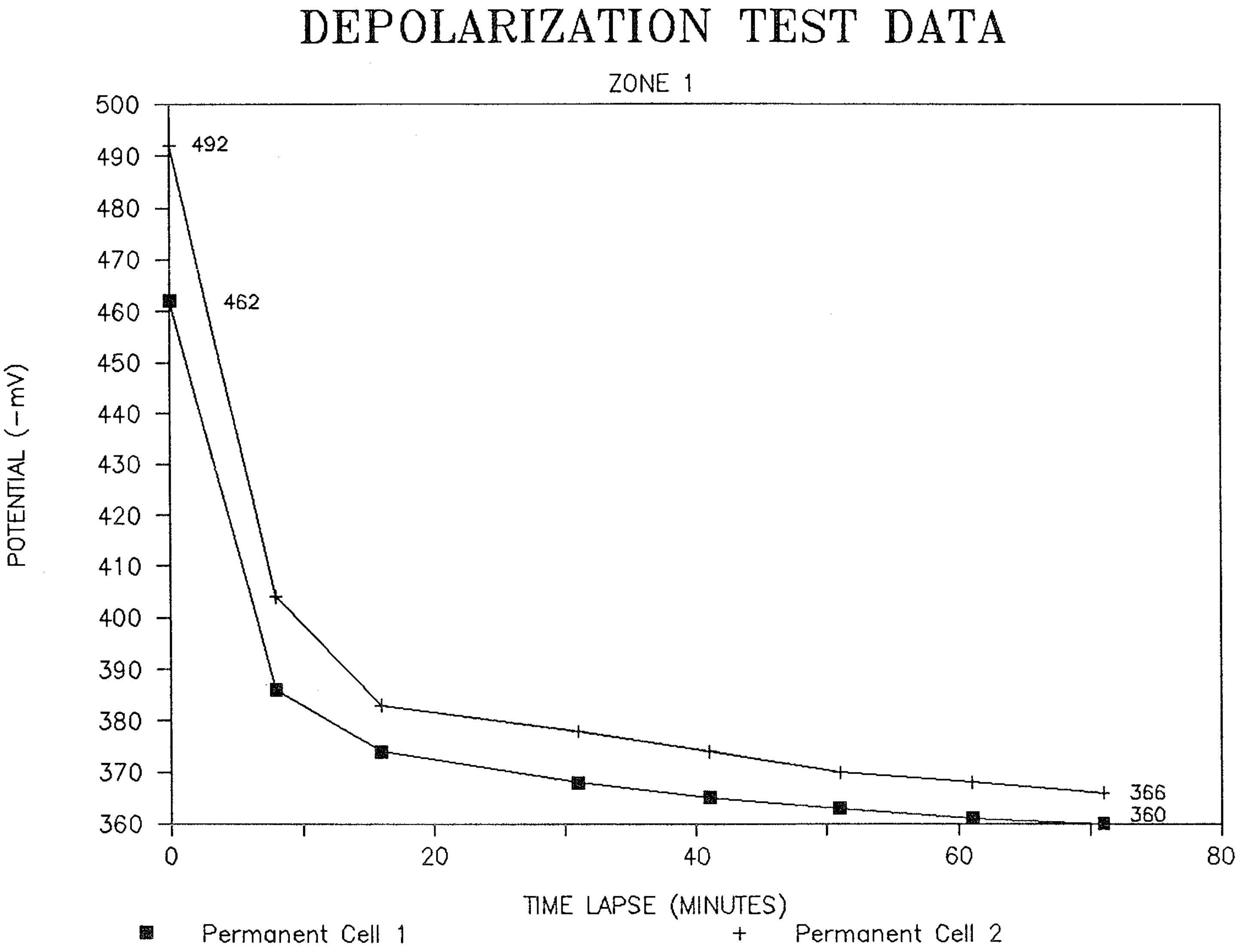


Figure 25. Depolarization test data on Zone 1 at initial evaluation, marine environment bridge, Norfolk, Virginia.

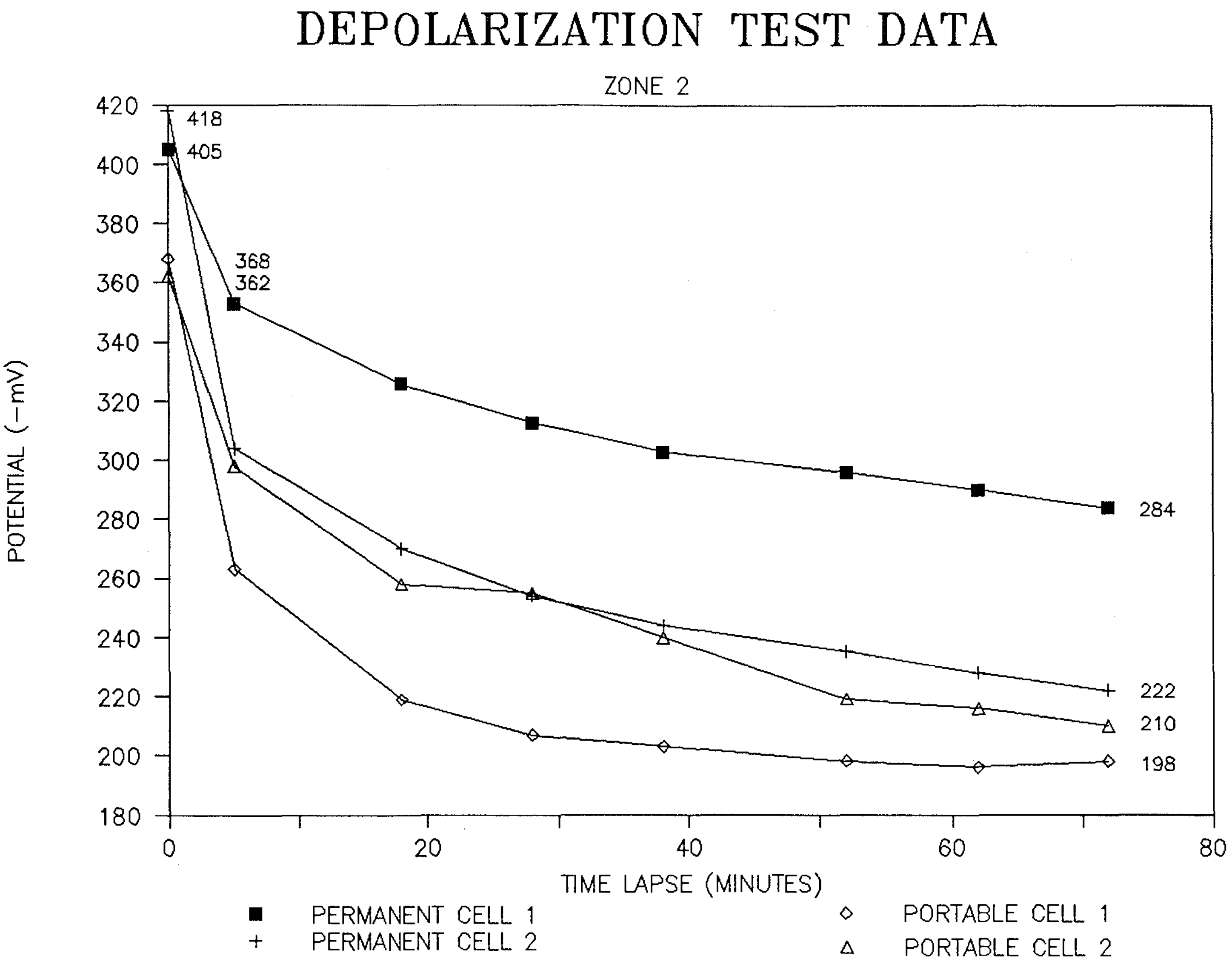


Figure 26. Depolarization test data on Zone 2 at initial evaluation, marine environment bridge, Norfolk, Virginia.

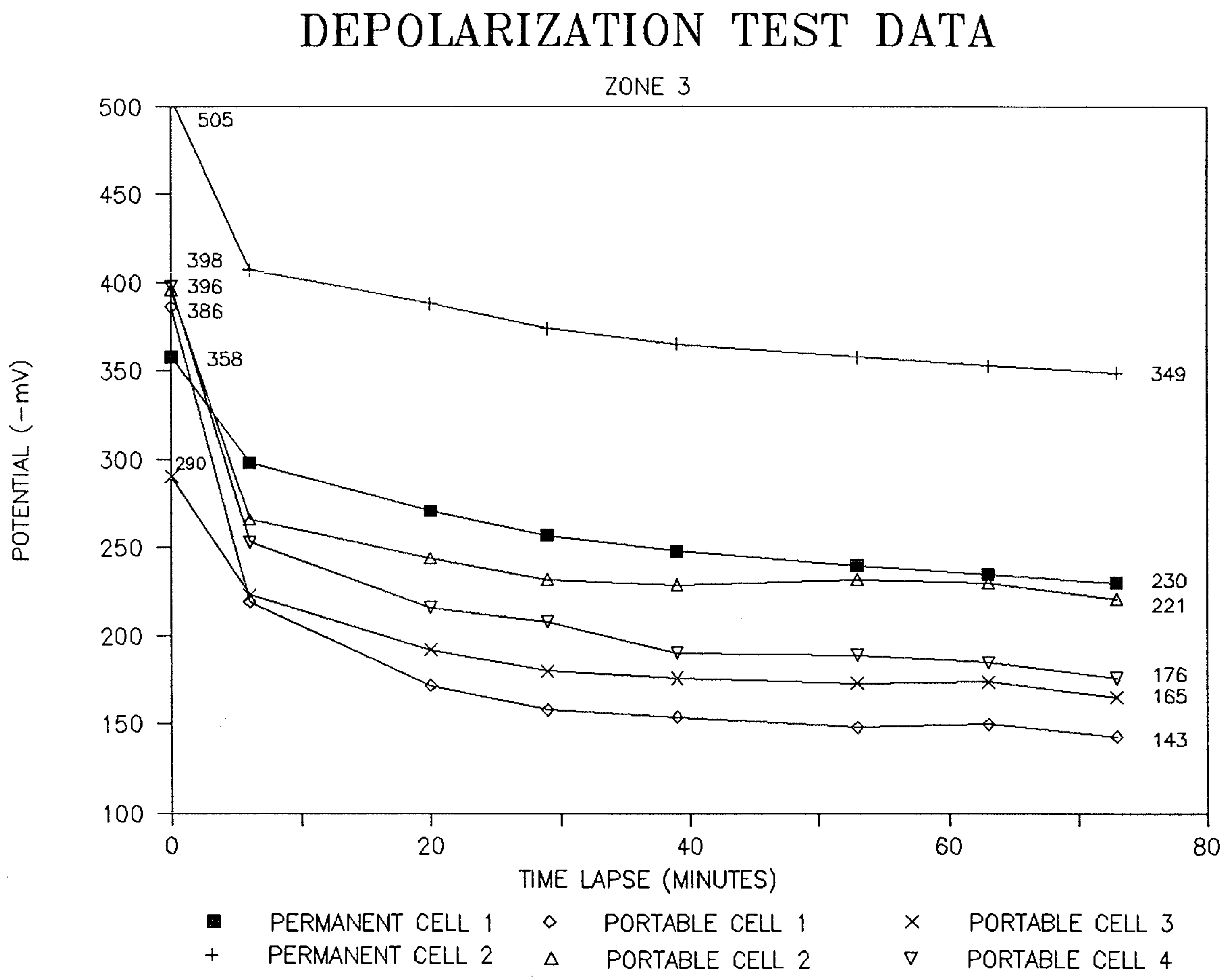


Figure 27. Depolarization test data on Zone 3 at initial evaluation, marine environment bridge, Norfolk, Virginia.

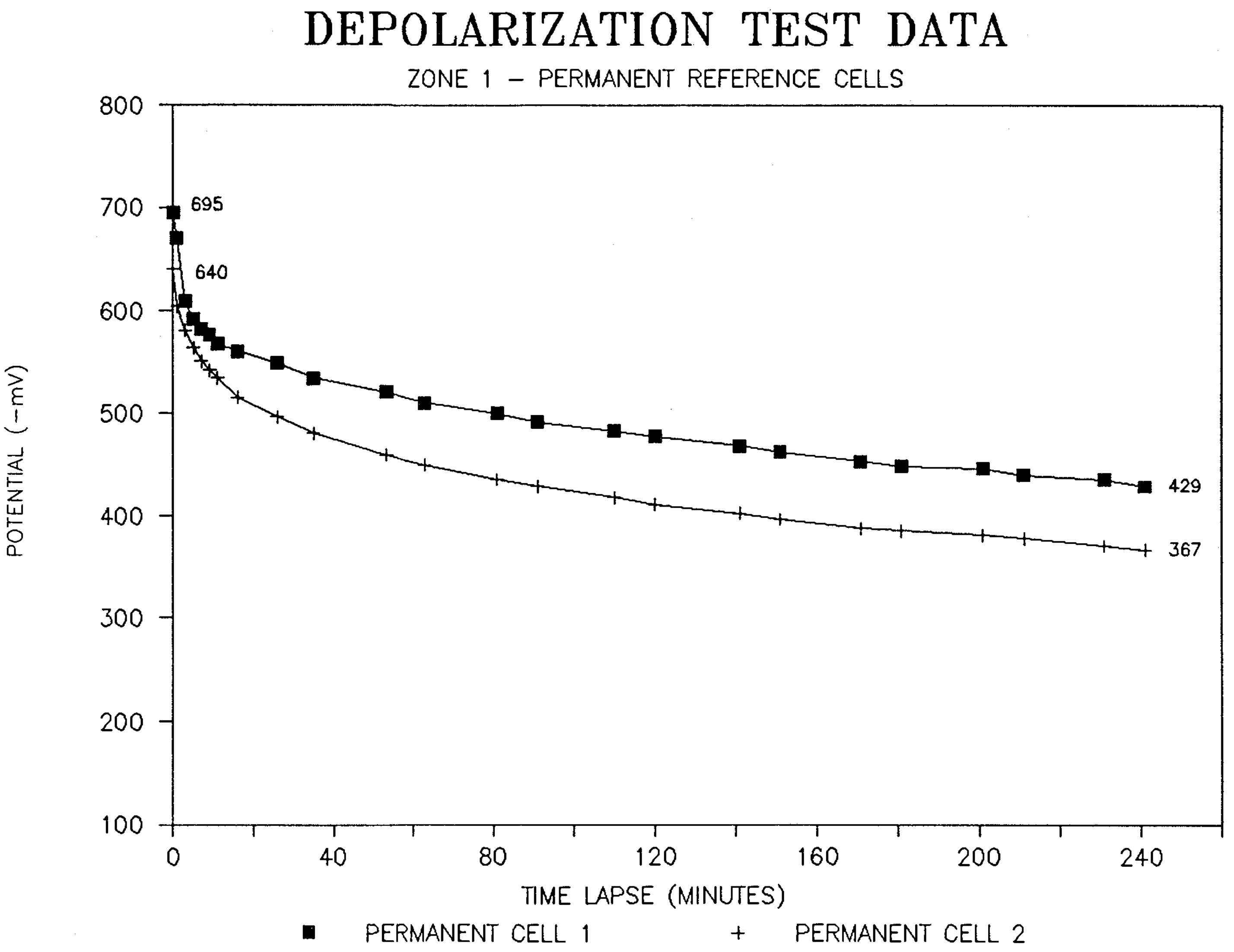


Figure 28. Depolarization test data on Zone 1 (permanent cells) at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

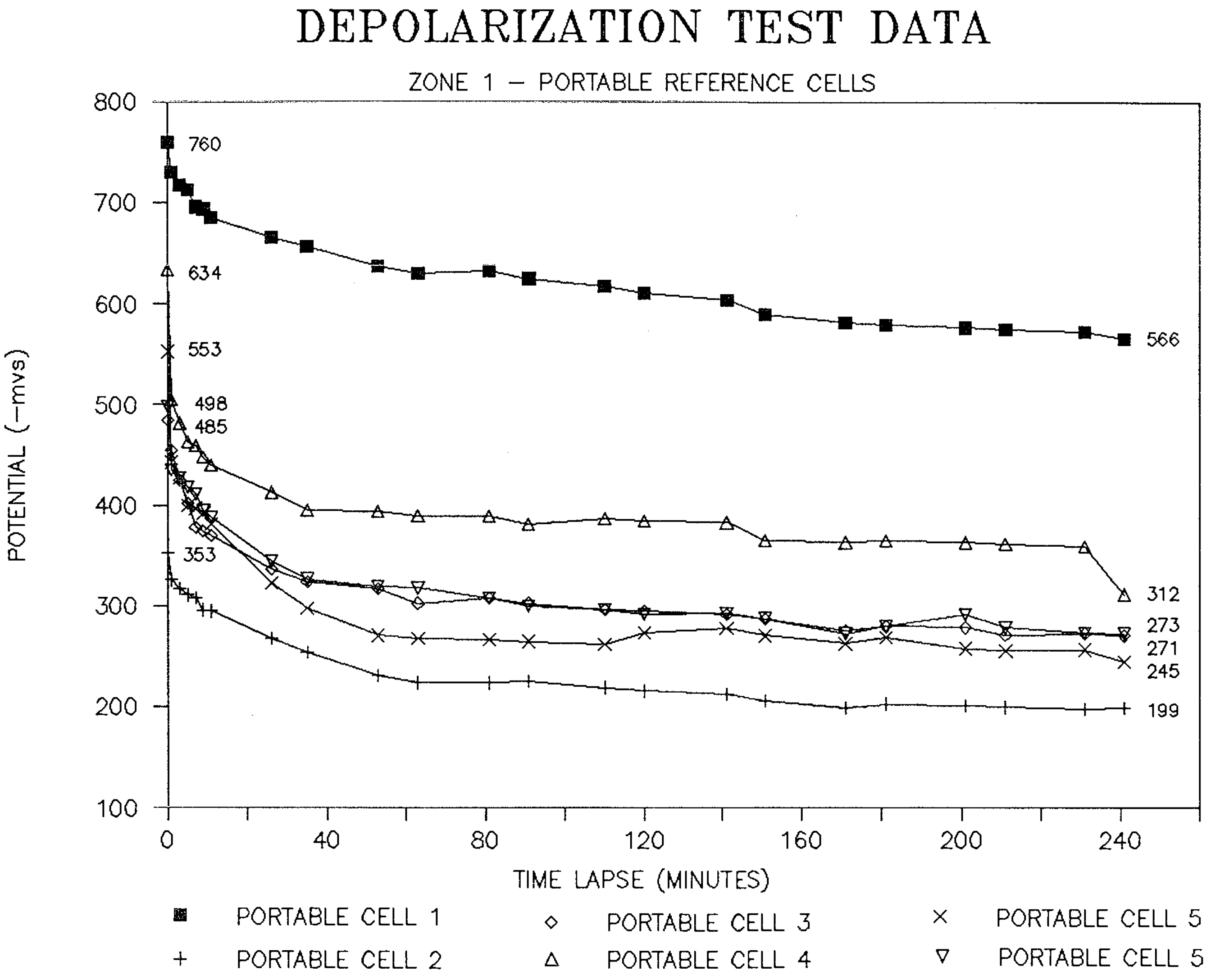


Figure 29. Depolarization test data on Zone 1 (portable cells) at 9-month evaluation, marine environment bridge, Norfolk, Virgina.

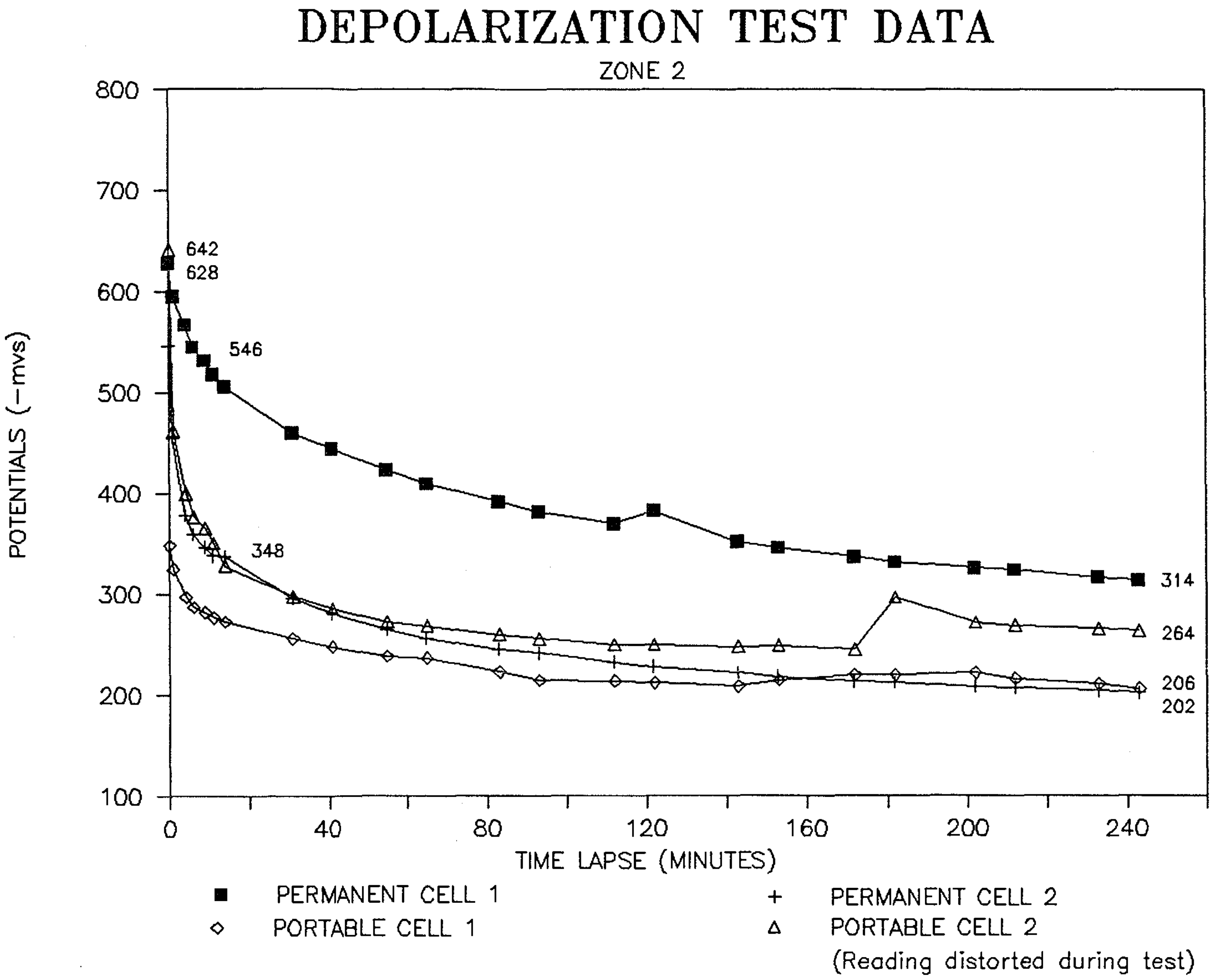


Figure 30. Depolarization test data on Zone 2 at 9-month evaluation, marine environment bridge, Norfolk, Virgina.

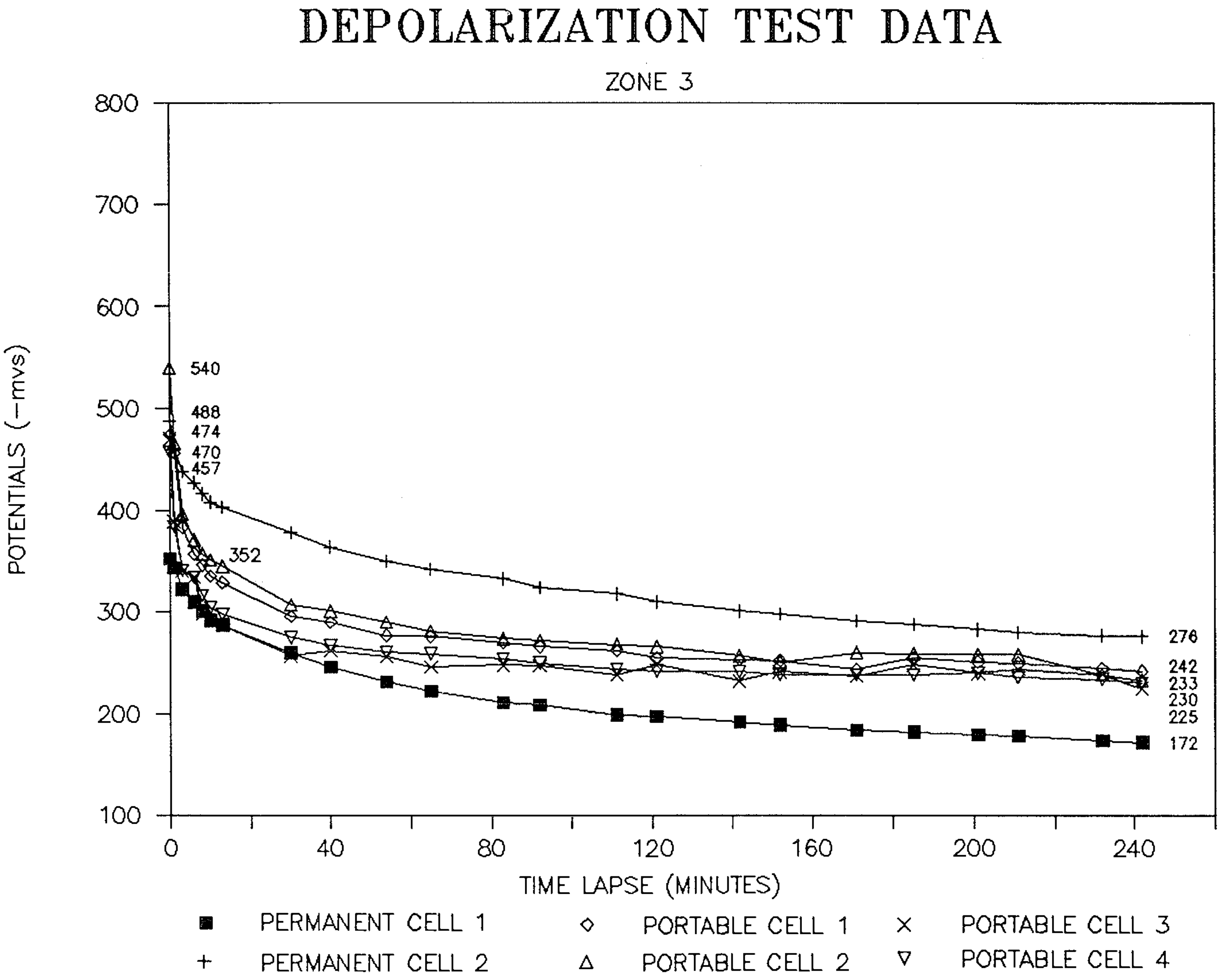


Figure 31. Depolarization test data on Zone 3 at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

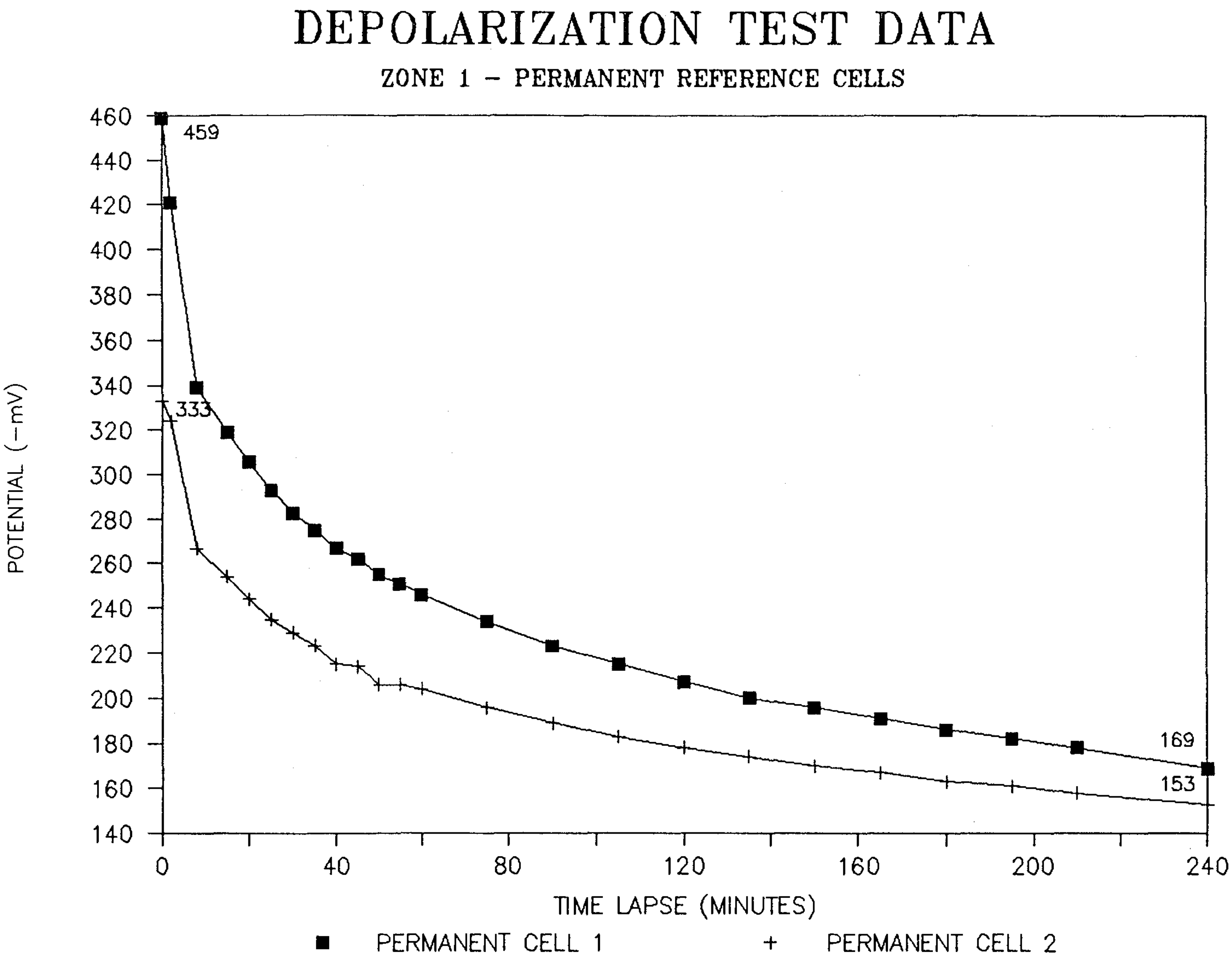


Figure 32. Depolarization test data on Zone 1 (permanent cells) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

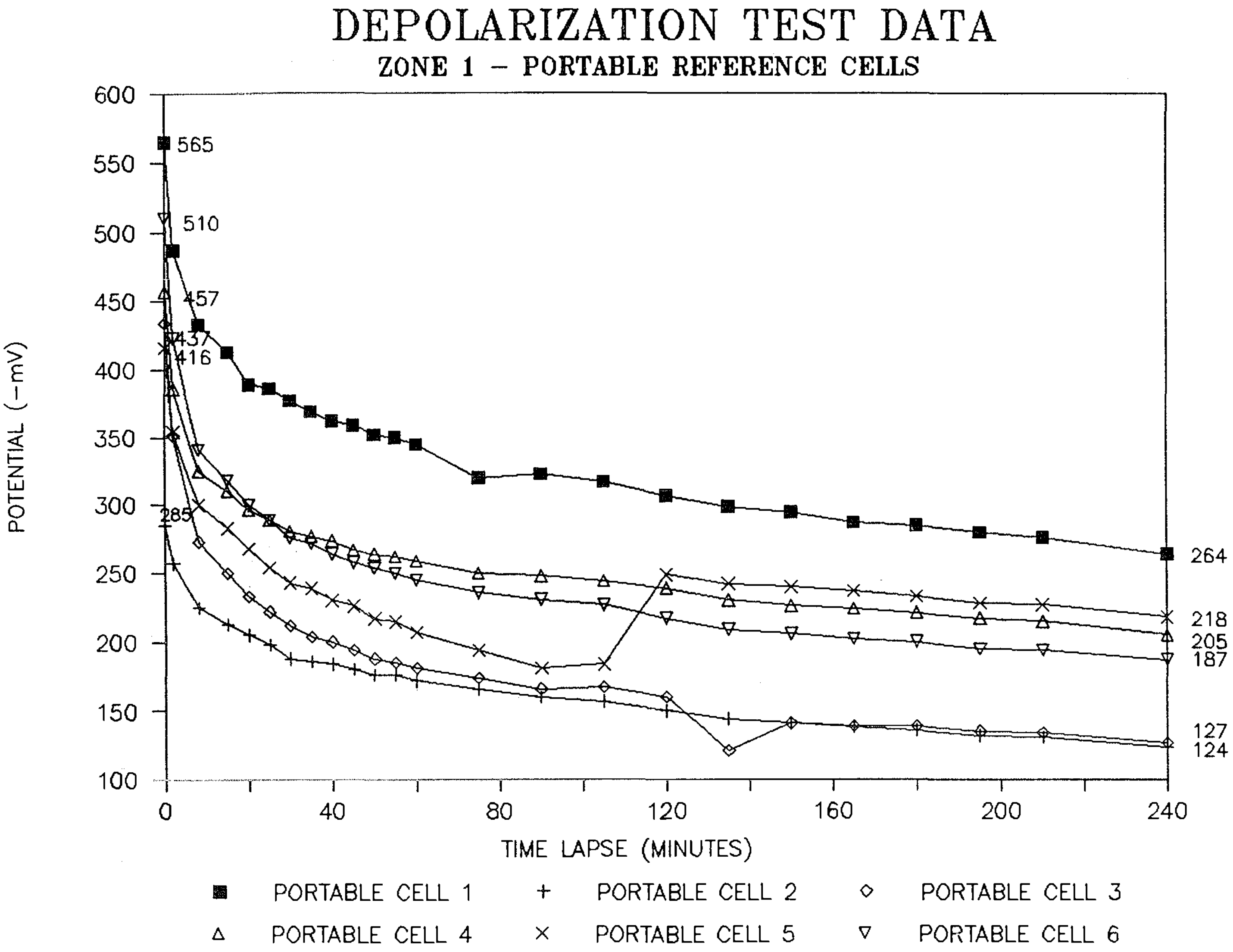


Figure 33. Depolarization test data on Zone 1 (portable cells) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

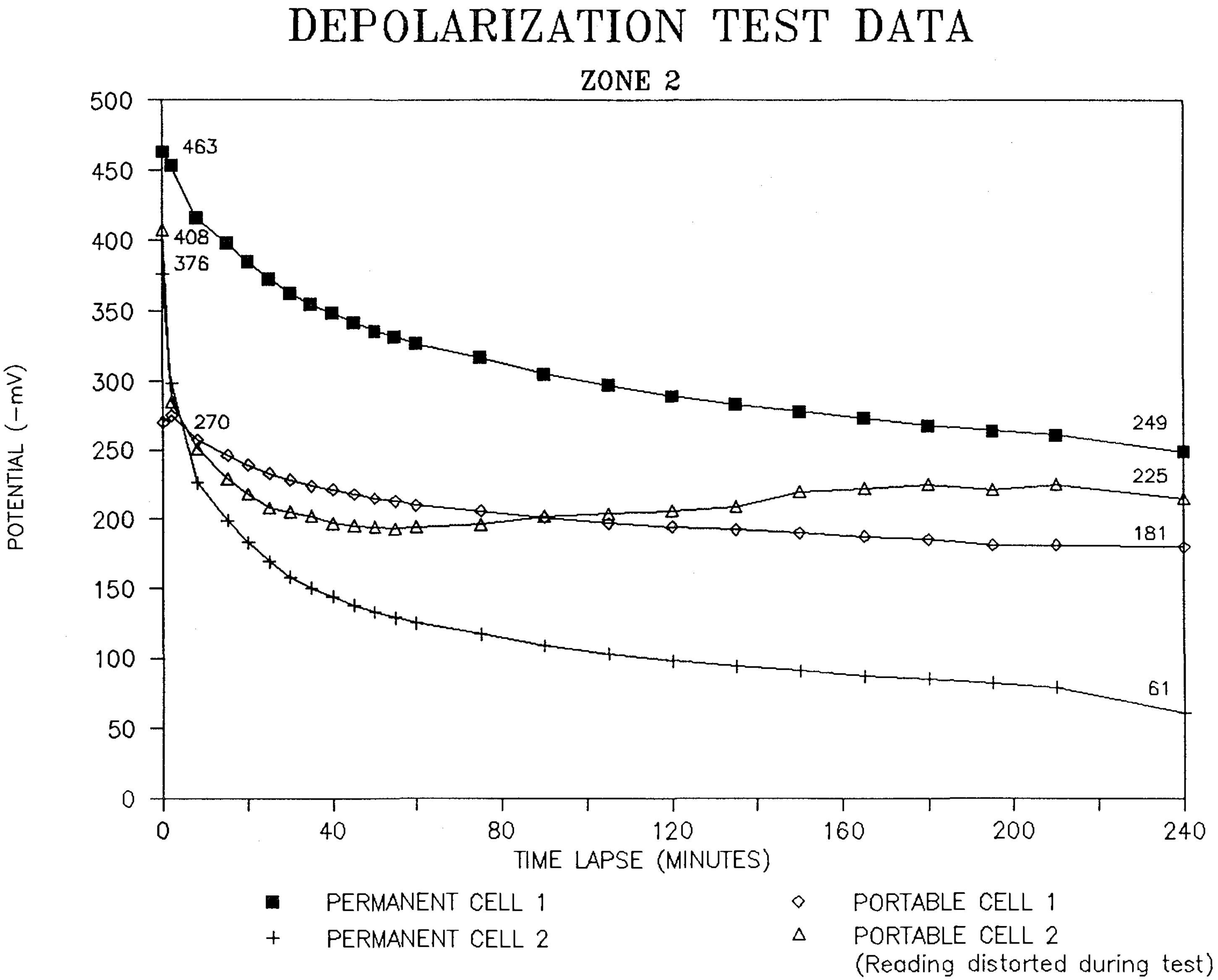


Figure 34. Depolarization test data on Zone 2 at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

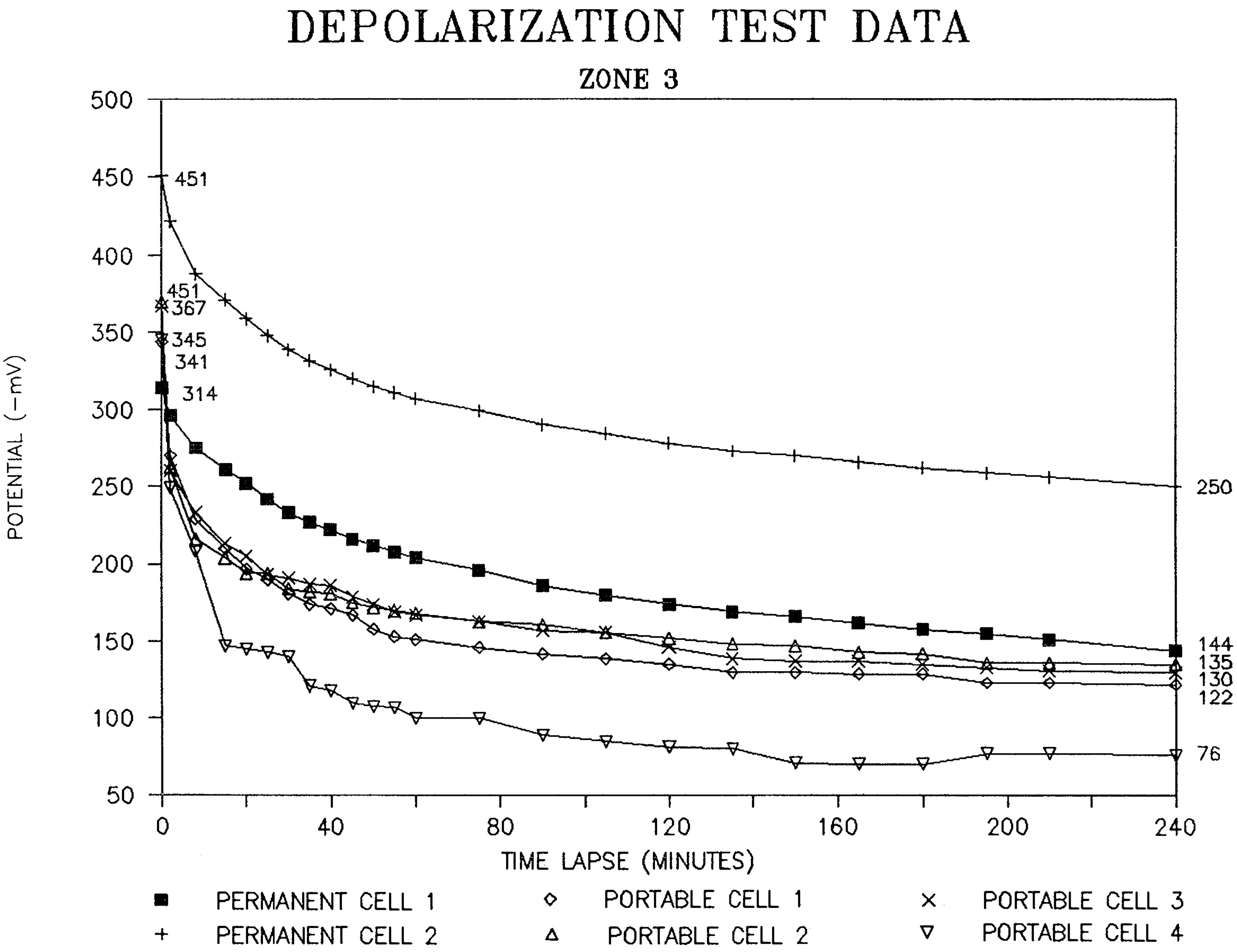


Figure 35. Depolarization test data on Zone 3 at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

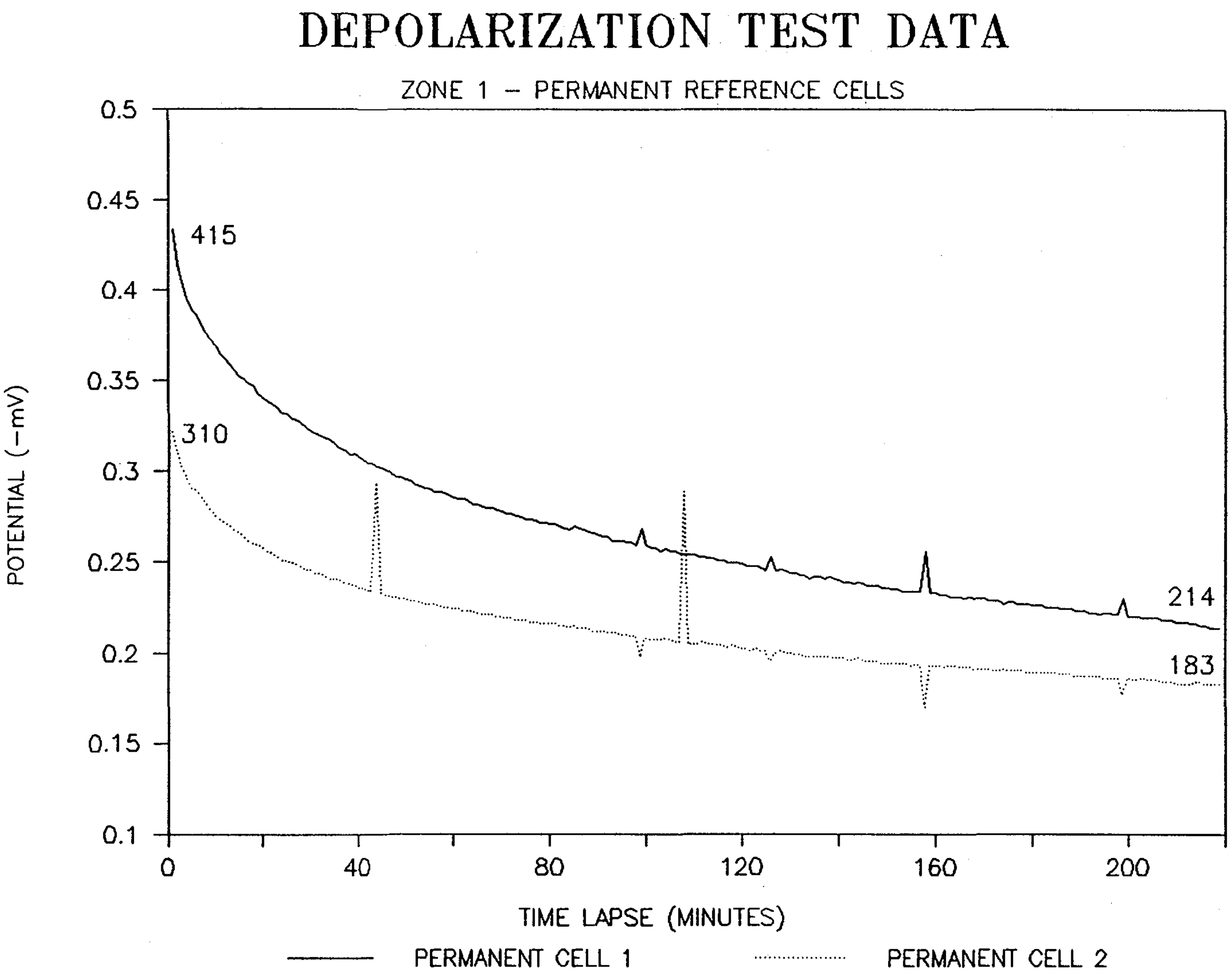


Figure 36. Depolarization test data on Zone 1 (permanent cells) at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

Reproduced from best available copy.

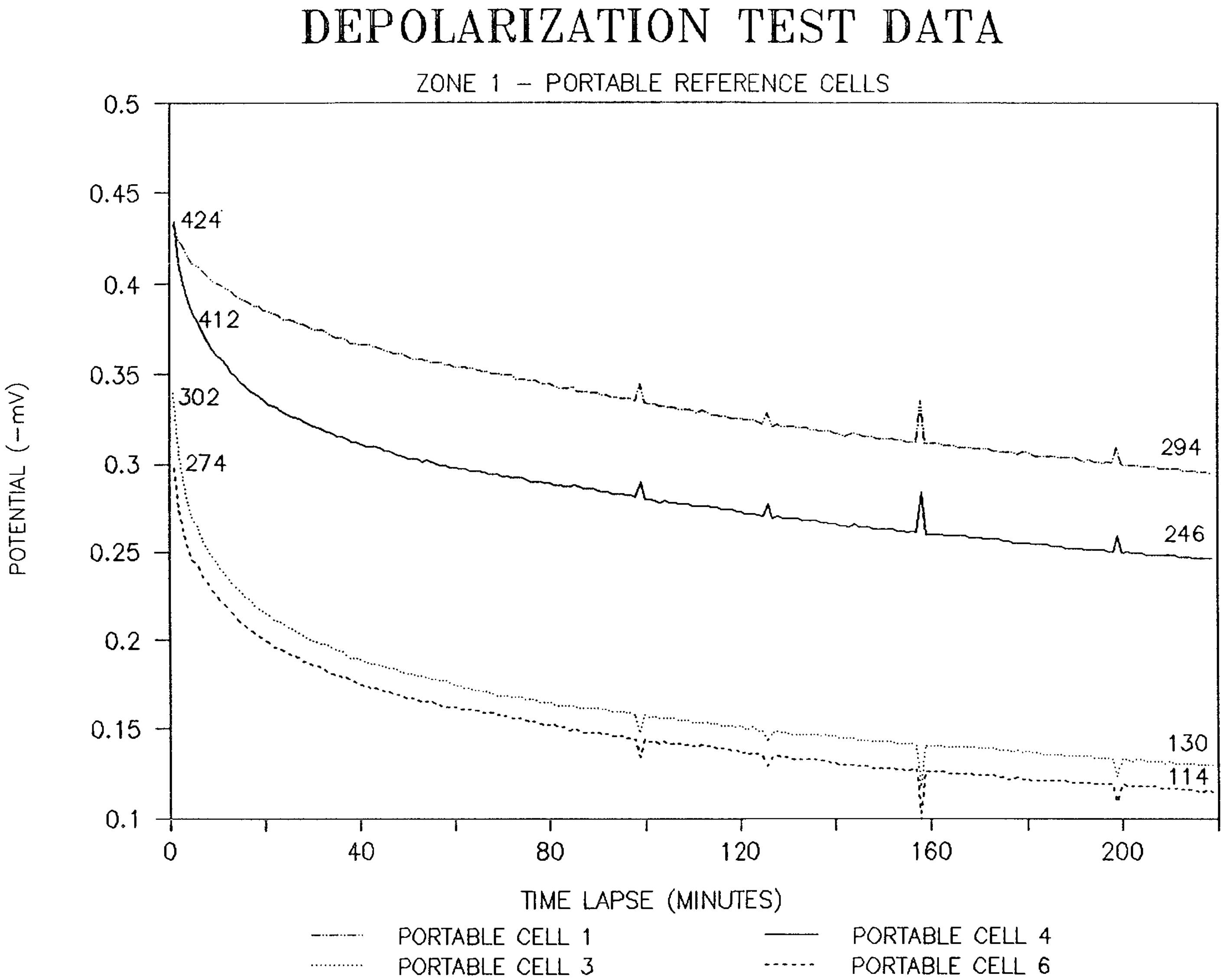


Figure 37. Depolarization test data on Zone 1 (portable cells) at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

Reproduced from best available copy.

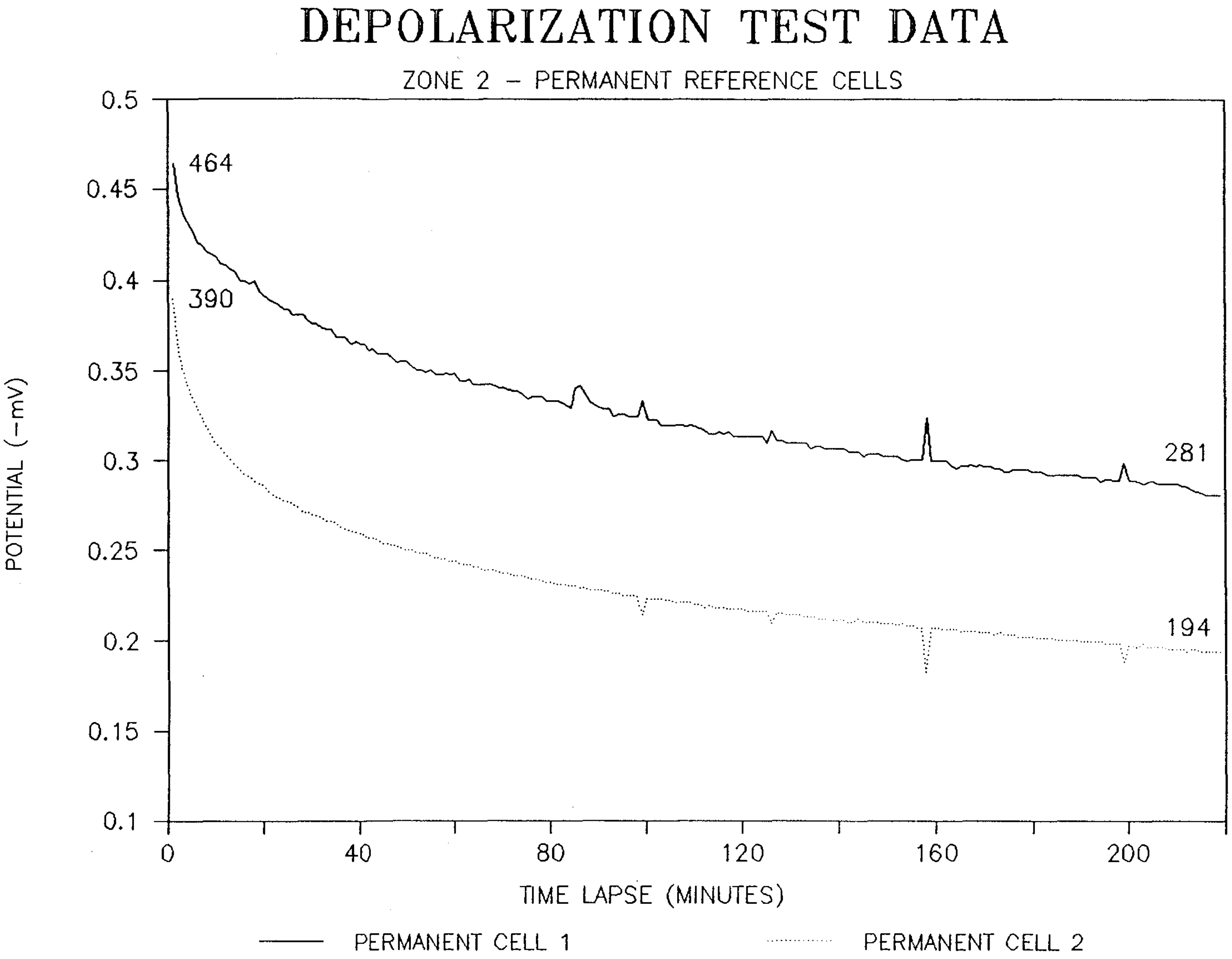


Figure 38. Depolarization test data on Zone 2 (permanent cells) at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

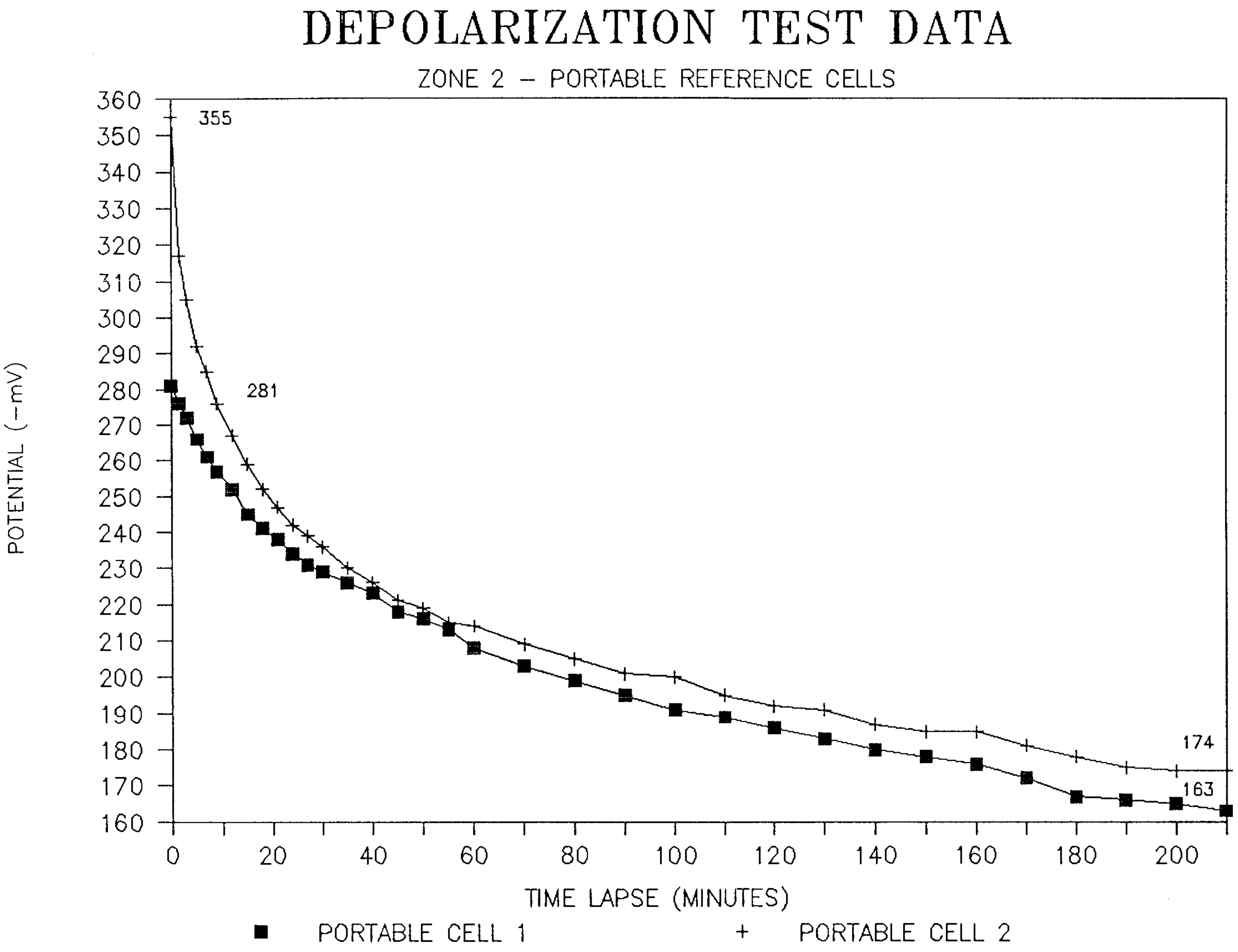


Figure 39. Depolarization test data on Zone 2 (portable cells) at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

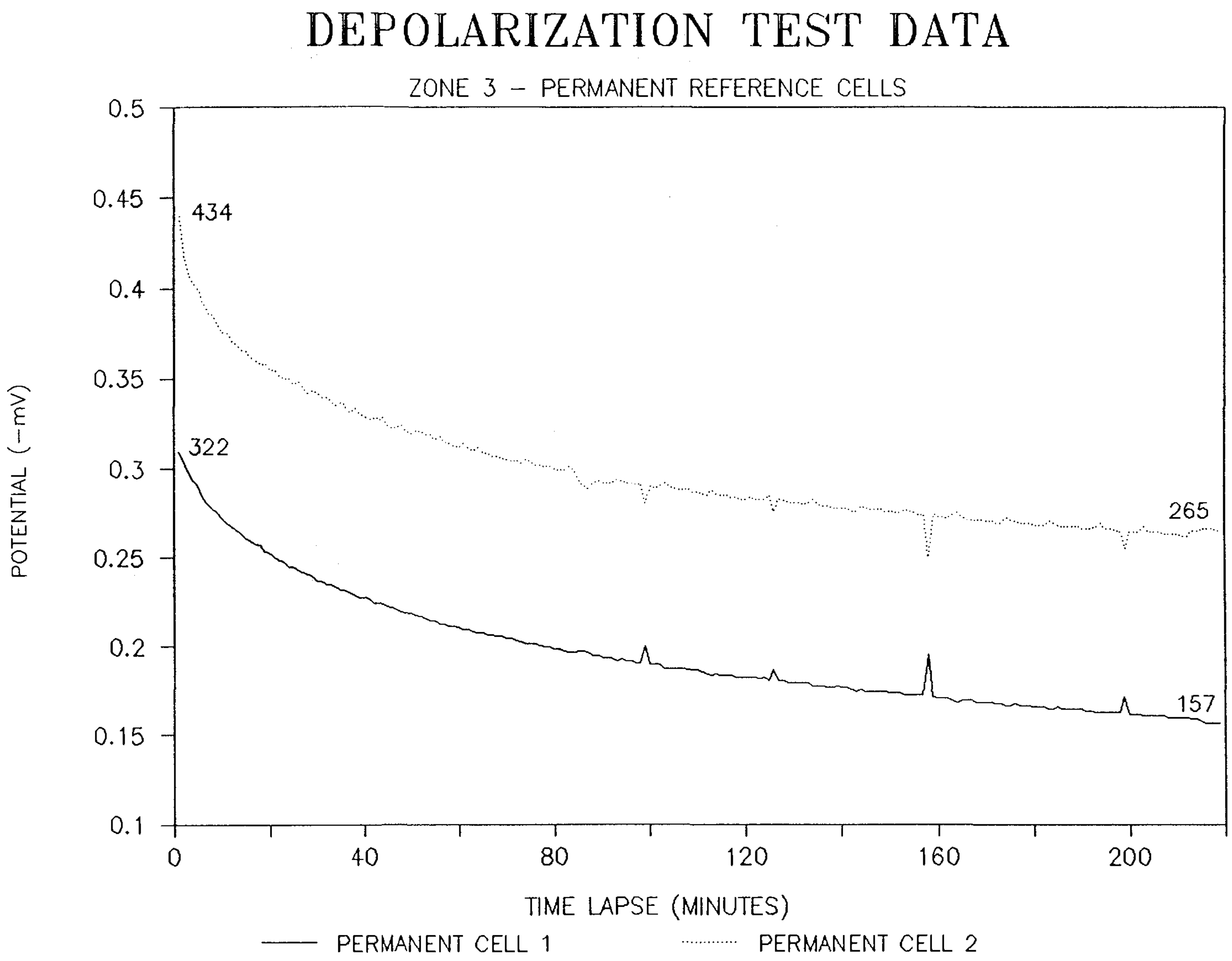


Figure 40. Depolarization test data on Zone 3 (permanent cells) at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

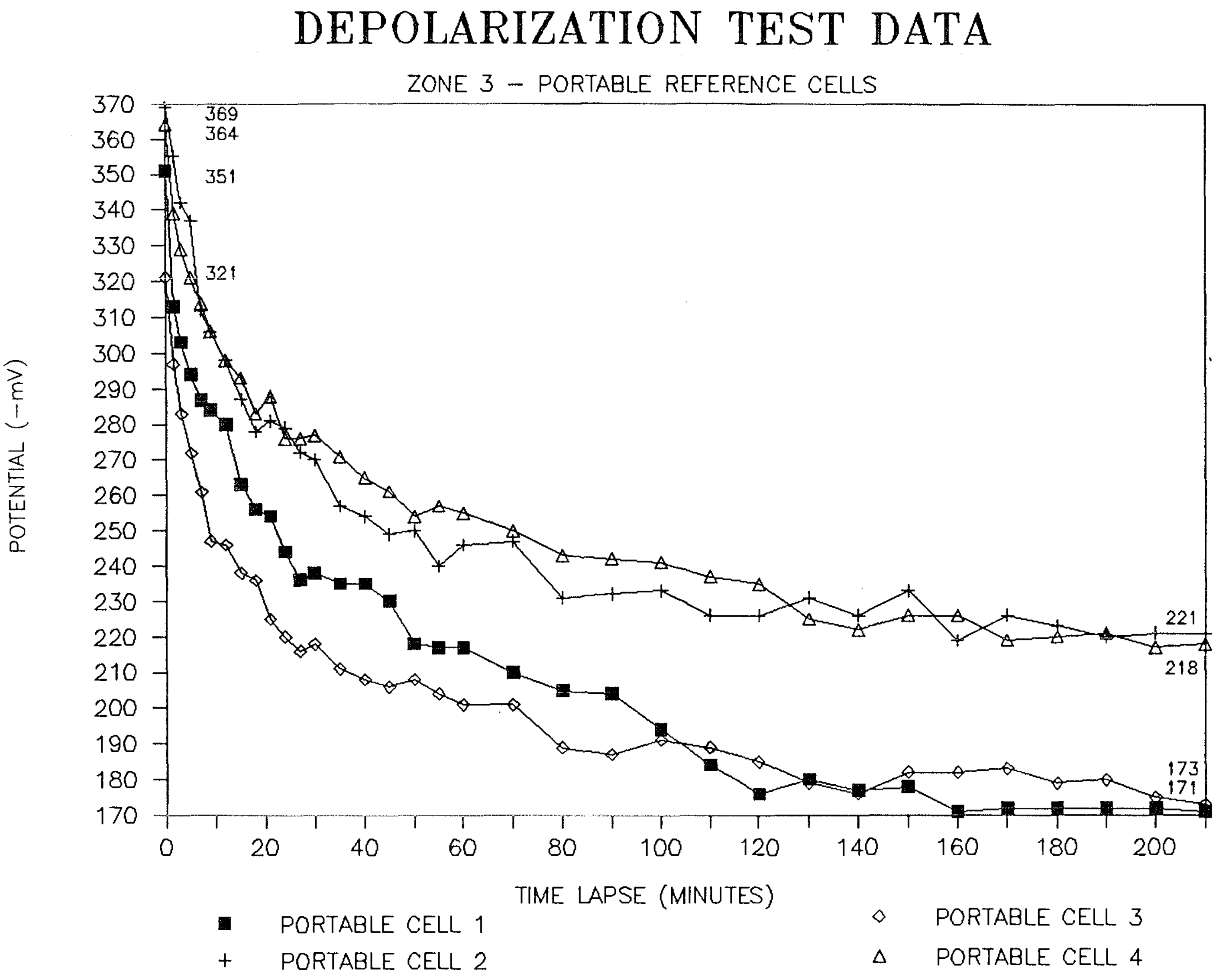


Figure 41. Depolarization test data on Zone 3 (portable cells) at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

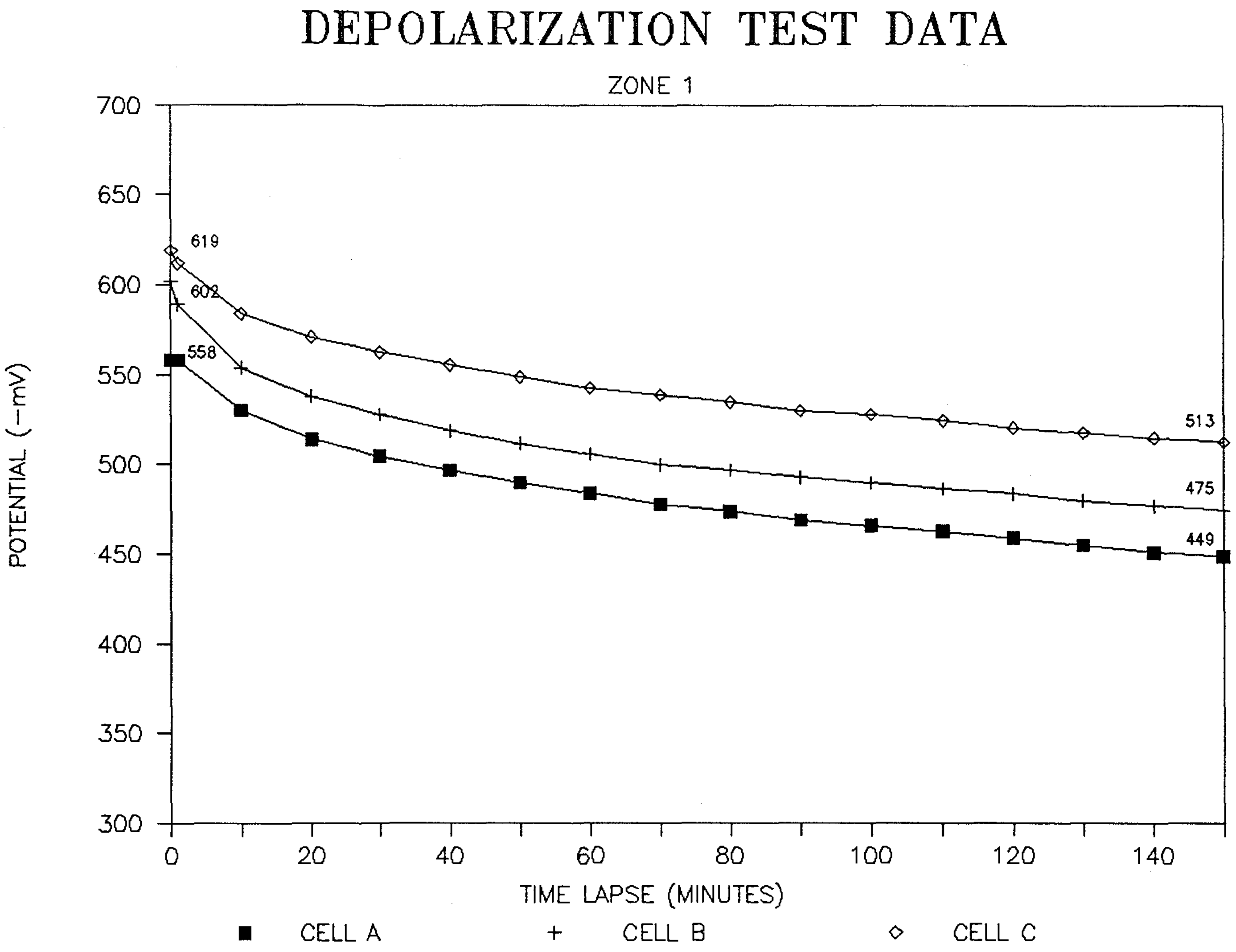


Figure 42. Depolarization test data on Zone 1 at initial evaluation, northern climate bridge, Cincinnati, Ohio.

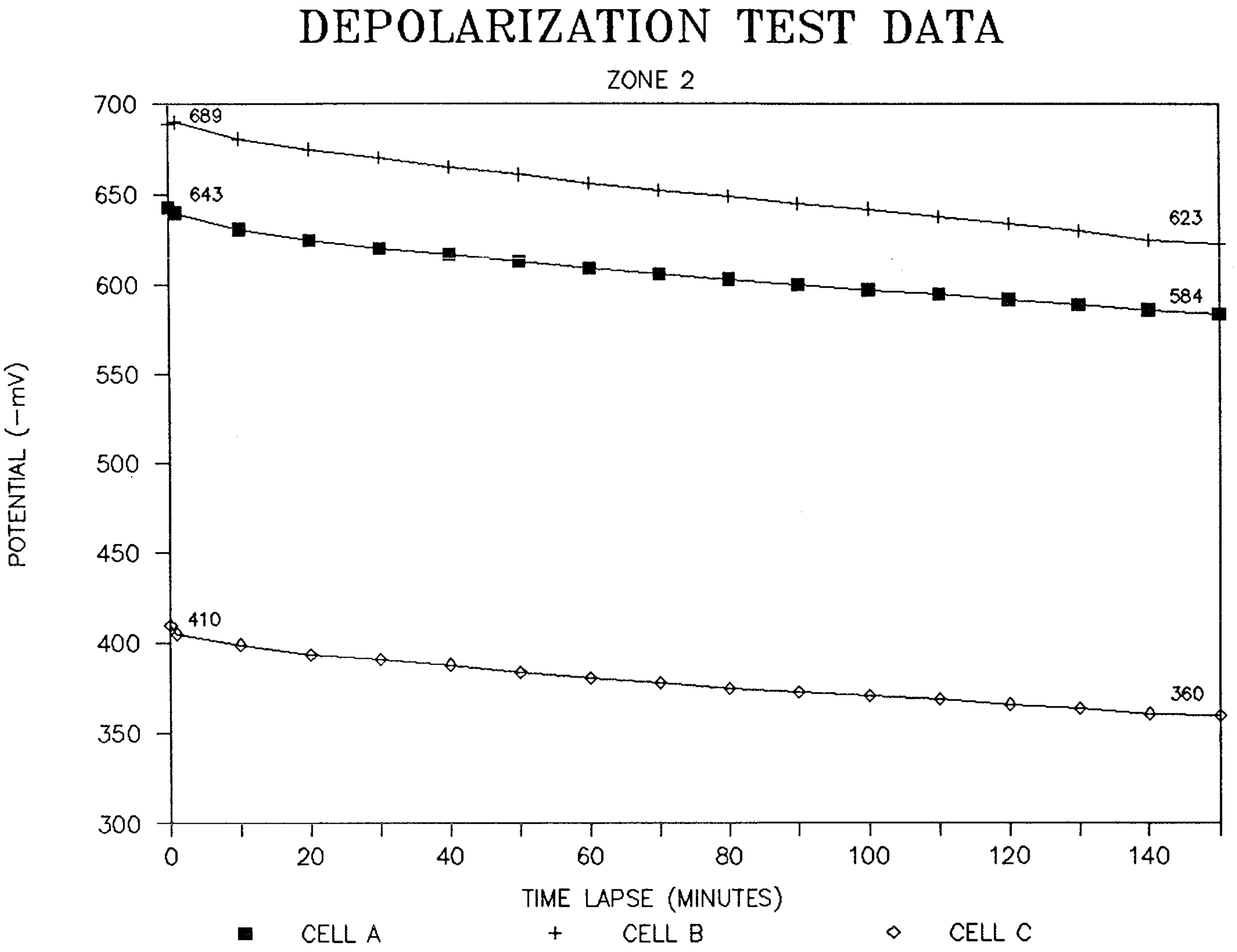


Figure 43. Depolarization test data on Zone 2 at initial evaluation, northern climate bridge, Cincinnati, Ohio.

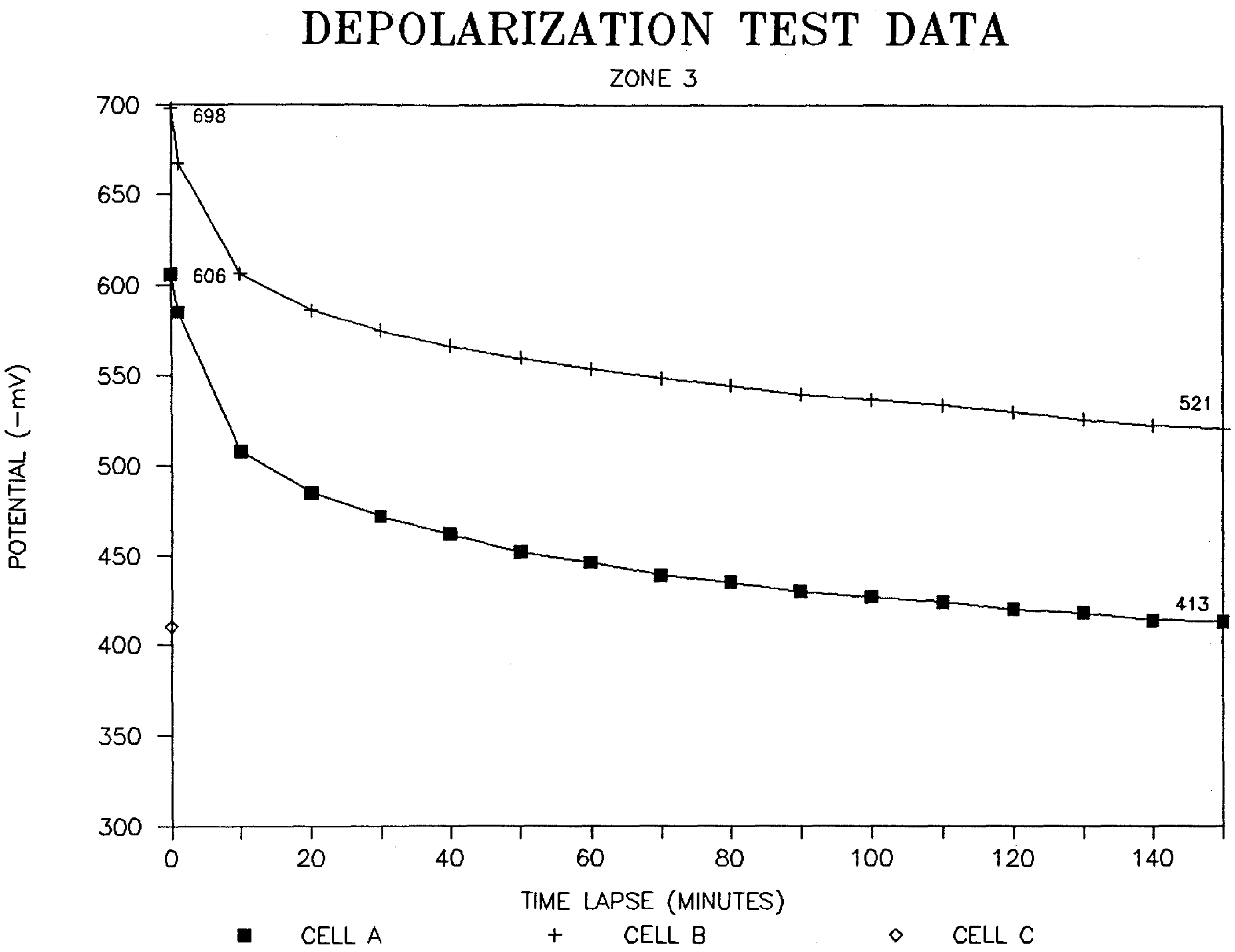


Figure 44. Depolarization test data on Zone 3 at initial evaluation, northern climate bridge, Cincinnati, Ohio.

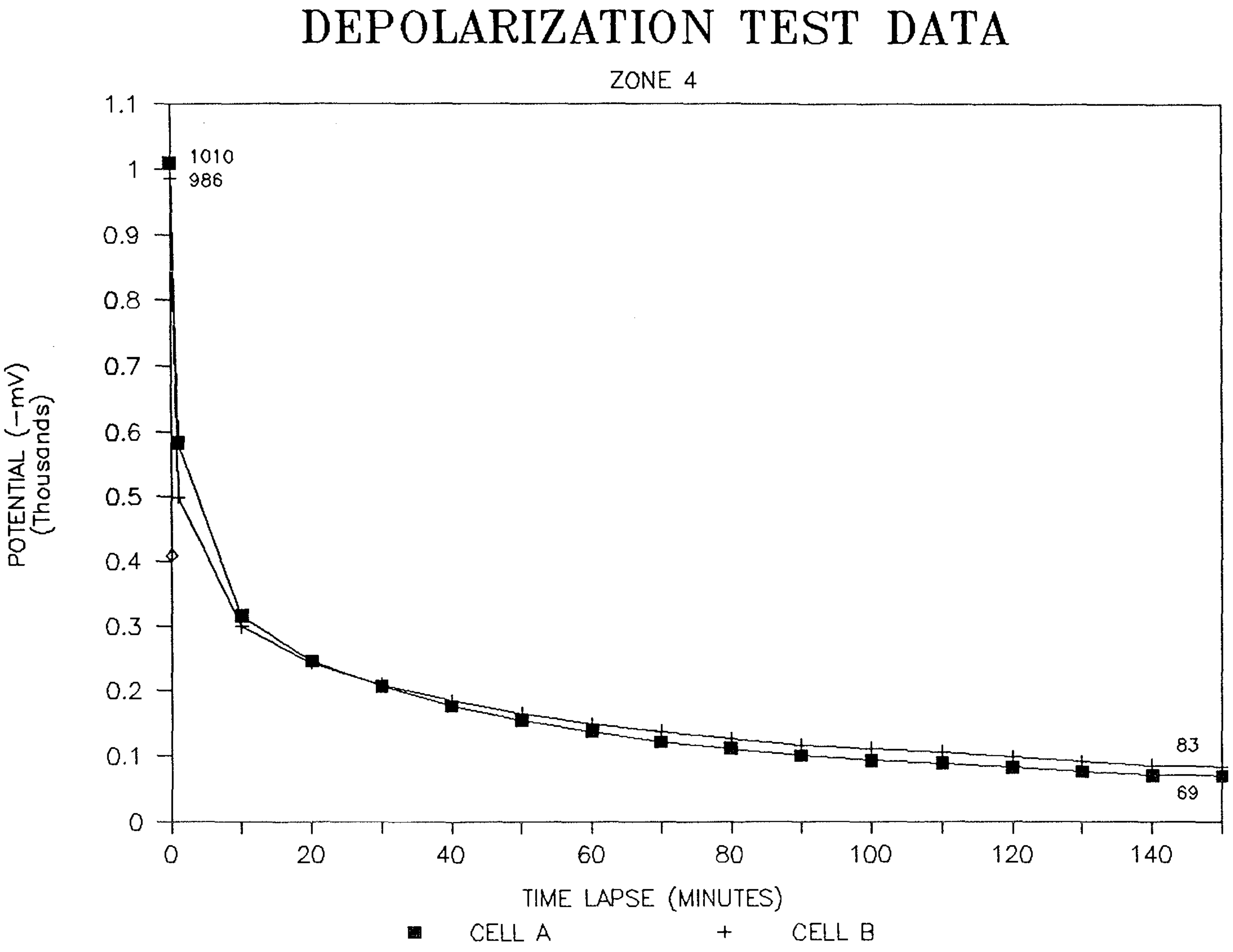


Figure 45. Depolarization test data on Zone 4 at initial evaluation, northern climate bridge, Cincinnati, Ohio.

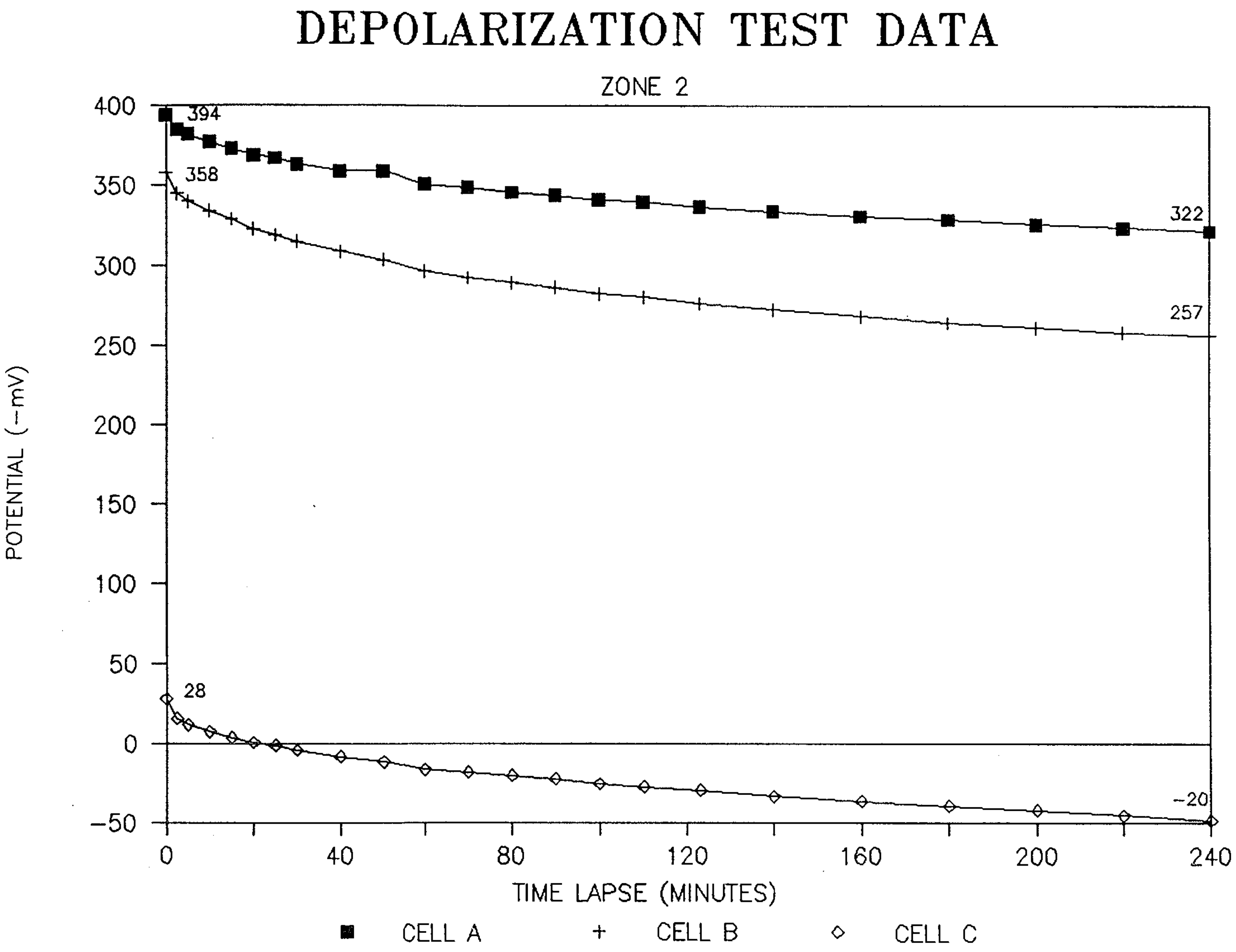


Figure 46. Depolarization test data on Zone 2 at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

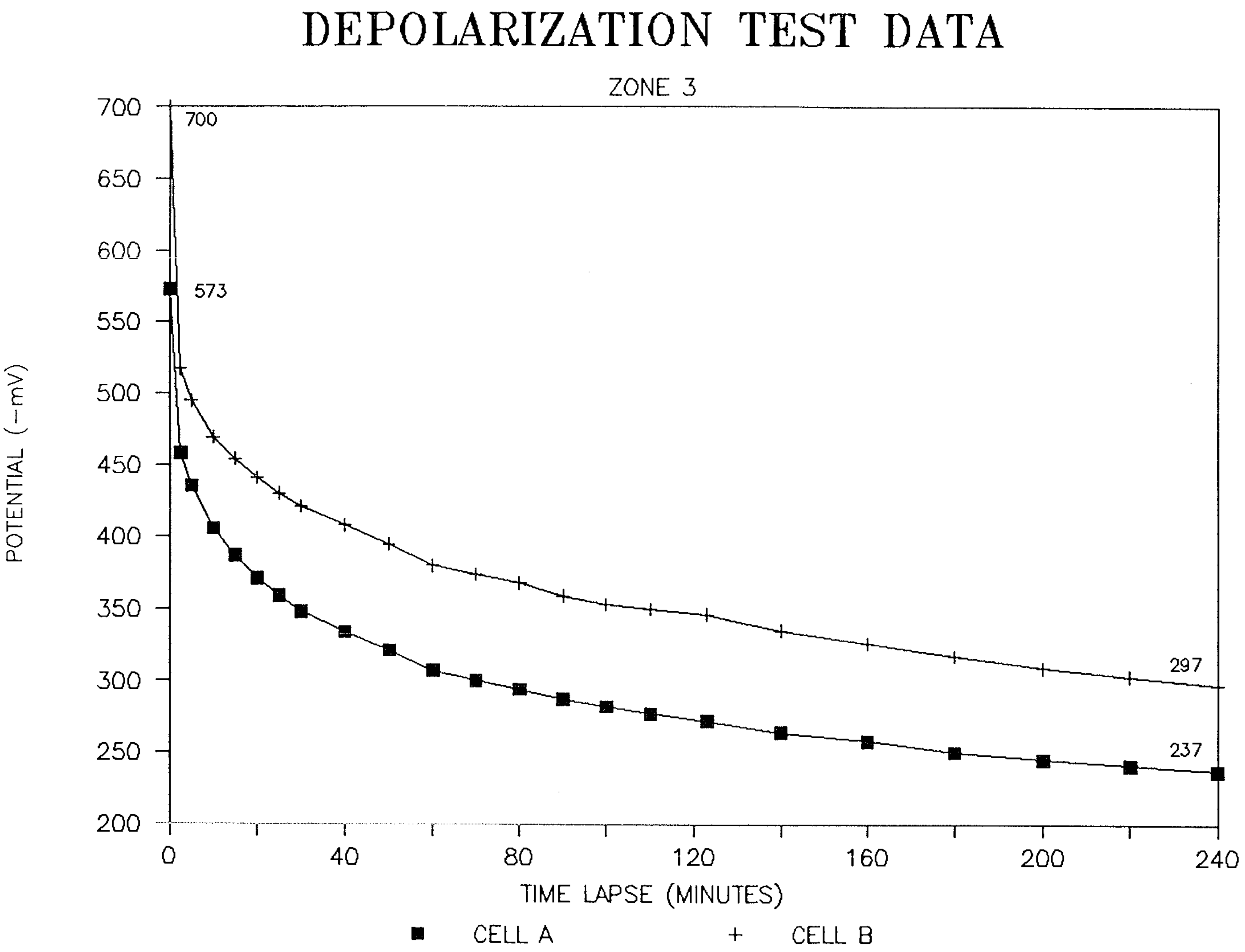


Figure 47. Depolarization test data on Zone 3 at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

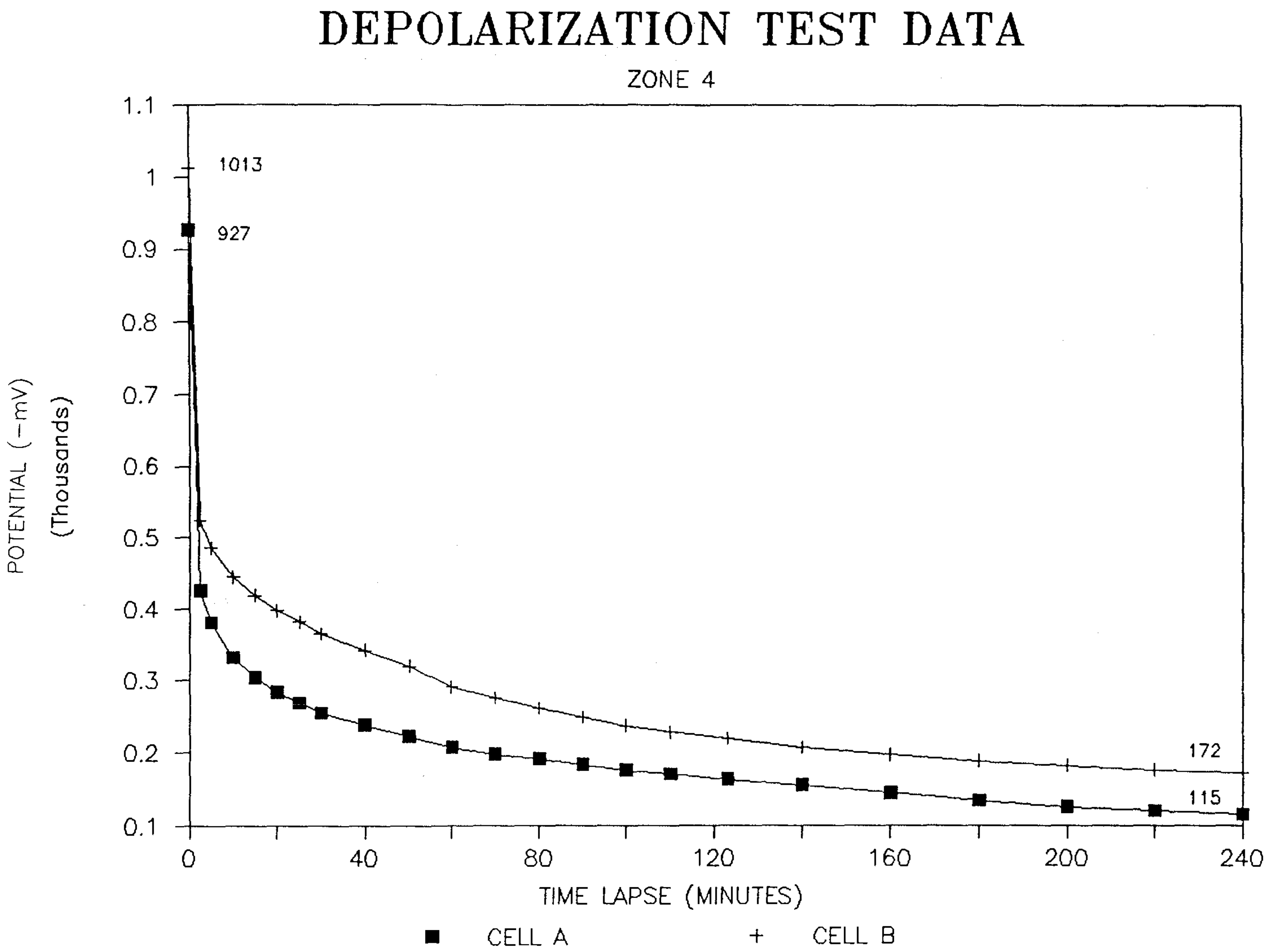


Figure 48. Depolarization test data on Zone 4 at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

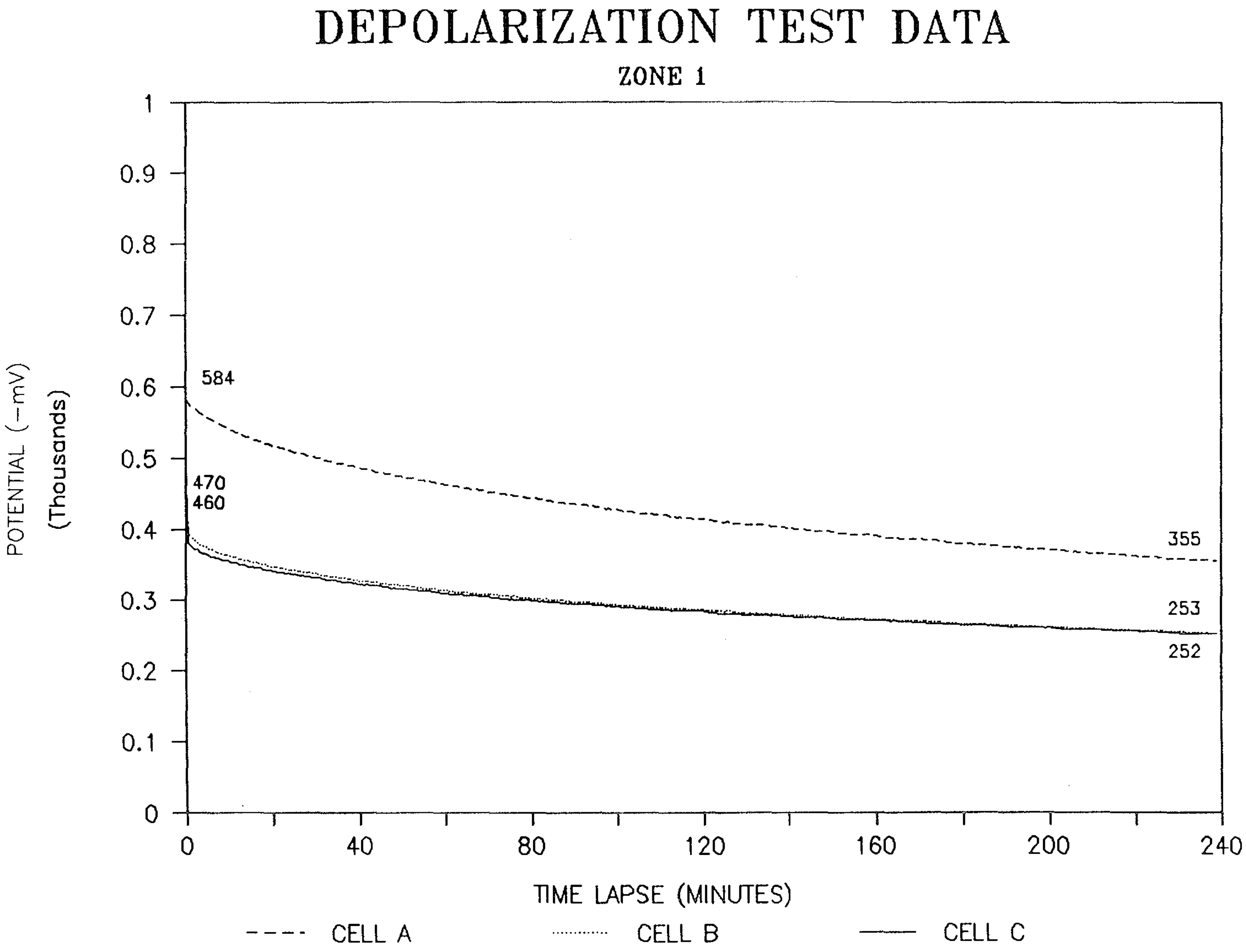


Figure 49. Depolarization test data on Zone 1 at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

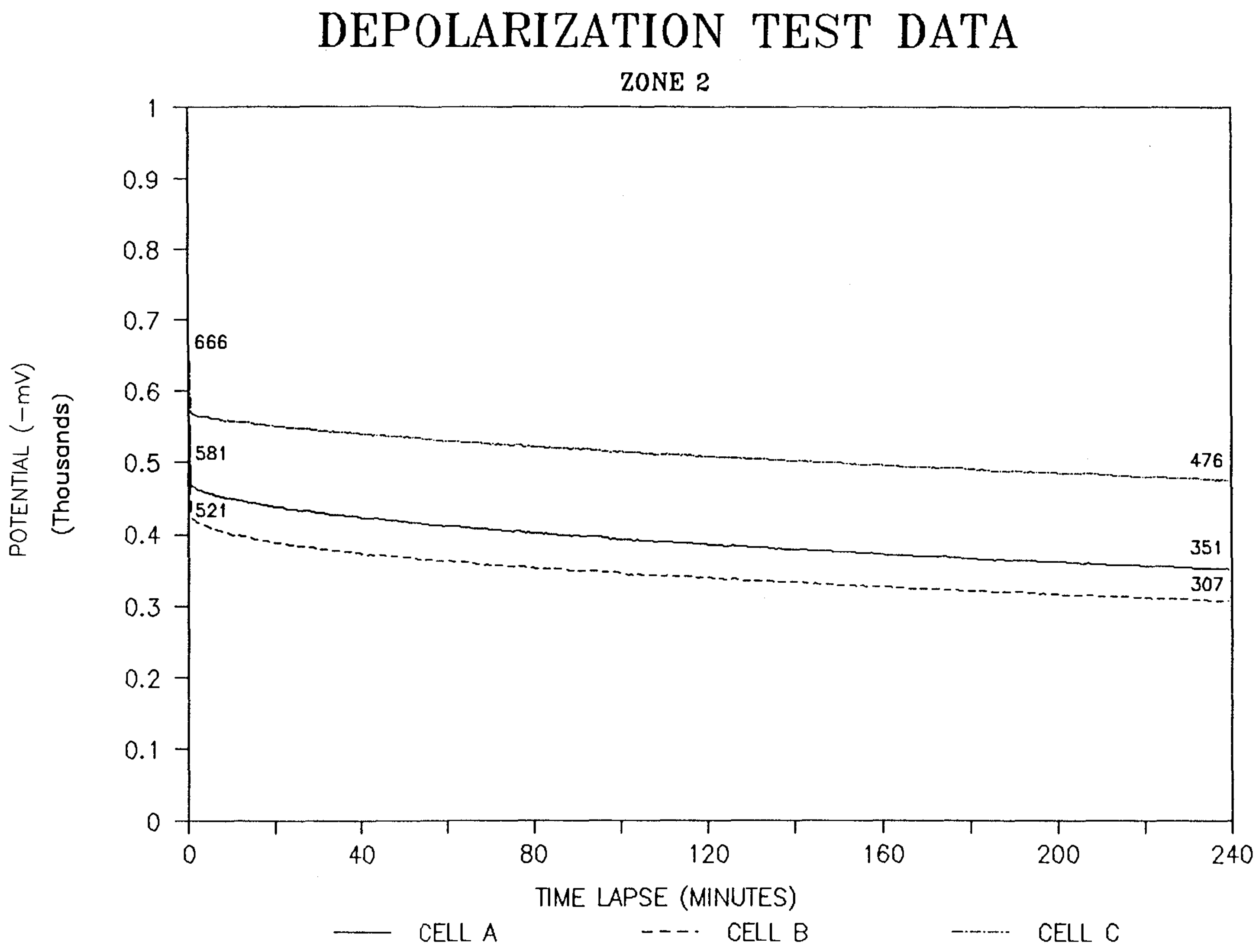


Figure 50. Depolarization test data on Zone 2 at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

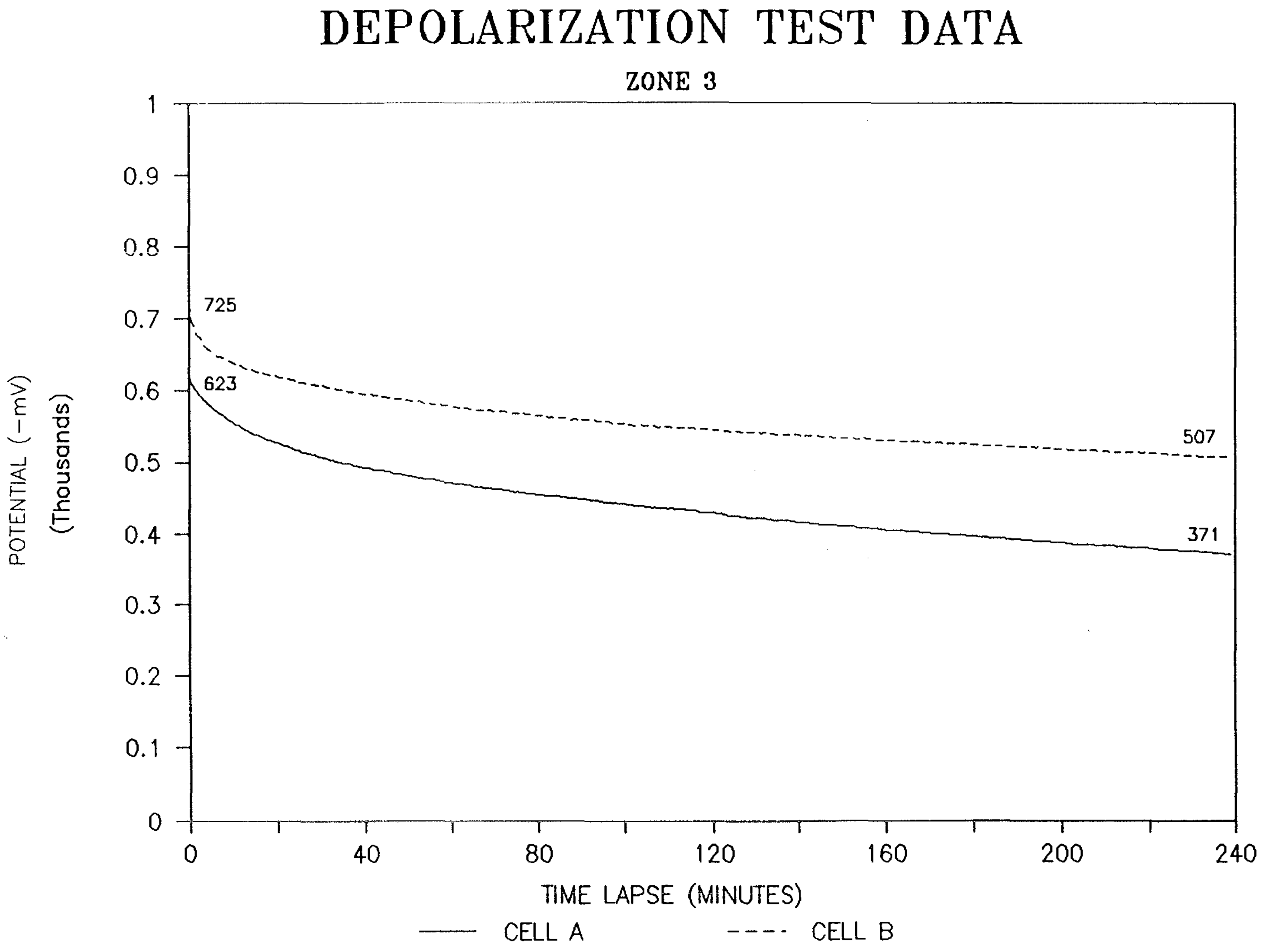


Figure 51. Depolarization test data on Zone 3 at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

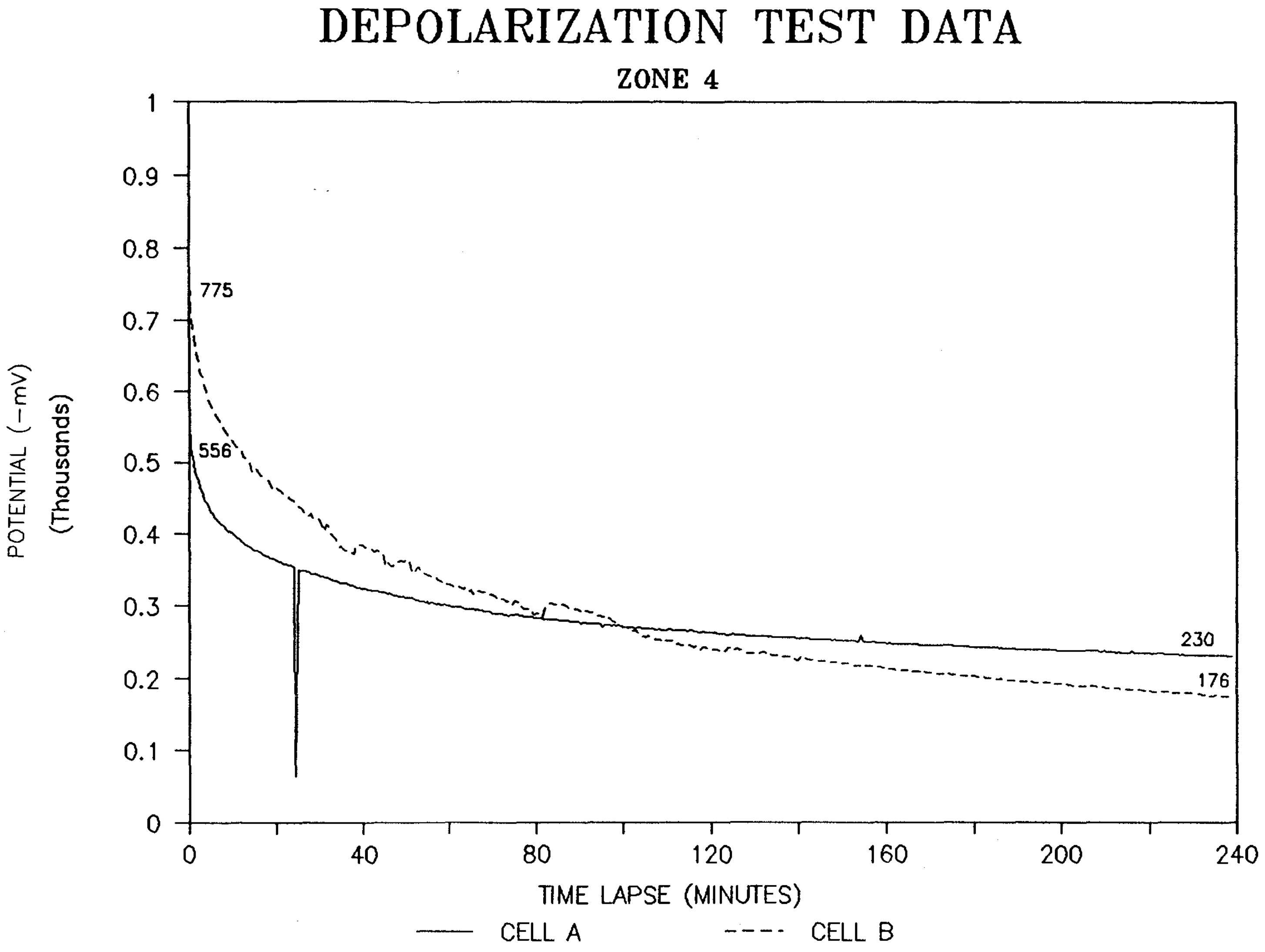


Figure 52. Depolarization test data on Zone 4 at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

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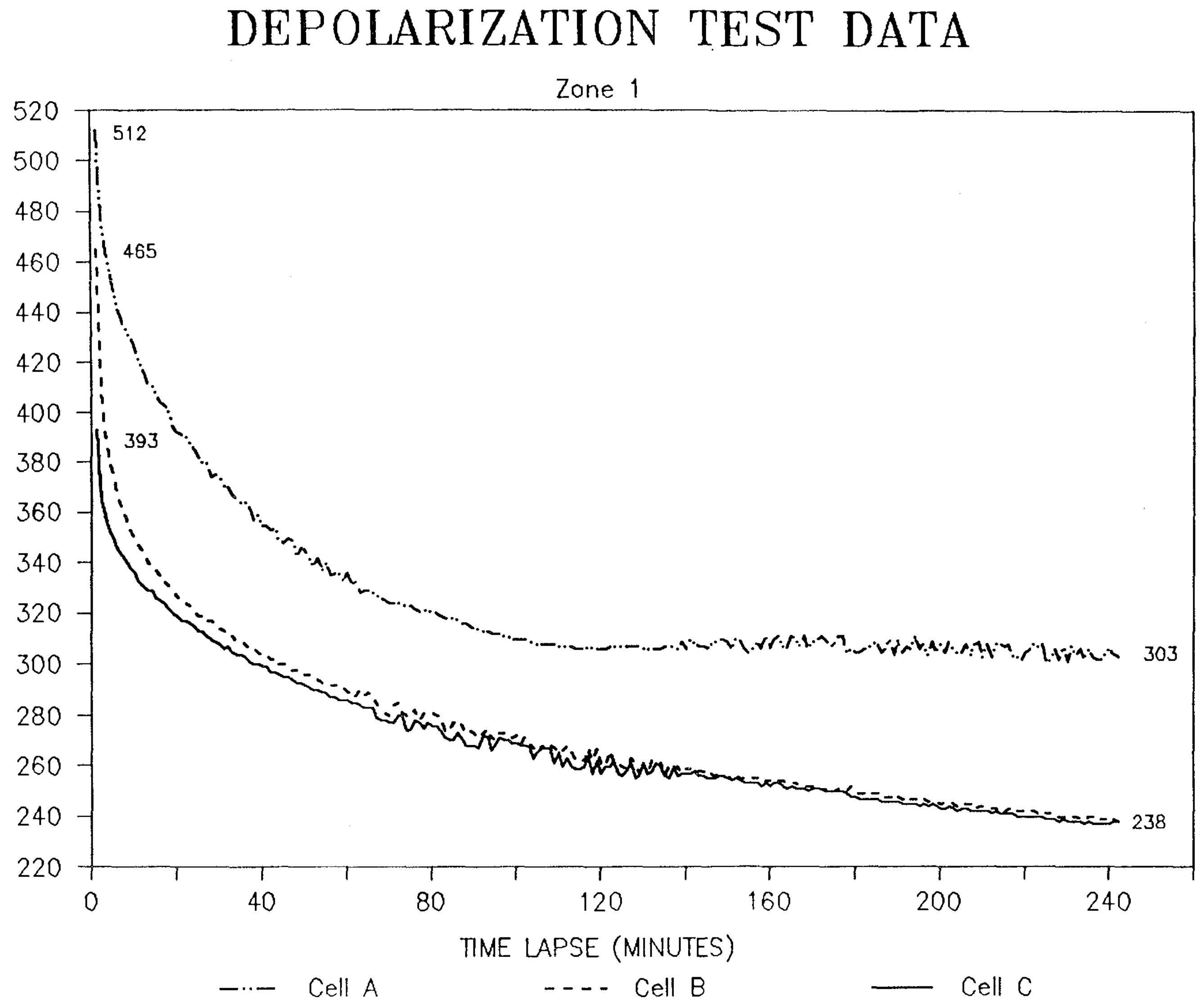


Figure 53. Depolarization test data on Zone 1 at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

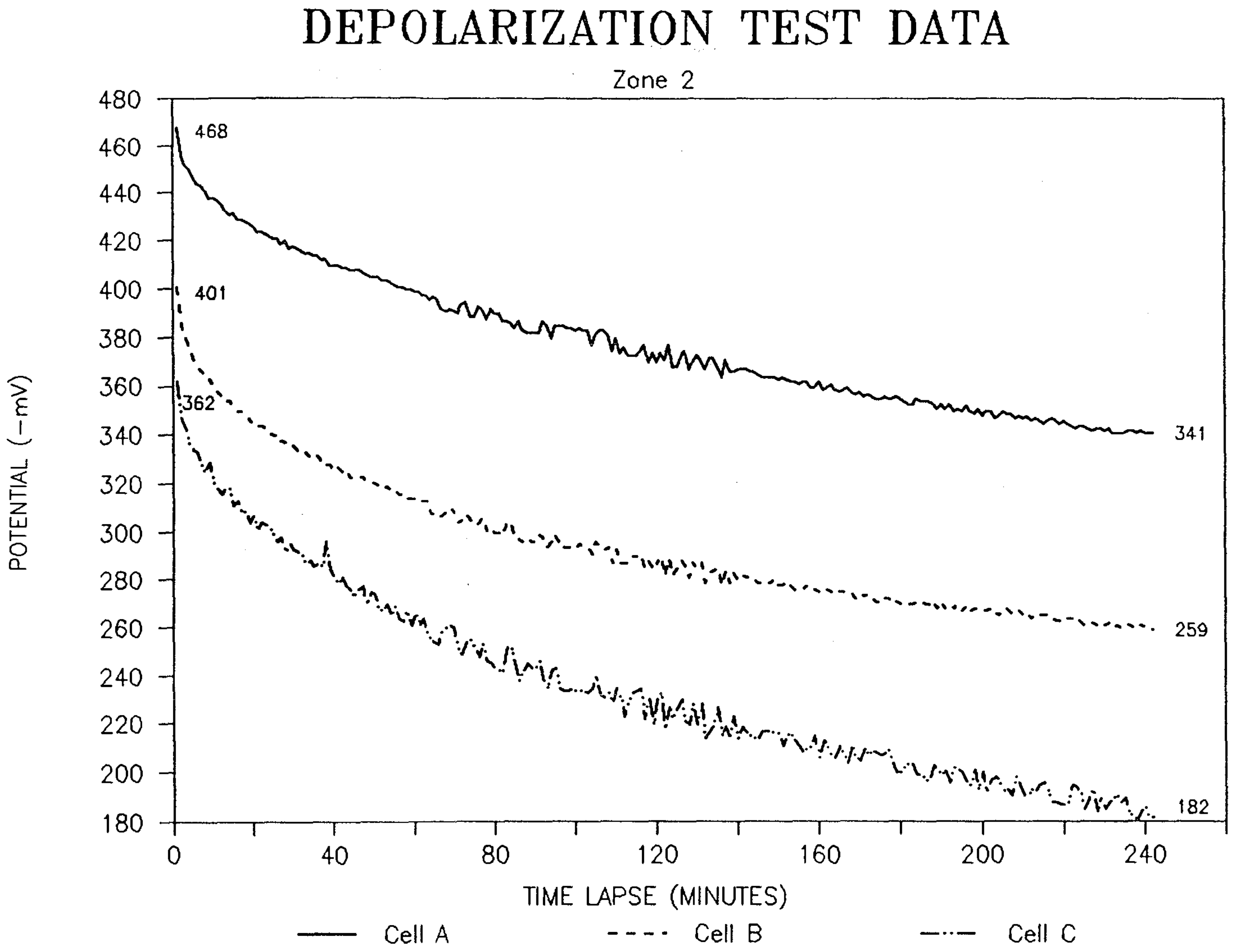


Figure 54. Depolarization test data on Zone 2 at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

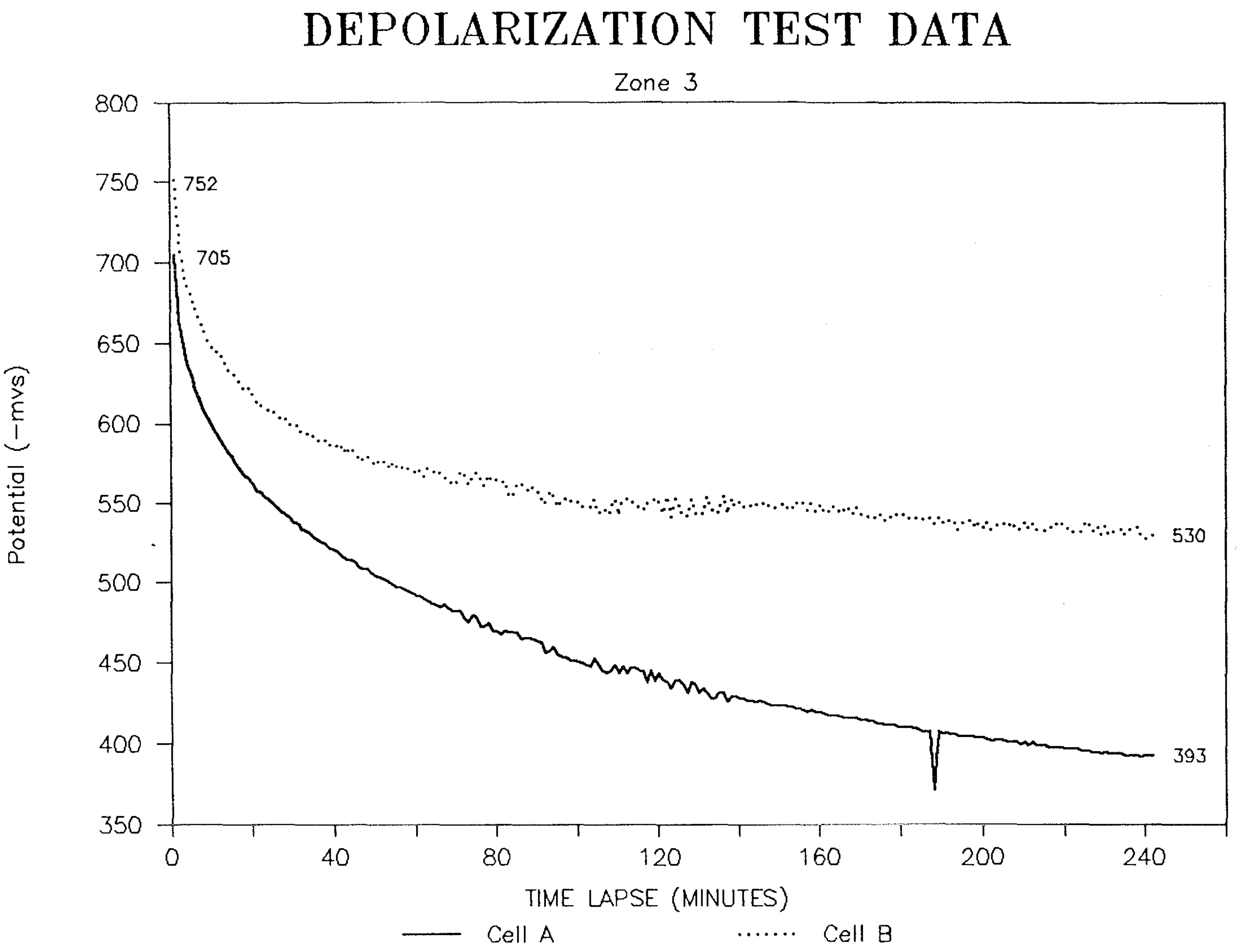


Figure 55. Depolarization test data on Zone 3 at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

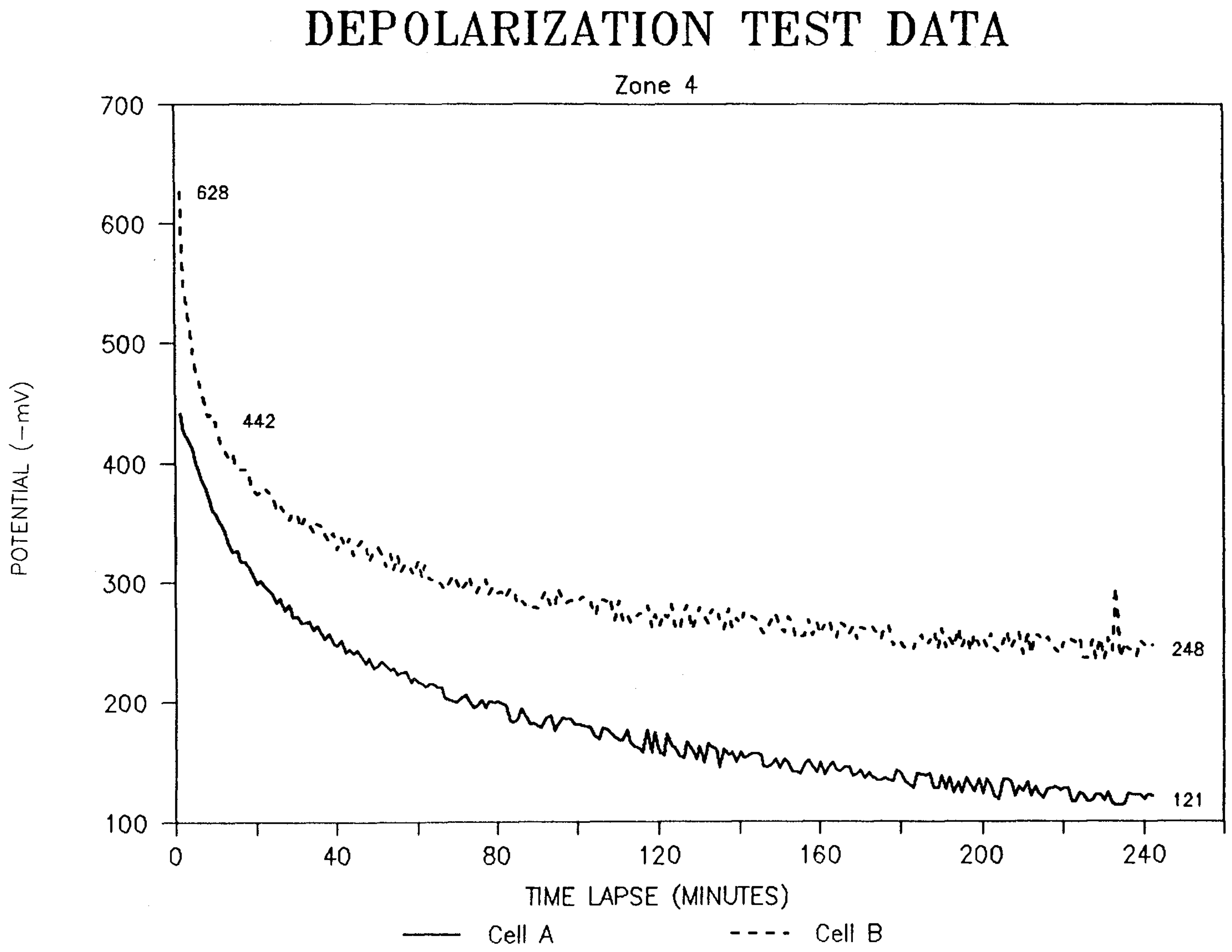


Figure 56. Depolarization test data on Zone 4 at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

APPENDIX C

E LOG I GRAPHS, COMPUTED CORROSION AND CATHODIC PROTECTION DATA

E Log I tests performed at four different evaluation periods on three cathodic protection systems on a marine environment bridge and four cathodic protection systems on a northern climate bridge.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                        ZONE 1 - CELL 1
-----------------------------------------------------------------
      TAFEL SLOPE      =       176.30 MILLIVOLTS/DECADE
      ICORR            =      2021..29 MILLIAMPS
      ECORR            =         -370 MILLIVOLTS
      IPROTECT         =      5123.42 MILLIAMPS
      EPROTECT         =      -441.22 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     0.54511
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99879
      NO. OF OBSERVATIONS USED                     =          17
=================================================================
```

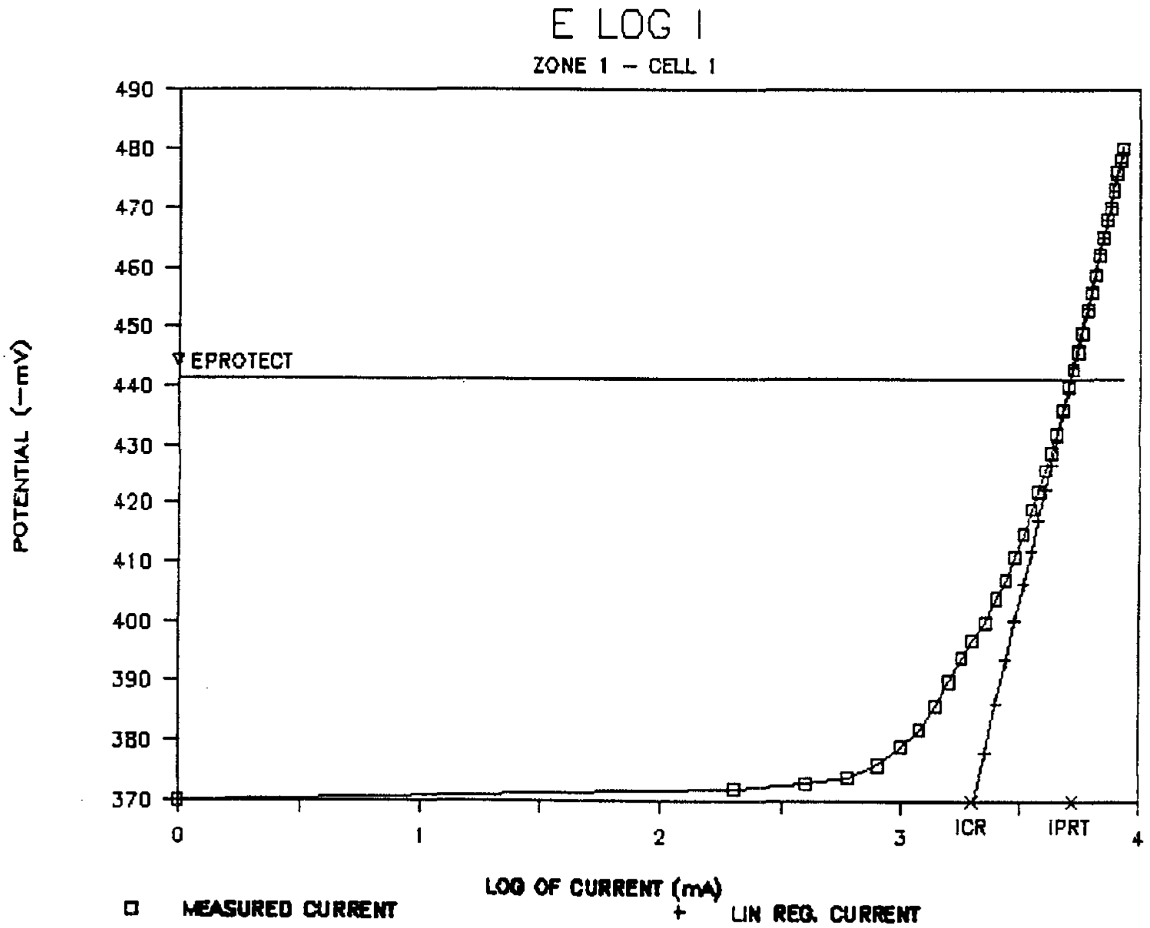


Figure 57. E Log I computed corrosion and cathodic protection data, Zone 1- reference cell 1 at initial evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                          ZONE 1 - CELL 2
-----------------------------------------------------------------
      TAFEL SLOPE      =       247.55 MILLIVOLTS/DECADE
      ICORR            =      2044.85 MILLIAMPS
      ECORR            =         -382 MILLIVOLTS
      IPROTECT         =      5123.50 MILLIAMPS
      EPROTECT         =      -480.75 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     0.81117
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99841
      NO. OF OBSERVATIONS USED                      =          15
=================================================================
```

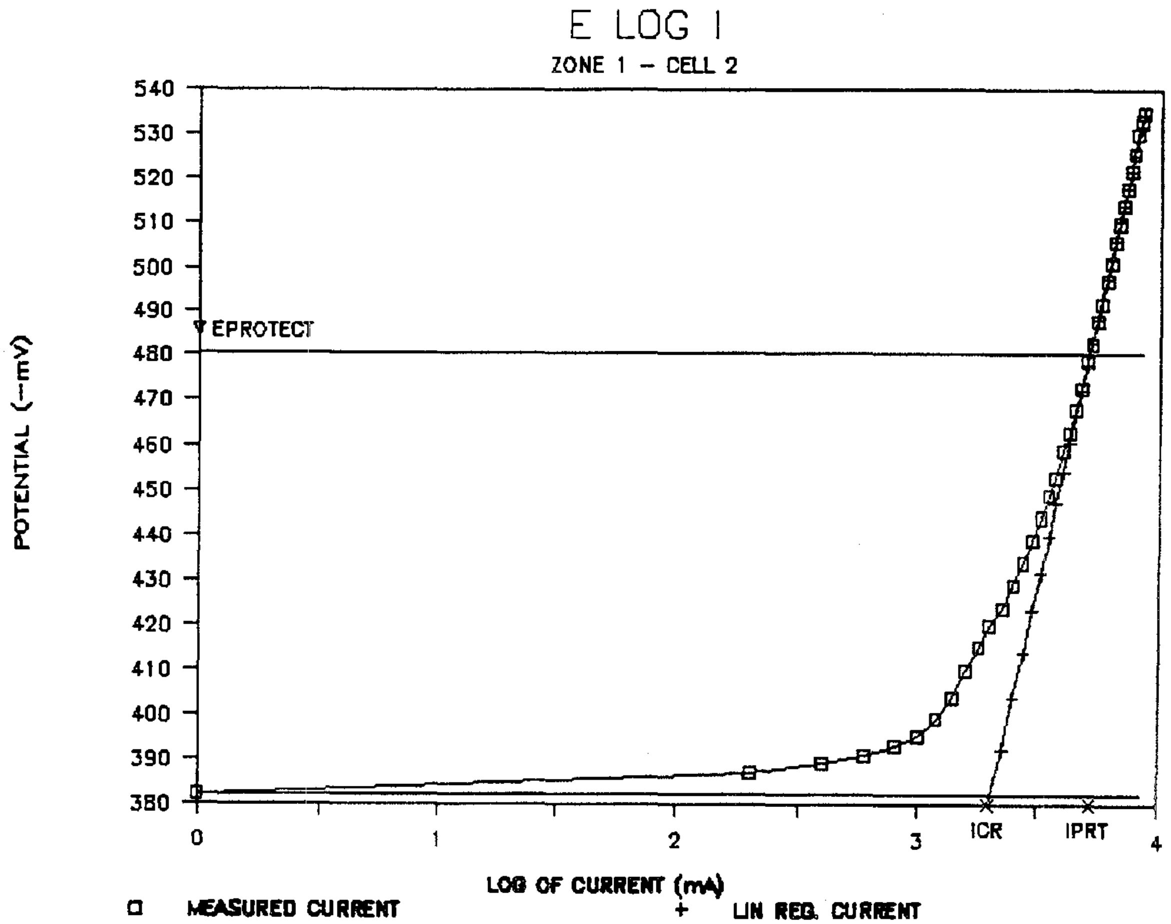


Figure 58. E Log I computed corrosion and cathodic protection data,
Zone 1 - reference cell 2 at initial evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                        ZONE 2 - CELL 1
-----------------------------------------------------------------
     TAFEL SLOPE     =       295.38 MILLIVOLTS/DECADE
     ICORR           =       349.17 MILLIAMPS
     ECORR           =         -258 MILLIVOLTS
     IPROTECT        =       674.54 MILLIAMPS
     EPROTECT        =      -342.47 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                 =     1.17571
     COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99900
     NO. OF OBSERVATIONS USED                     =          19
=================================================================
```

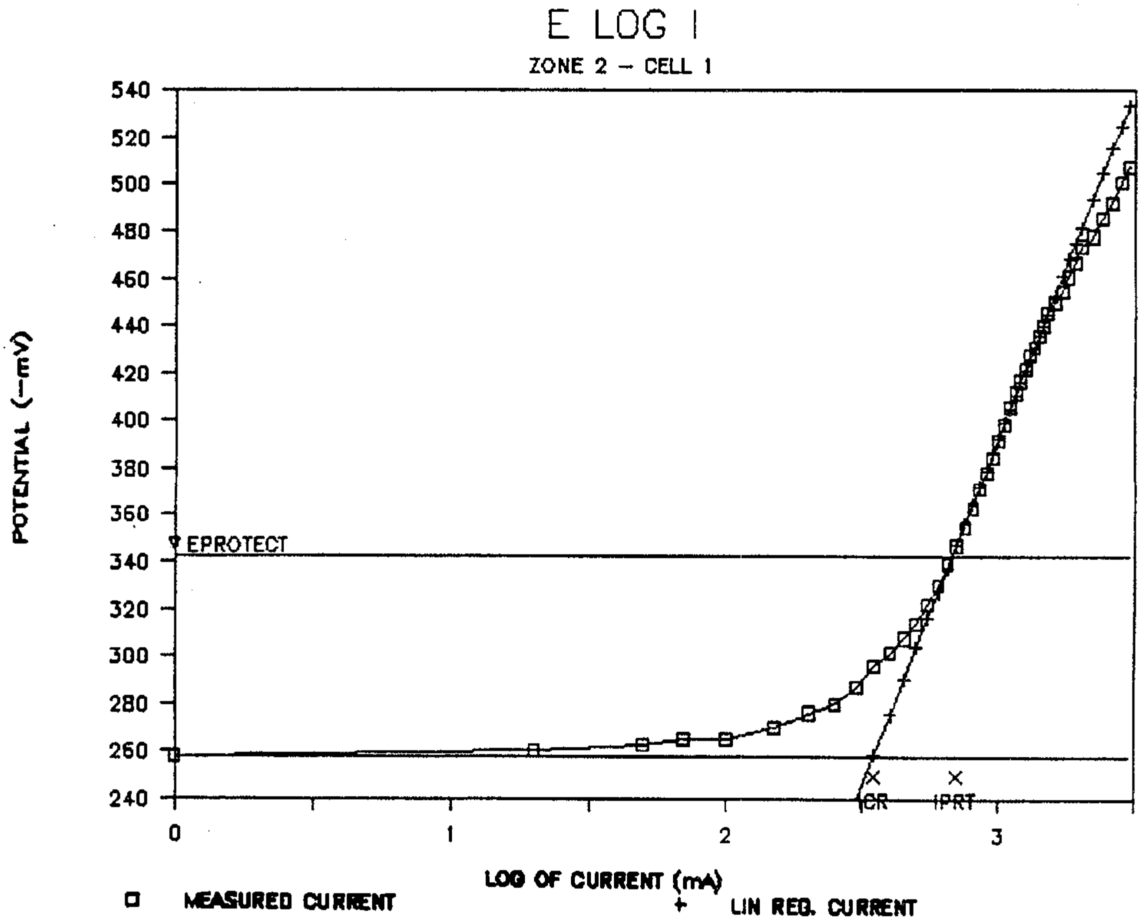


Figure 59. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 1 at initial evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                         ZONE 2 - CELL 2
-----------------------------------------------------------------
      TAFEL SLOPE       =        240.58 MILLIVOLTS/DECADE
      ICORR             =         45.53 MILLIAMPS
      ECORR             =          -181 MILLIVOLTS
      IPROTECT          =        474.34 MILLIAMPS
      EPROTECT          =       -425.87 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =      2.41797
      COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.99829
      NO. OF OBSERVATIONS USED                     =           33
=================================================================
```

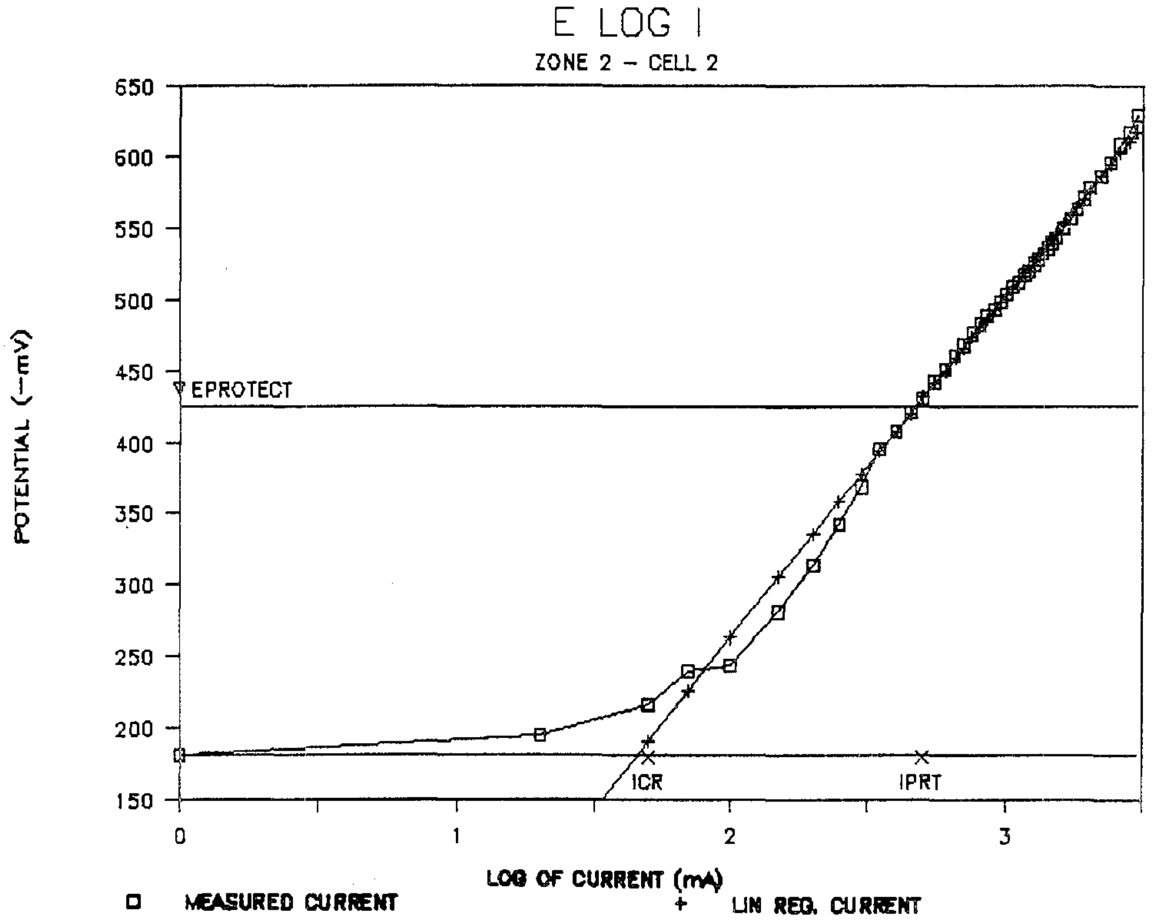


Figure 60. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 2 at initial evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                        ZONE 3 - CELL 1
-----------------------------------------------------------------
      TAFEL SLOPE      =        191.85 MILLIVOLTS/DECADE
      ICORR            =        137.75 MILLIAMPS
      ECORR            =          -205 MILLIVOLTS
      IPROTECT         =        524.39 MILLIAMPS
      EPROTECT         =       -316.38 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =      0.45409
      COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.99955
      NO. OF OBSERVATIONS USED                     =           14
=================================================================
```

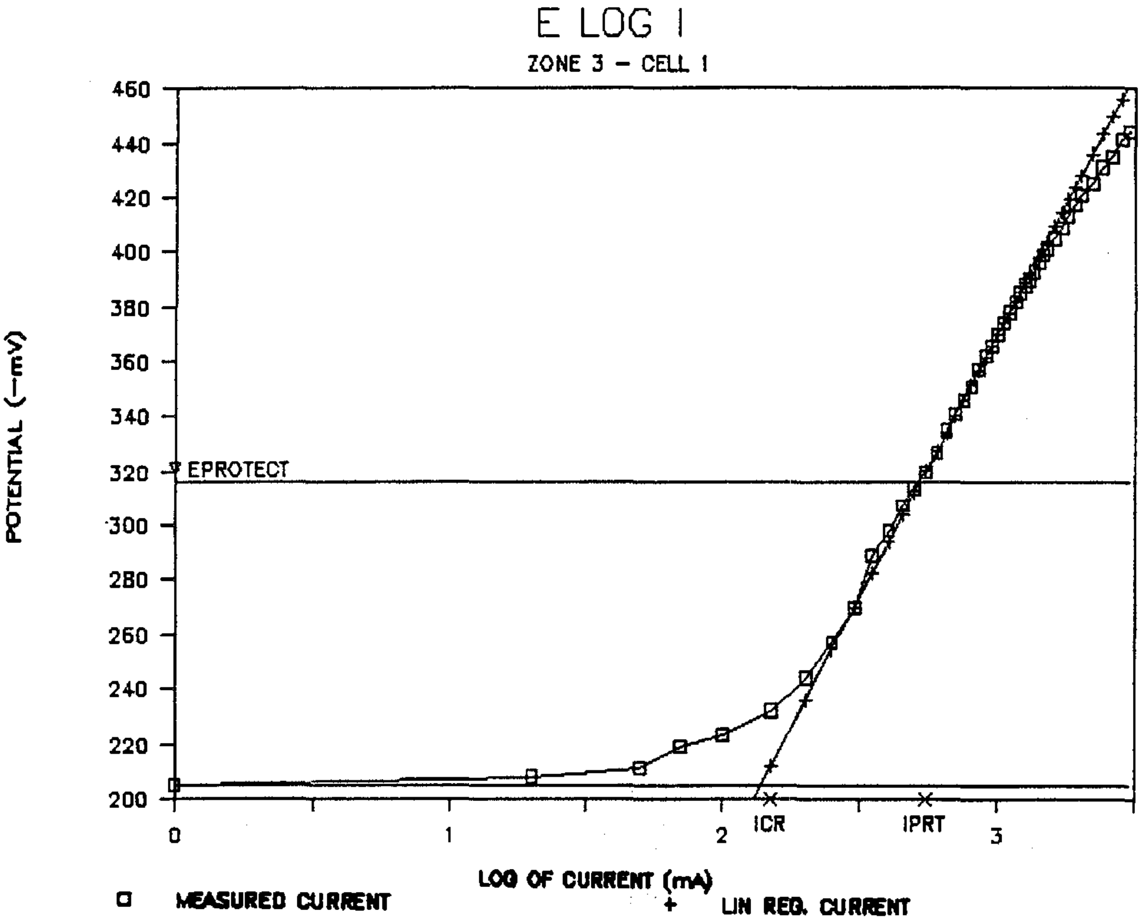


Figure 61. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell 1 at initial evaluation, marine environment bridge, Norfolk, Virginia.

```
================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                        ZONE 3 - CELL 2
----------------------------------------------------------------
      TAFEL SLOPE      =        266.11 MILLIVOLTS/DECADE
      ICORR            =        182.71 MILLIAMPS
      ECORR            =          -346 MILLIVOLTS
      IPROTECT         =        724.55 MILLIAMPS
      EPROTECT         =       -505.22 MILLIVOLTS
================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.64137
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99885
      NO. OF OBSERVATIONS USED                     =          27
================================================================
```

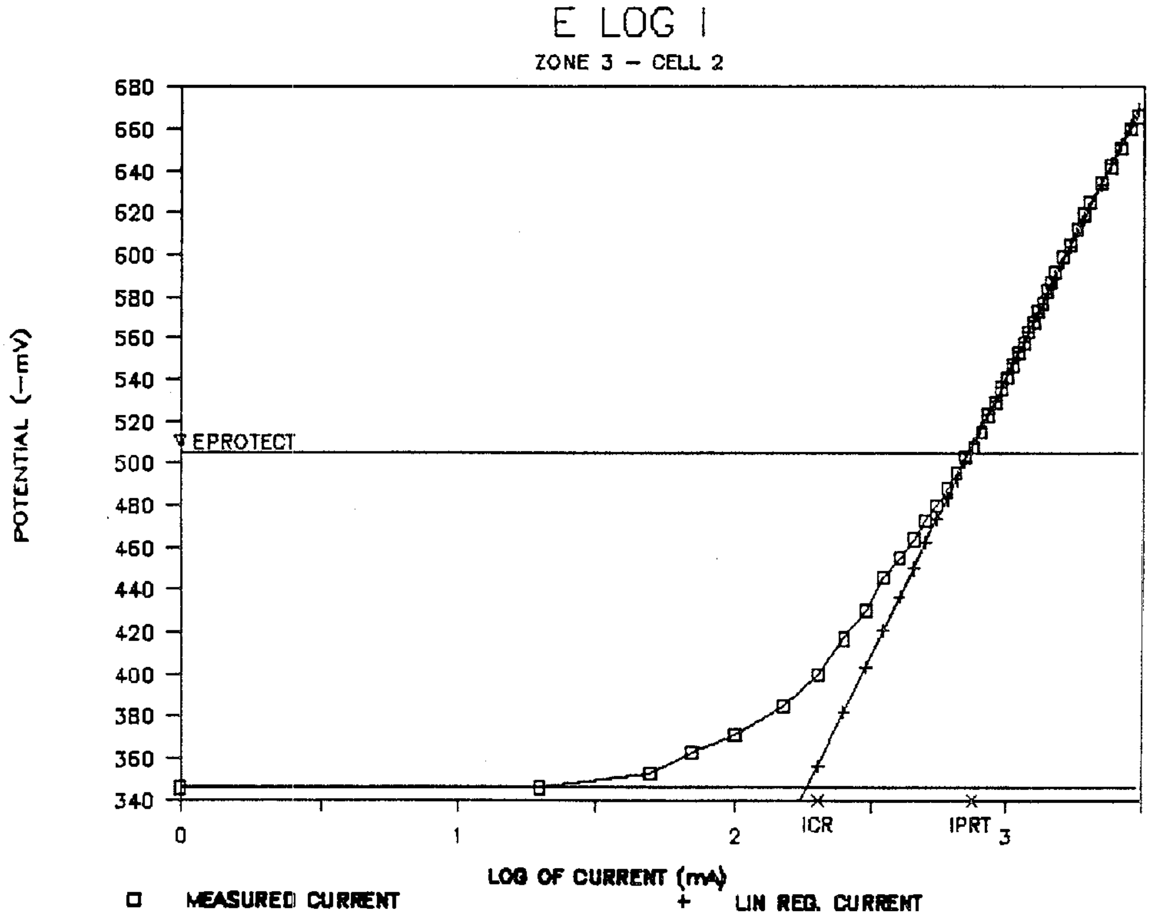


Figure 62. E Log I computed corrosion and cathodic protection data,
Zone 3 - reference cell 2 at initial evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 1 - REFERENCE CELL 1
-----------------------------------------------------------------
      TAFEL SLOPE       =        192.30 MILLIVOLTS/DECADE
      ICORR             =       1076.51 MILLIAMPS
      ECORR             =          -338 MILLIVOLTS
      IPROTECT          =       3498.65 MILLIAMPS
      EPROTECT          =       -436.44 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =      1.23349
      COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.99243
      NO. OF OBSERVATIONS USED                     =           11
=================================================================
```

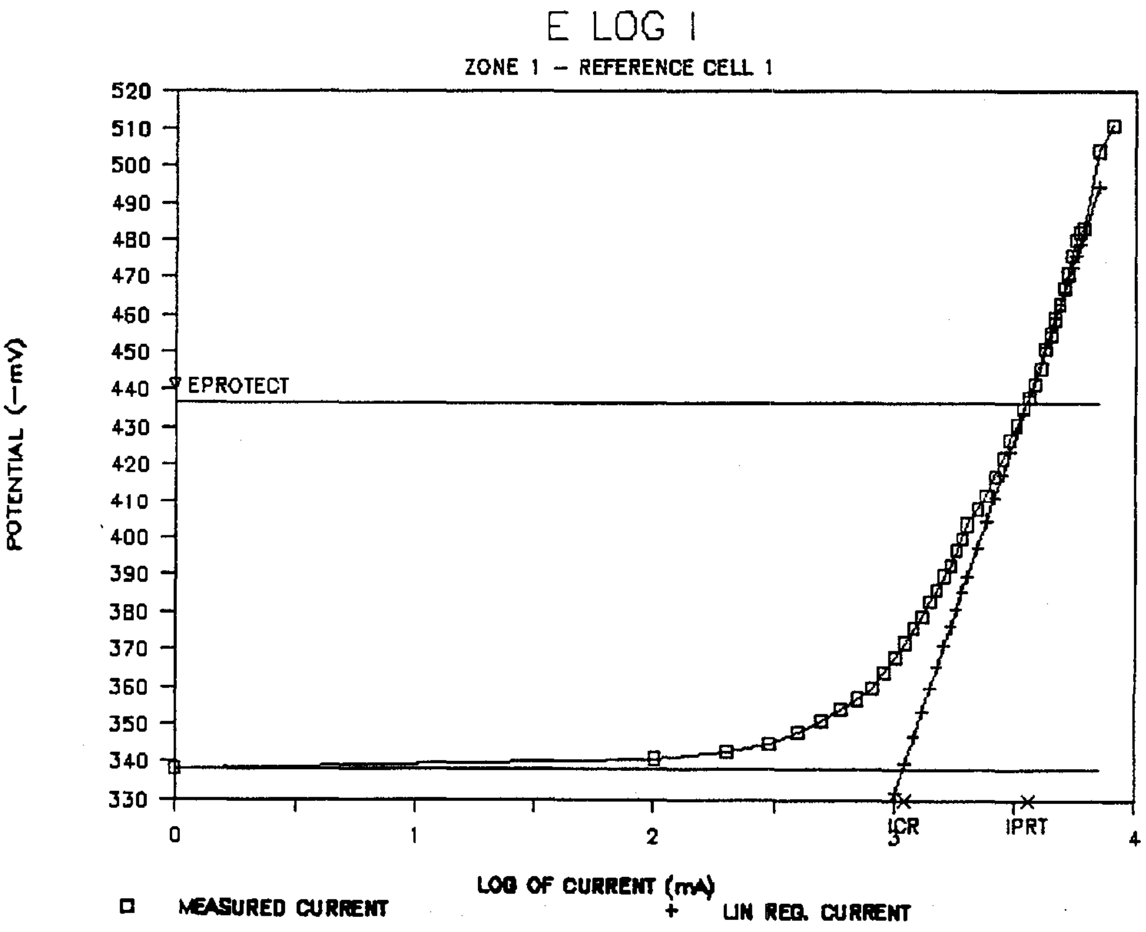


Figure 63. E Log I computed corrosion and cathodic protection data, Zone 1- reference cell 1 at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   ZONE 1 - REFERENCE CELL 2
-----------------------------------------------------------------
      TAFEL SLOPE      =        190.04 MILLIVOLTS/DECADE
      ICORR            =       1323.84 MILLIAMPS
      ECORR            =          -307 MILLIVOLTS
      IPROTECT         =       3698.74 MILLIAMPS
      EPROTECT         =       -391.80 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.22957
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99512
      NO. OF OBSERVATIONS USED                     =          15
=================================================================
```

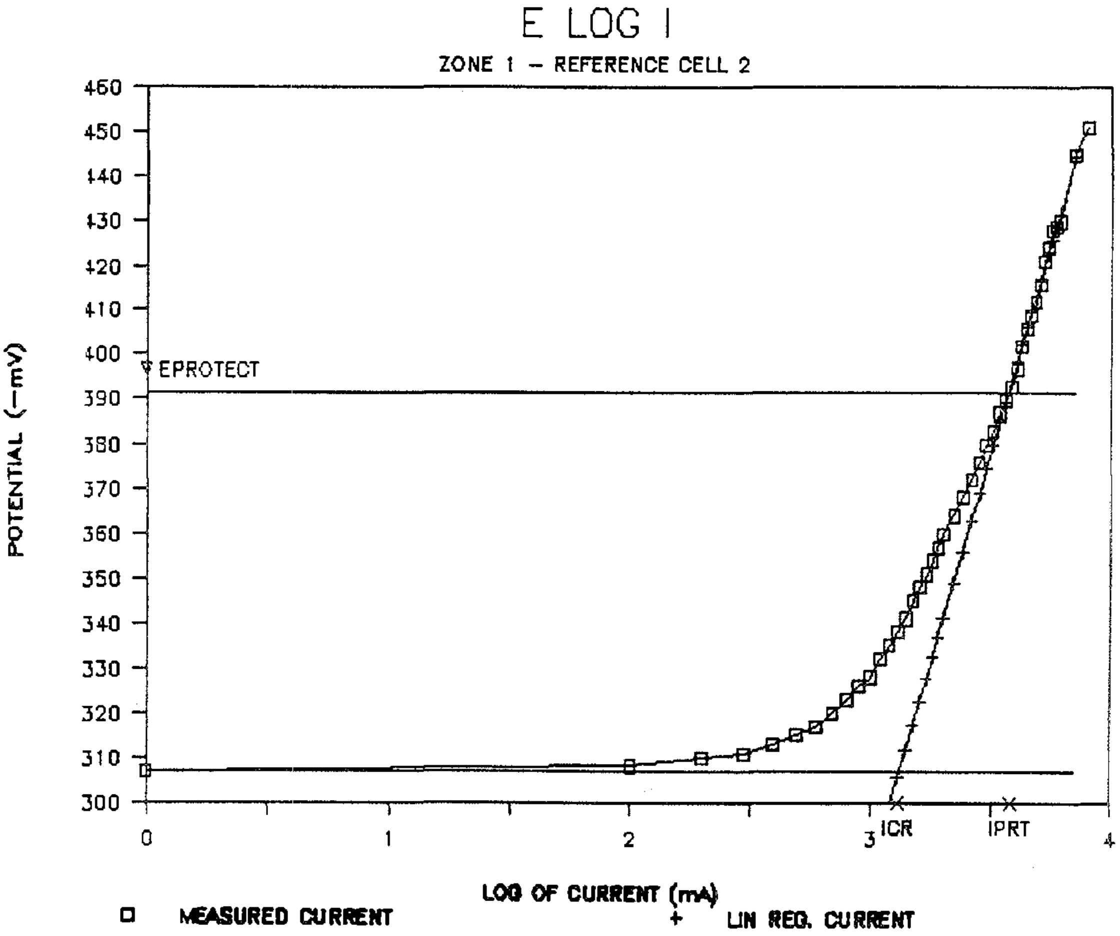


Figure 64. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell 2 at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   ZONE 2 - REFERENCE CELL 1
-----------------------------------------------------------------
      TAFEL SLOPE      =        902.45 MILLIVOLTS/DECADE
      ICORR            =        276.62 MILLIAMPS
      ECORR            =          -216 MILLIVOLTS
      IPROTECT         =        374.16 MILLIAMPS
      EPROTECT         =       -334.37 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     1.09102
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99826
      NO. OF OBSERVATIONS USED                      =           9
=================================================================
```

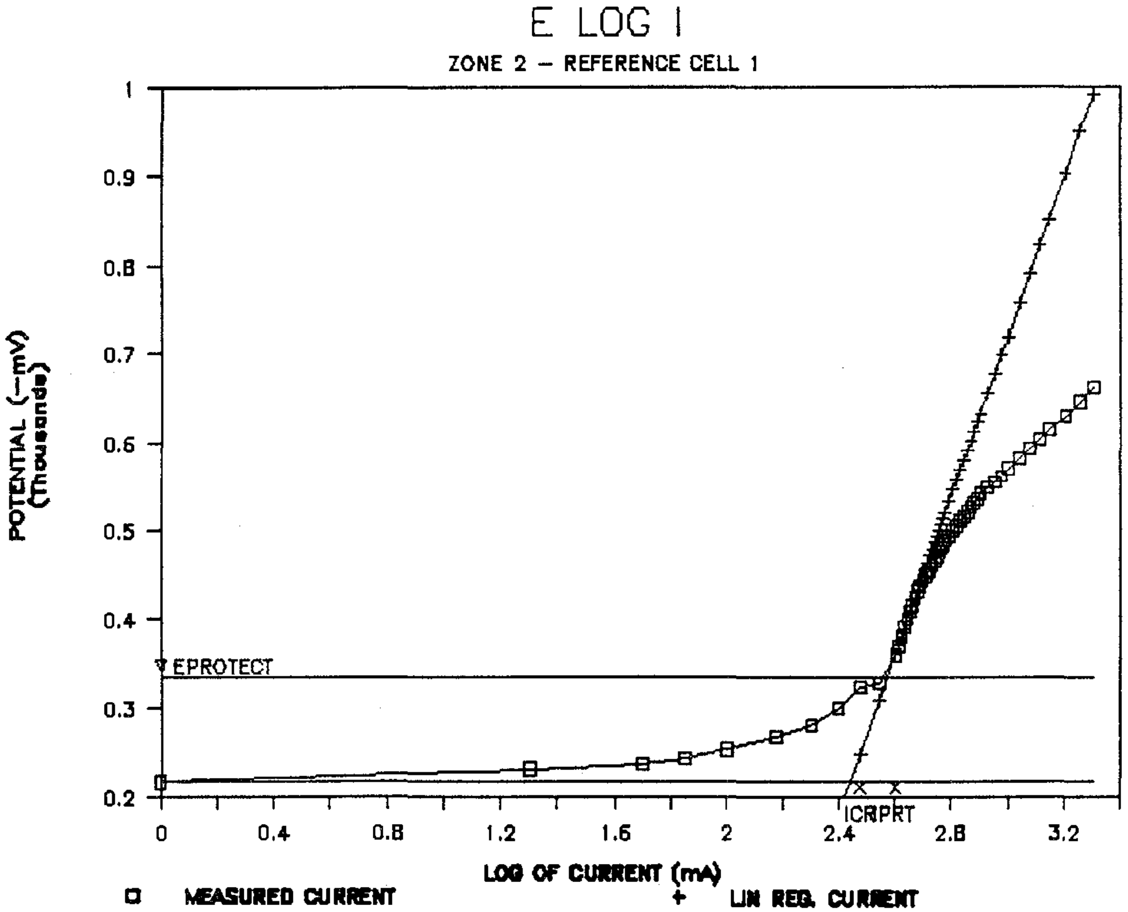


Figure 65. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 1 at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                  ZONE 2 - REFERENCE CELL 2
-----------------------------------------------------------------
      TAFEL SLOPE       =        856.05 MILLIVOLTS/DECADE
      ICORR             =        250.60 MILLIAMPS
      ECORR             =          -134 MILLIVOLTS
      IPROTECT          =        374.17 MILLIAMPS
      EPROTECT          =       -283.02 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     2.35689
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99238
      NO. OF OBSERVATIONS USED                      =          10
=================================================================
```

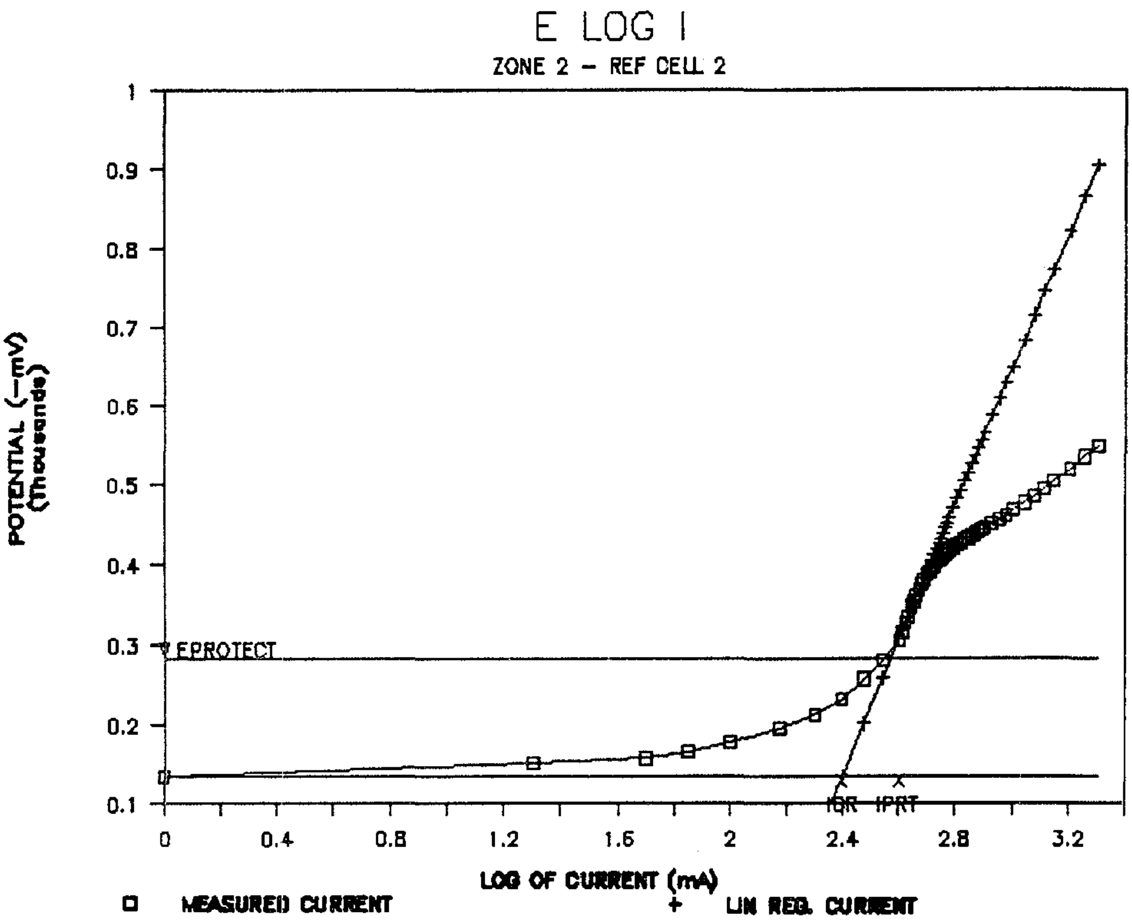


Figure 66. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 2 at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

```
==================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   ZONE 3 - REFERENCE CELL 1
------------------------------------------------------------------
      TAFEL SLOPE      =        772.78 MILLIVOLTS/DECADE
      ICORR            =        290.24 MILLIAMPS
      ECORR            =          -111 MILLIVOLTS
      IPROTECT         =        374.16 MILLIAMPS
      EPROTECT         =       -196.24 MILLIVOLTS
==================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
------------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                   =     1.95068
      COEFFICIENT OF DETERMINATION (R SQUARED)       =     0.99517
      NO. OF OBSERVATIONS USED                       =          12
==================================================================
```

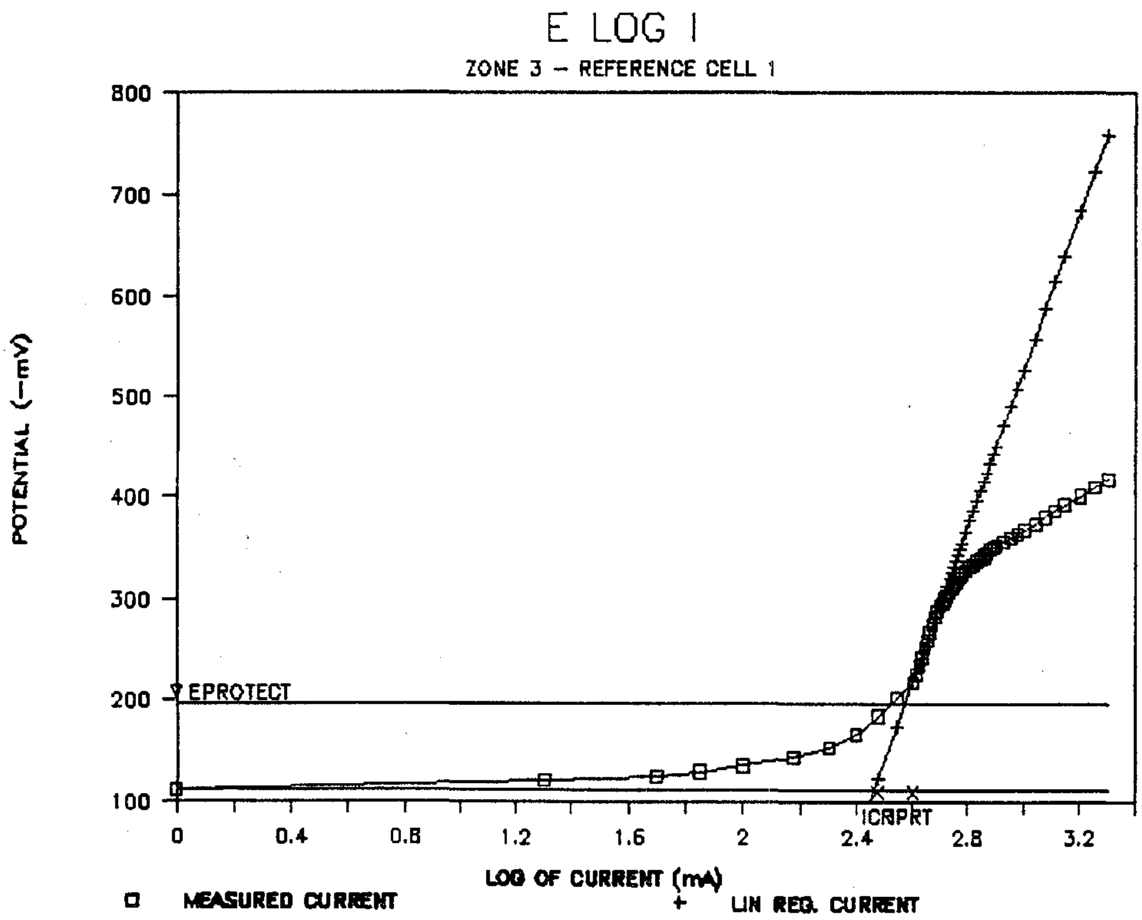


Figure 67. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell 1 at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                  ZONE 3 - REFERENCE CELL 2
-----------------------------------------------------------------
     TAFEL SLOPE     =        592.71 MILLIVOLTS/DECADE
     ICORR           =        247.38 MILLIAMPS
     ECORR           =          -207 MILLIVOLTS
     IPROTECT        =        404.97 MILLIAMPS
     EPROTECT        =       -333.87 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                  =     2.17865
     COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.98650
     NO. OF OBSERVATIONS USED                      =          10
=================================================================
```

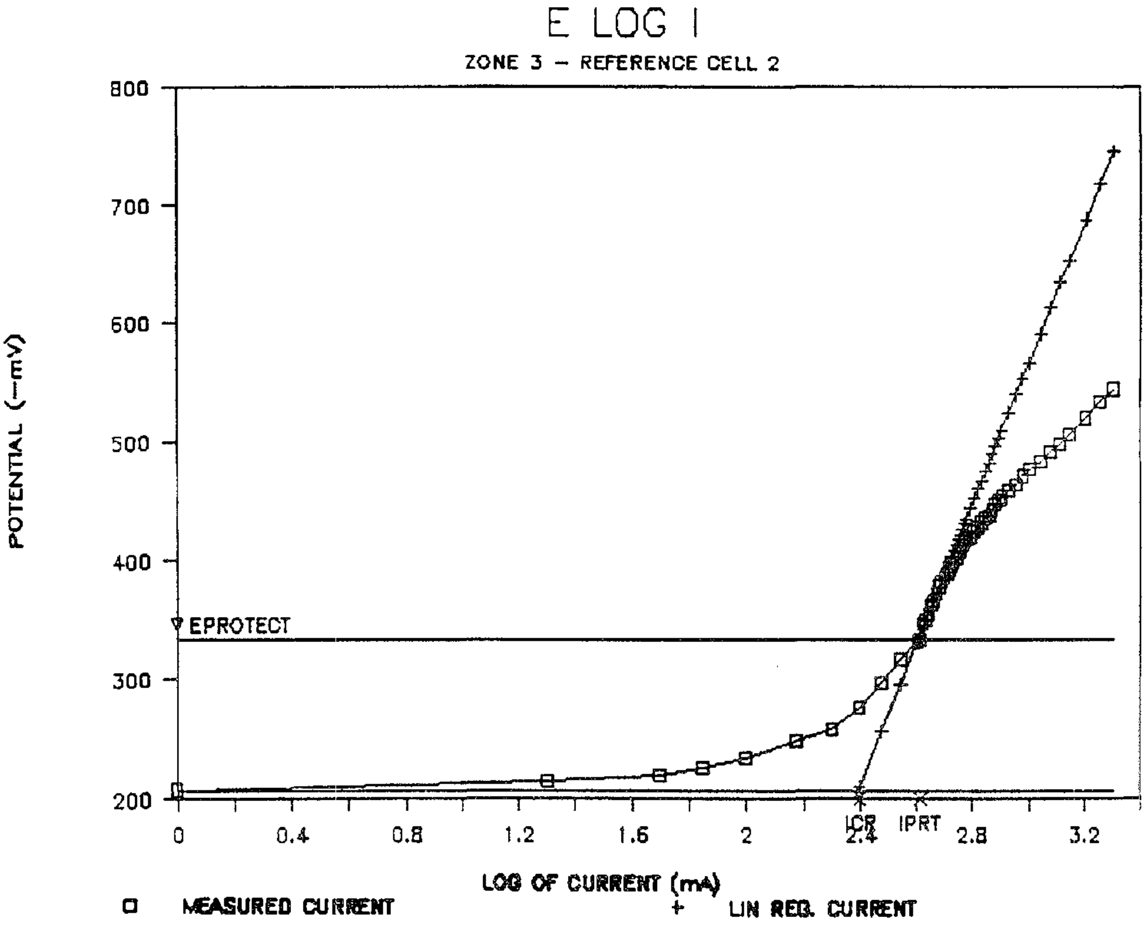


Figure 68. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell 2 at 9-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                 ZONE 1 - REFERENCE CELL 1 (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE     =        404.76 MILLIVOLTS/DECADE
      ICORR           =        764.60 MILLIAMPS
      ECORR           =           -83 MILLIVOLTS
      IPROTECT        =       2371.70 MILLIAMPS
      EPROTECT        =       -281.99 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                =     2.05262
      COEFFICIENT OF DETERMINATION (R SQUARED)    =     0.99765
      NO. OF OBSERVATIONS USED                    =          11
=================================================================
```

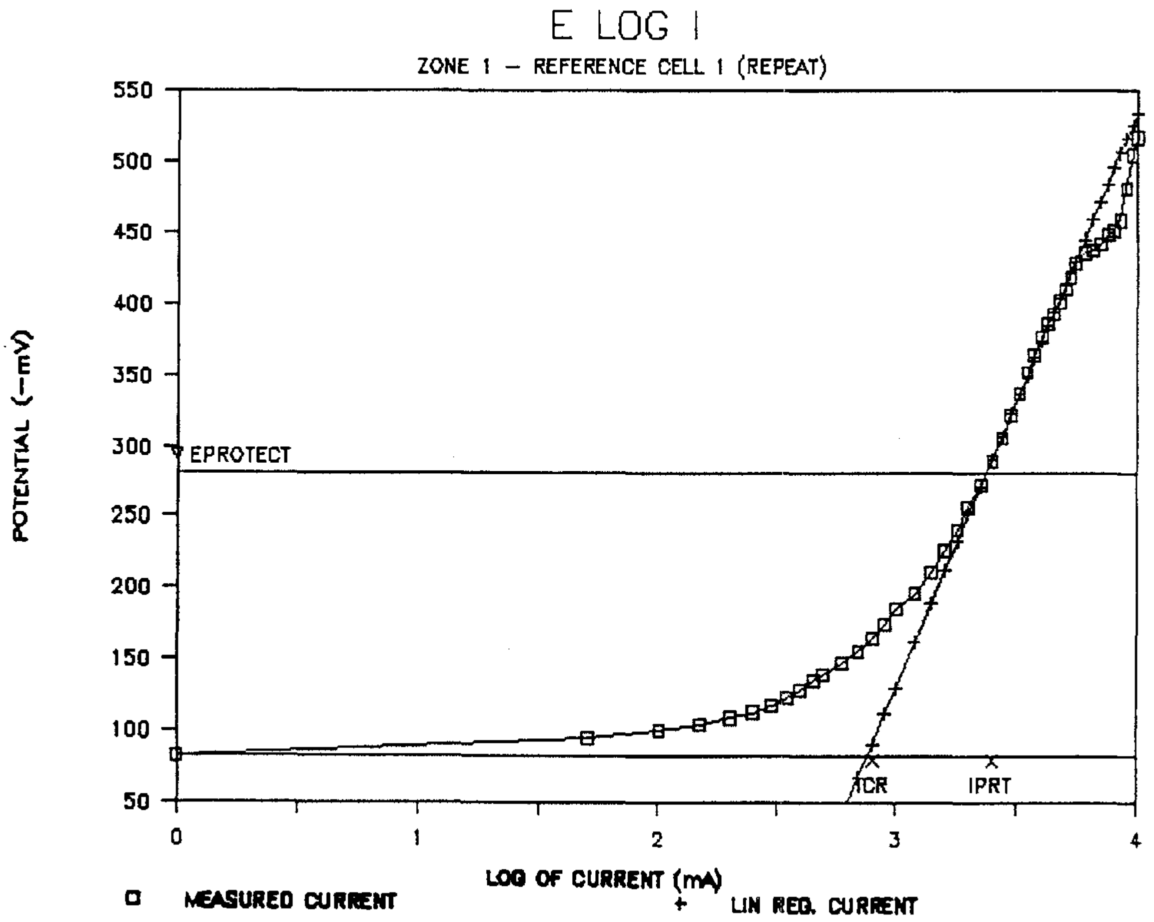


Figure 69. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell 1 (repeat) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                 ZONE 1 - REFERENCE CELL 2 (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE       =        282.91 MILLIVOLTS/DECADE
      ICORR             =        571.84 MILLIAMPS
      ECORR             =           -86 MILLIVOLTS
      IPROTECT          =       2121.32 MILLIAMPS
      EPROTECT          =       -247.07 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.46386
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99797
      NO. OF OBSERVATIONS USED                     =          13
=================================================================
```

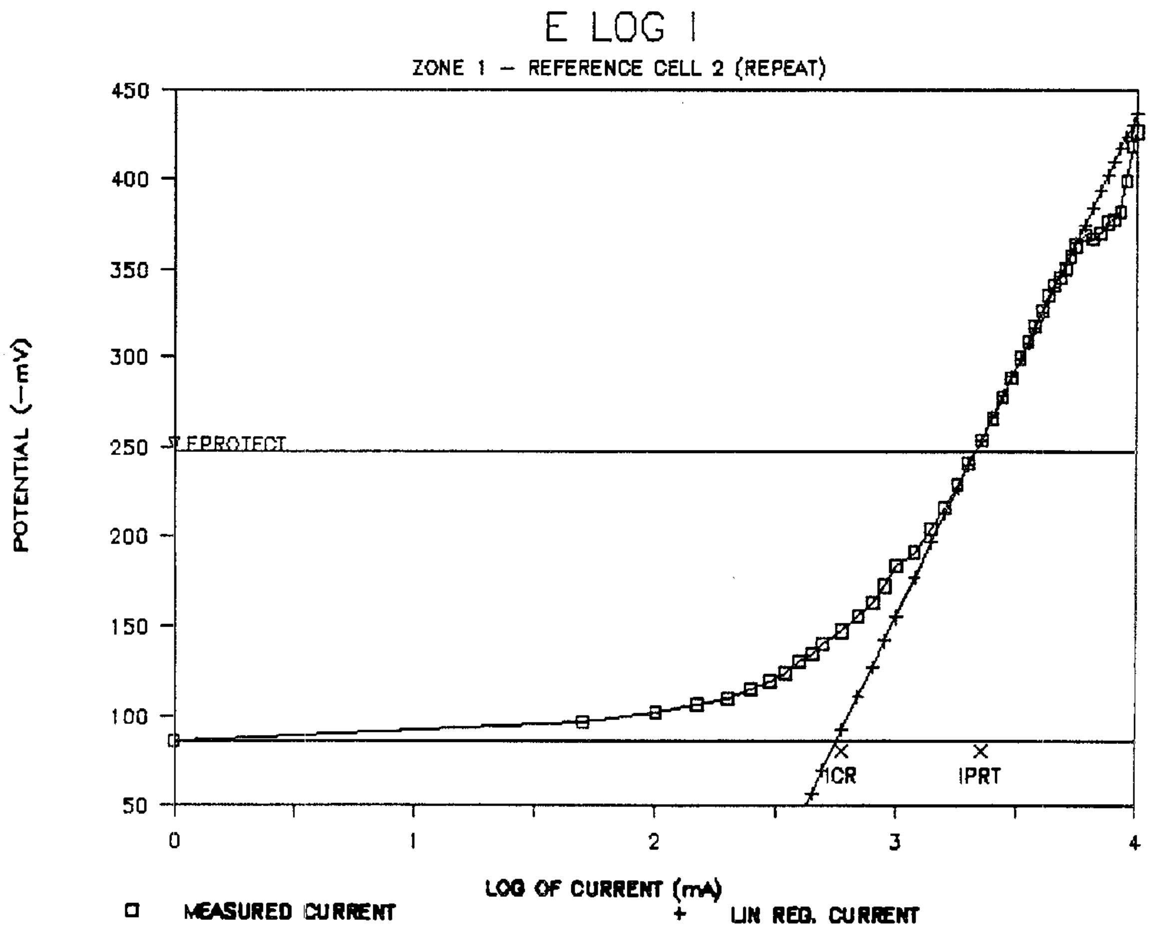


Figure 70. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell 2 (repeat) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                ZONE 2 - REFERENCE CELL 1 (REPEAT)
-----------------------------------------------------------------
     TAFEL SLOPE      =        501.87 MILLIVOLTS/DECADE
     ICORR            =        170.56 MILLIAMPS
     ECORR            =          -187 MILLIVOLTS
     IPROTECT         =        309.84 MILLIAMPS
     EPROTECT         =       -317.12 MILLIVOLTS
=================================================================


     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                  =     0.74191
     COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99970
     NO. OF OBSERVATIONS USED                      =          14
=================================================================
```

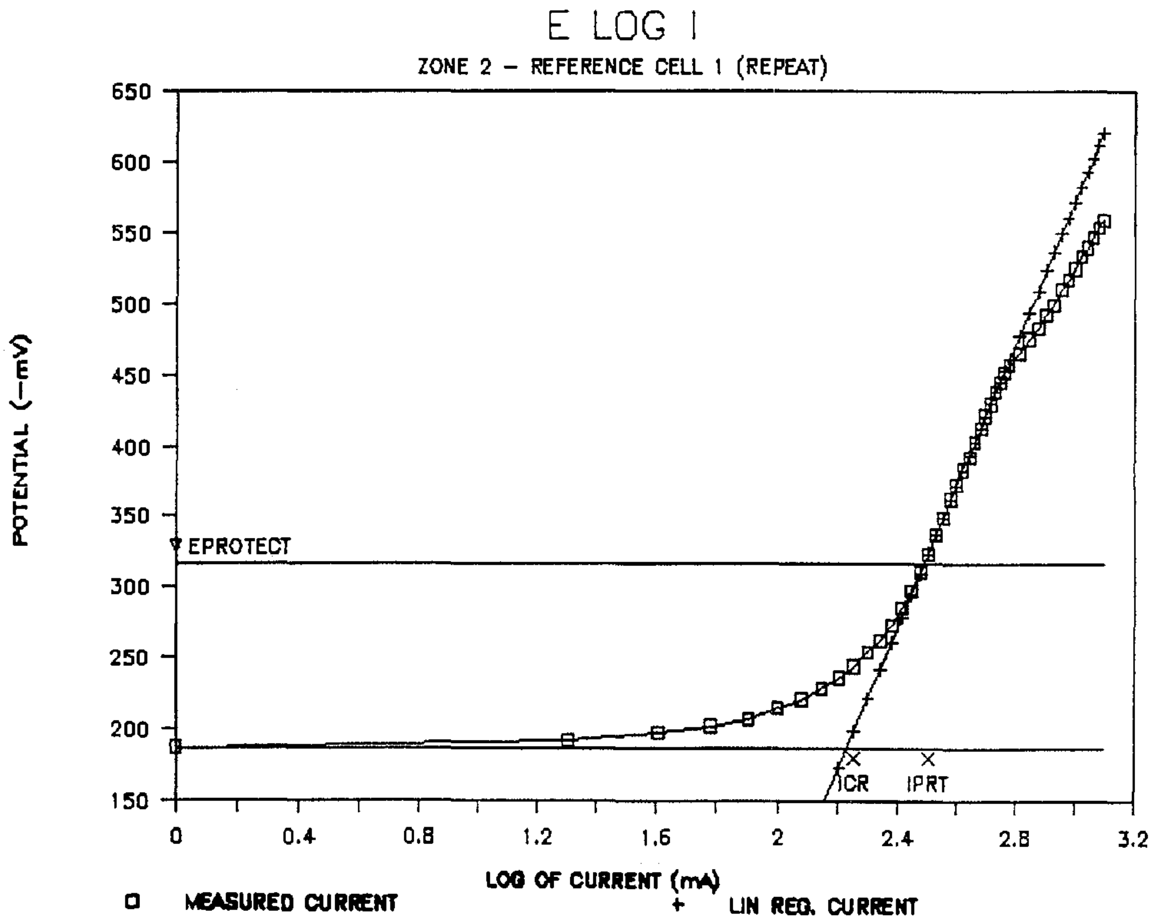


Figure 71. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 1 (repeat) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                 ZONE 2 - REFERENCE CELL 2 (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE      =        421.88 MILLIVOLTS/DECADE
      ICORR            =        115.39 MILLIAMPS
      ECORR            =           -25 MILLIVOLTS
      IPROTECT         =        289.83 MILLIAMPS
      EPROTECT         =       -193.74 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.18426
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99930
      NO. OF OBSERVATIONS USED                     =          17
=================================================================
```

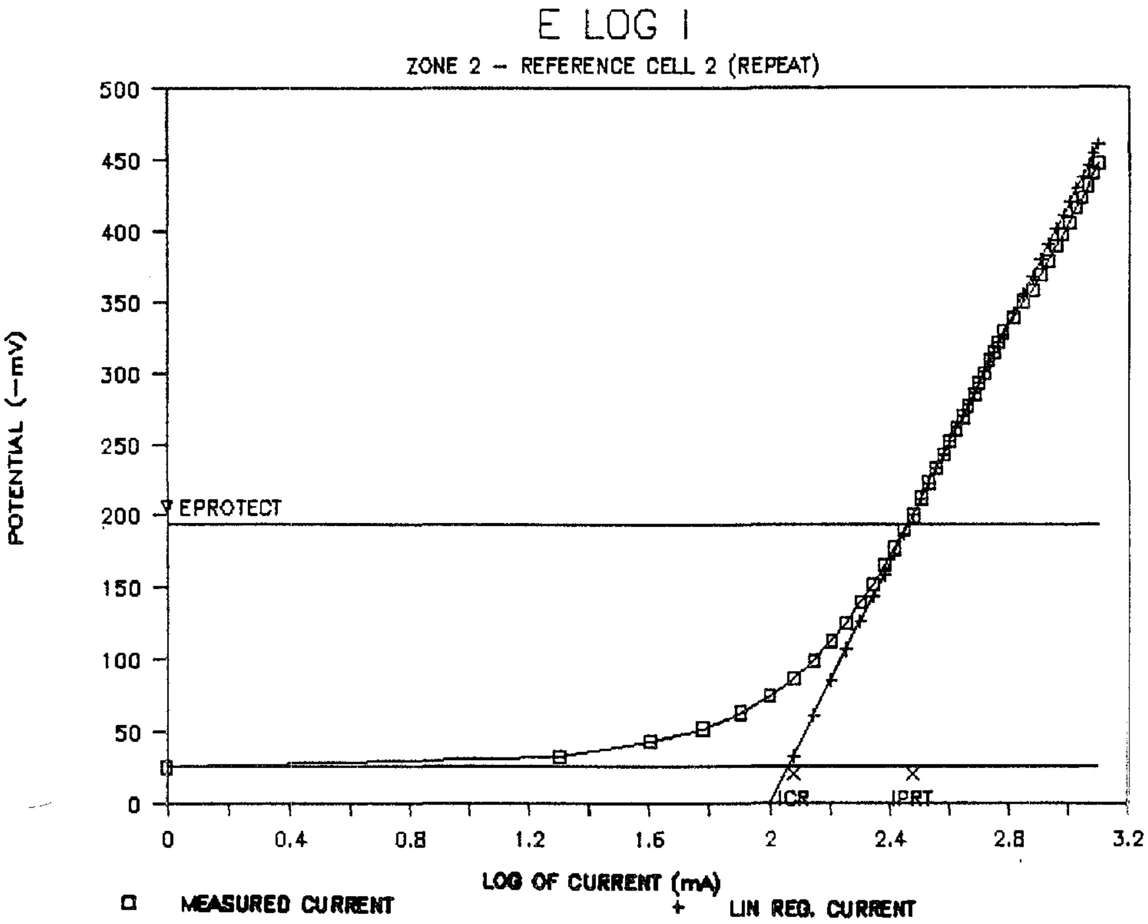


Figure 72. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 2 (repeat) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                ZONE 3 - REFERENCE CELL 1 (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE       =          406.81 MILLIVOLTS/DECADE
      ICORR             =          201.57 MILLIAMPS
      ECORR             =             -96 MILLIVOLTS
      IPROTECT          =          469.89 MILLIAMPS
      EPROTECT          =         -245.53 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =      0.37505
      COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.99967
      NO. OF OBSERVATIONS USED                     =            9
=================================================================
```

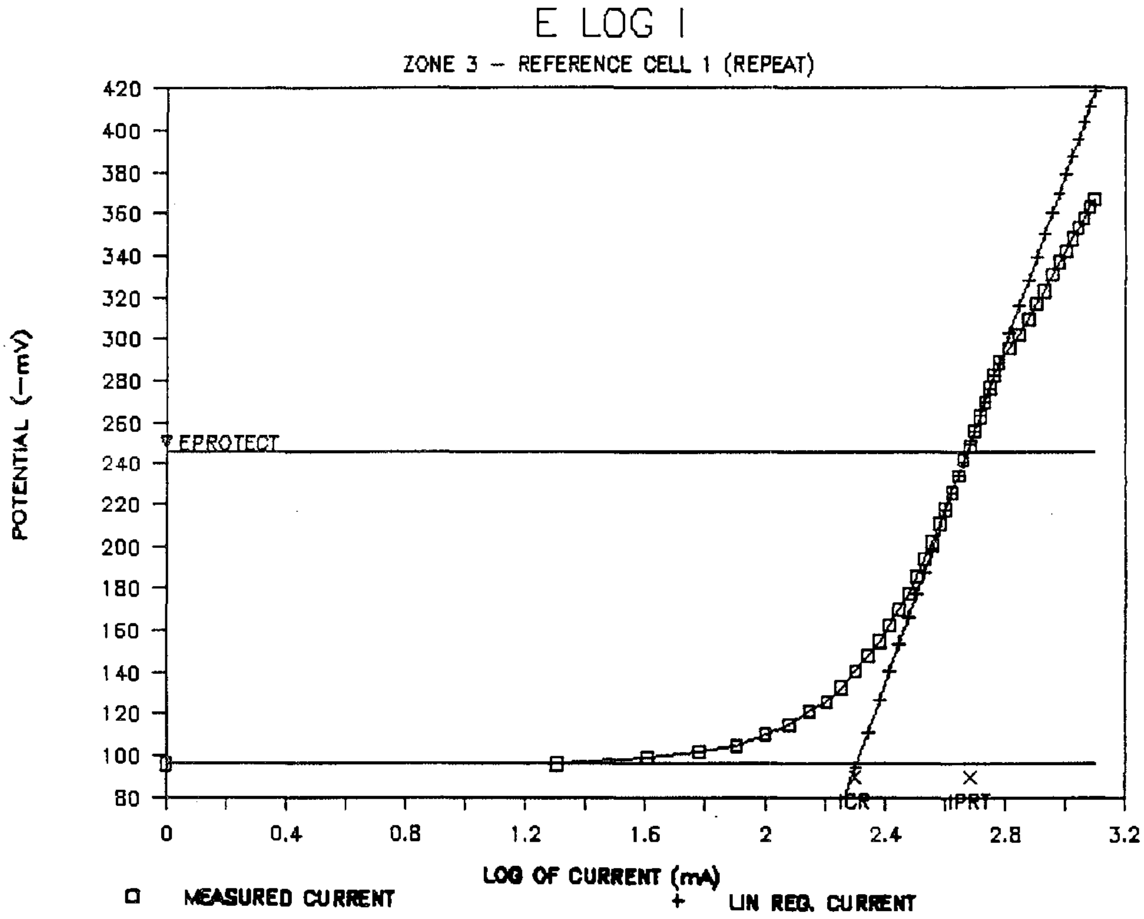


Figure 73. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell 1 (repeat) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                ZONE 3 - REFERENCE CELL 2 (REPEAT)
-----------------------------------------------------------------
     TAFEL SLOPE      =        280.14 MILLIVOLTS/DECADE
     ICORR            =        121.66 MILLIAMPS
     ECORR            =          -208 MILLIVOLTS
     IPROTECT         =        269.81 MILLIAMPS
     EPROTECT         =       -304.91 MILLIVOLTS
=================================================================


     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                 =      0.633513
     COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.999517
     NO. OF OBSERVATIONS USED                     =            16
=================================================================
```

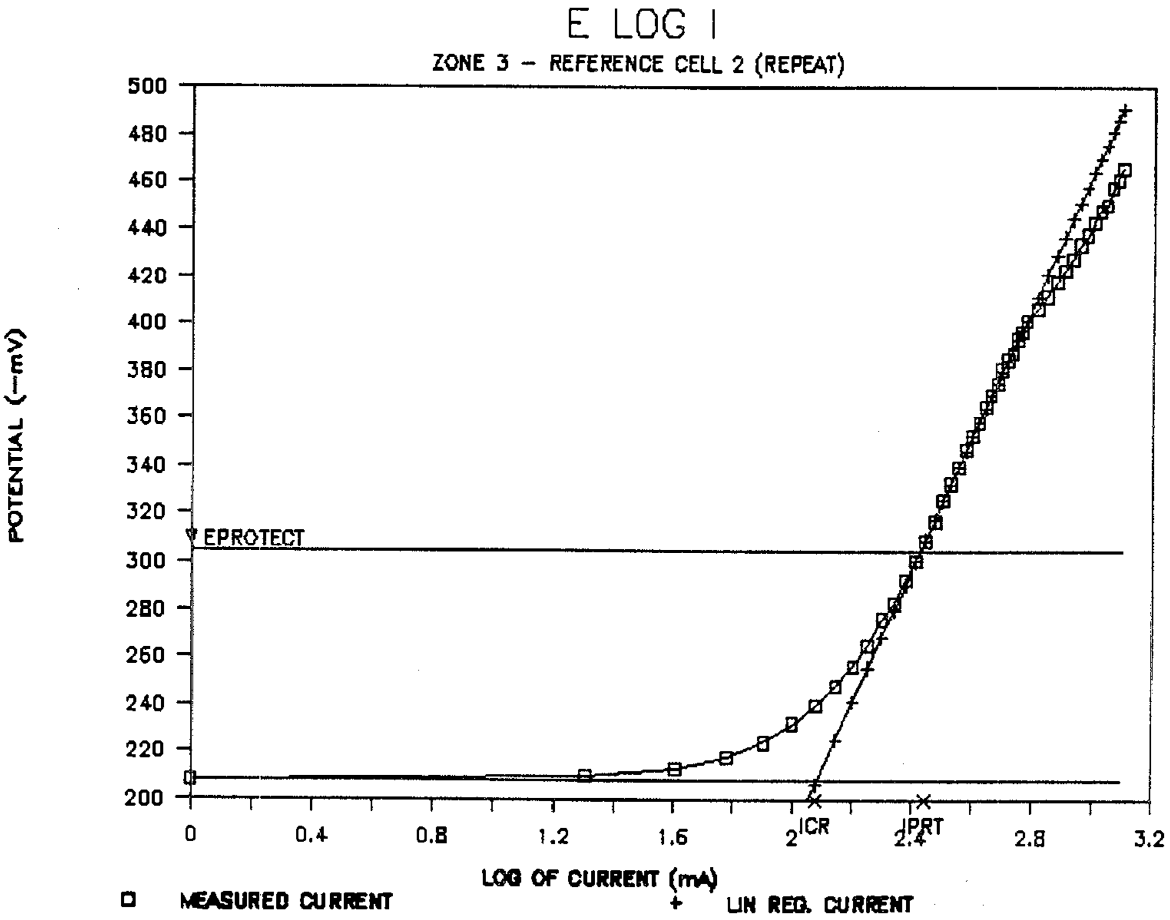


Figure 74. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell 2 (repeat) at 16-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    Zone 1 - Reference Cell 1
-----------------------------------------------------------------
      TAFEL SLOPE      =       306.57 MILLIVOLTS/DECADE
      ICORR            =       480.16 MILLIAMPS
      ECORR            =         -115 MILLIVOLTS
      IPROTECT         =      2097.55 MILLIAMPS
      EPROTECT         =      -311.31 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =      1.65021
      COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.99836
      NO. OF OBSERVATIONS USED                     =           15
=================================================================
```

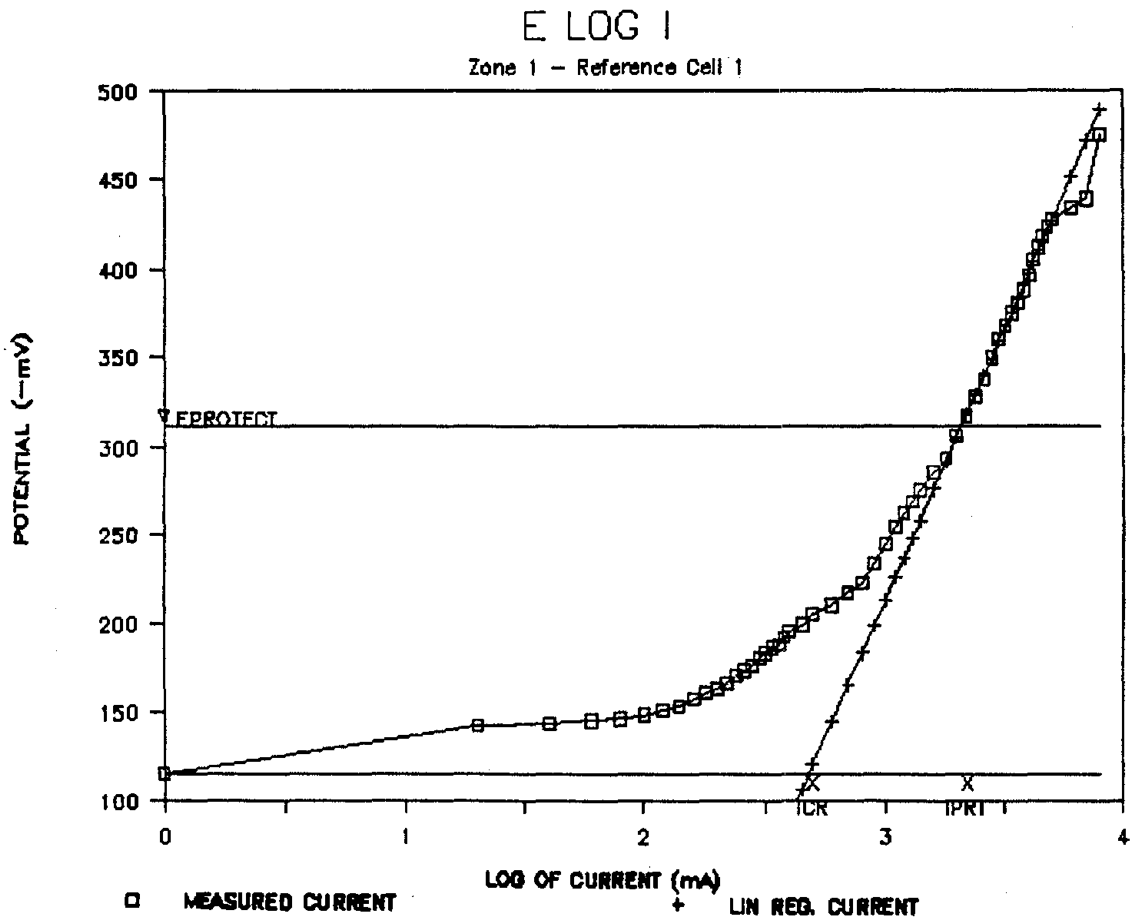


Figure 75. E Log I computed corrosion and cathodic protection data, Zone 1- reference cell 1 at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                  Zone 1 - Reference Cell 2
-----------------------------------------------------------------
      TAFEL SLOPE       =        185.73 MILLIVOLTS/DECADE
      ICORR             =        375.23 MILLIAMPS
      ECORR             =          -117 MILLIVOLTS
      IPROTECT          =       2097.62 MILLIAMPS
      EPROTECT          =       -255.82 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =      0.90283
      COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.99827
      NO. OF OBSERVATIONS USED                     =           15
=================================================================
```

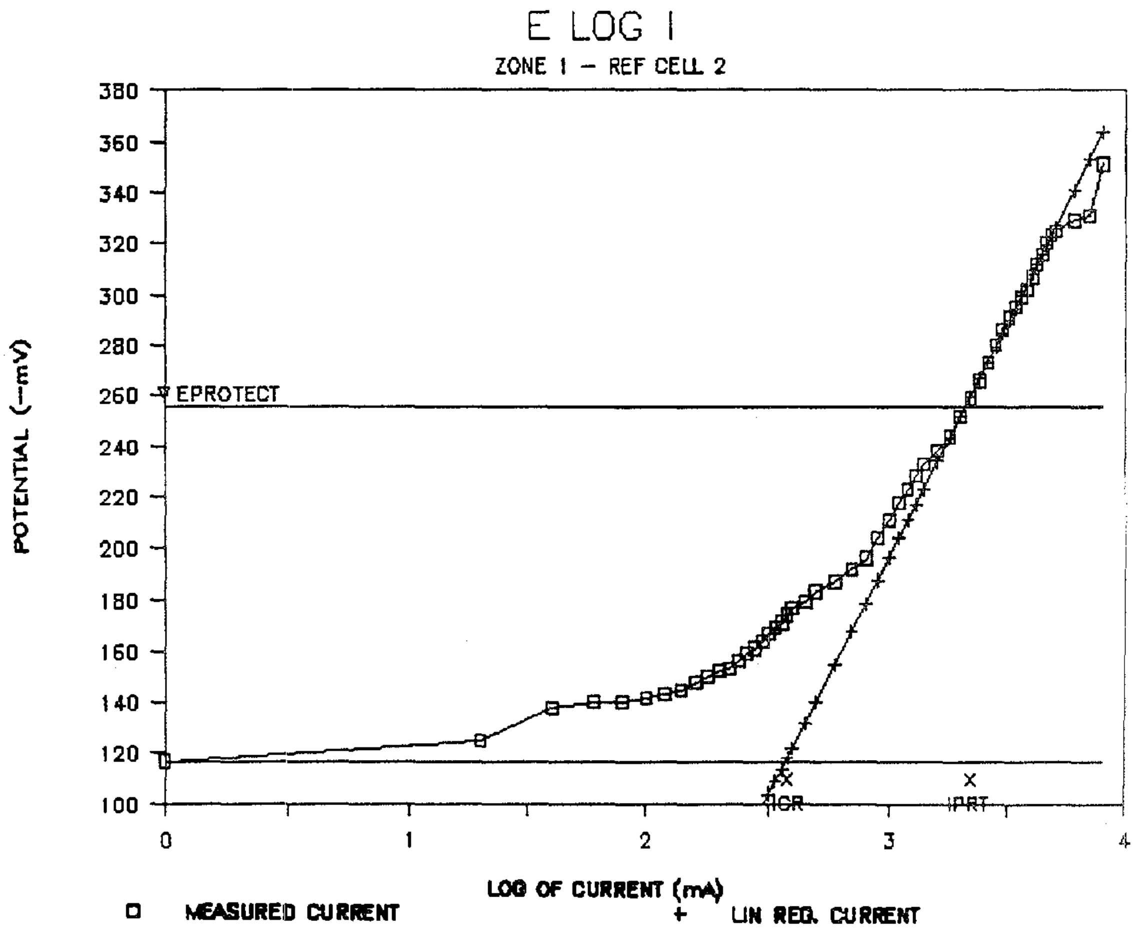


Figure 76. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell 2 at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    Zone 2 - Reference Cell 1
-----------------------------------------------------------------
      TAFEL SLOPE      =        484.96 MILLIVOLTS/DECADE
      ICORR            =        117.06 MILLIAMPS
      ECORR            =          -193 MILLIVOLTS
      IPROTECT         =        320.01 MILLIAMPS
      EPROTECT         =       -404.81 MILLIVOLTS
=================================================================
```

```
      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     3.43652
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99187
      NO. OF OBSERVATIONS USED                     =          13
=================================================================
```

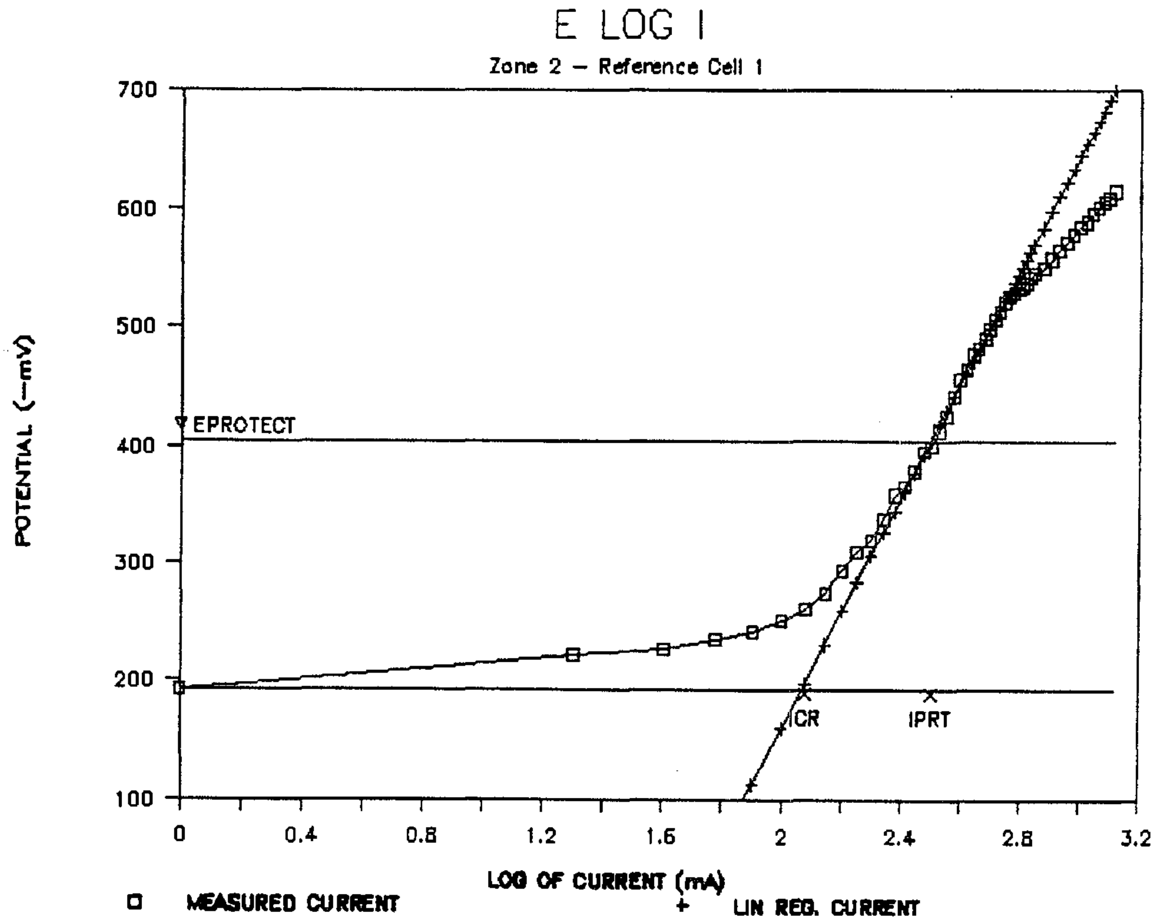


Figure 77. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 1 at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

```
==================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    Zone 2 - Reference Cell 2
------------------------------------------------------------------
      TAFEL SLOPE      =        413.24 MILLIVOLTS/DECADE
      ICORR            =        118.64 MILLIAMPS
      ECORR            =           -36 MILLIVOLTS
      IPROTECT         =        249.80 MILLIAMPS
      EPROTECT         =       -169.63 MILLIVOLTS
==================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
------------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     1.23709
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99956
      NO. OF OBSERVATIONS USED                      =          24
==================================================================
```

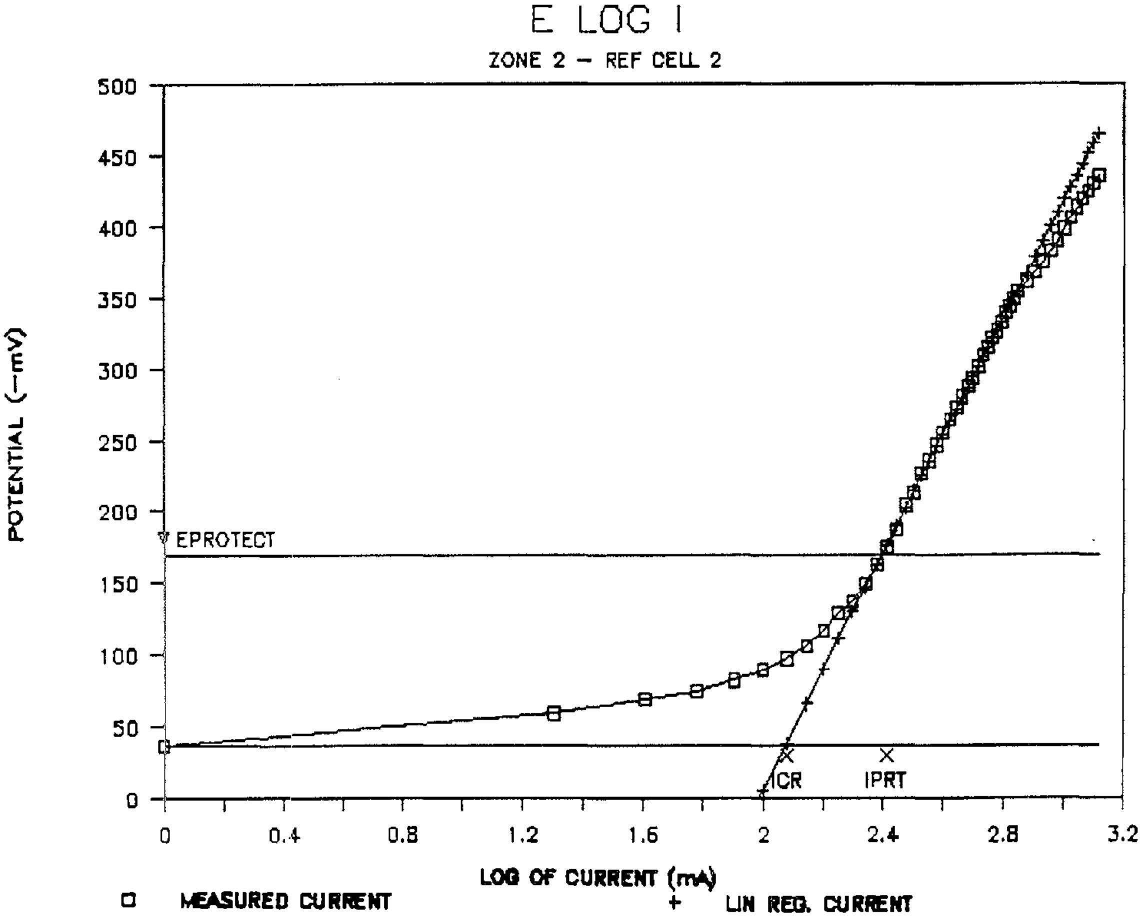


Figure 78. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell 2 at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

```
================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                  Zone 3 - Reference Cell 1
----------------------------------------------------------------
      TAFEL SLOPE      =        370.49 MILLIVOLTS/DECADE
      ICORR            =        157.15 MILLIAMPS
      ECORR            =          -103 MILLIVOLTS
      IPROTECT         =        309.84 MILLIAMPS
      EPROTECT         =       -212.22 MILLIVOLTS
================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.52821
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99811
      NO. OF OBSERVATIONS USED                     =          14
================================================================
```

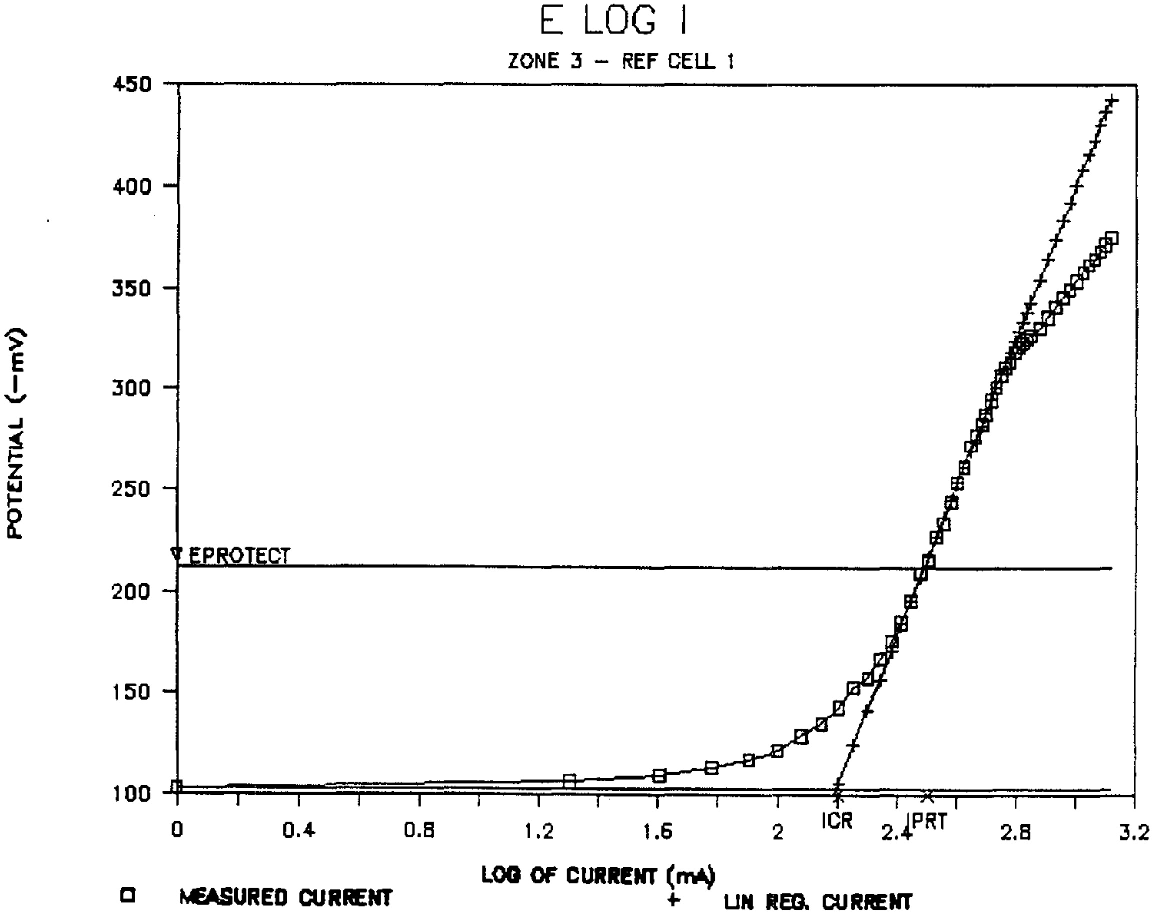


Figure 79. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell 1 at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    Zone 3 - Reference Cell 2
-----------------------------------------------------------------
     TAFEL SLOPE      =       286.82 MILLIVOLTS/DECADE
     ICORR            =       116.42 MILLIAMPS
     ECORR            =         -203 MILLIVOLTS
     IPROTECT         =       269.82 MILLIAMPS
     EPROTECT         =      -307.70 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                 =     0.96883
     COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99845
     NO. OF OBSERVATIONS USED                     =          14
=================================================================
```

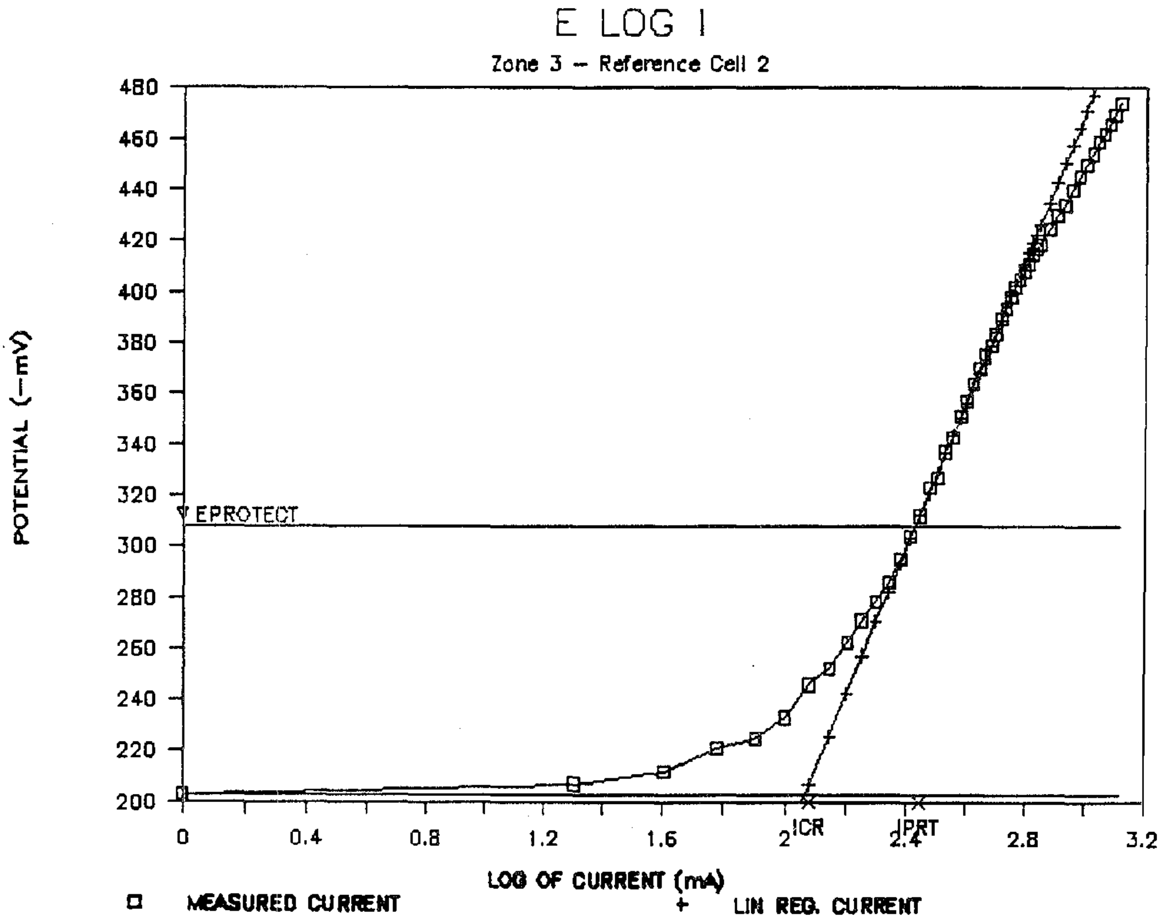


Figure 80. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell 2 at 23-month evaluation, marine environment bridge, Norfolk, Virginia.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   ZONE 1 - REFERENCE CELL A
-----------------------------------------------------------------
      TAFEL SLOPE      =        416.62 MILLIVOLTS/DECADE
      ICORR            =       2002.17 MILLIAMPS
      ECORR            =          -309 MILLIVOLTS
      IPROTECT         =       4974.39 MILLIAMPS
      EPROTECT         =       -472.66 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     0.85244
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99841
      NO. OF OBSERVATIONS USED                     =          14
=================================================================
```

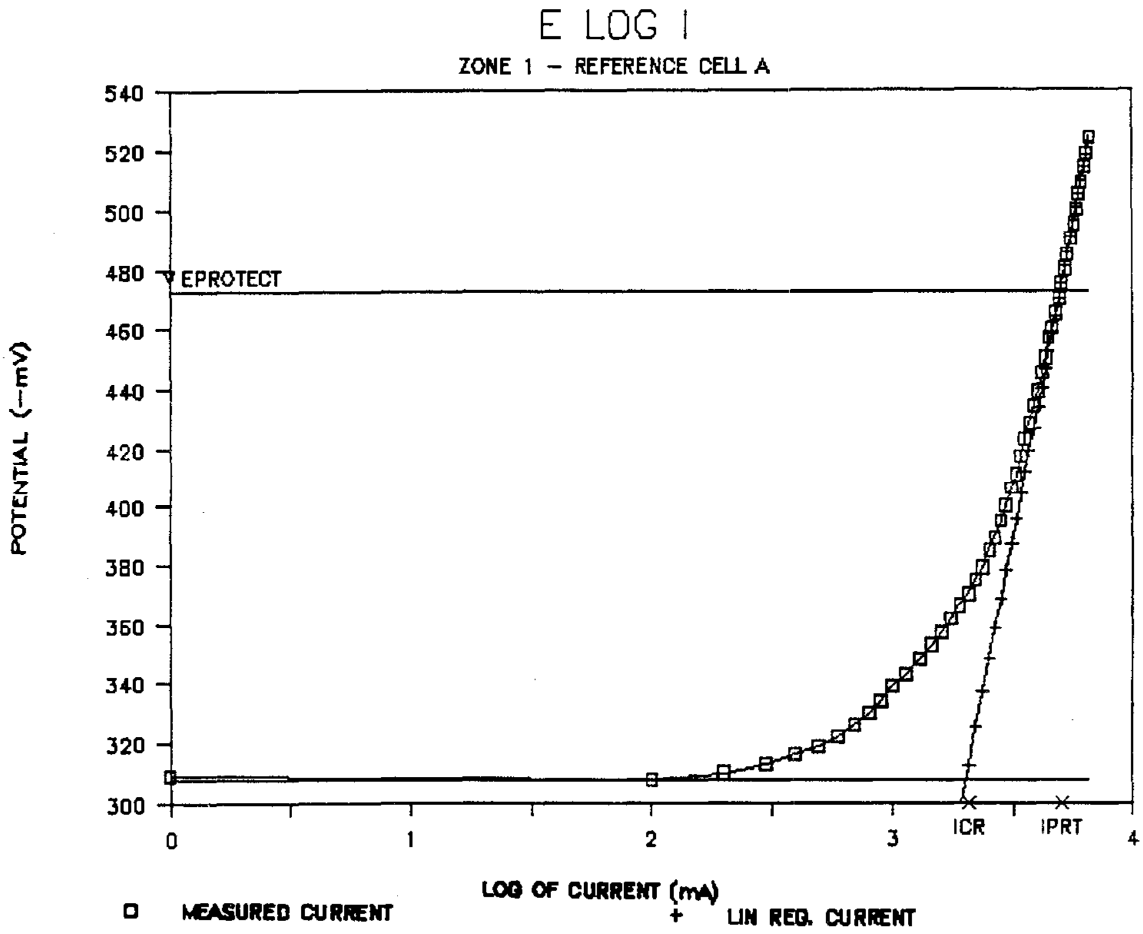


Figure 81. E Log I computed corrosion and cathodic protection data
Zone 1- reference cell A at initial evaluation,
northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                  ZONE 1 - REFERENCE CELL B
-----------------------------------------------------------------
      TAFEL SLOPE      =        321.65 MILLIVOLTS/DECADE
      ICORR            =       1032.96 MILLIAMPS
      ECORR            =          -386 MILLIVOLTS
      IPROTECT         =       3024.13 MILLIAMPS
      EPROTECT         =       -536.06 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     0.68859
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99968
      NO. OF OBSERVATIONS USED                      =          27
=================================================================
```

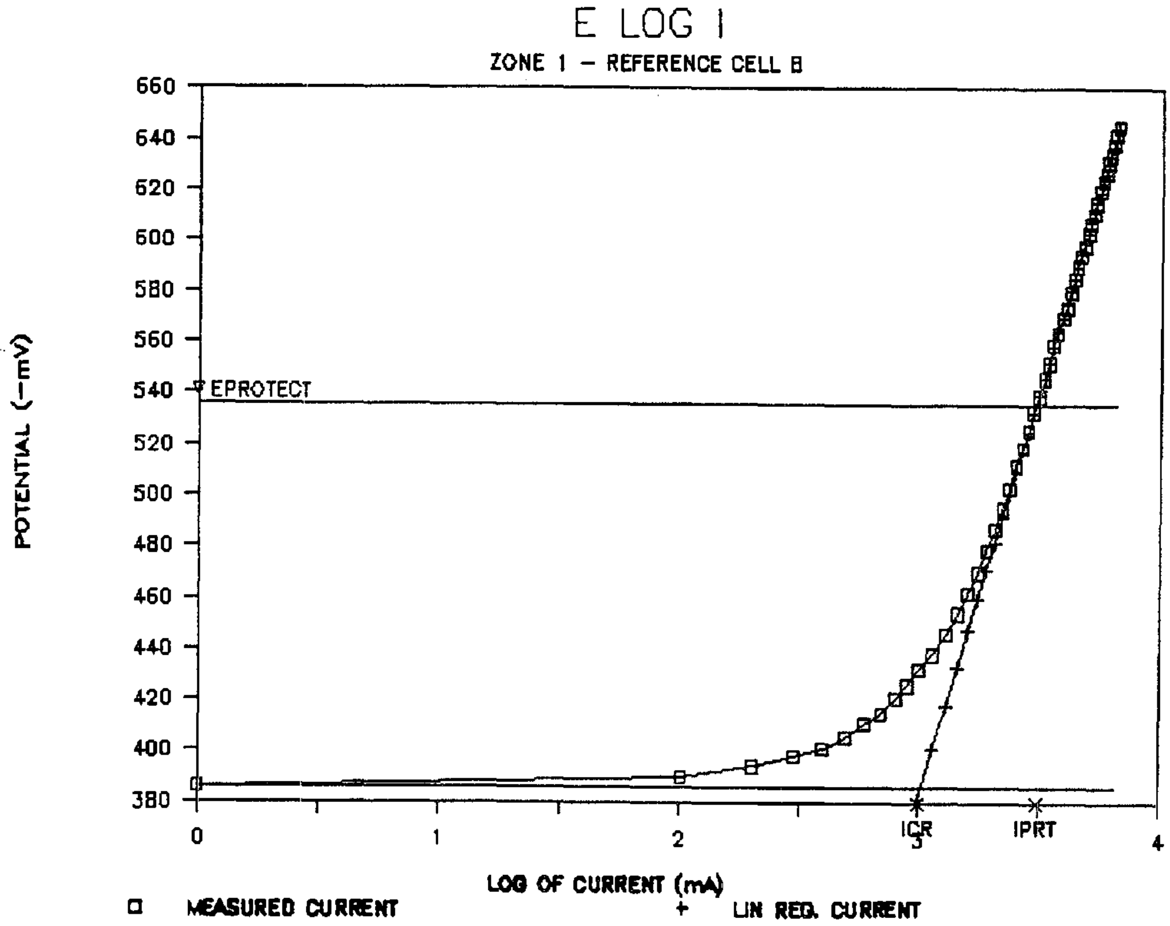


Figure 82. E Log I computed corrosion and cathodic protection data Zone 1 - reference cell B at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 1 - REFERENCE CELL C
-----------------------------------------------------------------
      TAFEL SLOPE      =       338.62 MILLIVOLTS/DECADE
      ICORR            =      1120.88 MILLIAMPS
      ECORR            =         -390 MILLIVOLTS
      IPROTECT         =      2873.99 MILLIAMPS
      EPROTECT         =      -528.47 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     0.66781
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99976
      NO. OF OBSERVATIONS USED                     =          28
=================================================================
```

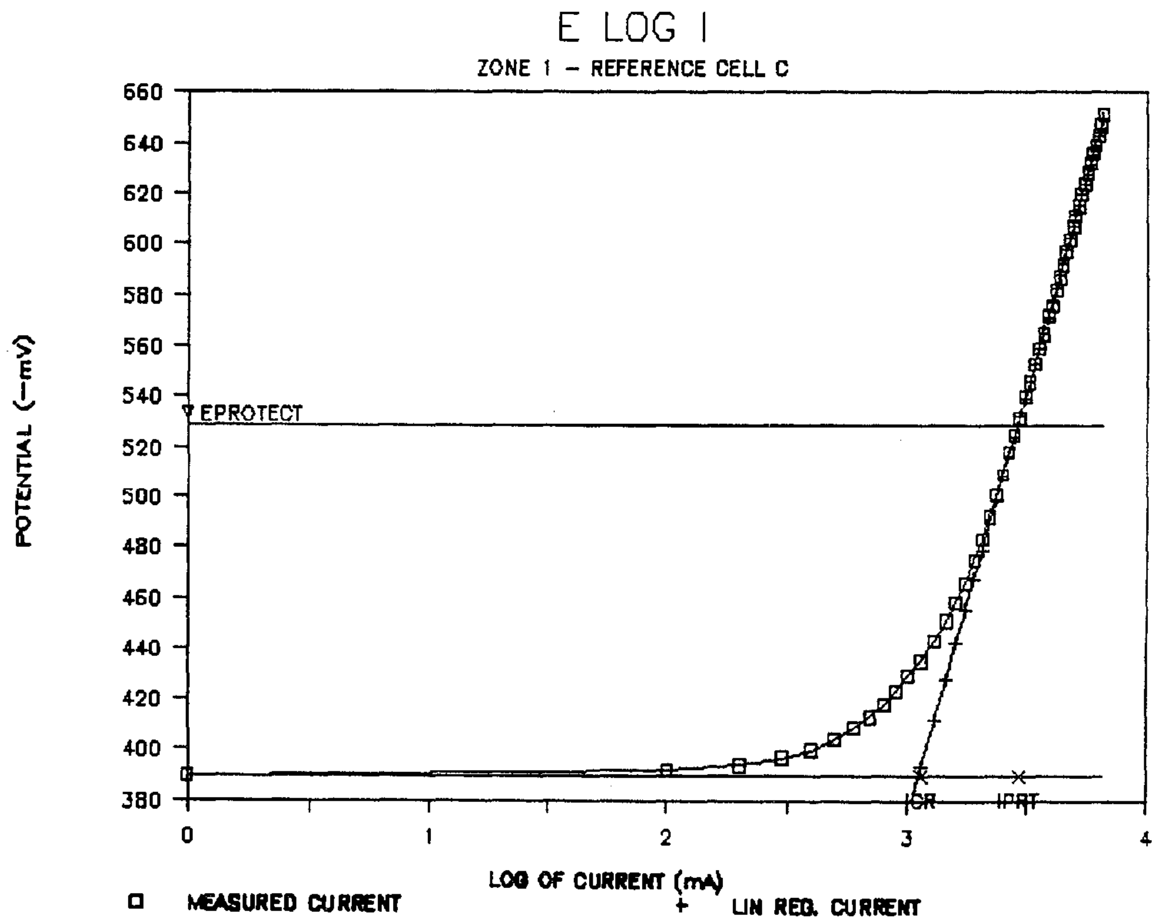


Figure 83. E Log I computed corrosion and cathodic protection data Zone 1 - reference cell C at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                  ZONE 2 - REFERENCE CELL A
-----------------------------------------------------------------
     TAFEL SLOPE       =       339.01 MILLIVOLTS/DECADE
     ICORR             =      1251.08 MILLIAMPS
     ECORR             =         -282 MILLIVOLTS
     IPROTECT          =      3324.17 MILLIAMPS
     EPROTECT          =      -425.88 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                 =     1.15200
     COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99910
     NO. OF OBSERVATIONS USED                     =          26
=================================================================
```

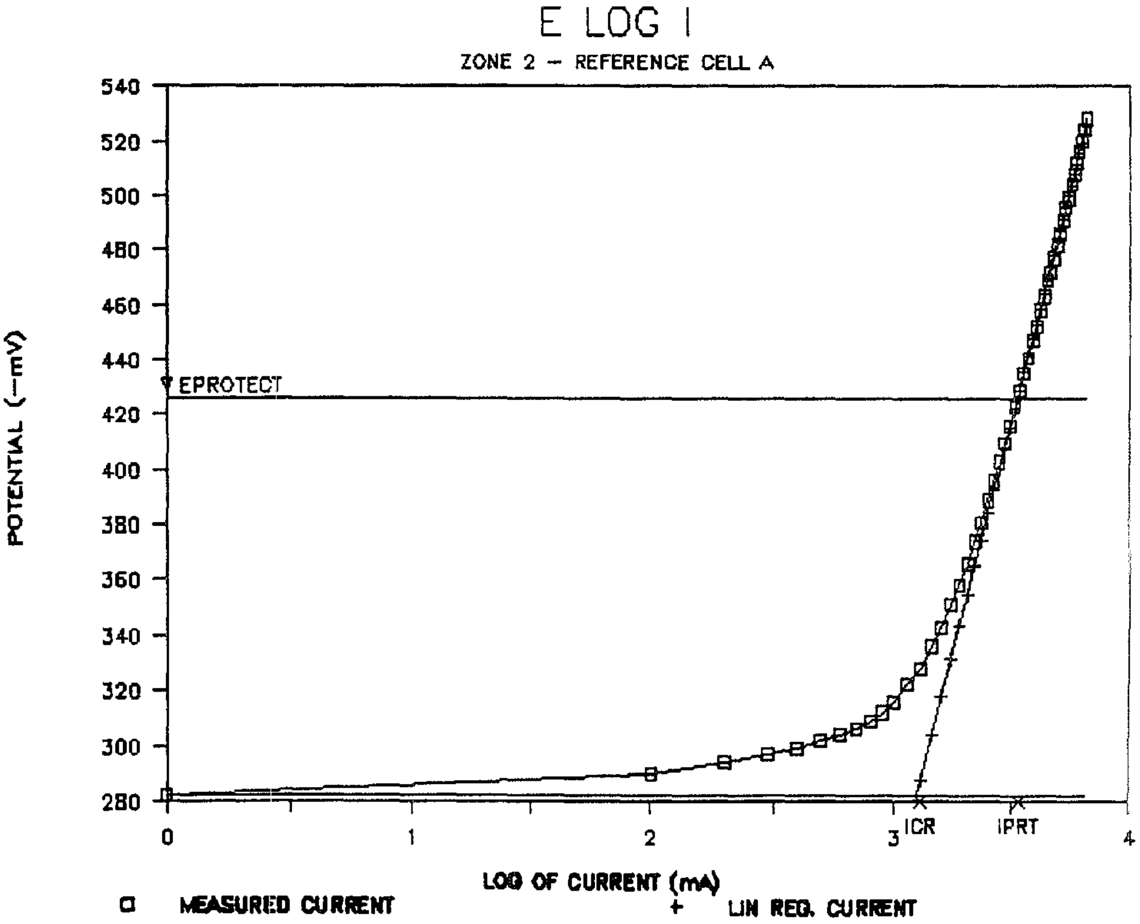


Figure 84. E Log I computed corrosion and cathodic protection data
Zone 2 - reference cell A at initial evaluation,
northern climate bridge, Cincinnati, Ohio.

```
=================================================================
      ELOGI COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   ZONE 2 - REFERENCE CELL B
-----------------------------------------------------------------
      TAFEL SLOPE      =       403.27 MILLIVOLTS/DECADE
      ICORR            =      1067.53 MILLIAMPS
      ECORR            =         -208 MILLIVOLTS
      IPROTECT         =      2874.03 MILLIAMPS
      EPROTECT         =      -381.45 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     0.93821
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99966
      NO. OF OBSERVATIONS USED                     =          28
=================================================================
```

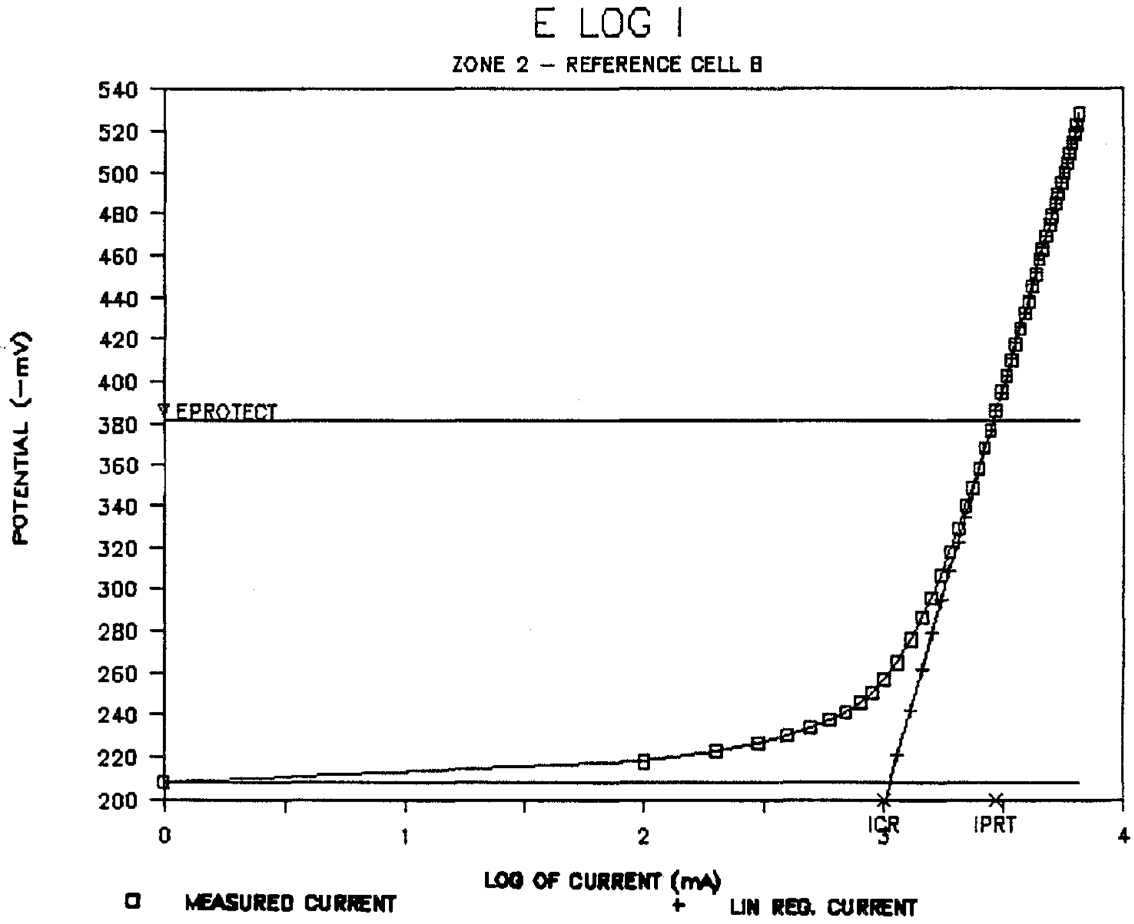


Figure 85. E Log I computed corrosion and cathodic protection data Zone 2 - reference cell B at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 2 - REFERENCE CELL C
-----------------------------------------------------------------
      TAFEL SLOPE      =        307.02 MILLIVOLTS/DECADE
      ICORR            =       1276.34 MILLIAMPS
      ECORR            =          -127 MILLIVOLTS
      IPROTECT         =       3474.19 MILLIAMPS
      EPROTECT         =       -260.52 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                   =    1.13428
      COEFFICIENT OF DETERMINATION (R SQUARED)       =    0.99860
      NO. OF OBSERVATIONS USED                       =         22
=================================================================
```

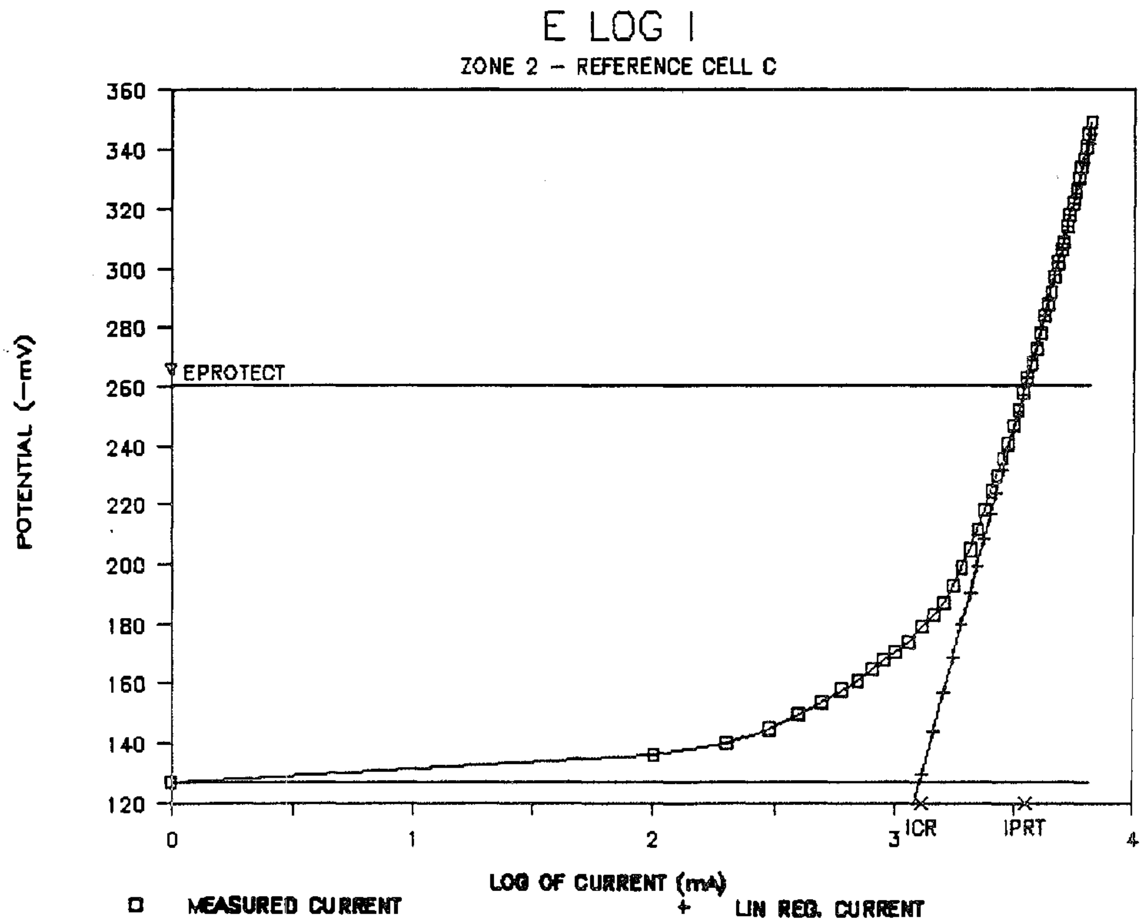


Figure 86. E Log I computed corrosion and cathodic protection data Zone 2 - reference cell C at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
       ZONE 3 - REFERENCE CELL A - NORTH SIDEWALK - TEST 2
-----------------------------------------------------------------
      TAFEL SLOPE      =        531.75 MILLIVOLTS/DECADE
      ICORR            =        844.04 MILLIAMPS
      ECORR            =          -319 MILLIVOLTS
      IPROTECT         =       1849.32 MILLIAMPS
      EPROTECT         =       -500.14 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.23911
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99877
      NO. OF OBSERVATIONS USED                     =          10
=================================================================
```

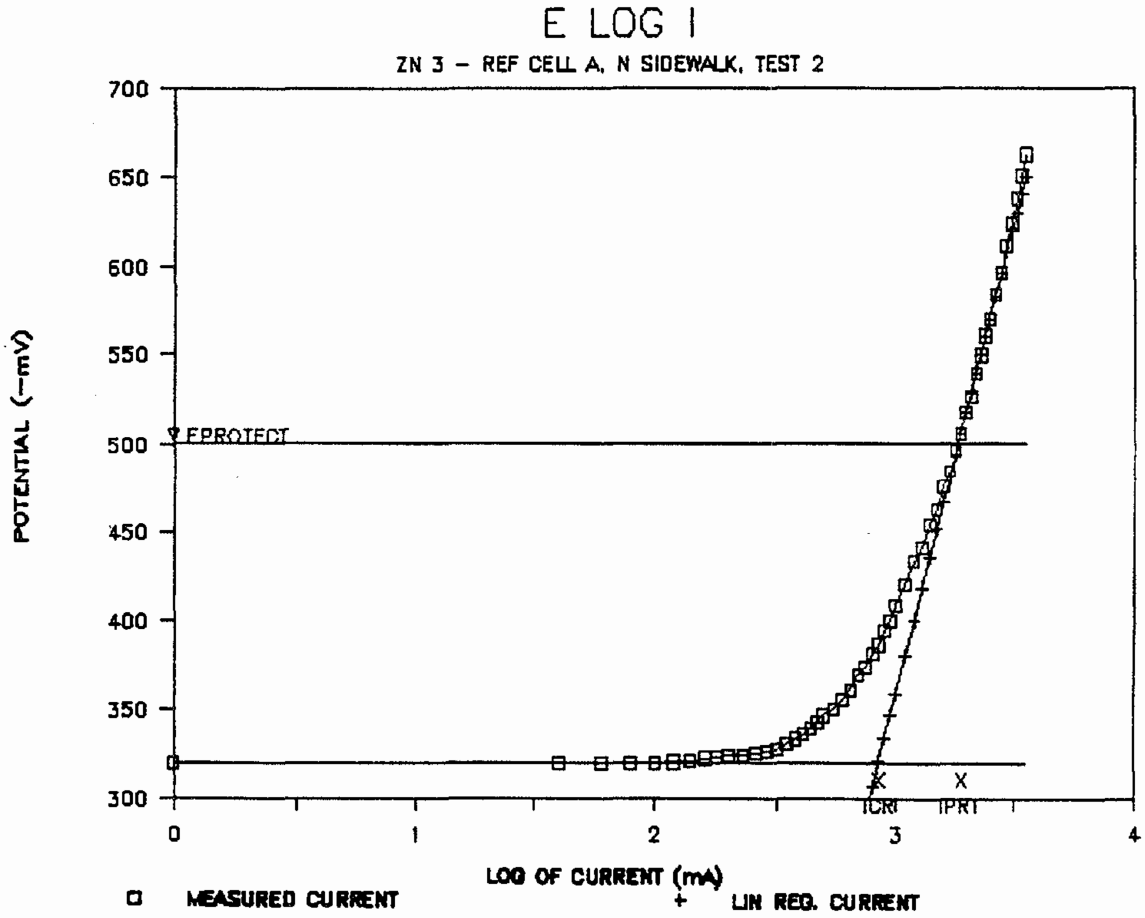


Figure 87. E Log I computed corrosion and cathodic protection data Zone 3 - reference cell A - north sidewalk (test 2) at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
      ZONE 3 - REFERENCE CELL B - SOUTH SIDEWALK - TEST 2
-----------------------------------------------------------------
     TAFEL SLOPE      =       696.70 MILLIVOLTS/DECADE
     ICORR            =       672.04 MILLIAMPS
     ECORR            =         -282 MILLIVOLTS
     IPROTECT         =      1949.34 MILLIAMPS
     EPROTECT         =      -604.22 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                 =     1.83221
     COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99906
     NO. OF OBSERVATIONS USED                     =          13
=================================================================
```

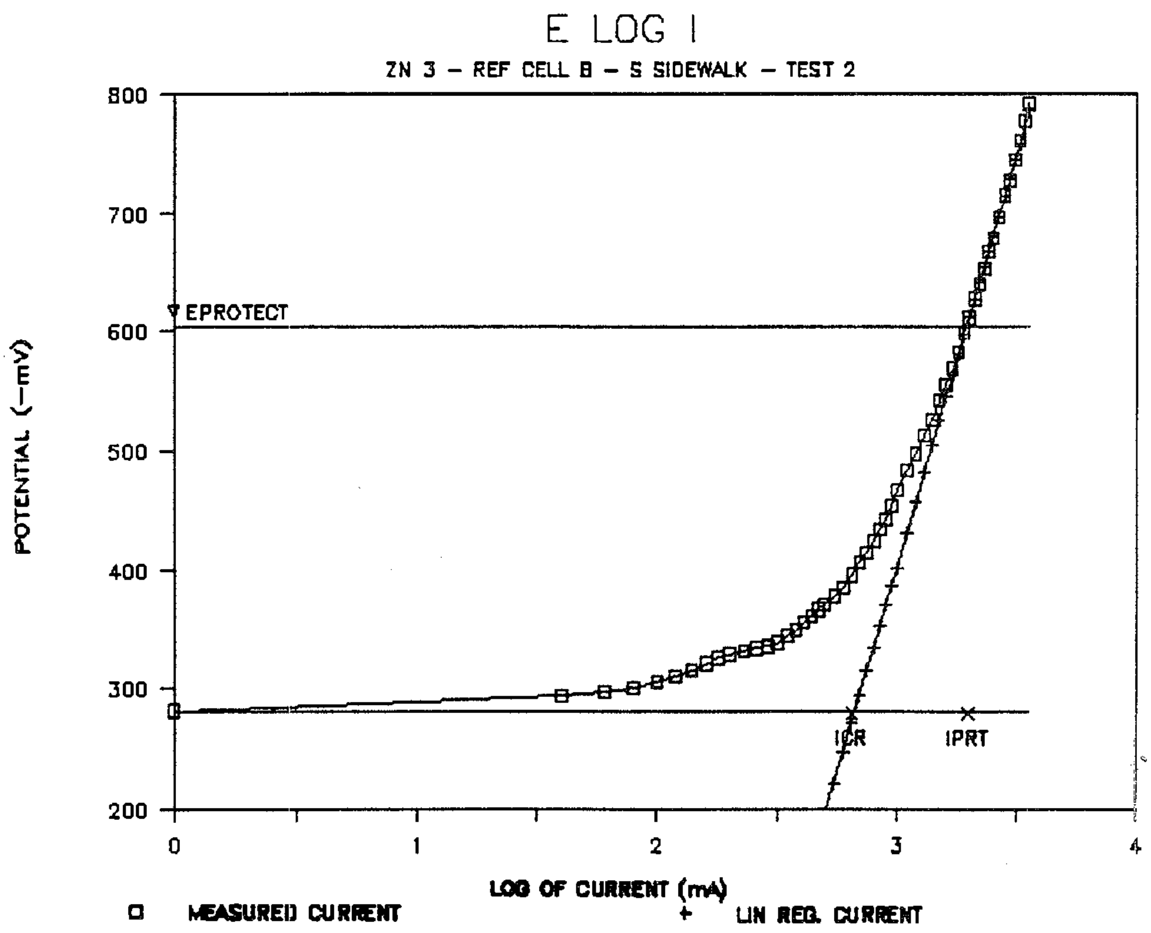


Figure 88. E Log I computed corrosion and cathodic protection data Zone 3 - reference cell B - south sidewalk (test 2) at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
        ZONE 4 - REFERENCE CELL A - WEST PIER - TEST #2
-----------------------------------------------------------------
     TAFEL SLOPE      =        822.17 MILLIVOLTS/DECADE
     ICORR            =        233.11 MILLIAMPS
     ECORR            =          -128 MILLIVOLTS
     IPROTECT         =       1449.14 MILLIAMPS
     EPROTECT         =       -780.44 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                  =      9.86643
     COEFFICIENT OF DETERMINATION (R SQUARED)      =      0.99308
     NO. OF OBSERVATIONS USED                      =           22
=================================================================
```

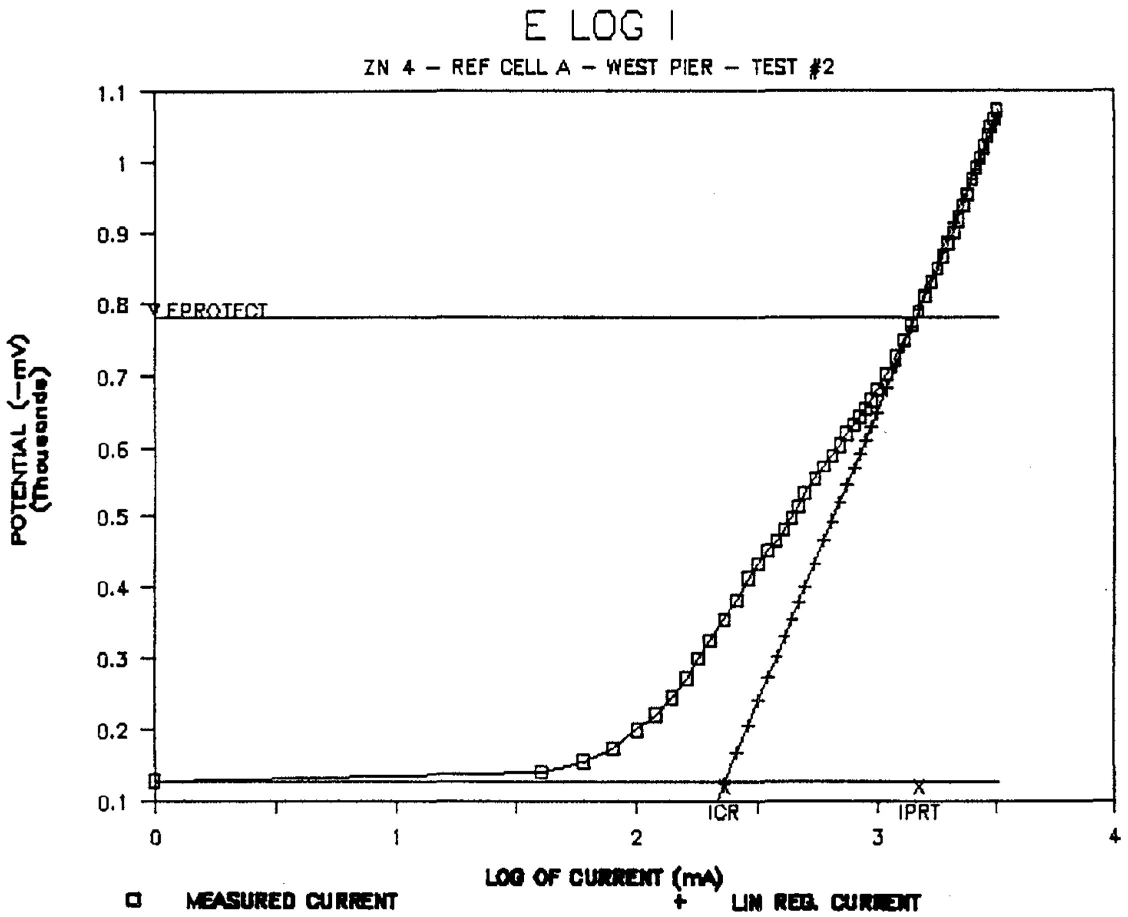


Figure 89. E Log I computed corrosion and cathodic protection data Zone 4 - reference cell A - west pier (test 2) at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
         ZONE 4 - REFERENCE CELL B - EAST PIER - TEST 2
-----------------------------------------------------------------
      TAFEL SLOPE      =        975.45 MILLIVOLTS/DECADE
      ICORR            =        394.09 MILLIAMPS
      ECORR            =          -144 MILLIVOLTS
      IPROTECT         =       1849.33 MILLIAMPS
      EPROTECT         =       -798.94 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     5.83708
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99623
      NO. OF OBSERVATIONS USED                     =          17
=================================================================
```

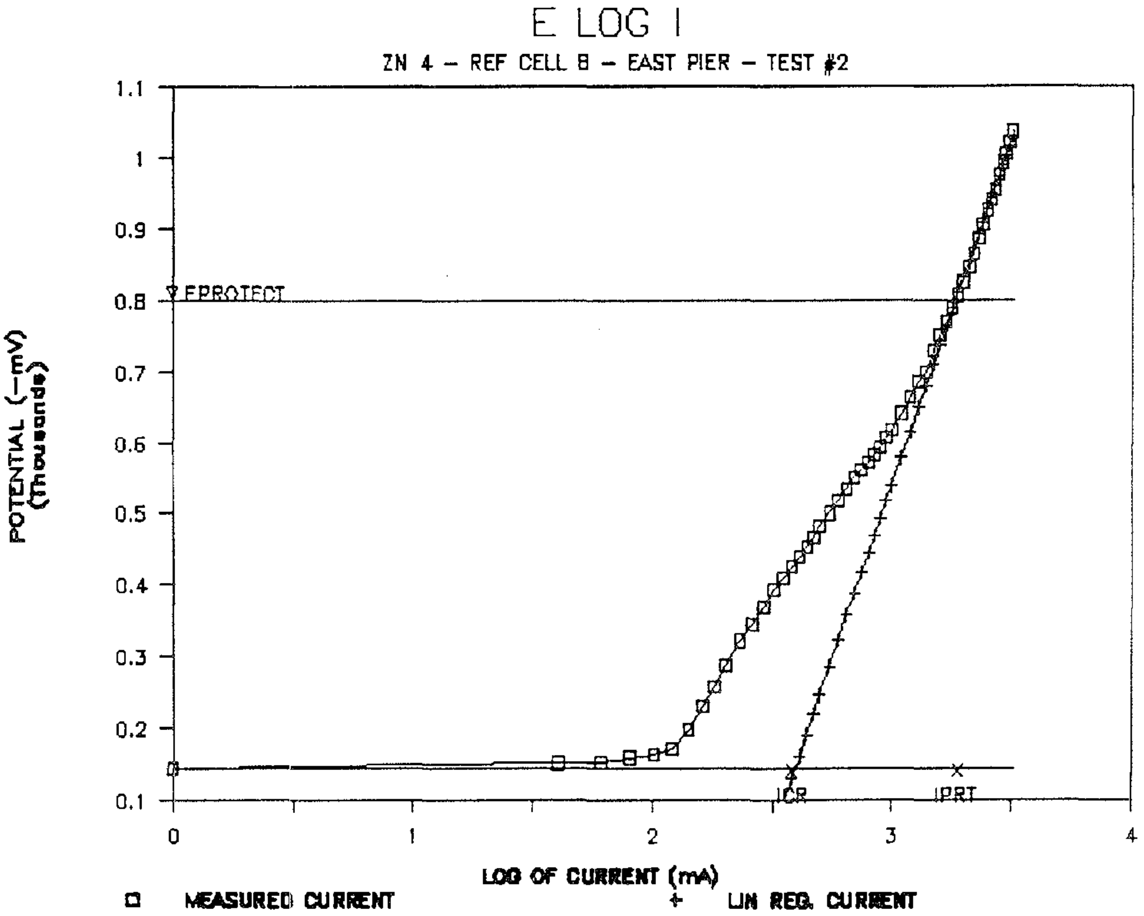


Figure 90. E Log I computed corrosion and cathodic protection data Zone 4 - reference cell B - east pier (test 2) at initial evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   ZONE 1 - REFERENCE CELL A
-----------------------------------------------------------------
      TAFEL SLOPE     =        241.71 MILLIVOLTS/DECADE
      ICORR           =       1165.08 MILLIAMPS
      ECORR           =          -245 MILLIVOLTS
      IPROTECT        =       2573.91 MILLIAMPS
      EPROTECT        =       -328.21 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                   =    1.50427
      COEFFICIENT OF DETERMINATION (R SQUARED)       =    0.99750
      NO. OF OBSERVATIONS USED                       =         22
=================================================================
```

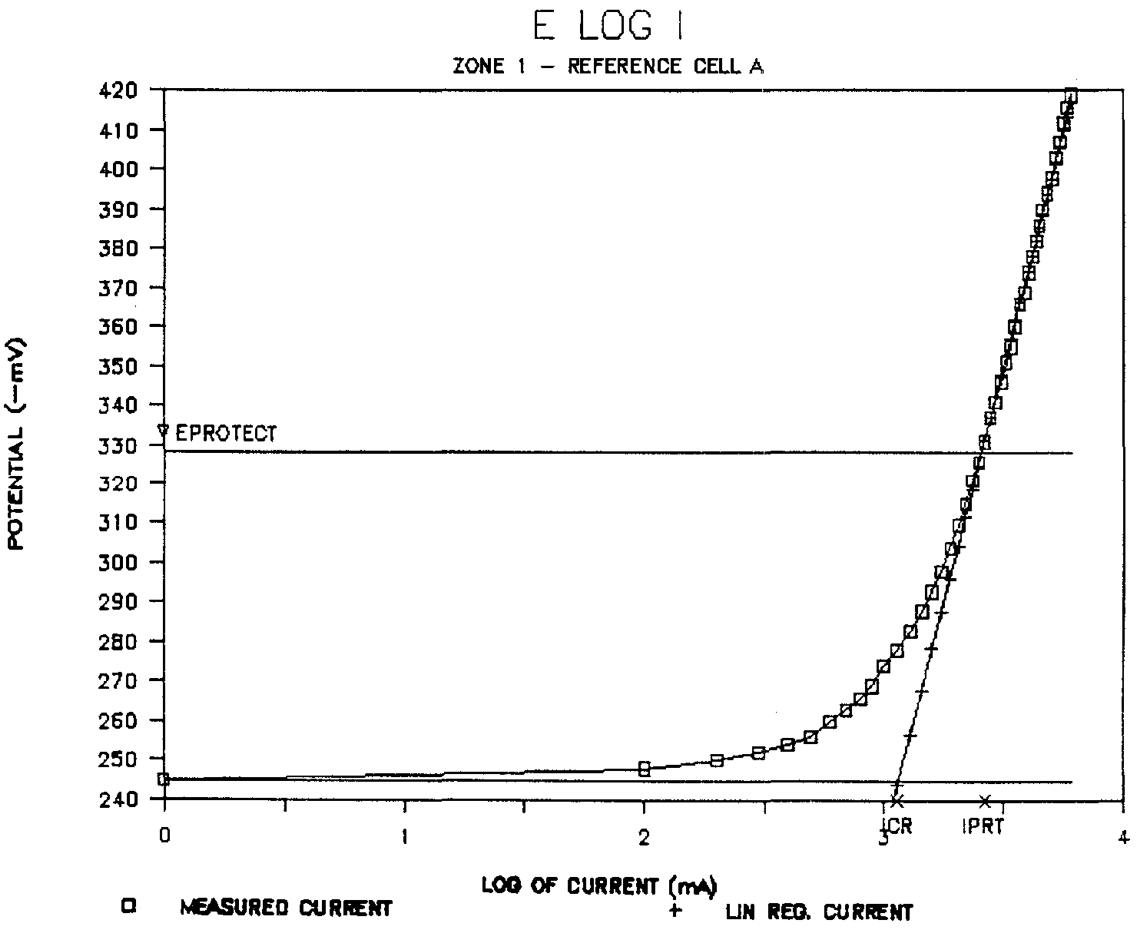


Figure 91. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell A at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 1 - REFERENCE CELL B
-----------------------------------------------------------------
      TAFEL SLOPE       =        336.12 MILLIVOLTS/DECADE
      ICORR             =       1005.90 MILLIAMPS
      ECORR             =          -175 MILLIVOLTS
      IPROTECT          =       2123.72 MILLIAMPS
      EPROTECT          =       -284.09 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =    1.18382
      COEFFICIENT OF DETERMINATION (R SQUARED)      =    0.99910
      NO. OF OBSERVATIONS USED                      =         22
=================================================================
```

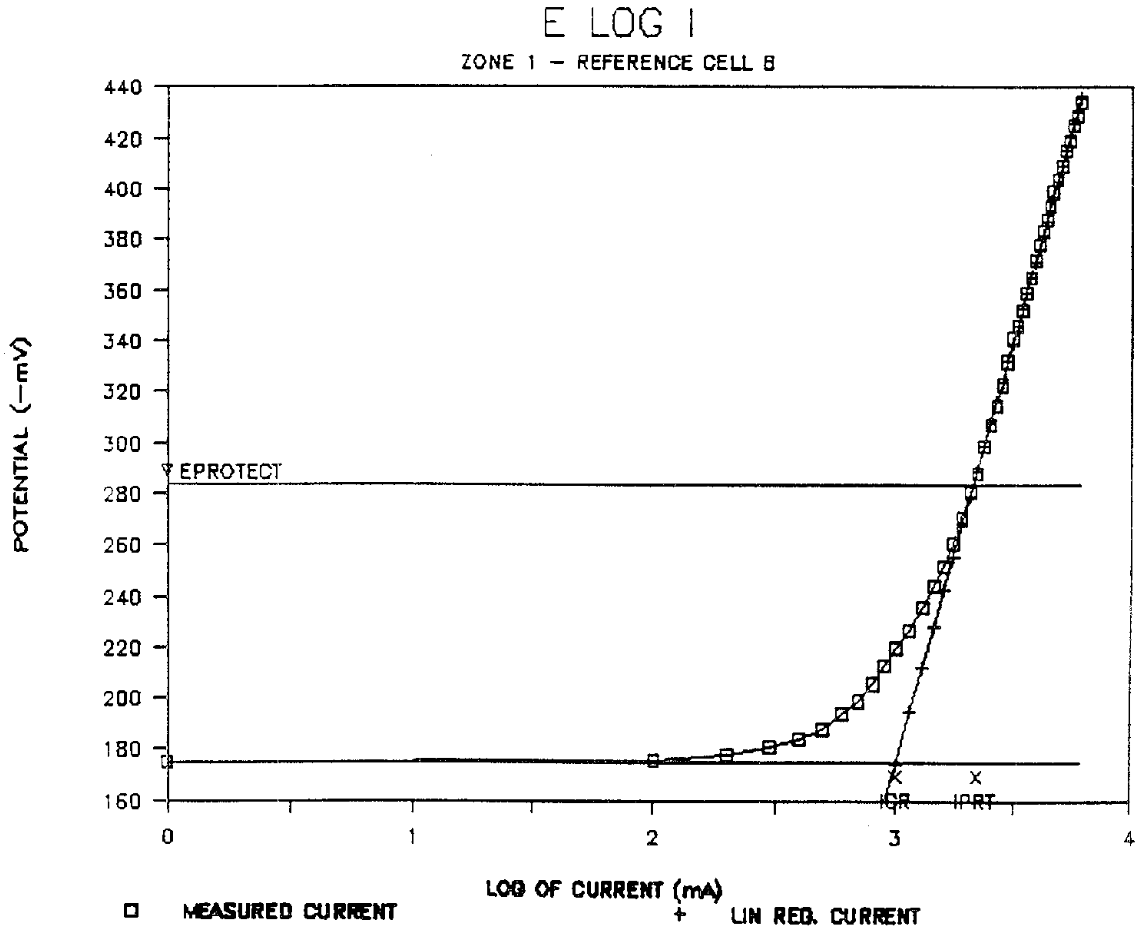


Figure 92. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell B at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 1 - REFERENCE CELL C
-----------------------------------------------------------------
      TAFEL SLOPE      =        349.21 MILLIVOLTS/DECADE
      ICORR            =       1033.03 MILLIAMPS
      ECORR            =          -115 MILLIVOLTS
      IPROTECT         =       2423.80 MILLIAMPS
      EPROTECT         =       -244.34 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     1.23207
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99909
      NO. OF OBSERVATIONS USED                      =          22
=================================================================
```

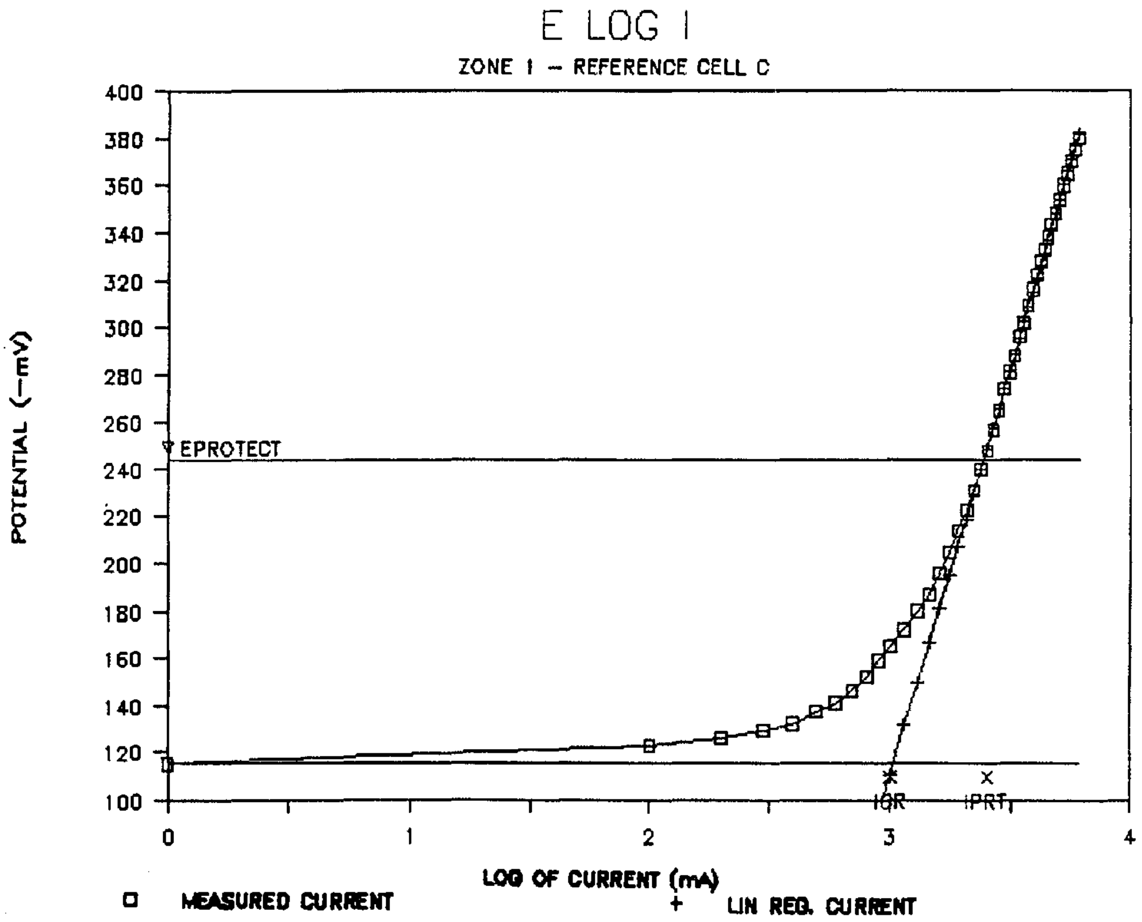


Figure 93. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell C at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 2 - REFERENCE CELL A
-----------------------------------------------------------------
      TAFEL SLOPE      =        184.71 MILLIVOLTS/DECADE
      ICORR            =       1734.99 MILLIAMPS
      ECORR            =          -286 MILLIVOLTS
      IPROTECT         =       3474.13 MILLIAMPS
      EPROTECT         =       -341.70 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     0.42741
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99815
      NO. OF OBSERVATIONS USED                      =          10
=================================================================
```

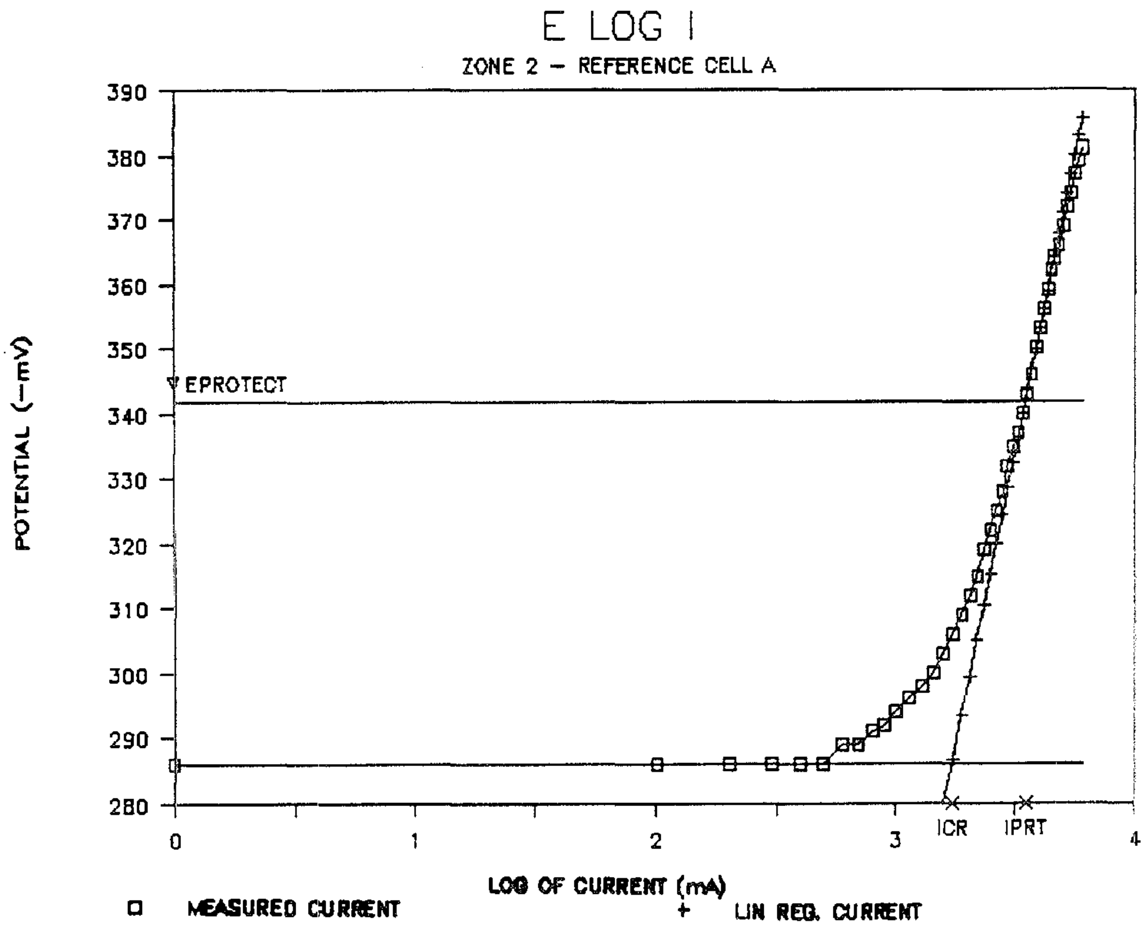


Figure 94. E Log I computed corrosion and cathodic protection data,
Zone 2 - reference cell A at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=====================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 2 - REFERENCE CELL B
---------------------------------------------------------------------
      TAFEL SLOPE      =       230.92 MILLIVOLTS/DECADE
      ICORR            =      1433.38 MILLIAMPS
      ECORR            =         -209 MILLIVOLTS
      IPROTECT         =      2723.99 MILLIAMPS
      EPROTECT         =      -273.39 MILLIVOLTS
=====================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
---------------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =    0.47431
      COEFFICIENT OF DETERMINATION (R SQUARED)      =    0.99920
      NO. OF OBSERVATIONS USED                      =         13
=====================================================================
```

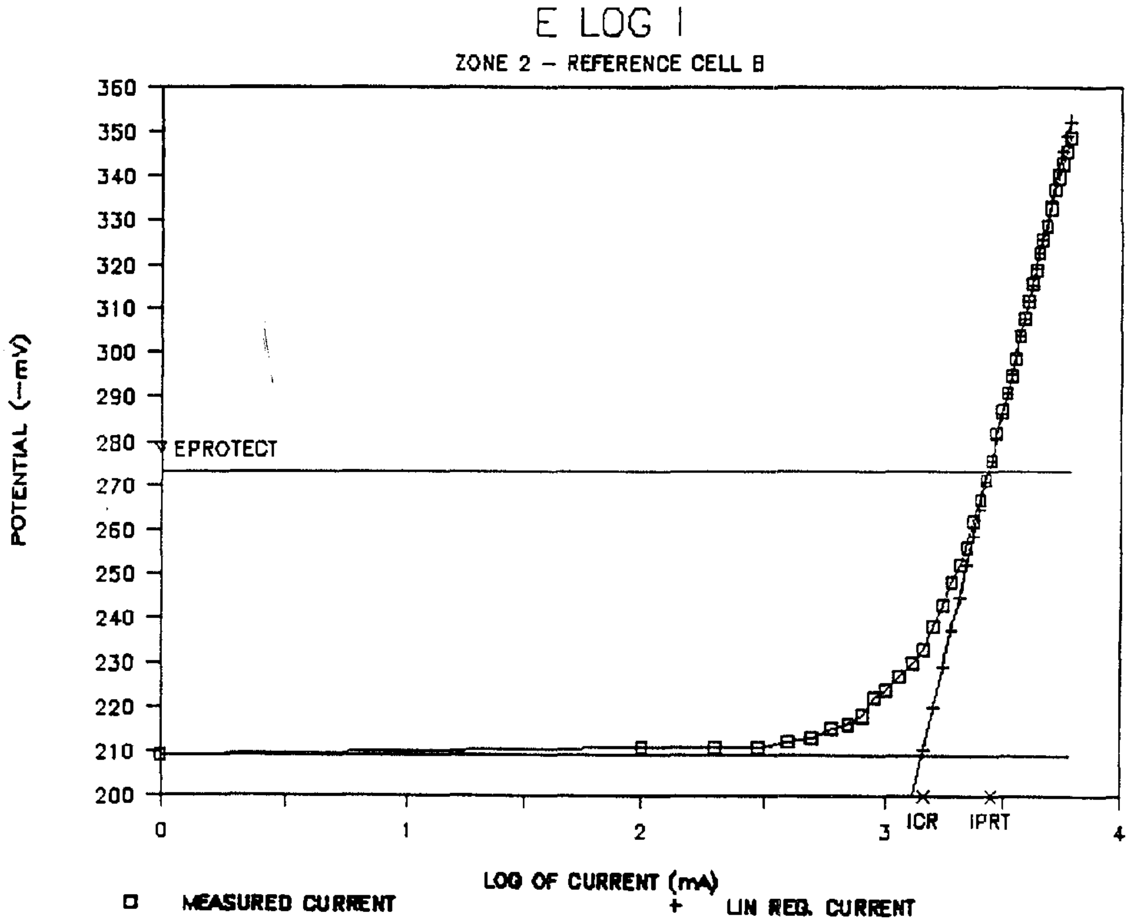


Figure 95. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell B at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    ZONE 2 - REFERENCE CELL C
-----------------------------------------------------------------
      TAFEL SLOPE    =         194.25 MILLIVOLTS/DECADE
      ICORR          =        2113.70 MILLIAMPS
      ECORR          =             17 MILLIVOLTS
      IPROTECT       =        3324.04 MILLIAMPS
      EPROTECT       =         -21.19 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     0.26388
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99971
      NO. OF OBSERVATIONS USED                     =          16
=================================================================
```

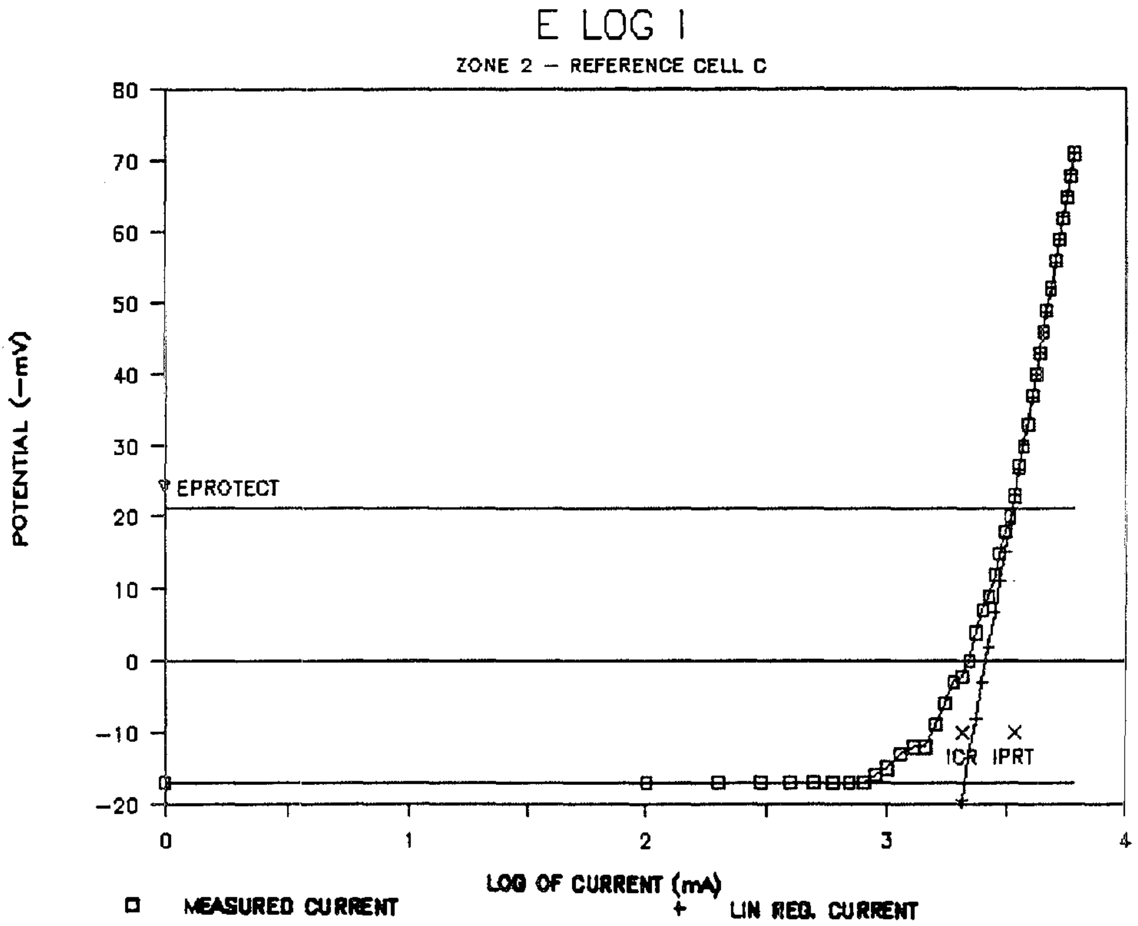


Figure 96. E Log I computed corrosion and cathodic protection data,
Zone 2 - reference cell C at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
  E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                ZONE 3 - REFERENCE CELL A
-----------------------------------------------------------------
      TAFEL SLOPE      =        504.81 MILLIVOLTS/DECADE
      ICORR            =        443.75 MILLIAMPS
      ECORR            =          -164 MILLIVOLTS
      IPROTECT         =       1079.80 MILLIAMPS
      EPROTECT         =       -358.96 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                =     2.16005
      COEFFICIENT OF DETERMINATION (R SQUARED)    =     0.99781
      NO. OF OBSERVATIONS USED                    =          23
=================================================================
```

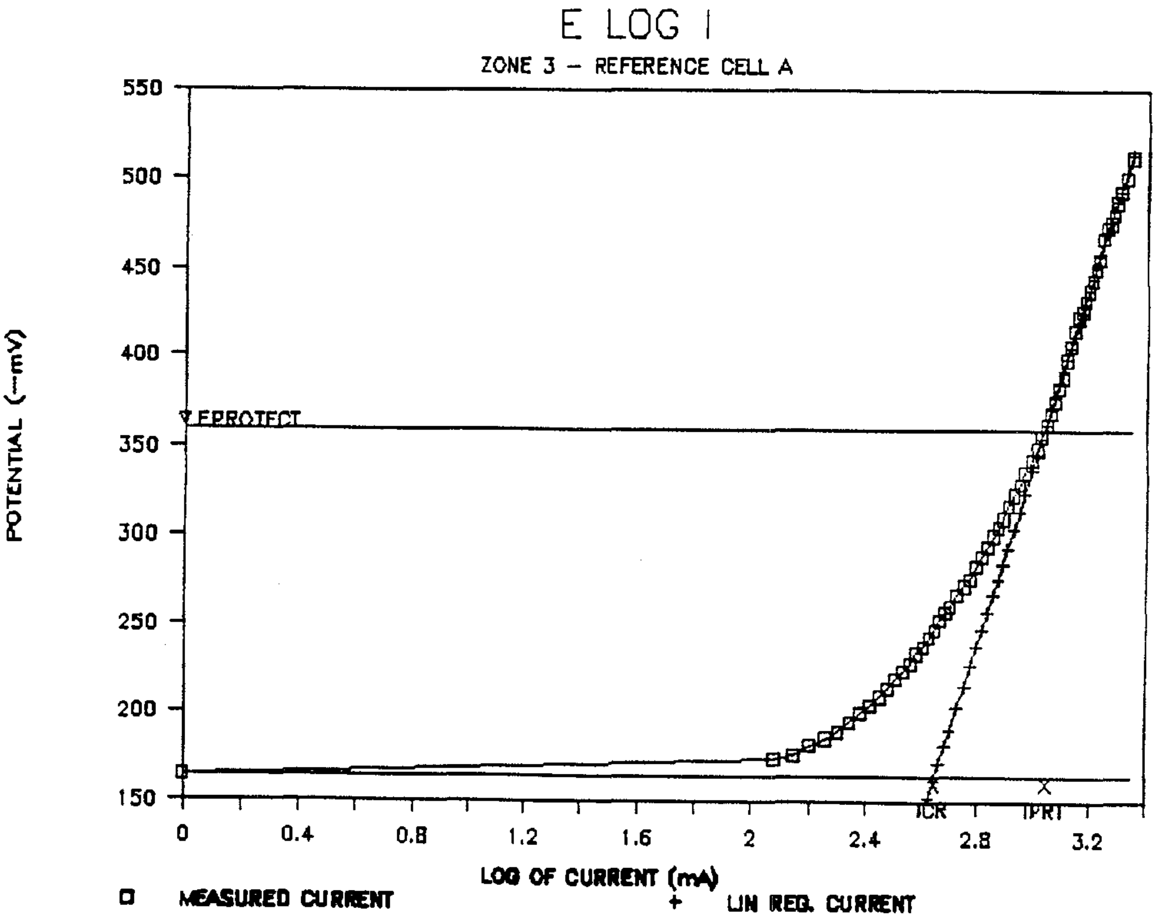


Figure 97. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell A at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                  ZONE 3 - REFERENCE CELL B
-----------------------------------------------------------------
      TAFEL SLOPE      =        665.81 MILLIVOLTS/DECADE
      ICORR            =        504.03 MILLIAMPS
      ECORR            =          -167 MILLIVOLTS
      IPROTECT         =       1079.82 MILLIAMPS
      EPROTECT         =       -387.31 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     3.91263
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99684
      NO. OF OBSERVATIONS USED                     =          26
=================================================================
```

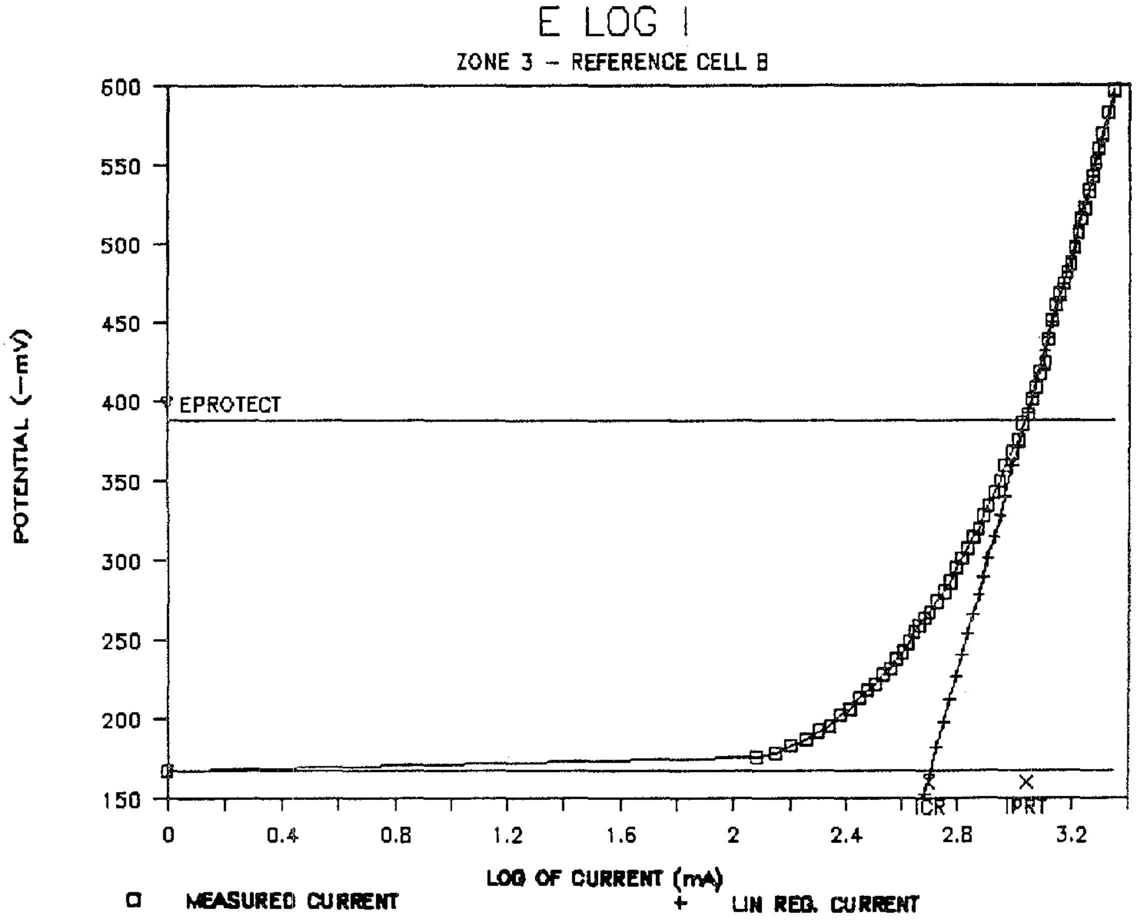


Figure 98. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell B at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
              ZONE 4 - REFERENCE CELL A - WEST PIER
-----------------------------------------------------------------
      TAFEL SLOPE      =      1252.63 MILLIVOLTS/DECADE
      ICORR            =       242.34 MILLIAMPS
      ECORR            =            3 MILLIVOLTS
      IPROTECT         =       639.92 MILLIAMPS
      EPROTECT         =      -525.23 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     3.46997
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99887
      NO. OF OBSERVATIONS USED                     =          28
=================================================================
```

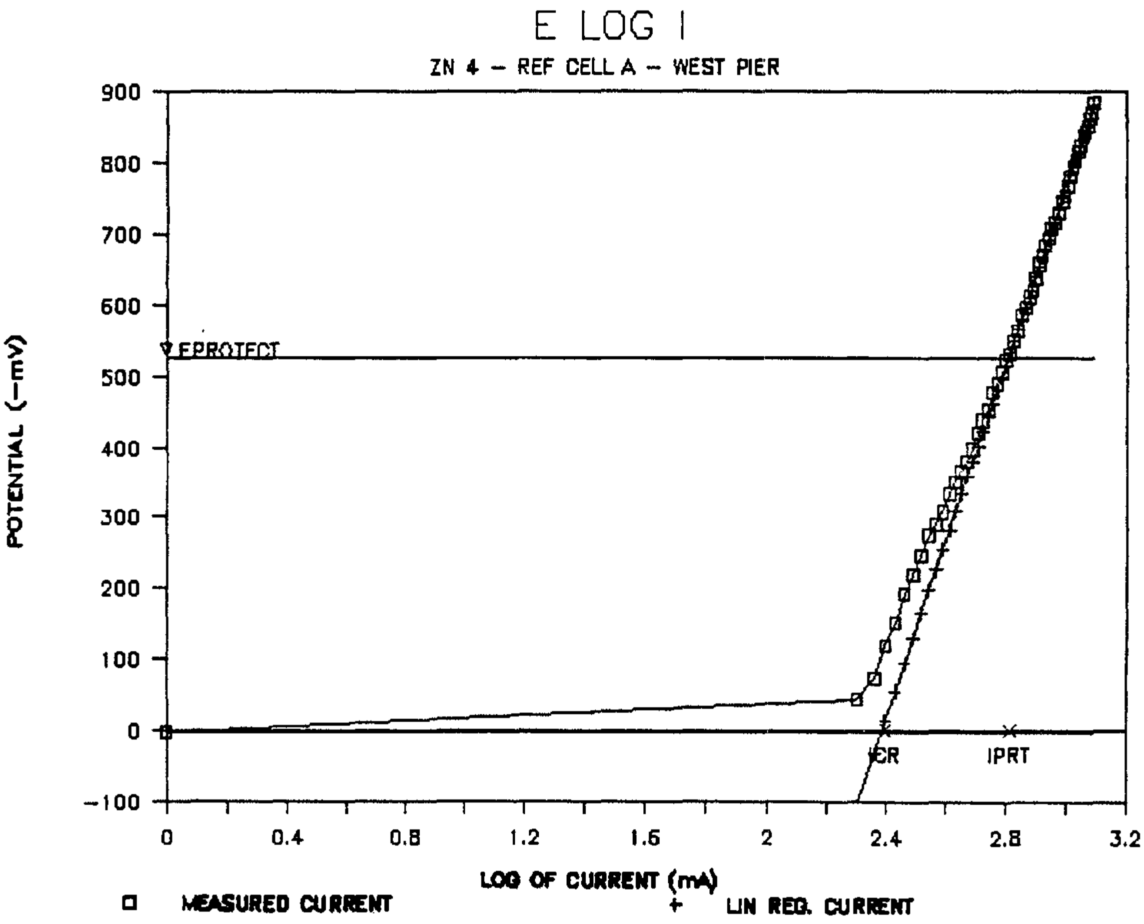


Figure 99. E Log I computed corrosion and cathodic protection data, Zone 4 - reference cell A - West Pier at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
   E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
            ZONE 4 - REFERENCE CELL B - EAST PIER
-----------------------------------------------------------------
      TAFEL SLOPE      =      1075.62 MILLIVOLTS/DECADE
      ICORR            =       215.85 MILLIAMPS
      ECORR            =         -105 MILLIVOLTS
      IPROTECT         =       599.91 MILLIAMPS
      EPROTECT         =      -582.51 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     2.49044
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99899
      NO. OF OBSERVATIONS USED                     =          20
=================================================================
```

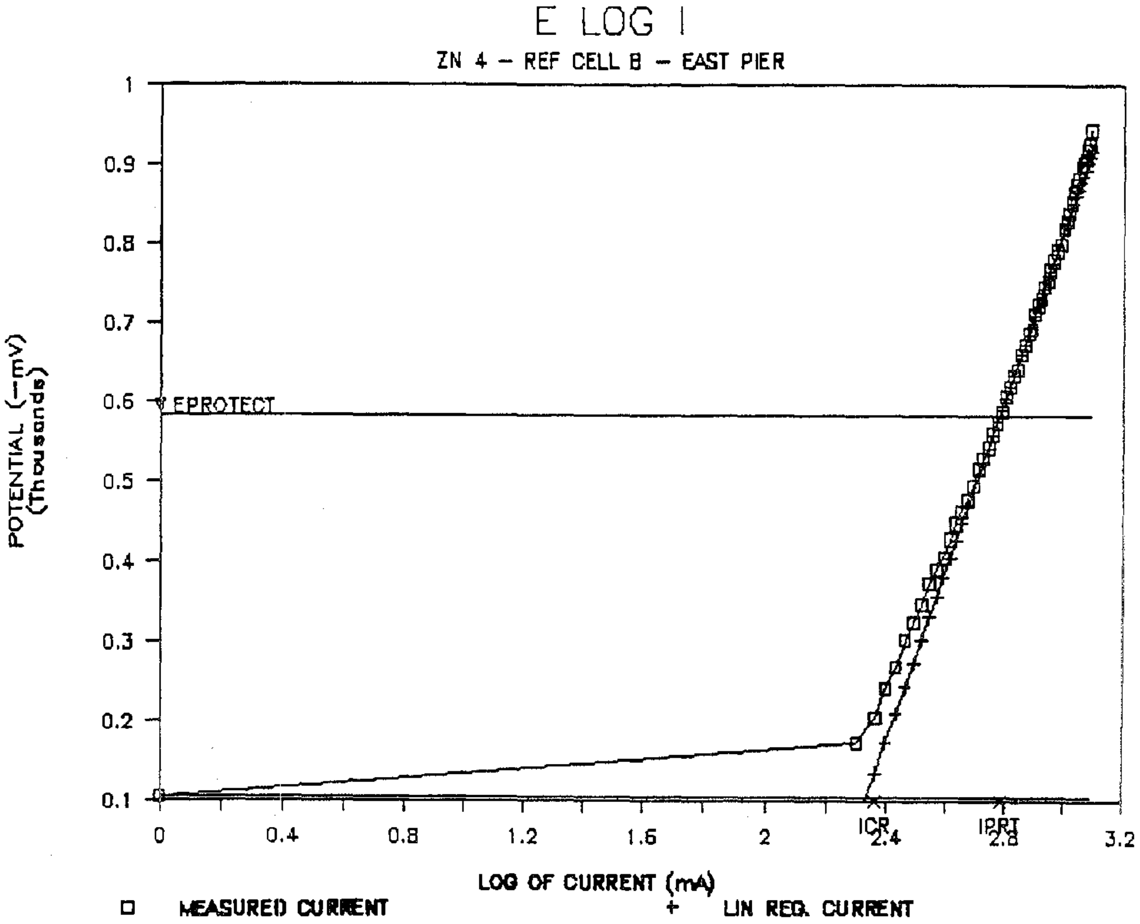


Figure 100. E Log I computed corrosion and cathodic protection data, Zone 4 - reference cell B - East Pier at 6-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                 ZONE 1 - REFERENCE CELL A (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE      =        390.09 MILLIVOLTS/DECADE
      ICORR            =        391.43 MILLIAMPS
      ECORR            =          -247 MILLIVOLTS
      IPROTECT         =       1849.27 MILLIAMPS
      EPROTECT         =       -510.06 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.10110
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99853
      NO. OF OBSERVATIONS USED                     =          13
=================================================================
```

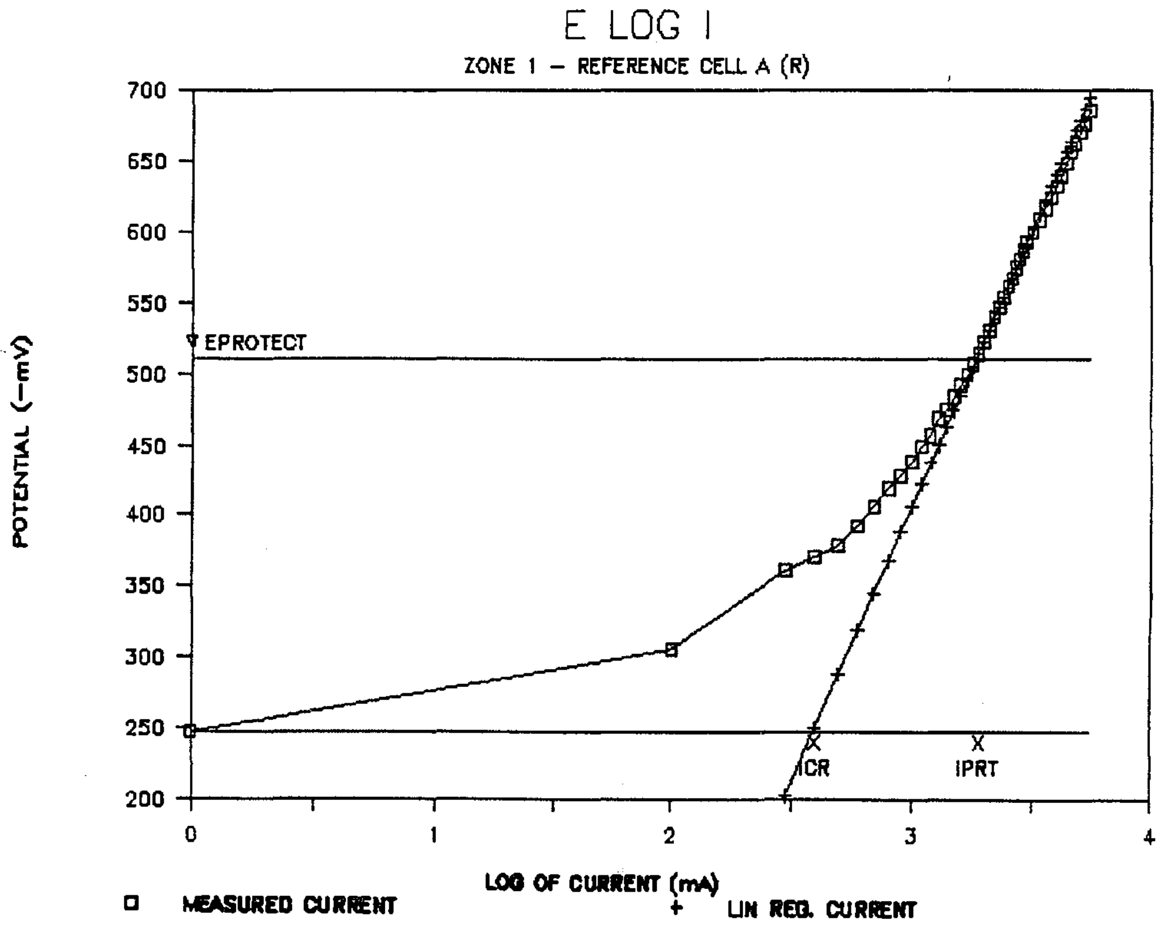


Figure 101. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell A (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                ZONE 1 - REFERENCE CELL B (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE      =        352.81 MILLIVOLTS/DECADE
      ICORR            =        692.00 MILLIAMPS
      ECORR            =          -209 MILLIVOLTS
      IPROTECT         =       1749.32 MILLIAMPS
      EPROTECT         =       -351.10 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.14987
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99770
      NO. OF OBSERVATIONS USED                     =          12
=================================================================
```

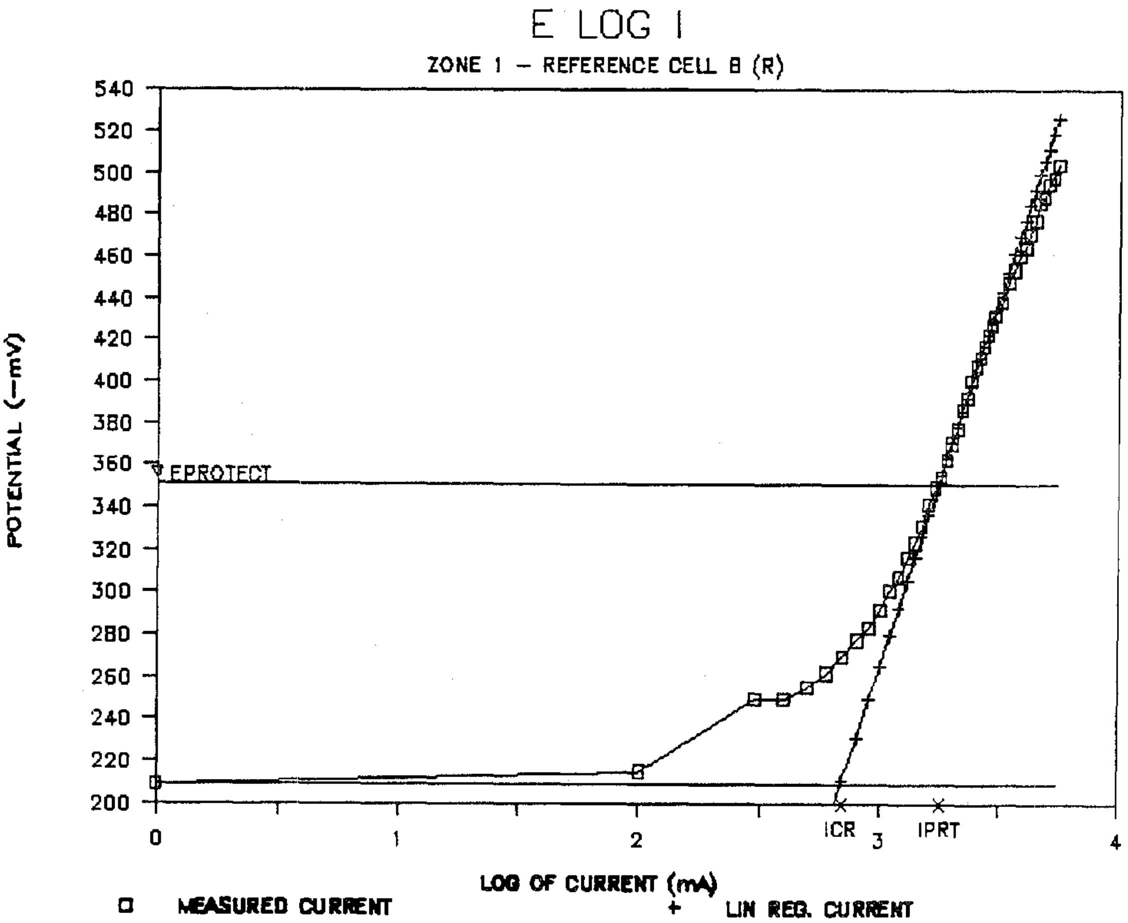


Figure 102. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell B (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                 ZONE 1 - REFERENCE CELL C (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE      =        325.95 MILLIVOLTS/DECADE
      ICORR            =        607.79 MILLIAMPS
      ECORR            =          -173 MILLIVOLTS
      IPROTECT         =       1849.33 MILLIAMPS
      EPROTECT         =       -330.52 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.20405
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99748
      NO. OF OBSERVATIONS USED                     =          13
=================================================================
```

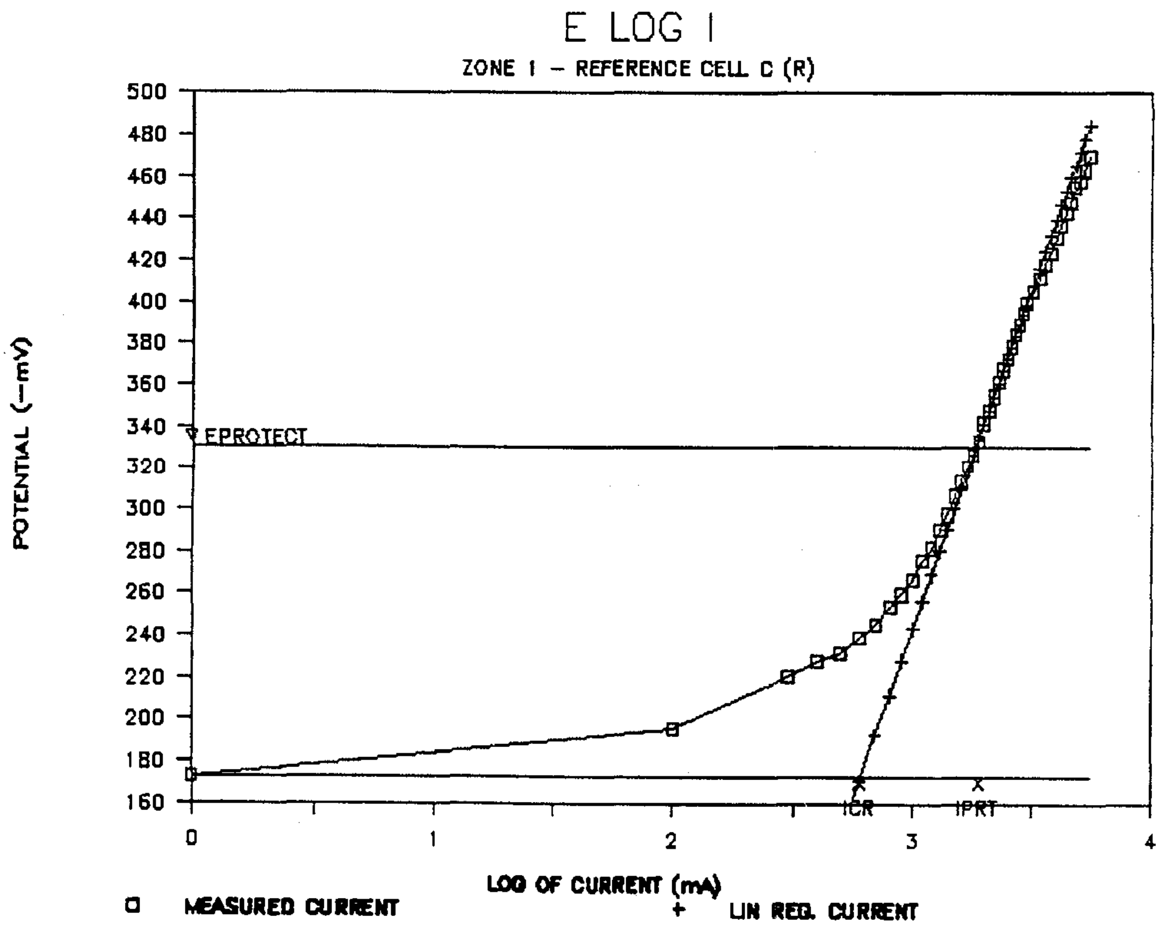


Figure 103. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell C (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
               ZONE 2 - REFERENCE CELL A (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE      =        196.80 MILLIVOLTS/DECADE
      ICORR            =       1234.26 MILLIAMPS
      ECORR            =          -264 MILLIVOLTS
      IPROTECT         =       3698.47 MILLIAMPS
      EPROTECT         =       -357.80 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     0.96224
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99408
      NO. OF OBSERVATIONS USED                     =          10
=================================================================
```

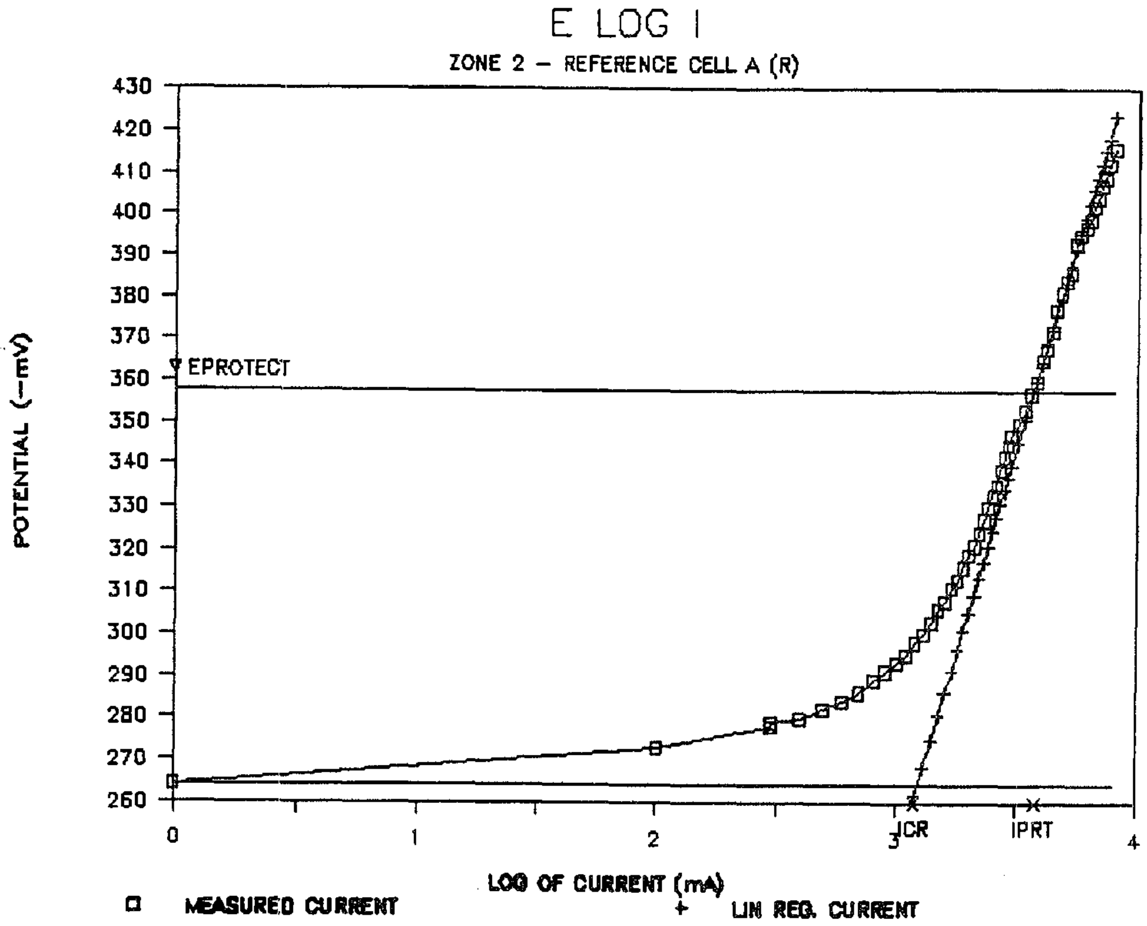


Figure 104. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell A (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
               ZONE 2 - REFERENCE CELL B (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE       =       269.12 MILLIVOLTS/DECADE
      ICORR             =      1125.09 MILLIAMPS
      ECORR             =         -214 MILLIVOLTS
      IPROTECT          =      3698.52 MILLIAMPS
      EPROTECT          =      -353.09 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     0.88264
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99791
      NO. OF OBSERVATIONS USED                      =          11
=================================================================
```

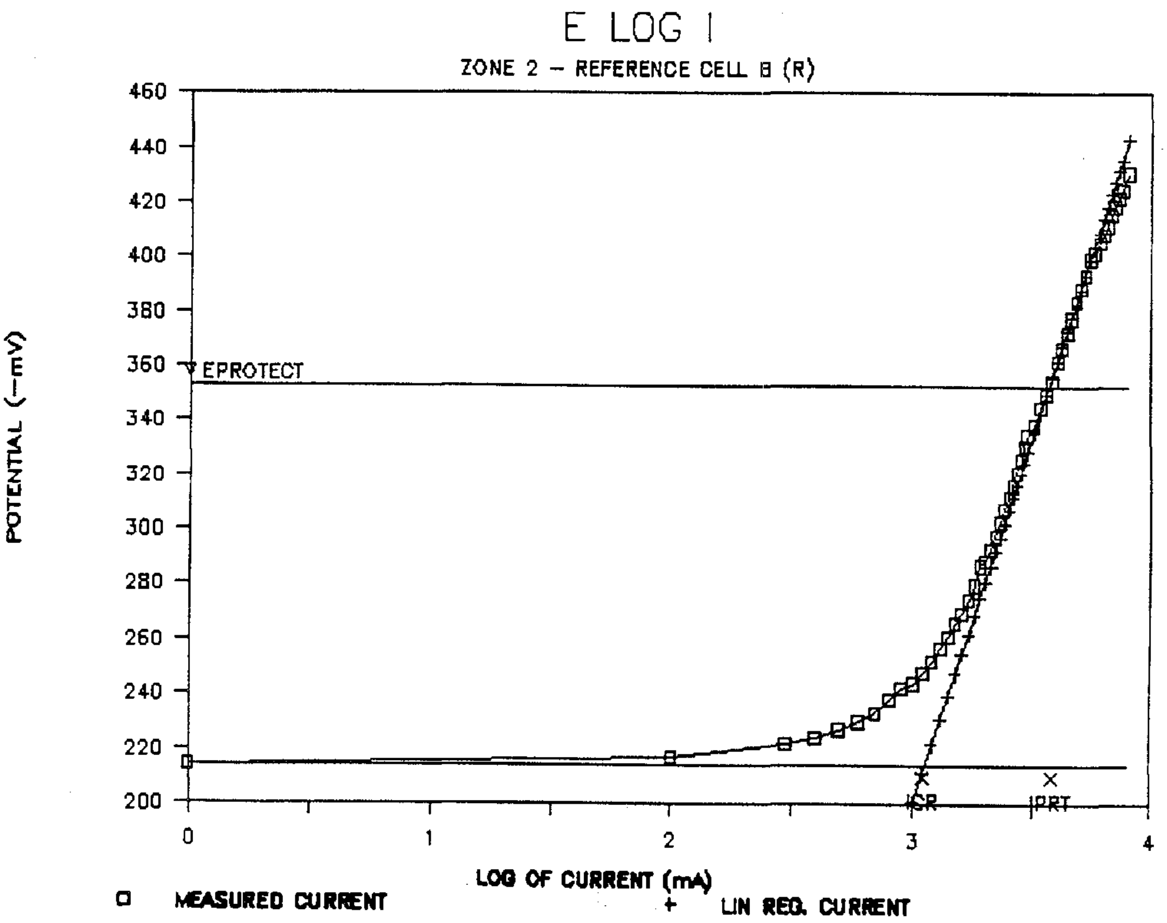


Figure 105. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell B (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
              ZONE 2 - REFERENCE CELL C (REPEAT)
-----------------------------------------------------------------
     TAFEL SLOPE      =        150.77 MILLIVOLTS/DECADE
     ICORR            =       1516.19 MILLIAMPS
     ECORR            =          -366 MILLIVOLTS
     IPROTECT         =       3698.59 MILLIAMPS
     EPROTECT         =       -424.39 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                  =     0.69627
     COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99840
     NO. OF OBSERVATIONS USED                      =          20
=================================================================
```

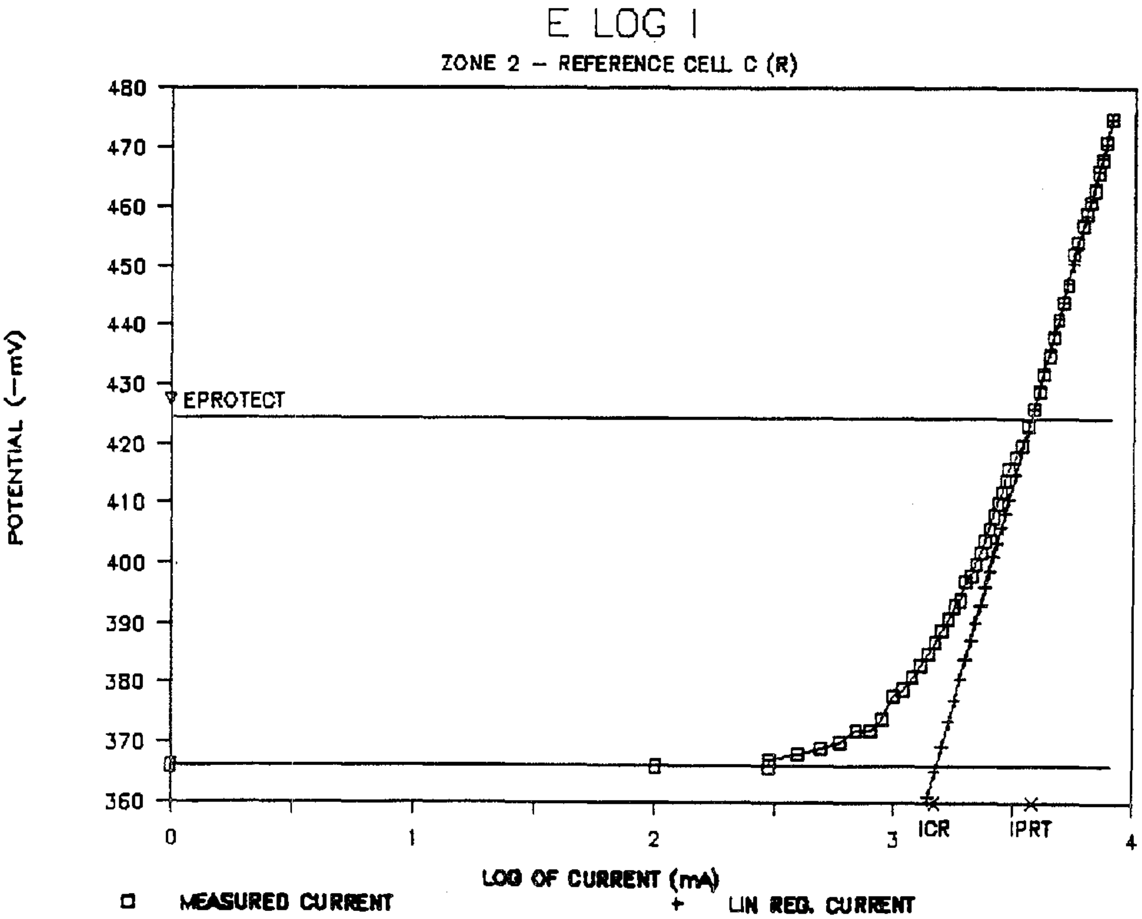


Figure 106. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell C (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
               ZONE 3 - REFERENCE CELL A (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE     =        980.50 MILLIVOLTS/DECADE
      ICORR           =        344.66 MILLIAMPS
      ECORR           =          -251 MILLIVOLTS
      IPROTECT        =        874.64 MILLIAMPS
      EPROTECT        =       -647.55 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     5.78246
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99775
      NO. OF OBSERVATIONS USED                     =          19
=================================================================
```

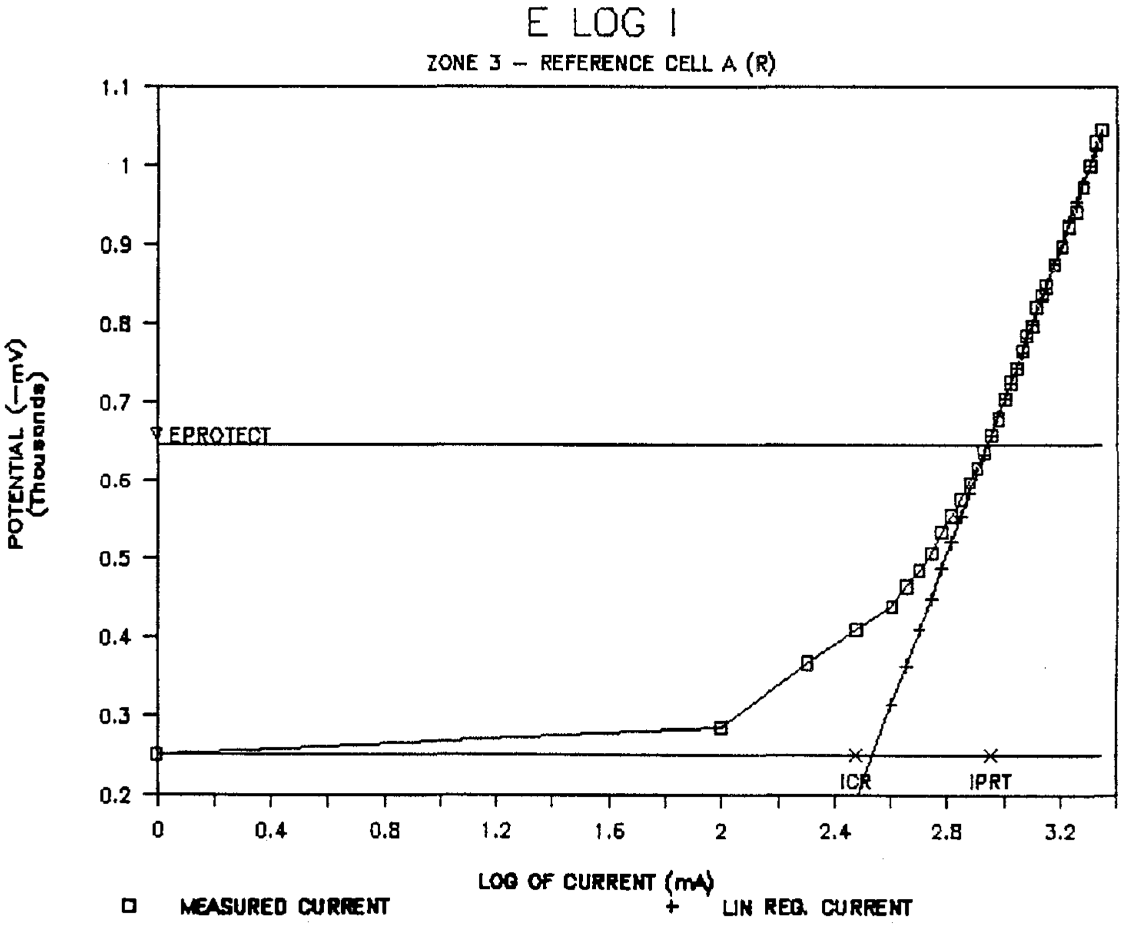


Figure 107. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell A (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                 ZONE 3 - REFERENCE CELL B (REPEAT)
-----------------------------------------------------------------
      TAFEL SLOPE      =       1488.04 MILLIVOLTS/DECADE
      ICORR            =        405.69 MILLIAMPS
      ECORR            =          -413 MILLIVOLTS
      IPROTECT         =        874.64 MILLIAMPS
      EPROTECT         =       -909.47 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     8.50013
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99733
      NO. OF OBSERVATIONS USED                      =          17
=================================================================
```

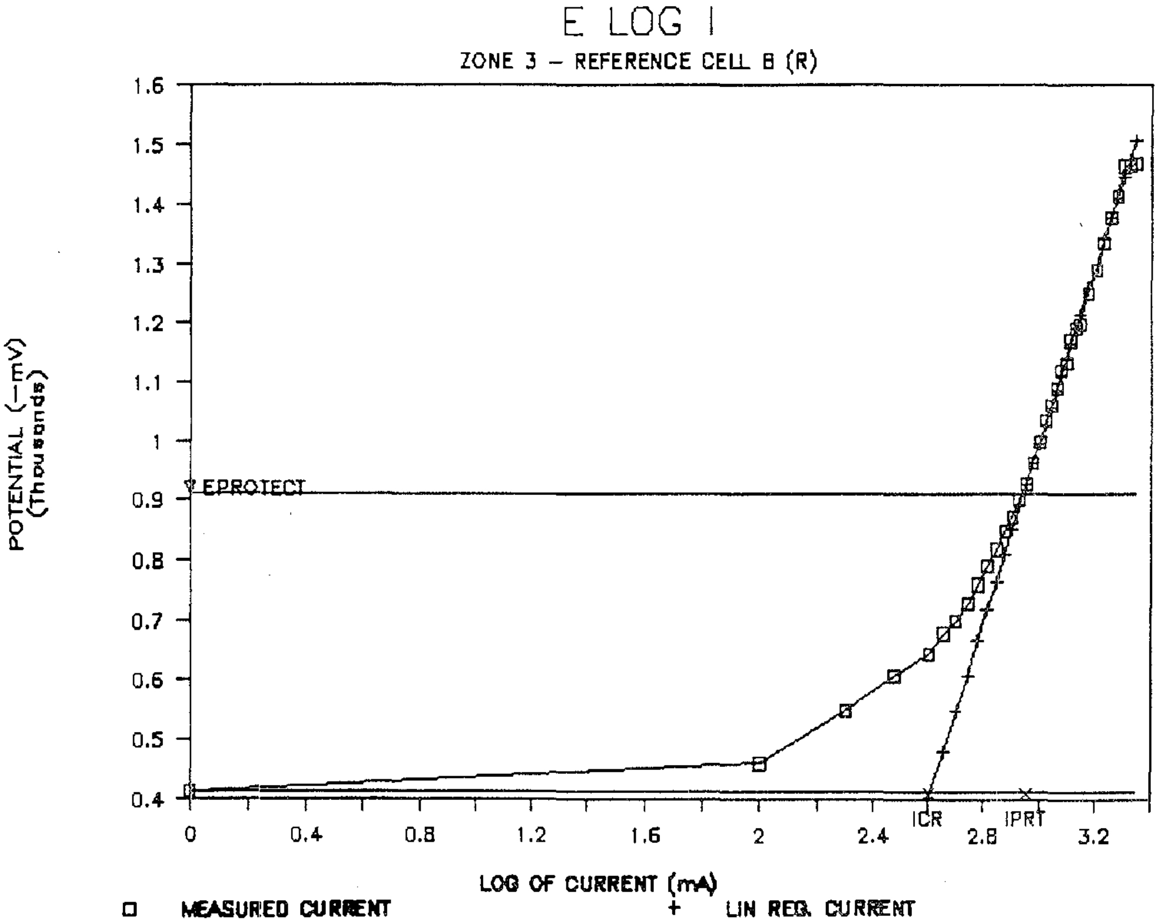


Figure 108. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell B (repeat) at 12-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   Zone 1 - Reference Cell A
-----------------------------------------------------------------
     TAFEL SLOPE      =        350.87 MILLIVOLTS/DECADE
     ICORR            =       1195.29 MILLIAMPS
     ECORR            =          -201 MILLIVOLTS
     IPROTECT         =       4098.79 MILLIAMPS
     EPROTECT         =       -388.78 MILLIVOLTS
=================================================================

     EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
     STANDARD ERROR OF Y ESTIMATE                 =      1.83599
     COEFFICIENT OF DETERMINATION (R SQUARED)     =      0.99865
     NO. OF OBSERVATIONS USED                     =           20
=================================================================
```

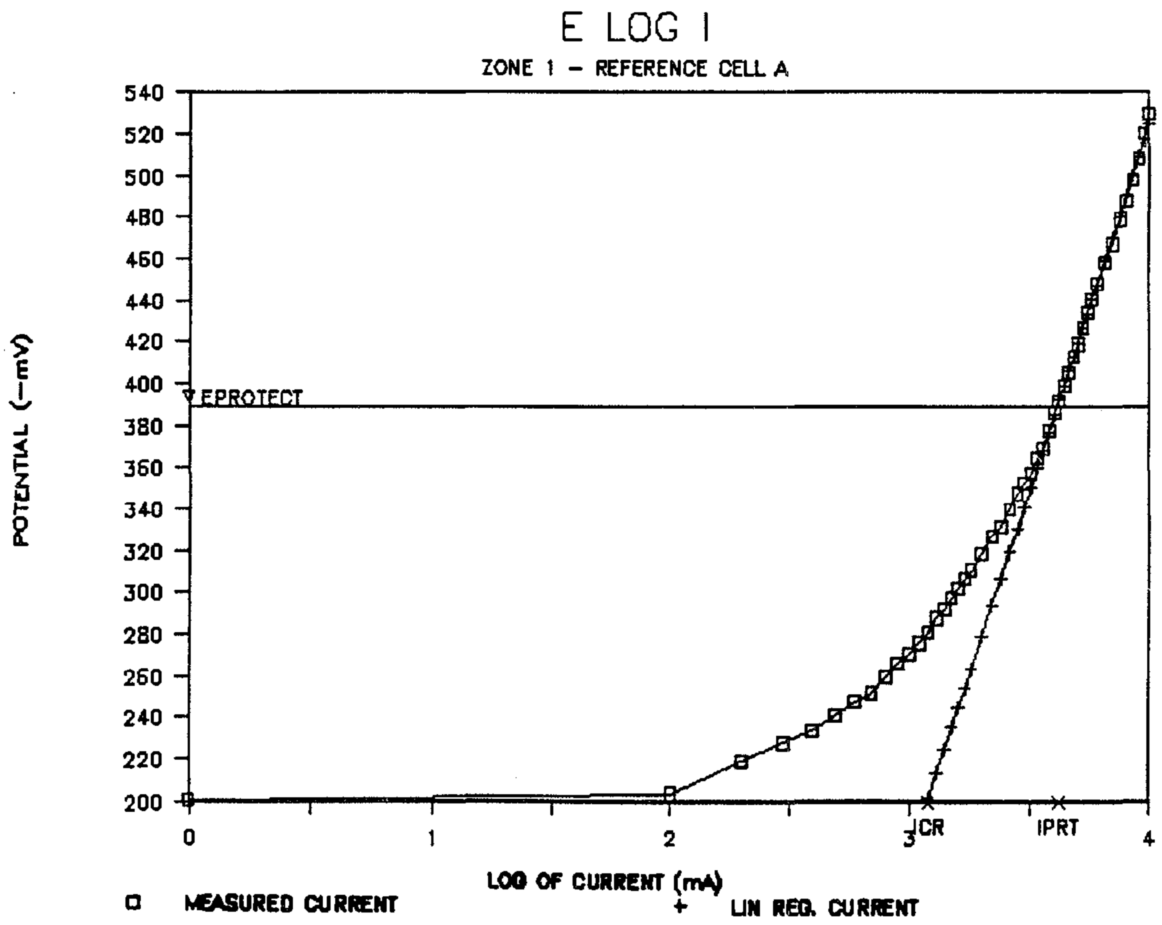


Figure 109. E Log I computed corrosion and cathodic protection data, Zone 1- reference cell A at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
    E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   Zone 1 - Reference Cell B
-----------------------------------------------------------------
      TAFEL SLOPE      =        254.30 MILLIVOLTS/DECADE
      ICORR            =       1472.65 MILLIAMPS
      ECORR            =          -171 MILLIVOLTS
      IPROTECT         =       3698.57 MILLIAMPS
      EPROTECT         =       -272.71 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.32261
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99867
      NO. OF OBSERVATIONS USED                     =          20
=================================================================
```

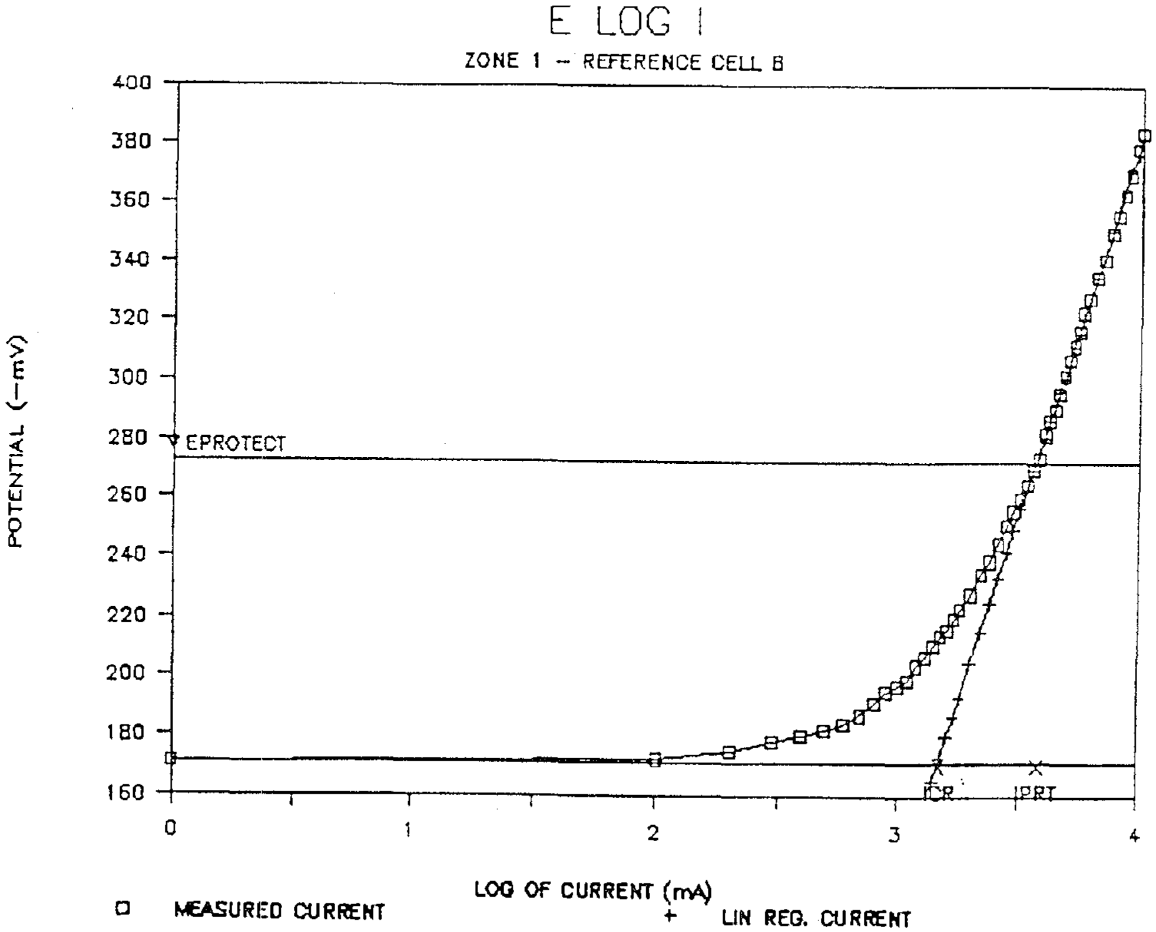


Figure 110. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell B at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   Zone 1 - Reference Cell C
-----------------------------------------------------------------
      TAFEL SLOPE      =        247.14 MILLIVOLTS/DECADE
      ICORR            =       1514.34 MILLIAMPS
      ECORR            =          -174 MILLIVOLTS
      IPROTECT         =       3698.67 MILLIAMPS
      EPROTECT         =       -267.84 MILLIVOLTS
=================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                 =     1.23319
      COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99887
      NO. OF OBSERVATIONS USED                     =          21
=================================================================
```

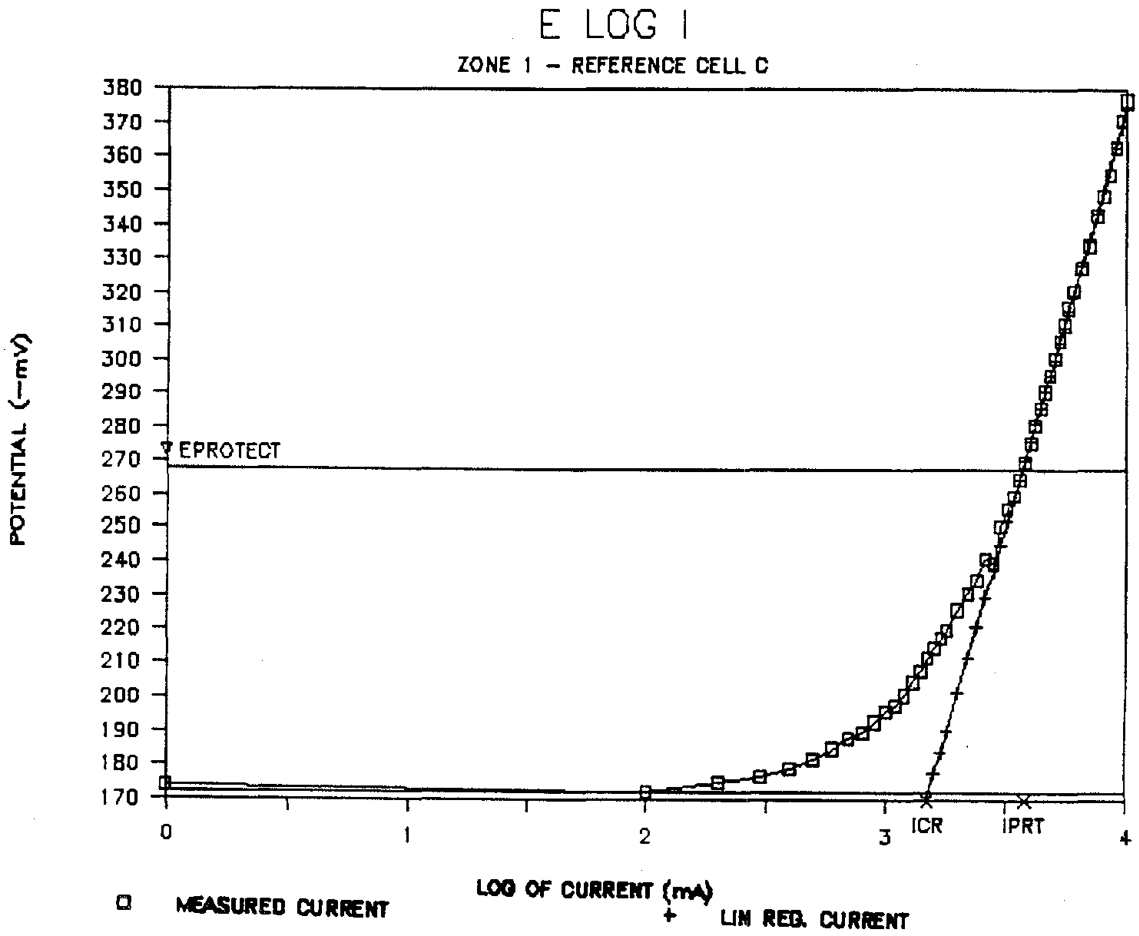


Figure 111. E Log I computed corrosion and cathodic protection data, Zone 1 - reference cell C at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   Zone 2 - Reference Cell A
----------------------------------------------------------------
      TAFEL SLOPE      =        154.57 MILLIVOLTS/DECADE
      ICORR            =       1330.88 MILLIAMPS
      ECORR            =          -253 MILLIVOLTS
      IPROTECT         =       3298.32 MILLIAMPS
      EPROTECT         =       -313.93 MILLIVOLTS
================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     0.74849
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99851
      NO. OF OBSERVATIONS USED                      =          18
================================================================
```

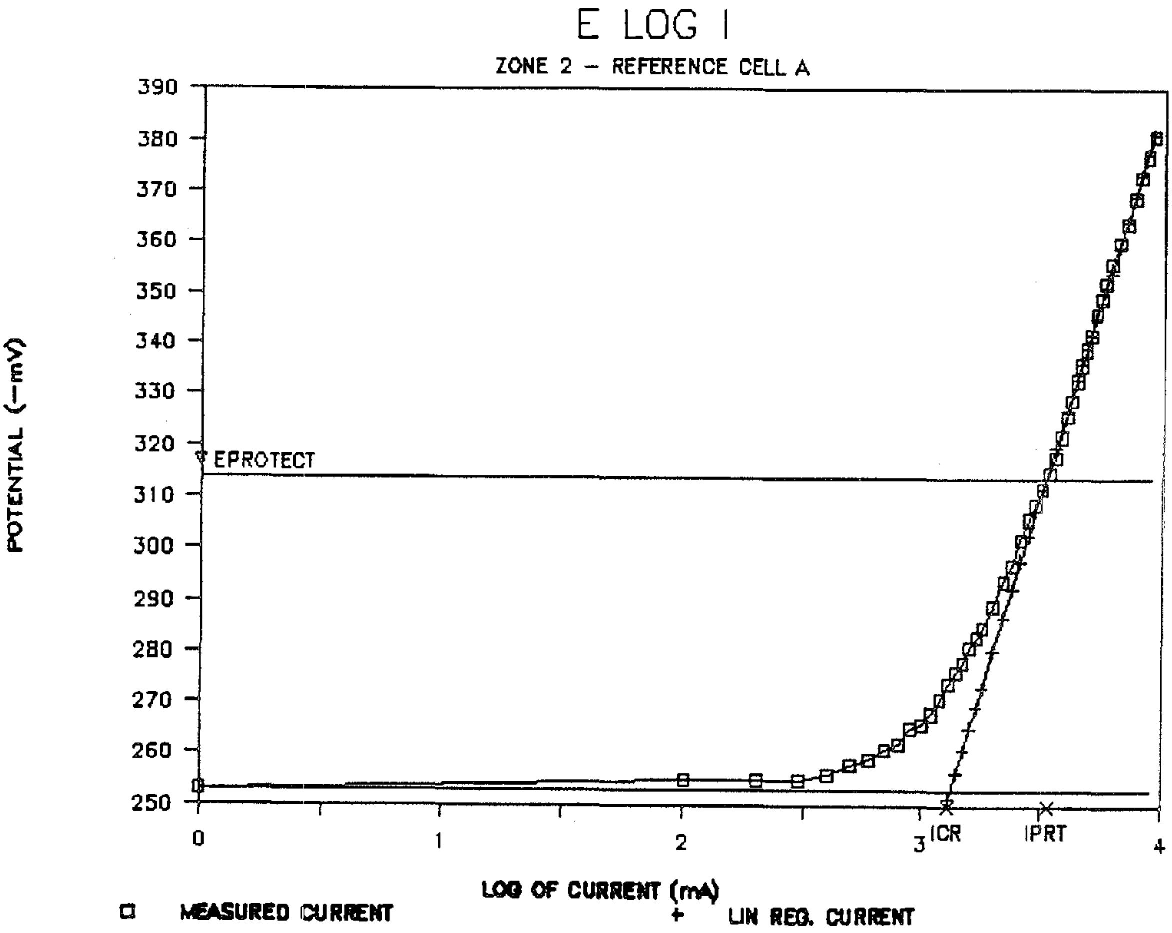


Figure 112. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell A at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                    Zone 2 - Reference Cell B
-----------------------------------------------------------------
      TAFEL SLOPE      =        239.24 MILLIVOLTS/DECADE
      ICORR            =       1422.46 MILLIAMPS
      ECORR            =          -182 MILLIVOLTS
      IPROTECT         =       3498.66 MILLIAMPS
      EPROTECT         =       -275.51 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     0.92003
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99747
      NO. OF OBSERVATIONS USED                      =          12
=================================================================
```

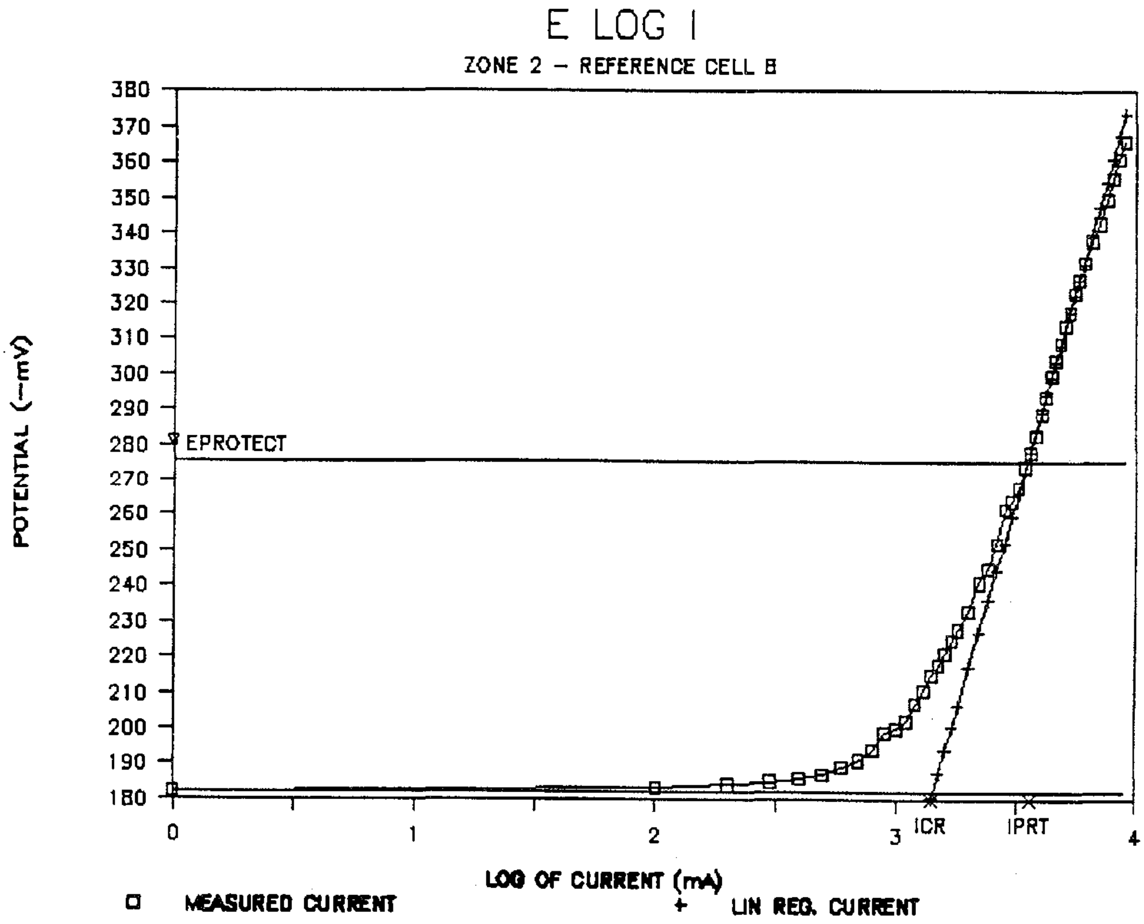


Figure 113. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell B at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=====================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                     Zone 2 - Reference Cell C
---------------------------------------------------------------------
      TAFEL SLOPE       =        195.58 MILLIVOLTS/DECADE
      ICORR             =       1805.11 MILLIAMPS
      ECORR             =           -68 MILLIVOLTS
      IPROTECT          =       3698.66 MILLIAMPS
      EPROTECT          =       -128.93 MILLIVOLTS
=====================================================================


      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
---------------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                    =     0.84630
      COEFFICIENT OF DETERMINATION (R SQUARED)        =     0.99900
      NO. OF OBSERVATIONS USED                        =          20
=====================================================================
```

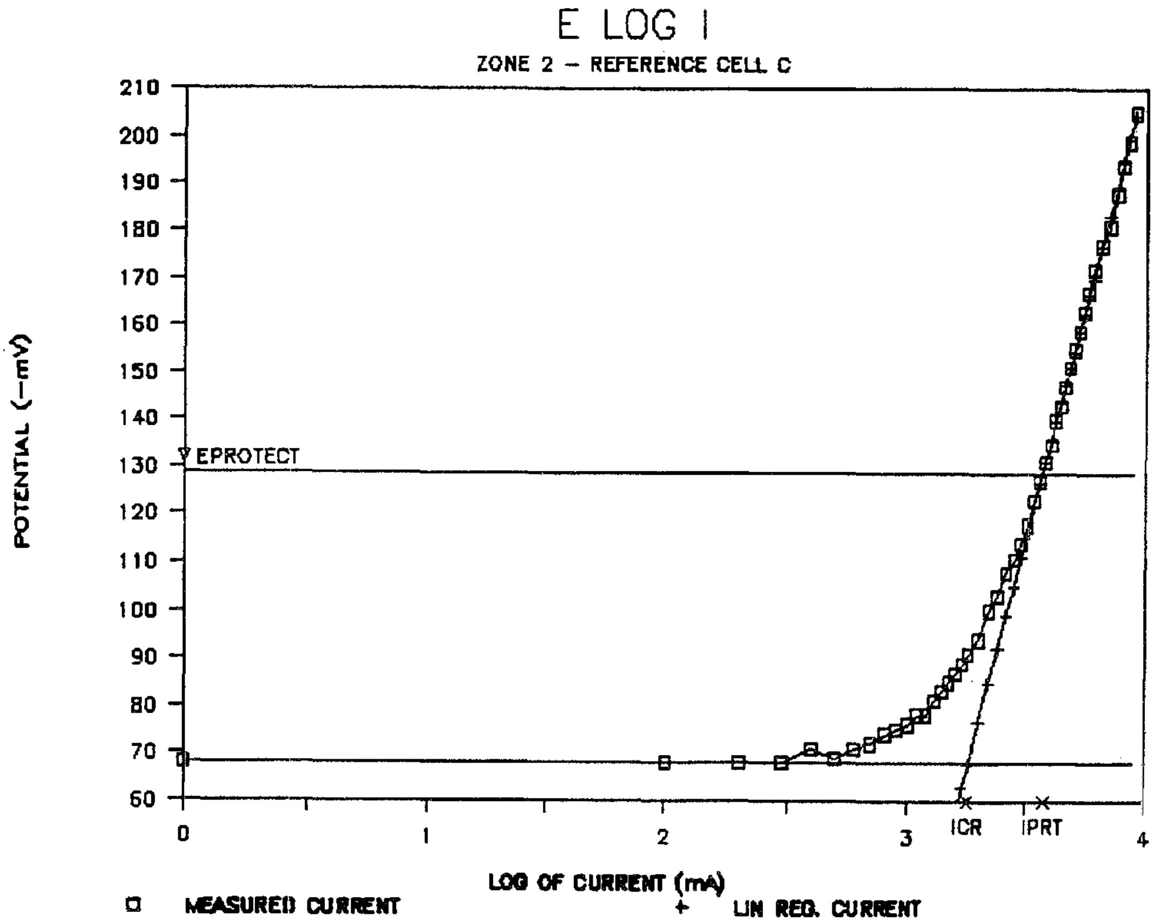


Figure 114. E Log I computed corrosion and cathodic protection data, Zone 2 - reference cell C at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
   E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                   Zone 3 - Reference Cell A
-----------------------------------------------------------------
    TAFEL SLOPE      =        772.35 MILLIVOLTS/DECADE
    ICORR            =        863.46 MILLIAMPS
    ECORR            =          -266 MILLIVOLTS
    IPROTECT         =       3098.40 MILLIAMPS
    EPROTECT         =       -694.57 MILLIVOLTS
=================================================================

    EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
    STANDARD ERROR OF Y ESTIMATE                 =     3.91616
    COEFFICIENT OF DETERMINATION (R SQUARED)     =     0.99662
    NO. OF OBSERVATIONS USED                     =          11
=================================================================
```

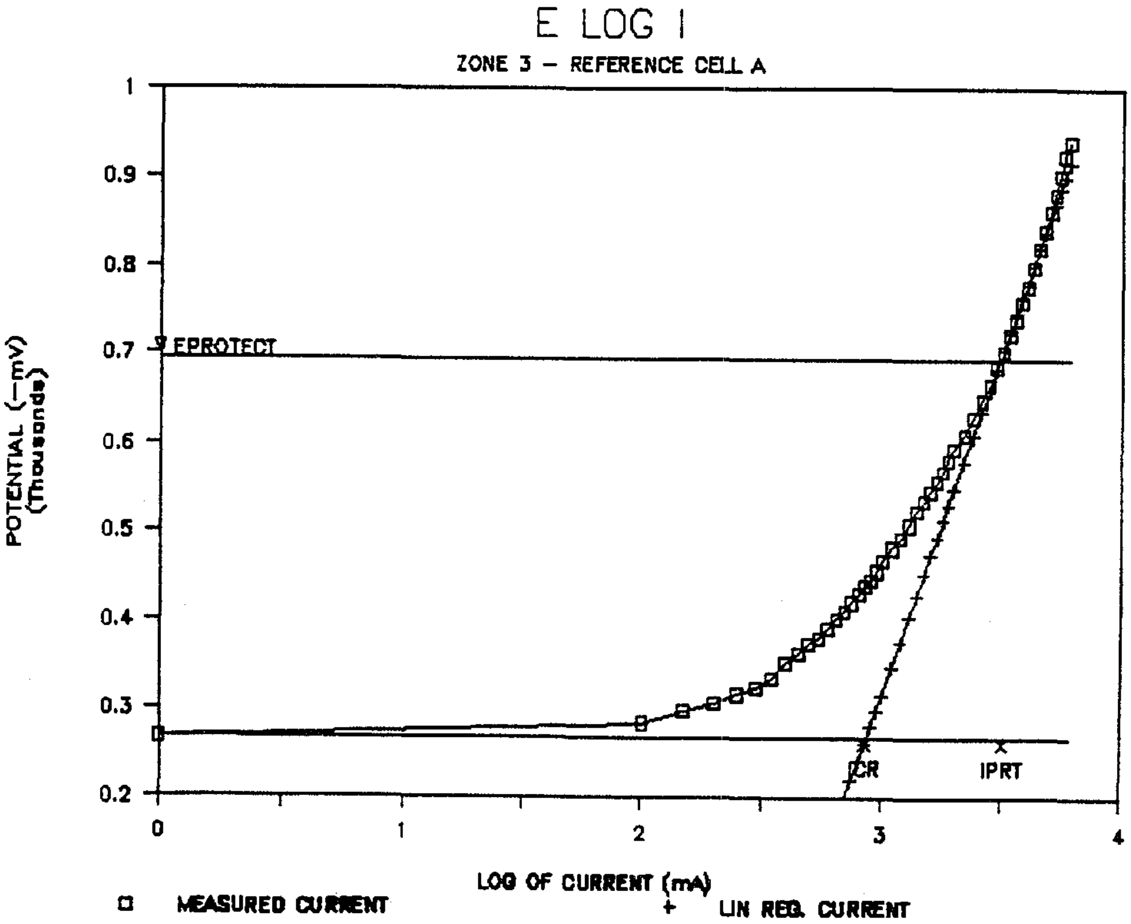


Figure 115. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell A at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

```
=================================================================
     E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
                     Zone 3 - Reference Cell B
-----------------------------------------------------------------
      TAFEL SLOPE      =        814.06 MILLIVOLTS/DECADE
      ICORR            =       1177.75 MILLIAMPS
      ECORR            =          -518 MILLIVOLTS
      IPROTECT         =       2898.26 MILLIAMPS
      EPROTECT         =       -816.37 MILLIVOLTS
=================================================================

      EVALUATION OF DATA FOR TAFEL LINE OF BEST FIT
-----------------------------------------------------------------
      STANDARD ERROR OF Y ESTIMATE                  =     3.40908
      COEFFICIENT OF DETERMINATION (R SQUARED)      =     0.99732
      NO. OF OBSERVATIONS USED                      =          10
=================================================================
```

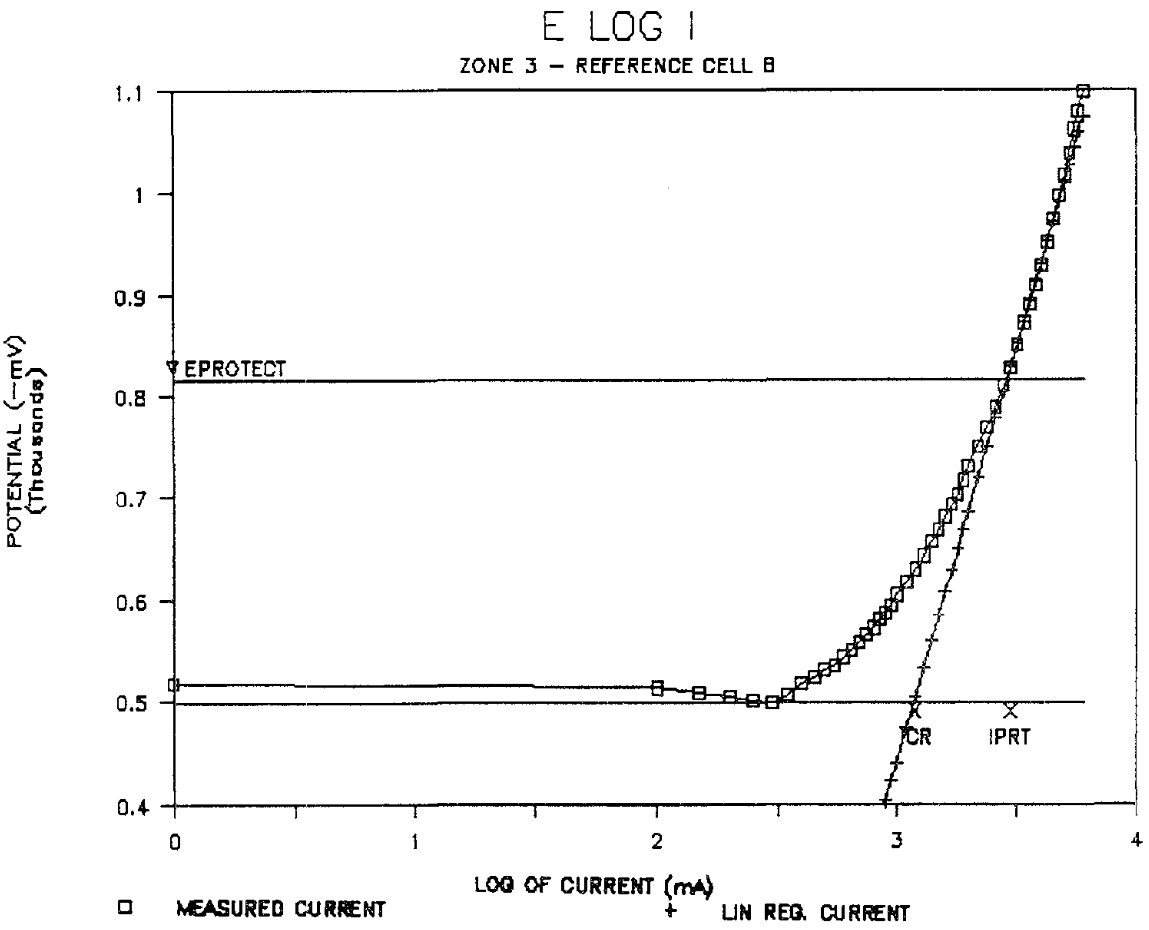


Figure 116. E Log I computed corrosion and cathodic protection data, Zone 3 - reference cell B at 18-month evaluation, northern climate bridge, Cincinnati, Ohio.

APPENDIX D
IMPROVED COKE-ASPHALT CATHODIC PROTECTION SYSTEM SUBSTUDY

The purpose of this substudy was to define and test the effectiveness of an improved coke-asphalt cathodic protection system for bridge decks. The improved system involves:

- Primary anode - platinized wire in slot backfilled with FHWA conductive polymer grout.
- Freeze-thaw protection: Hydrozo 56 vapor permeable surface sealer (penetrant) prior to overlay placement.
- Conductive overlay-Ontario Ministry of Transportation modified coke asphalt.

RESEARCH STUDY

Phase I of the study involved the performance of ASTM C672 deicer scaling tests on 0.50 water cement ratio, non-air-entrained concrete slabs with and without the sealer, to confirm sealer effectiveness. The deicer was 3 percent NaCl solution. The Hydrozo 56 was applied by brush in the manner recommended by the manufacturer (flood material onto surface, brush in, allowing concrete to take up the desired quantity and brush off excess such that no significant surface film remains). The application rate averaged 125 ft^2 per gallon ($3m^2/l$).

The unsealed slabs deteriorated rapidly, exhibiting moderate to severe scaling after only 5 cycles and severe scaling after 10 cycles. The sealed slabs showed little damage during that time and overall showed improvement by a factor of about 10 (i.e. 10 times as many cycles to equal deterioration). Figure 117 shows photographs after 15 cycles and table 32 presents all data.

Phase II involved the fabrication and testing of reinforced concrete slabs with the improved coke-asphalt cathodic protection systems. Two types of specimens - 1 ft^2 (0.09 m^2), 0.5 water cement ratio, non-air-entrained slabs and 2 ft^2 ($0.18m^2$), 0.42 water cement ratio, air-entrained slabs all with corroding reinforcing steel were used. Two slabs represented each variable (concrete type and sealed or unsealed). Primary anodes were installed by saw cutting a 1/4-in (0.6cm) wide and 1/2-in (1.25 cm) deep slot in the surface, applying a coating of catalyzed polymer resin (in the slot), inserting a 0.031-in (0.78 mm) diameter platinized niobium, copper core wire and backfilling with pourable FHWA conductive polymer grout (Hydrozo CP-12,000). Coke-breeze (Loresco DW1) was broadcast to excess on the filled slot. Resistivity of the conductive polymer grout was 0.83 ohm-cm. After 5 hours, the Hydrozo 56 penetrant was applied to half the specimens using the previously defined procedures. Figure 118 shows typical sealed slabs with primary anodes and steel molds in place for the coke-asphalt overlay.

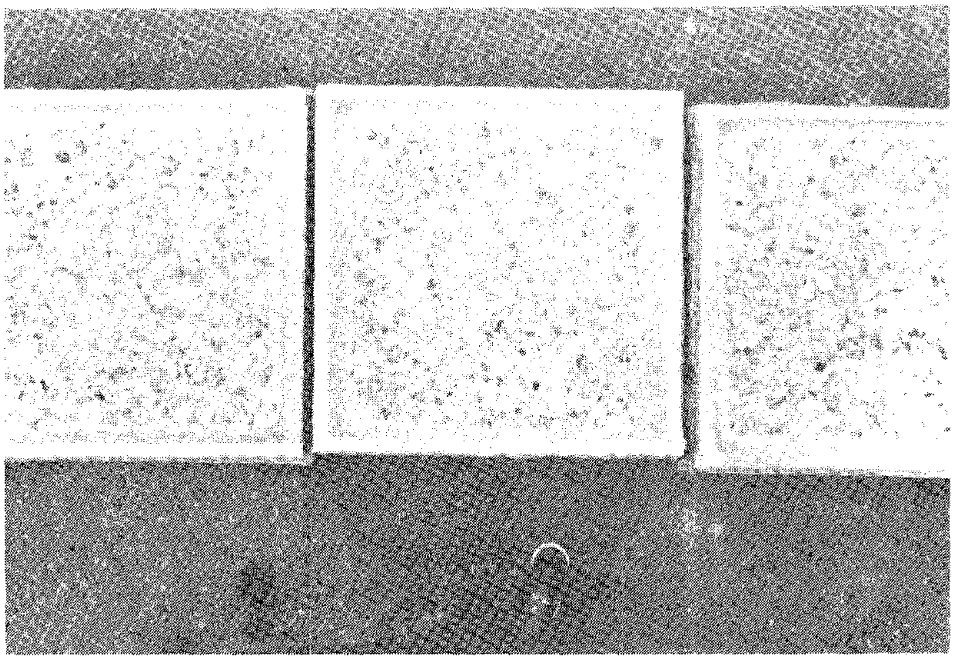
Table 32.

Deicer scaling test findings.
(ASTM C-672 with 3% NaCl solution)

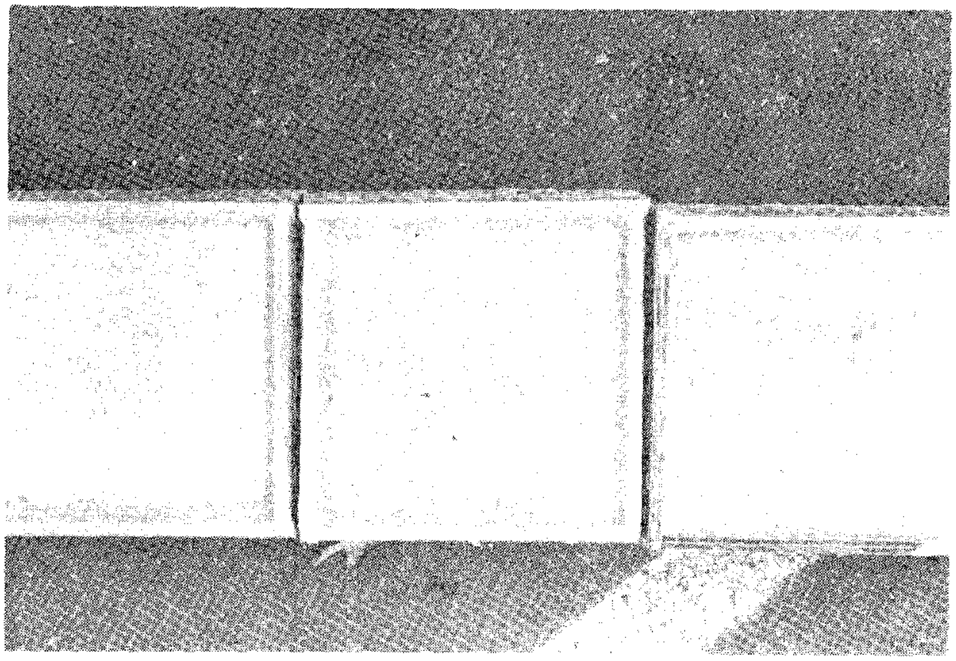
		Scaling Rating at Cycle Number								
Slab	**Variable**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**40**	**50**
F1	Hydrozo 56	0	0	1	2	2	2	2	3	4
F2	Hydrozo 56	0	0	0	1	1	1	1	2	3
F3	Hydrozo 56	0	0	0	1	1	1	2	3	5
Ave.	Hydrozo 56	0	0	0	1	1	1	2	3	4
F4	No Sealer	0	4	5	5	Removed from test				
F5	No Sealer	0	4	5	5	Removed from test				
F6	No Sealer	0	4	5	5	Removed from test				
Ave.	No Sealer	0	4	5	5					

Rating Key:

Rating	Condition of surface
0	No scaling
1	Very slight scaling (1/8 in (3.2 mm) depth, max, no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)



NO SEALER



HYDROZO 56

Figure 117. Deicer scaling slabs after 15 cycles.

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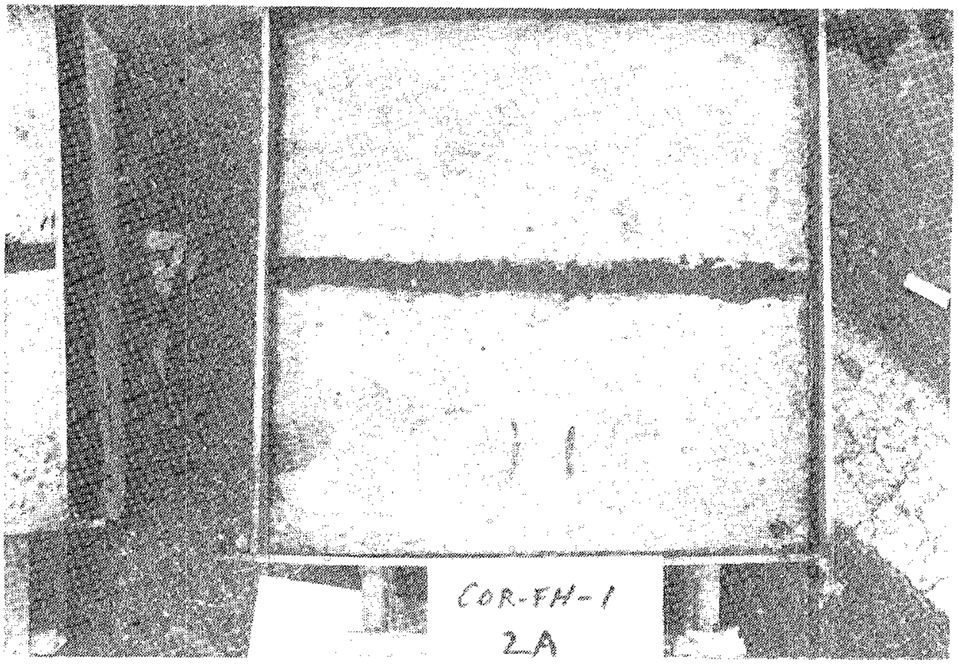
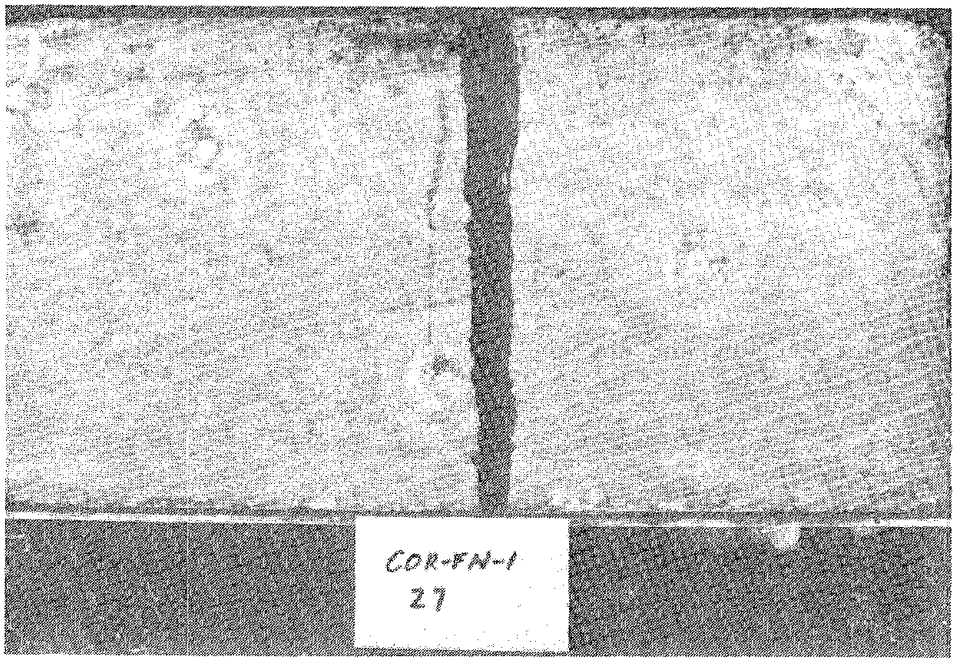


COR-FH-1



COR-FH-1

Figure 118. Typical slabs with primary anode, conductive polymer grout and sealer.

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The FHWA prepared and installed the modified coke-asphalt overlays on all slabs in accordance with Ontario Ministry of Transportation specifications and procedures. Boscan AC-20 asphalt with a 77 $^{\circ}$F (25 $^{\circ}$C) penetration of 89 and viscosities of 2363 Poise at 140 $^{\circ}$F (60 $^{\circ}$C)and 498 centistrokes at 275 $^{\circ}$F (135 $^{\circ}$C) was used. The aggregate blend consisted of 40 percent limestone coarse material, 15 percent sand and 45 percent coke breeze, sized per table 33. Properties of the mixture at asphalt contents ranging from 13 to 17 weight percent are shown in figure 119. An asphalt content of 15.75 percent was used for all specimens with a compacted thickness of 1.6-in and resulted in a compacted mixture resistivity of 1.9 ohm-cm. Resistivity samples purposely prepared at a higher void content (7% versus 3.3%) exhibited a resistivity of 1 ohm-cm.

Table 33.

Modified coke-asphalt cumulative percent passing - actual values[1].

Sieve	Blend[2]	Limestone[3] (40%)	Sand[4] (15%)	Coke Breeze[5] (45%)
3/4	100.0	100.0	100.0	100.0
1/2	86.9	69.7	100.0	100.0
3/8	76.0	43.5	100.0	100.0
4	57.4	2.6	100.0	91.9
8	41.0	0.2	84.9	62.7
16	30.3	0.2	60.7	48.2
30	22.7	0.2	43.3	35.1
50	15.6	0.2	25.2	24.1
100	8.6	0.2	15.5	13.4
200	4.5	0.2	7.8	7.1

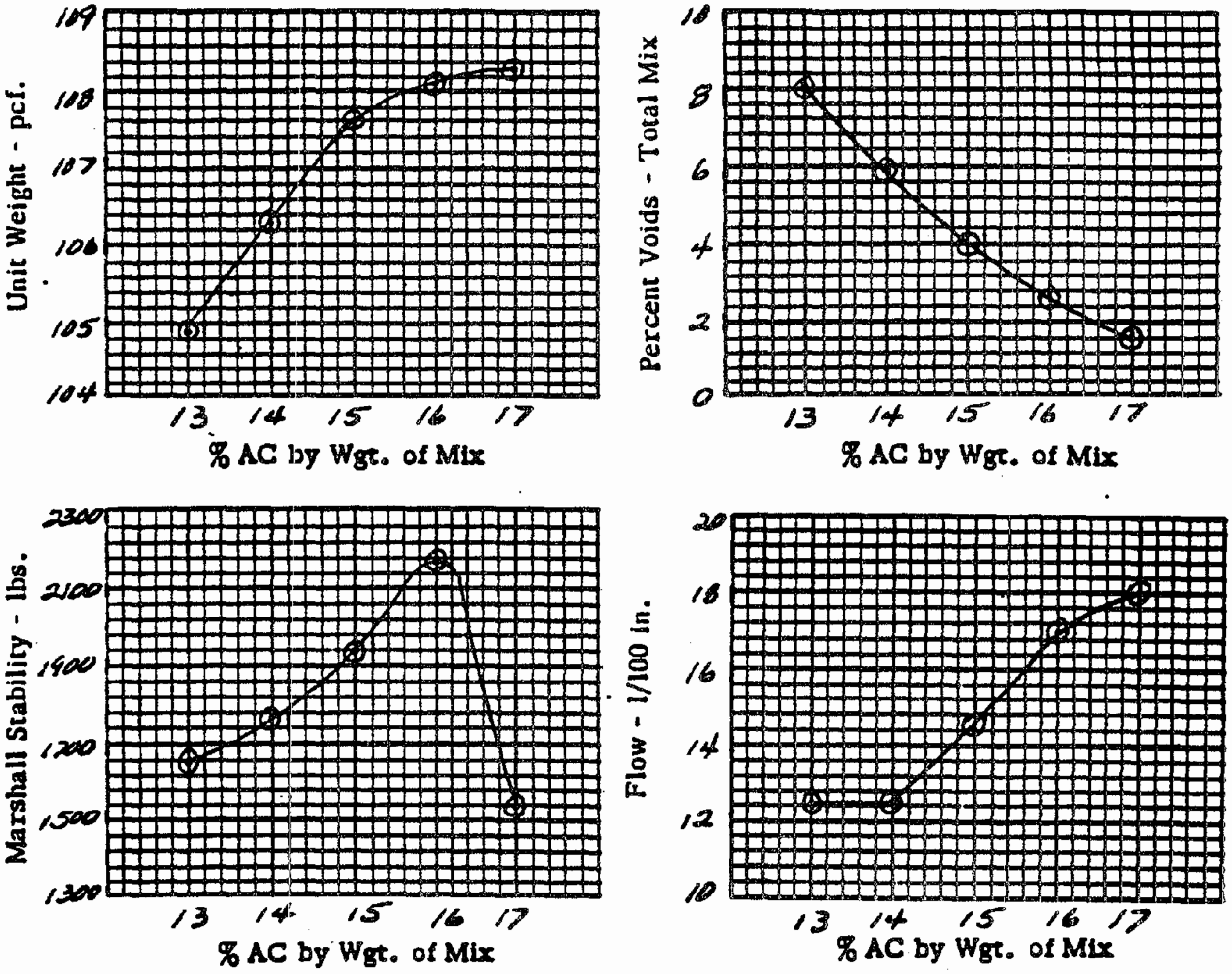
[1] Based on washed-sieve analysis, AASHTO, T11 and T27.

[2] Test results; not calculated using the three aggregate gradations.

[3] Meets AASHTO M43 Size No 67 specification.

[4] Meets AASHTO M29 Grading No 1 specification.

[5] Meets Ontario Ministry Specification SP 312.



MARSHALL METHOD

Job Identification: Coke-Asphalt Mixtures
Coarse Aggregate: 40%
Type: Limestone
Fine Aggregate: 15%
Type: Quartz sand
Coke Breeze: 45%
Type: ______________
Asphalt Cement Identification: B-5839
Date: 1/28/87

Figure 119. Properties of the coke-asphalt mixture.

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All specimens were then exposed to natural weathering on above ground racks and through outdoor exposure facility in Sterling, Virginia from February 1987 through April 1988 as shown in figure 120. No deterioration of the modified coke-asphalt or the underlying concrete occurred. In April 1987, two 2 ft^2 (0.18 m^2) slabs (one sealed and one unsealed) were E log I tested with voltage recording as a means of defining whether or not the sealer has any significant effect on circuit resistance and whether the improved system was functional. Figure 121 presents plots of top mat rebar half cell potential versus current with 3 cells on the unsealed slab and 3 cells on the sealed slab. The typical decrease in potential with increasing current indicative of efficient cathodic protection is seen in all instances. Figure 122 is a plot of system volts versus current for both slabs. No significant differences occurred as a result of the penetrant.

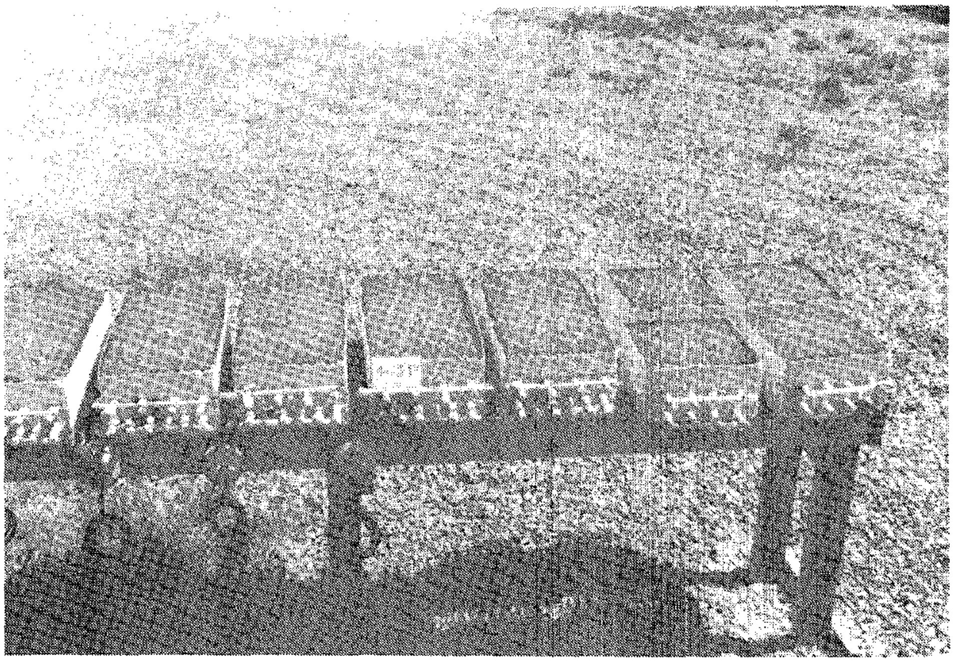

Figure 120. Overlaid slabs at outdoor exposure facility.

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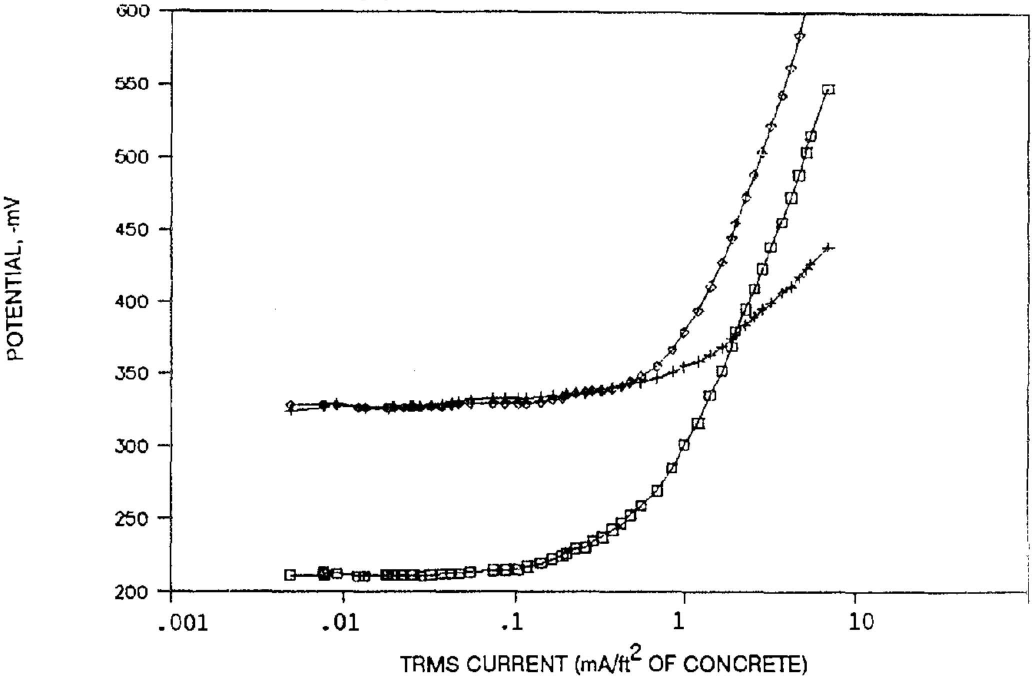
COR-FH-1: SLAB 24 - NO SEALER

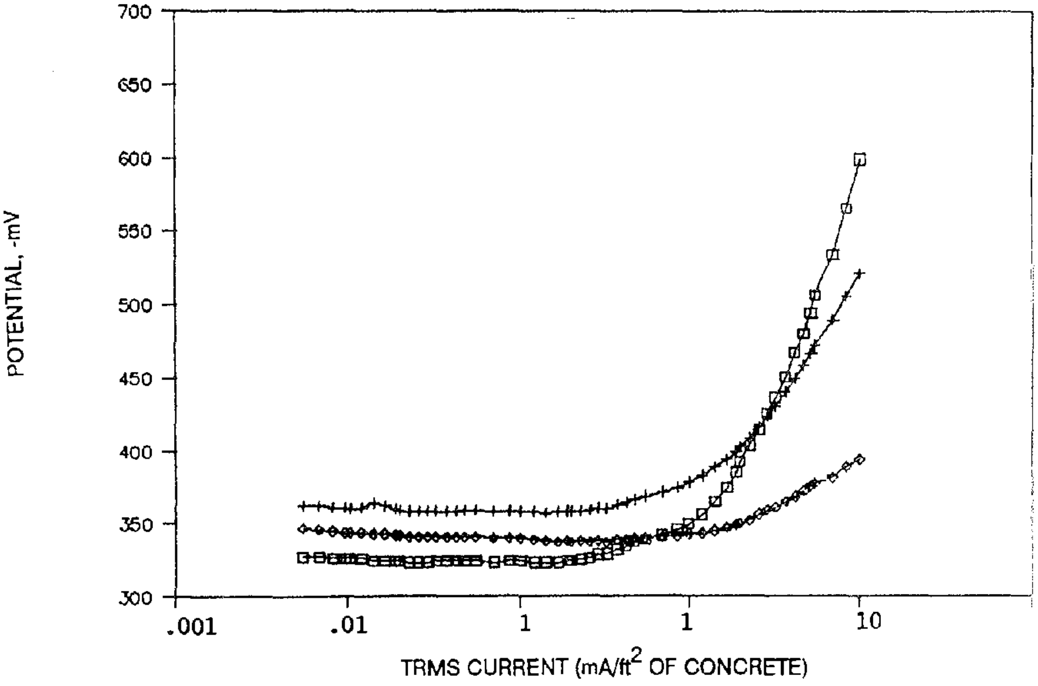
COR-FH-1: SLAB 27 - HYDROZO 56

Figure 121. E Log I test findings.

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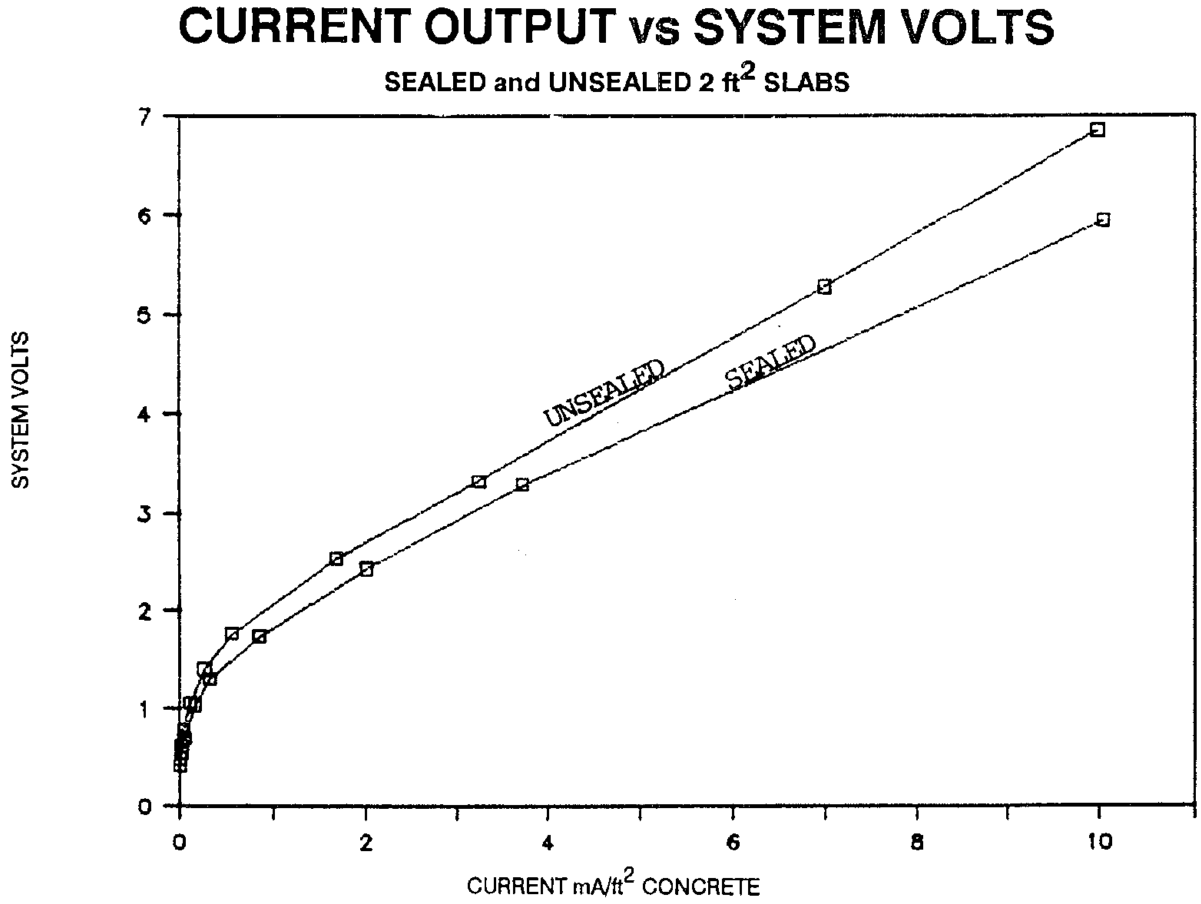

Figure 122. Plot of current output vs system voltage.

Further evidence of the effect of the penetrant on CP system performance was obtained by measuring the anode to rebar AC resistances throughout the exposure period. Initially, the resistances were very high, presumably the result of prolonged indoor storage prior to overlay. All resistances, however, decreased drastically upon outdoor storage with little differences for the sealed versus unsealed specimens after 5 months, as shown in table 34:

Table 34.

Average anode to rebar resistance (ohms).

Date	Temperature Degrees (F)	$1 ft^2$ slabs		$2 ft^2$ slabs	
		Unsealed	Sealed	Unsealed	Sealed
4-2-87	70	183	888	140	192
7-7-87	104	61	74	24	20
4-12-88	52	180	175	35	33

A measurement of the efficiency of the improved coke-asphalt system as a means of distributing the protective cathodic protection current at low voltages can be attained by comparing these resistances to those obtained on other systems. Many anode systems have been tested on the 1-ft (30 cm) by 2-ft (60 cm) reinforced concrete slabs. Resistance data are summarized in table 35 below comparing the improved coke-asphalt system to mesh anodes:

Table 35.

Resistance of improved coke-asphalt vs mesh anode.

	Average 70 Degree F. Resistance Anode to Rebar (ohms)
Improved Coke - Asphalt	30
Metal Oxide Coated Titanium Mesh and Concrete Overlay	42

These data indicate that the improved coke-asphalt system is very efficient and will provide effective cathodic protection.

CONCLUSIONS

The improved coke-asphalt cathodic protection system defined herein shows promise and should be further evaluated via experimental construction.

The recessed platinized niobium, copper core wire anode (0.031- or 0.062-in diameter) in FHWA conductive polymer grout is efficient and easy to install. Its use would permit overlay replacement without disruption of the primary anode.

The Hydrozo 56 sealer greatly enhanced the freeze-thaw durability of the portland cement concrete without interfering with the cathodic protection system's functioning. This should permit the use of the system on bridge decks without concern over the adequacy of the air-void system.

The Ontario modified coke-asphalt yielded excellent stability and other mixture characteristics. It is expected that it will perform well, when covered with a normal bituminous wearing course, even in high traffic volume areas. Mixture design studies are needed, however, to facilitate the use of readily available aggregates, graded to AASHTO standards, with this mix.

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