CATHODIC PROTECTION FOR REINFORCED CONCRETE BRIDGE DECK - BIG SPRING

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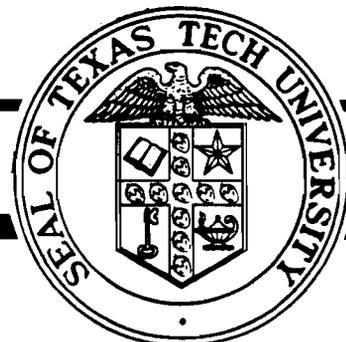
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16. Abstract

Five individual cathodic protection systems were installed on the U.S. 87 Missouri–Pacific Railroad overpass structure in Big Spring, Texas. The cathodic protection systems were installed in October 1988 as a demonstration project to compare the various systems. Three distributed anode types were used to protect the bridge deck: (1) titanium mesh; (2) conductive polymer; and (3) carbon strand. A hot-sprayed zinc conductive coating anode was applied to sidewalks and a median on the bridge deck, and a conductive paint anode was applied to a bridge bent. Performance data have been collected for each system since installation.

The purpose of this study was to assess the performance of the five different cathodic protection systems installed on the Big Spring bridge. The system assessment included determining the effectiveness of each system, performing a cost effectiveness study of the systems used to protect the bridge deck, preparing training aids for TxDOT personnel, and recommending a schedule for future evaluations and data collections. Only the titanium mesh distributed anode system continues to function. The hot-sprayed zinc anode system failed early in the study, and the reason for its failure is probably existing conditions of the sidewalk and median prior to system installation. The conductive paint has failed and the conductive coating is peeling and flaking extensively. A present value cost analysis is presented that considers bridge decks with and without cathodic protection. New and existing bridge decks were compared in the present value cost analysis.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons	0.9	tonnes	t
	(2000 lb)			
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
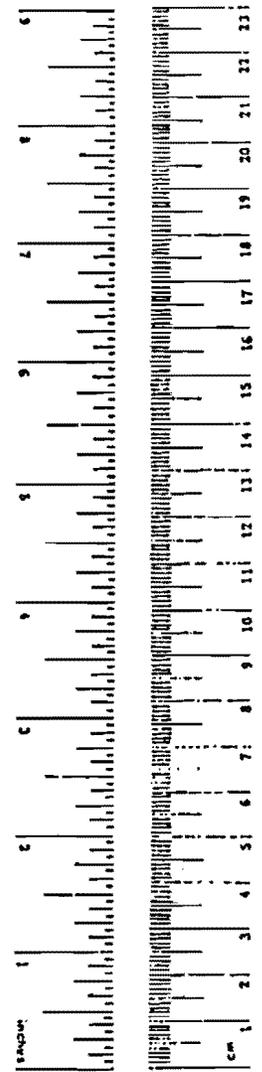
Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	

°F   -40   0   32   40   80   98.6   120   160   200   212   °F
°C   -40   -20   0   20   37   40   60   80   100   °C
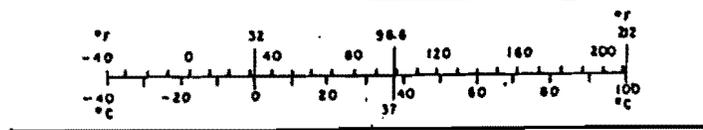
SUMMARY

Five individual cathodic protection systems were installed on the U.S. 87 Missouri Pacific Railroad overpass structure in Big Spring, Texas. The cathodic protection systems were installed in October 1988 as a demonstration project to compare the various systems. Three distributed anode types were used to protect the bridge deck: (1) titanium mesh; (2) conductive polymer; and (3) carbon strand. A hot-sprayed zinc conductive coating anode was applied to sidewalks and a median on the bridge deck, and a conductive paint anode was applied to a bridge bent. Performance data have been collected for each system since installation.

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Only the titanium mesh distributed anode system continues to function. The hot-sprayed zinc anode system failed early in the study, and the reason for its failure is probably existing conditions of the sidewalk and median prior to system installation. The conductive paint has failed and the conductive coating is peeling and flaking extensively. A present value cost analysis is presented that considers bridge decks with and without cathodic protection. New and existing bridge decks were compared in the present value cost analysis.

IMPLEMENTATION STATEMENT

Findings and results from this study will be used to choose the most appropriate bridge protection system for future projects. Recommendations from the evaluation will serve as a basis for including cathodic protection system options in future bridge design guidelines. These guideline supplements will be provided as they become available.

This final report was prepared to serve as a guideline for training TxDOT personnel in the principles and applications of cathodic protection. This document will reduce dependence upon outside contractors for system evaluations and help reduce any bias in evaluating future systems.

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1. INTRODUCTION

Deterioration of highway bridges through corrosion has become an extremely costly problem in both the United States and abroad. The Federal Highway Administration (FHWA) estimates that of the nation's 577,000 bridges, 226,000 (39% of the total) were deficient, and that 134,000 (23% of the total) were classified as structurally deficient, (SHRP, 1993 and FHWA, 1991). Structurally deficient bridges are those that are closed, restricted to light vehicles only, or that require immediate rehabilitation to remain open. The predominant cause of damage to most bridges is corrosion of the steel reinforcement. The United States Department of Transportation estimates that $90.9 billion will be needed to repair the damage on these existing bridges (FHWA, 1991). Similar problems exist in other countries. The head of the Structural Group of the United Kingdom's Transport and Road Research Laboratory states that concrete bridges were first constructed in the U.K. some 90 years ago (Tilly, 1987). In the time since then, the concrete bridges performed very well until the mid 1960's when rock salt was introduced for deicing during winter months. Consequential problems of corrosion of the reinforcing and prestressing steel have taken several years to become evident but are quickly becoming a significant problem.

The American Concrete Institute (ACI, 1992) classifies measures that can be taken in reinforced concrete construction to protect the steel against corrosion into three categories:

1. Design and construction practices that maximize the protection afforded by the portland cement concrete

2. Treatments that penetrate or are applied on the surface of the reinforced concrete member to exclude chloride ion from the concrete

3. Techniques that prevent corrosion of the reinforcement directly

The ACI suggests a number of measures (ACI, 1992) to protect against corrosion in new construction. A summary of suggested measures is given in Table 1.

Highway bridges in the State of Texas have experienced deterioration similar to other bridges in the U.S. Problems of epidemic proportions were realized in the early 1960's (Texas Bridge Design Guide) even though only a portion of the state lies above the "de-icing salt line." Bridge deck deterioration was manifested by cracking, scaling, and delamination of the concrete. Texas concluded that delaying the penetration of moisture would increase the durability of reinforced concrete bridge decks.

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TABLE 1. MEASURES TO PROTECT REINFORCING STEEL FROM CORROSION (ACI, 1992)

Category	Measure
Design and construction practices	Provide adequate drainage
	Provide adequate depth of cover to reinforcing steel
	Provide low permeability concrete
	Limit chloride content in concrete
	Control concrete cracking
Excluding external sources of chloride ion from concrete	Waterproof membranes
	Polymer impregnation
	Polymer concrete overlays
	Portland cement concrete overlays
	Low-slump concrete overlays
	Latex-modified concrete overlays
Protecting reinforcing steel from chloride ion	Non-corrosive steels
	coatings
Corrosion control	Chemical inhibitors
	Cathodic protection

Corrosion protection methods concentrate on delaying moisture intrusion and include the following:

1. Tight concrete specification requiring more cement, less water, cleaner aggregates, air entrainment, controlled placement temperature, better consolidation, improved curing, and longer protection from loads

2. Two-course asphaltic surface treatment or one course of latex asphalt and lightweight aggregate covered with a layer of asphaltic concrete

3. Linseed oil as a standard protective coating for all bridge decks that are not covered with asphaltic materials

A variety of experimental treatments have been tried in Texas including polymer impregnation, epoxy, polymer and polyester overlays, wax beads and cathodic protection. Cathodic protection is considered effective but expensive, while the other treatments are considered ineffective.

Corrosion protection measures for new bridges in Texas fall into one of the following categories:

1. Against corrosion from above

2. Against corrosion from below

Guidelines are specified according to geographical area with a number of recommended procedures including a variety of sealer applications, several configurations of epoxy coated reinforcing steel, and combinations of the recommended procedures. Final implementation is decided within districts leading to a lack of uniform guideline adherence. Presently, there is a complete lack of guidelines for cathodic protection systems within the State of Texas. Although national studies have concluded that cathodic protection is possibly the only practical method of arresting corrosion, it has not yet been fully proved for reinforced concrete bridges in service and requires maintenance throughout its life.

Two basic approaches to cathodic protection have been investigated in the past (Vrable, 1977): (1) Sacrificial anodes; and (2) Impressed current. Sacrificial anode methods of cathodic protection employ an anode more active in the electromotive force series than the metal to be protected. Impressed current methods of cathodic protection use an externally applied electrical current to maintain an electromotive potential in the metal being protected below the potential required for corrosion to proceed. Only systems employing impressed current were evaluated in the study reported herein. Vrable notes that although cathodic protection ranks highest among the available ways to prevent corrosion of reinforcing steel in bridge decks, it is the only available method for arresting corrosion in existing bridge decks. Furthermore, the Federal Highway Administration (FHWA) stated its position on cathodic protection systems in 1982 as follows:

> The only rehabilitation technique that has proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of the concrete is cathodic protection (Jackson, 1982).

2. PROBLEM STATEMENT

In a cooperative program with the Federal Highway Administration (FHWA) Demonstration Division, the Texas Department of Transportation (TxDOT), District 8 applied cathodic protection systems to the U.S. 87 Missouri Pacific Railroad overpass structure in Big Spring, Texas. Five individual cathodic protection systems were installed on the single structure to provide for a systematic and comparative evaluation of each system with regard to the ease of installation, effectiveness of operation, and ease of routine and major maintenance. The purpose of this study is to analyze data from the five cathodic protection systems and evaluate the performance of these systems to determine their effectiveness in preventing the corrosion of the reinforcing steel. The study also offers the opportunity to train TxDOT personnel in evaluation techniques and procedures and to develop recommendations for scheduling and data collection for future projects.

3. OBJECTIVES OF THE STUDY

The principal objective of this research is to assess the performance of the five different bridge protection systems installed on the U.S. 87 Missouri Pacific Railroad overpass structure in Big Spring, Texas. The system assessment included determining the effectiveness of each system, identifying the most cost-effective system, training TxDOT

personnel for future in-house evaluations, and recommending a schedule of future evaluations and data collections. Specific objectives of the study are described below:

1. Determine the effectiveness of each system in preventing corrosion of the reinforcing steel. The five cathodic protection systems have been installed on the structure for more than five years. Post-installation and activation testing of the systems was performed just after their completion and at 45 and 90 days after initial energization (Smith, 1990). The first objective is to collect additional data to determine performance after the initial testing.

2. Identify the most cost-effective system. A major concern for cathodic protection systems is their cost effectiveness. Smith (Smith, 1990) provided a breakdown of the overall actual cost for installing the five cathodic protection systems, but noted that true costs could only be determined by monitoring the system over a period of at least 15 to 25 years. One objective of this study is to perform a second cost analysis and lay the groundwork for future evaluations and cost analyses for long-term considerations.

3. Provide training for TxDOT personnel to facilitate future in-house evaluations. The development and application of cathodic protection systems to reinforced concrete bridges in Texas is in its early stages. Most of the technology to date has been developed for individual proprietary systems, and system developers are generally biased in recommending their own technology. One objective of this study is to provide TxDOT with an unbiased assessment of potential cathodic protection systems and provide training for TxDOT personnel for future in-house evaluations free from bias towards any particular cathodic system. This final report includes an extensive discussion of the history and principles of cathodic protection and is intended to provide a summary of the state-of-the art cathodic protection that can serve as a training tool.

4. Recommend a schedule of future evaluations and data collection. Long-term monitoring of the five cathodic protection systems located at the Big Spring site or any other systems to be installed in the future requires a plan for performing future evaluations and data collections. A part of this study is to develop a logical plan of action for collecting and analyzing data over a long period of time and accomplishing the requisite evaluations.

4. HISTORY AND BASIC PRINCIPLES OF CATHODIC PROTECTION

Corrosion is the degradation of metal by chemical attack. Most metals originate from ores as oxides, sulfides, or carbonates. Energy is required to extract the metals from the ores. In corrosion, the process is reversed and the metal degrades. Consequently, metals that are easily obtained or require simple smelting are less susceptible to corrosion than metals that require extensive processing (Morgan, 1959). For example, gold is found in its metallic state and does not corrode. Likewise, silver is readily obtainable and is highly resistant to corrosion.

4.1 Description of Corrosion.

Most corrosion occurs through the interaction of the two common processes of solution and oxidation (Van Vlack, 1967). Material components can be combined into solutions in a variety of ways. For example, sugar dissolves as molecules into water and the total amount of sugar that will dissolve is temperature dependent. Other materials dissolve as ions. Salt dissolves as sodium (Na^+) and chloride (Cl^-) ions. The sodium ion has one electron in its valence shell while the chloride ion readily adds one electron to its valence shell. Likewise, iron (Fe) in mild steel dissolves into ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions as expressed in Equations 1 and 2. Removal of electrons from the atom is defined as metal oxidation.

$$Fe \Longrightarrow Fe^{2+} + 2e^- \qquad\qquad (1)$$

$$Fe^{2+} \Longrightarrow Fe^{3+} + e^- \qquad\qquad (2)$$

The following generalizations may be made about chemical solution:

1. Small molecules and ions dissolve most readily.

2. Solution occurs more readily when the solvent and solute are structurally similar.

3. The presence of two solutes may produce greater solubility than the presence of only one.

4. The rate of solution increases with temperature.

Wollaston (circa 1815) regarded corrosion to be an electrochemical process and later it was suggested that rusting was also an electrochemical phenomenon (Morgan, 1959). Sir Humphry Davy (in 1823) was commissioned by the British Admiralty to investigate the corrosion of the copper sheathing of the hulls of wooden naval ships. Davy showed that when two dissimilar metals were electrically connected and immersed in water, the corrosion of one was accelerated while the other received a degree of protection. Later, de la Rive showed that impure zinc was corroded rapidly by the great number of bimetallic junctions that it contained. The corrosion of the zinc was attributed to numerous corrosion cells setup between the zinc and the impurities. Similar corrosion through local cells can occur in any metal in the presence of moisture. Some of the earliest studies of corrosion and electrochemical action were published by Luigi Galvani, a physician in Bologna, Italy (Uhlig, 1985). A combination of two electrical conductors or electrodes immersed in an electrolyte is called a Galvanic cell. Faraday, through a series of corrosion experiments, was able to derive his laws of electrochemical action that give the relationship between the current flowing and the associated corrosion.

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4.2 Galvanic Cell.

A combination of two electrical conductors (electrodes) immersed in an electrolyte is called a Galvanic cell in honor of Luigi Galvani (Uhlig, 1985). A Galvanic cell converts chemical energy into electrical energy as illustrated in Figure 1. When a low-resistance wire is attached to each electrode current flows through the metallic path from the positive electrode to the negative electrode. Electrons travel from the negative to the positive pole. Positive carriers flow in the opposite direction. Current is carried through the electrolyte by both negative and positive carriers known as ions. Ions are electrically charged atoms or groups of atoms. The net current in the electrolyte of a cell is always exactly equivalent to the total net current carried in the metallic path by electrons alone.
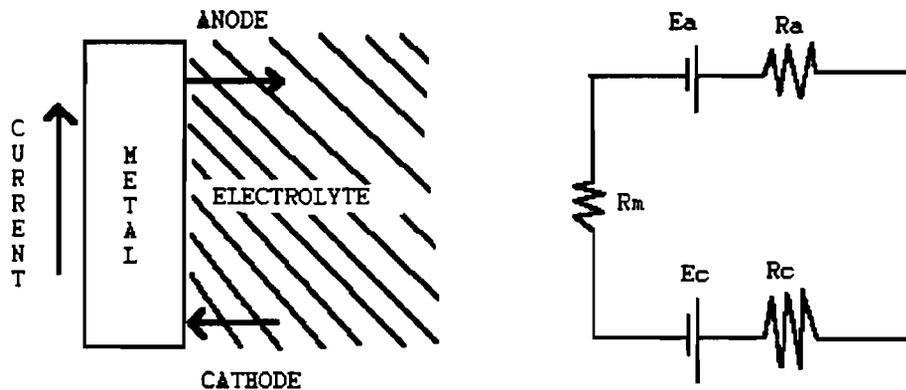
Figure 1. Simple Cell and Equivalent Circuit (Morgan, 1959)

Ohm's law relates current to electromotive potential and electrical resistance through the following equation:

$$I = E / R \qquad\qquad (3)$$

where: I = current (amps)
E = potential difference (volts)
R = resistance (ohms).

Galvanic corrosion always involves two different electrodes: a cathode and an anode. These electrodes may be large, physically separated electrodes, or microscopic areas on the same piece of metal. The former configuration is employed in laboratory research and teaching, and the latter is most often is the way corrosion actually occurs in practice. The reactions that occur at each electrode are termed half-cell reactions, since half of the net overall reaction occurs at each electrode. Corrosion occurs at the anode converting useful metal into metal ions and electrons. The electrons are removed by flow of electrical current. For corrosion of iron, the half-cell reactions is as follows:

$$Fe \Rightarrow Fe^{++} + 2e^-$$
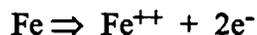
The half-cell reactions can be reversed. Ferrous ions are converted to metallic iron by supplying electrons to the electrode in the process of electroplating. Depending upon the

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nature of the electrolyte three different reactions commonly occur at the cathode as follows:

$$2H^+ + 2e^- \Rightarrow H_2 \qquad \text{(in acids)}$$

$$O_2 + H_2O + 4e^- \Rightarrow 4OH^- \quad \text{(in presence of oxygen)}$$

$$O_2 + 2H_2 + 4e^- \Rightarrow 2H_2O \quad \text{(both acids and oxygen)}$$
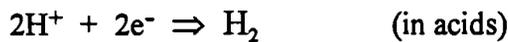
The second cathodic reaction above occurs in the corrosion of rebar in concrete.

4.3 Electromotive Force (Galvanic) Series.

A common method for quantifying the rate of chemical reactions is the Gibbs free-energy change (Uhlig, 1985). The value of Gibbs free-energy change can be either positive or negative with the more negative the value of the Gibbs free-energy change, the greater the tendency for the reaction to occur. Although the Gibbs free-energy change cannot be used to measure corrosion tendency, it is certain that for reaction conditions with positive values of Gibbs free-energy change, the corrosion reaction will not occur. For reaction conditions with negative values of Gibbs free-energy change, the reaction and thus corrosion will occur and the reaction rate can be either rapid or slow. Because corrosion is an electrochemical process, a better method of assessing the tendency of corrosion reactions is to report the electromotive force (emf) between the anode and cathode cells that are an integral part of the corrosion process. The electromotive force expressed in volts is the potential difference (E) as given in Equation 3. The greater the value of E for any Galvanic (corrosion) cell, the greater the tendency for the overall reaction of the cell. Corrosion cells can develop in a variety of types. Uhlig (1985) describes the following three main types of cells:

1. Dissimilar Electrode Cells. An example of a dissimilar electrode cell is a dry cell battery. Electrodes in the cell are made from two different materials separated by an electrolyte designed to create chemical reduction at the positive pole and oxidation at the negative pole when a short circuit or load is placed between the two poles. Current flows as the electrodes react and the greater the flow of current, the greater the corrosion (consumption) of the electrodes.

2. Concentration Cells. Concentration cells have electrodes made of identical metals in contact with a solution of differing composition. One type of concentration cell is a salt concentration cell. A Galvanic cell with one electrode exposed to a concentrated solution of electrolyte and the other electrode exposed to a diluted solution of electrolyte is an example of a salt concentration cell. A second type of concentration cell is the aeration cell. In an aeration cell, one electrode (cathode) is exposed to thoroughly aerated electrolyte while the other electrode (anode) is exposed to deaerated electrolyte. Differences in the oxygen concentration produce a potential difference and creates electricity (current) flow. Aeration corrosion cells can develop in aqueous environments such as seawater.

3. Differential Temperature Cells. Electrodes exposed to electrolyte at significantly different temperatures can also create current flow and resulting corrosion. Examples of temperature cells can occur in heat exchangers, boilers, immersion heaters, and similar equipment.

The electric potential developed between any two macroscopic half-cells can be measured in the laboratory and their relative potentials listed in a table of half-cell reactions as shown in Table 2. The potential developed can also be calculated based on the Gibbs free energy associated with the reaction. These potentials are stated at standard conditions, usually 25 C and 1.0 M concentration of ions in the electrolyte, with respect to reference cell reaction. The standard reference cell is the hydrogen electrode, the first cathodic reaction above. The hydrogen electrode has been selected because it is easily reversible and stable. Unfortunately, it is expensive and awkward to use. It requires a catalytic platinum surface on which the reaction takes place and a source of pure hydrogen. For this reason, other electrodes are generally used for experimental measurements. Some of these practical reference cells will be discussed later in this report.

The ions produced by the half-cell may react further and/or combine to form precipitates, (insoluble products). In the case of rebar corrosion, ferrous ions can be further oxidized to ferric ions with the loss of another electron. These iron ions can then combine with the hydroxide ions produced at the cathode to produce mixtures of ferric and ferrous hydroxide. Finally, the iron hydroxides can lose water to become iron oxides, (rust). The resulting rust occupies more space than the iron from which it was made, so internal pressures are generated within the concrete structure, causing it to crack and spall.

Looking at the table of half-cell voltages, one would expect iron to corrode rather rapidly in the presence of moisture and oxygen, since the potential difference between the anodic reaction and the second cathodic reaction is 0.84 volts. Rebar in concrete normally does not corrode because the iron is passive at very high pH's, as noted by the decreased corrosion rate at high pH's in Figure 3. Similarly, the stainless steel is stainless because it remains passive, even in low pH acid solutions, due to its chromium content. Passivity is the result of destroying the electrochemical activity of the anode surface with an exceedingly thin, and sometimes fragile, film which is electrochemically deposited. Unfortunately, for rebar in concrete, minor amounts of chloride ions in the concrete can destroy the passivity of iron even at high pH's. This fact is the primary electrochemical basis for the rebar corrosion problem.

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TABLE 2. STANDARD ELECTRODE POTENTIALS AT 25°

Oxidation (corrosion) reaction	Electrode potential, E° (volts vs. standard hydrogen electrode)
$Au \rightarrow Au^{3+} + 3e^-$	+1.498
$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$	+1.229
$Pt \rightarrow Pt^{2+} + 2e^-$	+1.200
$Ag \rightarrow Ag^+ + e^-$	+0.799
$2Hg \rightarrow Hg_2^{2+} + 2e^-$	+0.788
$Fe^{2+} \rightarrow Fe^{3+} + e^-$	+0.771
$4(OH)^- \rightarrow O_2 + 2H_2O + 4e^-$	+0.401
$Cu \rightarrow Cu^{2+} + 2e^-$	+0.337
$Sn^{2+} \rightarrow Sn^{4+} + 2e^-$	+0.150
$H_2 \rightarrow 2H^+ + 2e^-$	0.000
$Pb \rightarrow Pb^{2+} + 2e^-$	−0.126
$Sn \rightarrow Sn^{2+} + 2e^-$	−0.136
$Ni \rightarrow Ni^{2+} + 2e^-$	−0.250
$Co \rightarrow Co^{2+} + 2e^-$	−0.277
$Cd \rightarrow Cd^{2+} + 2e^-$	−0.403
$Fe \rightarrow Fe^{2+} + 2e^-$	−0.440
$Cr \rightarrow Cr^{3+} + 3e^-$	−0.744
$Zn \rightarrow Zn^{2+} + 2e^-$	−0.763
$Al \rightarrow Al^{3+} + 3e^-$	−1.662
$Mg \rightarrow Mg^{2+} + 2e^-$	−2.363
$Na \rightarrow Na^+ + e^-$	−2.714

More cathodic

(less tendency to corrode)

eactions are written as anodic half-cells. The more negative half-cell reaction, the more anodic the reaction is and the ater the tendency for corrosion or oxidation to occur.

More anodic

(greater tendency to corrode)

A corrosion (Galvanic) cell is formed when any piece of metal is immersed in an electrolyte due to small variations in potential over the surface of the metal or variations in the electrolyte concentration. Variations in electrolyte temperature or other parameters can also initiate corrosion cells. Depending upon specific conditions, the metal surface may divide simply into large anodic and cathodic areas or the whole surface may consist of a multitude of small cells. Anodes and cathodes can be as small as metal grain crystals. A typical corrosion cell and its representation as an equivalent electrical circuit are shown in Figure 1 (Morgan, 1959). E_a and E_c are the half-cell potentials associated with the anode and cathode respectively. The metal has a resistance R_m, R_a is the resistance associated with the anode, R_e is the resistance associated with the electrolyte, and R_c is the resistance associated with the cathode. The rate of corrosion depends upon the current that flows in the cell and the rate of metal weight loss increases as current increases. Current (i) flowing in the cell can be defined from Ohm's law in the following equation:

$$i = \frac{(Ea - Ec)}{(Rm + Ra + Re)} \tag{4}$$

The resistance associated with the metal is frequently very low, and the resistance associated with the electrolyte may vary greatly, depending upon the electrolyte composition and geometry of the cells. The resistance associated with the electrochemical surface of the anode and cathode is important in explaining corrosion processes. This electrochemical resistance is controlled by the net rates at which the electrode reactions can actually occur. The electrical potentials shown in Table 2 are for zero current flow or no net reaction on the electrode surface. To have a net reaction rate, it is necessary to displace the electrode potential from this condition of zero current flow by applying external voltage. The ratio of displacing voltage to resulting current has the units of

ohms, the resistance associated with the electrode. Connecting two half-cells together displaces the no current voltage of both cells and causes net current to flow. In the case of electrical batteries, the result is the desired generation of electric power. In the case of galvanic corrosion the result is destruction of the metal structure. In regard to electrochemistry, this resistance associated with the electrode surface is termed polarization.

It follows from the above discussion that if the electrical potential of the anode can be displaced in the positive direction, corrosion will cease and the anode will really become a cathode. This process is termed cathodic protection. For an ideal, small electrode, no net current flow would result in no corrosion. For a large corroding surface, large numbers of small local anodes and cathodes exist, and we normally observe no net external current flow. To achieve effective cathodic protection, sufficient current must be drawn from the structure to eliminate every local anode on the structure. Determining this current flow required to prevent corrosion, and the electrical potential required to achieve that current flow is the science and art of utilizing cathodic protection. The required electrical potential can be produced by an external reactive anode composed of a metal lower in the galvanic series than iron. Frequently, aluminum, zinc, or magnesium are used. An example is the magnesium rod found in hot water heaters to protect them from corrosion. Another option is to use an inert external anode and then supply the necessary dc. current from a power supply.

Sir Humphry Davy recommended cathodic protection of copper-sheathed ships in 1824. He proposed to use sacrificial blocks of iron attached to the copper hull. The technique was successful in reducing corrosion, but created fouling of the hull by marine organisms. The fouling reduced the speed of the ships and the idea was abandoned. Later, Davy's cousin Edmund Davy successfully protected the iron work of buoys by attaching zinc blocks. In 1840, Robert Mallet produced a zinc alloy particularly suited as a sacrificial anode for ship hulls. The first application of impressed electric current for protection of underground structures took place in England and in the United States, about 1910-1912 (Uhlig, 1985). Impressed current is used to cathodically protect buried pipelines, buried cables, canal gates, condensers, submarines, water tanks, marine pilings, offshore oil-drilling structures, and chemical equipment. The application of cathodic protection techniques to reinforced concrete bridges is a relatively recent event.

Stratfull (1957) investigated deterioration of the reinforced concrete on the San Mateo-Hayward bridge and determined the reinforcing steel in the concrete exhibited the same general galvanic properties of corrosion as does steel in soil or aqueous solutions. The relatively permeable concrete allowed salt-laden moisture to contact the reinforcing steel. The corrosion problem was further complicated due to an insufficient surface cover of concrete over the reinforcing steel. The chloride concentration in concrete adjacent to the corroded steel was as great as 0.86 percent of the dry weight of the mortar. Investigations of the bridge included both potential resistivity measurements at numerous locations on the bridge and other reinforced concrete members located near the bridge. Two types of reference cells were used to measure electrical potentials. One reference cell

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consisted of a porous cup filled with a saturated copper sulfate solution and a pure copper electrode. This reference cell was left in place during the period of measurement. The other reference cell was similar to the first but was constructed by filling a polyethylene bottle with saturated copper sulfate and a pure copper electrode. The second type of reference cell was hand held. Potential differences as great as 0.45 volts were detected at the concrete surface over distances of several feet or more. Resistivity measurements were made using four-electrode methods common in the geophysical and corrosion investigations of soils. In general, the resistivity of the concrete was found to decrease as the deterioration of the concrete increased. Continuing corrosion was evident in areas that had been repaired with shotcrete or overlays. Stratfull concluded it appeared worthwhile to develop a reliable method to cathodically protect the reinforced concrete.

4.4 Cathodic Protection of Reinforced Concrete Bridges.

In another study, Stratfull reported the results of investigating 22 bridges (Stratfull, 1975). Important findings from the study included the following:

1. The quantity of chlorides in concrete associated with the incidence of active corrosion of the steel is approximately 1.0 lbs/yd^3 (0.59 kg / m^3) of concrete.

2. The average potential of the steel in delaminated concrete was found to be -0.180 volts saturated copper - copper sulfate half-cell (CSE). For delaminated concrete, the average potential in small isolated areas was -0.385 volts whereas the average of the minimum and maximum values found in large corroding areas was -0.334 and -0.453 volts CSE respectively. For electrical potential greater than -0.35 volts CSE, there is great assurance of active corrosion.

Corrosion can occur in some circumstances in the absence of chloride ions (ACI, 1992). However, chloride ions are considered to be the major cause of premature corrosion of steel reinforcement. Chloride ions are common in nature (i.e., seawater) and small amounts are usually unintentionally contained in mix ingredients of concrete. Certain admixtures increase the chloride content in concrete. Exposure to deicing salts also increases chloride ion content in concrete. When oxygen and moisture are present in the concrete along with the chloride ions, corrosion can occur. The chloride laden, wet concrete serves as the electrolyte in a galvanic cell, and corrosion proceeds at a rate determined by various factors such as the following:

1. Gradients in chloride ion - Differences in chloride concentration can setup concentration cells (as described previously) and lead to macrocell corrosion.
2. Heterogeneities in the concrete and steel - Differences in the electromotive potential of the steel and concrete can create current flow leading to corrosion.
3. pH of the concrete pore water - The corrosion rate of iron is reduced as the

pH is increased. Concrete usually has a pH higher than 12.5 and protects steel from corrosion (Figure 2). Increases in chloride content cause loss of passivity in the steel and corrosion rates increase rapidly.
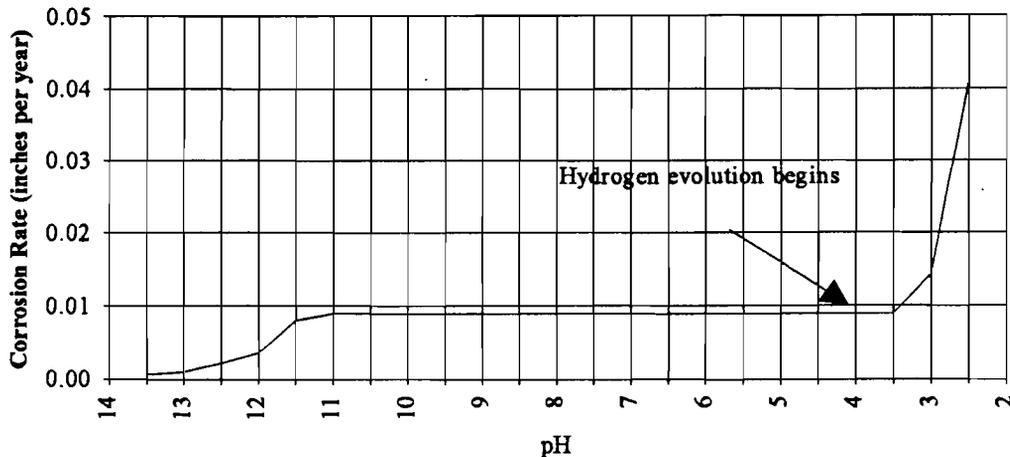
One inch = 2.54 cm

Figure 2. Effect of pH on Corrosion of Iron in Aerated Soft Water at Room Temperature (Uhlig, 1985)

4. Carbonation of the portland cement paste - Increases in carbon dioxide content decrease the pH of the concrete and increase the likelihood of corrosion activity.

5. Cracks in the concrete - Cracks allow rapid intrusion of chloride ions into the concrete.

6. Stray currents - Electric currents emanating from electric railways or other sources can create current flow pathways and greatly increase corrosion. Stray currents from electric traction systems caused major damage to pipelines buried nearby in the early 1900's.

7. Galvanic effects due to contact between dissimilar metals - The set effects up dissimilar electrode galvanic cells.

8. Depth of concrete cover - Depth slows the intrusion of chloride ions and delays contact with steel reinforcement.

4.5 Cathodic Protection System Components.

As previously stated, cathodic protection controls corrosion of steel in concrete by applying an external source of direct current to reverse the current flow in the electrochemical process. In 1911, a German, Herman Geppert, obtained letters patent on "a method of protecting articles from earth currents" and substantially described cathodic protection (Morgan, 1959). Thomas Edison tried to achieve cathodic protection of a ship at sea from a trailing impressed current anode but the materials and techniques available to him in the 1890s proved to be inadequate. Cathodic protection is used in protecting prestressed concrete water pipelines, buried reinforced concrete water tanks, steel reinforcement and linings of nuclear reactor containment vessels, and concrete coated

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pilings (SHRP, 1993). Cathodic protection can be applied using a sacrificial anode or an impressed current anode. Sacrificial anodes employ metals more noble in the electromotive series to prevent corrosion. The geometries of bridge decks preclude effective use of sacrificial anodes, so they are not discussed further. Impressed current systems are comprised of the following basic components:

1. External DC Power Source (Rectifier)
2. Current Distribution Hardware (Anode)
3. Conducting Electrolyte (Concrete)
4. Protected Metal (Reinforcing Steel)
5. Completed Circuit (Wiring)
6. Evaluation and Control Devices (Probes, Reference Cells, Controllers)

4.5.1 External DC Power Source

In a sacrificial anode system, the electromotive potential differences between the anode (more noble) and the cathode create a direct current flow and the cathodic metal is thus protected. Impressing direct current into the galvanic cell controls the current flow and likewise prevents corrosion of the metal being protected. Furthermore, sacrificial anodes are limited in their driving voltage. Impressed current systems can be adjusted to increase voltage and provide increased ranges of protection. The most convenient source of power for impressed current systems is standard alternating current (a.c.) commercially available. The a.c. current is converted to direct current (d.c.) power by a transformer rectifier and output power requirements can be selected. The cathodic protection of a large structure can consume a considerable amount of power. Protection current is regulated by controllers ranging from simple resistor circuits to sophisticated microprocessor controls. Constant current power supplies are frequently employed in cathodic protection systems. The constant current power supply automatically adjusts the applied voltage to compensate for changes in electrical resistivity of the system due to temperature, moisture content, etc. The current is frequently adjusted manually to meet criteria for adequate cathodic protection, but arrangements can be made for automatic current adjustment in response to reference cell voltages.

Not all structures requiring cathodic protection are near convenient commercial power sources. Other energy sources can be used to generate the d.c. power. Portable power generators, wind driven power generators, and more recently, solar-powered generators are used to provide the necessary power to impressed current cathodic protection systems. Both wind and solar-powered generators require battery storage to insure power availability upon demand. Wind-powered cathodic protection systems have been installed in Russia (Morgan, 1959) and a solar electric unit was installed as early as 1977 to power a cathodic protection system on the George Washington Parkway in the Washington D.C. area (SHRP, 1993).

4.5.2 Current Distribution Hardware

In a study for the Transportation Research Board (TRB), Vrable concluded that the essential electrical parameter for cathodic protection of a bridge deck in either sacrificial anode or impressed current systems is uniform current flow of appropriate value from a well-distributed anode system located on the deck surface (Vrable, 1977). In most cases, cathodic protection systems have only been installed on reinforced concrete bridges that have suffered deterioration (SHRP, 1993). Generally, the deteriorated concrete is removed and the anode is placed on the repaired, original top deck surface. In some cases, the concrete has been removed around the top mat steel and the anode placed beneath the top mat prior to concrete placement. Most installations are atop salt-contaminated concrete with the steel in most need of protection closest to the anode. Cathodic protection can also be cost effective in preventing corrosion when applied to new construction.

Various types of current distribution systems are available and are described in detail in a report by the Strategic Highway Research Program (SHRP, 1993). Summary descriptions of several anode types will be given in the subsequent discussion following categories given in SHRP, 1993. Two terms important to the discussion are primary anode and secondary anode defined in the following:

1. Primary Anode - Any anode material that acts as a contact medium for the secondary anode and distributes current from the power supply line to the secondary anode. The primary anode is sometimes called the anode conductor.
2. Secondary Anode - Any anode material that distributes the cathodic protection current to the entire surface of the structure under cathodic protection. The secondary anode is sometimes simply referred to as the anode.

Conductive Overlays. - The concept of a conductive overlay system is to deliver current through a primary anode to a pavement overlay system capable of distributing the current over a larger area. Materials used in the pavement overlay must be conductive. Mixtures of asphalt and metallurgical coke from coal (in place of a conventional aggregate) were first employed as conductive overlays.

Mr. Richard Stratfull and co-workers in the Caltrans developed a coke-asphalt system on the Sly Park Road Overcrossing bridge deck of U.S. Route 50 (Stratfull, 1975). Stratfull reasoned that carbon in the form of coke had long been used as an anode backfill material in cathodic protection systems and was an excellent candidate for current distribution systems in asphalt pavements. The specific electrical resistance of dry coke is 52 ohm-cm, which is about twice the electrical resistance of seawater and much less than water-saturated concrete at 10,000 ohm-cm. The primary anodes were iron-alloy discs 10 inches (25.4 cm) in diameter and 1.25 inches (3.2 cm) thick. Three rows of primary anodes were attached to the bridge deck with 12-feet (3.6-m) center-to-center spacing. A fast setting epoxy adhesive attached the anodes to the concrete. A tack coat of asphalt

emulsion was applied to the bridge deck and the coke-breeze asphaltic concrete was placed in 10-foot (3.04-m) widths. Thicknesses of coke-breeze asphaltic concrete varied from 2.5 to 3.5 inches (6 to 9 cm). The conductive overlay continued to function for more than 11 years without major changes other than replacement of the power source. Caltrans installed seven additional coke-asphalt overlay systems in 1974-1975 and FHWA promoted and funded projects involving cathodic protection of reinforced concrete structures through Demonstration Project No. 34. Fourteen additional coke-asphalt overlay cathodic protection systems were demonstrated from 1975 to 1980 (Jackson, 1982). Various other coke-asphalt systems have been installed in the U.S. (SHRP, 1993) and have operated effectively in arresting corrosion. Minor problems have included structural degradation of the overlay, increased dead load to the bridge, and required modifications to drains, expansion joints, approaches, and curbing due to the increased height of the pavement.

The Ontario Ministry of Transportation and Communications refined the original coke-asphalt overlay system by adding conventional aggregate to the coke-asphalt mix to improve stability and resistance to traffic loading. The conductive layer thickness is commonly 1.5 inches (4 cm) with a wearing course of conventional asphaltic concrete also 1.5 inches (4 cm) thick. Cables to the primary anode are placed in slots cut in the portland cement deck. Thirty of the coke-asphalt overlay systems were constructed in Ontario through 1984 and other similar systems have been installed in other parts of Canada. Research programs conducted by the Ontario Ministry of Transportation are discussed briefly in a paper by Schell (Schell, 1989).

Slotted Systems. - Another anode type developed in the mid 1970s involves platinized wires closely spaced to effectively distribute protective current over the bridge deck (SHRP, 1993). The wire is commonly 0.031 and 0.062 inches (0.8 and 1.6 mm) in diameter with a platinum layer 25-50 microinches (635 to 1270 micro meters) and various materials used as the wire core. The anode wire is placed in small slots cut into the deck with spacing of the slots no more than 1 foot (30 cm), as recommended by FHWA. Conductive backfill material is used to cover the wires. Early backfill materials produced gases and acids that attacked the platinized wire. Several proprietary backfill materials were tested with the platinized wire but were unsuccessful for various reasons including acid attack and poor durability (Highlands, 1991). Subsequently, the FHWA developed a conductive polymer grout with a compressive strength of 4,000 psi (28 mpa) in 4 hours, a resistivity of less than 10 ohm-cm, and excellent bond to concrete and freeze-thaw durability (SHRP, 1993). More than 100 slotted bridge deck cathodic protection systems were installed and operational by 1989.

Slotted bridge deck cathodic protection systems have evolved with regard to primary anode layout and materials. Redundancy in the system is provided by laying the wire in two directions to form a grid pattern. Multi-filament carbon strands are used to lower cost and increase tensile strength. Slot sizes and spacing were decreased to provide better performance. Later, titanium ribbon with a precious metal oxide coating was

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developed as a primary anode and the slot is backfilled with cementitious non-shrink grout. Titanium ribbon systems are currently being field tested (SHRP, 1993).

Distributed Anodes with Concrete Encapsulation. - An alternative method of distributing the protective current over the bridge deck was developed by placing the platinized wire directly on the concrete deck and mounding the conductive polymer concrete over the anode wires and strands. The mounded configuration is thought to improve current distribution and protect against acid attack. Conventional concrete or latex modified concrete are placed to complete the rigid overlay system. An alternate anode (Raychem Ferex) is also used with rigid overlays or other forms of concrete encapsulation. The anode is a copper conductor surrounded by a flexible polymeric anode material which does not require a conductive backfill. The anode can be woven into a mesh to evenly distribute the current and the conductive wires are sometimes held together with conductive cleats to increase redundancy. More than 50 demonstration projects have included the Raychem Ferex anode. Several field installations have exhibited problems with anode degradation and embrittlement. Problems are thought to result from local hot spots in the anode system.

A mixed metal oxide catalyst is sintered to a titanium mesh to form an Elgard anode system. The Elgard system has reported long life, uniform current distribution, stable, and sufficiently redundant characteristics. The anode operates below the chlorine discharge potential, and therefore, is not subject to acid attack. More than 100 mesh anode cathodic protection systems have been installed in 19 states. The mesh is rolled out onto and fastened to the concrete deck surface. Concrete is then placed on the mesh to encapsulate the wire. This anode has become the most widely used in recent years (SHRP, 1993).

Conductive Coatings. - NCHRP Project 12-19B, initiated in late 1982, was designed to develop the use of conductive coatings as secondary anodes for protecting concrete bridge substructures (Perenchio, 1985). Platinized wire is placed on the concrete surface and serves as the primary anode. The surface including the platinized wire is covered with the secondary anode consisting of forms of carbon dispersed in solvent or water based paints. Conductive paste or polymer grout is sometimes used to connect the wire with the paint. The conductive paint is black and is usually covered with a lighter colored paint for finishing. Early systems suffered problems in wet, freeze-thaw and splash zone environments. During installation, care must be taken to remove conductors in contact with the steel to be protected. Short-circuits waste power and can cause the steel in the area of the short-circuit to become anodic and undergo accelerated corrosion. Also, openings in the conductive coating can drastically increase its electrical resistance. Perenchio reports that openings as narrow as 0.01 inches (0.25 mm) increase resistance by a factor of 100 (Perenchio, 1985). Water-based conductive coatings were tested on the concrete piers of two bridges in Virginia (Clemena, 1990). Clemena concluded the water-based coating was promising with regard to relative ease of application and decreased health hazards compared to sprayed zinc.

Flame-sprayed zinc has also been developed as a conductive coating. The zinc coating in thicknesses ranging from 0.2 to 0.5 millimeters serves as a secondary anode covering the entire surface of the concrete being protected. Thermal-sprayed zinc anodes have been tested in several field trials (Berndt, 1993) in California, Virginia, Florida, and Canada. Protected structures include a pier of the Richmond-San Rafael bridge (San Francisco, California), soffit and top of the East Camino undercrossing bridge deck (Placerville, California), and pier bents of the Leslie Street Bridge (Ontario, Canada). Challenges to large-scale usage of thermal-sprayed anode technology include

1. Reducing costs via appropriate automation of the spraying process.
2. Determining the thermal spray parameters, surface preparation procedures and coating thickness that will maximize the quality of the coating-to-concrete (or metal) bond as well as optimize system economics.
3. Learning how the anodes can take advantage of the inherent porosity of sprayed coatings.
4. Predicting the long-term performance of thermal spray coatings.
5. Writing specifications that can be directly implemented by civil engineers.
6. Developing nondestructive methods for evaluating thermal-spray coatings.

Other Anode Systems - The following anode systems are being investigated for use in cathodic protection systems:

1. Conductive portland cement concrete.
2. Conductive ceramics.
3. Conductive rubber.
4. Precast conductive polymer anodes.

4.5.3 Conducting Electrolyte

Chloride ions are considered to be the major cause of premature corrosion of steel reinforcement. Oxygen and moisture must also be present for the concrete to act as an electrolyte and the electrochemical corrosion to occur.

Clear reported the effect of concrete mix design on chloride content at the level of reinforcing steel in a laboratory test slab (Clear, 1974). Data from Clear's study are given in Table 3 and is shown in Figure 3. He concluded that conventional bridge deck concrete, placed with strictest quality control is not impermeable to chlorides. The water-cement ratio of the concrete appears to be the primary determinant of the ability of portland cement concrete to resist chloride intrusion. Water-cement ratio also

significantly affects the rate of diffusion of oxygen into concrete saturated with water (ACI, 1992).

TABLE 3. EFFECT OF MIX DESIGN AND COVER DEPTH ON CHLORIDE MIGRATION
(Clear, 1974)

Description	Number of Slabs	Number of Cores	Cover Depth (in.)	(mm)	Chloride Content at Level of Reinforcing Steel (ppm of Cl⁻ on concrete (basis)) Average	Range	Number of Salt Applications
Water-cement ratio							
0.4	2	10	1.0	25	179	15 to 437	336
	2	10	2.0	50	18	13 to 28	337
	2	10	3.0	75	18	13 to 23	337
	1	3	0.25	6	2,355	2,289 to 2,450	359
0.5	2	10	1.0	25	912	386 to 1,555	334
	2	10	2.0	50	250	23 t0 562	348
	2	10	3.0	75	20	10 to 77	344
	1	3	0.25	6	3,249	2,437 to 4,332	341
0.6	1	3	1.0	25	1,407	960 to 1,701	313
	1	3	2.0	50	1,093	679 to 1,581	354
	2	6	3.0	75	189	105 to 255	316
	1	3	0.25	6	3,757	2,965 to 4,666	313
Cement Content (lb/cubic yard)							
563	2	6	1.0	25	904	235 to 1,369	333
658	2	10	1.0	25	912	386 to 1,555	334
752	2	6	1.0	25	1,147	444 to 2,010	330
Sand-stone ratio							
0.822	2	10	1.0	25	912	386 to 1,555	334
0.429	2	6	1.0	25	792	309 to 1,693	320

Notes: Cement content constant
Nominal cover depths

Moisture in concrete affects the rate of oxygen diffusion into concrete and also the electrical resistivity of the concrete as shown in Figure 4. (ACI, 1992). Some researchers indicate that when concrete electrical resistivity exceeds a level of 50 to 70 X 10^3 ohm-cm steel corrosion is negligible. Other authors believe steel corrosion is unlikely at concrete electrical resistivity above 10 X 10^3 ohm-cm. Perenchio reported that the electrical resistance of concrete with 1.5 pounds of chloride ion per cubic yard (0.89 kg/m^3)of concrete was approximately 10 times that of concrete with 15 pounds per cubic yard (8.9 kg/m^3) (Perenchio, 1985).
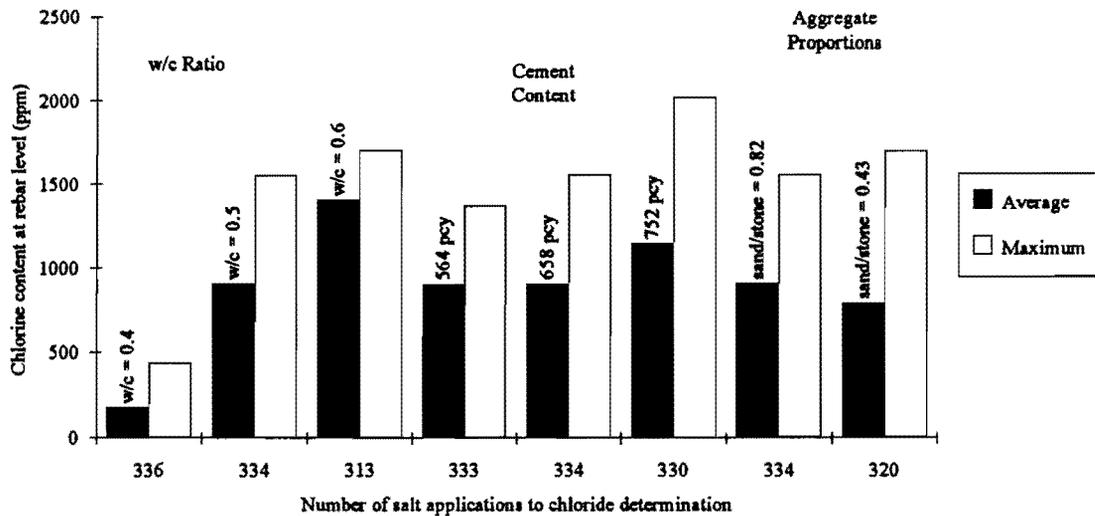
Figure 3. Effect of Mix Design Parameters (Clear, 1974)

In a study of Galvanic (sacrificial) anodes, Whiting noted that environmental factors play an important role in system functioning (Whiting, 1981). Highest current outputs and mostly negative potentials were encountered during warm, moist periods in mid-to-late spring. Under dry or cold conditions, current output decreases and some polarization was lost.
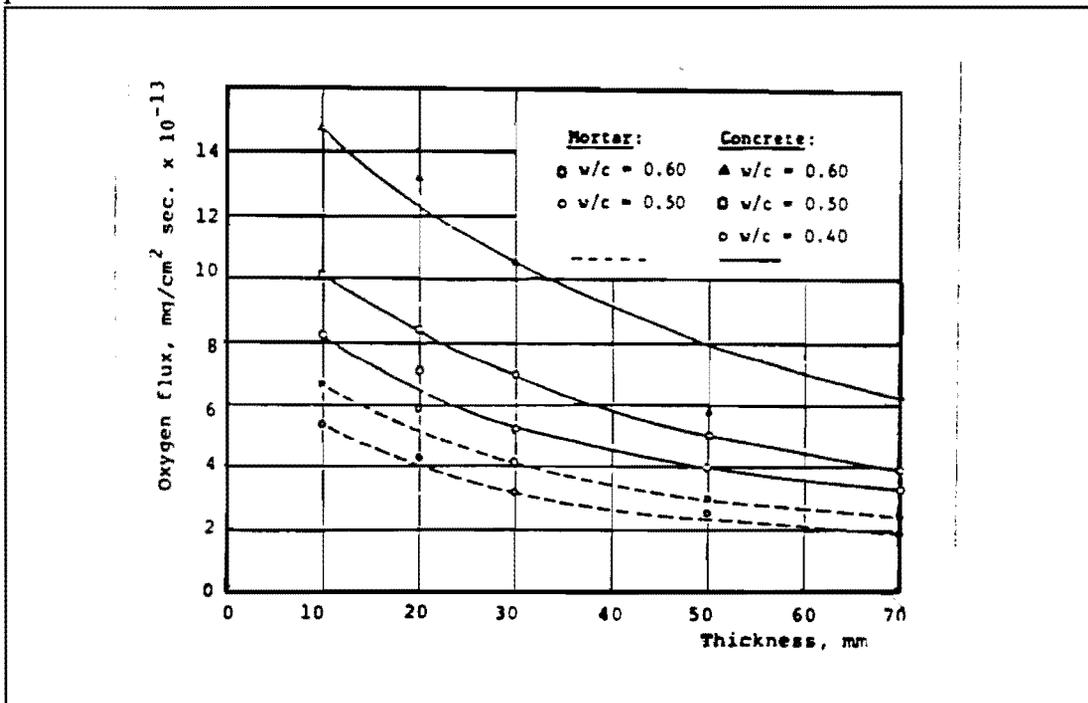
Figure 4. Effect of Water-Cement Ratio and Thickness on the Diffusion of Oxygen Through Mortar and Concrete (ACI, 1992)

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4.5.4 Protected Metal (Reinforcing Steel) and Completed Circuit (Wiring)

Stratfull emphasized the necessity of electrical continuity of the structure being protected in his report to the Transportation Research Board (Stratfull, 1975). He warns that portions of the structure under cathodic protection that are not electrically connected to the system can be caused to corrode by stray currents at an accelerated rate. In most reinforced concrete bridge decks, there are numerous steel bars. Any of the bars that is not electrically continuous can be damaged by stray current and the damage will be the same as experienced from electrochemical corrosion. It is imperative to ensure electrical continuity in the steel reinforcement being cathodically protected. Steel ties used in normal construction procedures are generally closely spaced and increase the likelihood of electrical continuity in the steel reinforcement. Stratfull tested for electrical continuity at 4 locations of the 3,300 square feet (1000 square meters) of bridge deck cathodically protected (Stratfull, 1975). The recommended procedure for establishing electrical continuity of the reinforcing steel leaves much to the judgment of the individual. Procedures require visual inspection to determine which areas are to be tested, marking and recording locations of the reinforcing steel grid, and testing for electrical connectivity in accordance with ASTM test method C876 (SHRP, 1993).

4.5.5 Evaluation and Control Devices (Probes, Reference Cells, Controllers)

As discussed earlier, corrosion can occur in small, local-action Galvanic cells or macro-Galvanic cells involving large electrodes. Cathodic protection mechanisms employ external current to polarize the cathodic elements of local-action cells to the open-circuit potential of the anodes. At the threshold of protection, the surface becomes equipotential (cathode and anode potentials become equal), and corrosion currents no longer flow (Uhlig, 1985).

If external current density is high enough, a net positive current enters the metal at all areas of the metal surface and there is no tendency for ions of the metal being protected to enter into solution. It is necessary to determine the net current flow in the Galvanic cell with no externally applied current in order to specify the level of externally applied current needed to provide cathodic protection. The electrical potential in the Galvanic cell caused by net current to or from an electrode, measured in volts, is called polarization. Polarization is measured using a reference cell as illustrated in Figure 5 (Uhlig, 1985). A two-compartment cell is separated by a sintered glass disk G. In Figure 5, electrode B is to be polarized by current from electrode D with uniform current density at electrode D. The probe L (sometimes called Luggin capillary) of reference cell R (or of a salt bridge between R and B) is placed close to the surface of B, thereby minimizing extraneous potentials caused by IR drop through the electrolyte. The electric potential of cell B-R is recorded for each value of current as read on ammeter A, allowing sufficient time for steady-state conditions. Polarization of B, whether anode or cathode, is recorded in volts with reference to half-cell electrode R for various values of current density. The potentials are often converted to the standard hydrogen scale. This method is called the direct method for measuring polarization and is the method frequently employed in corrosion studies. The simple electrical instrumentation in Figure 5 is replaced with computer-driven electronics for rapid and accurate data collection in modern laboratories. The

conditions for idealized measurements in laboratory are far different from those encountered in the field. In the laboratory, the effective position of the reference cell is within mm's of the electrode surface, in contrast to positioning a reference cell in the concrete, or on the exposed surface of the concrete. In the laboratory, the electrolyte solution is uniform in concentration, and the electrodes are small homogeneous, in contrast to actual field conditions. These differences between field and laboratory conditions make electrochemical measurements of rebar corrosion rates in the field a considerable challenge. This challenge has been reviewed recently (SHRP, 1992)
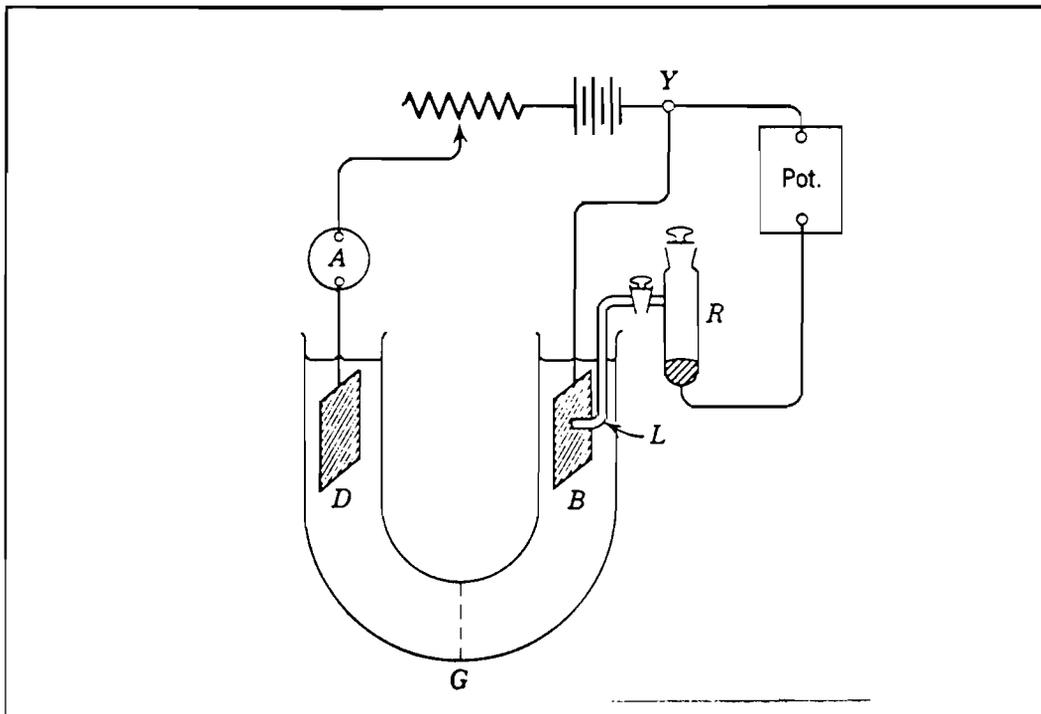
Figure 5. Cell for Measuring Polarization (Uhlig, 1985)

A portable reference cell (often referred to as a half-cell) is used to measure electrical (corrosion) potential at various locations on reinforced concrete bridge decks and assess the corrosion rates and need for cathodic protection. Results from such a survey are usually plotted on contour maps to identify corrosion activity of the reinforcing steel in the concrete. Permanent reference cells are embedded in the concrete to monitor the effectiveness of the cathodic protection system. In his early study of reinforced concrete bridge deck corrosion, Stratfull used two types of reference cells to measure electric potential (Stratfull, 1957). A hand held reference cell was used to measure electric potential on overhead and vertical surfaces. The hand-held reference cell was constructed by filling a polyethylene bottle with saturated copper sulfate and a pure copper electrode. Electrical connection was made to the copper electrode by bringing the thin copper electrode through a cork in the top of the bottle. Electrical junction to the copper sulfate solution was made by inserting a wick-filled glass tube through the cork to the solution. The external wicking was then placed in between a sponge used to actually contact the concrete and a wooden container used to hold the complete cell assembly. A

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plexiglas handle was attached to the wooden container to prevent "electrical shorting" of the cell through the operator. The second type of reference cell consisted of a porous cup filled with a saturated copper sulfate solution and a pure copper electrode. This reference cell was left in place during the period of measurement. In a later study (Stratfull, 1975), Stratfull demonstrated the use of half-cells to nondestructively determine the corrosion activity of steel in concrete. He measured half-cell potentials for 8 bridges having concrete delamination. For large areas of delamination, two or more measurements were made. The average of the maximum potentials was -0.453 volts and the average of the minimum potential within the same delaminations was -0.334 volts. In locations where the concrete was not delaminated, the average of all potential measurements was -0.180 volts. Perenchio describes preparations and measurements of half-cell potentials (Perenchio, 1985) and the use of half-cells to approximate "instant-off" potential. The instant-off potential measures the minimum negative polarization above the "free-corrosion potential" or the amount of depolarization that occurs after the protective current is interrupted. To accomplish the measurement, a voltmeter is setup in the circuit while the cathodic protection system is on and current is being delivered to the conductive anode. Then, the protective current is interrupted, and the potential is read immediately, say within a second or two of shutoff. This measurement approximates the "instant-off" potential. The structure is permitted to "depolarize" toward its "free-corrosion" condition. When the potential stabilizes at the "free-corrosion" condition, it is again measured. The time required to attain rough potential stability after depolarization might be as short as an hour, but some authorities believe that complete depolarization might take as long as a week. The potential difference between the two readings is the negative potential shift imparted by the cathodic protection system. In field trials, Perenchio observed slight seasonal variations in reference cell readings with potentials higher in winter and spring than in summer and fall (Perenchio, 1985).

E log I Test. The E log I test is often used to initially energize a cathodic protection system, but can also be performed on cathodic protection systems while in service (SHRP, 1993). For systems in service, the structure must be allowed to depolarize before performing the E log I test. Once the structure is depolarized to an equilibrium state, protective current to the structure is gradually increased and the resulting structure-to-reference cell potential is recorded for each current increment. The reference cell potential versus the logarithm of the applied current are plotted. Various relationships are postulated to describe the level of polarization necessary to bring about the specific anode and cathode reactions. One such relationship depends upon the particular reaction and the current density and is given by the following:

$$h = a + b \log i/i_o \qquad\qquad (10)$$

Equation 10 is known as the Tafel equation and is named after J. Tafel who first proposed a similar equation to express hydrogen overvoltage as a function of current density (Uhlig, 1985). A typical Tafel diagram is shown in Figure 6. The current required for cathodic protection is the value determined to occur at the beginning of linear behavior of the plot. Accuracy of the Tafel diagrams is subject to interpretation for field measurements..

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400 — E (protect)

380

360

Potential (millivolts)
340

320

300

280

260

0   0.5   1   1.5   2   2.5   3   3.5

log of Current (milli amps)
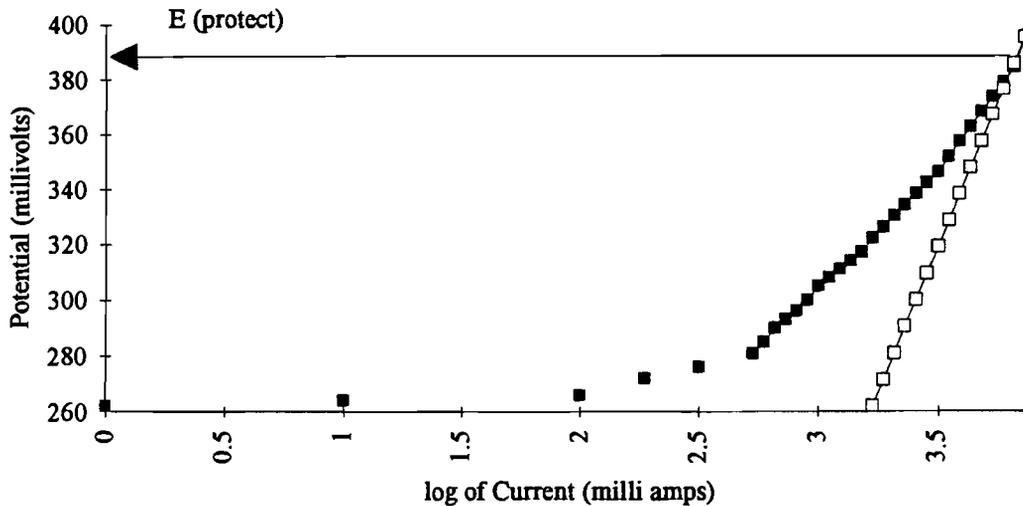
Figure 6. Typical Tafel Diagram for Big Spring Bridge (Smith, 1990)

Macro-cell Rebar Probes. Small lengths of reinforcing steel (rebar) can be used to monitor the typical flow of electric current at specific locations in the cathodically protected bridge deck. Usually the macrocell probes are cast in backfill containing a high concentration of salt to create the most "anodic" location in the area to be monitored. An insulated wire is connected between the macro-cell probe and the rebar system through a shunt resistor. The shunt resistor permits convenient observation of macro-cell currents. Rebar probe current flow is determined by measuring the potential across a shunt resistor and calculating the current from Ohm's law. If the macrocell rebar probe proves to be protected (current flow is net-cathodic) the reinforcement steel is considered protected from corrosion. The macrocell probes are not alone sufficient as a cathodic protection criterion, but do provide an indication of corrosion activity.

Electrical Resistance Measurements. The measurement of the resistance between various components of the cathodic protection system can provide valuable information on system effectiveness or help identify component problems (SHRP, 1993). The two most common measurements are the anode-to-structure and structure-to-reference cell resistance. Increasing anode-to-structure resistance can be a signal that the anode is depleting or that portions of the anode are no longer in the circuit. If the anode-to-structure resistance is low, an electrical short between the anode and steel reinforcement may be present. A change in structure-to-reference cell resistance can indicate a reference cell malfunction or other circuit problem. An AC resistance meter is generally used to measure electrical resistance.

Electrochemical methods of measuring corrosion rates were assessed in a study by the Strategic Highway Research Program (SHRP, 1992) and a summary of findings is given in Table 4. Furthermore, several commercially developed corrosion rate devices were evaluated, and their performance was reported. Because the commercial instruments operate on different principles they give different values of current. However, linear

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regression techniques were applied to develop interrelationships between currents measured by the different devices.

TABLE 4. COMPARISON OF ELECTROCHEMICAL METHODS OF CORROSION MEASUREMENT (SHRP, 1992)

TECHNIQUES	ADVANTAGES	DISADVANTAGES
Polarization Curves	Give information about steel's behavior at potentials other than E(corrosion)	Sometimes destructive
		Takes long time
Tafel Slope Extrapolation	Simultaneous determination of anodic and cathodic constants	IR drop effect is significant
Linear Polarization	Fast method (short measuring time)	Sweep rate dependence of polarization resistance
	Small perturbation (minimal disturbance of interface)	Separate measurement of Tafel slope required
	Simple method and low equipment cost	IR drop effect is significant
AC Impedance	Suitable for low conductivity media	Long measuring time (for low frequency region)
	Simultaneous determination of anodic and cathodic constants	Interpretation of results is difficult
		Extrapolation is needed sometimes
		Equipment is costly

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A permanent corrosion monitoring system was developed by the Institute for Building Materials Research at TH Aachen, Germany (Schiessl, 1992). The system is designed to indicate the corrosion risk for the reinforcement in concrete structures. Several macrocells are placed in the actual concrete structure at defined cover depths. Each macrocell consists of black steel (anode) and a noble metal (cathode). For passive conditions, the electrical current between the two electrodes is negligible. If, however, a critical chloride content is reached, or if the pH of the concrete decreases due to carbonation, the steel surface of the anode is no longer protected and current flows in the macrocell. Corrosion risk is monitored by measuring the electrical current in the macrocell.

100 mv Decay Measurements. The National Association of Corrosion Engineers, NACE, includes the 100 mv decay measurements as one criteria for the adequacy of cathodic protection. (NACE Standard RP0290-90). In this measurement, the reference electrode potential should decay, (become more positive), by 100 mv with respect to the instant off reference cell voltage within 4 hours. A major advantage of this technique is that it does not require long-term stability of the reference electrode. The method does not permit calculation of a corrosion rate. The 100 mv decay infers that current previously flowing to the anode structure has caused a favorable, cathodic, shift in potential near the structure being protected, since this favorable shift decays when the current is turned off. The choice of the 100 mv criteria is the result of consensus among experienced corrosion protection personnel. This technique was applied when the cathodic protection system on the U.S. 87 overpass was examined 45 and 90 days after being energized. It was also applied by Texas Tech personnel in the summer of 1993 to adjust several of the cathodic protection loops.

4.5.6 Remote Monitoring Systems

Although recommended procedure is to monitor cathodic protection systems monthly, in practice, 35 percent of the systems are monitored less frequently and some are never monitored (SHRP, 1993). Accomplishing the various measurements is a tedious and repetitive job involving mobilizing personnel to sometimes remote locations. However, advanced systems are developed to remotely monitor measurements from the cathodic protection system site. Remote monitoring systems consist of a data recorder unit, a modem and a personal computer in the office. Remote monitoring system options are available to meet the specific needs of the user and can include real-time measurements or storage at the remote site for later collection. Some systems can even turn the rectifier "on" and "off" and adjust the current or voltage output. Clemena reports remotely collecting 30 channels of performance data from conductive coating anode systems on ten piers in Virginia (Clemena, 1990).

4.5.7 Other Considerations

Several researchers have investigated possible adverse effects of cathodic protection on concrete, reinforcing steel, and the bond between concrete and reinforcing steel. Vrable exposed concrete cylinders to various levels of applied current and evaluated the resulting tensile strength of the concrete (Vrable, 1977). Results from the concrete tensile strength testing are summarized in Table 5. Vrable concluded that after 300 days of exposure to cathodic-protection current flow, there was no apparent degradation of the concrete due to current flow. Performance variations were attributed to test specimen quality.

Hydrogen embrittlement has been another concern regarding cathodic protection (SHRP, 1993). During application of cathodic protection, oxygen reduction occurs at the cathode surface. If the steel potential is driven more negative than -1.05 volts with the pH at 12.5, monatomic hydrogen can evolve. The hydrogen can diffuse into the metal lattice and collect at grain boundaries resulting in the phenomenon of hydrogen embrittlement. This phenomenon is more effective on high strength steels and not conventional reinforcement. FHWA has active research programs investigating the possibility of hydrogen embrittlement of prestressing or post-tensioning steels.

Vrable also investigated the effect of cathodic protection current flow on concrete-to-rebar bond strength (Vrable, 1977). He found the loss of bond strength is much less with increasing current density than with an increasing total ampere hour/square foot of applied current (Figures 7 and 8). He attributed the loss of bond strength to the formation of alkali hydroxides on the steel surface. The hydroxides are believed to attack the calcium and aluminum silicates within the concrete to form soluble silicates of much less strength. Vrable reported other work by the Jersey Production Research Company that showed the bond strength between the high-strength concrete and deformed reinforcing bars did not depend on the applied voltage or current, but on the total, applied ampere hours per square foot of embedded steel surface (Vrable, 1977). He also presented results from a study by Scott as given in Table 6. Cathodic protection system designers recommend that electrical potentials not be more negative than 1.1 volts in order to prevent detrimental effects of overprotection.

TABLE 5. EFFECT OF APPLIED CURRENT ON SPLITTING TENSILE STRENGTH (Vrable, 1977)

Specimen	Total Load (pounds)	Splitting Tensile Strength (psi)	Comments
Control - 30 day cure			
A	56,500	500	
B	53,500	473	
C	46,500	411	
Average	61,500	461	
300 days exposure to			
0.5 mA applied current			
1	65,000	575	80% shear
2	60,000	531	75% shear
3	59,500	527	80% shear
Average	61,500	544	
300 days exposure to			
1.0 mA applied current			
4	49,000	434	sandy pocket
5	51,000	451	sandy section through center
6	65,000	575	100% shear
Average	55,000	487	
300 days exposure to			
2.0 mA applied current			
7	64,500	570	80% shear, good matrix
8	57,500	509	75% shear
9	63,000	558	90% shear
Average	61,660	546	
Control - 300 day cure			
A	52,000	460	75% shear, erratic break
B	59,000	523	80% shear
C	51,000	452	80% shear, sandy matrix
Average	54,000	478	

One pound = 0.454 kg
One psi = 6,895 pa

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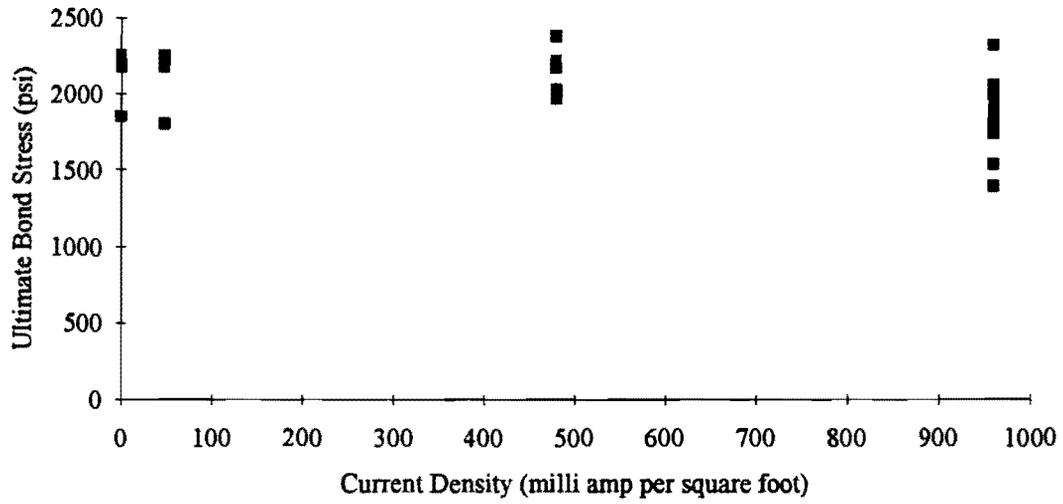
One psi = 6,895 pa
One sq ft = 0.093 sq meters

Figure 7. Effect of current density on ultimate bond stress (Vrable, 1977)
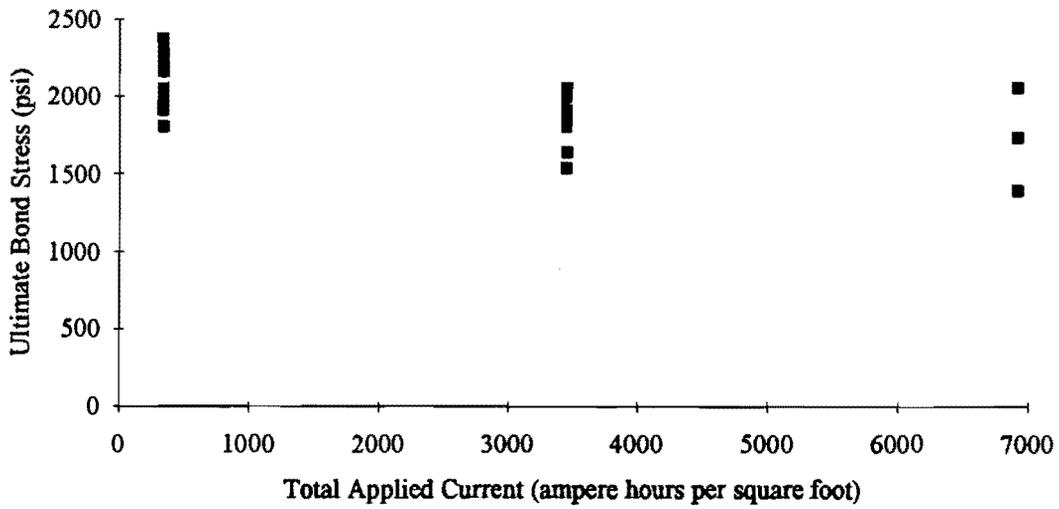
One psi = 6,895 pa
One sq ft = 0.093 sq meters

Figure 8. Effect of applied current on ultimate bond stress (Vrable, 1977)

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Ali suggests cathodic protection could have shortcomings regarding its effects on concrete strength (Ali, 1993). He reports the cathodic protection generates hydroxyl ion at the cathodic steel surface and a buildup of sodium and potassium ions in the hydrated cement at regions near the reinforcing bar due to the action of the impressed current. The generated hydroxyl ion raises the concentration of pore fluid levels. His study focused on concerns for alkali-silica reactions and found that increases in the pore fluid level can cause severe cracking and disintegration of the concrete. Ali warns against using cathodic protection on structures that might contain aggregates susceptible to alkali-silica reaction.

TABLE 6. EFFECT OF APPLIED VOLTAGE ON BOND STRENGTH
(Research by Scott, Vrable, 1977)

Applied Voltage (volts)	Specimen Potential (polarized potential of the steel rod measured to copper sulfate reference, volts)	Results of Exposure
0.75	-0.812	No loss of bond after 880 days
1.14	-1.052	No loss of bond after 880 days
1.54	-1.148	No loss of bond after 994 days
2.14	-1.156	Rod pulled out in 197 days

Recent research raises additional concerns for chloride intrusion of concrete structures submerged in sea-water (Nagataki, 1993). Nagataki reports that chloride ions can intrude in the concrete by condensation of the water-soluble chloride ion. He concludes that the presence of reinforcing steel bars in cement matrix containing internal chloride ion will result in higher internal chloride ion concentration around the steel bar than is found in other portions of the cement matrix.

Costs and Service Life. The following cost elements must be considered when estimating the total cost of a cathodic protection system:

1. Bridge evaluation
2. Removal of damaged concrete
3. Design of the cathodic protection system
4. Anode system
5. Rectifier
6. Monitoring Devices
7. Remote monitoring system
8. Maintenance

Cathodic protection system costs (for large installations) were identified in SHRP 1993 and are summarized in Table 7. None of the estimates given in Table 7 include the cost of traffic control, patching, or structural repair.

TABLE 7. AVAILABLE CP SYSTEMS AND ESTIMATED COSTS AND LIVES

Anode System	Structures Protected	Estimated Construction Cost, 1991 U.S. $/square foot ($/meter square)	Estimated Service Life, Years
Coke-Asphalt Overlay	Decks	$6 ($65)	20
Slotted Conductive Polymer Grout	Decks	$6 ($65)	15
Mounded Conductive Polymer w/Concrete Overlay	Decks	$9 ($97)	20
Titanium Mesh w/ Concrete Overlay	Decks	$9 ($97)	35
Titanium Mesh w/ Shotcrete	Substructures	$14 ($150)	35
Conductive Paint	Substructures	$5 ($54)	5
Sprayed Zinc	Substructures	$9 ($97)	15

5. CATHODIC PROTECTION SYSTEMS ON THE U.S. 87 RAILROAD OVERPASS BRIDGE - BIG SPRING

Five cathodic protection systems were installed on the U.S. 87 Missouri-Pacific Railroad overpass in Big Spring, Texas (Smith, 1990). The bridge structure was constructed in the early 1960's and is 581 feet (177 meters) long and 67 feet (20.4 meters) wide. The bridge has very steep grades and is often treated with deicing salts during winter months. Evaluation of the structure to determine the need for cathodic protection included measuring half-cell potentials, chloride content and percent of delamination of the concrete surface. Results from the evaluation are summarized in Table 8. The south end of the bridge is station 8 + 18.49 and the north end of the bridge is station 13 + 99.49.

Three distributed anode cathodic protection systems were installed on the bridge deck, and conductive coating systems were installed on the sidewalk portion of the bridge deck and one of the supporting bents. Smith (1990) presents a complete description of the bridge preparation and installation of the cathodic protection systems. The traffic lanes were milled approximately 2 inches (5.1 cm) on the bridge and approaches in preparation for installing the anodes and placing a dense concrete overlay. Each anode system and its installation is described in the following discussion.

Expanded Titanium Mesh (Manufactured by Elgard) Four separate zones were protected with titanium mesh anodes. A separate circuit energized each zone. The four zones were placed across the 67-foot (20-meter) width of the bridge deck and each zone was approximately 14 feet (4.3 meters) wide, as shown in the layout of cathodic protection systems given in Figure 9. Each zone was approximately 200 feet (61 meters) long. Concrete loosened by the milling operation was removed so that the exposed surface was sound concrete. Continuity of metallic surfaces in the concrete and the reinforcing steel was ensured. Special care was exercise to avoid anode placement closer than a quarter inch (6 mm) from embedded metals. The titanium mesh was spread over the surface of the zone to be protected and tacked down with insulating fasteners in preparation for concrete placement. Smith reports the titanium mesh was very easy to install but was the most difficult to maintain during placement of the dense concrete overlay. Problems occurred with the mesh tending to float during concrete placement. A short between the mesh and a concrete tie wire was easily discovered and corrected during construction.

Ferex 100 Anode Strand (Manufactured by Raychem Corporation). A flexible conductive polymer anode was used to distribute protective current in another four zones across the width of the bridge deck as shown in Figure 9. These four zones were also approximately 200 feet long. The same precautions as before were taken to ensure soundness of the repaired surface, electrical continuity of the reinforcing steel and other embedded metal, and separation of the anode from the embedded metal. The anode strands were anchored to the concrete surface with special fasteners and large loops (approximately 9 inches (23 cm)) were used as a method of bending the cables without

Begin Bridge
Station 8 + 18.49

Zone D1

Station 11 + 00

Zone A1

Zone A2

Zone A3

Zone A4

Zone B1

Zone B2

Zone B3

Zone B4

Station 11 + 00

Zone D2

Zone D3

Zone D1

Zone D4

N

Zone B1

Zone B2

Zone B3

Zone B4

Zone C1

Zone C2

Zone D2

Zone D3

Zone E
Bent 4

Zone D5

Zone D6

End Bridge
Station 13 + 99.49

Anode Types on Bridge Deck

Titanium Mesh

Conductive Polymer

Carbon Strand

Sprayed Zinc
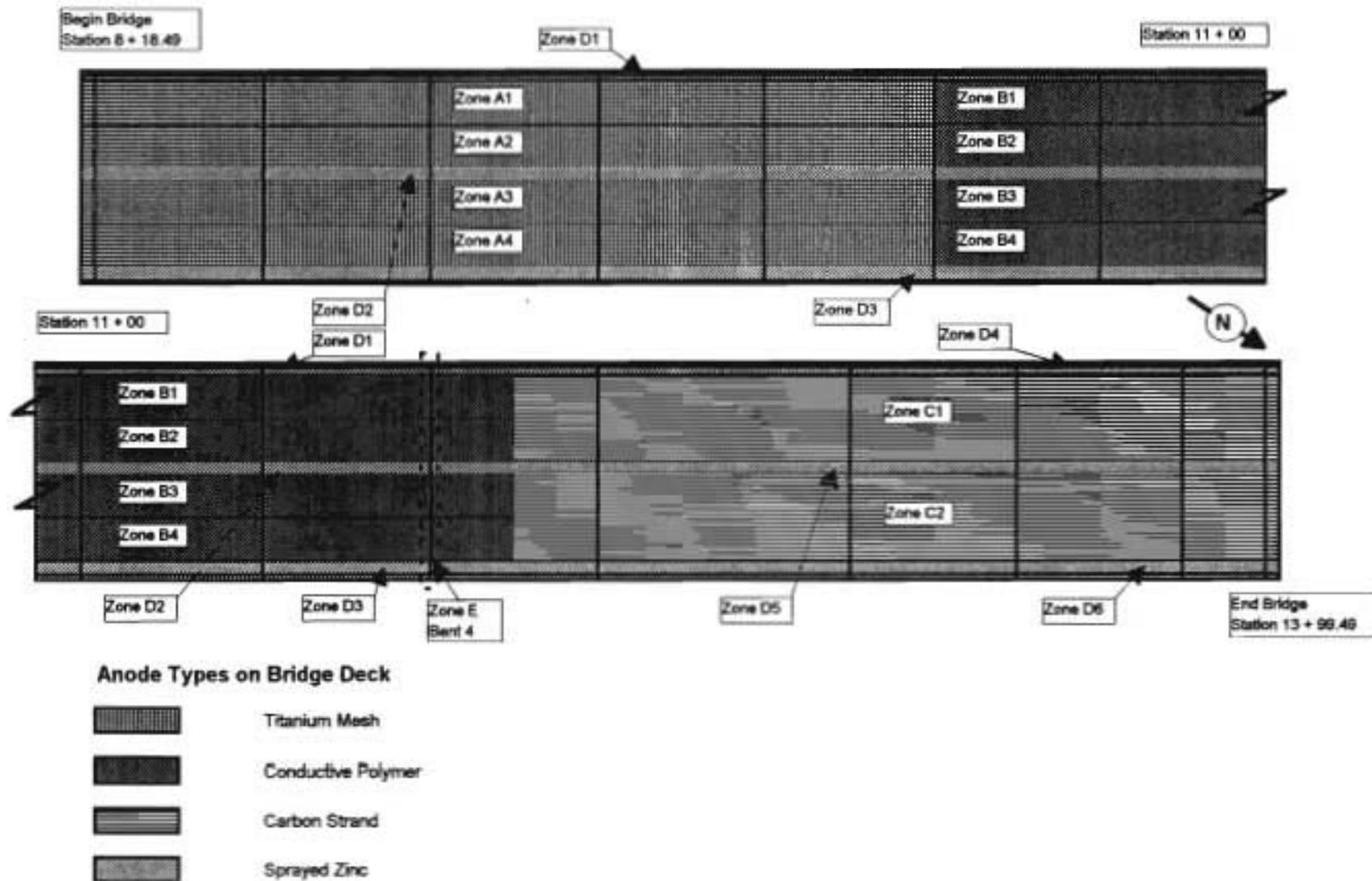
**Figure 9. Layout of Cathodic Protection Systems
on US 87 Overpass, Big Spring, Texas (Smith, 1990)**

TABLE 8. EVALUATION SUMMARY OF U.S. 87 OVERPASS IN BIG SPRING, TEXAS
(Smith, 1990)

Slab No.	Station (Area, Sq. Ft.)	Test Results		
		Delamination Area, Sq. Ft./ % of slab	Half-cell Potential Average Readings (Negative Volts)	Chloride Content (pounds per cubic yard)
	8 + 19.28			
1	8 + 60.61 (2,314.28)	141.2 / 6.1	0.3	*
2	9 + 01.71 (2,301.60)	96.6 / 4.2	0.25	*
3	9 + 42.81 (2,301.60)	341.8 / 14.85	0.22	*
4	9 + 83.91 (2,301.60)	250.8 / 10.9	0.18	*
5	10 + 25.01 (2,301.60)	474.0 / 20.59	0.24	3.3
6	10 + 66.11 (2,301.60)	462.6 / 20.1	0.22	4.8
7	11 + 07.21 (2,301.60)	435.0 / 18.9	0.2	2.9
8	11 + 48.31 (2,301.60)	233.6 / 10.15	0.16	3.7
9	11 + 89.41 (2,301.60)	284.2 / 12.35	0.19	*
10	12 + 30.74 (2,314.48)	247.6 / 10.7	0.19	3.6
11	12 + 63.74 (1,848.00)	63.7 / 3.45	0.16	*
12	12 + 97.74 (1,904.00)	285.6 / 15.0	0.22	3.2
13	13 + 31.74 (1,904.00)	261.8 / 13.75	0.17	*
14	13 + 65.74 (1,904.00)	326.5 / 17.15	0.15	*
15	13 + 98.74 (1,680.00)	19.4 / 1.15	0.11	*
Total	(32,281.76)	3924.4 / 12.16		

* no samples were taken in this area

One square foot = 0.093 square meters

One pound per cubic yard = 0.59 kg per cubic meter

kinking or breaking the primary anode wire. Smith reports the polymer anode was slightly more time consuming to install than the titanium mesh, but the system provided no interference to the placement of the dense concrete overlay (Smith, 1990). A corrosion engineering firm contracted to inspect the cathodic protection system installation found some wiring errors for the polymeric anode system at the junction box, but the errors were easily corrected.

Carbon Strand System (Manufactured by Rescon). The carbon strand system was employed in two zones across the width of the bridge deck as shown in Figure 9; therefore, each zone was twice as wide as zones used for the titanium mesh or conductive polymer anodes. Each zone was approximately 200 feet (61 meters) long. A platinized wire with carbon filament secondary strands comprised the primary anode. As discussed earlier, the carbon strands increase the strength of the anode and decrease cost. The secondary anode used to distribute the current was made of a carbon based backfill material (65 percent coke breeze) that was mounded over the primary anode. Mixing the conductive backfill material required a technical representative from the manufacturer and placement was accomplished by hand. The quantity of conductive backfill mixed was kept below the amount that could be placed in 30 minutes, and special care was required not to allow the backfill material to touch metal embedded in the concrete. Smith reports the carbon strand system was the most difficult to install and required several days. Furthermore, the process produced toxic fumes requiring frequent rotation of workers. Subsequent placement of the concrete was trouble-free.

Sprayed Zinc. Sidewalks and medians on the bridge were cathodically protected using a sprayed zinc conductive surface anode. The protected areas are shown in Figure 9. The six separate zones protected with sprayed zinc anodes were generally narrow (less than 5 feet (1.5 meters)) and long (approximately 400 feet (122 meters)). Concrete surfaces were cleaned and embedded metals were masked to prevent direct or near contact with the sprayed zinc. Hot zinc was sprayed onto the surface to form a layer 20 mils thick (tolerance of 3 mils plus or minus). Current distributing lead wires were AWG No. 10 stranded copper with THHN insulation. Placement of the sprayed zinc required a licensed individual. The application was uneven and because the location was on the sidewalk, non-conductive surfacing was required atop the zinc to prevent exposing pedestrians to the system. However, cracking of the top surface was discovered soon after installation of the sprayed zinc system and the corrosion engineering contractor reported several erratic electrical isolations in the zinc anode coating (Smith, 1990).

Conductive Paint Anode (Porter DAC-85). One pier cap was cathodically protected using conductive paint as the anode. Electrical continuity of the embedded metal and reinforcing steel was checked and exposed metal was masked to prevent contact or near contact with the conductive paint. Platinum wire formed the primary anode, and the conductive coating was graphite/acrylic with 42 percent solids. The conductive coating was required no less than 16 mils thick (dry). Smith reports installing the conductive paint was fairly simple and similar to many other operations of cap repair and maintenance.

The cathodic protection system in each zone was connected to the rectifier through an individual circuit. Each anode type, zone, and associated circuit number is identified in Table 9.

TABLE 9. ANODE TYPES, PROTECTED ZONES AND CIRCUITS

Anode Type	Zone	Circuit No.
Titanium Mesh	A1	1
	A2	2
	A3	3
	A4	4
Conductive Polymer (Ferex 100 Strand)	B1	5
	B2	6
	B3	7
	B4	8
Carbon Strand (Rescon)	C1	9
	C2	10
	D1	11
Sprayed Zinc	D2	12
	D3	13
	D4	14
	D5	15
	D6	16
Conductive Paint (Porter DAC - 85)	E	17

Reference Cells. One silver - silver chloride reference cell was installed in each of the 17 cathodically protected zones. The cathodic protection engineer determined locations for the reference cells, but failed to properly document their exact locations.

Rebar Probes. Short pieces of reinforcing steel were embedded as rebar probes in each of the 17 cathodically protected zones. Exact locations of each rebar probe were not documented.

Linear Polarization Probes. Three electrode linear polarization (3LP) probes were installed in 20 permanent locations on the bridge and a portable device was purchased to provide measurements at other locations. Two permanent probes were embedded in each cathodically protected zone on the bridge deck traffic lanes (2 probes in each of 10 zones). Two areas were provided for portable rate of corrosion measurements in zones not in the traffic lanes. Portable measurements included locations on the sidewalks, median and on the bent below the bridge deck.

Salt Applications. Deicing salt is applied to the U.S. 87 overpass bridge on an as needed basis. The salt is mixed with small rocks before application. Salt applications usually occur between November and February. Information obtained from TxDOT

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record salt applications for the period December 1992 through December 1993 on the following days:

December 1992:	4, 5, 13, 14, 15, 21, 22, and 31
January 1993:	1, 2, 10, 11, 13, 14, 18, 19, 20, and 29
December 1993:	22

6. RESULTS AND FINDINGS

The performance for each of the cathodic protection systems was periodically assessed by monitoring several data items including the following (Parker, 1992):

1. Anode current

2. Anode Voltage

3. Anode Conductance (not measured directly)

4. Reference Cell Voltage

5. Instant-off Reference Cell Voltage

6. Rebar Probe Voltage

7. Corrosion Rates via 3LP Procedure

There are two reasons for gathering and analyzing the data items listed above: first, to determine if the systems are performing as designed and adjusted for cathodic protection of the reinforced concrete bridge, and second, to estimate if the specified level of cathodic protection is adequate to prevent corrosion. The significance of each of the data items will be discussed before considering the performance of each type of cathodic protection system individually.

Anode Current. Anode current is the primary variable directly adjusted by the engineer to provide adequate cathodic protection of the bridge. Inadequate current may result in ineffective cathodic protection of the bridge, and excessive current may directly damage the bonding of concrete to the rebar and/or cause hydrogen embrittlement of the rebar. Criteria by which the adequacy of cathodic protection are determined have been discussed in the literature (Stratfull, 1983), and recommended practice established (SHRP, 1993).

A cathodic protection consultant during the installation of the cathodic protection systems established the desired currents for each of the 17 circuits based on E vs log(I) data taken on each circuit. Sufficient current was supplied to cause the protected rebar

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potential, with respect to the reference cell, to be in the linear, all-cathodic region, observed on the E vs log (I) plot. Exceptions were made to this adjustment criteria when the current required would be in excess of the manufacturers recommendation for the particular anode system. After approximately 45 and 90 days of operation, the anode current settings for each cathodic protection system were adjusted on the basis of a positive depolarization shift of 100 to 150 mv. The depolarization shift is the potential between the reference cell and the rebar measured at instant-off conditions and after 4 hours without power, and initial measurements are reported in Table 16 of the consultants report (Smith, 1990). Based upon depolarization shifts, currents to the anode systems were adjusted as listed in Table 23 of the consultants report (Smith, 1990). The current adjustments have not been changed since the adjustment after 90 days of operation.

Anode Voltage. The anode voltage is automatically adjusted by each rectifier circuit to supply the current selected for each cathodic protection circuit. The maximum available anode voltage is determined by the rectifier design. For the rectifier system installed at the Big Spring bridge, the maximum available voltage is 25 volts for circuits 1 through 13 and 50 volts for circuits 14 through 17. If the resistance in a cathodic protection circuit increases, the voltage is automatically increased by the rectifier to provide the selected current until the maximum voltage available from the circuit is achieved.

Anode Conductance. Anode conductance is calculated by dividing the anode current by the anode voltage. Its units are reciprocal ohms, frequently called mhos. This parameter has been found useful in observing the failure of the cathodic protection circuits on the Big Spring bridge. As the conductance of a circuit approaches zero, the resistance of the circuit approaches infinity, and it is impossible to supply the required amount of current to the system.

Reference Cell Voltage. The electrochemical potential of a section of steel rebar determines its susceptibility to corrosion. This potential is measured by comparison with the potential of a stable reference cell. Although the steel is always negative with respect to the reference cell, the minus sign has been omitted when recording and graphing the data. Thus, a larger value indicates that the steel is more negative, i.e., more cathodic and better protected against corrosion.

For the bridge deck, silver chloride reference cells were placed near the center of each protected zone. The locations of the reference cells in the other systems were not documented. If the reference cells are stable, observed changes in reference cell potential reflect changes in the potential of the rebar, with respect to the electrolyte (concrete) in the vicinity of the reference cell. Unfortunately, reference cell potentials may not be stable over long periods or extremes of temperature. Reference cell stability has been discussed in the literature (Schell, 1989). The problem of reference cell stability is minimized when polarization shifts are used to evaluate the adequacy of the current supplied to a cathodic protection circuit, as the consultant did in his 45- and 90- day adjustments of the currents to the present cathodic protection systems. Even with a stable reference cell the observed

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reference cell voltages fluctuate considerably. Voltage fluctuations have been attributed to the varying availability of oxygen to the cathode, due to changes in moisture within the concrete (Stratfull, 1983). The voltage gradients induced in the concrete by the anode current are also measured as a part of the observed reference potentials. Voltage gradient problems are circumvented by using "instant-off" reference cell voltages as discussed in the next paragraph.

Instant-off Reference Cell Voltages. The voltage gradients in the slab caused by the current flowing through the slab can be eliminated by turning the current off, and instantly measuring the reference cell voltage. In this case, the term "instant" must be defined since the anode begins to depolarize "instantly." The instructions provided to personnel taking data at the Big Spring bridge were to record the second reading on the digital voltmeter after cut-off of the anode current.

Rebar Probe Voltage. The rebar probe voltage is actually measured across a 10-ohm shunt connecting the rebar probe to the remainder of the rebar being cathodically protected, so it really is a measurement of rebar probe current, and the voltage value can be multiplied by 100 to get the rebar current in milliamps. If the current flowing from the rebar probe is positive, the probe is negative with respect to the remaining rebar and so is more cathodic and better protected than the remaining rebar. If the current flow is negative, the rebar probe is actually corroding. The rebar probe current is not an absolute measurement of corrosion rates, since the probe could contain both anodic and cathodic sections, and we are observing only the net external current flow. To obtain an actual measurement of corrosion rates, more complex procedures are required.

Corrosion Rates via 3LP Measurement. Corrosion rates can be directly measured by the linear polarization method. This technique is based on proven theory, and has been adapted for use in reinforced concrete structures. However, 3LP measurements cannot be used while the bridge is being cathodically protected (Clear, 1989). The cathodic protection consultant recorded three sets of measurements prior to energizing the cathodic protection system, and after approximately 45 and 90 days of operation. Results from the initial 3LP measurements are given in Table 19 of the consultant's report (Smith, 1990). The data indicated corrosion rates of about 2 mils per year at six locations, which would normally predict slab failure in 2 to 10 years (Clear, 1989). Measurements with the 3LP system require the cathodic protection system current be turned off for 24 to 48 hours prior to testing, so measurements exhibit little or no relation to corrosion rates observed while the bridge is under cathodic protection. One additional set of 3LP measurements was gathered after 546 days of operation.

Data from each cathodic protection circuit will be considered in groups that contain the same anode materials. Monthly data records are presented in the appendix. In order to illustrate the system performance, monthly readings are averaged by calendar quarter (three months) and plotted in the following figures. In some cases, data were recorded more or less than three times during the quarter. The quarterly averages presented were calculated based upon the number of data collections.

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<u>Elgard 150 titanium mesh (Bridge deck zones A1 - A4, Rectifier Circuits 1 - 4).</u>
Circuits protected by Elgard 150 titanium mesh exhibited stable, long term operation. The desired anode current is maintained without significant increases in anode voltage. The rebar probe remains positive, indicating the probe is cathodic with respect to the remainder of the rebar. Circuits 1 and 4 exhibit some evidence of irregular behavior with regard to anode current beginning in January 1993. Reference cell voltage and instant-off reference cell voltage indicate problems with Circuit 1 began in January 1991. It is likely the problems are associated with the reference cell and not the cathodic protection system.

Swiat tested Elgard 150 titanium mesh anode systems (with modified HCR Thorotop overlay) on bridge piers in a northern climate (Swiat, 1987). The study also included an Elgard 210 titanium mesh with a latex modified concrete overlay. No delamination or disbondment was found for the Elgard 150 system on the piers throughout the 18-month evaluation. Several cracks were observed on sidewalks protected by the Elgard 210 anode system. The cracks were first observed at 6 months and increased throughout the study and eventually led to concrete delamination. Swiat investigated the delaminated areas by coring the concrete. He concluded the cracks originated from damage which had not been repaired properly during placement of the anode systems.
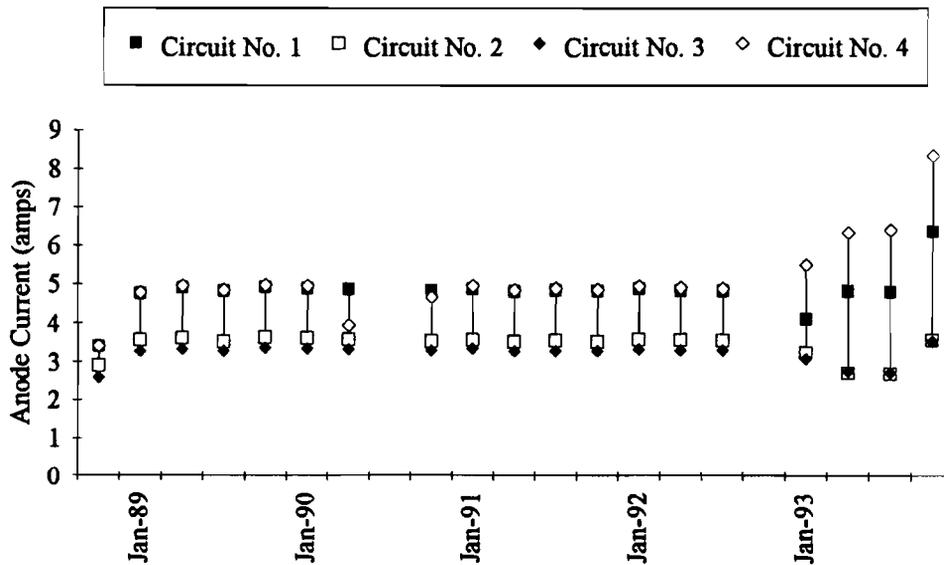
Figure 10. Anode Current, Quarterly Averages - Titanium Mesh Anode
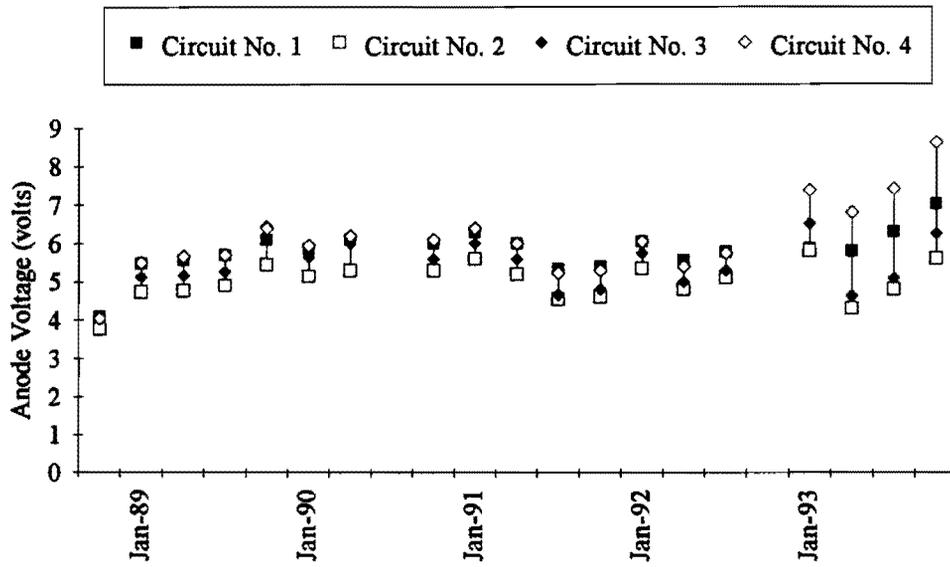
Figure 11. Anode Voltage, Quarterly Averages - Titanium Mesh Anode
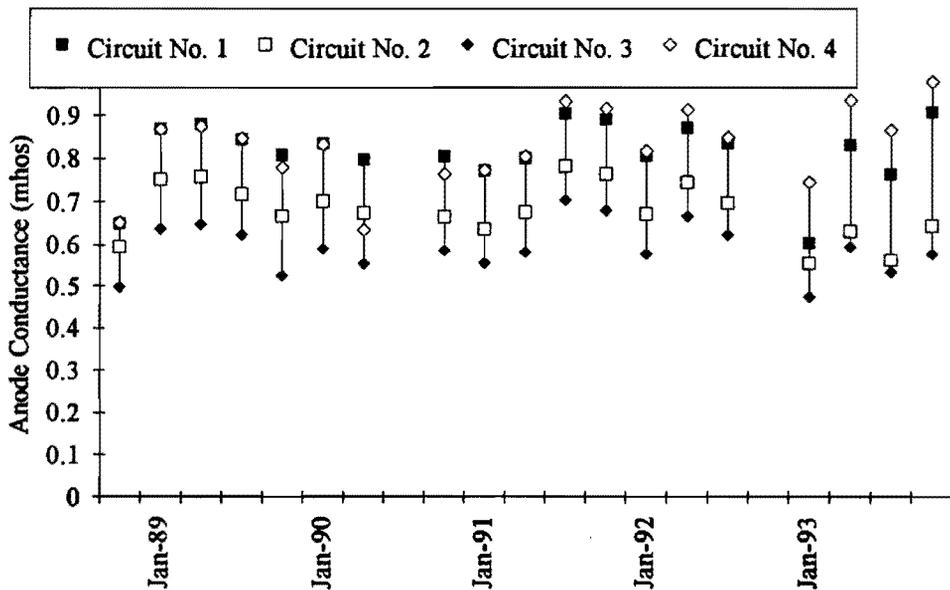
Figure 12. Anode Conductance, Quarterly Averages - Titanium Mesh Anode

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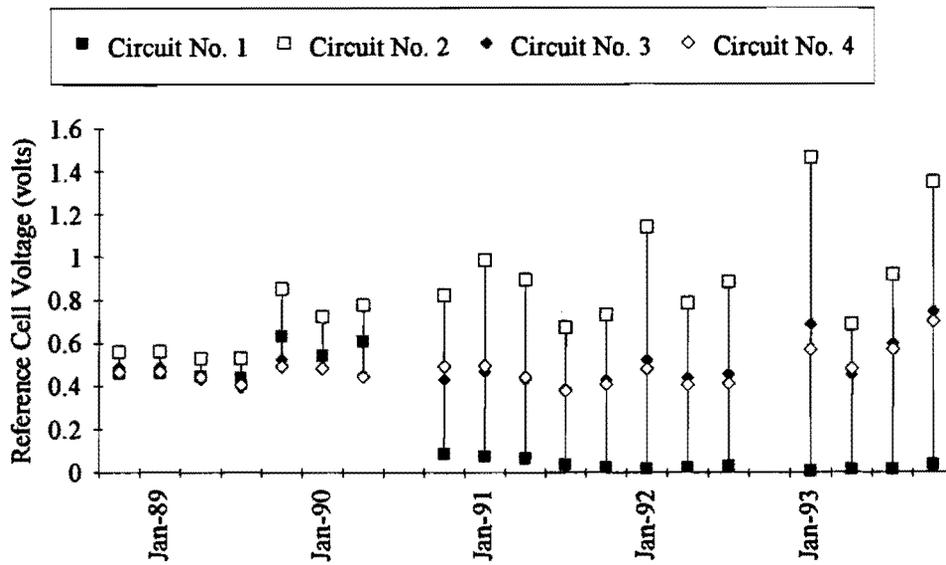
Figure 13. Reference Cell Voltage, Quarterly Averages - Titanium Mesh Anode
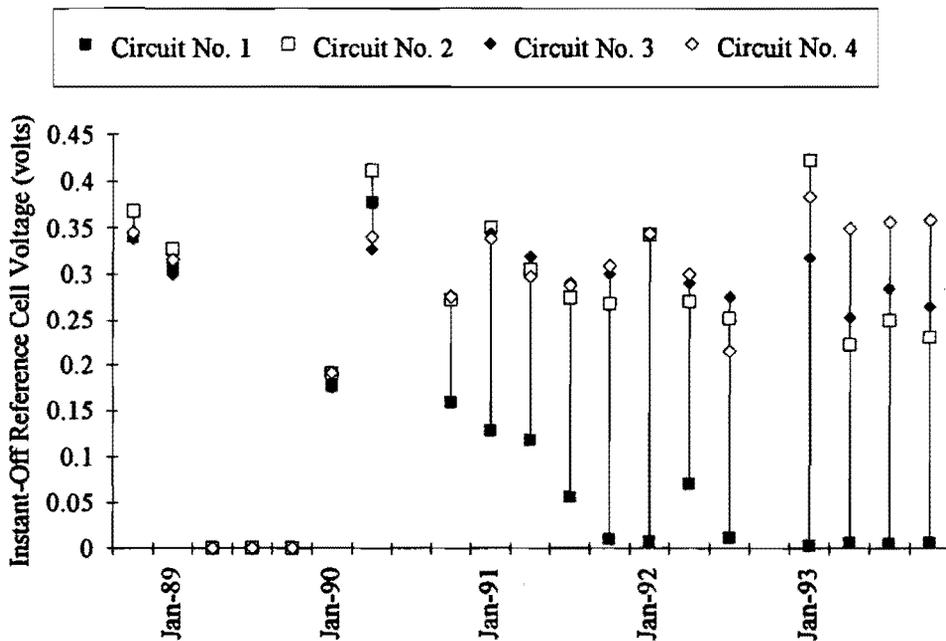
Figure 14. Instant-off Reference Cell Voltage, Quarterly Averages - Titanium Mesh Anode

41
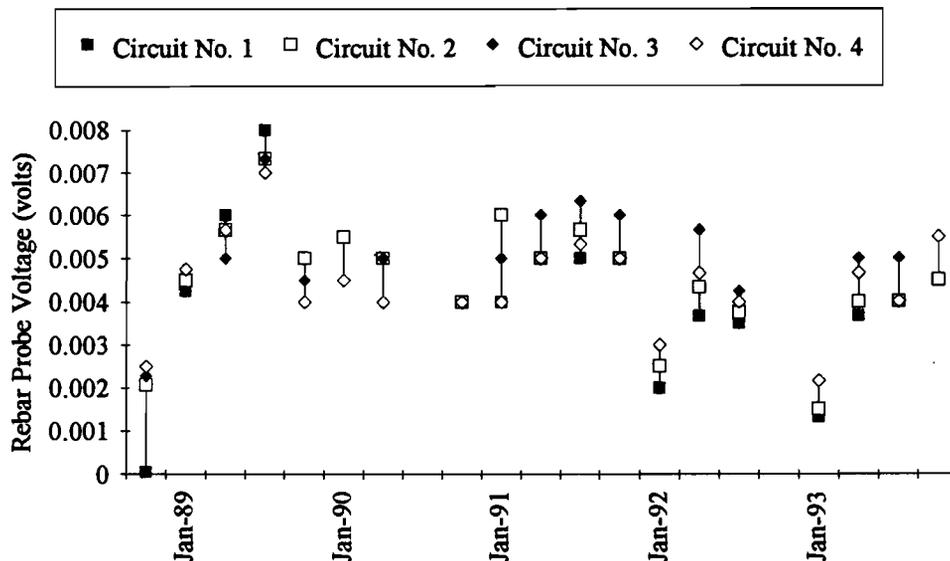
Figure 15. Rebar Probe Voltage, Quarterly Averages - Titanium Mesh Anode

Raychem Ferex 100 Conductive Polymer (Bridge deck zones B1 - B4, Rectifier circuits 5 - 8). Circuits protected by Raychem Ferex 100 performed satisfactorily until the third quarter of 1990 (approximately 500 days) at which time voltage increases were necessary to maintain the desired anode current. By the second quarter of 1991, (approximately 1,000 days) the rectifier was unable to supply sufficient voltage to maintain the current, so the anode current began to decrease. In the third quarter of 1991, (approximately 1,100 days) none of the circuits were receiving a significant amount of electrical current. Deterioration of the circuits is better seen in the plot of circuit conductance versus time. The conductance decreases linearly from January 1990 until the third quarter of 1991. All circuits with Raychem Ferex 100 have failed.

In another research program, Swiat tested the Raychem Ferex 100 flexible polymeric material with a latex modified concrete overlay on a bridge deck in a northern climate (Swiat, 1987). The general appearance of the concrete was good throughout the 18-month evaluation and no delamination was detected. The concrete cover over the top of the strand popped out over a small length (less than an inch) and exposed the strand. He observed current fluctuations several times during the study but concluded the fluctuations were due to controller malfunction or voltage limitations.

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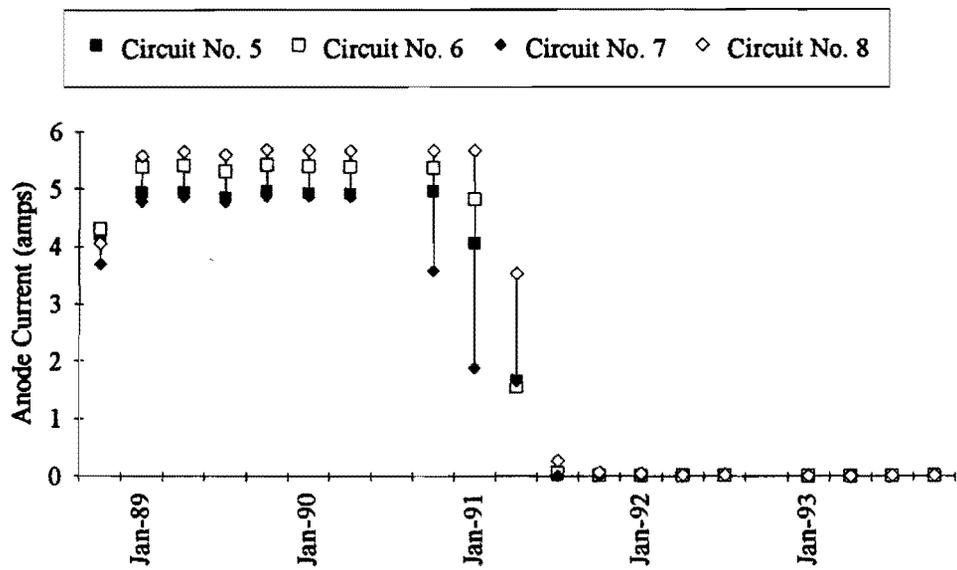
Figure 16. Anode Current, Quarterly Averages - Conductive Polymer Anode
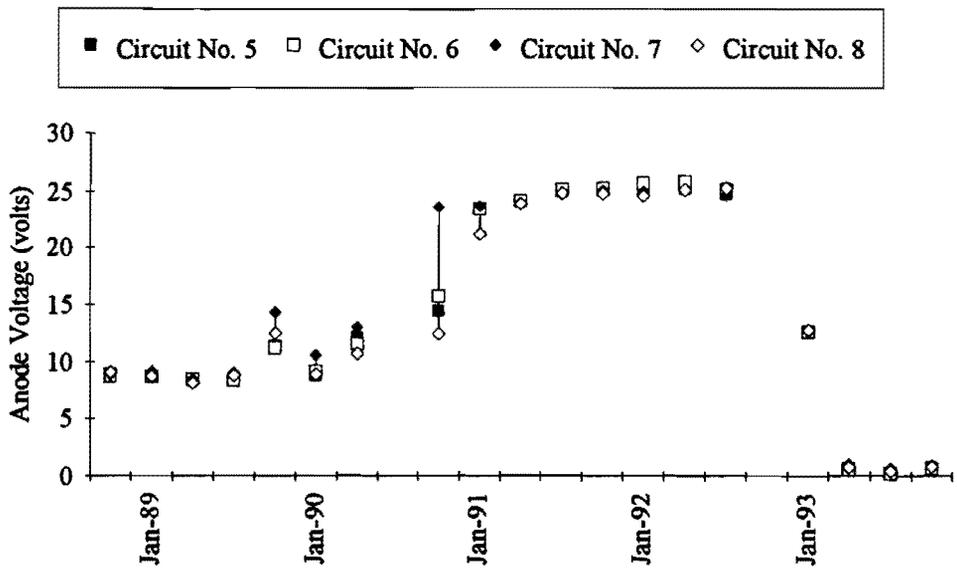
Figure 17. Anode Voltage, Quarterly Averages - Conductive Polymer Anode

43
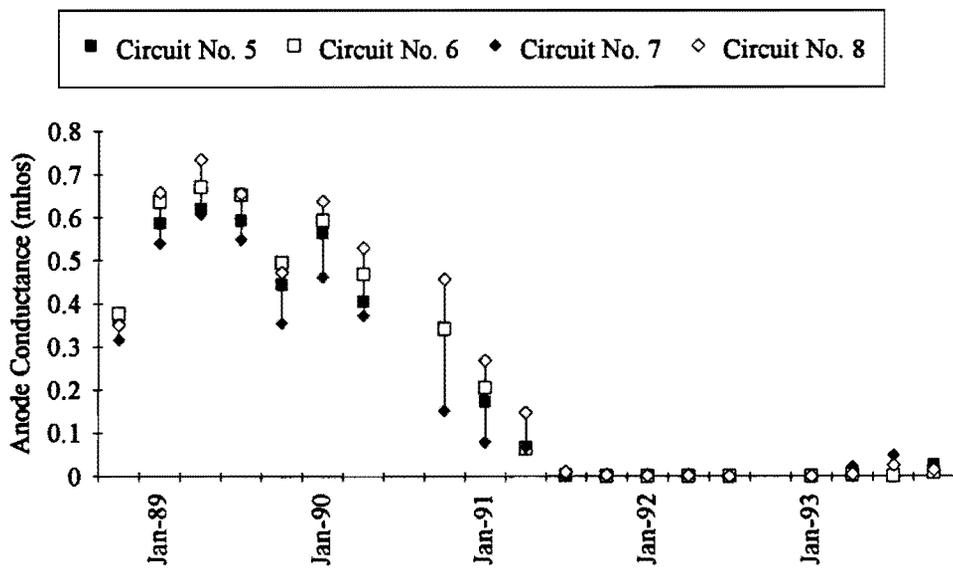
Figure 18. Anode Conductance, Quarterly Averages - Conductive Polymer Anode
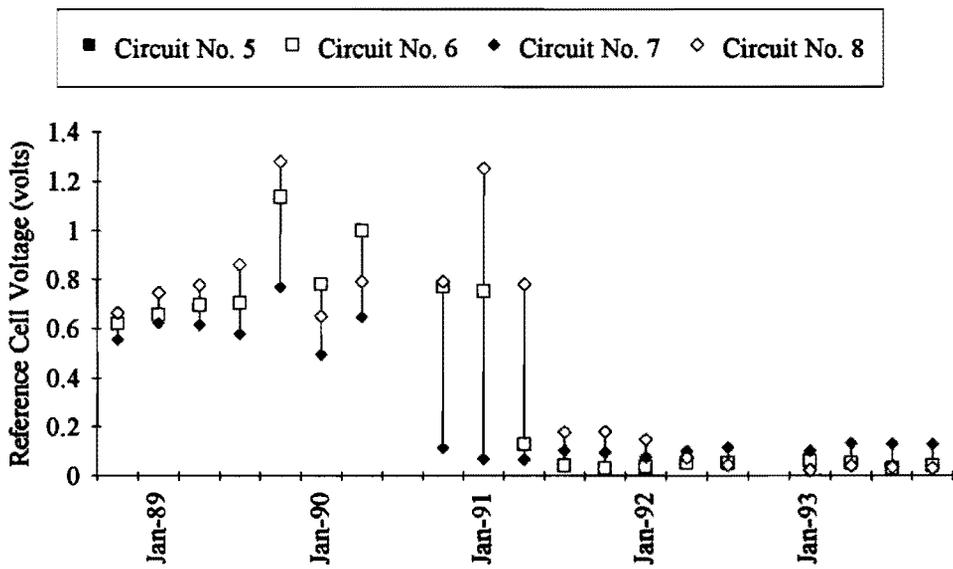
Figure 19. Reference Cell Voltage, Quarterly Averages - Conductive Polymer Anode

44
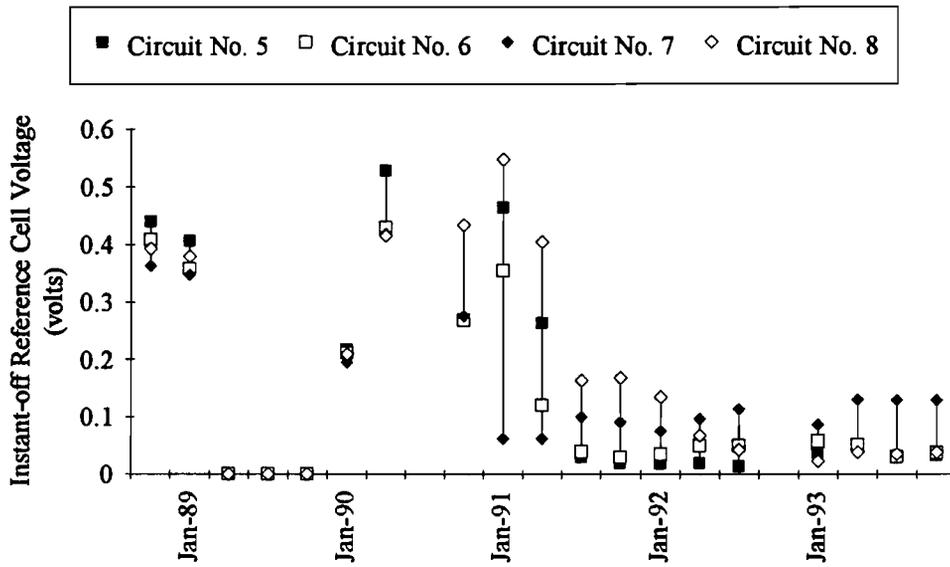
Figure 20. Instant-off Reference Cell Voltage, Quarterly Averages - Conductive Polymer Anode
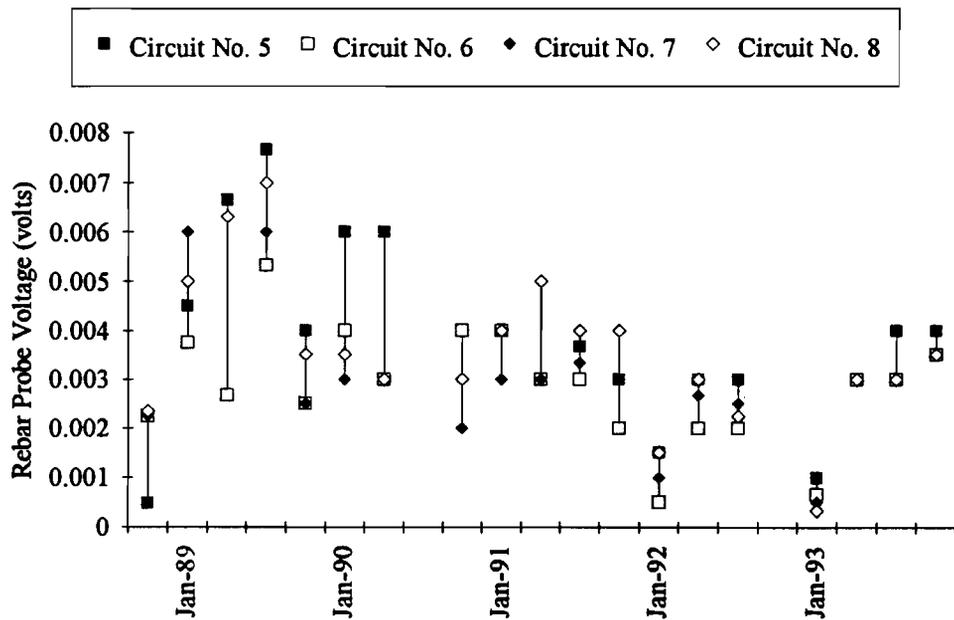
Figure 21. Rebar Probe Voltage, Quarterly Averages - Conductive Polymer Anode

Rescon Rigid Conductive Polymer Concrete, Carbon Strand (Bridge deck zones
C1 and C2, Circuits 9 and 10). The desired anode current has been maintained in circuits
9 and 10 since installation. Circuit 10 required increases in voltage to maintain current
beginning in January 1993 with a corresponding decrease in reference cell voltage. The
relatively rapid changes could be an indication of future difficulties for the two circuits
using the Rescon anodes. The rectifier can supply up to 25 volts to circuits 9 and 10.

Swiat tested a conductive polymer slotted anode system on a bridge in a southern
marine environment (Swiat, 1987). He reported the system provided effective corrosion
control to the reinforcing steel of the bridge deck. However, visual inspection of the
bridge deck over a 23-month period revealed discoloring of the concrete at high current
discharge areas. Swiat attributed the discoloration to the formation of acid which was
attacking concrete. The acid attack led to disbondment of a small area of concrete (1
square inch (6.5 square cm)) but no other disbondment was noted.
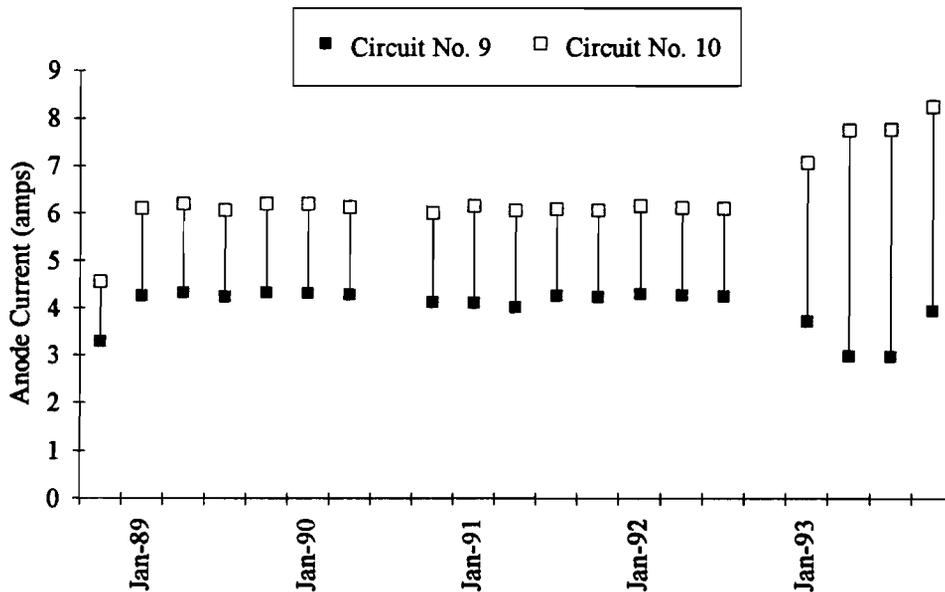
Figure 22. Anode Current, Quarterly Averages - Carbon Strand Anode
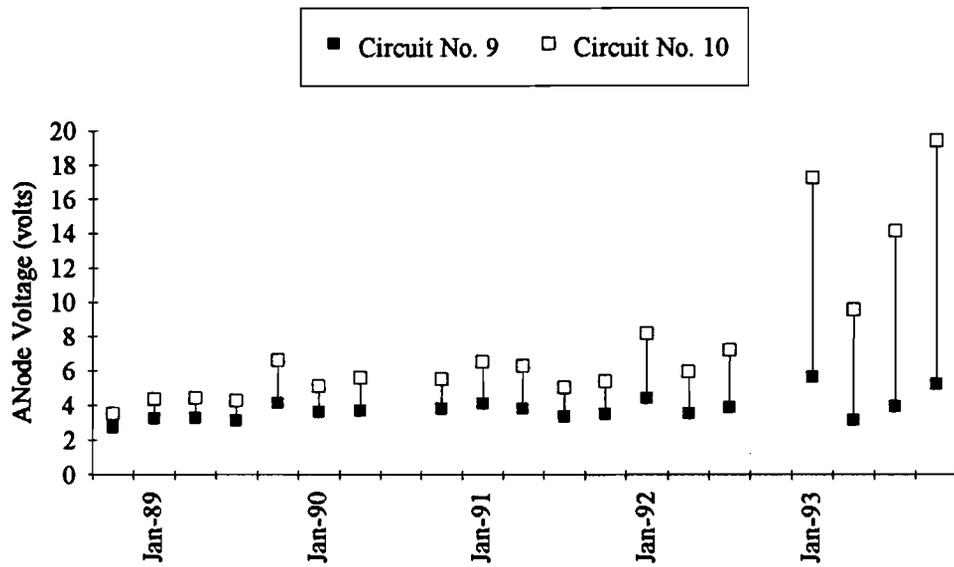
Figure 23. Anode Voltage, Quarterly Averages - Carbon Strand Anode
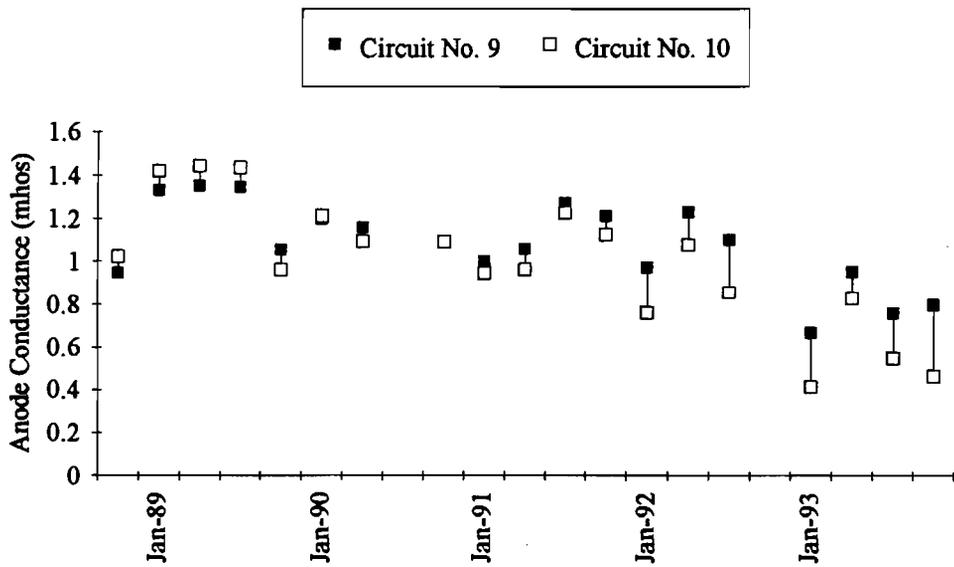
Figure 24. Anode Conductance, Quarterly Averages - Carbon Strand Anode

47
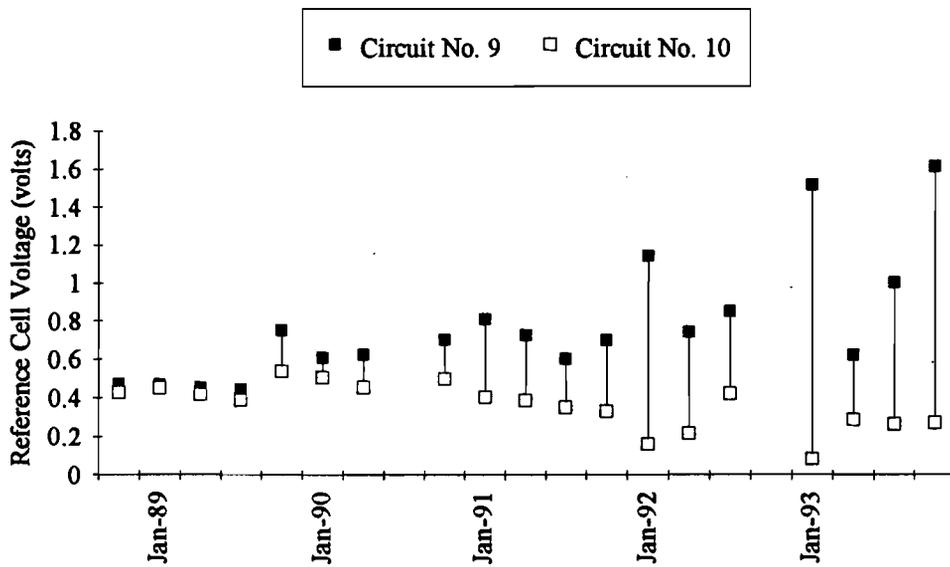
Figure 25. Reference Cell Voltage, Quarterly Averages - Carbon Strand Anode
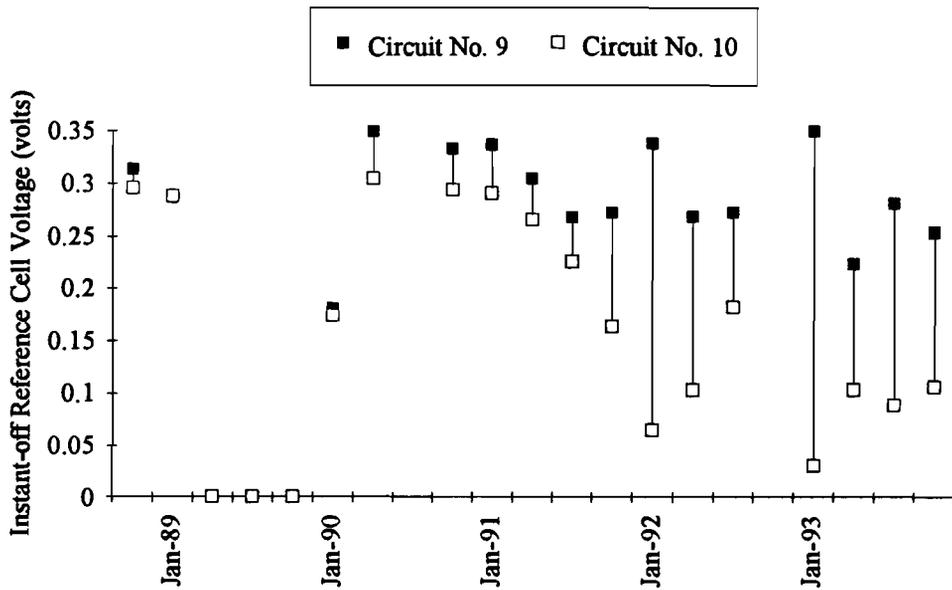
Figure 26. Instant-off Reference Cell Voltage, Quarterly Averages - Carbon Strand Anode

48
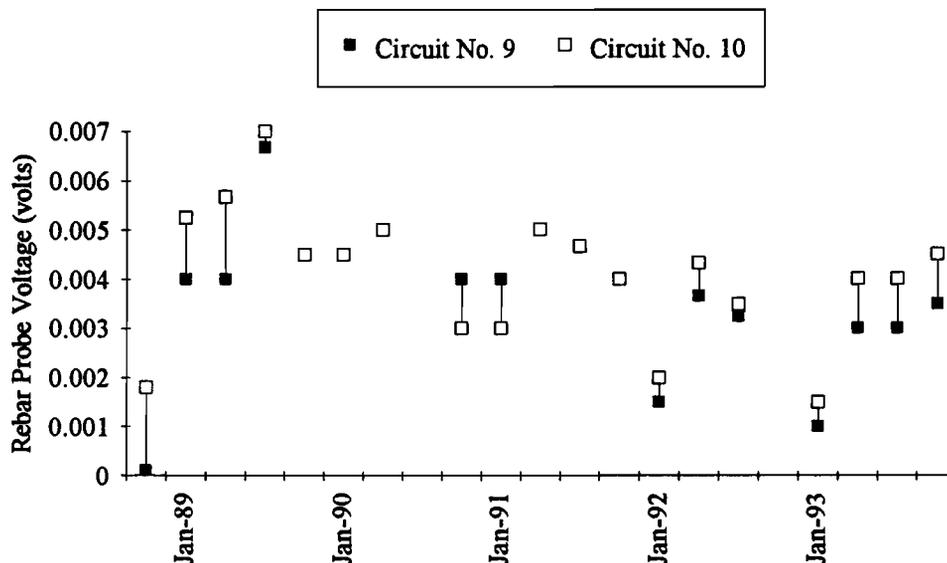
Figure 27. Rebar Probe Voltage, Quarterly Averages - Carbon Strand Anode

<u>Hot Sprayed Zinc (Sidewalks and Median zones D1 - D6, Circuits 11 - 16)</u>. Based upon anode currents and voltages, it appears that all of the zinc sprayed circuits have failed. In fact, this failure occurred rather quickly, in the third quarter of 1989 (approximately 200 days). Failures are detected by the steep rise in anode voltage to the maximum possible supplied by the rectifier. A similar conclusion can be drawn by looking at the plots of conductance. Table 20 in the consultant's report (Smith, 1990), noted high resistances and increasing resistances in three of the circuits, 11, 12, and 13, in the first 90 days of operation. It appears that a combination of disbondment and cracking of the zinc caused these failures. The rebar currents have been quite low after failure to supply current to the anodes, and some times they were negative indicating that the rebar probe was anodic with respect to the remaining rebar. In contrast, the instant-off cell voltages have remained relatively constant. Current to circuits 11 through 16 was turned off in the second quarter of 1993.

Swiat tested a zinc spray anode system on a reinforced concrete bridge pier in a southern marine environment (Swiat, 1987). After 23 months, the general appearance of the pier was in good condition except for one small rust stain at a location of a short to rebar. Two delaminations of about 2-inch (5 cm) diameter were found near rebar chairs that were not electrically continuous with the cathodic protection system. No other delaminations were observed during the 23-month evaluation.

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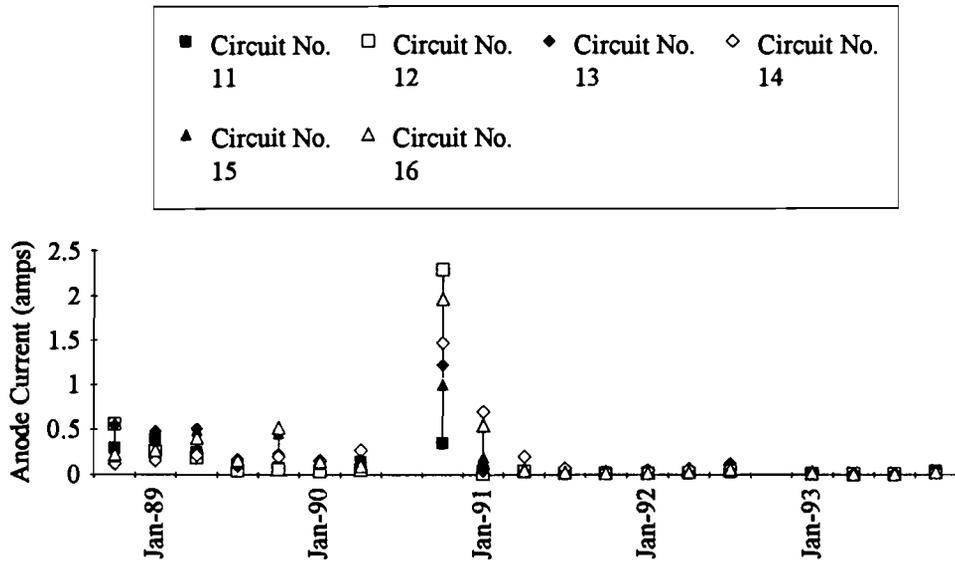
Figure 28. Anode Current, Quarterly Averages - Sprayed Zinc Anode
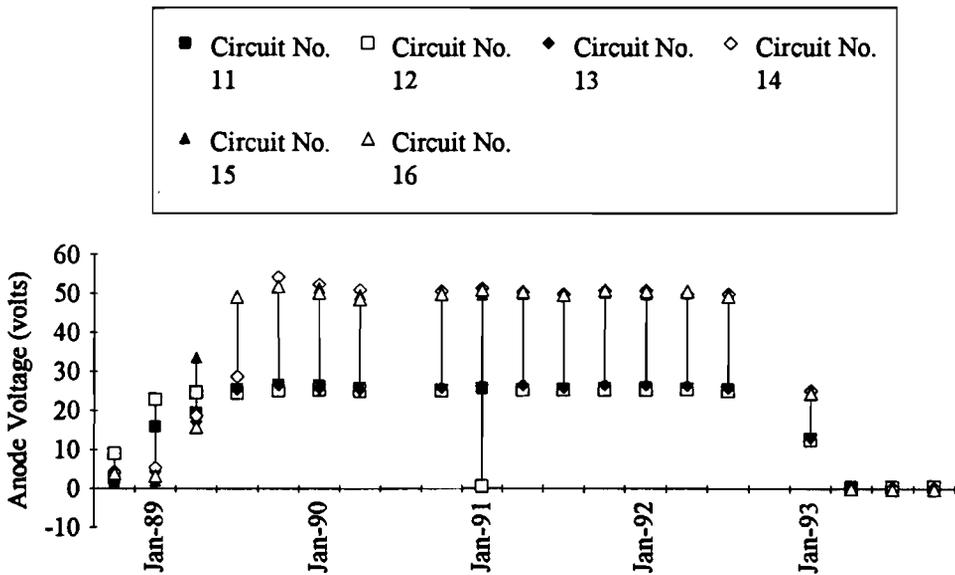
Figure 29. Anode Voltage, Quarterly Averages - Sprayed Zinc Anode
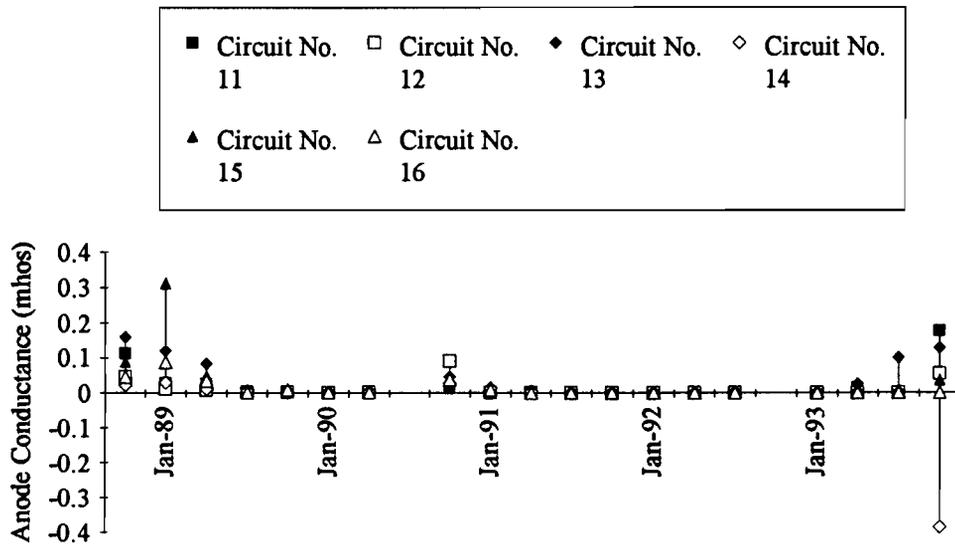
Figure 30. Anode Conductance, Quarterly Averages - Sprayed Zinc Anode
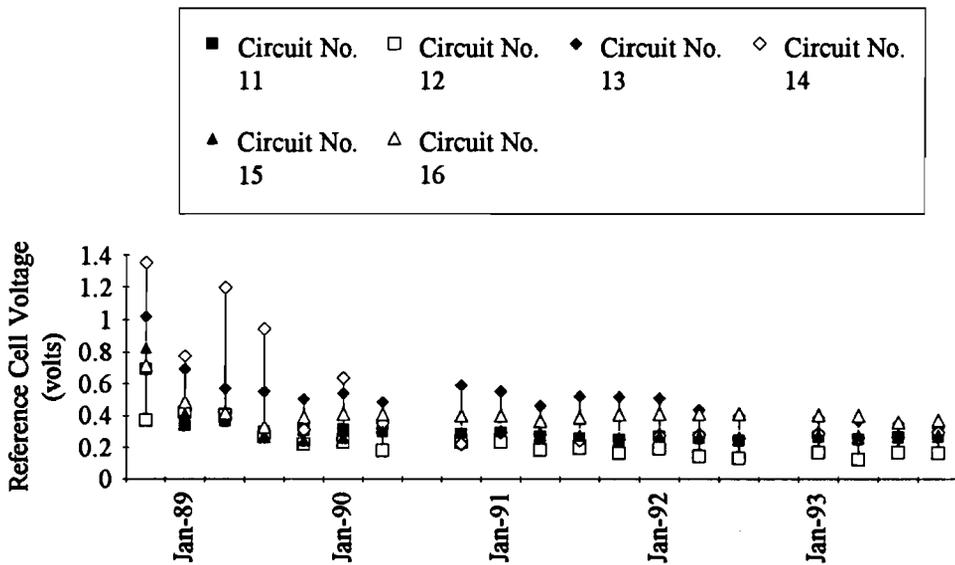
Figure 31. Reference Cell Voltage, Quarterly Averages - Sprayed Zinc Anode

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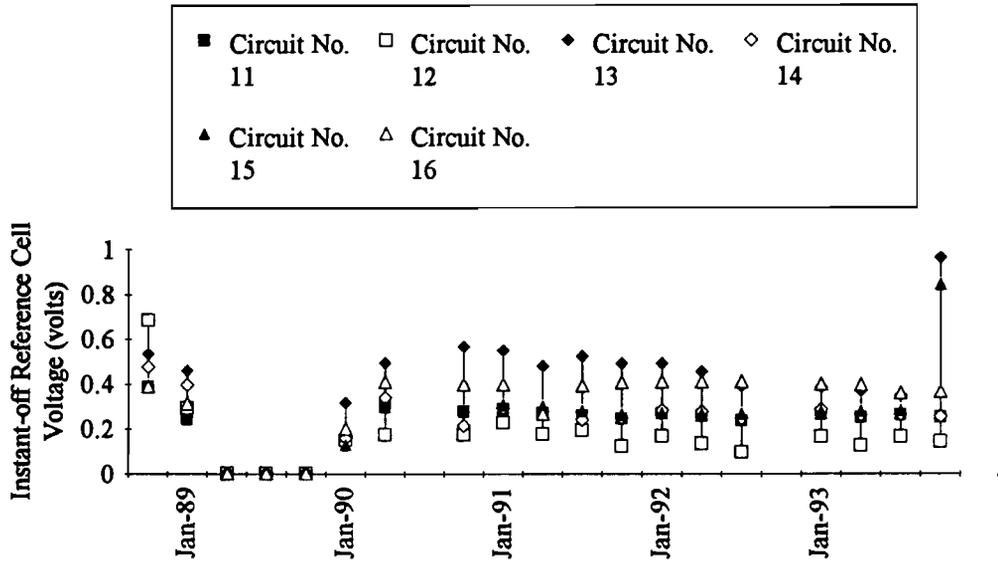
Figure 32. Instant-off Reference Cell Voltage, Quarterly Averages - Sprayed Zinc Anode
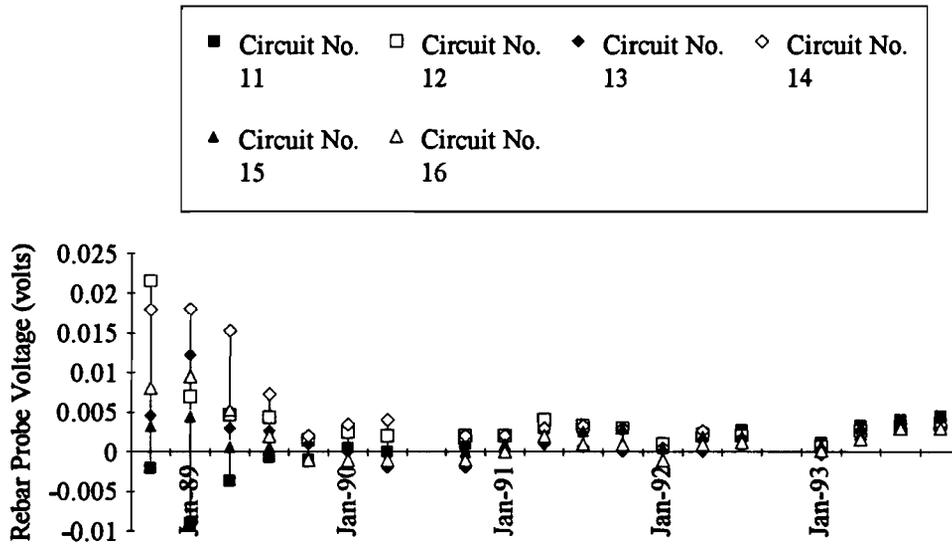
Figure 33. Rebar Probe Voltage, Quarterly Averages - Sprayed Zinc Anode

Porter DAC-85 Conductive Paint (Pier cap zone E, Circuit 17). The current to circuit 17 was adequate but erratic until mid-1992. As the conductive paint anode began to fail maximum voltage in the circuit (50 volts) was required to try and maintain current. The system has failed and the conductive paint is peeling and flaking from the bridge pier.

Swiat tested a conductive polymer spray anode system on a bridge pier in a southern marine environment (Swiat, 1987). Discoloration of the decorative overcoat was found 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. Swiat believes the rust stains indicate locations of electrically discontinuous rebar chairs, which will eventually lead to concrete disbondment. Later, the conductive polymer suffered blistering throughout the columns. The decorative overcoat appeared darker (black shadowing) with time. Perenchio observed scaling of conductive coatings on cathodically protected bridge piers and attributed the scaling to acid production or chlorine gas generation (Perenchio, 1985). He also noted freeze-thaw problems drastically affect coating adherence.
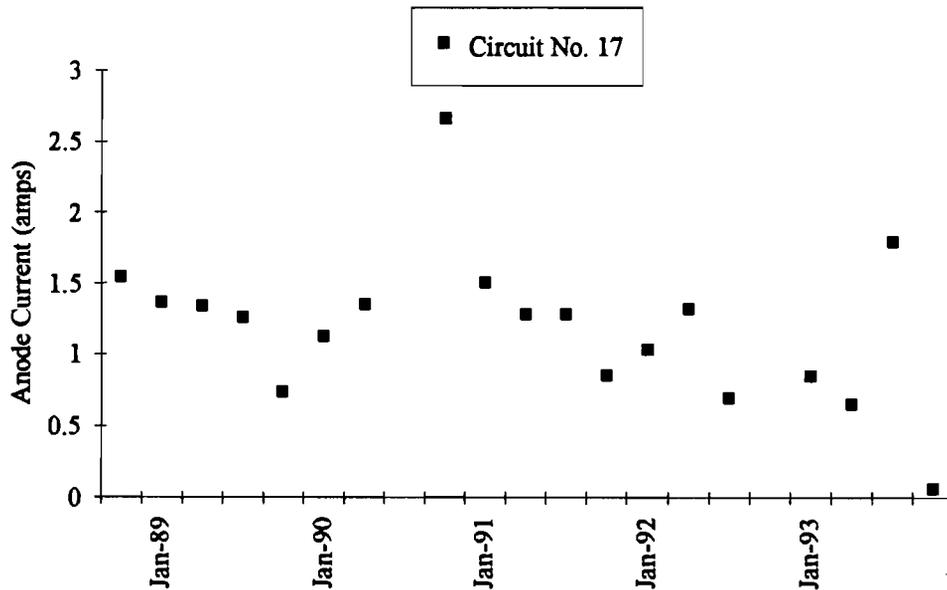
Figure 34. Anode Current, Quarterly Averages - Conductive Paint Anode

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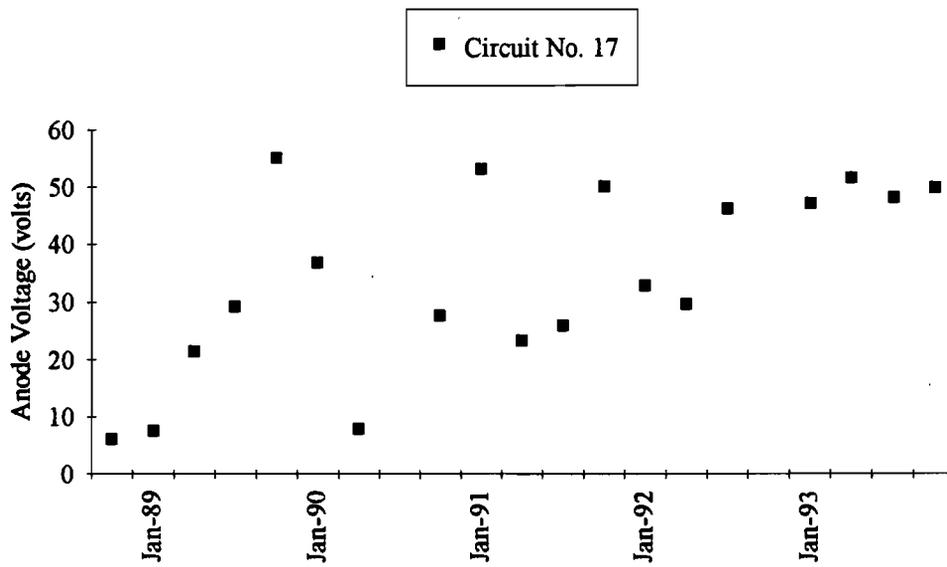
Figure 35. Anode Voltage, Quarterly Averages - Conductive Paint Anode
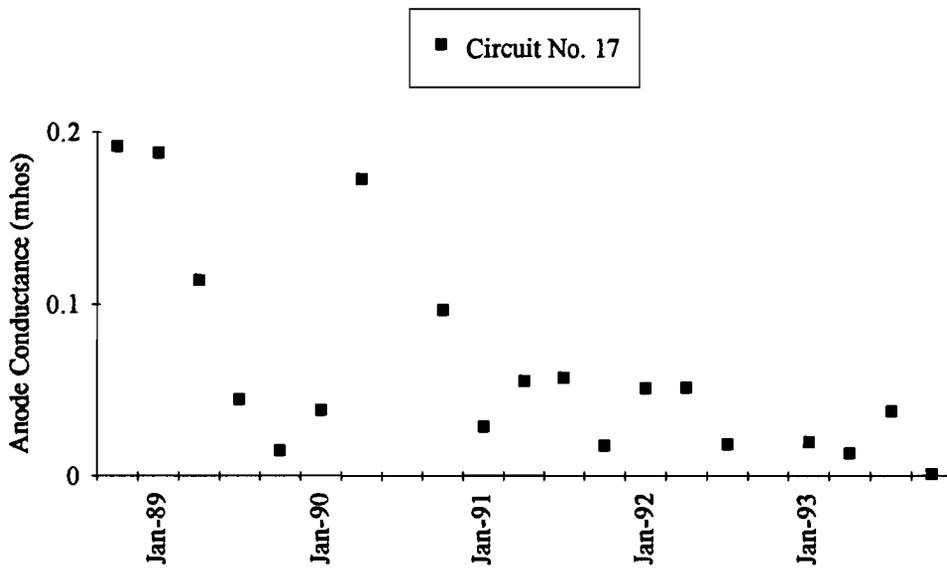
Figure 36. Anode Conductance, Quarterly Averages - Conductive Paint Anode
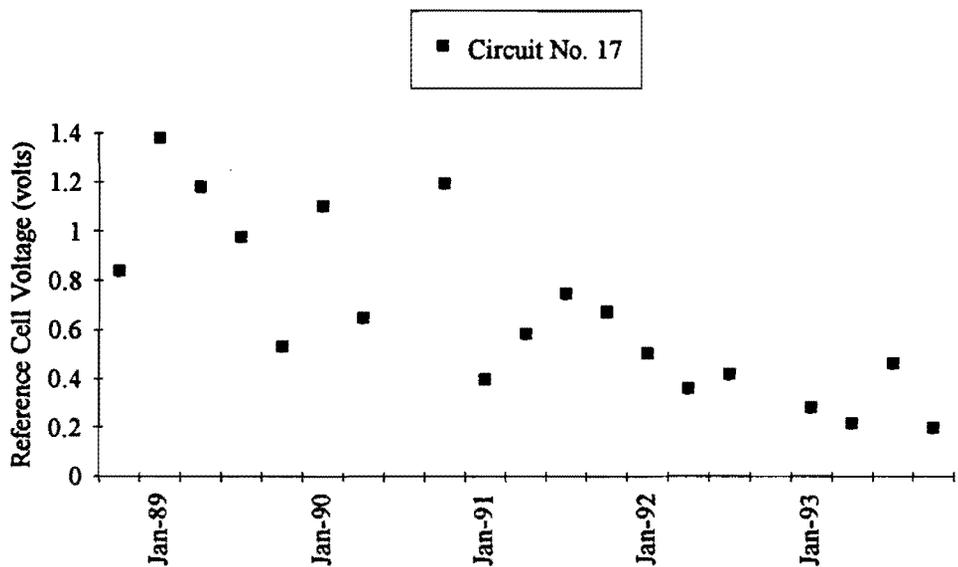
Figure 37. Reference Cell Voltage, Quarterly Averages - Conductive Paint Anode
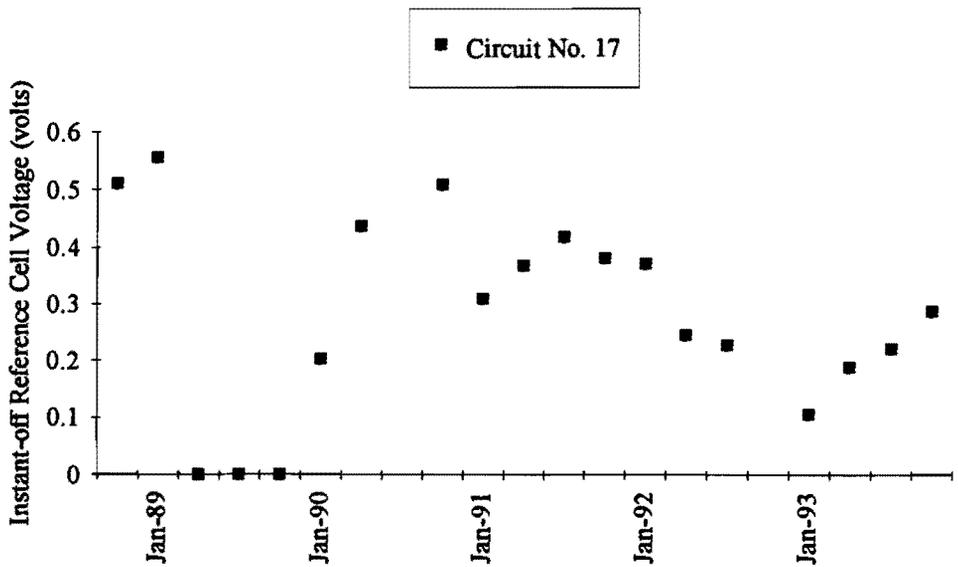
Figure 38. Instant-off Reference Cell Voltage, Quarterly Averages - Conductive Paint Anode
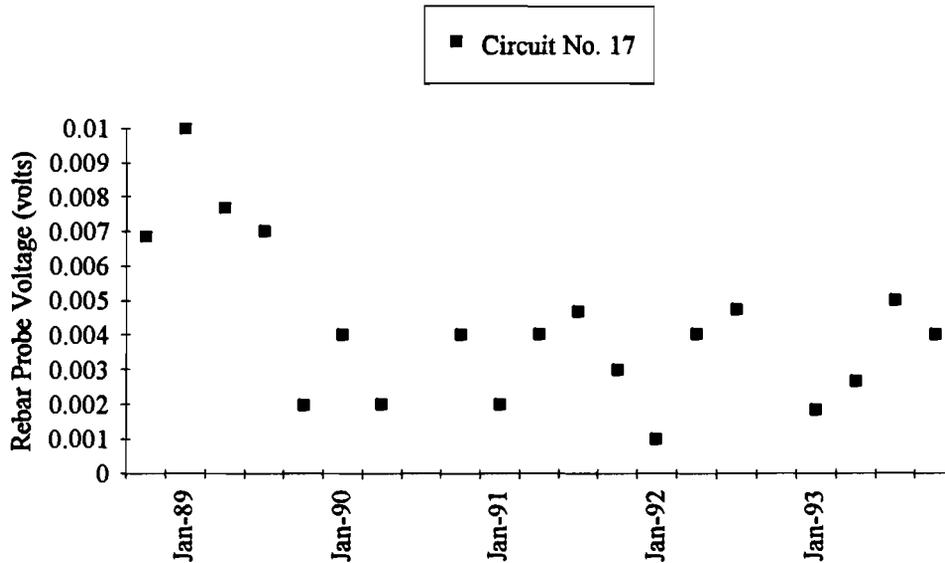
Figure 39. Rebar Probe Voltage, Quarterly Averages - Conductive Paint Anode

7. COST EFFECTIVENESS STUDY

Present value life cycle cost methods were used to compare several alternatives for bridge deck construction or repair. Alternatives included bridge decks with and without cathodic protection. Sprayed zinc and conductive paint anodes were not included in the comparison because neither is intended for protecting bridge decks. Following accepted methods (Silano, 1993, Grant, 1982), steps in the life cycle cost analysis included the following:

1. A base life of 80 years was considered. Most references consider a normal bridge to have a life span of 40 years (Jackson, 1982). For the purposes of this study, it was assumed an effective cathodic protection system will double the life span of the bridge being protected (80 years). Bridge life spans are determined by a number of factors in addition to deck deterioration (e.g., changes in traffic patterns and routing). A base life of 80 years represents two life spans of a typical bridge and one life span of a cathodically protected bridge.

2. The cost of money was arbitrarily taken as 7.5 per cent per annum. Rates of 6.0 and 10.0 were also considered.

3. Cost element items, costs and expected service lives were identified for bridge decks with and without cathodic protection (Table 10). Details of each cost element are described in the following:

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Without Cathodic Protection

a. Construct New Bridge and Replace Bridge Deck - Several bridge decks have been constructed or replaced in the Big Spring area with costs ranging from $35 to $45 per square foot (psf). An average cost of $40 psf ($430 per square meter, psm) was selected. The service life of 40 years was chosen based upon average bridge life.

b. Repair Bridge Deck - In the analysis, major repairs are expected every 20 years throughout the life of the bridge. Repairing the Big Spring bridge deck in preparation of installing the cathodic protection systems cost $18,075 for 3,615 square yards of surface ($0.56 psf, $6.02 psm).

c. Periodic Inspection - Approximately 100 hours of labor was required to inspect the bridge deck for damage before installing the cathodic protection systems. Periodic inspections after major bridge deck repair are required on a biannual basis. cost of the biannual inspection is 4 hours at $28/per hour for the total area being protected ($0.0017 psf, $0.018 psm, annually).

d. Maintenance - The Big Spring bridge required approximately $82,000 in maintenance the 10 years prior to installing the cathodic protection systems. Based upon the total bridge deck area, the average annual cost for maintenance was $0.252 psf ($2.71 psm) in the analysis.

With Cathodic Protection

a. Construct New Bridge Deck - The same cost was used as for bridge decks without cathodic protection.

b. Anode Systems - Costs reported by Smith (Smith, 1990) were used for each anode. Service lives were approximated based upon recommendations from SHRP, 1993.

c. Repair Bridge Deck - Repairs should not be required if the cathodic protection system is effective.

d. Periodic Inspection - Annual costs were estimated the same as for bridge decks without cathodic protection.

e. Maintenance - Thus far no maintenance has been required on the

Big Spring bridge deck, but some cathodic protection systems have failed. However, further monitoring is required to establish actual long-term maintenance costs.

f. Power - The average monthly power bill for the total area being protected is $55.75 ($0.021 psf, $0.23 psm, annually).

g. Monitoring - Collecting data at the bridge site by TxDOT personnel cost approximately $28 per month ($0.01 psf, $0.107 psm, annually). The telephone bill for the remote monitoring system is $28.36 monthly ($0.01 psf, $0.107 psm, annually). Additionally, the remote monitoring system cost $6357 initially ($0.20 psf, $0.107 psm). Monitoring cost depend upon the location of the systems and number of systems active. For the purposes of this cost analysis, monitoring costs were $0.01 psf, $0.107 psm, annually.

TABLE 10. COST ELEMENT ITEMS,
COSTS AND SERVICE LIVES

Item	Service Life	Cost ($'s Per sq. ft.)	Cost ($'s Per sq. mtr)
Without Cathodic Protection			
New Bridge Deck	40 years	40	430
Repair Bridge Deck	20 years	0.56	6.02
Periodic Inspection	biannually	0.0017	0.018
Maintenance	yearly	0.252	2.71
With Cathodic Protection			
New Bridge Deck	80 years	40	430
Anode System			
Titanium Mesh	40 years	6.95	74.77
Conductive Polymer	40 years	5.91	63.58
Carbon Strand	20 years	7.17	77.14
Repair Bridge Deck	not required		
Periodic Inspection	yearly	0.0017	0.018
Maintenance	lack data		
Power	yearly	0.021	0.23
Monitoring	yearly		
At Site		0.01	0.107
Remote System		0.2 each	2.15 each
Telephone		0.01	0.107

Cost schedules for new bridge construction, and repair of bridge decks 10, 20, and 30 years old are shown in Figures 40 through 43, respectively. For a new bridge deck without cathodic protection (Figure 40) the original cost is $40 psf. The deck requires repair every 20 years at $0.56 psf. With the titanium mesh or conductive polymer anode the original construction costs are the same for the bridge deck with additional costs for the cathodic protection system ($6.95 psf for the titanium mesh anode or $5.91 psf for the conductive polymer anode). Because their service life is 40 years, the titanium mesh or

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conductive polymer anode must be replaced once during the 80-year life cycle. No other bridge deck repairs are required. The carbon strand anode system must be replaced every 20 years. Annual costs for the bridge deck without cathodic protection total $0.338 psf while annual costs for the bridge deck with cathodic protection total #0.127 psf. Similar cost schedules are presented for existing bridge decks in Figures 41 through 43. To provide a common basis for comparison, the 10-year old bridge is repaired at the beginning of the life cycle (Figure 41). The bridge without cathodic protection is repaired every 20 years, with replacement every 40 years from its original construction. Cathodic protection systems installed at the time of repair avoid later deck repair and replacement costs, but the cathodic protection systems must be replaced according to their individual service life. Annual costs are the same as previously described. Similar cost schedules are developed for 20 and 30 year old bridges (Figures 42 and 43 respectively). Salvage values are determined using straight line depreciation for cost elements with service life remaining at the end of the 80 year life cycle. Results from the cost analysis are summarized in Table 11. Cathodic protection of new construction appears to be marginally cost effective for the least expensive anode system (conductive polymer anode) at 6.0 percent interest. For higher interest rates, the new construction without cathodic protection is more cost effective in each case. For existing bridges, repair without cathodic protection is more cost effective for all cases. However, because of the uncertainties in choosing costs for this analysis, no clear choice can be made regarding the economics of cathodic protection of bridge decks in circumstances similar to the U.S. 87 overpass in Big Spring.

Although the results from the study indicate cathodic protection is not as cost effective as new construction or repair of existing bridge decks without cathodic protection, other factors should be considered. Costs for construction or replacement of the bridge deck in Big Spring are estimated at approximately $35 to $40 psf, ($377 to $430 psm) for a "turnkey" job. Similar construction at other locations could have much greater costs for traffic diverting or construction mobilization. Also, maintenance costs for the unprotected bridge deck were averaged from approximate 10-year costs for a bridge with moderate traffic. Higher maintenance costs are expected for bridges with heavy traffic loads. Furthermore, there is a paucity of information on maintenance costs of bridge decks with cathodic protection systems. Monitoring systems over longer periods of time is needed to establish long-term maintenance costs. Long-term monitoring is also required to determine if cathodic protection actually doubles the life of a bridge deck.

New Bridge without Cathodic Protection

	20 years	40 years	60 years	80 years

Repair
($0.56 psf)

New Bridge
($40 psf)

New Bridge
($40 psf)

Repair
($0.56 psf)

Annual Costs:
Periodic Inspection
Maintenance
Total = $0.2538 psf

Titanium Mesh Anode

	40 years	80 years

New Bridge ($40 psf)

Cathodic Protection System
($6.95 psf)

Cathodic Protection System
($6.95 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Conductive Polymer Anode

	40 years	80 years

New Bridge ($40 psf)

Cathodic Protection System
($5.91 psf)

Cathodic Protection System
($5.91 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Carbon Strand Anode

	20 years	40 years	60 years	80 years

New Bridge
($40 psf)

Cathodic Protection System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

$1 per square foot = $10.76 per square meter

Figure 40. Cost Schedule for New Bridge Construction with and Without Cathodic Protection

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Depreciated Value = $10 psf

Salvage Value = $10 psf

Repair Existing Bridge without Cathodic Protection

| | 10 years | | 30 years | | 50 years | | 70 years | 80 years |

Repair
($0.56 psf)

New Bridge ($40 psf)

Repair
($0.56 psf)

New Bridge ($40 psf)

Repair
($0.56 psf)

Annual Costs:
Periodic Inspection
Maintenance
Total = $0.2538 psf

Titanium Mesh Anode

| | 10 years | | | 80 years |

Repair
($0.56 psf)
Cathodic
Protection
System
($6.95 psf)

New Bridge ($40 psf)

Cathodic Protection System
$6.95 psf

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Conductive Polymer Anode

| | 10 years | | 40 years | | 80 years |

Repair
($0.56 psf)
Cathodic
Protection
System
($5.91 psf)

New Bridge ($40 psf)

Cathodic Protection System
$5.91 psf

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Carbon Strand Anode

| | 10 years | 20 years | | 40 years | | 60 years | 80 years |

Repair
($0.56 psf)
Cathodic
Protection
System
($7.17 psf)

New Bridge
($40 psf)

Cathodic
Protection
System
($7.17 psf)

Cathodic Protection System
$7.17 psf

Cathodic Protection System
$7.17 psf

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

$1 per square foot = $10.76 per square meter

Figure 41. Cost Schedule for Repairing 30 Year Old Bridge with and Without Cathodic Protection

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Depreciated Value = $20 psf

Salvage Value = $20 psf

Repair Existing Bridge without Cathodic Protection

20 years 40 years 60 years 80 years

Repair
($0.56 psf)

New Bridge ($40 psf)

Repair
($0.56 psf)

New Bridge ($40 psf)

Annual Costs:
Periodic Inspection
Maintenance
Total = $0.2538 psf

Titanium Mesh Anode

20 years 60 years 80 years

Repair
($0.56 psf)
Cathodic
Protection
System
($6.95 psf)

New Bridge
($40 psf)
Cathodic Protection System
($6.95 psf)

Cathodic Protection System
($6.95 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Conductive Polymer Anode

20 years 60 years 80 years

Repair
($0.56 psf)
Cathodic
Protection
System
($5.91 psf)

New Bridge
($40 psf)
Cathodic Protection System
($5.91 psf)

Cathodic Protection System
($5.91 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Carbon Strand Anode

20 years 40 years 60 years 80 years

Repair
($0.56 psf)
Cathodic
Protection
System
($7.17 psf)

New Bridge
($40 psf)
Cathodic Protection System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

$1 per square foot = $10.76 per square meter

Figure 42. Cost Schedule for Repairing 20 Year Old Bridge With and Without Cathodic Protection

Depreciated Value = $10 psf   Salvage Value = $10 psf

Repair Existing Bridge without Cathodic Protection

| 10 years | 30 years | 50 years | 70 years | 80 years |

Repair
($0.56 psf)

New Bridge ($40 psf)

Repair
($0.56 psf)

New Bridge ($40 psf)

Repair
($0.56 psf)

Annual Costs:
Periodic Inspection
Maintenance
Total = $0.2538 psf

Titanium Mesh Anode

| 10 years | 50 years | 80 years |

Repair
($0.56 psf)
Cathodic
Protection
System
($6.95 psf)

New Bridge ($40 psf)
Cathodic
Protection
System
($6.95 psf)

Cathodic Protection System
($6.95 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Conductive Polymer Anode

| 10 years | 50 years | 80 years |

Repair
($0.56 psf)
Cathodic
Protection
System
($5.91 psf)

New Bridge ($40 psf)
Cathodic
Protection
System
($5.91 psf)

Cathodic Protection System
($5.91 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

Carbon Strand Anode

| 10 years | 30 years | 50 years | 70 years | 80 years |

Repair
($0.56 psf)
Cathodic
Protection
System
($7.17 psf)

New Bridge
($40 psf)
Cathodic
Protection
System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Cathodic Protection System
($7.17 psf)

Annual Costs:
Periodic Inspection
Maintenance
Power
Monitoring
Telephone
Total = $0.0327 psf

$1 per square foot = $10.76 per square meter

Figure 43. Cost Schedule for Repairing 30 Year Old Bridge With and Without Cathodic Protection

TABLE 11. Present Values for Bridge Deck Alternatives

Alternative	Interest Rate		
New Construction	6.00%	7.50%	10.00%
Without Cathodic Protection	48.27	45.73	43.51
Titanium Mesh Anode	48.17	47.77	47.43
Conductive Polymer Anode	47.02	46.67	46.37
Carbon Strand Anode	50.86	49.78	48.74
10 Year Old Bridge			
Without Cathodic Protection	42.31	38.81	35.51
Titanium Mesh Anode	46.06	43.26	40.52
Conductive Polymer Anode	44.82	42.09	39.42
Carbon Strand Anode	48.95	45.39	41.88
20 Year Old Bridge			
Without Cathodic Protection	38.30	33.84	29.18
Titanium Mesh Anode	42.71	39.03	34.83
Conductive Polymer Anode	41.31	37.73	33.63
Carbon Strand Anode	43.70	39.70	35.24
30 Year Old Bridge			
Without Cathodic Protection	39.27	34.45	28.89
Titanium Mesh Anode	44.55	40.88	35.99
Conductive Polymer Anode	42.87	39.31	34.54
Carbon Strand Anode	46.27	42.08	36.72

8. CONCLUSIONS

The performance of five cathodic protection systems installed on the U.S. 87 Missouri Pacific Railroad overpass structure was evaluated. Present values of bridge decks with and without cathodic protection were compared for new construction and repair of existing structures. The following conclusions resulted from the study:

1. Cathodic protection has successfully prevented corrosion in a variety of applications for many years. It was first used to protect reinforced concrete bridge decks more than 30 years ago and is now a mature technology.

2. Cathodic protection is recognized by FHWA as the only rehabilitation technique that has proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of the concrete.

3. Several varieties of anode systems are available to distribute the protective current to the reinforced concrete. Three primary anode systems were tested on the Big Spring bridge deck, and two conductive coatings were

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tested on other structural elements.

4. The performance of the rectifier system has been satisfactory, with one exception. The written procedure to measure instant off voltages involves pulling the control card for each rectifier circuit. This has resulted in apparent wear on the connectors to the card. This has resulted in intermittent operation of some rectifier circuits. Great care has to be exercised when reinserting the card to be sure a good connection is obtained.

5. The Elgard 150 titanium mesh anode provided stable operation and protection to the bridge deck. Its operation on the Big Spring bridge is consistent with the findings of other investigators. Titanium mesh anodes are reported to have service lives of 35 to 40 years.

6. The Raychem Ferex 100 conductive polymer anode performance began to deteriorate after one year of operation as noted by the decrease in conductance (Figure 18). It completely failed after two years of operation. Other researchers reported performance fluctuations in similar systems, but the duration of the study was less than 2 years.

7. The Rescon Rigid Conductive Polymer Concrete, Carbon Strand anode has exhibited recent fluctuations in performance. Once circuit (#9) of the Rescon Rigid Conductive Polymer Concrete, Carbon Strand anode has remained in stable operation. The other circuit (#10) essentially failed in late 1993, as noted by applying the maximum available voltage while current declined. Other researchers report similar findings but noted some discoloration of concrete near the anode which was attributed to acid formation and attack.

8. Hot sprayed zinc anode systems were applied to sidewalks and medians. The anode systems failed in less than 1 year. However, other researchers report success in using the sprayed zinc anode systems and it is possible the failures on the Big Spring bridge are due to the condition of the sidewalk and median before anode installation. In other research, a titanium mesh anode system was installed on a sidewalk and suffered the same sort of failure observed on the Big Spring bridge.

9. The Porter DAC-85 Conductive Paint anode system has failed and the conductive paint is peeling and flaking extensively.

10. Cathodic protection was not found to be universally cost effective for the new construction and repair of existing bridge alternatives considered for the Big Spring bridge scenario. The least expensive anode system (conductive polymer) was marginally cost effective for new construction,

but no systems were cost effective when considering the repair of existing bridges. However, the cost effectiveness study required a number of unsubstantiated assumptions and costs in the Big Spring area could vary considerably from costs at other locations. Costs of traffic control in major metropolitan areas could be much greater. Furthermore, the light salting required in Big Spring does not lead to the major bridge deck deteriorations experienced in other locations.

11.   Remote monitoring of cathodic protection systems is a convenient method of data collection. However, the Big Spring bridge is close in proximity to the protected bridge and labor costs were no more than the monthly telephone bill for the remote monitoring system.

9. RECOMMENDATIONS

Several recommendations are proposed based upon the evaluation of the five cathodic protection systems installed on the U.S. 87 Missouri Railroad overpass.

1.   Based on data gathered for the U.S. 87 overpass in Big spring, only the titanium mesh anode can be recommended for future installations. Manufacturers of the other anode systems should be contacted concerning possible reasons for failures of their respective systems.

2.   Based on an economic analysis of the U.S. 87 overpass circumstances, use of cathodic protection can not be strongly recommended for future similar applications.

3.   It is recommended that monitoring of the U.S. 87 overpass bridge continue indefinitely. Continued monitoring will permit long-term data to be gathered on the reliability of the four titanium mesh circuits and the one remaining carbon anode circuit.

APPENDIX A:

List of References

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LIST OF REFERENCES

1. ACI Manual of Concrete Practice 1992, Part 1, Materials and General Properties of Concrete.

2. Ali, Mohammed Galam, and Rasheeduzzafar, "Cathodic Protection Current Accelerates Alkali-Silika Reaction", ACF Materials Journal, pp 247-252, May-June 1993.

3. Berndt, Christopher C. and Herman, Herbert, "Thermal Spraying, Major Advances Noted in Thermal Spray Technology", pp 23-25, Advanced Materials and Processes, January 1993.

4. Cathodic Protection of Reinforced Concrete Bridge Elements: A State-of-the-Art Report, Strategic Highway Research Program, SHRP-S-337, ELTECH Research Corporation, 1993.

5. Clear, K.C., "Time to Corrosion of Reinforcing Steel in Concrete Slabs", Transportation Research Record 500, Transportation Research Board, National Research Council, Washington, D.C., 1974.

6. Clemena, Gerardo G., and Jackson, Donald R., "Cathodic Protection of the Concrete Piers of Two Bridges in Virginia Using a Water-Based Conductive Coating", Transportation Research Board Record 1304, 1990.

7. Flis, Janusz, Sehgal, Akshey, et.al., "Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 2: Method for Measuring the Corrosion Rate of Reinforcing Steel", Strategic Highway Research Program, National Research Council, Washington, D.C., 1992.

8. Grant, Eugene L., Ireson, W. Grant, et. al., "Principles of Engineering Economy", John Wiley and Sons, Inc., New York, 1982.

9. Highlands, Keith R., "Cathodic Protection for Reinforced Concrete Bridge Decks", Research Projects 75-15, 80-12, and 82-14, Final Report, Commonwealth of Pennsylvania Department of Transportation, November, 1991.

10. Jackson, Donald R., "Cathodic Protection for Reinforced Concrete Bridge Decks", Interim Report, Demonstration Project No. 34, Report No. FHWA-DP-34-2, October, 1982.

11. Morgan, Joh H., "Cathodic Protection, Its Theory and Practice in Preventing Corrosion", Leonard Hill Books Limited, London, 1959.

12. Nagataki, Shigeyoshi, Otsuhi, Nobuaki, et.al., "Condensation of Chloride Ion in Hardened Cement Matrix Materials on Embedded Steel Bars", ACI Materials Journal, pp 323-332, July-August 1993.

13. 1991 Report to Congress, Federal Highway Administration, June, 1991.

14. Parker, Harry W., Feingold, Robert W., Nash, Phillip T., "Initial Analysis of Cathodic Protection Systems on US 87 Railroad Overpass Bridge, Big Spring, Texas", Research Report 500-2, sponsored by Texas Department of Transportation in cooperation with U.S. Department of Transportation, Federal Highway Administration, Lubbock, TX, May, 1992.

15. Perenchio, W.F., Landgren, J.R., and West, R.E., "Cathodic Protection of Concrete Bridge Substructures", National Cooperative Highway Research Program Report 278, October, 1985.

16. Schell, Hannah G. and Manning, David G., "Research Direction in Cathodic Protection for Highway Bridges", materials Processing, pp 11-15, October, 1989.

17. Schiessel, Peter and Raupach, Michael, "Monitoring Systems for teh Corrosion Risk of Steel in Concrete Structures", Concrete International, Volume 14, Number 7, pp 52-55, July, 1992.

18. Silano, Louis C., (Editor), and Henderson, Arnold G., (Associate Editor), "Bridge Inspection and Rehabilitation", John Wiley and Sons, Inc., New York, 1993.

19. Smith, Linda, "Cathodic Bridge Deck Protection", Report No. TX/91-500/554-1, Texas Department of Transportation, Austin, Texas, August, 1990.

20. Smith, William F., "Foundations of Materials Science and Engineering", McGraw-Hill, Inc., New York, 1993.

21. Stratfull, R.F., "The Corrosion of Steel in a Reinforced Concrete Bridge", Corrosion, 13, pp 173-178, 1957.

22. Stratfull, R.F., "Corrosion Testing of Bridge Decks", Transportation Research Board, Transportation Research Record No. 539, pp 50-59, 1975.

23. Stratfull, R.F., "Criteria for the Cathodic Protection of Bridge Decks", Chapter 18 in *Corrosion of Reinforcement in Concrete Construction*, Society of Chemical Engineers, Chichester, West Sussex, England, 1983.

24. Swiat, Wayne J. and Bushman, James B., "Further Improvements in Cathodic Protection", Federal Highway Administration Report No. FHWA-RD-88-267, August, 1987.

25. Texas Bridge Design Guide

26. Tilly, G.P., "Performance and Serviceability of Concrete Bridges", Bridge Evaluation Repair and Rehabilitation, the University of Michigan, 1987.

27. Tonini, D.E. and Dean, S.W., editors, "Chloride Corrosion of Steel in Concrete", a Symposium presented at the Seventy-ninth Annual Meeting, American Society for Testing and Materials, Chicago, IL, 27 June - 2 July, 1976.

28. Uhlig, Herbert H., "Corrosion and Corrosion Control", John Wiley and Sons, New York, 1985.

29. Van Vlack, Lawrence H., "Elements of Material Science", Addison-Wesley Publishing Compnay, Reading, MA, April, 1967.

30. Vrable, John B., "Cathodic Protection for reinforced Concrete Bridge Decks: Laboratory Phase", National Cooperative Highway Research Program Report 180, 1977.

31. Whiting, D. and Stark, D., "Galvanic Cathodic Protection for Reinforced Concrete Bridge Decks, Field Evaluation", National Cooperative Highway Research Program Report 234, June, 1981.

APPENDIX B:

Data Listing

Date:	10/28/88	10/28/88	12/13/88	12/15/88
Days since last reading:	0	0	46	2
Days since start-up (10/28/88):	0	0	46	48
Tester:	Corrpro	Corrpro	Corrpro	Corrpro

 # 1: TITANIUM MESH

Rebar Probe (volts)	-0.01380	-0.00200	0.006	0.010
Reference Cell (volts)	0.360	0.449	0.541	0.501
Anode Voltage	0.57	4.98	5.6	5.2
Anode Current (amps)	0.00	4.50	4.62	4.50
Ref. Cell Instant-off (volts)		0.401	0.511	0.450
Conductance (mhos)		0.904	0.825	0.865
Voltage drop in ref. circuit		0.048	0.030	0.051

 # 2: TITANIUM MESH

Rebar Probe (volts)	-0.00670	0.00200	0.006	0.007
Reference Cell (volts)	0.304	0.588	0.711	0.640
Anode Voltage	0.45	4.71	5.3	4.6
Anode Current (amps)	0.00	4.00	4.11	3.48
Ref. Cell Instant-off (volts)		0.416	0.566	0.489
Conductance (mhos)		0.849	0.775	0.757
Voltage drop in ref. circuit		0.172	0.145	0.151

 # 3: TITANIUM MESH

Rebar Probe (volts)	-0.00290	0.00200	0.006	0.004
Reference Cell (volts)	0.266	0.427	0.668	0.596
Anode Voltage	0.46	4.68	5.9	5.1
Anode Current (amps)	0.00	3.50	3.62	3.19
Ref. Cell Instant-off (volts)		0.360	0.532	0.461
Conductance (mhos)		0.748	0.614	0.625
Voltage drop in ref. circuit		0.067	0.136	0.135

 # 4: TITANIUM MESH

Rebar Probe (volts)	-0.00200	0.00200	0.005	0.005
Reference Cell (volts)	0.352	0.460	0.546	0.510
Anode Voltage	0.45	4.83	5.7	5.2
Anode Current (amps)	0.00	4.50	4.62	4.50
Ref. Cell Instant-off (volts)		0.410	0.514	0.456
Conductance (mhos)		0.932	0.811	0.865
Voltage drop in ref. circuit		0.050	0.032	0.054

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	-0.006	0.001	0.006	0.007
Reference Cell (volts)	0.321	0.481	0.617	0.562
Anode Voltage	0.5	4.8	5.6	5.0
Anode Current (amps)	0.00	4.13	4.24	3.92
Ref. Cell Instant-off (volts)		0.397	0.531	0.464
Conductance (mhos)		0.858	0.756	0.778
Voltage drop in ref. circuit		0.084	0.086	0.098

Date:	1/31/89	2/1/89	2/2/89	3/13/89
Days since last reading:	47	1	1	39
Days since start-up (10/28/88):	95	96	97	136
Tester:	Corrpro	Corrpro	Corrpro	MC,DR,DE

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.005	0.002	0.004	0.006
Reference Cell (volts)	0.508	0.404	0.479	0.461
Anode Voltage	5.4	5.4	5.5	5.6
Anode Current (amps)	4.44	4.80	4.85	4.93
Ref. Cell Instant-off (volts)	0.440	0.371	0.418	
Conductance (mhos)	0.822	0.889	0.882	0.880
Voltage drop in ref. circuit	0.068	0.033	0.061	

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.004	0.005	0.004	0.005
Reference Cell (volts)	0.616	0.508	0.574	0.543
Anode Voltage	4.8	4.6	4.7	4.8
Anode Current (amps)	3.44	3.55	3.56	3.64
Ref. Cell Instant-off (volts)	0.465	0.395	0.449	
Conductance (mhos)	0.717	0.772	0.757	0.758
Voltage drop in ref. circuit	0.151	0.113	0.125	

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.002	0.005	0.005	0.005
Reference Cell (volts)	0.557	0.441	0.501	0.466
Anode Voltage	5.4	4.8	5.1	5.2
Anode Current (amps)	3.15	3.26	3.28	3.35
Ref. Cell Instant-off (volts)	0.425	0.380	0.392	
Conductance (mhos)	0.583	0.679	0.643	0.644
Voltage drop in ref. circuit	0.132	0.061	0.109	

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.004	0.005	0.004	0.006
Reference Cell (volts)	0.505	0.428	0.485	0.466
Anode Voltage	5.5	5.3	5.5	5.7
Anode Current (amps)	4.44	4.81	4.86	4.97
Ref. Cell Instant-off (volts)	0.443	0.389	0.433	
Conductance (mhos)	0.807	0.908	0.884	0.872
Voltage drop in ref. circuit	0.062	0.039	0.052	

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.004	0.004	0.004	0.006
Reference Cell (volts)	0.547	0.445	0.510	0.484
Anode Voltage	5.3	5.0	5.2	5.3
Anode Current (amps)	3.87	4.11	4.14	4.22
Ref. Cell Instant-off (volts)	0.443	0.384	0.423	
Conductance (mhos)	0.732	0.812	0.792	0.789
Voltage drop in ref. circuit	0.103	0.061	0.087	

Date:	4/13/89	5/26/89	6/13/89	7/17/89
Days since last reading:	31	43	18	34
Days since start-up (10/28/88):	167	210	228	262
Tester:	DR,DE,TD	DR	JM,DR	DR,KC

 # 1: TITANIUM MESH

	4/13/89	5/26/89	6/13/89	7/17/89
Rebar Probe (volts)	0.006	0.006	0.006	0.009
Reference Cell (volts)	0.532	0.371	0.442	0.416
Anode Voltage	5.8	5.3	5.6	5.6
Anode Current (amps)	4.95	4.85	4.87	4.78
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.853	0.915	0.870	0.854
Voltage drop in ref. circuit				

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.005	0.006	0.006	0.008
Reference Cell (volts)	0.632	0.438	0.523	0.486
Anode Voltage	5.0	4.5	4.8	4.8
Anode Current (amps)	3.65	3.57	3.59	3.49
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.730	0.793	0.748	0.727
Voltage drop in ref. circuit				

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.004	0.006	0.005	0.009
Reference Cell (volts)	0.525	0.364	0.411	0.388
Anode Voltage	5.6	4.6	5.3	5.1
Anode Current (amps)	3.36	3.29	3.33	3.29
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.600	0.715	0.628	0.645
Voltage drop in ref. circuit				

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.005	0.007	0.005	0.008
Reference Cell (volts)	0.508	0.395	0.426	0.406
Anode Voltage	6.0	5.3	5.7	5.6
Anode Current (amps)	4.99	4.90	4.92	4.81
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.832	0.925	0.863	0.859
Voltage drop in ref. circuit				

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.005	0.006	0.006	0.009
Reference Cell (volts)	0.549	0.392	0.451	0.424
Anode Voltage	5.6	4.9	5.4	5.3
Anode Current (amps)	4.24	4.15	4.18	4.09
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.754	0.837	0.777	0.771
Voltage drop in ref. circuit				

Date:	8/18/89	9/19/89	10/31/89	11/28/89
Days since last reading:	32	32	42	28
Days since start-up (10/28/88):	294	326	368	396
Tester:	DR	DR	DR	DR

1: TITANIUM MESH

Rebar Probe (volts)	0.009	0.006	0.005	0.005
Reference Cell (volts)	0.403	0.505	0.525	0.744
Anode Voltage	5.6	5.9	5.9	6.3
Anode Current (amps)	4.80	4.83	4.85	4.99
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.857	0.819	0.822	0.792
Voltage drop in ref. circuit				

2: TITANIUM MESH

Rebar Probe (volts)	0.009	0.005	0.006	0.004
Reference Cell (volts)	0.498	0.605	0.718	0.984
Anode Voltage	4.8	5.1	5.2	5.7
Anode Current (amps)	3.50	3.54	3.56	3.68
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.729	0.694	0.685	0.646
Voltage drop in ref. circuit				

3: TITANIUM MESH

Rebar Probe (volts)	0.008	0.005	0.005	0.004
Reference Cell (volts)	0.375	0.423	0.456	0.599
Anode Voltage	4.9	5.8	5.8	7.1
Anode Current (amps)	3.25	3.27	3.30	3.41
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.663	0.564	0.569	0.480
Voltage drop in ref. circuit				

4: TITANIUM MESH

Rebar Probe (volts)	0.008	0.005	0.004	0.004
Reference Cell (volts)	0.393	0.428	0.445	0.546
Anode Voltage	5.5	6.0	6.0	6.8
Anode Current (amps)	4.81	4.85	4.89	5.04
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.875	0.808	0.815	0.741
Voltage drop in ref. circuit				

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.009	0.005	0.005	0.004
Reference Cell (volts)	0.417	0.490	0.536	0.718
Anode Voltage	5.2	5.7	5.7	6.5
Anode Current (amps)	4.09	4.12	4.15	4.28
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.781	0.721	0.723	0.665
Voltage drop in ref. circuit				

Date:	1/9/90	1/17/90	4/26/90	11/19/90
Days since last reading:	12	8	99	207
Days since start-up (10/28/88):	408	416	515	722
Tester:	DR,DE	DR	DE,TD	JM,DE

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.005	0.006	0.005	0.004
Reference Cell (volts)	0.542	0.551	0.612	0.087
Anode Voltage	5.9	5.8	6.1	6.0
Anode Current (amps)	4.90	4.87	4.86	4.83
Ref. Cell Instant-off (volts)	0.354		0.377	0.159
Conductance (mhos)	0.831	0.840	0.797	0.805
Voltage drop in ref. circuit	0.188		0.235	-0.072

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.005	0.006	0.005	0.004
Reference Cell (volts)	0.722	0.725	0.777	0.822
Anode Voltage	5.2	5.1	5.3	5.3
Anode Current (amps)	3.62	3.59	3.57	3.52
Ref. Cell Instant-off (volts)	0.382		0.411	0.272
Conductance (mhos)	0.696	0.704	0.674	0.664
Voltage drop in ref. circuit	0.340		0.366	0.550

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.004	0.005	0.005	0.004
Reference Cell (volts)	0.489	0.483	0.453	0.433
Anode Voltage	5.7	5.6	6.0	5.6
Anode Current (amps)	3.35	3.32	3.32	3.28
Ref. Cell Instant-off (volts)	0.351		0.327	0.277
Conductance (mhos)	0.588	0.593	0.553	0.586
Voltage drop in ref. circuit	0.138		0.126	0.156

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.004	0.005	0.004	0.004
Reference Cell (volts)	0.491	0.480	0.446	0.495
Anode Voltage	6.0	5.9	6.2	6.1
Anode Current (amps)	4.97	4.93	3.93	4.66
Ref. Cell Instant-off (volts)	0.383		0.340	0.276
Conductance (mhos)	0.828	0.836	0.634	0.764
Voltage drop in ref. circuit	0.108		0.106	0.219

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.005	0.006	0.005	0.004
Reference Cell (volts)	0.561	0.560	0.572	0.459
Anode Voltage	5.7	5.6	5.9	5.8
Anode Current (amps)	4.21	4.18	3.92	4.07
Ref. Cell Instant-off (volts)	0.368		0.364	0.246
Conductance (mhos)	0.736	0.743	0.664	0.705
Voltage drop in ref. circuit	0.194		0.208	0.213

Date:	3/28/91	5/15/91	7/31/91	8/16/91
Days since last reading:	129	48	77	16
Days since start-up (10/28/88):	851	899	976	992
Tester:	DE,KC	DE	DE	JM,DE

1: TITANIUM MESH

Rebar Probe (volts)	0.004	0.005	0.005	0.005
Reference Cell (volts)	0.075	0.067	0.047	0.036
Anode Voltage	6.3	6.0	5.5	5.2
Anode Current (amps)	4.86	4.80	4.84	4.82
Ref. Cell Instant-off (volts)	0.128	0.118	0.078	0.076
Conductance (mhos)	0.771	0.800	0.880	0.927
Voltage drop in ref. circuit	-0.053	-0.051	-0.031	-0.040

2: TITANIUM MESH

Rebar Probe (volts)	0.006	0.005	0.005	0.006
Reference Cell (volts)	0.986	0.893	0.768	0.595
Anode Voltage	5.6	5.2	4.8	4.3
Anode Current (amps)	3.56	3.51	3.56	3.53
Ref. Cell Instant-off (volts)	0.350	0.305	0.293	0.266
Conductance (mhos)	0.636	0.675	0.742	0.821
Voltage drop in ref. circuit	0.636	0.588	0.475	0.329

3: TITANIUM MESH

Rebar Probe (volts)	0.005	0.006	0.006	0.007
Reference Cell (volts)	0.470	0.436	0.396	0.383
Anode Voltage	6.0	5.6	5.0	4.4
Anode Current (amps)	3.33	3.26	3.30	3.27
Ref. Cell Instant-off (volts)	0.344	0.319	0.302	0.286
Conductance (mhos)	0.555	0.582	0.660	0.743
Voltage drop in ref. circuit	0.126	0.117	0.094	0.097

4: TITANIUM MESH

Rebar Probe (volts)	0.004	0.005	0.005	0.006
Reference Cell (volts)	0.497	0.445	0.394	0.367
Anode Voltage	6.4	6.0	5.5	5.0
Anode Current (amps)	4.95	4.83	4.90	4.87
Ref. Cell Instant-off (volts)	0.338	0.297	0.290	0.287
Conductance (mhos)	0.773	0.805	0.891	0.974
Voltage drop in ref. circuit	0.159	0.148	0.104	0.080

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.005	0.005	0.005	0.006
Reference Cell (volts)	0.507	0.460	0.401	0.345
Anode Voltage	6.1	5.7	5.2	4.7
Anode Current (amps)	4.18	4.10	4.15	4.12
Ref. Cell Instant-off (volts)	0.290	0.260	0.241	0.229
Conductance (mhos)	0.684	0.716	0.793	0.866
Voltage drop in ref. circuit	0.217	0.201	0.161	0.117

Date:	9/10/91	10/9/91	1/7/92	3/19/92
Days since last reading:	25	29	90	72
Days since start-up (10/28/88):	1,017	1,046	1,136	1,208
Tester:	DE	DE	DE	DE

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.005	0.005	0.002	0.002
Reference Cell (volts)	0.027	0.025	0.018	0.019
Anode Voltage	5.3	5.4	5.9	6.2
Anode Current (amps)	4.80	4.81	4.85	4.89
Ref. Cell Instant-off (volts)	0.013	0.010	0.008	0.007
Conductance (mhos)	0.906	0.891	0.822	0.789
Voltage drop in ref. circuit	0.014	0.015	0.010	0.012

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.006	0.005	0.002	0.003
Reference Cell (volts)	0.654	0.732	0.975	1.309
Anode Voltage	4.5	4.6	5.1	5.6
Anode Current (amps)	3.53	3.51	3.56	3.60
Ref. Cell Instant-off (volts)	0.263	0.268	0.295	0.390
Conductance (mhos)	0.784	0.763	0.698	0.643
Voltage drop in ref. circuit	0.391	0.464	0.680	0.919

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.006	0.006	0.003	0.003
Reference Cell (volts)	0.394	0.433	0.489	0.559
Anode Voltage	4.6	4.8	5.5	6.0
Anode Current (amps)	3.26	3.26	3.30	3.33
Ref. Cell Instant-off (volts)	0.282	0.300	0.329	0.354
Conductance (mhos)	0.709	0.679	0.600	0.555
Voltage drop in ref. circuit	0.112	0.133	0.160	0.205

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.005	0.005	0.003	0.003
Reference Cell (volts)	0.388	0.413	0.459	0.508
Anode Voltage	5.2	5.3	5.9	6.2
Anode Current (amps)	4.86	4.85	4.91	4.96
Ref. Cell Instant-off (volts)	0.285	0.309	0.342	0.346
Conductance (mhos)	0.935	0.915	0.832	0.800
Voltage drop in ref. circuit	0.103	0.104	0.117	0.162

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.006	0.005	0.003	0.003
Reference Cell (volts)	0.366	0.401	0.485	0.599
Anode Voltage	4.9	5.0	5.6	6.0
Anode Current (amps)	4.11	4.11	4.16	4.20
Ref. Cell Instant-off (volts)	0.211	0.222	0.244	0.274
Conductance (mhos)	0.833	0.812	0.738	0.697
Voltage drop in ref. circuit	0.155	0.179	0.242	0.325

Date:	4/17/92	5/15/92	6/11/92
Days since last reading:	29	28	27
Days since start-up (10/28/88):	1,237	1,265	1,292
Tester:	DE	DE	DE

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.002	0.004	0.005
Reference Cell (volts)	0.022	0.024	0.030
Anode Voltage	6.1	5.3	5.3
Anode Current (amps)	4.84	4.82	4.82
Ref. Cell Instant-off (volts)	0.190	0.010	0.012
Conductance (mhos)	0.793	0.909	0.909
Voltage drop in ref. circuit	-0.168	0.014	0.018

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.003	0.005	0.005
Reference Cell (volts)	1.149	0.586	0.622
Anode Voltage	5.4	4.5	4.5
Anode Current (amps)	3.56	3.55	3.53
Ref. Cell Instant-off (volts)	0.347	0.226	0.237
Conductance (mhos)	0.659	0.789	0.784
Voltage drop in ref. circuit	0.802	0.360	0.385

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.004	0.006	0.007
Reference Cell (volts)	0.507	0.404	0.414
Anode Voltage	5.8	4.6	4.6
Anode Current (amps)	3.30	3.29	3.29
Ref. Cell Instant-off (volts)	0.321	0.276	0.274
Conductance (mhos)	0.569	0.715	0.715
Voltage drop in ref. circuit	0.186	0.128	0.140

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.003	0.005	0.006
Reference Cell (volts)	0.472	0.367	0.382
Anode Voltage	6.0	5.1	5.1
Anode Current (amps)	4.91	4.91	4.89
Ref. Cell Instant-off (volts)	0.327	0.283	0.290
Conductance (mhos)	0.818	0.963	0.959
Voltage drop in ref. circuit	0.145	0.084	0.092

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.003	0.005	0.006
Reference Cell (volts)	0.538	0.345	0.362
Anode Voltage	5.8	4.9	4.9
Anode Current (amps)	4.15	4.14	4.13
Ref. Cell Instant-off (volts)	0.296	0.199	0.203
Conductance (mhos)	0.710	0.844	0.842
Voltage drop in ref. circuit	0.241	0.147	0.159

Date:	7/9/92	8/7/92	8/25/92	9/22/92
Days since last reading:	28	29	18	28
Days since start-up (10/28/88):	1,320	1,349	1,367	1,395
Tester:	DE	HP,RF	DE	DE

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.003	0.005	0.004	0.002
Reference Cell (volts)	0.033	0.033	0.026	0.025
Anode Voltage	6.0	6.0	5.4	5.7
Anode Current (amps)	4.80	4.81	4.78	4.84
Ref. Cell Instant-off (volts)	0.012	0.014	0.010	0.010
Conductance (mhos)	0.800	0.802	0.885	0.849
Voltage drop in ref. circuit	0.021	0.019	0.016	0.015

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.004	0.004	0.004	0.003
Reference Cell (volts)	0.989	1.000	0.716	0.833
Anode Voltage	5.3	5.3	4.8	5.0
Anode Current (amps)	3.52	3.53	3.56	3.56
Ref. Cell Instant-off (volts)	0.287	0.250	0.225	0.246
Conductance (mhos)	0.664	0.666	0.742	0.712
Voltage drop in ref. circuit	0.702	0.750	0.491	0.587

 # 3: TITANIUM MESH

				0.298
Rebar Probe (volts)	0.004	0.004	0.005	0.004
Reference Cell (volts)	0.463	0.471	0.424	0.482
Anode Voltage	5.6	5.5	4.9	5.2
Anode Current (amps)	3.27	3.27	3.30	3.31
Ref. Cell Instant-off (volts)	0.285	0.270	0.262	0.284
Conductance (mhos)	0.584	0.595	0.673	0.637
Voltage drop in ref. circuit	0.178	0.201	0.162	0.198

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.004	0.004	0.005	0.003
Reference Cell (volts)	0.411	0.431	0.395	0.423
Anode Voltage	6.0	5.9	5.4	5.7
Anode Current (amps)	4.86	4.86	4.85	4.91
Ref. Cell Instant-off (volts)	0.291	0.287	0.283	
Conductance (mhos)	0.810	0.824	0.898	0.861
Voltage drop in ref. circuit	0.120	0.144	0.112	0.125

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.004	0.004	0.005	0.003
Reference Cell (volts)	0.474	0.484	0.390	0.441
Anode Voltage	5.7	5.7	5.1	5.4
Anode Current (amps)	4.11	4.12	4.12	4.16
Ref. Cell Instant-off (volts)	0.219	0.205	0.195	0.210
Conductance (mhos)	0.715	0.721	0.800	0.765
Voltage drop in ref. circuit	0.255	0.279	0.195	0.231

Date:	1/8/93	2/12/93	2/26/93	2/26/93
Days since last reading:	108	35	14	0.50
Days since start-up (10/28/88):	1,503	1,538	1,552	1,553
Tester:	DE	DE	RF	RF

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.003	0.001	0.001	0.001
Reference Cell (volts)	0.010	0.007	0.007	0.008
Anode Voltage	6.9	6.9	7.2	6.3
Anode Current (amps)	4.90	4.88	4.96	4.92
Ref. Cell Instant-off (volts)	0.004	0.003	0.003	0.003
Conductance (mhos)	0.710	0.707	0.689	0.781
Voltage drop in ref. circuit	0.006	0.004	0.004	0.005

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.003	0.001	0.001	0.001
Reference Cell (volts)	1.642	1.607	1.931	1.117
Anode Voltage	6.4	6.4	6.8	4.9
Anode Current (amps)	3.62	3.59	3.66	2.81
Ref. Cell Instant-off (volts)	0.456	0.472	0.566	0.348
Conductance (mhos)	0.566	0.561	0.538	0.573
Voltage drop in ref. circuit	1.186	1.135	1.365	0.769

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.003	0.002	0.002	0.002
Reference Cell (volts)	0.701	0.749	0.829	0.625
Anode Voltage	7.4	6.9	7.6	5.4
Anode Current (amps)	3.37	3.33	3.40	2.78
Ref. Cell Instant-off (volts)	0.330	0.331	0.339	0.319
Conductance (mhos)	0.455	0.483	0.447	0.515
Voltage drop in ref. circuit	0.371	0.418	0.490	0.306

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.003	0.002	0.002	0.002
Reference Cell (volts)	0.557	0.571	0.584	0.602
Anode Voltage	7.1	7.0	7.5	7.6
Anode Current (amps)	5.00	4.93	5.04	6.39
Ref. Cell Instant-off (volts)	0.379	0.385	0.381	0.396
Conductance (mhos)	0.704	0.704	0.672	0.841
Voltage drop in ref. circuit	0.178	0.186	0.203	0.206

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.003	0.002	0.002	0.002
Reference Cell (volts)	0.728	0.734	0.838	0.588
Anode Voltage	7.0	6.8	7.3	6.1
Anode Current (amps)	4.22	4.18	4.27	4.23
Ref. Cell Instant-off (volts)	0.292	0.298	0.322	0.267
Conductance (mhos)	0.609	0.614	0.587	0.678
Voltage drop in ref. circuit	0.435	0.436	0.516	0.322

Date:	3/5/93	3/18/93	4/27/93	5/28/93
Days since last reading:	7	13	40	31
Days since start-up (10/28/88):	1,560	1,573	1,613	1,644
Tester:	RF	HP,RF	DE,JS	DE,TM

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.001	0.001	0.002	0.004
Reference Cell (volts)	0.007	0.002	0.013	0.015
Anode Voltage	6.7	1.2	6.0	5.5
Anode Current (amps)	4.90	0.00	4.82	4.80
Ref. Cell Instant-off (volts)	0.003	0.002	0.005	0.005
Conductance (mhos)	0.731	0.000	0.803	0.873
Voltage drop in ref. circuit	0.004	0.000	0.008	0.010

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.001	0.002	0.003	0.004
Reference Cell (volts)	1.241	1.236	0.811	0.554
Anode Voltage	5.3	5.1	4.5	4.0
Anode Current (amps)	2.81	2.80	2.71	2.70
Ref. Cell Instant-off (volts)	0.340	0.350	0.258	0.197
Conductance (mhos)	0.530	0.549	0.602	0.675
Voltage drop in ref. circuit	0.901	0.886	0.553	0.357

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.002	0.002	0.004	0.005
Reference Cell (volts)	0.635	0.583	0.486	0.415
Anode Voltage	5.9	5.9	4.8	4.3
Anode Current (amps)	2.78	2.78	2.77	2.73
Ref. Cell Instant-off (volts)	0.303	0.284	0.275	0.240
Conductance (mhos)	0.471	0.471	0.577	0.635
Voltage drop in ref. circuit	0.332	0.299	0.211	0.175

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.002	0.002	0.003	0.004
Reference Cell (volts)	0.609	0.520	0.488	0.454
Anode Voltage	8.0	7.0	7.0	6.4
Anode Current (amps)	6.39	5.20	6.32	6.29
Ref. Cell Instant-off (volts)	0.396	0.359	0.352	0.333
Conductance (mhos)	0.799	0.743	0.903	0.983
Voltage drop in ref. circuit	0.213	0.161	0.136	0.121

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.002	0.002	0.003	0.004
Reference Cell (volts)	0.623	0.585	0.450	0.360
Anode Voltage	6.5	4.8	5.6	5.1
Anode Current (amps)	4.22	2.70	4.16	4.13
Ref. Cell Instant-off (volts)	0.261	0.249	0.223	0.194
Conductance (mhos)	0.633	0.441	0.721	0.791
Voltage drop in ref. circuit	0.363	0.337	0.227	0.166

Date:	6/30/93	8/31/93	10/7/93	11/2/93
Days since last reading:	33	62	37	26
Days since start-up (10/28/88):	1,677	1,739	1,776	1,802
Tester:	DE	DE	PN	PN

 # 1: TITANIUM MESH

Rebar Probe (volts)	0.005	0.004	0.005	
Reference Cell (volts)	0.019	0.015	0.019	0.050
Anode Voltage	5.9	6.3	5.9	6.8
Anode Current (amps)	4.80	4.80	4.80	7.38
Ref. Cell Instant-off (volts)	0.007	0.005	0.007	
Conductance (mhos)	0.814	0.762	0.814	1.082
Voltage drop in ref. circuit	0.012	0.010	0.012	0.050

 # 2: TITANIUM MESH

Rebar Probe (volts)	0.005	0.004	0.005	
Reference Cell (volts)	0.696	0.919	0.696	1.232
Anode Voltage	4.4	4.8	4.4	5.3
Anode Current (amps)	2.70	2.69	2.70	4.14
Ref. Cell Instant-off (volts)	0.211	0.250	0.211	
Conductance (mhos)	0.614	0.560	0.614	0.777
Voltage drop in ref. circuit	0.485	0.669	0.485	1.232

 # 3: TITANIUM MESH

Rebar Probe (volts)	0.006	0.005	0.006	
Reference Cell (volts)	0.468	0.599	0.468	0.698
Anode Voltage	4.8	5.1	4.8	5.9
Anode Current (amps)	2.73	2.71	2.73	4.11
Ref. Cell Instant-off (volts)	0.245	0.284	0.245	
Conductance (mhos)	0.569	0.531	0.569	0.692
Voltage drop in ref. circuit	0.223	0.315	0.223	0.698

 # 4: TITANIUM MESH

Rebar Probe (volts)	0.007	0.004	0.007	
Reference Cell (volts)	0.506	0.571	0.506	0.671
Anode Voltage	7.0	7.4	7.0	8.3
Anode Current (amps)	6.40	6.40	6.40	9.63
Ref. Cell Instant-off (volts)	0.360	0.356	0.360	
Conductance (mhos)	0.914	0.865	0.914	1.164
Voltage drop in ref. circuit	0.146	0.215	0.146	0.671

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)	0.006	0.004	0.006	
Reference Cell (volts)	0.422	0.526	0.422	0.663
Anode Voltage	5.5	5.9	5.5	6.6
Anode Current (amps)	4.16	4.15	4.16	6.32
Ref. Cell Instant-off (volts)	0.206	0.224	0.206	
Conductance (mhos)	0.728	0.680	0.728	0.929
Voltage drop in ref. circuit	0.217	0.302	0.217	0.663

Date:	11/24/93	12/22/93	12/23/93
Days since last reading:	22	28	1
Days since start-up (10/28/88):	1,824	1,852	1,853
Tester:	PN	PN	PN

 # 1: TITANIUM MESH

Rebar Probe (volts)			
Reference Cell (volts)	0.036	0.023	0.081
Anode Voltage	7.0	7.5	8.7
Anode Current (amps)	7.44	7.41	6.33
Ref. Cell Instant-off (volts)			
Conductance (mhos)	1.064	0.988	0.732
Voltage drop in ref. circuit	0.036	0.023	0.081

 # 2: TITANIUM MESH

Rebar Probe (volts)			
Reference Cell (volts)	1.366	1.782	2.107
Anode Voltage	5.5	6.2	7.4
Anode Current (amps)	4.20	4.17	3.42
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.764	0.675	0.465
Voltage drop in ref. circuit	1.366	1.782	2.107

 # 3: TITANIUM MESH

Rebar Probe (volts)			
Reference Cell (volts)	0.759	0.965	0.997
Anode Voltage	6.3	6.7	8.7
Anode Current (amps)	4.17	4.17	3.27
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.667	0.620	0.375
Voltage drop in ref. circuit	0.759	0.965	0.997

 # 4: TITANIUM MESH

Rebar Probe (volts)			
Reference Cell (volts)	0.687	0.892	0.870
Anode Voltage	8.5	9.3	11.3
Anode Current (amps)	9.60	9.63	8.37
Ref. Cell Instant-off (volts)			
Conductance (mhos)	1.133	1.041	0.740
Voltage drop in ref. circuit	0.687	0.892	0.870

1-4: AVERAGE VALUES: TITANIUM MESH

Rebar Probe (volts)			
Reference Cell (volts)	0.712	0.916	1.014
Anode Voltage	6.8	7.4	9.0
Anode Current (amps)	6.35	6.35	5.35
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.907	0.831	0.578
Voltage drop in ref. circuit	0.712	0.916	1.014

Date:	10/28/88	10/28/88	12/13/88	12/15/88
Days since last reading:	0	0	46	2
Days since start-up (10/28/88):	0	0	46	48
Tester:	Corrpro	Corrpro	Corrpro	Corrpro

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	-0.00625	0.00015	0.004	0.004
Reference Cell (volts)	0.352	0.837	1.092	0.978
Anode Voltage	0.45	13.79	11.4	10.2
Anode Current (amps)	0.00	5.80	5.98	5.01
Ref. Cell Instant-off (volts)		0.470	0.679	0.612
Conductance (mhos)		0.421	0.525	0.491
Voltage drop in ref. circuit		0.367	0.413	0.366

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	-0.00104	0.00101	0.005	0.004
Reference Cell (volts)	0.335	0.644	0.751	0.758
Anode Voltage	0.15	13.63	10.7	10.4
Anode Current (amps)	0.00	5.80	5.92	5.50
Ref. Cell Instant-off (volts)		0.479	0.597	0.558
Conductance (mhos)		0.426	0.553	0.529
Voltage drop in ref. circuit		0.165	0.154	0.200

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	-0.00197	0.00202	0.005	0.004
Reference Cell (volts)	0.302	0.518	0.773	0.628
Anode Voltage	0.19	13.30	10.9	11.2
Anode Current (amps)	0.00	5.00	5.09	4.71
Ref. Cell Instant-off (volts)		0.399	0.573	0.479
Conductance (mhos)		0.376	0.467	0.421
Voltage drop in ref. circuit		0.119	0.200	0.149

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	-0.00175	0.00212	0.005	0.004
Reference Cell (volts)	0.323	0.587	0.926	0.825
Anode Voltage	0.17	14.77	10.3	11.0
Anode Current (amps)	0.00	4.80	5.93	5.51
Ref. Cell Instant-off (volts)		0.410	0.618	0.545
Conductance (mhos)		0.325	0.576	0.501
Voltage drop in ref. circuit		0.177	0.308	0.280

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	-0.003	0.001	0.005	0.004
Reference Cell (volts)	0.328	0.647	0.886	0.797
Anode Voltage	0.2	13.9	10.8	10.7
Anode Current (amps)	0.00	5.35	5.73	5.18
Ref. Cell Instant-off (volts)		0.440	0.617	0.549
Conductance (mhos)		0.387	0.530	0.485
Voltage drop in ref. circuit		0.207	0.269	0.249

Date:	1/31/89	2/1/89	2/2/89	3/13/89
Days since last reading:	47	1	1	39
Days since start-up (10/28/88):	95	96	97	136
Tester:	Corrpro	Corrpro	Corrpro	MC,DR,DE

5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.005	0.003	0.006
Reference Cell (volts)	1.055	0.521	0.901	1.001
Anode Voltage	10.0	6.4	9.3	8.9
Anode Current (amps)	4.97	4.88	4.91	4.97
Ref. Cell Instant-off (volts)	0.636	0.420	0.570	
Conductance (mhos)	0.497	0.763	0.528	0.558
Voltage drop in ref. circuit	0.419	0.101	0.331	

6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.003	0.002	0.007	0.003
Reference Cell (volts)	0.822	0.372	0.692	0.743
Anode Voltage	9.8	6.5	9.3	9.1
Anode Current (amps)	5.45	5.32	5.34	5.43
Ref. Cell Instant-off (volts)	0.596	0.337	0.499	
Conductance (mhos)	0.556	0.818	0.574	0.597
Voltage drop in ref. circuit	0.226	0.035	0.193	

7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.006	0.006	0.005	0.007
Reference Cell (volts)	0.734	0.482	0.666	0.613
Anode Voltage	10.4	6.8	9.6	9.7
Anode Current (amps)	4.67	4.78	4.81	4.89
Ref. Cell Instant-off (volts)	0.520	0.388	0.482	
Conductance (mhos)	0.449	0.703	0.501	0.504
Voltage drop in ref. circuit	0.214	0.094	0.184	

8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.006	0.005	0.003	0.006
Reference Cell (volts)	0.840	0.577	0.710	0.852
Anode Voltage	9.7	6.7	9.0	9.2
Anode Current (amps)	5.46	5.56	5.61	5.68
Ref. Cell Instant-off (volts)	0.563	0.451	0.506	
Conductance (mhos)	0.563	0.830	0.623	0.617
Voltage drop in ref. circuit	0.277	0.126	0.204	

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.005	0.005	0.005	0.006
Reference Cell (volts)	0.863	0.488	0.742	0.802
Anode Voltage	10.0	6.6	9.3	9.2
Anode Current (amps)	5.14	5.14	5.17	5.24
Ref. Cell Instant-off (volts)	0.579	0.399	0.514	
Conductance (mhos)	0.516	0.778	0.557	0.569
Voltage drop in ref. circuit	0.284	0.089	0.228	

Date:	4/13/89	5/26/89	6/13/89	7/17/89
Days since last reading:	31	43	18	34
Days since start-up (10/28/88):	167	210	228	262
Tester:	DR,DE,TD	DR	JM,DR	DR,KC

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.007	0.008	0.005	0.008
Reference Cell (volts)	1.053	0.432	1.163	0.808
Anode Voltage	9.6	6.0	9.4	8.1
Anode Current (amps)	4.99	4.89	4.92	4.84
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.520	0.815	0.523	0.598
Voltage drop in ref. circuit				

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.001	0.005	0.002	0.006
Reference Cell (volts)	0.867	0.395	0.823	0.681
Anode Voltage	10.1	6.1	9.1	8.0
Anode Current (amps)	5.45	5.36	5.40	5.29
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.540	0.879	0.593	0.661
Voltage drop in ref. circuit				

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.006	0.008	0.006	0.007
Reference Cell (volts)	0.760	0.439	0.645	0.554
Anode Voltage	9.8	5.8	9.8	8.4
Anode Current (amps)	4.91	4.80	4.85	4.75
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.501	0.828	0.495	0.565
Voltage drop in ref. circuit				

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.005	0.008	0.006	0.009
Reference Cell (volts)	0.849	0.545	0.940	0.871
Anode Voltage	9.1	5.7	9.5	8.5
Anode Current (amps)	5.70	5.60	5.65	5.57
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.626	0.982	0.595	0.655
Voltage drop in ref. circuit				

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.005	0.007	0.005	0.008
Reference Cell (volts)	0.882	0.453	0.893	0.729
Anode Voltage	9.7	5.9	9.5	8.3
Anode Current (amps)	5.26	5.16	5.21	5.11
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.547	0.876	0.552	0.620
Voltage drop in ref. circuit				

Date:	8/18/89	9/19/89	10/31/89	11/28/89
Days since last reading:	32	32	42	28
Days since start-up (10/28/88):	294	326	368	396
Tester:	DR	DR	DR	DR

5: CONDUCTIVE POLYMER CABLE

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.010	0.005	0.005	0.003
Reference Cell (volts)	0.509	1.225	1.002	1.366
Anode Voltage	6.8	10.4	9.9	12.8
Anode Current (amps)	4.84	4.87	4.89	5.03
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.712	0.468	0.494	0.393
Voltage drop in ref. circuit				

6: CONDUCTIVE POLYMER CABLE

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.008	0.002	0.003	0.002
Reference Cell (volts)	0.467	0.967	0.888	1.393
Anode Voltage	6.9	10.1	9.6	12.7
Anode Current (amps)	5.30	5.33	5.35	5.48
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.768	0.528	0.557	0.431
Voltage drop in ref. circuit				

7: CONDUCTIVE POLYMER CABLE

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.007	0.004	0.003	0.002
Reference Cell (volts)	0.492	0.691	0.668	0.870
Anode Voltage	7.2	11.4	11.4	17.2
Anode Current (amps)	4.76	4.79	4.81	4.93
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.661	0.420	0.422	0.287
Voltage drop in ref. circuit				

8: CONDUCTIVE POLYMER CABLE

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.008	0.004	0.004	0.003
Reference Cell (volts)	0.695	1.014	1.009	1.551
Anode Voltage	7.1	10.7	10.1	14.8
Anode Current (amps)	5.59	5.62	5.64	5.73
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.787	0.525	0.558	0.387
Voltage drop in ref. circuit				

5-8: AVERAGE VALUES: POLYMER CABLE

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.008	0.004	0.004	0.003
Reference Cell (volts)	0.541	0.974	0.892	1.295
Anode Voltage	7.0	10.7	10.3	14.4
Anode Current (amps)	5.12	5.15	5.17	5.29
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.732	0.485	0.508	0.375
Voltage drop in ref. circuit				

Date:	1/9/90	1/17/90	4/26/90	11/19/90
Days since last reading:	12	8	99	207
Days since start-up (10/28/88):	408	416	515	722
Tester:	DR,DE	DR	DE,TD	JM,DE

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.005	0.007	0.006	0.004
Reference Cell (volts)	0.781	0.819	1.131	0.994
Anode Voltage	8.7	8.8	12.1	14.4
Anode Current (amps)	4.95	4.91	4.90	4.96
Ref. Cell Instant-off (volts)	0.434		0.528	0.269
Conductance (mhos)	0.569	0.558	0.405	0.344
Voltage drop in ref. circuit	0.347		0.603	0.725

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.003	0.005	0.003	0.004
Reference Cell (volts)	0.756	0.803	0.998	0.768
Anode Voltage	9.0	9.2	11.5	15.7
Anode Current (amps)	5.42	5.38	5.38	5.36
Ref. Cell Instant-off (volts)	0.422		0.429	0.268
Conductance (mhos)	0.602	0.585	0.468	0.341
Voltage drop in ref. circuit	0.334		0.569	0.500

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.002	0.004	0.003	0.002
Reference Cell (volts)	0.552	0.433	0.647	0.110
Anode Voltage	10.5	10.6	13.0	23.6
Anode Current (amps)	4.89	4.85	4.85	3.58
Ref. Cell Instant-off (volts)	0.389		0.419	0.275
Conductance (mhos)	0.466	0.458	0.373	0.152
Voltage drop in ref. circuit	0.163		0.228	-0.165

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.003	0.004	0.003	0.003
Reference Cell (volts)	0.669	0.630	0.790	0.790
Anode Voltage	9.1	8.7	10.7	12.4
Anode Current (amps)	5.69	5.65	5.65	5.66
Ref. Cell Instant-off (volts)	0.419		0.416	0.433
Conductance (mhos)	0.625	0.649	0.528	0.456
Voltage drop in ref. circuit	0.250		0.374	0.357

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.003	0.005	0.004	0.003
Reference Cell (volts)	0.690	0.671	0.892	0.666
Anode Voltage	9.3	9.3	11.8	16.5
Anode Current (amps)	5.24	5.20	5.20	4.89
Ref. Cell Instant-off (volts)	0.416		0.448	0.311
Conductance (mhos)	0.566	0.562	0.443	0.323
Voltage drop in ref. circuit	0.274		0.444	0.354

Date:	3/28/91	5/15/91	7/31/91	8/16/91
Days since last reading:	129	48	77	16
Days since start-up (10/28/88):	851	899	976	992
Tester:	DE,KC	DE	DE	JM,DE

5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.003	0.003	0.004
Reference Cell (volts)	1.066	0.420	0.030	0.037
Anode Voltage	23.5	24.1	24.1	25.5
Anode Current (amps)	4.06	1.66	0.04	0.01
Ref. Cell Instant-off (volts)	0.464	0.262	0.029	0.037
Conductance (mhos)	0.173	0.069	0.002	0.000
Voltage drop in ref. circuit	0.602	0.158	0.001	0.000

6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.003	0.003	0.003
Reference Cell (volts)	0.752	0.125	0.044	0.043
Anode Voltage	23.4	24.2	25.1	25.0
Anode Current (amps)	4.82	1.55	0.07	0.08
Ref. Cell Instant-off (volts)	0.354	0.120	0.044	0.042
Conductance (mhos)	0.206	0.064	0.003	0.003
Voltage drop in ref. circuit	0.398	0.005	0.000	0.001

7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.003	0.003	0.003	0.004
Reference Cell (volts)	0.066	0.064	0.095	0.101
Anode Voltage	23.7	24.0	24.8	24.8
Anode Current (amps)	1.88	1.65	0.01	0.01
Ref. Cell Instant-off (volts)	0.062	0.062	0.098	0.101
Conductance (mhos)	0.079	0.069	0.000	0.000
Voltage drop in ref. circuit	0.004	0.002	-0.003	0.000

8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.005	0.004	0.004
Reference Cell (volts)	1.252	0.780	0.208	0.138
Anode Voltage	21.1	23.9	24.7	24.9
Anode Current (amps)	5.66	3.53	0.43	0.24
Ref. Cell Instant-off (volts)	0.547	0.404	0.186	0.134
Conductance (mhos)	0.268	0.148	0.017	0.010
Voltage drop in ref. circuit	0.705	0.376	0.022	0.004

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.004	0.004	0.003	0.004
Reference Cell (volts)	0.784	0.347	0.094	0.080
Anode Voltage	22.9	24.1	24.7	25.1
Anode Current (amps)	4.11	2.10	0.14	0.09
Ref. Cell Instant-off (volts)	0.357	0.212	0.089	0.079
Conductance (mhos)	0.182	0.087	0.006	0.003
Voltage drop in ref. circuit	0.427	0.135	0.005	0.001

Date:	9/10/91	10/9/91	1/7/92	3/19/92
Days since last reading:	25	29	90	72
Days since start-up (10/28/88):	1,017	1,046	1,136	1,208
Tester:	DE	DE	DE	DE

 # 5: CONDUCTIVE POLYMER CABLE

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.004	0.003	0.001	0.002
Reference Cell (volts)	0.024	0.020	0.025	0.013
Anode Voltage	25.5	25.2	25.0	25.0
Anode Current (amps)	0.01	0.01	0.00	0.01
Ref. Cell Instant-off (volts)	0.021	0.019	0.023	0.013
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.003	0.001	0.002	0.000

 # 6: CONDUCTIVE POLYMER CABLE

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.003	0.002	0.000	0.001
Reference Cell (volts)	0.033	0.030	0.028	0.042
Anode Voltage	25.3	25.2	25.5	25.8
Anode Current (amps)	0.02	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.031	0.029	0.028	0.042
Conductance (mhos)	0.001	0.000	0.000	0.000
Voltage drop in ref. circuit	0.002	0.001	0.000	0.000

 # 7: CONDUCTIVE POLYMER CABLE

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.003	0.003	0.001	0.001
Reference Cell (volts)	0.100	0.091	0.078	0.069
Anode Voltage	24.8	25.0	24.9	25.0
Anode Current (amps)	0.01	0.01	0.00	0.01
Ref. Cell Instant-off (volts)	0.099	0.091	0.079	0.070
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.001	0.000	-0.001	-0.001

 # 8: CONDUCTIVE POLYMER CABLE

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.004	0.004	0.001	0.002
Reference Cell (volts)	0.181	0.178	0.172	0.114
Anode Voltage	25.0	24.8	24.5	24.8
Anode Current (amps)	0.14	0.07	0.06	0.05
Ref. Cell Instant-off (volts)	0.168	0.168	0.161	0.107
Conductance (mhos)	0.006	0.003	0.002	0.002
Voltage drop in ref. circuit	0.013	0.010	0.011	0.007

5-8: AVERAGE VALUES: POLYMER CABLE

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.004	0.003	0.001	0.002
Reference Cell (volts)	0.085	0.080	0.076	0.060
Anode Voltage	25.2	25.1	25.0	25.2
Anode Current (amps)	0.05	0.03	0.02	0.02
Ref. Cell Instant-off (volts)	0.080	0.077	0.073	0.058
Conductance (mhos)	0.002	0.001	0.001	0.001
Voltage drop in ref. circuit	0.005	0.003	0.003	0.002

Date:	4/17/92	5/15/92	6/11/92
Days since last reading:	29	28	27
Days since start-up (10/28/88):	1,237	1,265	1,292
Tester:	DE	DE	DE

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.002	0.003	0.004
Reference Cell (volts)	0.013	0.025	0.027
Anode Voltage	25.2	25.1	25.5
Anode Current (amps)	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.011	0.022	0.023
Conductance (mhos)	0.000	0.000	0.000
Voltage drop in ref. circuit	0.002	0.003	0.004

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.001	0.002	0.003
Reference Cell (volts)	0.047	0.053	0.053
Anode Voltage	25.8	25.6	25.9
Anode Current (amps)	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.045	0.051	0.051
Conductance (mhos)	0.000	0.000	0.000
Voltage drop in ref. circuit	0.002	0.002	0.002

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.001	0.003	0.004
Reference Cell (volts)	0.081	0.101	0.109
Anode Voltage	25.2	24.9	25.3
Anode Current (amps)	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.080	0.100	0.108
Conductance (mhos)	0.000	0.000	0.000
Voltage drop in ref. circuit	0.001	0.001	0.001

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.002	0.003	0.004
Reference Cell (volts)	0.101	0.060	0.050
Anode Voltage	24.7	25.2	25.5
Anode Current (amps)	0.04	0.02	0.03
Ref. Cell Instant-off (volts)	0.094	0.058	0.048
Conductance (mhos)	0.002	0.001	0.001
Voltage drop in ref. circuit	0.007	0.002	0.002

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.002	0.003	0.004
Reference Cell (volts)	0.061	0.060	0.060
Anode Voltage	25.2	25.2	25.6
Anode Current (amps)	0.02	0.01	0.02
Ref. Cell Instant-off (volts)	0.058	0.058	0.058
Conductance (mhos)	0.001	0.000	0.001
Voltage drop in ref. circuit	0.003	0.002	0.002

Date:	7/9/92	8/7/92	8/25/92	9/22/92
Days since last reading:	28	29	18	28
Days since start-up (10/28/88):	1,320	1,349	1,367	1,395
Tester:	DE	HP,RF	DE	DE

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.003	0.004	0.003	0.002
Reference Cell (volts)	0.012	0.018	0.021	0.015
Anode Voltage	24.6	24.7	24.7	25.0
Anode Current (amps)	0.01	0.01	0.01	0.02
Ref. Cell Instant-off (volts)	0.008	0.014	0.019	0.015
Conductance (mhos)	0.000	0.000	0.000	0.001
Voltage drop in ref. circuit	0.004	0.004	0.002	0.000

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.002	0.003	0.002	0.001
Reference Cell (volts)	0.052	0.051	0.050	0.050
Anode Voltage	25.2	25.1	24.9	25.2
Anode Current (amps)	0.01	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.050	0.049	0.049	0.049
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.002	0.002	0.001	0.001

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.003	0.003	0.003	0.001
Reference Cell (volts)	0.100	0.109	0.121	0.120
Anode Voltage	24.6	24.7	24.6	24.9
Anode Current (amps)	0.01	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.100	0.110	0.121	0.123
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	-0.001	0.000	-0.003

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.003	0.003	0.002	0.001
Reference Cell (volts)	0.043	0.041	0.046	0.041
Anode Voltage	25.5	25.3	24.9	25.2
Anode Current (amps)	0.02	0.02	0.03	0.02
Ref. Cell Instant-off (volts)	0.041	0.043	0.045	0.040
Conductance (mhos)	0.001	0.001	0.001	0.001
Voltage drop in ref. circuit	0.002	-0.002	0.001	0.001

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.003	0.003	0.003	0.001
Reference Cell (volts)	0.052	0.055	0.060	0.057
Anode Voltage	25.0	25.0	24.8	25.1
Anode Current (amps)	0.01	0.01	0.02	0.02
Ref. Cell Instant-off (volts)	0.050	0.054	0.059	0.057
Conductance (mhos)	0.000	0.000	0.001	0.001
Voltage drop in ref. circuit	0.002	0.001	0.001	0.000

	1/8/93	2/12/93	2/26/93	2/26/93
Date:	1/8/93	2/12/93	2/26/93	2/26/93
Days since last reading:	108	35	14	0.50
Days since start-up (10/28/88):	1,503	1,538	1,552	1,553
Tester:	DE	DE	RF	RF

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.002	0.000	0.000	0.002
Reference Cell (volts)	0.036	0.037	0.035	0.044
Anode Voltage	24.7	24.7	24.6	0.5
Anode Current (amps)	0.01	0.01	0.02	0.00
Ref. Cell Instant-off (volts)	0.033	0.036	0.035	0.044
Conductance (mhos)	0.000	0.000	0.001	0.000
Voltage drop in ref. circuit	0.003	0.001	0.000	0.000

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.002	0.000	0.001	0.000
Reference Cell (volts)	0.056	0.057	0.055	0.059
Anode Voltage	24.7	24.7	24.7	0.6
Anode Current (amps)	0.00	0.00	0.01	0.00
Ref. Cell Instant-off (volts)	0.055	0.056	0.055	0.059
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.001	0.001	0.000	0.000

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.002	0.000	0.000	0.000
Reference Cell (volts)	0.099	0.095	0.093	0.104
Anode Voltage	24.8	24.7	24.6	0.9
Anode Current (amps)	0.01	0.01	0.01	0.00
Ref. Cell Instant-off (volts)	0.020	0.094	0.092	0.104
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.079	0.001	0.001	0.000

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.001	0.000	0.000	0.000
Reference Cell (volts)	0.021	0.020	0.019	0.025
Anode Voltage	25.0	24.9	24.8	0.7
Anode Current (amps)	0.01	0.01	0.01	0.00
Ref. Cell Instant-off (volts)	0.020	0.020	0.019	0.025
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.001	0.000	0.000	0.000

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.002	0.000	0.000	0.001
Reference Cell (volts)	0.053	0.052	0.051	0.058
Anode Voltage	24.8	24.8	24.7	0.7
Anode Current (amps)	0.01	0.01	0.01	0.00
Ref. Cell Instant-off (volts)	0.032	0.052	0.050	0.058
Conductance (mhos)	0.000	0.000	0.001	0.000
Voltage drop in ref. circuit	0.021	0.001	0.000	0.000

Date:	3/5/93	3/18/93	4/27/93	5/28/93
Days since last reading:	7	13	40	31
Days since start-up (10/28/88):	1,560	1,573	1,613	1,644
Tester:	RF	HP,RF	DE,JS	DE,TM

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.001	0.001	0.002	0.003
Reference Cell (volts)	0.038	0.039	0.050	0.053
Anode Voltage	0.5	0.4	0.6	0.7
Anode Current (amps)	0.00	0.00	0.00	0.00
Ref. Cell Instant-off (volts)	0.038	0.039	0.050	0.053
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.000	0.001	0.002	0.003
Reference Cell (volts)	0.057	0.058	0.057	0.050
Anode Voltage	0.4	0.2	0.5	0.7
Anode Current (amps)	0.00	0.00	0.00	0.01
Ref. Cell Instant-off (volts)	0.057	0.058	0.057	0.050
Conductance (mhos)	0.000	0.000	0.000	0.014
Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.000	0.001	0.002	0.003
Reference Cell (volts)	0.103	0.107	0.126	0.134
Anode Voltage	0.8	0.7	1.1	1.0
Anode Current (amps)	0.00	0.00	0.00	0.03
Ref. Cell Instant-off (volts)	0.103	0.107	0.126	0.134
Conductance (mhos)	0.000	0.000	0.000	0.030
Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.000	0.001	0.002	0.003
Reference Cell (volts)	0.024	0.026	0.033	0.040
Anode Voltage	0.6	0.5	0.8	0.9
Anode Current (amps)	0.00	0.00	0.00	0.00
Ref. Cell Instant-off (volts)	0.024	0.026	0.033	0.040
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.000	0.001	0.002	0.003
Reference Cell (volts)	0.056	0.058	0.067	0.069
Anode Voltage	0.6	0.5	0.8	0.8
Anode Current (amps)	0.00	0.00	0.00	0.01
Ref. Cell Instant-off (volts)	0.056	0.058	0.067	0.069
Conductance (mhos)	0.000	0.000	0.000	0.011
Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

Date:	6/30/93	8/31/93	10/7/93	11/2/93
Days since last reading:	33	62	37	26
Days since start-up (10/28/88):	1,677	1,739	1,776	1,802
Tester:	DE	DE	PN	PN

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.004	0.004	
Reference Cell (volts)	0.038	0.028	0.038	0.023
Anode Voltage	0.6	0.3	0.6	0.9
Anode Current (amps)	0.00	0.00	0.00	0.00
Ref. Cell Instant-off (volts)	0.038	0.028	0.038	
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.023

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.044	0.030	0.044	0.037
Anode Voltage	0.4	0.2	0.4	0.8
Anode Current (amps)	0.00	0.00	0.00	0.00
Ref. Cell Instant-off (volts)	0.044	0.030	0.044	
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.037

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.129	0.128	0.129	0.135
Anode Voltage	0.8	0.6	0.8	1.1
Anode Current (amps)	0.03	0.03	0.03	0.00
Ref. Cell Instant-off (volts)	0.129	0.128	0.129	
Conductance (mhos)	0.038	0.050	0.038	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.135

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.042	0.035	0.042	0.024
Anode Voltage	0.6	0.4	0.6	1.0
Anode Current (amps)	0.01	0.01	0.01	0.00
Ref. Cell Instant-off (volts)	0.042	0.035	0.042	
Conductance (mhos)	0.017	0.025	0.017	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.024

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.063	0.055	0.063	0.055
Anode Voltage	0.6	0.4	0.6	0.9
Anode Current (amps)	0.01	0.01	0.01	0.00
Ref. Cell Instant-off (volts)	0.063	0.055	0.063	
Conductance (mhos)	0.014	0.019	0.014	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.055

Date:	11/24/93	12/22/93	12/23/93
Days since last reading:	22	28	1
Days since start-up (10/28/88):	1,824	1,852	1,853
Tester:	PN	PN	PN

 # 5: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)			
Reference Cell (volts)	0.020	0.033	0.039
Anode Voltage	0.9	0.9	0.7
Anode Current (amps)	0.03	0.00	0.09
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.034	0.000	0.124
Voltage drop in ref. circuit	0.020	0.033	0.039

 # 6: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)			
Reference Cell (volts)	0.038	0.038	0.051
Anode Voltage	0.8	0.8	0.6
Anode Current (amps)	0.00	0.00	0.03
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.000	0.000	0.048
Voltage drop in ref. circuit	0.038	0.038	0.051

 # 7: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)			
Reference Cell (volts)	0.125	0.123	0.114
Anode Voltage	1.0	1.1	0.9
Anode Current (amps)	0.00	0.00	0.03
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.000	0.000	0.035
Voltage drop in ref. circuit	0.125	0.123	0.114

 # 8: CONDUCTIVE POLYMER CABLE

Rebar Probe (volts)			
Reference Cell (volts)	0.019	0.019	0.032
Anode Voltage	1.0	1.0	0.8
Anode Current (amps)	0.00	0.00	0.03
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.000	0.000	0.038
Voltage drop in ref. circuit	0.019	0.019	0.032

5-8: AVERAGE VALUES: POLYMER CABLE

Rebar Probe (volts)			
Reference Cell (volts)	0.051	0.053	0.059
Anode Voltage	0.9	1.0	0.8
Anode Current (amps)	0.01	0.00	0.05
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.009	0.000	0.061
Voltage drop in ref. circuit	0.051	0.053	0.059

Date:	10/28/88	10/28/88	12/13/88	12/15/88
Days since last reading:	0	0	46	2
Days since start-up (10/28/88):	0	0	46	48
Tester:	Corrpro	Corrpro	Corrpro	Corrpro

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	-0.00961	0.00105	0.005	0.004
Reference Cell (volts)	0.299	0.490	0.551	0.536
Anode Voltage	0.24	2.99	4.1	3.5
Anode Current (amps)	0.00	4.50	4.46	4.20
Ref. Cell Instant-off (volts)		0.397	0.430	0.426
Conductance (mhos)		1.505	1.088	1.200
Voltage drop in ref. circuit		0.093	0.121	0.110

 # 10: CARBON FIBER

Rebar Probe (volts)	-0.00296	0.00215	0.004	0.004
Reference Cell (volts)	0.280	0.429	0.515	0.487
Anode Voltage	0.24	3.51	5.4	4.9
Anode Current (amps)	0.00	6.00	6.17	6.03
Ref. Cell Instant-off (volts)		0.355	0.423	0.404
Conductance (mhos)		1.709	1.143	1.231
Voltage drop in ref. circuit		0.074	0.092	0.083

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	-0.003	0.002	0.005	0.004
Reference Cell (volts)	0.145	0.460	0.533	0.512
Anode Voltage	0.1	3.3	4.8	4.2
Anode Current (amps)	0.00	5.25	5.32	5.12
Ref. Cell Instant-off (volts)		0.376	0.427	0.415
Conductance (mhos)		1.607	1.115	1.215
Voltage drop in ref. circuit		0.084	0.107	0.097

Date:	1/31/89	2/1/89	2/2/89	3/13/89
Days since last reading:	47	1	1	39
Days since start-up (10/28/88):	95	96	97	136
Tester:	Corrpro	Corrpro	Corrpro	MC,DR,DE

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	0.004	0.003	0.005	0.004
Reference Cell (volts)	0.522	0.406	0.475	0.459
Anode Voltage	3.6	2.7	3.4	3.3
Anode Current (amps)	4.13	4.26	4.29	4.37
Ref. Cell Instant-off (volts)	0.411	0.351	0.387	
Conductance (mhos)	1.147	1.578	1.262	1.324
Voltage drop in ref. circuit	0.111	0.055	0.088	

 # 10: CARBON FIBER

Rebar Probe (volts)	0.005	0.005	0.005	0.006
Reference Cell (volts)	0.511	0.379	0.463	0.447
Anode Voltage	5.0	3.6	4.5	4.4
Anode Current (amps)	5.96	6.07	6.13	6.24
Ref. Cell Instant-off (volts)	0.434	0.325	0.395	
Conductance (mhos)	1.192	1.686	1.362	1.418
Voltage drop in ref. circuit	0.077	0.054	0.068	

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	0.005	0.004	0.005	0.005
Reference Cell (volts)	0.517	0.393	0.469	0.453
Anode Voltage	4.3	3.2	4.0	3.9
Anode Current (amps)	5.05	5.17	5.21	5.31
Ref. Cell Instant-off (volts)	0.423	0.338	0.391	
Conductance (mhos)	1.170	1.632	1.312	1.371
Voltage drop in ref. circuit	0.094	0.055	0.078	

Date:	4/13/89	5/26/89	6/13/89	7/17/89
Days since last reading:	31	43	18	34
Days since start-up (10/28/88):	167	210	228	262
Tester:	DR,DE,TD	DR	JM,DR	DR,KC

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	0.004	0.003	0.005	0.007
Reference Cell (volts)	0.544	0.358	0.453	0.410
Anode Voltage	3.8	2.7	3.3	3.1
Anode Current (amps)	4.38	4.28	4.32	4.21
Ref. Cell Instant-off (volts)				
Conductance (mhos)	1.153	1.585	1.309	1.358
Voltage drop in ref. circuit				

 # 10: CARBON FIBER

Rebar Probe (volts)	0.005	0.006	0.006	0.008
Reference Cell (volts)	0.485	0.350	0.416	0.374
Anode Voltage	5.4	3.5	4.4	4.0
Anode Current (amps)	6.26	6.13	6.19	6.04
Ref. Cell Instant-off (volts)				
Conductance (mhos)	1.159	1.751	1.407	1.510
Voltage drop in ref. circuit				

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	0.005	0.005	0.006	0.008
Reference Cell (volts)	0.515	0.354	0.435	0.392
Anode Voltage	4.6	3.1	3.9	3.6
Anode Current (amps)	5.32	5.21	5.26	5.13
Ref. Cell Instant-off (volts)				
Conductance (mhos)	1.156	1.668	1.358	1.434
Voltage drop in ref. circuit				

Date:	8/18/89	9/19/89	10/31/89	11/28/89
Days since last reading:	32	32	42	28
Days since start-up (10/28/88):	294	326	368	396
Tester:	DR	DR	DR	DR

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.007	0.006	0.005	0.004
Reference Cell (volts)	0.391	0.523	0.585	0.915
Anode Voltage	2.9	3.5	3.7	4.6
Anode Current (amps)	4.22	4.25	4.26	4.40
Ref. Cell Instant-off (volts)				
Conductance (mhos)	1.455	1.214	1.151	0.957
Voltage drop in ref. circuit				

 # 10: CARBON FIBER

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.008	0.005	0.005	0.004
Reference Cell (volts)	0.373	0.423	0.474	0.598
Anode Voltage	3.8	5.1	5.4	7.9
Anode Current (amps)	6.06	6.10	6.13	6.26
Ref. Cell Instant-off (volts)				
Conductance (mhos)	1.595	1.196	1.135	0.792
Voltage drop in ref. circuit				

9-10: AVERAGE VALUES: CARBON FIBER

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.008	0.006	0.005	0.004
Reference Cell (volts)	0.382	0.473	0.530	0.757
Anode Voltage	3.4	4.3	4.6	6.3
Anode Current (amps)	5.14	5.18	5.20	5.33
Ref. Cell Instant-off (volts)				
Conductance (mhos)	1.525	1.205	1.143	0.874
Voltage drop in ref. circuit				

Date:	1/9/90	1/17/90	4/26/90	11/19/90
Days since last reading:	12	8	99	207
Days since start-up (10/28/88):	408	416	515	722
Tester:	DR,DE	DR	DE,TD	JM,DE

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	0.004	0.005	0.005	0.004
Reference Cell (volts)	0.604	0.608	0.624	0.700
Anode Voltage	3.6	3.6	3.7	3.8
Anode Current (amps)	4.34	4.29	4.29	4.13
Ref. Cell Instant-off (volts)	0.362		0.349	0.332
Conductance (mhos)	1.206	1.192	1.159	1.087
Voltage drop in ref. circuit	0.242		0.275	0.368

 # 10: CARBON FIBER

Rebar Probe (volts)	0.004	0.005	0.005	0.003
Reference Cell (volts)	0.507	0.498	0.453	0.496
Anode Voltage	5.1	5.1	5.6	5.5
Anode Current (amps)	6.21	6.17	6.13	6.00
Ref. Cell Instant-off (volts)	0.348		0.305	0.294
Conductance (mhos)	1.218	1.210	1.095	1.091
Voltage drop in ref. circuit	0.159		0.148	0.202

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	0.004	0.005	0.005	0.004
Reference Cell (volts)	0.556	0.553	0.539	0.598
Anode Voltage	4.4	4.4	4.7	4.7
Anode Current (amps)	5.28	5.23	5.21	5.07
Ref. Cell Instant-off (volts)	0.355		0.327	0.313
Conductance (mhos)	1.212	1.201	1.127	1.089
Voltage drop in ref. circuit	0.201		0.212	0.285

Date:	3/28/91	5/15/91	7/31/91	8/16/91
Days since last reading:	129	48	77	16
Days since start-up (10/28/88):	851	899	976	992
Tester:	DE,KC	DE	DE	JM,DE

9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	0.004	0.005	0.005	0.005
Reference Cell (volts)	0.808	0.723	0.691	0.508
Anode Voltage	4.1	3.8	3.7	3.1
Anode Current (amps)	4.11	4.02	4.28	4.25
Ref. Cell Instant-off (volts)	0.336	0.305	0.304	0.245
Conductance (mhos)	1.002	1.058	1.157	1.371
Voltage drop in ref. circuit	0.472	0.418	0.387	0.263

10: CARBON FIBER

Rebar Probe (volts)	0.003	0.005	0.005	0.005
Reference Cell (volts)	0.404	0.384	0.363	0.330
Anode Voltage	6.5	6.3	5.7	4.4
Anode Current (amps)	6.15	6.06	6.13	6.09
Ref. Cell Instant-off (volts)	0.290	0.265	0.253	0.235
Conductance (mhos)	0.946	0.962	1.075	1.384
Voltage drop in ref. circuit	0.114	0.119	0.110	0.095

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	0.004	0.005	0.005	0.005
Reference Cell (volts)	0.606	0.554	0.527	0.419
Anode Voltage	5.3	5.1	4.7	3.8
Anode Current (amps)	5.13	5.04	5.21	5.17
Ref. Cell Instant-off (volts)	0.313	0.285	0.279	0.240
Conductance (mhos)	0.974	1.010	1.116	1.378
Voltage drop in ref. circuit	0.293	0.269	0.249	0.179

Date:	9/10/91	10/9/91	1/7/92	3/19/92
Days since last reading:	25	29	90	72
Days since start-up (10/28/88):	1,017	1,046	1,136	1,208
Tester:	DE	DE	DE	DE

9: CARBON FIBER / CONDUCTIVE ASPHALT

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.004	0.004	0.001	0.002
Reference Cell (volts)	0.602	0.696	0.992	1.284
Anode Voltage	3.3	3.5	4.2	4.7
Anode Current (amps)	4.24	4.23	4.29	4.32
Ref. Cell Instant-off (volts)	0.253	0.272	0.326	0.349
Conductance (mhos)	1.285	1.209	1.021	0.919
Voltage drop in ref. circuit	0.349	0.424	0.666	0.935

10: CARBON FIBER

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.004	0.004	0.002	0.002
Reference Cell (volts)	0.357	0.328	0.160	0.155
Anode Voltage	5.0	5.4	7.3	9.1
Anode Current (amps)	6.06	6.06	6.13	6.19
Ref. Cell Instant-off (volts)	0.186	0.163	0.068	0.061
Conductance (mhos)	1.212	1.122	0.840	0.680
Voltage drop in ref. circuit	0.171	0.165	0.092	0.094

9-10: AVERAGE VALUES: CARBON FIBER

	9/10/91	10/9/91	1/7/92	3/19/92
Rebar Probe (volts)	0.004	0.004	0.002	0.002
Reference Cell (volts)	0.480	0.512	0.576	0.720
Anode Voltage	4.2	4.5	5.8	6.9
Anode Current (amps)	5.15	5.15	5.21	5.26
Ref. Cell Instant-off (volts)	0.220	0.218	0.197	0.205
Conductance (mhos)	1.248	1.165	0.931	0.800
Voltage drop in ref. circuit	0.260	0.295	0.379	0.515

Date:	4/17/92	5/15/92	6/11/92
Days since last reading:	29	28	27
Days since start-up (10/28/88):	1,237	1,265	1,292
Tester:	DE	DE	DE

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	0.002	0.004	0.005
Reference Cell (volts)	1.109	0.554	0.563
Anode Voltage	4.4	3.2	3.1
Anode Current (amps)	4.28	4.27	4.26
Ref. Cell Instant-off (volts)	0.337	0.237	0.231
Conductance (mhos)	0.973	1.334	1.374
Voltage drop in ref. circuit	0.772	0.317	0.332

 # 10: CARBON FIBER

Rebar Probe (volts)	0.003	0.005	0.005
Reference Cell (volts)	0.191	0.225	0.233
Anode Voltage	8.1	5.0	4.9
Anode Current (amps)	6.13	6.12	6.11
Ref. Cell Instant-off (volts)	0.086	0.109	0.113
Conductance (mhos)	0.757	1.224	1.247
Voltage drop in ref. circuit	0.105	0.116	0.120

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	0.003	0.005	0.005
Reference Cell (volts)	0.650	0.390	0.398
Anode Voltage	6.3	4.1	4.0
Anode Current (amps)	5.21	5.20	5.19
Ref. Cell Instant-off (volts)	0.212	0.173	0.172
Conductance (mhos)	0.865	1.279	1.311
Voltage drop in ref. circuit	0.439	0.217	0.226

Date:	7/9/92	8/7/92	8/25/92	9/22/92
Days since last reading:	28	29	18	28
Days since start-up (10/28/88):	1,320	1,349	1,367	1,395
Tester:	DE	HP,RF	DE	DE

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

	7/9/92	8/7/92	8/25/92	9/22/92
Rebar Probe (volts)	0.004	0.004	0.003	0.002
Reference Cell (volts)	0.941	0.913	0.713	0.830
Anode Voltage	4.1	4.0	3.6	3.8
Anode Current (amps)	4.24	4.24	4.24	4.27
Ref. Cell Instant-off (volts)	0.295	0.275	0.257	0.263
Conductance (mhos)	1.034	1.060	1.178	1.124
Voltage drop in ref. circuit	0.646	0.638	0.456	0.567

 # 10: CARBON FIBER

	7/9/92	8/7/92	8/25/92	9/22/92
Rebar Probe (volts)	0.004	0.004	0.003	0.003
Reference Cell (volts)	0.450	0.435	0.394	0.400
Anode Voltage	7.8	7.4	6.3	7.2
Anode Current (amps)	6.09	6.08	6.10	6.14
Ref. Cell Instant-off (volts)	0.198	0.178	0.179	0.171
Conductance (mhos)	0.781	0.822	0.968	0.853
Voltage drop in ref. circuit	0.252	0.257	0.215	0.229

9-10: AVERAGE VALUES: CARBON FIBER

	7/9/92	8/7/92	8/25/92	9/22/92
Rebar Probe (volts)	0.004	0.004	0.003	0.003
Reference Cell (volts)	0.696	0.674	0.554	0.615
Anode Voltage	6.0	5.7	5.0	5.5
Anode Current (amps)	5.17	5.16	5.17	5.21
Ref. Cell Instant-off (volts)	0.247	0.227	0.218	0.217
Conductance (mhos)	0.907	0.941	1.073	0.988
Voltage drop in ref. circuit	0.449	0.448	0.336	0.398

Date:	1/8/93	2/12/93	2/26/93	2/26/93
Days since last reading:	108	35	14	0.50
Days since start-up (10/28/88):	1,503	1,538	1,552	1,553
Tester:	DE	DE	RF	RF

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	0.001	0.001	0.001	0.001
Reference Cell (volts)	1.728	1.852	2.077	1.081
Anode Voltage	6.3	6.5	7.4	4.2
Anode Current (amps)	4.36	4.30	4.40	3.09
Ref. Cell Instant-off (volts)	0.384	0.378	0.384	0.314
Conductance (mhos)	0.692	0.662	0.595	0.736
Voltage drop in ref. circuit	1.344	1.474	1.693	0.767

 # 10: CARBON FIBER

Rebar Probe (volts)	0.002	0.001	0.001	0.002
Reference Cell (volts)	0.082	0.071	0.066	0.097
Anode Voltage	15.6	16.2	19.8	14.9
Anode Current (amps)	6.22	6.17	6.28	7.91
Ref. Cell Instant-off (volts)	0.026	0.025	0.017	0.028
Conductance (mhos)	0.399	0.381	0.317	0.531
Voltage drop in ref. circuit	0.056	0.046	0.049	0.069

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	0.002	0.001	0.001	0.002
Reference Cell (volts)	0.905	0.962	1.072	0.589
Anode Voltage	11.0	11.4	13.6	9.6
Anode Current (amps)	5.29	5.24	5.34	5.50
Ref. Cell Instant-off (volts)	0.205	0.202	0.201	0.171
Conductance (mhos)	0.545	0.521	0.456	0.633
Voltage drop in ref. circuit	0.700	0.760	0.871	0.418

Date:	3/5/93	3/18/93	4/27/93	5/28/93
Days since last reading:	7	13	40	31
Days since start-up (10/28/88):	1,560	1,573	1,613	1,644
Tester:	RF	HP,RF	DE,JS	DE,TM

9: CARBON FIBER / CONDUCTIVE ASPHALT

	3/5/93	3/18/93	4/27/93	5/28/93
Rebar Probe (volts)	0.001	0.001	0.002	0.003
Reference Cell (volts)	1.169	1.168	0.695	0.516
Anode Voltage	4.7	4.7	3.4	2.8
Anode Current (amps)	3.11	3.07	2.99	2.96
Ref. Cell Instant-off (volts)	0.311	0.323	0.237	0.205
Conductance (mhos)	0.662	0.653	0.879	1.057
Voltage drop in ref. circuit	0.858	0.845	0.458	0.311

10: CARBON FIBER

	3/5/93	3/18/93	4/27/93	5/28/93
Rebar Probe (volts)	0.001	0.002	0.003	0.004
Reference Cell (volts)	0.078	0.088	0.233	0.284
Anode Voltage	17.9	19.1	10.7	7.7
Anode Current (amps)	7.93	7.90	7.80	7.69
Ref. Cell Instant-off (volts)	0.024	0.061	0.078	0.110
Conductance (mhos)	0.443	0.414	0.729	0.999
Voltage drop in ref. circuit	0.054	0.027	0.155	0.174

9-10: AVERAGE VALUES: CARBON FIBER

	3/5/93	3/18/93	4/27/93	5/28/93
Rebar Probe (volts)	0.001	0.002	0.003	0.004
Reference Cell (volts)	0.624	0.628	0.464	0.400
Anode Voltage	11.3	11.9	7.1	5.3
Anode Current (amps)	5.52	5.49	5.40	5.33
Ref. Cell Instant-off (volts)	0.168	0.192	0.158	0.158
Conductance (mhos)	0.552	0.533	0.804	1.028
Voltage drop in ref. circuit	0.456	0.436	0.307	0.243

Date:	6/30/93	8/31/93	10/7/93	11/2/93
Days since last reading:	33	62	37	26
Days since start-up (10/28/88):	1,677	1,739	1,776	1,802
Tester:	DE	DE	PN	PN

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.650	1.000	0.650	1.510
Anode Voltage	3.2	3.9	3.2	4.9
Anode Current (amps)	2.96	2.96	2.96	4.56
Ref. Cell Instant-off (volts)	0.226	0.281	0.226	
Conductance (mhos)	0.925	0.759	0.925	0.938
Voltage drop in ref. circuit	0.424	0.719	0.424	1.510

 # 10: CARBON FIBER

Rebar Probe (volts)	0.005	0.004	0.005	
Reference Cell (volts)	0.336	0.263	0.336	0.404
Anode Voltage	10.2	14.1	10.2	23.1
Anode Current (amps)	7.71	7.75	7.71	11.70
Ref. Cell Instant-off (volts)	0.123	0.089	0.123	
Conductance (mhos)	0.756	0.550	0.756	0.506
Voltage drop in ref. circuit	0.213	0.174	0.213	0.404

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)	0.005	0.004	0.005	
Reference Cell (volts)	0.493	0.632	0.493	0.957
Anode Voltage	6.7	9.0	6.7	14.0
Anode Current (amps)	5.34	5.36	5.34	8.13
Ref. Cell Instant-off (volts)	0.175	0.185	0.175	
Conductance (mhos)	0.840	0.654	0.840	0.722
Voltage drop in ref. circuit	0.319	0.447	0.319	0.957

Date:	11/24/93	12/22/93	12/23/93
Days since last reading:	22	28	1
Days since start-up (10/28/88):	1,824	1,852	1,853
Tester:	PN	PN	PN

 # 9: CARBON FIBER / CONDUCTIVE ASPHALT

Rebar Probe (volts)			
Reference Cell (volts)	1.622	2.174	2.681
Anode Voltage	5.1	6.1	8.1
Anode Current (amps)	4.68	4.68	3.78
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.919	0.774	0.465
Voltage drop in ref. circuit	1.622	2.174	2.681

 # 10: CARBON FIBER

Rebar Probe (volts)			
Reference Cell (volts)	0.316	0.178	0.115
Anode Voltage	22.6	23.3	22.8
Anode Current (amps)	9.99	9.93	2.25
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.441	0.426	0.099
Voltage drop in ref. circuit	0.316	0.178	0.115

9-10: AVERAGE VALUES: CARBON FIBER

Rebar Probe (volts)			
Reference Cell (volts)	0.969	1.176	1.398
Anode Voltage	13.9	14.7	15.4
Anode Current (amps)	7.34	7.31	3.02
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.680	0.600	0.282
Voltage drop in ref. circuit	0.969	1.176	1.398

Date:	10/28/88	10/28/88	12/13/88	12/15/88
Days since last reading:	0	0	46	2
Days since start-up (10/28/88):	0	0	46	48
Tester:	Corrpro	Corrpro	Corrpro	Corrpro

 # 11: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.01225	-0.00290	-0.003	0.010
Reference Cell (volts)	0.271	1.420	0.364	0.700
Anode Voltage	-0.23	5.62	1.9	2.4
Anode Current (amps)	0.00	0.35	0.44	0.38
Ref. Cell Instant-off (volts)		0.572	0.485	0.490
Conductance (mhos)		0.062	0.232	0.158
Voltage drop in ref. circuit		0.848	-0.121	0.210

 # 12: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.00845	0.04550	0.0085	0.041
Reference Cell (volts)	0.255	1.220	*OOS*	*OOS*
Anode Voltage	-0.15	10.95	17.7	7.2
Anode Current (amps)	0.00	0.90	0.98	0.33
Ref. Cell Instant-off (volts)		0.570	1.194	0.971
Conductance (mhos)		0.082	0.055	0.046
Voltage drop in ref. circuit		0.650		

 # 13: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.00693	0.00425	0.010	0.011
Reference Cell (volts)	0.361	2.140	0.815	0.758
Anode Voltage	-0.24	13.46	2.5	2.1
Anode Current (amps)	0.00	0.85	0.86	0.49
Ref. Cell Instant-off (volts)		0.830	0.680	0.624
Conductance (mhos)		0.063	0.344	0.233
Voltage drop in ref. circuit		1.310	0.135	0.134

 # 14: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.00848	0.03010	0.034	0.016
Reference Cell (volts)	0.297	2.730	1.464	0.926
Anode Voltage	-0.36	6.39	7.8	2.4
Anode Current (amps)	0.00	0.15	0.25	0.08
Ref. Cell Instant-off (volts)		0.610	0.797	0.499
Conductance (mhos)		0.023	0.032	0.033
Voltage drop in ref. circuit		2.120	0.667	0.427

 # 15: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.01489	0.00620	0.011	0.011
Reference Cell (volts)	0.295	1.290	1.030	0.712
Anode Voltage	-0.23	3.81	2.4	1.5
Anode Current (amps)	0.00	0.25	0.33	0.24
Ref. Cell Instant-off (volts)		0.540	0.559	0.491
Conductance (mhos)		0.066	0.138	0.160
Voltage drop in ref. circuit		0.750	0.471	0.221

 # 16: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.00123	0.00967	0.012	0.012
Reference Cell (volts)	0.380	1.050	0.825	0.605
Anode Voltage	-0.35	6.85	6.0	2.7
Anode Current (amps)	0.00	0.30	0.40	0.20
Ref. Cell Instant-off (volts)		0.450	0.627	0.479
Conductance (mhos)		0.044	0.067	0.074
Voltage drop in ref. circuit		0.600	0.198	0.126

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)	-0.009	0.015	0.012	0.017
Reference Cell (volts)	0.333	1.642	0.900	0.740
Anode Voltage	-0.3	7.8	6.4	3.1
Anode Current (amps)	0.00	0.47	0.54	0.29
Ref. Cell Instant-off (volts)		0.595	0.724	0.592
Conductance (mhos)		0.057	0.145	0.117
Voltage drop in ref. circuit		1.046	0.270	0.224

Date:	1/31/89	2/1/89	2/2/89	3/13/89
Days since last reading:	47	1	1	39
Days since start-up (10/28/88):	95	96	97	136
Tester:	Corrpro	Corrpro	Corrpro	MC,DR,DE

11: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.002	-0.012	-0.010	-0.012
Reference Cell (volts)	0.451	0.311	0.318	0.276
Anode Voltage	9.2	9.7	19.5	25.1
Anode Current (amps)	0.36	0.36	0.42	0.40
Ref. Cell Instant-off (volts)	0.359	0.312	0.311	
Conductance (mhos)	0.039	0.037	0.022	0.016
Voltage drop in ref. circuit	0.092	-0.001	0.007	

12: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.010	0.006	0.008	0.004
Reference Cell (volts)	0.661	0.353	0.337	0.327
Anode Voltage	24.8	15.8	24.9	25.1
Anode Current (amps)	0.22	0.32	0.25	0.20
Ref. Cell Instant-off (volts)	0.530	0.328	0.317	
Conductance (mhos)	0.009	0.020	0.010	0.008
Voltage drop in ref. circuit	0.131	0.025	0.020	

13: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.011	0.011	0.015	0.012
Reference Cell (volts)	0.774	0.653	0.675	0.652
Anode Voltage	4.7	2.5	4.1	6.1
Anode Current (amps)	0.47	0.45	0.46	0.53
Ref. Cell Instant-off (volts)	0.673	0.569	0.596	
Conductance (mhos)	0.100	0.180	0.112	0.087
Voltage drop in ref. circuit	0.101	0.084	0.079	

14: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.011	0.028	0.015	0.018
Reference Cell (volts)	0.676	0.864	0.752	0.814
Anode Voltage	5.1	3.0	5.6	7.5
Anode Current (amps)	0.11	0.13	0.15	0.22
Ref. Cell Instant-off (volts)	0.500	0.554	0.536	
Conductance (mhos)	0.022	0.043	0.027	0.029
Voltage drop in ref. circuit	0.176	0.310	0.216	

15: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.006	0.002	0.000	0.010
Reference Cell (volts)	0.523	0.349	0.315	0.468
Anode Voltage	2.1	0.8	0.9	4.2
Anode Current (amps)	0.25	0.41	0.45	0.51
Ref. Cell Instant-off (volts)	0.405	0.289	0.285	
Conductance (mhos)	0.119	0.513	0.500	0.121
Voltage drop in ref. circuit	0.118	0.060	0.030	

16: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.008	0.014	0.008	0.008
Reference Cell (volts)	0.508	0.434	0.518	0.489
Anode Voltage	3.0	1.9	3.3	5.0
Anode Current (amps)	0.19	0.25	0.28	0.36
Ref. Cell Instant-off (volts)	0.440	0.365	0.444	
Conductance (mhos)	0.063	0.132	0.085	0.072
Voltage drop in ref. circuit	0.068	0.069	0.074	

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)	0.007	0.008	0.006	0.007
Reference Cell (volts)	0.599	0.494	0.486	0.504
Anode Voltage	8.2	5.6	9.7	12.2
Anode Current (amps)	0.27	0.32	0.34	0.37
Ref. Cell Instant-off (volts)	0.485	0.403	0.415	
Conductance (mhos)	0.059	0.154	0.126	0.056
Voltage drop in ref. circuit	0.114	0.091	0.071	

Date:	4/13/89	5/26/89	6/13/89	7/17/89
Days since last reading:	31	43	18	34
Days since start-up (10/28/88):	167	210	228	262
Tester:	DR,DE,TD	DR	JM,DR	DR,KC

 # 11: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.002	-0.009	-0.004	-0.001
Reference Cell (volts)	0.530	0.257	0.311	0.297
Anode Voltage	6.9	25.8	25.3	25.3
Anode Current (amps)	0.48	0.08	0.15	0.12
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.070	0.003	0.006	0.005
Voltage drop in ref. circuit				

 # 12: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.006	0.005	0.003	0.005
Reference Cell (volts)	0.708	0.244	0.252	0.220
Anode Voltage	24.4	25.0	24.3	24.2
Anode Current (amps)	0.36	0.08	0.11	0.06
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.015	0.003	0.005	0.002
Voltage drop in ref. circuit				

 # 13: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.008	0.000	0.001	0.004
Reference Cell (volts)	0.767	0.478	0.468	0.504
Anode Voltage	2.6	25.6	23.1	25.3
Anode Current (amps)	0.54	0.40	0.57	0.15
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.208	0.016	0.025	0.006
Voltage drop in ref. circuit				

 # 14: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.021	0.012	0.013	0.013
Reference Cell (volts)	1.456	0.759	1.378	1.148
Anode Voltage	12.1	23.4	20.2	13.6
Anode Current (amps)	0.24	0.18	0.22	0.10
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.020	0.008	0.011	0.007
Voltage drop in ref. circuit				

 # 15: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.008	-0.004	-0.002	0.002
Reference Cell (volts)	0.547	0.276	0.284	0.282
Anode Voltage	4.0	51.1	45.7	49.3
Anode Current (amps)	0.52	0.45	0.50	0.17
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.130	0.009	0.011	0.003
Voltage drop in ref. circuit				

 # 16: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.014	0.002	0.000	0.003
Reference Cell (volts)	0.717	0.276	0.262	0.289
Anode Voltage	6.1	19.8	21.2	49.0
Anode Current (amps)	0.41	0.38	0.43	0.22
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.067	0.019	0.020	0.004
Voltage drop in ref. circuit				

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)	0.010	0.001	0.002	0.004
Reference Cell (volts)	0.788	0.382	0.493	0.457
Anode Voltage	9.4	28.5	26.6	31.1
Anode Current (amps)	0.43	0.26	0.33	0.14
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.085	0.010	0.013	0.005
Voltage drop in ref. circuit				

Date:	8/18/89	9/19/89	10/31/89	11/28/89
Days since last reading:	32	32	42	28
Days since start-up (10/28/88):	294	326	368	396
Tester:	DR	DR	DR	DR

 # 11: HOT-SPRAYED ZINC

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	-0.001	0.000	-0.001	-0.001
Reference Cell (volts)	0.302	0.299	0.307	0.307
Anode Voltage	25.4	25.5	26.0	27.1
Anode Current (amps)	0.12	0.05	0.10	0.04
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.005	0.002	0.004	0.001
Voltage drop in ref. circuit				

 # 12: HOT-SPRAYED ZINC

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.005	0.003	0.002	0.001
Reference Cell (volts)	0.274	0.301	0.199	0.237
Anode Voltage	24.1	24.6	24.8	25.2
Anode Current (amps)	0.04	0.02	0.09	0.02
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.002	0.001	0.004	0.001
Voltage drop in ref. circuit				

 # 13: HOT-SPRAYED ZINC

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.003	0.001	0.001	0.001
Reference Cell (volts)	0.556	0.595	0.509	0.499
Anode Voltage	25.4	25.6	25.5	27.4
Anode Current (amps)	0.08	0.03	0.09	0.36
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.003	0.001	0.004	0.013
Voltage drop in ref. circuit				

 # 14: HOT-SPRAYED ZINC

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.005	0.004	0.003	0.001
Reference Cell (volts)	0.812	0.872	0.412	0.205
Anode Voltage	22.2	50.1	52.1	56.3
Anode Current (amps)	0.15	0.23	0.21	0.19
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.007	0.005	0.004	0.003
Voltage drop in ref. circuit				

 # 15: HOT-SPRAYED ZINC

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.001	-0.001	-0.001	-0.001
Reference Cell (volts)	0.285	0.273	0.270	0.220
Anode Voltage	49.2	49.5	50.3	53.9
Anode Current (amps)	0.10	0.20	0.29	0.63
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.002	0.004	0.006	0.012
Voltage drop in ref. circuit				

 # 16: HOT-SPRAYED ZINC

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.002	0.001	-0.001	-0.001
Reference Cell (volts)	0.333	0.373	0.385	0.395
Anode Voltage	49.1	49.5	49.9	53.5
Anode Current (amps)	0.18	0.08	0.17	0.86
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.004	0.002	0.003	0.016
Voltage drop in ref. circuit				

11-16: AVERAGE VALUES: ZINC

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.003	0.001	0.001	0.000
Reference Cell (volts)	0.427	0.452	0.347	0.311
Anode Voltage	32.6	37.5	38.1	40.6
Anode Current (amps)	0.11	0.10	0.16	0.35
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.004	0.002	0.004	0.008
Voltage drop in ref. circuit				

Date:	1/9/90	1/17/90	4/26/90	11/19/90
Days since last reading:	12	8	99	207
Days since start-up (10/28/88):	408	416	515	722
Tester:	DR,DE	DR	DE,TD	JM,DE

 # 11: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.000	0.001	0.000	0.001
Reference Cell (volts)	0.306	0.314	0.300	0.282
Anode Voltage	26.4	26.2	25.7	25.2
Anode Current (amps)	0.03	0.06	0.14	0.35
Ref. Cell Instant-off (volts)	0.296		0.299	0.276
Conductance (mhos)	0.001	0.002	0.005	0.014
Voltage drop in ref. circuit	0.010		0.001	0.006

 # 12: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.002	0.003	0.002	0.002
Reference Cell (volts)	0.277	0.188	0.179	0.229
Anode Voltage	25.3	25.0	24.8	25.1
Anode Current (amps)	0.03	0.04	0.05	2.28
Ref. Cell Instant-off (volts)	0.303		0.172	0.172
Conductance (mhos)	0.001	0.002	0.002	0.091
Voltage drop in ref. circuit	-0.026		0.007	0.057

 # 13: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.001	0.001	-0.002	-0.002
Reference Cell (volts)	0.572	0.507	0.482	0.585
Anode Voltage	26.0	25.5	25.3	25.9
Anode Current (amps)	0.21	0.07	0.14	1.22
Ref. Cell Instant-off (volts)	0.634		0.493	0.564
Conductance (mhos)	0.008	0.003	0.006	0.047
Voltage drop in ref. circuit	-0.062		-0.011	0.021

 # 14: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.002	0.005	0.004	0.002
Reference Cell (volts)	0.372	0.900	0.350	0.217
Anode Voltage	52.6	52.0	50.8	50.5
Anode Current (amps)	0.14	0.17	0.27	1.47
Ref. Cell Instant-off (volts)	0.320		0.340	0.212
Conductance (mhos)	0.003	0.003	0.005	0.029
Voltage drop in ref. circuit	0.052		0.010	0.005

 # 15: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.002	-0.001	-0.001	0.000
Reference Cell (volts)	0.258	0.265	0.301	0.296
Anode Voltage	51.7	51.0	49.6	49.8
Anode Current (amps)	0.16	0.09	0.17	1.00
Ref. Cell Instant-off (volts)	0.259		0.299	0.279
Conductance (mhos)	0.003	0.002	0.003	0.020
Voltage drop in ref. circuit	-0.001		0.002	0.017

 # 16: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.001	-0.001	-0.001	-0.001
Reference Cell (volts)	0.414	0.405	0.407	0.400
Anode Voltage	50.8	49.5	48.5	49.8
Anode Current (amps)	0.15	0.15	0.10	1.96
Ref. Cell Instant-off (volts)	0.405		0.411	0.398
Conductance (mhos)	0.003	0.003	0.002	0.039
Voltage drop in ref. circuit	0.009		-0.004	0.002

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)	0.000	0.001	0.000	0.000
Reference Cell (volts)	0.367	0.430	0.337	0.335
Anode Voltage	38.8	38.2	37.5	37.7
Anode Current (amps)	0.12	0.10	0.15	1.38
Ref. Cell Instant-off (volts)	0.370		0.336	0.317
Conductance (mhos)	0.003	0.002	0.004	0.040
Voltage drop in ref. circuit	-0.003		0.001	0.018

Date:	3/28/91	5/15/91	7/31/91	8/16/91
Days since last reading:	129	48	77	16
Days since start-up (10/28/88):	851	899	976	992
Tester:	DE,KC	DE	DE	JM,DE

 # 11: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.002	0.003	0.003	0.003
Reference Cell (volts)	0.289	0.268	0.253	0.263
Anode Voltage	25.7	25.4	25.0	24.8
Anode Current (amps)	0.05	0.03	0.02	0.03
Ref. Cell Instant-off (volts)	0.287	0.270	0.259	0.267
Conductance (mhos)	0.002	0.001	0.001	0.001
Voltage drop in ref. circuit	0.002	-0.002	-0.006	-0.004

 # 12: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.002	0.004	0.003	0.004
Reference Cell (volts)	0.232	0.184	0.224	0.144
Anode Voltage	0.5	25.2	25.2	25.1
Anode Current (amps)	0.00	0.03	0.01	0.01
Ref. Cell Instant-off (volts)	0.227	0.175	0.226	0.140
Conductance (mhos)	0.000	0.001	0.000	0.000
Voltage drop in ref. circuit	0.005	0.009	-0.002	0.004

 # 13: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.000	0.001	0.002	0.001
Reference Cell (volts)	0.549	0.460	0.544	0.471
Anode Voltage	26.5	26.5	26.2	25.3
Anode Current (amps)	0.04	0.03	0.01	0.02
Ref. Cell Instant-off (volts)	0.547	0.478	0.546	0.478
Conductance (mhos)	0.002	0.001	0.000	0.001
Voltage drop in ref. circuit	0.002	-0.018	-0.002	-0.007

 # 14: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.002	0.003	0.003	0.004
Reference Cell (volts)	0.289	0.277	0.237	0.245
Anode Voltage	51.2	50.2	49.6	49.4
Anode Current (amps)	0.70	0.20	0.06	0.09
Ref. Cell Instant-off (volts)	0.290	0.276	0.241	0.245
Conductance (mhos)	0.014	0.004	0.001	0.002
Voltage drop in ref. circuit	-0.001	0.001	-0.004	0.000

 # 15: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.001	0.002	0.002	0.003
Reference Cell (volts)	0.307	0.295	0.280	0.285
Anode Voltage	49.7	49.9	49.7	49.1
Anode Current (amps)	0.20	0.07	0.01	0.02
Ref. Cell Instant-off (volts)	0.306	0.300	0.285	0.288
Conductance (mhos)	0.004	0.001	0.000	0.000
Voltage drop in ref. circuit	0.001	-0.005	-0.005	-0.003

 # 16: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.000	0.002	0.000	0.002
Reference Cell (volts)	0.400	0.367	0.381	0.403
Anode Voltage	50.9	50.5	49.3	49.2
Anode Current (amps)	0.55	0.05	0.02	0.03
Ref. Cell Instant-off (volts)	0.398	0.267	0.390	0.409
Conductance (mhos)	0.011	0.001	0.000	0.001
Voltage drop in ref. circuit	0.002	0.100	-0.009	-0.006

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)	0.001	0.003	0.002	0.003
Reference Cell (volts)	0.344	0.309	0.320	0.302
Anode Voltage	34.1	38.0	37.5	37.2
Anode Current (amps)	0.26	0.07	0.02	0.03
Ref. Cell Instant-off (volts)	0.343	0.294	0.325	0.305
Conductance (mhos)	0.005	0.002	0.001	0.001
Voltage drop in ref. circuit	0.002	0.014	-0.005	-0.003

Date:	9/10/91	10/9/91	1/7/92	3/19/92
Days since last reading:	25	29	90	72
Days since start-up (10/28/88):	1,017	1,046	1,136	1,208
Tester:	DE	DE	DE	DE

 # 11: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.003	0.003	0.001	0.001
Reference Cell (volts)	0.247	0.245	0.263	0.273
Anode Voltage	25.4	25.6	25.5	26.2
Anode Current (amps)	0.00	0.01	0.02	0.01
Ref. Cell Instant-off (volts)	0.246	0.243	0.263	0.273
Conductance (mhos)	0.000	0.000	0.001	0.000
Voltage drop in ref. circuit	0.001	0.002	0.000	0.000

 # 12: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.003	0.003	0.001	0.001
Reference Cell (volts)	0.215	0.162	0.233	0.150
Anode Voltage	25.5	25.2	25.2	25.1
Anode Current (amps)	0.01	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.215	0.123	0.189	0.145
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.039	0.044	0.005

 # 13: HOT-SPRAYED ZINC

Rebar Probe (volts)	-0.001	0.000	0.001	0.000
Reference Cell (volts)	0.545	0.513	0.600	0.413
Anode Voltage	26.2	26.4	26.1	26.9
Anode Current (amps)	0.01	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.545	0.489	0.547	0.434
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.024	0.053	-0.021

 # 14: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.003	0.003	0.000	0.001
Reference Cell (volts)	0.248	0.248	0.293	0.258
Anode Voltage	50.2	50.6	49.8	51.3
Anode Current (amps)	0.05	0.03	0.05	0.04
Ref. Cell Instant-off (volts)	0.235	0.247	0.311	0.252
Conductance (mhos)	0.001	0.001	0.001	0.001
Voltage drop in ref. circuit	0.013	0.001	-0.018	0.006

 # 15: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.003	0.003	0.000	0.001
Reference Cell (volts)	0.274	0.264	0.290	0.247
Anode Voltage	50.1	50.2	49.6	50.0
Anode Current (amps)	0.01	0.01	0.01	0.01
Ref. Cell Instant-off (volts)	0.275	0.266	0.296	0.244
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	-0.001	-0.002	-0.006	0.003

 # 16: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.001	0.001	-0.001	-0.001
Reference Cell (volts)	0.381	0.406	0.425	0.400
Anode Voltage	50.3	50.7	49.9	51.1
Anode Current (amps)	0.02	0.02	0.02	0.02
Ref. Cell Instant-off (volts)	0.383	0.407	0.418	0.405
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	-0.002	-0.001	0.007	-0.005

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)	0.002	0.002	0.000	0.000
Reference Cell (volts)	0.318	0.306	0.351	0.290
Anode Voltage	38.0	38.1	37.7	38.4
Anode Current (amps)	0.02	0.02	0.02	0.02
Ref. Cell Instant-off (volts)	0.317	0.296	0.337	0.292
Conductance (mhos)	0.000	0.000	0.001	0.000
Voltage drop in ref. circuit	0.002	0.011	0.013	-0.002

Date:	4/17/92	5/15/92	6/11/92	Date:
Days since last reading:	29	28	27	Days since last reading:
Days since start-up (10/28/88):	1,237	1,265	1,292	Days since start-up (10/28/88):
Tester:	DE	DE	DE	Tester:

 # 11: HOT-SPRAYED ZINC   **# 11: HOT-SPRAYED ZINC**

Rebar Probe (volts)	0.002	0.002	0.003	Rebar Probe (volts)
Reference Cell (volts)	0.270	0.253	0.254	Reference Cell (volts)
Anode Voltage	25.7	25.4	25.6	Anode Voltage
Anode Current (amps)	0.01	0.01	0.02	Anode Current (amps)
Ref. Cell Instant-off (volts)	0.264	0.253	0.253	Ref. Cell Instant-off (volts)
Conductance (mhos)	0.000	0.000	0.001	Conductance (mhos)
Voltage drop in ref. circuit	0.006	0.000	0.001	Voltage drop in ref. circuit

 # 12: HOT-SPRAYED ZINC   **# 12: HOT-SPRAYED ZINC**

Rebar Probe (volts)	0.001	0.002	0.003	Rebar Probe (volts)
Reference Cell (volts)	0.155	0.127	0.142	Reference Cell (volts)
Anode Voltage	25.5	25.2	25.6	Anode Voltage
Anode Current (amps)	0.01	0.01	0.01	Anode Current (amps)
Ref. Cell Instant-off (volts)	0.147	0.117	0.139	Ref. Cell Instant-off (volts)
Conductance (mhos)	0.000	0.000	0.000	Conductance (mhos)
Voltage drop in ref. circuit	0.008	0.010	0.003	Voltage drop in ref. circuit

 # 13: HOT-SPRAYED ZINC   **# 13: HOT-SPRAYED ZINC**

Rebar Probe (volts)	-0.001	0.000	0.001	Rebar Probe (volts)
Reference Cell (volts)	0.428	0.437	0.439	Reference Cell (volts)
Anode Voltage	26.8	26.2	26.0	Anode Voltage
Anode Current (amps)	0.01	0.01	0.03	Anode Current (amps)
Ref. Cell Instant-off (volts)	0.442	0.473	0.444	Ref. Cell Instant-off (volts)
Conductance (mhos)	0.000	0.000	0.001	Conductance (mhos)
Voltage drop in ref. circuit	-0.014	-0.036	-0.005	Voltage drop in ref. circuit

 # 14: HOT-SPRAYED ZINC   **# 14: HOT-SPRAYED ZINC**

Rebar Probe (volts)	0.002	0.003	0.003	Rebar Probe (volts)
Reference Cell (volts)	0.286	0.275	0.279	Reference Cell (volts)
Anode Voltage	50.0	49.5	49.4	Anode Voltage
Anode Current (amps)	0.04	0.05	0.09	Anode Current (amps)
Ref. Cell Instant-off (volts)	0.281	0.267	0.277	Ref. Cell Instant-off (volts)
Conductance (mhos)	0.001	0.001	0.002	Conductance (mhos)
Voltage drop in ref. circuit	0.005	0.008	0.002	Voltage drop in ref. circuit

 # 15: HOT-SPRAYED ZINC   **# 15: HOT-SPRAYED ZINC**

Rebar Probe (volts)	0.001	0.002	0.003	Rebar Probe (volts)
Reference Cell (volts)	0.266	0.266	0.275	Reference Cell (volts)
Anode Voltage	50.1	49.9	50.1	Anode Voltage
Anode Current (amps)	0.02	0.02	0.02	Anode Current (amps)
Ref. Cell Instant-off (volts)	0.262	0.267	0.276	Ref. Cell Instant-off (volts)
Conductance (mhos)	0.000	0.000	0.000	Conductance (mhos)
Voltage drop in ref. circuit	0.004	-0.001	-0.001	Voltage drop in ref. circuit

 # 16: HOT-SPRAYED ZINC   **# 16: HOT-SPRAYED ZINC**

Rebar Probe (volts)	0.000	0.001	0.002	Rebar Probe (volts)
Reference Cell (volts)	0.409	0.414	0.414	Reference Cell (volts)
Anode Voltage	50.4	50.5	50.5	Anode Voltage
Anode Current (amps)	0.02	0.03	0.03	Anode Current (amps)
Ref. Cell Instant-off (volts)	0.402	0.410	0.418	Ref. Cell Instant-off (volts)
Conductance (mhos)	0.000	0.001	0.001	Conductance (mhos)
Voltage drop in ref. circuit	0.007	0.004	-0.004	Voltage drop in ref. circuit

11-16: AVERAGE VALUES: ZINC   **11-16: AVERAGE VALUES: ZINC**

Rebar Probe (volts)	0.001	0.002	0.003	Rebar Probe (volts)
Reference Cell (volts)	0.302	0.295	0.301	Reference Cell (volts)
Anode Voltage	38.1	37.8	37.9	Anode Voltage
Anode Current (amps)	0.02	0.02	0.03	Anode Current (amps)
Ref. Cell Instant-off (volts)	0.300	0.298	0.301	Ref. Cell Instant-off (volts)
Conductance (mhos)	0.000	0.001	0.001	Conductance (mhos)
Voltage drop in ref. circuit	0.003	-0.003	-0.001	Voltage drop in ref. circuit

7/9/92	8/7/92	8/25/92	9/22/92	Date:	1/8/93	2/12/93
28	29	18	28	Days since last reading:	108	35
1,320	1,349	1,367	1,395	Days since start-up (10/28/88):	1,503	1,538
DE	HP,RF	DE	DE	Tester:	DE	DE

11: HOT-SPRAYED ZINC

7/9/92	8/7/92	8/25/92	9/22/92		1/8/93	2/12/93
0.003	0.003	0.003	0.002	Rebar Probe (volts)	0.002	0.001
0.250	0.248	0.236	0.227	Reference Cell (volts)	0.282	0.292
25.6	25.3	24.8	25.7	Anode Voltage	25.2	25.2
0.02	0.02	0.04	0.03	Anode Current (amps)	0.01	0.02
0.251	0.226	0.235	0.227	Ref. Cell Instant-off (volts)	0.280	0.288
0.001	0.001	0.002	0.001	Conductance (mhos)	0.000	0.001
-0.001	0.022	0.001	0.000	Voltage drop in ref. circuit	0.002	0.004

12: HOT-SPRAYED ZINC

7/9/92	8/7/92	8/25/92	9/22/92		1/8/93	2/12/93
0.002	0.003	0.002	0.001	Rebar Probe (volts)	0.001	0.001
0.140	0.138	0.124	0.119	Reference Cell (volts)	0.199	0.183
24.9	24.9	24.6	25.1	Anode Voltage	25.0	24.8
0.02	0.00	0.13	0.02	Anode Current (amps)	0.01	0.01
0.138	0.126		0.118	Ref. Cell Instant-off (volts)	0.197	0.177
0.001	0.000	0.005	0.001	Conductance (mhos)	0.000	0.000
0.002	0.012	0.124	0.001	Voltage drop in ref. circuit	0.002	0.006

13: HOT-SPRAYED ZINC

7/9/92	8/7/92	8/25/92	9/22/92		1/8/93	2/12/93
0.001	0.002	0.001	-0.001	Rebar Probe (volts)	0.001	-0.001
0.400	0.409	0.403	0.38	Reference Cell (volts)	0.375	0.383
26.0	26.0	24.4	26.0	Anode Voltage	25.6	26.0
0.03	0.18	0.10	0.18	Anode Current (amps)	0.02	0.02
0.404	0.360	0.408	0.385	Ref. Cell Instant-off (volts)	0.375	0.380
0.001	0.007	0.004	0.007	Conductance (mhos)	0.001	0.001
-0.004	0.049	-0.005	-0.005	Voltage drop in ref. circuit	0.000	0.003

14: HOT-SPRAYED ZINC

7/9/92	8/7/92	8/25/92	9/22/92		1/8/93	2/12/93
0.002	0.002	0.002	0.001	Rebar Probe (volts)	0.001	0.001
0.266	0.256	0.260	0.244	Reference Cell (volts)	0.276	0.315
51.0	48.5	47.9	51.3	Anode Voltage	49.7	49.8
0.04	0.05	0.07	0.16	Anode Current (amps)	0.04	0.06
0.268	0.201	0.261	0.244	Ref. Cell Instant-off (volts)	0.276	0.311
0.001	0.001	0.001	0.003	Conductance (mhos)	0.001	0.001
-0.002	0.055	-0.001	0.000	Voltage drop in ref. circuit	0.000	0.004

15: HOT-SPRAYED ZINC

7/9/92	8/7/92	8/25/92	9/22/92		1/8/93	2/12/93
0.002	0.002	0.002	0.002	Rebar Probe (volts)	0.001	0.001
0.254	0.278	0.278	0.257	Reference Cell (volts)	0.274	0.283
49.2	49.2	48.1	49.9	Anode Voltage	49.0	49.2
0.03	0.03	0.04	0.17	Anode Current (amps)	0.04	0.05
0.256	0.279	0.280	0.26	Ref. Cell Instant-off (volts)	0.273	0.279
0.001	0.001	0.001	0.003	Conductance (mhos)	0.001	0.001
-0.002	-0.001	-0.002	-0.003	Voltage drop in ref. circuit	0.001	0.004

16: HOT-SPRAYED ZINC

7/9/92	8/7/92	8/25/92	9/22/92		1/8/93	2/12/93
0.002	0.002	0.001	0	Rebar Probe (volts)	0.001	0.000
0.419	0.404	0.401	0.412	Reference Cell (volts)	0.367	0.395
49.6	49.4	47.6	49.6	Anode Voltage	48.6	49.0
0.03	0.03	0.05	0.14	Anode Current (amps)	0.03	0.05
0.423	0.399	0.402	0.413	Ref. Cell Instant-off (volts)	0.367	0.393
0.001	0.001	0.001	0.003	Conductance (mhos)	0.001	0.001
-0.004	0.005	-0.001	-0.001	Voltage drop in ref. circuit	0.000	0.002

11-16: AVERAGE VALUES: ZINC

7/9/92	8/7/92	8/25/92	9/22/92		1/8/93	2/12/93
0.002	0.002	0.002	0.001	Rebar Probe (volts)	0.001	0.001
0.288	0.289	0.284	0.273	Reference Cell (volts)	0.296	0.309
37.7	37.2	36.2	37.9	Anode Voltage	37.2	37.3
0.03	0.05	0.07	0.12	Anode Current (amps)	0.03	0.04
0.290	0.265	0.264	0.275	Ref. Cell Instant-off (volts)	0.295	0.305
0.001	0.002	0.002	0.003	Conductance (mhos)	0.001	0.001
-0.002	0.024	0.019	-0.001	Voltage drop in ref. circuit	0.001	0.004

2/26/93	2/26/93	Date:	3/5/93	3/18/93	4/27/93	5/28/93
14	0.50	Days since last reading:	7	13	40	31
1,552	1,553	Days since start-up (10/28/88):	1,560	1,573	1,613	1,644
RF	RF	Tester:	RF	HP,RF	DE,JS	DE,TM

 # 11: HOT-SPRAYED ZINC

2/26/93	2/26/93		3/5/93	3/18/93	4/27/93	5/28/93
0.001	0.002	Rebar Probe (volts)	0.001	0.000	0.002	0.003
0.296	0.289	Reference Cell (volts)	0.273	0.164	0.258	0.252
25.1	0.1	Anode Voltage	0.3	0.2	0.4	0.5
0.02	0.00	Anode Current (amps)	0.00	0.00	0.00	0.01
0.295	0.289	Ref. Cell Instant-off (volts)	0.273	0.164	0.258	0.252
0.001	0.000	Conductance (mhos)	0.000	0.000	0.000	0.020
0.001	0.000	Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 12: HOT-SPRAYED ZINC

2/26/93	2/26/93		3/5/93	3/18/93	4/27/93	5/28/93
0.000	0.001	Rebar Probe (volts)	0.000	0.001	0.002	0.002
0.183	0.154	Reference Cell (volts)	0.131	0.150	0.123	0.129
24.7	0.2	Anode Voltage	0.1	0.0	0.1	0.1
0.02	0.00	Anode Current (amps)	0.00	0.00	0.00	0.00
0.183	0.154	Ref. Cell Instant-off (volts)	0.131	0.150	0.123	0.129
0.001	0.000	Conductance (mhos)	0.000	0.000	0.000	0.000
0.000	0.000	Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 13: HOT-SPRAYED ZINC

2/26/93	2/26/93		3/5/93	3/18/93	4/27/93	5/28/93
-0.001	0.000	Rebar Probe (volts)	-0.001	0.000	0.000	0.001
0.394	0.406	Reference Cell (volts)	0.366	0.384	0.367	0.384
25.8	0.7	Anode Voltage	0.5	0.3	0.5	0.6
0.02	0.00	Anode Current (amps)	0.00	0.00	0.01	0.02
0.394	0.406	Ref. Cell Instant-off (volts)	0.366	0.384	0.367	0.384
0.001	0.000	Conductance (mhos)	0.000	0.000	0.020	0.033
0.000	0.000	Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 14: HOT-SPRAYED ZINC

2/26/93	2/26/93		3/5/93	3/18/93	4/27/93	5/28/93
0.000	-0.001	Rebar Probe (volts)	0.000	0.001	0.002	0.002
0.316	0.308	Reference Cell (volts)	0.228	0.272	0.271	0.255
49.8	0.3	Anode Voltage	0.2	0.1	0.1	0.1
0.04	0.00	Anode Current (amps)	0.00	0.00	0.00	0.00
0.316	0.308	Ref. Cell Instant-off (volts)	0.228	0.272	0.271	0.255
0.001	0.000	Conductance (mhos)	0.000	0.000	0.000	0.000
0.000	0.000	Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 15: HOT-SPRAYED ZINC

2/26/93	2/26/93		3/5/93	3/18/93	4/27/93	5/28/93
0.000	0.001	Rebar Probe (volts)	0.001	0.001	0.002	0.003
0.276	0.272	Reference Cell (volts)	0.290	0.267	0.264	0.291
49.0	0.3	Anode Voltage	0.2	0.3	0.2	0.1
0.14	0.00	Anode Current (amps)	0.00	0.00	0.00	0.00
0.276	0.272	Ref. Cell Instant-off (volts)	0.290	0.267	0.264	0.291
0.003	0.000	Conductance (mhos)	0.000	0.000	0.000	0.000
0.000	0.000	Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 16: HOT-SPRAYED ZINC

2/26/93	2/26/93		3/5/93	3/18/93	4/27/93	5/28/93
-0.001	0.002	Rebar Probe (volts)	-0.001	0.000	0.001	0.001
0.407	0.423	Reference Cell (volts)	0.391	0.418	0.423	0.398
49.0	0.2	Anode Voltage	-0.3	-0.2	0.0	0.0
0.04	0.00	Anode Current (amps)	0.00	0.00	0.00	0.00
0.407	0.423	Ref. Cell Instant-off (volts)	0.391	0.418	0.423	0.398
0.001	0.000	Conductance (mhos)	0.000	0.000	0.000	0.000
0.000	0.000	Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

11-16: AVERAGE VALUES: ZINC

2/26/93	2/26/93		3/5/93	3/18/93	4/27/93	5/28/93
0.000	0.001	Rebar Probe (volts)	0.000	0.001	0.002	0.002
0.312	0.309	Reference Cell (volts)	0.280	0.276	0.284	0.285
37.2	0.3	Anode Voltage	0.2	0.1	0.2	0.2
0.05	0.00	Anode Current (amps)	0.00	0.00	0.00	0.01
0.312	0.309	Ref. Cell Instant-off (volts)	0.280	0.276	0.284	0.285
0.001	0.000	Conductance (mhos)	0.000	0.000	0.003	0.009
0.000	0.000	Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

Date:	6/30/93	8/31/93	10/7/93	11/2/93
Days since last reading:	33	62	37	26
Days since start-up (10/28/88):	1,677	1,739	1,776	1,802
Tester:	DE	DE	PN	PN

 # 11: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.005	0.004	0.005	
Reference Cell (volts)	0.240	0.263	0.240	0.277
Anode Voltage	0.5	0.4	0.5	0.3
Anode Current (amps)	0.01	0.00	0.01	0.00
Ref. Cell Instant-off (volts)	0.240	0.263	0.240	
Conductance (mhos)	0.020	0.000	0.020	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.277

 # 12: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.120	0.165	0.120	0.164
Anode Voltage	0.2	0.3	0.2	0.5
Anode Current (amps)	0.00	0.00	0.00	0.00
Ref. Cell Instant-off (volts)	0.120	0.165	0.120	
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.164

 # 13: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.351	0.348	0.351	0.325
Anode Voltage	0.5	0.1	0.5	0.4
Anode Current (amps)	0.01	0.01	0.01	0.00
Ref. Cell Instant-off (volts)	0.351	0.348	0.351	0.325
Conductance (mhos)	0.020	0.100	0.020	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 14: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.247	0.262	0.247	0.325
Anode Voltage	0.1	0.1	0.1	0.4
Anode Current (amps)	0.00	0.00	0.00	0.00
Ref. Cell Instant-off (volts)	0.247	0.262	0.247	
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.325

 # 15: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.005	0.004	0.005	
Reference Cell (volts)	0.279	0.283	0.279	0.318
Anode Voltage	0.1	0.1	0.1	0.0
Anode Current (amps)	0.00	0.00	0.00	0.00
Ref. Cell Instant-off (volts)	0.279	0.283	0.279	0.318
Conductance (mhos)	0.000	0.000	0.000	0.000
Voltage drop in ref. circuit	0.000	0.000	0.000	0.000

 # 16: HOT-SPRAYED ZINC

Rebar Probe (volts)	0.003	0.003	0.003	
Reference Cell (volts)	0.371	0.358	0.371	0.409
Anode Voltage	0.0	-0.3	0.0	-0.2
Anode Current (amps)	0.00	0.00	0.00	-0.03
Ref. Cell Instant-off (volts)	0.371	0.358	0.371	
Conductance (mhos)	#DIV/0!	0.000	#DIV/0!	0.150
Voltage drop in ref. circuit	0.000	0.000	0.000	0.409

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)	0.004	0.003	0.004	
Reference Cell (volts)	0.268	0.280	0.268	0.303
Anode Voltage	0.2	0.1	0.2	0.2
Anode Current (amps)	0.00	0.00	0.00	-0.01
Ref. Cell Instant-off (volts)	0.268	0.280	0.268	
Conductance (mhos)	#DIV/0!	0.017	#DIV/0!	0.025
Voltage drop in ref. circuit	0.000	0.000	0.000	0.196

Date:	11/24/93	12/22/93	12/23/93
Days since last reading:	22	28	1
Days since start-up (10/28/88):	1,824	1,852	1,853
Tester:	PN	PN	PN

 # 11: HOT-SPRAYED ZINC

Rebar Probe (volts)			
Reference Cell (volts)	0.270	0.291	0.249
Anode Voltage	0.3	0.3	0.2
Anode Current (amps)	0.00	0.00	0.24
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.000	0.000	1.039
Voltage drop in ref. circuit	0.270	0.291	0.249

 # 12: HOT-SPRAYED ZINC

Rebar Probe (volts)			
Reference Cell (volts)	0.140	0.207	0.165
Anode Voltage	0.4	0.3	0.3
Anode Current (amps)	0.03	0.00	0.09
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.067	0.000	0.261
Voltage drop in ref. circuit	0.140	0.207	0.165

 # 13: HOT-SPRAYED ZINC

Rebar Probe (volts)			
Reference Cell (volts)	0.320	0.313	0.266
Anode Voltage	0.4	0.2	0.2
Anode Current (amps)	0.00	0.00	0.15
Ref. Cell Instant-off (volts)	0.320	0.313	0.266
Conductance (mhos)	0.000	0.000	0.647
Voltage drop in ref. circuit	0.000	0.000	0.000

 # 14: HOT-SPRAYED ZINC

Rebar Probe (volts)			
Reference Cell (volts)	0.295	0.355	0.275
Anode Voltage	0.0	0.0	-0.1
Anode Current (amps)	0.00	0.00	0.18
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.000	0.000	-2.308
Voltage drop in ref. circuit	0.295	0.355	0.275

 # 15: HOT-SPRAYED ZINC

Rebar Probe (volts)			
Reference Cell (volts)	0.265	0.300	0.245
Anode Voltage	0.1	0.9	0.5
Anode Current (amps)	0.00	0.00	0.12
Ref. Cell Instant-off (volts)	0.265	0.300	0.245
Conductance (mhos)	0.000	0.000	0.221
Voltage drop in ref. circuit	0.000	0.000	0.000

 # 16: HOT-SPRAYED ZINC

Rebar Probe (volts)			
Reference Cell (volts)	0.398	0.359	0.321
Anode Voltage	-0.2	-0.3	-0.2
Anode Current (amps)	0.00	0.03	0.15
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.000	-0.093	-0.882
Voltage drop in ref. circuit	0.398	0.359	0.321

11-16: AVERAGE VALUES: ZINC

Rebar Probe (volts)			
Reference Cell (volts)	0.281	0.304	0.254
Anode Voltage	0.2	0.2	0.2
Anode Current (amps)	0.01	0.01	0.16
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.011	-0.016	-0.171
Voltage drop in ref. circuit	0.184	0.202	0.168

Date:	10/28/88	10/28/88	12/13/88	12/15/88
Days since last reading:	0	0	46	2
Days since start-up (10/28/88):	0	0	46	48
Tester:	Corrpro	Corrpro	Corrpro	Corrpro

17: CONDUCTIVE PAINT

Rebar Probe (volts)	-0.00509	0.00851	0.013	0.011
Reference Cell (volts)	0.253	1.160	*OOS*	1.945
Anode Voltage	0.026	7.06	9.9	7.3
Anode Current (amps)	0.00	2.25	2.39	1.52
Ref. Cell Instant-off (volts)		0.400	0.956	0.691
Conductance (mhos)		0.319	0.241	0.208
Voltage drop in ref. circuit		0.760		1.254

Date:	1/31/89	2/1/89	2/2/89	3/13/89
Days since last reading:	47	1	1	39
Days since start-up (10/28/88):	95	96	97	136
Tester:	Corrpro	Corrpro	Corrpro	MC,DR,DE

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.011	0.013	0.009	0.007
Reference Cell (volts)	1.929	1.335	1.209	1.040
Anode Voltage	7.9	5.5	7.0	9.5
Anode Current (amps)	1.49	1.29	1.31	1.36
Ref. Cell Instant-off (volts)	0.795	0.690	0.740	
Conductance (mhos)	0.189	0.235	0.187	0.143
Voltage drop in ref. circuit	1.134	0.645	0.469	

Date:	4/13/89	5/26/89	6/13/89	7/17/89
Days since last reading:	31	43	18	34
Days since start-up (10/28/88):	167	210	228	262
Tester:	DR,DE,TD	DR	JM,DR	DR,KC

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.009	0.010	0.004	0.008
Reference Cell (volts)	1.735	1.008	0.789	0.806
Anode Voltage	7.8	46.5	9.8	33.5
Anode Current (amps)	1.38	1.28	1.35	1.24
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.177	0.028	0.138	0.037
Voltage drop in ref. circuit				

Date:	8/18/89	9/19/89	10/31/89	11/28/89
Days since last reading:	32	32	42	28
Days since start-up (10/28/88):	294	326	368	396
Tester:	DR	DR	DR	DR

 # 17: CONDUCTIVE PAINT

	8/18/89	9/19/89	10/31/89	11/28/89
Rebar Probe (volts)	0.008	0.005	0.003	0.001
Reference Cell (volts)	1.064	1.054	0.758	0.302
Anode Voltage	27.2	26.8	49.6	60.6
Anode Current (amps)	1.27	1.28	1.28	0.20
Ref. Cell Instant-off (volts)				
Conductance (mhos)	0.047	0.048	0.026	0.003
Voltage drop in ref. circuit				

Date:	1/9/90	1/17/90	4/26/90	11/19/90
Days since last reading:	12	8	99	207
Days since start-up (10/28/88):	408	416	515	722
Tester:	DR,DE	DR	DE,TD	JM,DE

 # 17: CONDUCTIVE PAINT

	1/9/90	1/17/90	4/26/90	11/19/90
Rebar Probe (volts)	0.003	0.005	0.002	0.004
Reference Cell (volts)	0.701	1.492	0.647	1.192
Anode Voltage	51.5	22.1	7.8	27.6
Anode Current (amps)	1.00	1.25	1.35	2.66
Ref. Cell Instant-off (volts)	0.408		0.437	0.509
Conductance (mhos)	0.019	0.057	0.173	0.096
Voltage drop in ref. circuit	0.293		0.210	0.683

Date:	3/28/91	5/15/91	7/31/91	8/16/91
Days since last reading:	129	48	77	16
Days since start-up (10/28/88):	851	899	976	992
Tester:	DE,KC	DE	DE	JM,DE

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.002	0.004	0.003	0.006
Reference Cell (volts)	0.394	0.581	0.684	0.775
Anode Voltage	53.2	23.3	20.0	17.3
Anode Current (amps)	1.50	1.28	1.29	1.28
Ref. Cell Instant-off (volts)	0.308	0.367	0.407	0.427
Conductance (mhos)	0.028	0.055	0.065	0.074
Voltage drop in ref. circuit	0.086	0.214	0.277	0.348

Date:	9/10/91	10/9/91	1/7/92	3/19/92
Days since last reading:	25	29	90	72
Days since start-up (10/28/88):	1,017	1,046	1,136	1,208
Tester:	DE	DE	DE	DE

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.005	0.003	0.001	0.001
Reference Cell (volts)	0.770	0.668	0.578	0.424
Anode Voltage	40.3	50.0	15.2	50.2
Anode Current (amps)	1.27	0.85	1.32	0.74
Ref. Cell Instant-off (volts)	0.423	0.381	0.398	0.344
Conductance (mhos)	0.032	0.017	0.087	0.015
Voltage drop in ref. circuit	0.347	0.287	0.180	0.080

Date:	4/17/92	5/15/92	6/11/92
Days since last reading:	29	28	27
Days since start-up (10/28/88):	1,237	1,265	1,292
Tester:	DE	DE	DE

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.003	0.004	0.005
Reference Cell (volts)	0.472	0.304	0.301
Anode Voltage	29.4	42.3	17.0
Anode Current (amps)	1.31	1.33	1.31
Ref. Cell Instant-off (volts)	0.366	0.231	0.138
Conductance (mhos)	0.045	0.031	0.077
Voltage drop in ref. circuit	0.106	0.073	0.163

Date:	7/9/92	8/7/92	8/25/92	9/22/92
Days since last reading:	28	29	18	28
Days since start-up (10/28/88):	1,320	1,349	1,367	1,395
Tester:	DE	HP,RF	DE	DE

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.003	0.003	0.011	0.002
Reference Cell (volts)	0.230	0.321	0.942	0.174
Anode Voltage	51.5	49.6	30.5	53.0
Anode Current (amps)	0.36	0.69	1.37	0.35
Ref. Cell Instant-off (volts)	0.187	0.238	0.331	0.153
Conductance (mhos)	0.007	0.014	0.045	0.007
Voltage drop in ref. circuit	0.043	0.083	0.611	0.021

Date:	1/8/93	2/12/93	2/26/93	2/26/93
Days since last reading:	108	35	14	0.50
Days since start-up (10/28/88):	1,503	1,538	1,552	1,553
Tester:	DE	DE	RF	RF

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.005	0.001	0.001	0.001
Reference Cell (volts)	0.621	0.190	0.108	0.126
Anode Voltage	33.1	49.2	50.2	50.3
Anode Current (amps)	1.38	0.88	0.46	0.56
Ref. Cell Instant-off (volts)	0.134	0.091	0.040	0.049
Conductance (mhos)	0.042	0.018	0.009	0.011
Voltage drop in ref. circuit	0.487	0.099	0.068	0.077

Date:	3/5/93	3/18/93	4/27/93	5/28/93
Days since last reading:	7	13	40	31
Days since start-up (10/28/88):	1,560	1,573	1,613	1,644
Tester:	RF	HP,RF	DE,JS	DE,TM

 # 17: CONDUCTIVE PAINT

	3/5/93	3/18/93	4/27/93	5/28/93
Rebar Probe (volts)	0.001	0.002	0.002	0.003
Reference Cell (volts)	0.329	0.305	0.081	0.207
Anode Voltage	48.9	50.3	53.3	49.3
Anode Current (amps)	1.36	0.44	0.34	0.96
Ref. Cell Instant-off (volts)	0.204	0.112	0.047	0.162
Conductance (mhos)	0.028	0.009	0.006	0.019
Voltage drop in ref. circuit	0.125	0.193	0.034	0.045

Date:	6/30/93	8/31/93	10/7/93	11/2/93
Days since last reading:	33	62	37	26
Days since start-up (10/28/88):	1,677	1,739	1,776	1,802
Tester:	DE	DE	PN	PN

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)	0.003	0.005	0.003	
Reference Cell (volts)	0.354	0.457	0.354	0.354
Anode Voltage	51.8	48.0	51.8	51.8
Anode Current (amps)	0.66	1.79	0.66	0.66
Ref. Cell Instant-off (volts)	0.354	0.220	0.354	
Conductance (mhos)	0.013	0.037	0.013	0.013
Voltage drop in ref. circuit	0.000	0.237	0.000	0.354

Date:	11/24/93	12/22/93	12/23/93
Days since last reading:	22	28	1
Days since start-up (10/28/88):	1,824	1,852	1,853
Tester:	PN	PN	PN

 # 17: CONDUCTIVE PAINT

Rebar Probe (volts)			
Reference Cell (volts)	0.000	0.001	0.001
Anode Voltage	51.5	47.2	48.1
Anode Current (amps)	0.15	2.10	-5.01
Ref. Cell Instant-off (volts)			
Conductance (mhos)	0.003	0.044	-0.104
Voltage drop in ref. circuit	0.000	0.001	0.001