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Cathodic Protection of Concrete Bridges: A Manual of Practice

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Abstract

The purpose of this document is to provide explanation, guidance, and direction concerning cathodic protection of concrete bridge elements to the highway engineer who wants to incorporate cathodic protection in a bridge project. After providing background information on corrosion fundamentals, the manual is divided into three main sections: Design, Construction, and Operation and Maintenance. An appendix provides standard specifications for cathodic protection systems for both decks and substructures. These specifications are modeled after those currently being developed under the American Association of State Highway and Transportation Officials (AASHTO), Associated General Contractors (AGC) and American Road and Transportation Builders' Association (ARTBA) Task Force 29 and provide a basis for other sections of the manual. It is hoped that this document will be a useful reference for engineers who design and prepare specifications or who oversee turnkey operations.

Executive Summary

This manual provides information for Engineers and Highway Officials intending to use cathodic protection on reinforced concrete bridge elements.

"Introduction" and "Corrosion and Cathodic Protection Fundamentals" sections first provide the reader with background information on the nature and extent of the problem of corrosion of steel in concrete. The corrosion problem addressed in this manual is primarily that induced by chloride contamination resulting from the use of deicing salt or from seawater. Chloride ion in sufficient concentration disrupts the passive film which is normally present on steel in concrete, and exposes the reinforcing steel for corrosion. This is one of the most serious problems affecting the infrastructure today. Cathodic protection is a means of preventing or deterring this corrosion process by making the reinforcing steel a cathode, thus suppressing the current which flows from an anode in a corrosion cell.

Although many different types of systems have been tried for the cathodic protection of steel in concrete, systems described in this manual are restricted to those with a demonstrated successful history of use on several structures for at least two years. These include conductive coke-asphalt, slotted anode system, distributed anode with concrete encapsulation, conductive coating, and thermally sprayed zinc. Other systems, although they may prove useful in the future, are still considered experimental. Each of these systems is described in the three major parts of this manual: "Design", "Construction", and "Operation and Maintenance".

The first of the three major parts of this manual describes the design of the various cathodic protection systems used for both bridge decks and substructures. The design of the anode element is unique for each type of system. Calculation of anode voltage drop, which should not exceed 300 millivolts, is described for each anode system. There are many considerations which influence the selection of the system for a particular bridge element, including survey factors, economics, intended lifetime, and environmental, safety and traffic concerns, and these are all discussed in detail. Design current is based on a requirement of 1.5 milliamps per square foot of steel surface within 8 inches of the anode. Power supply design emphasizes simplicity, ruggedness, and reliability. Recommended reference cells include only silver/silver chloride and graphite. Two reference cells per zone are recommended, and the different criteria for locating reference cells are reviewed. Of these criteria, the most important is to place the reference cells in a highly anodic area.

Procedures for estimating the cost of a cathodic protection system are also provided. These procedures are based on data obtained from the literature, from actual monitored projects, and the experiences of the writers. Step-by-step examples are given.

The second part of this manual deals with construction issues for a cathodic protection system. Construction details for each type of anode system are described. It is important to insure that all metallic components to be protected are electrically continuous, and methods for testing and establishing continuity are described. Proper installation procedures for reference cells and other monitors are also covered. Two start-up and operating criteria are recommended in this manual: 100 millivolt polarization decay, and E log I analysis. The advantages and disadvantages of each criterion is discussed. The use of macrocell devices as indicators of the cathodic protection current required is also covered.

The third part of the manual deals with operation and maintenance of an installed and operational cathodic protection system. Monthly monitoring is recommended to provide assurance that the system is providing continuous service. By tracking the data in simple form, performance irregularities can be identified and simple adjustments made. Annual monitoring is conducted in greater detail, including testing of the system according to the accepted cathodic protection criteria. Adjustments in the level of protection are made at that time. Troubleshooting guidelines for typical cathodic protection systems are also provided.

The joint cooperative committee of American Association of State Highway and Transportation Officials (AASHTO), Associated General Contractors (AGC), and American Road and Transportation Builders' Association (ARTBA) Task Group 29 guide specifications for bridge deck cathodic protection systems are presented in the Appendix of this manual, and the body of the manual was written not to conflict with the AASHTO guide specifications. At the time of final submission of the manual document, the deck specifications were being prepared for AASHTO ballot. Significant changes in the document as a result of balloting are not expected.

1

Introduction

Corrosion is an electrochemical process in which the energy gained by steel in its conversion from iron ore is released. The released energy combines with chlorides and water in the environment that surrounds the reinforcing steel and produces the corrosive product that exerts detrimental tensile forces in the concrete. Cathodic protection supplies external energy in the form of direct current to the steel surface of the concrete. This process reverses the natural current flow and forces reinforcing steel to function as a current-receiving cathode, thereby controlling corrosion. This control is accomplished by using impressed direct current that makes the reinforcing steel receive energy (electrons) rather than lose it. When it loses energy, reinforcing steel corrodes. When it receives energy, the steel becomes the cathode in a cathodic protection system. The direct current is supplied from an anode, the second part of the circuit. The chloride-laden concrete is the conductor between the anode and the cathode, and the reinforcing steel and system wiring completes the electrical circuit.

Cathodic protection is the only standard procedure available to control corrosion and the resulting concrete damage in existing reinforced concrete bridge members. Therefore, its use should be considered whenever a structure is located in a severe chloride (de-icing salt or marine) environment. New and replacement members can be cathodically protected or prepared for cathodic protection during construction, but cathodic protection is more commonly installed as part of a rehabilitation procedure to extend the life of the structure.

The energy to power a cathodic protection system can be obtained from the small, naturally occurring voltage difference between metals. Such systems, called "sacrificial," work well under water and are being studied for above-ground applications in select, very moist environments. However, these systems are not detailed in this manual.

This manual has been prepared to help engineers select, design, construct and operate and maintain cathodic protection systems for above-ground reinforced concrete bridge members.

The first major use of cathodic protection to halt corrosion damage in reinforcing steel on bridge members occurred in 1973 with the installation of a coke-asphalt cathodic protection system on the Sly Park bridge deck in California. The developmental work for this installation was performed by Richard F. Stratfull and his associates from the California Department of Transportation. Since that time, a number of cathodic protection systems have been developed, tested, and implemented.

In 1982, the Federal Highway Administration (FHWA) issued a position paper that strongly endorsed the use of cathodic protection as a rehabilitation technique for bridge decks. By 1985, more than 4 million sq. ft. of above-ground reinforced concrete structures had been cathodically protected. By 1992, more than 350 cathodic protection systems had been installed on more than 10 million sq. ft. of bridge structures in North America, primarily on bridge decks.

The use of cathodic protection is NOT recommended on the following structures:

1. Prestressed and post-tensioned bridge members. This applies only to members that contain high-strength steel in the concrete that will be used to transmit current. It does not apply to conventionally reinforced bridge decks that are supported by prestressed girders. In such bridges, only the prestressed girders should not be directly protected.

2. Concrete members constructed with alkali-reactive aggregates. Cathodic protection will not halt alkali reactivity and may aggravate it.

All other reinforced concrete members are candidates for cathodic protection. There are, however, a number of factors that could influence the choice of anode system and the cost of that system. These are detailed in the Design section.

Most above-ground reinforced-concrete cathodic protection systems require external power and are called impressed-current systems. Power is usually obtained from the local public utility, although solar power is also feasible.

An impressed-current cathodic protection system requires only these basic components:

1. DC power source (rectifier).
2. Current distribution hardware (anode).
3. Conducting electrolyte (concrete).
4. Reinforcing steel being protected (cathode).
5. Complete circuit (wiring).
6. Evaluation and control devices (probes, reference cells, controller).

Cathodic protection systems (anodes) that are now commonly used are as follows:

1. Conductive Coke-Asphalt Overlay System. This system uses cast iron alloy anodes, a conductive asphaltic-concrete overlay, and a conventional asphaltic-concrete wearing surface.

2. Slotted Anode System. This system involves the insertion of an anode system made up of platinized wire, carbon strand, and conductive polymer grout into slots cut into the bridge deck. The system can be used with or without an overlay.

3. Distributed Anode System with Concrete Encapsulation. This system involves the placement of anodes on the concrete surface after repair and cleaning, followed by encapsulation of the anode in concrete. Encapsulation consists of an overlay for a bridge deck, and cast-in-place concrete or shotcrete for vertical and horizontal substructure surfaces. A conductive polymer-mound anode, similar to that described for slotted systems but without slots, and catalyzed titanium mesh anodes are the most common systems for decks. The catalyzed titanium mesh can also be used on vertical and overhead substructure elements.

4. Conductive Coating System. This system uses platinized wire and conductive carbon-based paints to cover the entire surface to be protected. The black conductive paint is typically covered with a gray cosmetic overcoat. This system is used primarily on nontraffic surfaces that are not seriously exposed to continuous wetting during either construction or operation.

5. Thermally Sprayed Zinc System. For this system, molten zinc is sprayed onto the entire concrete surface after repair and cleaning. It has been widely used on vertical and horizontal substructure members and experimentally used with an asphalt overlay on a bridge deck surface. Thermally sprayed zinc has also been experimentally used as a sacrificial anode (e.g., without an external power supply).

Typical construction costs and estimated service lives for these systems are presented in table 1. Other cathodic protection anodes currently under development include sprayed zinc with asphalt wearing surfaces, conductive polymer overlays, and titanium ribbon-slotted systems. Discussion of these systems is beyond the scope of this manual.

Cathodic protection can be implemented by highway agencies that do not have in-depth corrosion engineering expertise, detailed system designs, or project-specific plans and specifications. Agencies can use guide specifications in the appendix 650 for decks and 655 for substructures, which include detailed design, construction, inspection, and activation guidelines. The owner of the structure need only complete the appropriate design-specific checklist. These checklists define the owner's preferences with respect to the anode and other system components. The process can require as little as a few hours when the "Contractor Recommend" and "Contractor Design" options are selected for rectifiers and circuits, in which case, the state must answer only these questions:

- What are the elements to be protected (i.e., a deck or substructure)?
- What anode system is desired?
- Is a remote monitoring system desired and, if so, should it include an office computer?

Details for addressing these questions are presented in the "Design" section of this manual.

If the highway agency chooses to perform all or part of the corrosion engineering (i.e., detailed design, inspection, and activation) on its own, procedures for doing so are provided in the manual. In that case, the specifications in the appendix remain valid. However, sections 650.30 and 650.40 for decks or 655.30 and 655.40 for substructures must be appropriately modified.

The cost-estimating process has also been simplified so that an estimate for cathodic protection and overlay, if any, (but not traffic control) can be obtained in a few hours. The only required additional input information is as follows:

- Total surface area to be cathodically protected.
- Percent of the area that is delaminated and spalled.
- Amount of reinforcing steel cover.

All cathodic protection systems should be monitored and adjusted when needed. Normally, such adjustments are made annually during the first few years of operation, which is neither difficult nor costly. With remote monitoring, the monitoring can be done from the office without visiting each bridge site. Monitoring, adjustment, and maintenance cost estimates are provided along with the construction cost estimate in order to determine long-term costs.

This manual is organized into the following three main chapters:

Chapter 3, Design. This section provides step-by-step procedures for design of cathodic protection systems including cost estimating.

Chapter 4, Construction. Construction guidance is provided for each system.

Chapter 5, Operation and Maintenance. Instructions and guidelines for operation, testing, maintenance, and troubleshooting are provided.

Chapter 2 titled, "Corrosion and Cathodic Protection Fundamentals," was included to provide those responsible for overseeing a cathodic protection installation with an understanding of corrosion processes and prevention technology.

The guide specifications for both bridge deck and substructure cathodic protection systems and recommended practices and test methods are found in the appendix.

Cathodic protection is a proven, cost-effective method for controlling corrosion of reinforcing steel in above-ground reinforced concrete members. Several cathodic protection options are available and should be considered as alternatives for concrete protection in rehabilitation projects as well as in new construction.

Other cathodic protection anodes currently under development include sprayed zinc with asphalt wearing surfaces, conductive polymer overlays, and titanium ribbon-slotted systems. Discussion of these systems is beyond the scope of this manual.

Table 1. Available Cathodic Protection Systems, Estimated Cost and Service Life

Anode System	Structures Protected	Estimated Construction Cost, (U.S. $ per sq. ft.)	Estimated Service Life (years)[1]
Coke-asphalt overlay	Decks	6	20
Slotted conductive polymer grout	Decks	7	15
Mounded conductive polymer concrete overlay	Decks	9	20
Titanium mesh concrete overlay	Decks	9	35
Titanium mesh shotcrete	Substructures	14	35
Conductive paint	Substructures	7	5
Sprayed zinc without enclosure	Substructures	8	20
Sprayed zinc with enclosure	Substructures	14	20

1. Based on expert opinions of the authors of the report

2

Corrosion and Cathodic Protection Fundamentals

Corrosion of Metals

Metals are normally found in nature as oxides or variations of oxides. These metal oxides are called ores and are at their lowest, stable energy level. To obtain metal from ore, the ore is subjected to extreme heat to break the chemical attraction among the different elements. The metal is then subjected to alloying, rolling, bending, and other operations to obtain the desired finished product. All the refining and production steps add energy to the ore and raise it to a higher, but unstable, energy state. When this finished, higher energy-level metal, is exposed to the atmosphere, an imbalance of energy exists. The metal can be maintained by supplying energy from an external source. However, metals begin to return to ores when the energy supplied is insufficient to maintain them at the high energy level required to keep them as metals. The process of metal releasing energy and returning to its natural state is called corrosion.

Corrosion is often caused by the presence of oxygen and moisture on the metal surface. The most common example is the corrosion of steel. **Figure 1** depicts the cycle. As steel corrodes in soil, water, or concrete, an electric current is generated and chemical and physical changes in the metal occur. Corrosion products form that eventually revert to stable oxides.

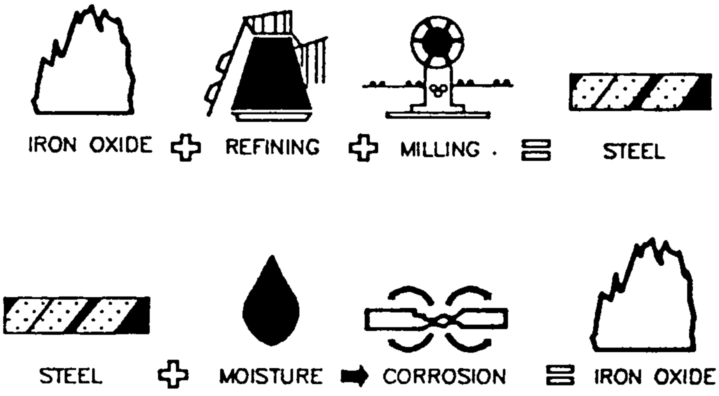

Figure 1. Iron ore naturally reverts to iron oxide.

Four basic elements are required for corrosion to occur: at least two metals, or two locations on a single metal, that are at different energy levels; an electrolyte; and a metallic connection. **Figure 2** illustrates these basic components. The two metals involved in the corrosion process are called electrodes. The electrode releasing electrical energy is called the anode, and the one receiving the electrical energy is a cathode.

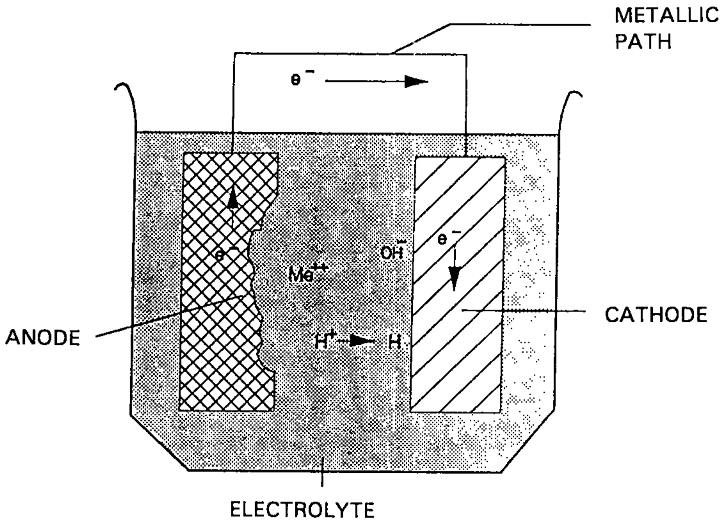

Figure 2. The basic elements of all corrosion cells.

The electrochemical reactions occurring at the anode and cathode are as follows:

1. The anodic reaction involving dissolution of metal, called oxidation.

   metal → metal ions(dissolved in solution) + electrons (e^-)

   $= M \rightarrow M^{n+} + ne^-$, where n = number of electrons involved in the reaction

2. The cathodic reaction in neutral or alkaline solutions, where reduction of dissolved oxygen is usually observed.

   Electrons + water + oxygen → hydroxyl ions

   $= 4e^- + 2H_2O + O_2 \rightarrow 4OH^-$

3. The cathodic reaction in acid solutions, where the formation of hydrogen occurs.

   Hydrogen ions + electrons → hydrogen gas

   $= 2H^+ + 2e^- \rightarrow H_2$

When combined, the four basic elements form a galvanic corrosion cell. A common example of this type of cell is the carbon zinc flashlight battery (**figure 3**). Metallic zinc is lost to the electrolyte in the form of positively charged zinc ions as the zinc corrodes and the zinc case accumulates a negative charge (electrons). If the zinc case and the carbon rod are connected by a wire, the excess electrons at the zinc case flow to the carbon rod. To complete the circuit, a positive charge is transported by the ions in solution to the carbon rod. Thus, the corrosion process involving the zinc case, carbon rod, electrolyte, and conductor produces the electrical energy required to light the bulb. The flow of electrons in the conductor is the electronic current, while the flow of ionic charge in the electrolyte is the ionic current.

The driving force that pushes the electric current is the difference in energy levels or the potential difference between the two metals. This force is the voltage of the cell. **Table 2** shows a list of the relative potentials or energy levels for some metals. Any metal with a higher energy level can release energy to any metal below it and thereby corrode. Similarly, any metal at a lower energy level can receive energy from any metal above it and be protected from corrosion. The quantity of metal lost by a corroding anode is proportional to the magnitude of the current flowing in the corrosion cell.

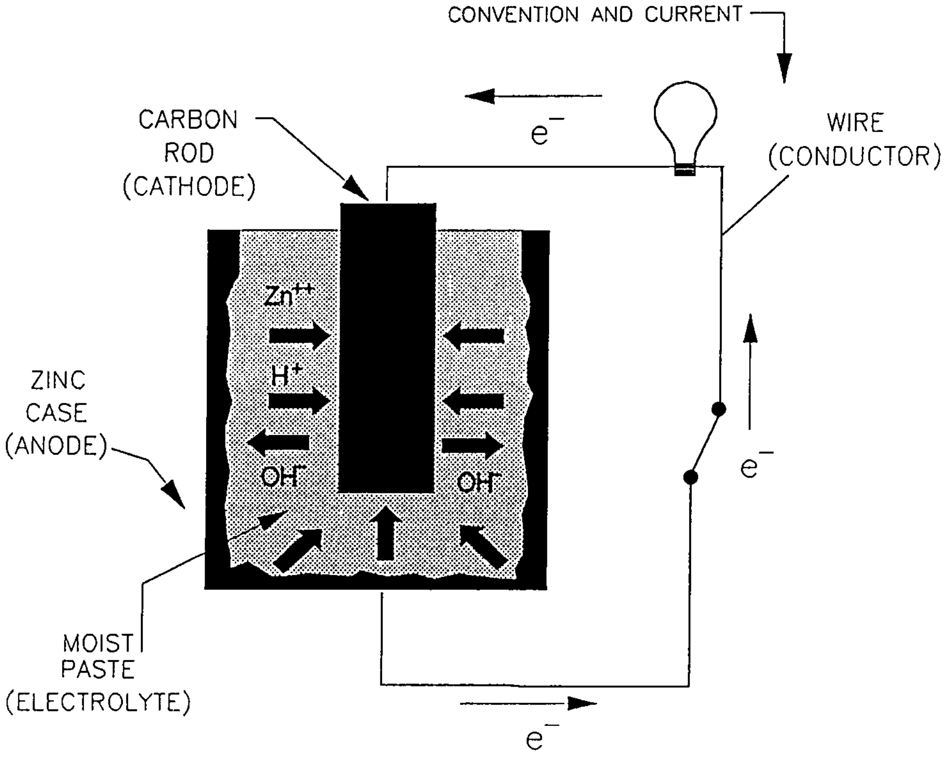

Figure 3. A battery is a corrosion cell.

Table 2. Relative Potentials or Energy Levels of Various Metals

Energy Level	Metal
High	Magnesium
	Aluminum
	Zinc
	Steel in concrete with chloride
	Steel in concrete without chloride
	Copper
	Silver
	Platinum
Low	Gold

In the case of a one-metal system, corrosion often occurs without an obvious anode and cathode. Consider a steel rod immersed in water that contains soluble salts. Because of the energy differences on the surface created during manufacturing or exposure, some areas on the metal surface are anodic while other areas are cathodic. For example, when steel is manufactured, the concentration of carbon is not uniform throughout the metal. The metal grains and grain boundaries may have different carbon concentrations. Since there is a potential difference between these areas, the electrons flow from the anodic sites via the body of the metal to the cathodic locations. The electrical circuit is completed by releasing metal from the anodic sites as ions into the surrounding electrolyte, and steel corrodes. The complementary reaction that occurs at the cathodic sites is the reduction of dissolved oxygen to form hydroxyl ions. Corrosion in a one-metal system can also be caused by differences in the electrolyte, such as varying concentrations of oxygen or chlorides. (For a more detailed description of corrosion processes and the underlying principles, consult the references at the end of this section.)

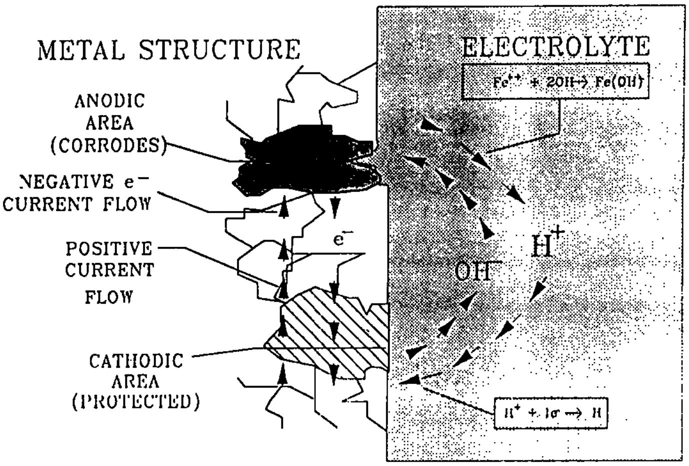

Figure 4. Single metal corrosion cell.

Corrosion of Steel in Concrete

Reinforcing steel in concrete normally does not corrode because of the formation of passive film on the surface of the steel. This film is a diffusion-barrier layer of reaction products, such as oxides formed by small initial corrosion processes. The process of hydration of cement in freshly placed concrete develops a high alkalinity, which in the presence of oxygen stabilizes the oxide film on the surface of embedded steel, ensuring continuing protection while the alkalinity is retained. Normally, concrete exhibits a pH above 12.4 because of the presence of calcium hydroxide, potassium hydroxide, and sodium hydroxide (the term pH is a measure of alkalinity or acidity, ranging from highly alkaline at 14 to highly acidic at zero, with neutrality at 7). Although the precise nature of this film is unknown, it isolates the steel from the environment and slows further corrosion as long as the film is intact. However, there are two major situations in which corrosion of reinforcement can occur:

(1.) carbonation, and
(2.) chloride contamination.

Carbonation is a process in which the carbon dioxide from the atmosphere diffuses through the porous concrete and neutralizes the alkalinity of concrete according to the following reaction:

Calcium hydroxide = carbon dioxide → calcium carbonate + water
$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

The pH is reduced to approximately 8 or 9, and the oxide film is no longer stable. With an adequate supply of oxygen and moisture, corrosion will start.

The penetration of structural concrete by carbonation is a slow process, the rate of which is determined by the rate at which carbon dioxide can penetrate concrete. The rate of penetration primarily depends on the porosity and permeability of concrete. It is rarely a problem in highway structures because these are built with good, quality concrete that has high cover. The role of chloride in inducing reinforcement corrosion is well documented. Chloride ions from the environment or de-icing salts get into concrete or are in the materials used to make the concrete. If chloride ions are present in sufficient quantity, they disrupt the passive film and expose the reinforcing steel to further corrosion. The American Concrete Institute's Committee Report ACI 222R-85, "Corrosion of Metals in Concrete,"[1] limits water soluble chlorides to 0.20 percent by weight of cement (about 1.3 lbs./yd.^{3}) for conventionally reinforced concrete structures.

De-icing salts are the major source of chlorides on the bridges in this country. Other sources include admixtures containing chlorides that are used to accelerate curing; aggregates and mixing water; and, in coastal areas, ocean spray carried by the wind. (The action of splashing waves also places chloride-bearing water in contact with concrete structures.)

The removal of the passive film from reinforcing steel leads to the galvanic corrosion processes discussed previously. Chloride ions within the concrete are usually not uniformly distributed. The steel areas exposed to higher concentrations of chlorides become anodic, and breakdown of the oxide film eventually occurs. In other areas, the steel remains passive. A classic example of this uneven exposure is the application of de-icing salts to a bridge in which the top reinforcement mat receives more chloride than the bottom mat. This uneven distribution results in a macrocell in which large anodic sites in the top mat and large cathodic sites in the bottom mat are encountered. The concrete acts as the electrolyte and the metallic conductor is provided by wire ties, chair supports, and the steel bars. **Figures 5** through **7** illustrate the general corrosion processes involved.

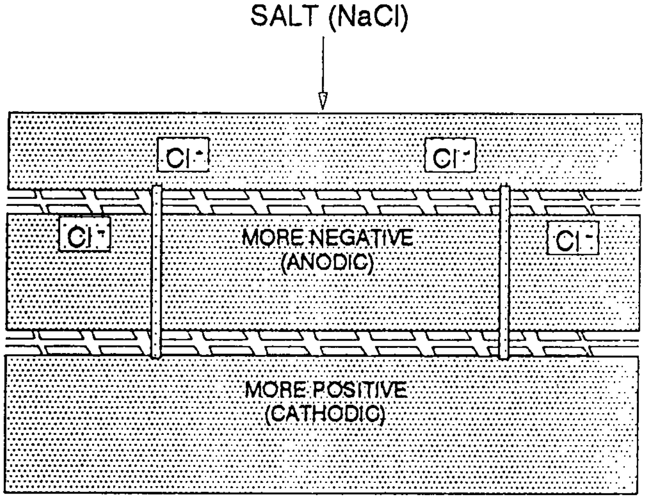

Figure 5. **Differences in chloride ion concentration establish differences in the electrical potential that forms the active-passive steel.**

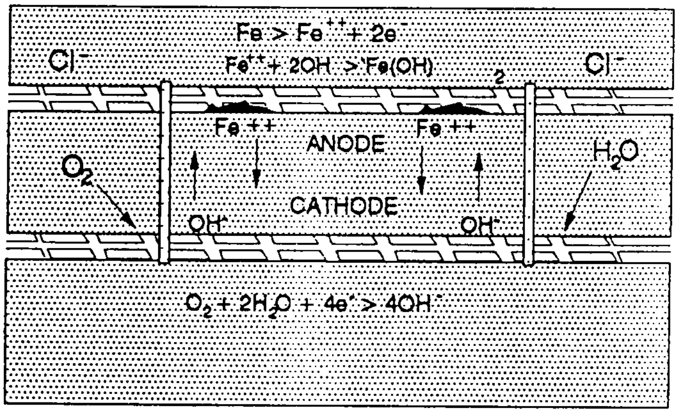

Figure 6. **The potential difference causes corrosion reactions to occur at the rebar in the chloride-contaminated concrete.**

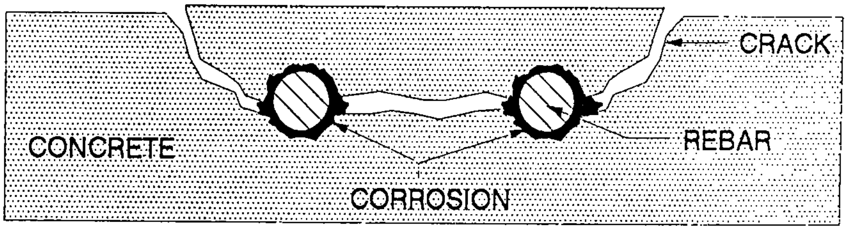

Figure 7. Corrosion-induced cracking of concrete.

Differences within the metal's grain structure or different residual stress levels can also lead to galvanic corrosion. When chlorides are uniformly distributed around steel, local action cells (microcells) form and dominate the corrosion process. Anodic and cathodic sites may be observed very close to each other on the same bar under such circumstances. This microcell effect usually leads to a type of localized corrosion known as pitting corrosion. In this case, metal loss from anodic sites creates a pit. As corrosion proceeds, the condition inside the pit becomes progressively more acidic and further loss occurs from the bottom of the pit rather than from around the mouth. The cross-sectional area of the steel is progressively reduced to a point at which the steel can no longer carry the applied loading.

All the corrosion processes described above require oxygen. In the absence of oxygen, the corrosion rate is appreciably reduced even with chloride concentrations above the threshold limit, except in acid solutions. However, keeping oxygen from the reinforcing steel in field structures is very difficult, if not impossible.

Corrosion of reinforcing steel in concrete produces rust that occupies as much as three or four times the volume of original steel. This situation adds to the tensile stress on the concrete. If this tensile stress exceeds the tensile fracture limits of the concrete, the concrete cracks and delamination and spalling occur (**figure** 7).

There are many ways to correct the damage caused by corrosion of reinforcing steel. However, the Federal Highway Administration's (FHWA) "Memorandum to Regional Federal Highway Administrators," dated April 23, 1982, states that "The only rehabilitation technique that has proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of concrete is cathodic protection." T. J. Hull[2] calculated a total savings of approximately $89 billion by adopting cathodic protection for rehabilitating damaged bridge decks as opposed to replacing them.

Cathodic Protection Fundamentals

A metal can be protected from corrosion in an ionically conducting environment by being connected to a current source of negative polarity. Current is applied to the reinforcing steel (cathode) through the concrete (electrolyte) via a second electrode (anode). Only those parts of the reinforcing steel that the current enter will be protected from further corrosion. Cathodic protection is applicable to the reinforcing steel of any structure or part of any structure when the steel is in continuous contact with the concrete electrolyte and where the reinforcement itself is continuous.

Cathodic protection is defined as the reduction or elimination of metal corrosion by making the metal a cathode via an impressed direct current (DC) instead of releasing current, or by connecting it to a sacrificial anode. Cathodic areas do not normally corrode. If, all the anodic areas were forced to function as current-receiving cathodic areas, the entire metallic structure would be a cathode and corrosion would be controlled. As long as the proper amount of direct current flows from the electrolyte to the metal, it will remain a cathode and will not undergo further corrosion.

An impressed-current cathodic protection system requires only these few basic components:

1. External DC power source (rectifier).
2. Current distribution hardware (anode).
3. Conducting electrolyte (concrete).
4. Reinforcing steel being protected (cathode).
5. Completed circuit (wiring).
6. Evaluation control devices (probes, reference cells, controllers).

A typical impressed-current cathodic protection system for a deck is shown in **figure 8**.

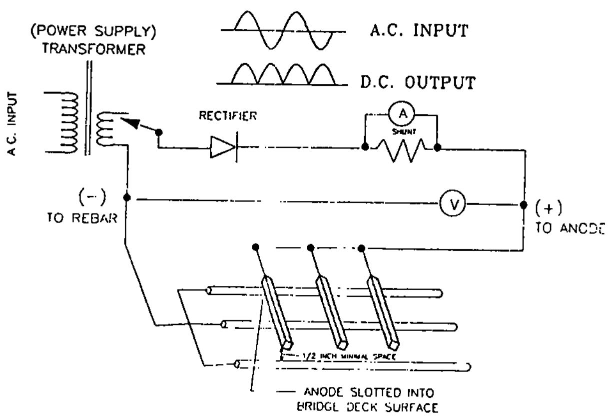

Figure 8. Schematic of cathodic protection system components.

A rectifier is a device used to convert alternating current (AC) to direct current. A rectifier works on the same principle as an AC adapter for a calculator or a car battery charger. In an impressed-current cathodic protection system, the rectifier provides power (i.e., voltage and current) and controls the amount of power to each zone. Rectifiers are available in many types and operating outputs. Mainly, they are designed to provide either constant direct current or constant DC voltage to the anode system. **Figures 9** and **10** show some commonly used rectifiers.

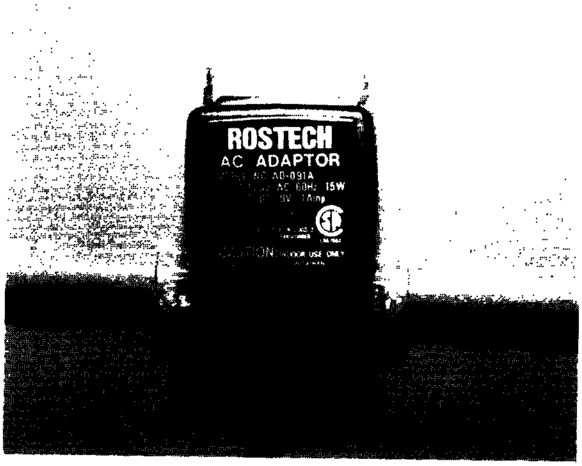

Figure 9. An AC adapter for a calculator is a simple type of AC/DC rectifier.

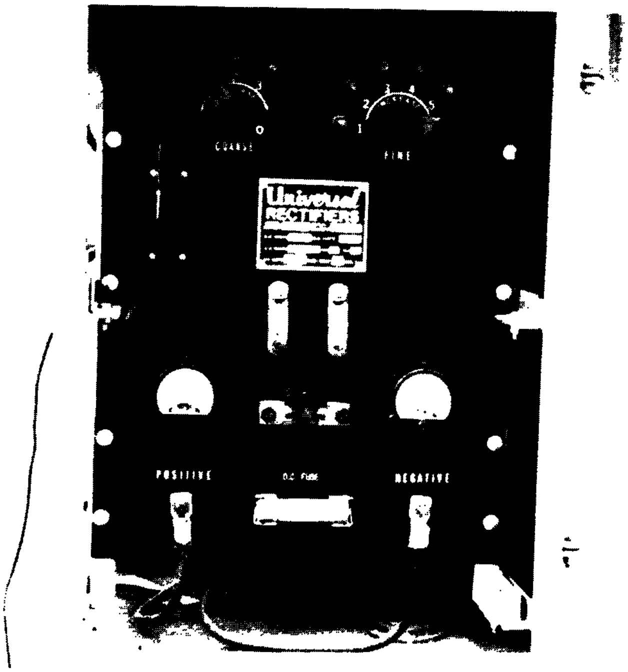

Figure 10. Cathodic protection rectifier.

A sacrificial anode system uses a more reactive metal (anode) such as zinc, aluminum, or magnesium to create the flow of current. This is galvanic anode cathodic protection. The direct current is generated by the potential difference between the anode and reinforcing steel when connected. The sacrificial anode will corrode during this process and be consumed. Current will flow from the anode through the electrolyte to the corroding reinforcing steel. However, the direct current produced by a sacrificial anode system is often not adequate to prevent corrosion of steel in concrete because of the low natural voltage difference between the sacrificial metal and the reinforcing steel and the high resistivity of the concrete in most highway environments.

The anode is one of the critical components in a cathodic protection system. It is used to distribute protective current to the reinforcing steel and, as such, it provides locations for anodic reactions to take place in lieu of the reinforcing steel. By using relatively inert materials and proper power levels in impressed-current systems, anode degradation can be minimized. Intensive research and product development by federal and state agencies and by private industry have led to the following anode systems:

1. Coke-breeze asphalt conductive overlay system with high-silicon cast-iron pancake anode (**figure 11**).

2. Slotted systems -
   - (a.) platinum wire/carbon strand with FHWA conductive polymer grout backfill (**figure 12**);
   - (b.) mixed-metal oxide-coated titanium ribbon with cementitious nonshrink grout backfill (**figure 13**).
3. Distributed anodes with concrete encapsulation -
   - (a.) mixed-metal oxide-coated titanium mesh (**figure 14**);
   - (b.) platinum wire/carbon strand with FHWA conductive polymer mounds (**figure 15**).
4. Conductive coatings -
   - (a.) conductive paints and mastics (**figure 16**);
   - (b.) flamed or arc-sprayed zinc (**figure 17**).

Figure 11. Placing conductive coke asphalt over pancake anodes.

Figure 12. Hand-placing FHWA conductive polymer into anode slots covering platinum wires and carbon strands.

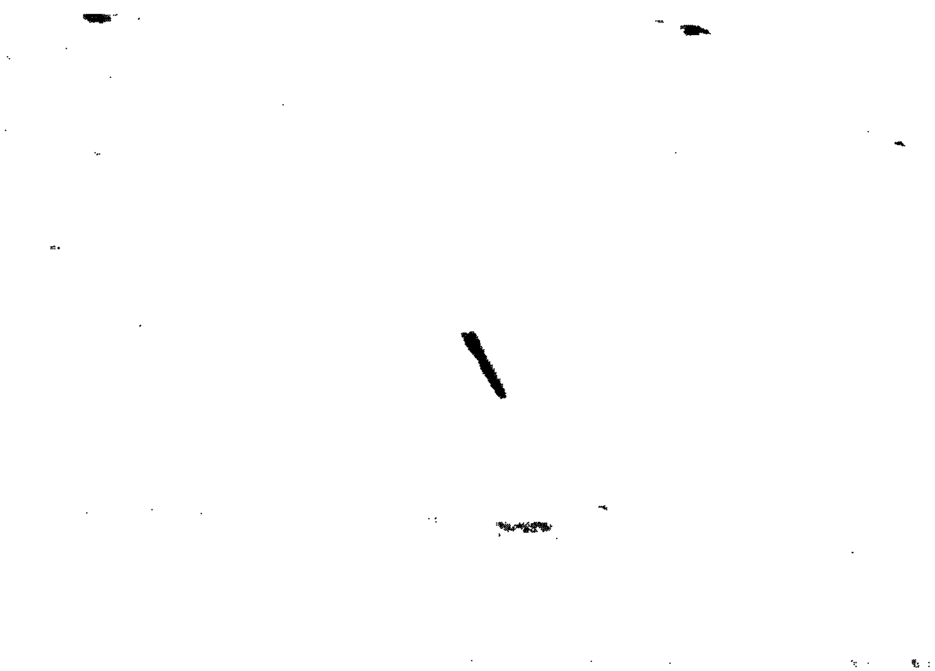

Figure 13. Mixed-metal oxide ribbons installed in anode slot.

Figure 14. Mixed-metal oxide mesh installed on a bridge deck prior to concrete overlay.

Figure 15. Installation of conductive polymer mounds over carbon strands.

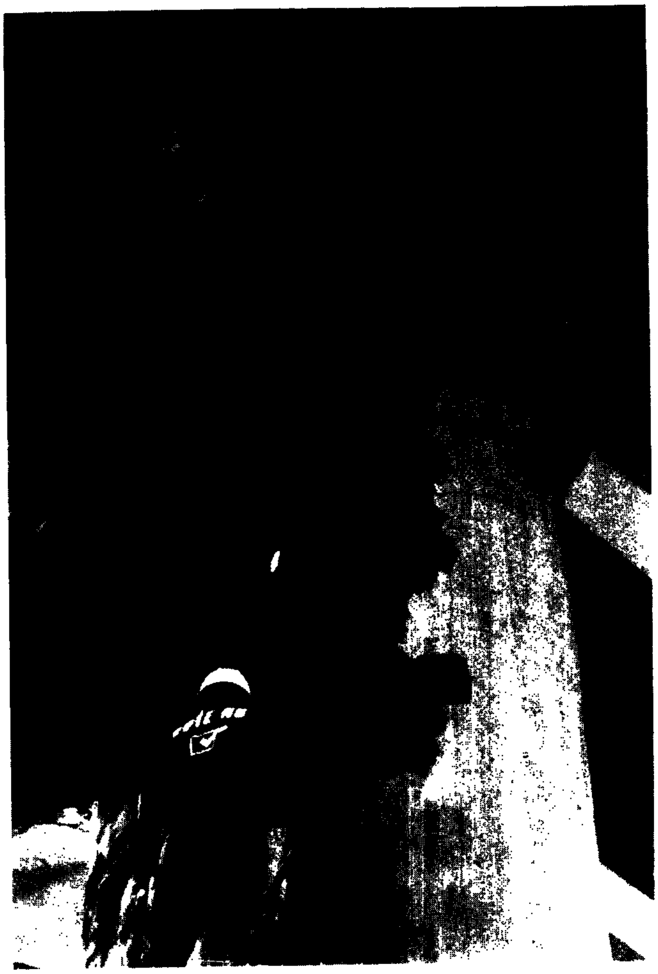

Figure 16. Application of conductive paint on a bridge substructure.

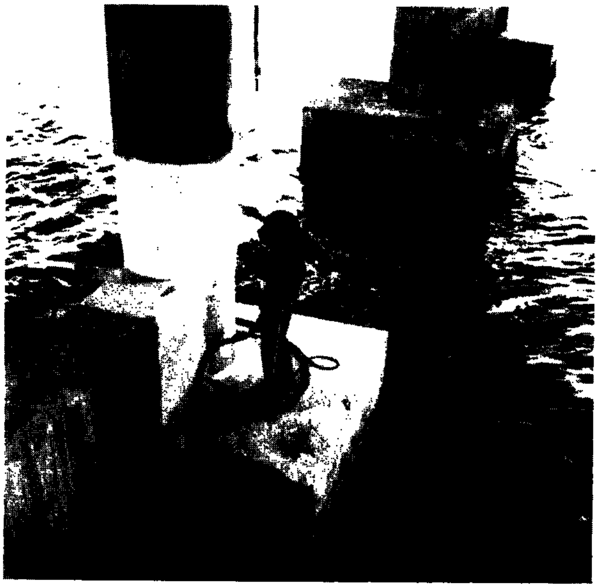

Figure 17. Arc-sprayed zinc anode installation on a bridge substructure.

Reference cells are used to evaluate cathodic protection levels. The cells may be portable or permanently embedded in the concrete structure. The most commonly used embedded reference cells are silver-silver chloride and graphite. **Figure 18** shows a silver-silver chloride reference cell that can be used on a bridge deck.

Figure 18. A silver-silver chloride reference cell installed in a bridge deck. (Note that no reinforced steel is exposed.)

A macrocell corrosion probe is another device used to evaluate cathodic protection performance. The probe consists of a segment of reinforcing steel cast in a salty mortar block (chloride content is typically 15 lbs./cu.yd.) that is then embedded in the concrete. The flow of current between the monitoring probe and the reinforcing mat helps to determine whether the steel is being adequately protected. **Figure 19** shows a monitoring probe.

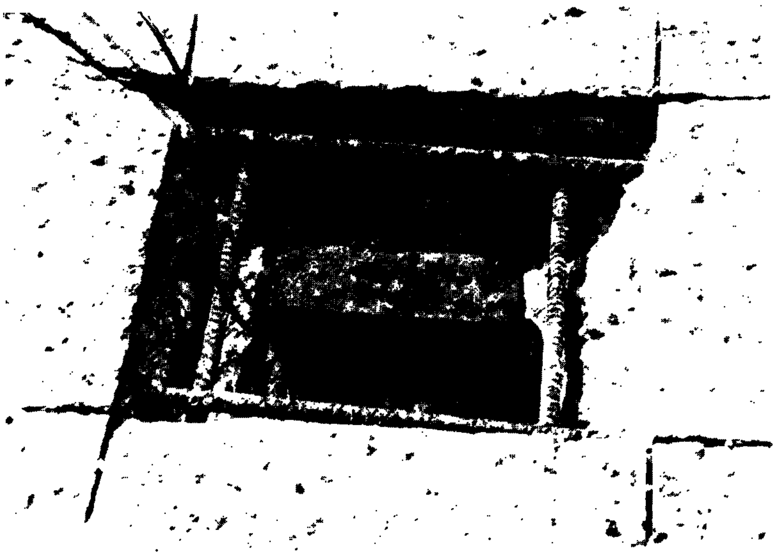

Figure 19. Macrocell corrosion probe placed in concrete. (Note that steel is exposed.)

Wiring required for a cathodic protection system includes the following:

1. Reinforcing steel connected to the cathodic protection power supply negative (-) terminals.
2. Anode connected to the cathodic protection power supply positive (+) terminals.
3. Reinforcing steel connected to the monitor system ground terminals.
4. Reference cells and monitoring probes connected to their corresponding monitor system terminals.

All wiring is routed to the rectifier or monitoring boxes, as appropriate, in conduits attached to external surfaces of the concrete structure. Any necessary splices are made in junction boxes.

The use of cathodic protection is still the best tool available for mitigating corrosion. However, it should be understood that cathodic protection will neither replace steel that is already lost nor return corroded reinforcement to its original cross section.

Some areas of a reinforced concrete structure that appear sound may in fact be experiencing corrosion distress with tensile stress near rupture levels. Such areas may crack, spall, or delaminate after the application of cathodic protection. The cathodic protection field continues to evolve as materials, application methods, and protection criteria are refined. The reader is encouraged to consult the references and the remainder of this manual for more detailed information on cathodic protection of reinforcing steel in concrete.

3

Design

Once the use of cathodic protection has been decided upon, the system must be designed. During the design phase, the designer will face a number of choices based on the construction and condition of the structure, the surrounding environment, and economic factors. This section provides the nonspecialist engineer with general guidelines for designing cathodic protection systems for typical bridge structures. In the event that a structure is in some way atypical, design parameters may fall outside the guidelines presented here. In that case, the services of an experienced cathodic protection specialist engineer may be required.

First, the various cathodic protection systems, or anode types, commonly used today are described. Systems suitable for deck surfaces are presented first, followed by those suitable for bridge substructures. For each system, a sample calculation is given to illustrate how voltage drop in the anode structure may be determined. A design that results in too great a voltage drop in the anode will cause poor distribution of current to the zone. Three hundred millivolts is commonly used as an upper limit for voltage drop in the anode from the power feed to a point farthest from the power feed.

Next, the rationale for selecting a cathodic protection system is discussed. One element of this selection process is the estimation of relative costs. These costs are detailed in the appendix.

Design information for the other elements needed for cathodic protection systems is then presented, as well as design information common to all systems.

Finally, a guide to estimating the cost of a cathodic protection system is given.

Types Of Cathodic Protection Systems

Different cathodic protection systems are best characterized by the anode they employ. The anode is the most vital part of the system. Since the conductivity of concrete is rather low, which prevents the current from being distributed over long distances, the anode must cover essentially the entire concrete surface. Furthermore, since corrosion reactions take place on the anode surface, the surface is subjected to extremely harsh conditions. The detrimental effects of the anodic environment should not be underestimated. Only anodes with a proven long-term history of use in concrete can be used with confidence. Newer anode types should undergo extensive laboratory testing and test-yard performance. Several different anodes have a significant history of use in concrete, and these are classified and described separately in this section. There are, however, a number of general principles that the designer should consider regardless of the anode chosen.

First, the anode should be physically rugged and not easily damaged, either during construction or during its operating life.

Second, the design of the anode should include redundancy in the current-carrying pathways so that future cracking or careless coring will not render the system inoperative.

Third, the anode design should result in a uniform distribution of current to the steel. This requirement would be ideally satisfied by an overlay or coating that uniformly covers the entire concrete surface. In practice, however, relatively uniform distribution of current can be supplied by discrete anodes, provided they are properly spaced. It is difficult to generalize about the distribution of current resulting from discrete anode spacing, but designers have found a 12-in. spacing to be generally acceptable, whereas an 18-in. spacing is usually excessive. Any design with anode spacing greater than 12- in. should be field tested on the structure in question for adequate distribution of current.

For the same reason, anodes of separate electrical zones should be spaced at least 2-in. apart but not more than 12-in. apart. Spacing closer than 2-in. may interfere with the individual automatic controllers of each anode zone while a spacing greater than 12-in. may result in inadequate protection between zones.

Anodes should also be installed not less than 2-in., nor more than 6-in. from exposed surface steel, such as expansion joints, drains, and other hardware. Spacing closer than 2-in. may cause excessive current at that point, while spacing greater than 6-in. may result in inadequate protection of these components.

No matter which anode is chosen, a voltage drop will result because of the resistance present within the anode itself. This drop will cause higher current to flow near the point of electrical feed and lower current to flow farther away. If this disparity of current is too great, insufficient current may be distributed to steel far from the electrical feed point. The excessive current near the electrical feed may result in overprotection of the steel at that point, with possible concrete degradation and reduced anode life.

Calculating the current distribution as a result of resistive losses is a complex exercise in electrical network analysis and beyond the scope of this manual. A simple approximation can be used as a guideline for locating anode power feed points. The calculation is based on the assumption that an anode resistance loss (IR drop) or voltage drop of 300 mV can be tolerated within an anode zone. It has been estimated that this drop will cause the steel farthest from the electrical feed to receive no less than 80 percent of the average current applied to that zone. An IR loss other than 300 mV may be used, but the same number should be applied equally to all anode types.

Current will be continually discharged over a long length of anode, and although this discharge may not be uniform, the average current flow through the anode structure will be one-half of the current entering the anode because the anode is distributing current through its length. Therefore, for a segment of anode of any width, the average potential drop over the length of the anode will be

$$E=\frac{(IR)}{2}$$

or, using the 300 mV criterion

$$0.300=\frac{(IR)}{2}$$

or,

$$0.300=\frac{(XI_a)(XR_a)}{2}$$

where X = length of anode in feet from power feed to the point farthest from the power feed ($2X$ = distance between power feed points),

I_a = the average current discharge per linear foot of anode segment, and

R_a = the resistance per linear foot of anode segment.

The resistance of an anode of any dimension can be calculated from its resistivity, a number that is normally provided by the anode supplier. Resistivity is an intensive property of the anode material, and is usually expressed in ohm-cm. Therefore,

$$X = \sqrt{\frac{0.600}{(I_a)(R_a)}}$$

Examples of this calculation will be given in each section that describes the different anode types.

When determining the amount of anode material to be used, it is important to consider the effects of the anode reaction products on the concrete. The two major anodic oxidation reactions that take place in concrete involve the evolution of either oxygen or chlorine, as follows:

$$H_2O \rightarrow 1/2O_2 + 2e^- + 2H^+$$

and

$$2Cl^- \rightarrow Cl_2 + 2e^-$$

In concrete, which has a relatively high pH value, the chlorine will undergo rapid hydrolysis, expressed as follows:

$$Cl_2 + H_2O \rightarrow ClO^- + Cl^- + 2H^+$$

Therefore, for either anodic reaction or any combination of the two reactions, one atom of acid (H^+) will be generated for the passage of each electron. Experience has demonstrated that if these reaction products are produced at a high rate because of high anode operating current densities, damage to concrete near the anode surface will result. If anode reaction products are generated slowly, they will diffuse into the concrete without causing any problems. Therefore, current density of 10 $mA/ft.^2$ on the anode surface is usually specified as a maximum.

Calculating the surface area of certain types of anodes is not straightforward. The surface area of complex anodes, such as titanium mesh, is usually provided by the manufacturer.

Anode Systems For Deck Surfaces

Conductive Coke-Asphalt Overlay

Advantages

-Anode current density is low.
-Increase of dead load is modest.
-Cost is relatively low.
-Riding surface is good.

Disadvantages

-Not suitable for concrete with inadequate air void system.
-Drains and expansion joints must be raised.
-Deck profile is raised.

This type of cathodic protection system was first used in 1973 to protect the Sly Park bridge deck in California from corrosion. A number of improvements have been made since that time, and the system described here was developed by the Ontario Ministry of Transportation and Communications.

The system uses electrically conductive asphaltic concrete that is placed on the prepared concrete surface and is overlaid with conventional asphaltic concrete as a wearing course.

If a bridge deck is exposed to freezing and thawing conditions, the adequate air void must be determined. Cores should be obtained in accordance with American Society for Testing Materials (ASTM) C-42, and air voids determined by ASTM C-457. If air voids in the concrete are not adequate, this system should not be used because water will readily flow through the asphaltic overlay and accelerate freeze-thaw deterioration.

Pancake-shaped, high-silicon cast-iron anodes are used as current sources in the overlay. These are commonly called "primary anodes." This term is not strictly correct because the silicon iron is intended to act only as an electrical contact to the conductive overlay or secondary anode. This usage is retained here because it is commonly used in the cathodic protection industry.

These anodes are typically spaced at 25-ft. intervals and are arranged in lines with several anodes connected in "strings." Each anode string typically contains three to four individual anodes. One anode normally provides current for 500 sq. ft. to 800 sq. ft. of deck surface. End anodes are located no more than 10-ft. from the end of the deck or from a joint. When possible, the primary anodes are located in the curb areas of the deck.

Primary anodes and lead wires are placed in holes and slots cut into the deck surface, which permits replacement of the conductive overlay without damaging the primary anodes, wiring or instrumentation. The primary anode hole is 2 in. deep and 1 ft. sq. and is located between reinforcing bars when possible. The bottom of the hole, and the bottom and sides of the anode are coated with epoxy. Lead wire slots are cut, and, after placing the anode and lead wires, the holes and slots are backfilled with mortar. When complete, the top surface of the primary anode is flush with the concrete deck surface.

Voltage probes, which are used in monitoring system performance, are also installed. These probes are graphite, about 6-in. long x 1-in. square. Voltage probes with lead wires are recessed into the deck in a manner similar to that described for primary anodes, except that the probe and hole are not coated with epoxy. When complete, the top of the probe is flush with the concrete deck surface.

The conductive coke-asphalt overlay is placed at a thickness of 1 1/2 in. over the entire deck surface, to within 6 in. of any exposed steel, such as expansion joints. These areas are filled with non conductive asphalt hot mix. The conductive coke-asphalt mix utilizes coke breeze from coal refining with a gradation of 3/8 in. or smaller. The three components of the total aggregate are typically 45 percent coke breeze, 40 percent coarse aggregate, and 15 percent fine aggregate. Asphalt cement content is typically 15 percent by mass. The approved mixture exhibits the following properties:

Marshall stability	1200 minimum
Flow	6-16
Resistivity	3 ohm-cm maximum

An example calculation of anode voltage drop for a coke-asphalt overlay is as follows:

Calculate the voltage drop for an overlay element 1 ft. wide x 12.5 ft. long, assuming an average concrete surface current density of 1.5 mA/ft.^{2}.

$$\text{Overlay Resistance (R)} = \frac{\text{(Resistivity)(Lenth)}}{\text{(Cross Sectional Area)}}$$

$$= \frac{3\,\text{ohm-cm x } 381\,\text{cm}}{116.1\,\text{cm}^2}$$

$$= 9.85\,\text{ohm}$$

$$\text{Overlay Current (I)} = \text{(Current Density) (Area)}$$

$$= 1.5\,\text{mA/ft.}^2 \text{ x } 12.5\,\text{ft.}^2$$

$$= 18.75\,\text{mA}$$

$$\text{Overlay IR Drop} = \frac{(\text{Resistance})\ (\text{Current})}{2}$$

$$= \frac{9.85\,\text{ohms} \times 18.75\,\text{mA}}{2}$$

$$= 92\,\text{mV}$$

Conductive Polymer Systems

Conductive polymer-grout anode systems have been used both in slotted and mounded configurations. Both utilize primary anodes of platinized, niobium-clad copper-core wire and high-purity pitch-based carbon-filament-wrapped bundles (40,000 filaments per bundle). Electronically conductive polymer concrete, the secondary anode, is used to encapsulate the primary anodes so that current is discharged from as great a surface as possible to prevent high current densities at the anode. High densities would occur if the primary anodes were encased in a cementitious grout. (Here again, the terms "primary" anode and "secondary" anode are used, despite the technical inaccuracy, because of their common use in the cathodic protection industry.)

The conductive polymer grout consists of vinyl ester resin with additives and a coke-breeze filler. Coke breeze provides the conductive medium in the grout to pass electrical current. The grout formulation in **table 3** was developed by the Federal Highway Administration (FHWA):

Table 3. FHWA Grout Formulation

Components	Concentration
Vinyl ester resin (Hetron D-1115, manufactured by Ashland Chemical Co., Columbus, Ohio, or approved equal)	35% by wt. of total mixture
Coke breeze DW1	65% by wt. of total mixture
Silane couling agent (A-174)	1% by wt. of resin
Wetting agent (Surfynol 440)	1% by wt. of resin
Cobalt naphthenate (6% cobalt)	0.5% by wt. of resin
Titanium dioxide (RHD 6X)	1% by wt. of resin
Methyl ethyl ketone peroxide (9% active oxygen)	2% by wt. of resin

If the placement temperature is 60°F or less, dimethyl aniline is added to the resin at a rate of 0.5 percent by weight. Titanium dioxide is added only to slotted-system mixes to give the grout a concrete gray color.

Both coke-asphalt and polymer system configurations require that anodes be placed in a similar pattern. The primary platinized wire of 0.031-in. or 0.062-in. diameter is typically placed at 25-ft. spacing for straight runs or up to 50-ft. spacing if another primary anode is looped around the entire zone. The loop, if used, is continuous with two power feeds on opposite sides of the loop. The smaller wire is used only when individual primary platinized wire anodes do not exceed 50 ft. of wire embedded in a zone. The secondary carbon filament anodes are placed transverse to the primary platinized anodes at spacing determined during the design of the system.

Conductive Polymer Slotted Systems

Advantages

- Dead load is not increased.
- Roadway grade and profile are not changed.
- Drains and curbs do not require modification.
- Time of installation is short.
- Equipment for installation is minimal.

Disadvantages

- Resin is flammable and has a short shelf life.
- Resin storage and handling conditions are critical.
- Concrete must be dry during application and curing.
- Grout has short working time.
- Deck temperature must be at least 40° F.
- Cover over the reinforcing steel must be at least 1 in.
- Riding surface is not renewed.

Slotted conductive polymer systems have primary and secondary anodes placed in sawcut slots about 1/4 in. wide and 1/2 in. to 3/4 in. deep in the structure slab. The slots are filled with conductive polymer grout. The slots are spaced 6 in. apart when the design current density is 1.5 mA/ft.^{2} of concrete surface. The average anode current density must not exceed 5 mA/ft.^{2}. Slots wider than 3/8 in. are not recommended because of long-term durability requirements. Normally, the slots are left exposed to traffic. However, the state of Missouri has numerous bridge decks that have slotted systems overlaid with asphalt concrete and portland cement concrete wearing surfaces.

The following sample calculation is given for the IR drop in a conductive polymer slotted system:

Assumptions (see **figure 20**) -

Average current density (concrete)	1.5 mA/ft.^{2}
Platinized wire	0.031 in. diameter.
Platinized wire resistance	16 milli ohms/ft.
Platinized wire spacing	25 ft.
Platinized wire length	25 ft.
Carbon filament resistance	1 ohm/ft.
Carbon filament spacing	0.5 ft.
Carbon filament length	25 ft.

(a.) Calculate the voltage drop in the primary anode wire as follows:

$$\text{Platinized Wire Resistance (R)} = (\text{Resistance per ft.}) \times (\text{Length})$$

$$= \frac{0.016\,\text{ohm}}{\text{ft.}} \times 25\text{ft.}$$

$$= .400\,\text{ohm}$$

$$\text{Platinized Wire Current(I)} = (\text{Current Density}) \times (\text{Area})$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \times 625\,\text{ft.}^2$$

$$= 938\,\text{mA}$$

$$\text{Platinized Wire IR Drop} = \frac{(\text{Resistance}) \times (\text{Current})}{2}$$

$$= \frac{0.400\,\text{ohm} \times 938\,\text{mA}}{2}$$

$$= 188\,\text{mV}$$

(b.) Calculate the voltage drop in the secondary anode as follows:

$$\text{Carbon Filament Resistance (IR)} = (\text{Resistance per ft.}) \times (\text{Length})$$

$$= \frac{1\,\text{ohm}}{\text{ft.}} \times 12.5\,\text{ft.}$$

$$= 12.5\,\text{ohm}$$

$$\text{Carbon Filament Current (I)} = (\text{Current Density}) \times (\text{Area})$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \times 6.25\,\text{ft.}^2$$

$$= 9.38\,\text{mA}$$

$$\text{Carbon Filament IR Drop} = \frac{(\text{Resistance}) \times (\text{Current})}{2}$$

$$= \frac{12.5\,\text{ohm} \times 9.38\,\text{mA}}{2}$$

$$= 59\,\text{Mv}$$

(c.) Calculate the total anode voltage drop as follows:

$$\text{Total Anode IR Drop} = (\text{Platinized Wire IR Drop}) + (\text{Carbon Filament IR Drop}$$

$$= 188\,\text{mV} + 59\,\text{mV}$$

$$= 247\,\text{mV}$$

Conductive Polymer Mounded Systems

Advantages

- Equipment for anode installation is minimal.
- Construction traffic can ride on anode grid.
- Concrete cover over steel can be minimal.
- Riding surface is new.

Disadvantages

- Resin is flammable and has short shelf life.
- Resin storage and handling conditions are critical.
- Concrete must be dry during application and curing.
- Grout has short working time.
- Deck temperature must be at least 40° F during installation.
- Dead load is increased because of concrete overlay.
- Drains and expansion joints must be raised.
- Deck elevation is raised.

Mounded conductive polymer anode systems have a layout similar to slotted systems. The mounded system, however, is placed directly on top of the existing structural slab. After the

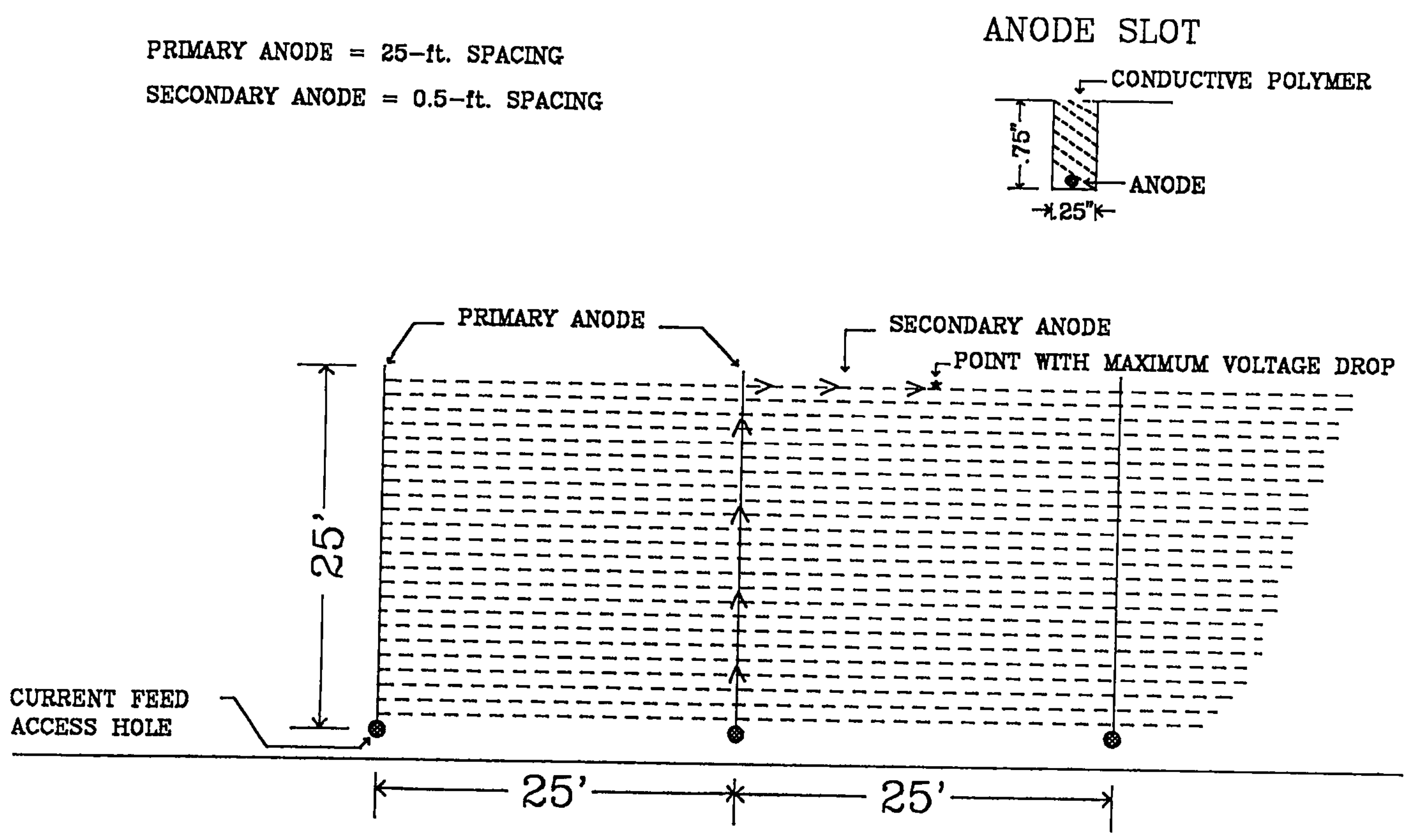

Figure 20. Conductive polymer slotted system.

mounded system is installed, the entire deck is overlaid with a 2-in. thick concrete overlay. The polymer mounds are 1 1/4 to 1 3/4 in. wide and 3/8 in. deep. The carbon filament anodes are typically spaced 12 in. apart when the design current density is 1.5 mA/ft.^{2} of concrete surface. The average anode design current density must not exceed 7.5 mA/ft.^{2}. The viscosity of the polymer grout can be controlled by adding coke breeze beyond the amount supplied for each batch, which prevents flowing on decks with a grade or cross-slope.

The overlay chosen must have a volume resistivity of less than 50,000 ohm-cm. Overlays that meet this requirement and that have been used include low-slump, superplasticized, and latex-modified styrene butadiene rubber (SBR) concrete.

The following sample calculation is given for the IR drop in a conductive polymer mounded system:

Assumptions (see **figure 21**) -

Average current density (concrete)	1.5 mA/ft.^{2}
Platinized wire	0.062 in. diameter
Platinized wire resistance	4.1 milli ohms/ft.
Platinized wire anode spacing	25 ft.
Platinized wire length	25 ft.
Carbon filament anode resistance	1 ohm/ft.
Carbon filament anode spacing	1 ft.
Carbon filament anode length	25 ft.

(a.) Calculate the voltage drop in the primary anode wire as follows:

$$\text{Platinized Wire Resistance(R)} = \text{(Resistance per ft.)} \times \text{(Length)}$$

$$= \frac{0.0041\,\text{ohm}}{\text{ft.}} \times 25\,\text{ft.}$$

$$= 0.1025\,\text{ohm}$$

$$\text{Platinized Wire Current (I)} = \text{(Current Density)} \times \text{(Area)}$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \times 625\,\text{ft.}^2$$

$$= 938\,\text{mA}$$

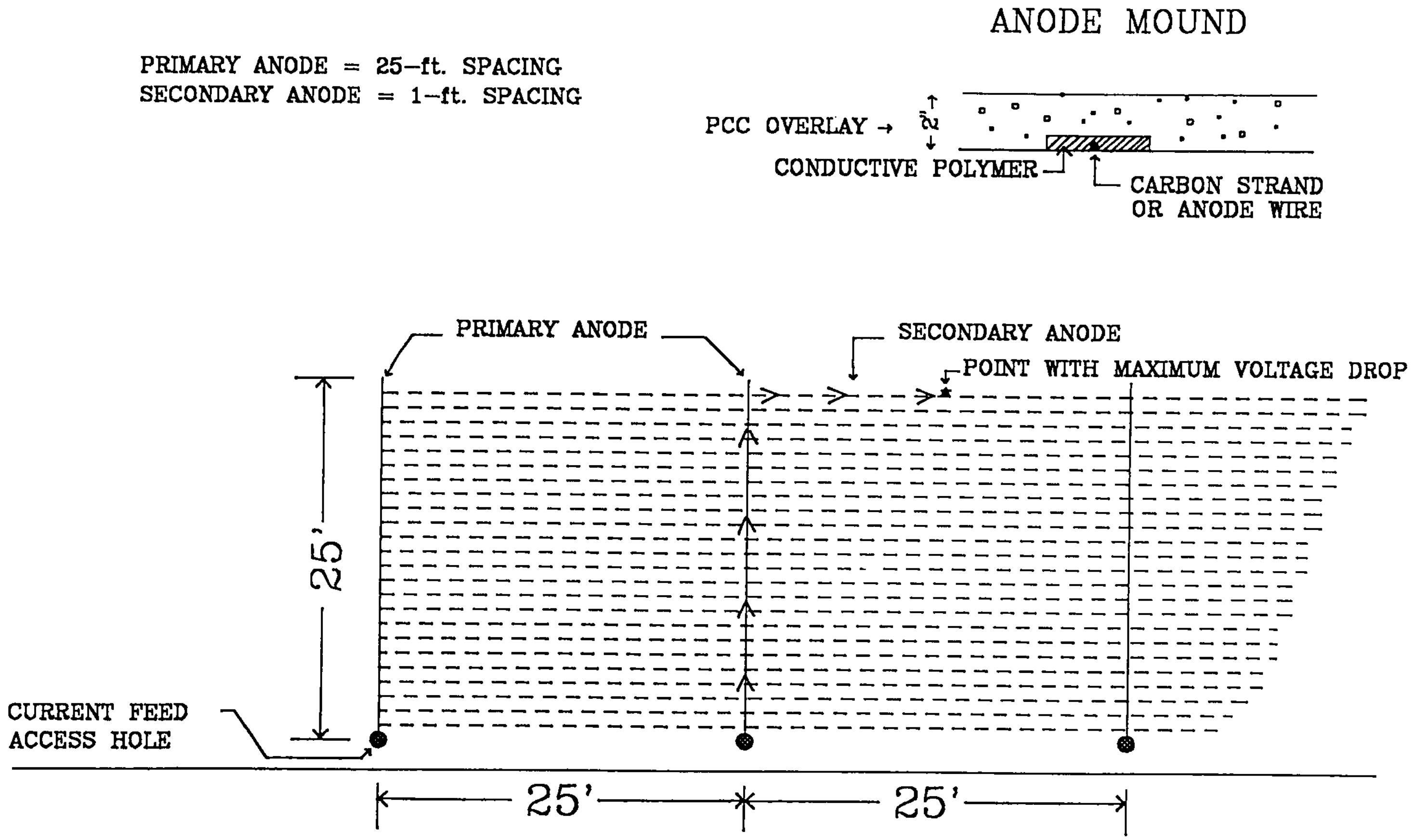

Figure 21. Conductive polymer mounded system.

$$\text{Platinized Wire IR Drop} = \frac{(\text{Resistance}) \times (\text{Current})}{2}$$

$$= \frac{0.1025\,\text{ohm} \times 938\,\text{mA}}{2}$$

$$= 48\,\text{mV}$$

(b.) Calculate the voltage drop in the secondary anode as follows:

$$\text{Carbon Filament Anode Resistance (R)} = (\text{Resistance per ft.}) \times (\text{Length})$$

$$= \frac{1\,\text{ohm}}{\text{ft.}} \times 12.5\,\text{ft.}$$

$$= 12.5\,\text{ohm}$$

$$\text{Carbon Filament Anode Current (I)} = (\text{Current Density}) \times (\text{Area})$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \times 12.5\,\text{ft.}^2$$

$$= 18.75\,\text{mA}$$

$$\text{Carbon Filament Anode IR Drop} = \frac{(\text{Resistance}) \times (\text{Current})}{2}$$

$$= \frac{12.5\,\text{ohm} \times 18.75\,\text{mA}}{2}$$

$$= 117\,\text{mV}$$

(c.) Calculate the total anode voltage drop as follows:

$$\text{Total IR Drop} = (\text{Platinized Wire IR Drop}) + (\text{Carbon Filament IR Drop})$$

$$= 48\,\text{mV} + 117\,\text{mV}$$

$$= 165\,\text{mV}$$

Mesh Anodes with Concrete Encapsulation

Advantages

- Life of concrete is longer.
- Minimal concrete cover is required over steel reinforcing.
- Riding surface is new.

Disadvantages

- Initial cost is relatively high.
- Deck load is increased because an overlay is required.
- Deck profile is raised.
- Drains and expansion joints must be raised.

Mesh anode systems with concrete overlays became available about 1984 or 1985. The first such system utilized a copper conductor surrounded by a conductive polymeric anode material (commonly referred to as a flexible polymer wire anode). The wire-like material was fastened to the concrete surface in either a straight line or a mesh configuration. A cementitious overlay was then applied to the structure. A number of field installations exhibited problems with anode degradation and embrittlement by 1990. This system is seldom used today and is not described further in this manual.

A second type of mesh anode became available in 1985, consisting of an expanded titanium mesh catalyzed by a mixed-metal oxide coating. This type of anode exhibits long life, uniform current distribution, oxygen-specific reaction, and good redundancy. Titanium mesh anodes have become the most widely used anodes for cathodic protection of decks.

The primary anodes, commonly called distributor bars, are typically solid Grade 1 titanium strips that are 0.5 in. wide and 0.040 in. thick. Distributor bars are run perpendicular to the longest dimension of the mesh and are attached to the mesh using resistance welding at least every 3 in.

Another distributor system uses a titanium rod mechanically fastened to the mesh with niobium crimp connectors, but this system has not been widely used.

Titanium distributor bars are normally routed through holes in the deck, and connection to the power distribution system is made in junction boxes under the deck. The bars are protected from shorting to the deck holes with heat-shrink insulation.

Prior to design of a system, these anodes should pass an accelerated life test, such as the test being finalized by a National Association of Corrosion Engineers (NACE) committee. The anode-concrete combination should also be able to operate without excessive formation of an anode reaction product. The distance between distributor bars is typically 50 ft. to 200 ft. and is determined by voltage-drop calculations. A minimum of two power feeds should be provided for each electrical zone.

Mesh anodes provide good redundancy in the event of future isolated damage caused by construction activity or concrete cracking. The actual surface area of the anode typically ranges from 0.15 sq. ft. to 0.30 sq. ft. of anode per square foot of concrete. The design current density per square foot of concrete divided by this ratio establishes the anode current density per square foot. Normally, this density should not exceed 10 mA/ft.^{2} of anode surface area.

The following example calculation provides the anode current density for a titanium mesh anode with a surface area ratio of 0.21, operated at 1.5 mA/ft.^{2} of concrete:

$$\text{Anode Current Density} = \frac{(\text{Current Density - Concrete})}{(\text{Surface Area Ratio})}$$

$$= \frac{1.5\,\text{mA/ft}^2}{0.21}$$

$$= 7.14\,\text{mA/ft}^2 \text{ of Anode}$$

Since this number is under 10.0 mA/ft.^{2}, it is considered acceptable.

Titanium anode meshes are typically supplied in widths of 45 in. to 48 in. and weights of 26 lbs. to 65 lbs. per 1,000 sq. ft.

The mixed-metal oxide coating composition is proprietary and varies for different manufacturers. Since anode lifetime and performance depend on coating composition, anodes from new suppliers should be thoroughly tested.

Anode mesh is fastened to the concrete surface using non metallic pins driven into holes drilled into the concrete. Fasteners are installed on 1-ft. to 4-ft. centers, depending on the nature of the overlay and the structure.

If overlay is needed to encapsulate and protect an anode, several items must be considered. The first is whether the overlay must withstand vehicular traffic. The second is how thick the overlay must be to protect the anode. The third is what type of physical environment the overlay must withstand. The overlay must be compatible with the designed cathodic protection system.

When the overlay is used as the riding surface on a bridge deck, a high-quality, durable overlay must be specified. Examples of overlays that have been successfully used on bridge decks include low-slump, latex-modified, and conventional concretes. These provide the strength and wear characteristics necessary for a wearing surface. The thickness of the overlay must be sufficient to protect and encapsulate the anode and to provide good bonding and physical properties.

The exposure of the overlay to environmental conditions must also be considered. Since most bridge deck cathodic protection systems will be used in areas subject to freeze-thaw cycling, the selected overlay must have a proven record of withstanding expected exposure conditions. Although this fact may seem simplistic, its importance cannot be overstated.

Any type concrete overlay must be tested with a specific anode to determine the compatibility of the two. Parameters to be considered include electrical resistivity, formation of anode reaction products, and overlay-substrate bond strength over time. The overlay must have an electrical resistivity of less than 50,000 ohm-cm.

Formation of anode reaction products depends on the current density and makeup of the overlay. Overlay materials prone to the formation of anode reaction products exhibit white or orange areas around the anode after a period of operation. Loss of overlay-substrate bond over the anticipated lifetime of the overlay must not occur, so that the overlay can continue to function both electrically and structurally. The required test data should be available from each anode manufacturer, detailing the results and performance of the anode with each recommended type of overlay.

The following example calculation determines the voltage drop in a titanium mesh anode system (see **figure 22**):

Assumptions -

Anode current density (concrete)	1.5 mA/ft.^{2}
Current distributor resistance	0.005 ohm/ft.
Current distributor spacing	100 ft.
Current distributor length	16 ft.
Mesh resistance	0.014 ohm/ft. (4 ft. width)

(a.) Calculate voltage drop in current distributor as follows:

$$\begin{aligned} \text{Distibutor Resistance (R)} &= \text{(Resistance per ft.) x (Length)} \\ &= \frac{0.005\,\text{ohm}}{\text{ft.}} \text{ x } 16\,\text{ft.} \\ &= 0.08\,\text{ohm} \end{aligned}$$

$$\text{Distibutor Current (I)} = (\text{Current Density}) \text{ x } (\text{Area})$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \text{ x } 1600\,\text{ft.}^2$$

$$= 2400\,\text{mA}$$

$$\text{Distributor IR Drop} = \frac{(\text{Resistance}) \text{ x } (\text{Current})}{2}$$

$$= \frac{0.080\,\text{ohms x } 2400\,\text{mA}}{2}$$

$$= 96\,\text{mV}$$

(b.) Calculate voltage drop in mesh as follows:

$$\text{Mesh Resistance (R) (4 ft. width)} = (\text{Resistance per ft.}) \text{ x } (\text{Length})$$

$$= \frac{0.014\,\text{ohm}}{\text{ft.}} \text{ x } 50\,\text{ft.}$$

$$= 0.70\,\text{ohm}$$

$$\text{Mesh Current (I) (4 ft. width)} = (\text{Current Density}) \text{ x } (\text{Area})$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \text{ x } 200\,\text{ft.}^2$$

$$= 300\,\text{mA}$$

$$\text{Mesh IR Drop} = \frac{(\text{Resistance}) \text{ x } (\text{Current})}{2}$$

$$= \frac{0.70\,\text{ohm x } 300\,\text{mA}}{2}$$

$$= 105\,\text{mV}$$

PRIMARY ANODE = 100-ft. SPACING
SECONDARY ANODE = CONTINUOUS MESH-
4-ft.-WIDE STRIPS

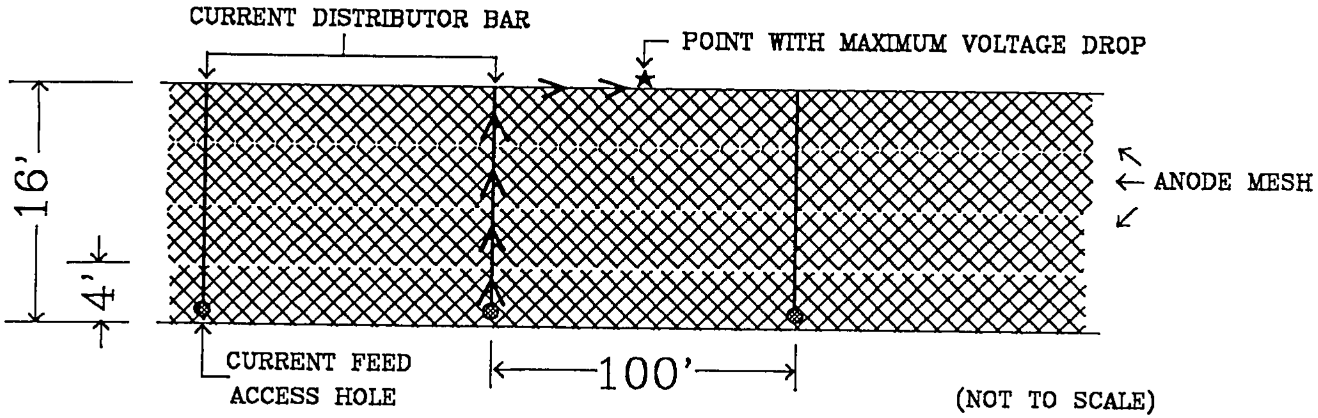

Figure 22. Titanium mesh anode system.

(c.) Calculate total anode voltage drop as follows:

$$\text{Total IR Drop} = (\text{Distributor IR Drop}) + (\text{Mesh IR Drop})$$
$$= 96\,\text{mV} + 105\,\text{mV}$$
$$= 201\,\text{mV}$$

Anode Systems For Substructures

Conductive coatings are often chosen as anodes for substructure cathodic protection because of certain useful properties. They are thin and therefore do not increase dead load or reduce overhead clearance on the structure. Since they are applied to the surface, they are easily renewed in the event of anode damage or consumption. They are particularly suited for application to substructures because they are not normally encapsulated (although encapsulation has been tried). Conductive coatings that have been applied to highway structures include carbon-based paints, conductive polymer-based coating, and spray-applied zinc. Of these, carbon-based paints and spray-applied zinc are discussed below. The conductive polymer coating developed by the Federal Highway Administration (FHWA) has only been applied to one highway substructure and although it is working successfully, has not been utilized enough to warrant detailed description here. Titanium mesh anode material, with shotcrete or gunnite encapsulation, has had some success on highway substructures.

Carbon-based Paints

Advantages

- Dead load is not increased.
- Decorative detail is not lost.
- Paints are easily renewed.
- Paints are relatively inexpensive.
- They have low anode current density.

Disadvantages

- Life is relatively short.
- Voltage is high when concrete surface is subject to drying.
- Shorting is possible.
- Anode resistance is high.
- Debond caused by high moisture content and freeze-thaw conditions is possible.

Carbon-based paint is typically selected when a relatively low-cost system is required for a service life of about five years before maintenance. It is not used for riding surfaces since it is not abrasion resistant and cannot be overlaid. Its use is not recommended in very moist areas or in splash zones. It is also subject to shorting problems in structures that have wire ties, chairs, or reinforcing steel near the surface. If any of these items pertain to the structure being considered for cathodic protection, a preliminary trial test should be conducted.

Conductive-paint design parameters, such as dry-film thickness, paint resistivity, and primary anode configuration, are usually supplied by the paint manufacturer. It is important for the designer to understand these parameters, however, in the event that modification is needed for the structure being considered.

The primary, or distributor, anode is usually a small (0.031 in. or 0.062 in. diameter) platinized wire embedded in the coating. The use of a primary anode is necessary since the coating itself does not have sufficient conductivity to support the flow of current over long distances. Primary anode wires are typically copper-cored niobium with an outer layer of platinum. The wire is normally 35 percent niobium in the cross-sectional area and is coated with a minimum of 25 micro inches of platinum. Linear resistance of the wires is 16 milliohm/ft. for 0.031-in.-diameter wire, and 4.1 milliohm/ft. for 0.062-in.-diameter wire. Conduction between the primary anode wire and the paint is often made using thickened forms of conductive paint or mastic, sometimes applied over non metallic tape or mesh. Spacing between primary anode wires varies, depending on coating conductivity and structure geometry.

Paint thickness varies from 8 mil to 20 mil of dry-film thickness, and resistivity varies from 1 ohm-cm to 10 ohm-cm.

Surface preparation is usually specified by the supplier and is important for proper bonding of the paint.

Following application of the anode coating, a top coat is usually applied for decoration and safety since the conductive paint is black. (A wide choice of top-coat colors are available. The top coat also protects the underlying conductive paint from environmental degradation and influences the moisture content of the thin layer of concrete immediately beneath the anode coating.

The following example calculation is given for the voltage drop in a carbon-based paint anode (see **figure 23**).

Assumptions -

Average current density (concrete)	1.5 mA/ft.^{2}
Primary anode wire	0.031 in. diameter
Primary anode resistance	16 milliohm/ft.

Assumptions (cont.)

Primary anode spacing	5 ft. on center
Primary anode wire length	25 ft.
Effective area	5 ft. x 25 ft. = 125 ft.^{2}
Paint resistivity	3 ohm-cm
Dry-film thickness	10 mil

(a.) Calculate voltage drop in the primary anode wire as follows:

$$\text{Primary Wire Resistance (R)} = (\text{Resistance per ft.}) \times (\text{Length})$$

$$= \frac{0.016\,\text{ohm}}{\text{ft.}} \times 25\,\text{ft.}$$

$$= 0.400\,\text{ohm}$$

$$\text{Primary Wire Current (I)} = (\text{Current Density}) \times (\text{Area})$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \times 125\,\text{ft.}^2$$

$$= 188\,\text{mA}$$

$$\text{Primary Wire IR Drop} = \frac{(\text{Resistance}) \times (\text{Current})}{2}$$

$$= \frac{0.40\,\text{ohm} \times 188\,\text{mA}}{2}$$

$$= 38\,\text{mV}$$

(b.) Calculate voltage drop in the conductive paint (for strip 2.5 ft. long x 1.0 ft. wide), as follows:

$$\text{Paint Resistance (R)} = \frac{(\text{Resistance}) \times (\text{Length})}{(\text{Cross Section Area})}$$

$$= \frac{3\,\text{ohm-cm} \times 76.2\,\text{cm}}{0.774\,\text{cm}^2}$$

$$= 295\,\text{ohm}$$

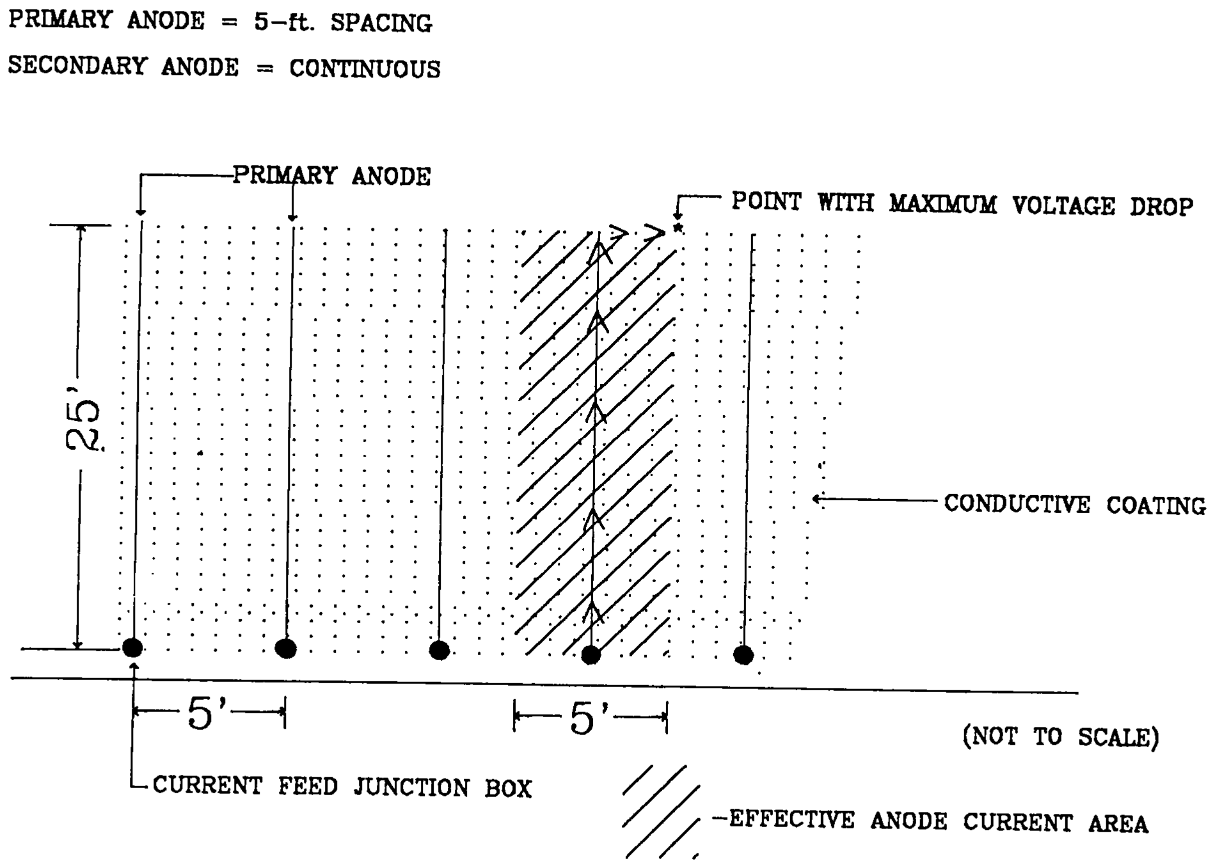

Figure 23. Conductive coating system.

$$\text{Paint Current (I)} = (\text{Current Density}) \times (\text{Area})$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \times 2.5\,\text{ft.}^2$$

$$= 3.75\,\text{mA}$$

$$\text{Paint IR Drop} = \frac{(\text{Resistance}) \times (\text{Current})}{2}$$

$$= \frac{295\,\text{ohm} \times 3.75\,\text{mA}}{2}$$

$$= 553\,\text{mV}$$

(c.) Calculate total anode voltage drop as follows:

Total IR-Drop = (Primary Wire IR-Drop) + (Paint IR-Drop)
= 38 mV + 553 mV
= 591 mV

As this example shows, anode IR drop for conductive-paint systems often exceeds the 300 mV criterion. Unless this specification is relaxed, primary anode conductors must be placed very close together.

Zinc Coatings

Advantages

- Dead load is not increased.
- No overhead clearance is lost.
- No decorative detail is lost.
- Coatings are easily renewed.
- Anode current density is low.

Disadvantages

- Lifetime is moderate.
- Voltage is high when concrete surface is subject to drying.
- Shorting can be a problem.
- Zinc coatings raise environmental and safety concerns.
- Coatings are consumable.

Zinc coatings are receiving significant attention as cathodic protection anodes, particularly for highway substructures. Although pioneered many years ago, zinc anodes have only recently been used in large-scale concrete projects. As a result, significant advances have been made in the application and use of zinc.

Zinc is fundamentally different from all other anodes used with concrete in that it is consumable. Zinc will quantitatively dissolve to form oxide, hydroxide, and carbonate according to Faraday's Law. Thus, zinc can supply a maximum theoretical output of 372 ampere-hours per pound of zinc. In other words, a coating of zinc 1 mil thick can theoretically supply 1.5 mA/ft.^{2} of current for 9,200 hours, or a little more than one year. The following formula can be used to determine the theoretical thickness of zinc:

$$\text{Years (desired)} \times \text{mA/ft.}^2 \times 0.633 = \text{mil zinc}$$

$$\text{Example: } (15 \text{ years}) \times (1.5 \text{ mA/ft.}^2) \times (0.633) = 14 \text{ mil zinc}$$

The thickness calculated above refers to solid zinc. An equal amount of zinc applied by flame or arc spray will be thicker because it is porous. Also, all the zinc applied cannot be utilized electrochemically since a base thickness is needed for conduction of current. Zinc thickness on field structures typically ranges from 8 mil to 20 mil.

Zinc has been applied to concrete by both flame spray and arc spray. Both processes involve melting zinc in the form of wire and atomizing the liquid zinc onto the concrete surface by means of compressed air. Arc spray, which melts zinc by use of an electric arc struck between two zinc wires, has become the preferred process. The optimum system currently available uses an arc-spray gun operating at 600 amperes, which can provide a 20-mil-thick application rate of about 110 sq. ft. per hour.

Environmental and safety concerns are an important consideration for either method of zinc application, although they are somewhat less of a problem with arc spray. Zinc dust and fumes, which result from spraying molten zinc, are hazardous and must be carefully contained and dealt with. Precautions are taken to protect workers and the environment during spraying operations. Typically, these include completely enclosed work areas, and air-supplied respirators for workers within the enclosures. Vacuum-collection systems are used to collect overspray, which ranges from 30 percent to 50 percent for flame spray and from 10 percent to 20 percent for arc spray.

The primary anodes, commonly called primary distributors or connectors, are typically titanium strips or small copper, brass, or stainless steel plates. These are epoxied to the concrete surface, and contact to the zinc is provided when the zinc is applied. The primary anodes are spaced according to convenience and geometry, with at least two distributors per zone provided for redundancy. IR drop in the anode is not normally a concern since zinc is a very effective conductor of electricity.

Installation and quality control techniques for the spray application of zinc on concrete are still evolving. Measurement techniques for zinc thickness, density, and bond strength are being refined.

Methods of dealing with shorts to steel are particularly important. Special care must be taken to locate exposed wire ties, chairs, rebar, or other surface steel that might contact the zinc coating. Installation procedures normally include monitoring for shorts, as well as automatic shutdown of the spraying operation in the event of contact with steel.

There have been recent trials involving the use of zinc as a sacrificial anode on concrete. In these trials, the natural negative potential of zinc provides a driving voltage for cathodic protection, and no external power supply is needed. The trial system has had limited but successful use where concrete resistance is very low, as in coastal structures in hot, moist climates. At this time, sacrificial zinc systems are still in the development stage.

An example calculation for determining the anode voltage drop for zinc coating follows:

Calculate voltage drop for a coating element 1 ft. wide x 25 ft. long. Since this anode is consumed during its lifetime, calculations are based on a thickness one-half that of the applied thickness.

Assumptions -

Current required	1.5 mA/ft.^{2}
Zinc thickness	20 mil (10 mil effective)
Zinc resistivity	6 x 10^{-6} ohm-cm
Distance from primary	25 ft. (762 cm)

$$\text{Zinc Resistance (R)} = \frac{\text{(Resistivity) x (Length)}}{\text{(Cross Section Area)}}$$

$$= \frac{6 \times 10^{-6}\,\text{ohm-cm} \times 762\,\text{cm}}{0.774\,\text{cm}^2}$$

$$= 0.006\,\text{ohm}$$

$$\text{Zinc Current (I)} = \text{(Current Density) x (Area)}$$

$$= \frac{1.5\,\text{mA}}{\text{ft.}^2} \times 25\,\text{ft.}^2$$

$$= 37.5\,\text{mA}$$

$$\text{Zinc IR Drop} = \frac{(\text{Resistance}) \times (\text{Current})}{2}$$

$$= \frac{0.006\,\text{ohm} \times 37.5\,\text{mA}}{2}$$

$$= 0.11\,\text{mV}$$

From this calculation, it is obvious that voltage drop in the zinc coating is seldom a concern.

Mesh Anodes with Concrete Encapsulation

The same types of encapsulated anode mesh and current distributor bars are used for substructures as for deck surfaces, and the method of fastening to the concrete is essentially the same. More complicated geometry requires more fastening per unit area.

One problem encountered with these systems has been maintaining the bond between the overlay and the original concrete. Particular care must be taken with the shotcreting specification and the application of the shotcrete.

Calculations for anode voltage drop are the same as for a mesh anode applied to a deck surface, and the previous example calculation may be used as a guide.

Selection Of Anode Systems

There are a number of owner and structure factors that will influence the choice and cost of an anode system. These factors, discussed below, are best considered after collecting the following information on the candidate bridge member.

Survey Factors

1. Review construction specifications, plans, and test reports.
2. Examine previous repair reports, specifications, and construction reports, especially those involving epoxy injection or high-resistivity patching materials.

3. Consider condition survey information, such as

   (a.) percent spalls and delaminations;

   (b.) half-cell survey;

   (c.) chloride content; and

   (d.) visual inspection, including
   - the quality of the existing riding surface,
   - the presence or absence of concrete scaling or other freeze-thaw distress,
   - the presence of silica fume or polymer concrete patching materials,
   - the presence of exposed reinforcing steel (i.e., low cover),
   - the extent of concrete cracking,
   - any evidence of past epoxy injection,
   - availability and proximity of AC power,
   - presence of epoxy-coated steel, or
   - evidence of leakage through joints onto substructure;

   (e.) petrographic analyses of cores for air void parameters and the presence or absence of alkali-reactive aggregates;

   (f.) reinforcing steel cover and electrical continuity of the reinforcing steel and other metallic elements embedded in the concrete.

Owner Factors

1. Define the service life of the structure.

2. Define the acceptability of maintenance in the future (i.e., is a low first-cost system that will require significant maintenance every five years acceptable?).

3. Determine if remote monitoring is needed.

Structure factors must be considered. Cathodic protection will not halt freeze-thaw deterioration of the concrete itself. Thus, rehabilitation of structures that have both corrosion and freeze-thaw distress must be carefully designed to address both problems. Generally, this dual situation limits available cathodic protection options in freeze-thaw environments by eliminating systems involving asphaltic-concrete overlays, unless a compatible and effective sealer is first applied that will not interfere with delivery of the protective current. Appropriate systems then, include those that enhance durability of the underlying concrete by sealing it or encapsulating it with a new, high-quality concrete layer.

If the concrete contains aggregates that are alkali reactive, the application of cathodic protection may accelerate the alkali-silica reaction near the steel. Although this acceleration has not been shown to be detrimental to the structure, cathodic protection should not be routinely applied in such cases.

Electrical continuity of the reinforcing steel network is required for effective cathodic protection. Experience has shown that electrical continuity is normally present on the uncoated reinforcing steel in most bridge structures and is not usually a limiting factor in the selection process. The cost of testing for continuity and continuity bonding must be considered when preparing the construction cost estimate. Continuity bonding of steel may be extensive, particularly on old structures.

The concrete in the bridge member must be ionically conductive. It generally is, although there are a few situations in which the presence of a very resistive component may increase rehabilitation costs and make the cathodic protection installation less cost-effective. These situations are ones in which (1) silica fume, epoxy polymer, or other specialty concrete patch formulations with resistivities in excess of 50,000 ohm-cm are present in large amounts in patches, or (2) epoxy injection has been used to bond previous delaminations. Generally, the presence of epoxy in cracks perpendicular to the anode is not a problem; but the presence of continuous epoxy layers parallel to the anode and between the anode and reinforcing steel is a problem. Penetrating sealants may also result in a highly resistive component.

Cover over the reinforcing steel is important. Level of cover does not eliminate cathodic protection as an option, but can affect costs and the selection of anodes. Obviously, it will be difficult to install a slotted system (3/4-in. deep slots) if a large percentage of the reinforcing steel has a concrete cover of less than 3/4 in.
The anode cannot directly contact the reinforcing steel (at even one location) in impressed-current systems. Therefore, it may be necessary to insulate exposed or low-cover steel areas with a nonconductive material or to add a thin concrete layer prior to anode installation. These requirements all increase construction costs.

Alternating current (AC) power is used with most impressed-current cathodic protection systems. Therefore, the availability and proximity of AC power is a cost consideration. When AC power is not available nearby, solar power can be considered.

To summarize, cathodic protection is possible if the bridge meets the following conditions:

1. It is not prestressed.
2. It does not contain alkali-reactive aggregate.
3. It has an adequate entrained air void structure for the environment.
4. Ninety-five percent or more of its reinforcing steel cover is more than 1 in.

5. It contains little high-resistivity patch material.

6. It has an available AC power source.

If the bridge element does not satisfy items (1) or (2), cathodic protection is not recommended except as a carefully planned and executed research effort. If (1) and (2) are satisfied, but items (3), (4), or (6) are not, cathodic protection is possible, but some anode systems may not be applicable and special costs must be considered. If the element does not satisfy item (5), special cost considerations must be addressed or only partial protection installed. A summary of available anode systems is presented in **table 4**.

Cathodic Protection Systems for Deck Surfaces

Selecting a cathodic protection system depends on a number of considerations, including structural, environmental, and economic conditions.

Certain conditions may preclude the use of a particular system. For example, if the concrete has an inadequate entrained air void system, water trapped in a conductive asphalt overlay will accelerate freeze-thaw damage, and another system must be chosen. If the concrete cover over the reinforcing steel is less than 1 in., then a slotted conductive polymer system should not be used because of the potential for shorts. If a bridge has structural or overhead clearance limitations, it may not be possible to apply the thick overlay required for mounded conductive polymer or mesh anode systems.

Another concern relates to the environment and safety. The vinyl ester resin used in conductive polymer systems is flammable and has strict handling and storage requirements. If local regulations regarding such substances are rigorous, the choice of a system will be affected.

Traffic is another consideration. If it is not possible to reroute traffic, or if a structure can be closed to traffic for only a few hours, a slotted conductive polymer system may be advantageous. Slot cutting may be done during low-volume periods, and the conductive polymer can support traffic loads about one hour after placement.

Weather may also be a factor. Conductive polymer for both slotted and mounded systems can only be applied to dry concrete. This situation can result in weather-related delays.

Table 4. Estimated Service Life and Maximum Anode Current Density for Available Cathodic Protection Systems

Anode System	Structure Protected	Estimated Service Life (years)[1]	Maximum Anode Current Density ($mA/ft.^2$)
Coke-asphalt overlay	Decks	20	2
Slotted conductive polymer grout	Decks	15	5
Mounded conductive polymer with concrete overlay	Decks	20	7.5
Titanium mesh with concrete overlay	Decks	35	10
Titanium mesh with shotcrete overlay	Substructures	35	10
Conductive paint	Substructures	5	2
Sprayed zinc	Substructures	15	2

[1] Based on expert opinions of the authors of the report.

If there are no structural limitations, it may be desirable to use a system with an overlay to provide a new riding surface. A slotted conductive polymer system does not renew the surface and creates in a striped appearance, which some consider visually unappealing.

Economics will also influence the choice of a cathodic protection system. Some general estimating guidelines are provided in the appendix, but local conditions may influence contractor costs.

Anode Systems for Substructures

Other issues influence the choice of systems for substructures. Both carbon-based conductive coatings and zinc have the advantage of being very thin and therefore of preserving the original structure form and decorative detail. They also contribute no additional load to structures with load limitations. Since they are surface coatings, both are also relatively easy to renew in the future.

However, carbon-based paint and zinc systems both raise environmental and safety concerns. The solvents for some carbon-based paints are volatile organic compounds (VOCs) and raise concern about VOC emissions. Zinc dust and fumes, which result from both flame and arc-sprayed zinc, must be carefully dealt with. Typically, the spraying is done inside complete enclosures. Workers inside the enclosures must wear air-supplied respirator masks. Vacuum systems process the air inside the enclosure and collect overspray.

Zinc and carbon-based paint are especially subject to shorting. Shorting occurs when the conductive coating comes into contact with embedded steel components that extend to the concrete surface. This is a special concern on substructures that have large amounts of cracking or surface-exposed steel in the form of chairs, tie wires, or other steel components. For zinc systems, monitoring is conducted during the spraying operation, and the spraying is interrupted when a short is detected. Downtime in such cases may be substantial. For carbon-based paint systems, monitoring for shorts during installation is not possible because sufficient conductivity of the paint does not develop until some drying has occurred.

Carbon paints have had problems maintaining bond with the concrete, particularly in cool, damp environments. Zinc has a better history of maintaining bond, but still has a limited lifetime since it is constantly dissolving at a rate based on the anode operating current density. Zinc is also subject to self-corrosion at the rate of 0.044 mil to 0.2 mil per year.

The mesh cathodic protection system offers the promise of a longer lifetime, but has suffered problems with the bond of the required encapsulant to the substructure. Recent improvements in the material have been encouraging, with no debonding after two years.

The calculations for IR drop show that carbon-based coatings exhibit higher resistance losses. Such systems should be carefully designed to make sure steel farthest from the power feed is still receiving adequate current.

Finally, as with deck systems, economics will play a part in the selection process.

Selection Of Other Elements

Establishing Cathodic Protection Zones

Cathodic protection systems are usually divided into a number of electrical zones that operate independently of one another. Different areas of the structure are likely to have different current requirements and should therefore be independently controlled. These different current requirements are primarily due to different reinforcing steel densities per square foot of concrete surface area, but may also be due to different chloride or moisture content in the environment. Dividing a system into several zones makes it easier to locate and correct defects and short circuits. It is also common to provide an extra electrical circuit that can be used in the event of power failure. Providing this circuit is more practical when the system consists of a number of independent zones. For these reasons, specifying a larger number of smaller zones for more precise control seems beneficial. However, excessive zoning results in increased installation and power supply costs. Since at least two embedded monitoring devices are recommended for each zone, cost for the purchase and installation of monitoring equipment will be higher.

Historically, zone sizes for bridge decks range from 5,000 $ft.^2$ to 10,000 $ft.^2$ and for bridge substructures, from 1,000 $ft.^2$ to 5,000 $ft.^2$. Zone sizes on very large uniform areas should be large as well.

Determining Design Current Requirements

Once the electrical zones have been determined, a design current must be chosen for each. Preliminary testing to estimate the initial current requirements can be conducted, but such testing is usually not cost-effective. The normal practice is to use a rule-of-thumb guideline to arrive at a conservative design current. The actual current required, which is usually well below design current, is determined by testing after system installation.

Several guidelines have been suggested for arriving at a design current. One rule of thumb is to provide 1.5 mA/ft.^{2} of steel surface that is within 8 in. of the anode. For conventionally reinforced bridge decks, a design current of 2 mA/ft.^{2} of concrete has historically been used. Some recent experience indicates that this level might reasonably be reduced to 1.5 mA/ft.^{2} of concrete in the future.

While these guidelines have been generally accepted, the designer must be aware that the actual current required depends on many complex factors, and these sometime dictate different design criteria. Current requirements on actual structures have been reported ranging from 0.1 mA/ft.^{2} to 4.0 mA/ft.^{2} of concrete, depending on steel and concrete conditions. Future experience may make it possible to establish more definitive guidelines; but for the time being, it is prudent to remain conservative.

Unless detailed investigation is undertaken, it is suggested that a design current be used based on the criterion of 1.5 mA/ft.^{2} of steel surface that is within 8 in. of the anode. If the steel density varies within a zone, the design current should be based on the area of greatest steel surface within that zone. This will ensure that the anode design is adequate.

The following sample calculation is provided for determining the design current:

The bridge construction specification for a conventional cast-in-place bridge deck calls for a top mat of #6 rebar at 7-in. spacing crossed by #4 rebar at 7-in. spacing, and a bottom mat of crossing #5 rebars at 7-in. spacing. All rebar steel is less than 8 in. from the top surface of the deck. Calculate a design current for cathodic protection of this bridge deck with a total surface area of 10,000 ft.^{2}.

Calculating the steel surface area in 1 sq. ft. of the concrete deck described above gives the following:

#4	0.225 ft.^{2}s/ft.^{2}c
#5	0.562 ft.^{2}s/ft.^{2}c
#6	0.336 ft.^{2}s/ft.^{2}c
Total	1.123 ft.^{2}s/ft.^{2}c

(Note: ft.^{2}s = square foot of steel
ft.^{2}c = square foot of concrete)

Using a current density of 1.5 mA/ft.^{2}s of steel surface gives the following calculation:

Design Current = 1.5 mA/ft.^{2}s x 1.123 ft.^{2}s/ft.^{2}c
= 1.685 mA/ft.^{2}c

If the deck is divided into two electrical zones of equal size, then each zone will have a design current of

$$\frac{1.685\frac{\text{mA}}{\text{ft.}^2\text{c}} \text{ x } 10{,}000\text{ft.}^2\text{c}}{2}$$

$$=8.42$$

(See **figure 24.**)

Power Supply and Electrical Components

A power supply is necessary to provide a source of direct current (DC) to operate a cathodic protection system. This power supply should meet certain requirements to ensure safe, reliable, long-term operation. The complexity of many existing cathodic protection power supplies and associated reliability problems indicate the need for a power supply that is simple in design, rugged, and easy to maintain.

Design Types

The power supplies commonly used today can be grouped into the following four types:

1. The simple rectifier consists of a tapped transformer and a rectifying element such as a silicon diode. Even though the voltage can be selected by choosing the appropriate tap, it is essentially unregulated because the actual output voltage will have some variation with load. The output is pulsed DC. Widely used in the pipeline industry, it is a readily available, relatively inexpensive, reliable, off-the-shelf item.

2. The saturable core reactor is a transformer with a special core design that provides a means of setting and maintaining the voltage more accurately than the simple rectifier. When coupled with a rectifying element, its output is pulsed DC. It is reasonably priced and fairly rugged.

3. Conventional voltage and current-controlled rectifiers utilize feedback circuits and silicon-controlled rectifiers or thyristors to regulate the voltage or current. The output from unfiltered versions of these rectifiers often have a high, short-duration spike. Some concern has been expressed about the effect of the spikes on long-term system performance.

4. Switch-mode rectifiers operate by changing the voltage from 60 hertz to between 60,000 hertz and 120,000 hertz. This change provides a relatively flat output with minor ripple. Again, voltage and current control are provided by feedback circuits. The other advantage is that at higher frequencies, the components are much smaller and more efficient. This design is very popular for computers.

Simplicity, ruggedness, and reliability appear to be the most important qualities for a power supply. Generally accepted practice indicates that the power supply should be a regulated design capable of operating under either current or voltage control. At present, constant-current control is more widely used because it has the advantage of more closely controlling the electrochemistry that occurs at the steel surface and is more directly related to steel potential.

Simple rectifiers are not typically used because they are an unregulated design. A properly designed saturable core reactor (SCR) can provide a very reliable power supply that meets most of the design criteria. Also, SCR designs generally provide a reliable, low-cost, regulated power supply. Switch-mode designs have been on the market only a short period of time, and their complexity of design raises questions about their reliability and maintenance requirements.

The power supply selected should have well-documented performance data on its operation. It should have clearly demonstrated reliability, ruggedness, and ease of maintenance under field conditions. All electronic component assemblies should be encapsulated in epoxy resin or varnishes that are recommended by the component manufacturer to prevent exposure to the environment. They must have a demonstrated ability to withstand operational hazards such as voltage transients, lightning strikes, operator abuse, vandalism, high- and low-temperature extremes, vibration, high humidity levels, dust, rain, and dirt.

The power supply cabinet should meet National Electrical Manufacturers Association (NEMA) classification requirements for location and use. The cabinet may be made of several different types of materials including hot-dipped galvanized steel, stainless steel, and paint over galvanized steel. Recent experience has shown that stainless steel cabinetry is generally the most cost-effective alternative.

The power supply should be located to provide easy accessibility for future monitoring and wiring.

Sizing

Since cathodic protection zone size may range from about 1,000 ft.^{2} to 10,000 ft.^{2}, power supply output is typically 2 amperes to 20 amperes with a relatively low output voltage (typically 24 volts DC). A very modest power requirement of 50 watts to 500 watts per

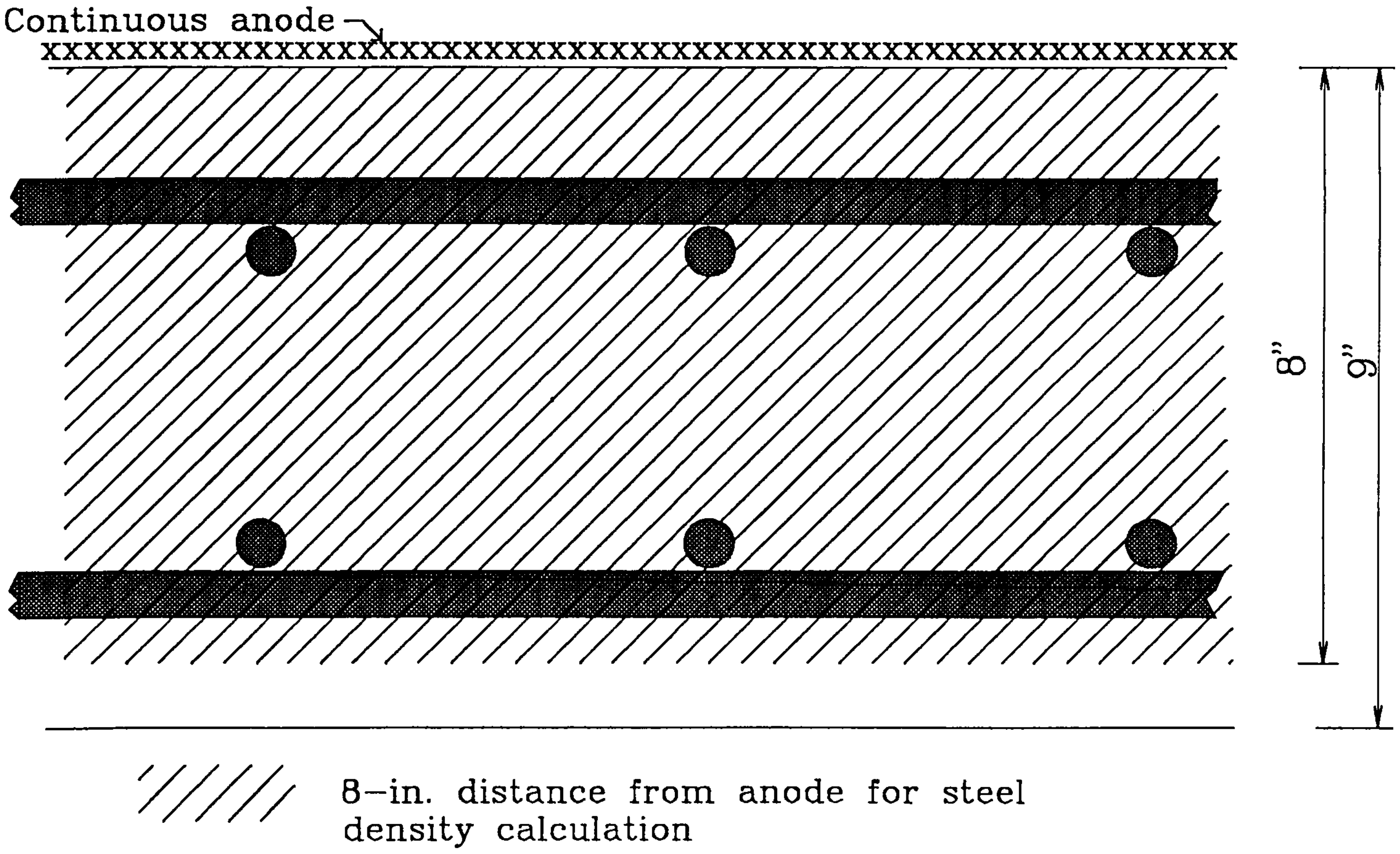

Figure 24. Area for steel density calculation.

zone results from this output.

Options

The cathodic protection power supply can be equipped with numerous options including panel meters, protection devices, switches, IR drop-free devices that measure cathodic protection potential, and remote monitoring units. These accessory items are not typically basic components of the power supply but are intended to enhance its usefulness.

Panel meters can be included for monitoring the applied voltage and current and rebar probe currents, and to monitor half-cell potentials with embedded reference electrodes. Panel meters may be analog meters with an indicating needle or digital meters. The digital meter provides good accuracy, high resolution, high input impedance, excellent visibility, and higher durability. Digital meters can have either a liquid crystal display (LCD) that provides good visibility in bright-light conditions or a light-emitting diode display (LED) that provides good visibility in low-light conditions. LED displays are more reliable in cold climates.

Protection devices are typically included to protect the power supply from premature failure caused by voltage surges, current overloads, and lightning strikes. Overload devices include circuit breakers and fuses. A circuit breaker protects the power supply from AC overloads and also functions as an on/off switch to disconnect AC power from the unit. A fully magnetic circuit breaker is standard. Fuses are utilized to prevent overloads to a particular component or circuit. Metal-oxide varistors (MOV) can be included on the AC and DC side to protect sensitive components from any high voltage surges that may occur. Lightning arresters are also typically included, such as expulsion arresters for AC protection or gas-filled arresters for DC protection.

Selector switches are included to facilitate monitoring of the numerous zones that may be present in a structure. They allow easy switching from zone to zone or from reference cell to reference cell.

Because half-cell potential measurement errors can be incurred while a cathodic protection system is powered, it is necessary to monitor instant-off potentials. For this reason, power supplies can include devices that eliminate these errors by automatically measuring the instant-off (IR drop-free) potentials. Instant-off readings can also be made if an interrupter is provided in the output circuit. Verification of acceptable instant-off measurements must be done with an oscilloscope.

All of the above options contribute to the degree of complexity that is engineered into a reliable power supply. They also affect the overall rectifier cost. As a result, they need to be included judiciously.

Wiring and Conduit

The external electrical wiring and hardware used to complete a cathodic protection installation is often overlooked by the designer. All wiring should conform to local and national electric codes. Some important factors to consider during this phase are as follows:

1. Wiring splices outside the structural concrete should be made in junction boxes and protected from corrosion by coating or plating. Splices within the concrete structure should be avoided whenever possible but if used, must have an environmentally sealed, waterproof connection.
2. All embedded cable insulation should be suitable for direct burial in that environment, typically high-molecular-weight polyethylene (HMWPE).
3. Where wiring abrades against concrete at bends or openings, it should be protected with an appropriate plastic sleeve.
4. Conduits should be securely fastened to the structure at locations accessible for future maintenance, but should also be placed away from the public.
5. Connectors, pull boxes, expansion fittings, and terminal boxes must be compatible with the overall conduit layout.
6. Wiring for reference cells, monitoring probes, and their associated grounds to the reinforcement should be in a separate conduit from the anode and system negative feeds and always separate from the AC system feed lines.
7. Shielded wiring may be necessary for reference and monitor circuits in areas of high-frequency electrical noise, such as from nearby radio transmission towers, airport radar stations, and other similar sources.

DC wiring from the rectifier to the anode and reinforcing steel must be properly sized based on the design current and length of the wire. If the wire is too small, voltage drop in the wire will be excessive. This drop may result in insufficient voltage at the anode or poor distribution of current where wires of different length supply current to a single electrical zone.

Figure 25 may be used as an approximate guide for the selection of wire size, based on amperage, wire length, and an allowable IR drop of 1 volt. For example, if the wire is required to transfer 10 amperes a distance of 200 ft., the selection of #4 American Wire Gauge (AWG) wire will result in a loss of 1 volt (two wires, each 200 ft. long for a total of 400 ft.).

Conduit size is selected from standard electrical code tables based on the size and number of conductors to be contained in each conduit run.

Location

The power supply cabinet should be located with several factors in mind. First, the location should provide for convenient connection to the available AC power source. Second, it should provide easy access for future monitoring and maintenance. Third, the location should discourage damage from vandalism and traffic. Finally, the power supply location must not be subjected to water drainage from highways or bridges, or to salt-contaminated snow from snow removal operations.

Reference Cells and Monitors

Monitoring devices are vital elements of a cathodic protection system. It is only by measuring the potential of the steel with respect to these monitors that the corrosive state and hence the effectiveness of the protection system can be judged. Since cathodic protection systems are intended to function for several years, the potential measurements must be reliable and accurate over long periods of time. Reference electrodes may be either portable or permanently embedded. The following discussion applies principally to embedded reference electrodes that are normally used with cathodic protection systems.

Reference Electrodes

A reference electrode is one whose potential is known and against which the potential of another electrode may be measured. The act of measuring the electrode's potential must cause no significant departure from equilibrium conditions. In order for this situation to be true, a reference electrode for use in concrete must possess the following properties:

1. Show a small deviation of potential when current is passed.

2. Return to its standard potential following the passage of current.

3. Have a stable potential with time.

4. Have a minimum response to changes in temperature and other environmental changes.

5. Be relatively insensitive to impurities.

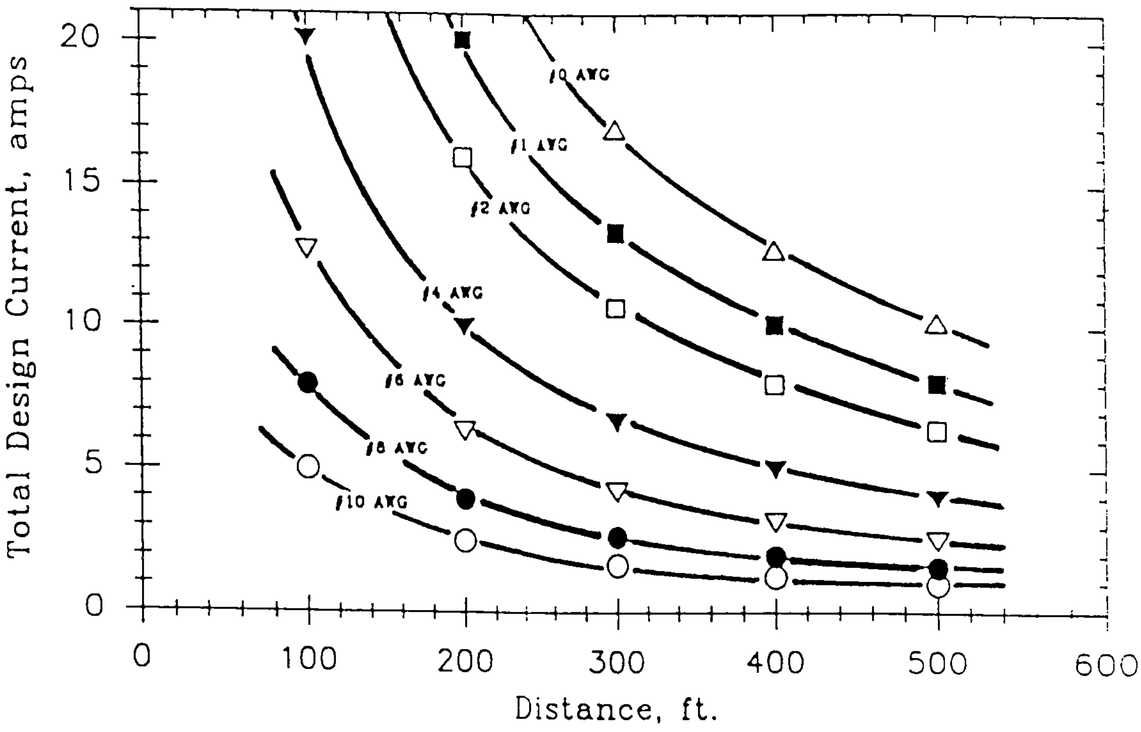

Figure 25. Wire sizing.

6. Have low electrical resistance.

7. Function well in high pH environments.

8. Be rugged enough to accommodate construction practice and repeated freeze-thaw cycling.

9. Lend itself to reproducible fabrication.

Although steel potential can be measured from the surface of the concrete, this measurement is usually considered less convenient and less accurate than measurement using embedded reference electrodes.

Several types of embedded reference electrodes have been proposed and tested for use in concrete. These include "true" reference electrodes such as copper-copper sulfate, silver-silver chloride, mercury-mercurous chloride (calomel), molybdenum-molybdenum trioxide and manganese-manganese dioxide. These are regarded as true reference electrodes because the concentration of all reactants is controlled at the electrode-electrolyte interface. Consequently, the potential at which these electrodes operate may be calculated, at least in theory. A number of other electrodes that may be classified as "pseudo" reference electrodes have also been proposed. These include graphite, platinum, mixed-metal oxide, zinc, and lead. Although the potential of pseudo electrodes may remain stable in certain situations, this potential depends on an electrolyte coming into contact with their surface and is subject to change as the environment changes. Calculating the potential of such electrodes is usually impossible.

To choose a reference electrode, the designer must first decide what purpose the electrode has in the system. If the reference electrode is only intended to provide a stable potential for a four-hour depolarization test, then several choices are possible. If the reference electrode is needed to accurately determine actual steel potentials over long periods of time, the choice will be more limited. Only silver-silver chloride and graphite have a proven history of use in North America. Of these two, only silver-silver chloride is considered a true reference electrode capable of establishing actual steel potentials.

The silver-silver chloride electrode has evolved in the United States as the standard reference electrode for reinforcing steel in concrete. Its performance in the electrochemical industry is also well established and accepted. The chloride concentration within the electrode should be carefully controlled and separated from the environment by a ceramic frit or other porous separator. The potential of this electrode will vary somewhat, depending on the concentration of chloride, but, once constructed, it should remain relatively stable. Unfortunately, silver-silver chloride electrodes are sometimes supplied with glass elements inside, which has led to breakage and failure in some field applications.

The graphite reference electrode has been extensively tested and used in Ontario, Canada.

Graphite is not a true reference electrode, but is more properly called a pseudo reference electrode. However, graphite's potential in concrete has proven relatively stable over short periods of time. The graphite reference is considered sufficient to conduct short-term depolarization tests, but it should not be used to measure the true potential of steel.

Other proposed reference electrodes have either proven unreliable or do not have sufficient history of operation to be recommended in this manual. In particular, copper-copper sulfate has proven unreliable as a permanent reference electrode and should not be used for that purpose.

At least two permanent reference electrodes should be placed in each electrical zone. Electrodes installed in this way will serve as a check on each other.

When choosing a location for embedded reference cells, the following criteria are recommended:

1. Choose the most anodic (corrosive) area.
2. Select an area of sound original concrete.
3. Select the location farthest from the power feed.
4. Choose the area of highest steel density.
5. Select an area that represents typical concrete cover.

Unfortunately, it is usually impossible to satisfy all of these location criteria. For example, the most corrosive area will seldom have sound concrete around the bar and is unlikely to be located at a point farthest from the power feed. In such cases, a location must be chosen based on the relative importance of these factors. Of the criteria listed above, the first - locating the reference in a highly anodic area - is most important. This will ensure that steel in even the most corrosive location will be effectively monitored. It is also important to install at least one reference electrode at a point farthest from the power feed that will generally receive the least cathodic protection current. If meeting these requirements is especially difficult in a particular structure, it may be prudent to install more than two reference electrodes per zone.

Ideally, the reference electrode should be installed with the measuring tip adjacent to the steel, while leaving the steel in original sound concrete. This position ensures that the potential of the steel at the measuring point best represents the condition of the original structure. The reference electrode should be placed at the same level as the reinforcing steel and backfilled with concrete containing chloride at a concentration approximating that of the surrounding concrete. This practice will minimize errors that may occur as a result of measuring across regions of different concentrations.

If it is necessary to take potential measurements at several places within the zone, it may be too expensive or complex to install embedded reference electrodes at each desired measurement point. Instead, data from embedded cells may be supplemented with that from portable reference electrodes placed on the concrete surface. Measurements taken from the surface may contain errors and these errors may be significant.

Accuracy of potential measurements taken at the concrete surface can be improved by the use of potential wells. In this case, a hole is drilled down to the steel surface, fitted with a plastic sleeve, and filled with mortar or grout. The steel potential can then be taken at the exposed end of the potential well. This procedure is inexpensive, and the reference electrode is always easy to verify and change. The obvious disadvantage of this procedure is the need to manually test at that location on the structure, which may result in accessibility and traffic control problems.

Macrocells

Embedded macrocells are optional devices that are sometimes installed to provide additional information regarding cathodic protection current requirements. The macrocell is an exposed 5-in. length of #5 reinforced steel that is placed in cement mortar typically containing 15 lbs. of salt per cubic yard. This precast macrocell is placed in an excavation in which the reinforced steel is exposed on all sides. The excavation is then patched with chloride-free concrete. When the macrocell is connected to the reinforcing steel through a 10-ohm resistor for monitoring purposes, a strong galvanic corrosion cell is established.

The corrosion current flowing to the macrocell can be monitored, and when proper cathodic protection current is applied, the corrosion current will be reversed. The macrocell is constructed to be the most anodic site. Therefore, if the macrocell is protected, other reinforcement may be safely assumed to be protected as well.

Remote Monitoring Units

A remote monitoring unit (RMU) collects, stores, and transmits operational data from each zone of a cathodic protection system. RMU's eliminate the need for the operator of a cathodic protection system to visit the structure each time data are collected. This is beneficial when large numbers of structures must be monitored or when the sites are not easily accessible because of location or distance.

RMUs can be designed to fill the following four functions:

1. Record instant-off (IR drop-free) reinforcing steel potentials, zone voltage, and zone current at predetermined intervals.

2. Perform depolarization tests.

3. Check the system status and notify a central computer of any malfunction.

4. Allow user input either from a remote site or from an on-site computer.

The last item is an innovation that enables the operator to control and monitor each cathodic protection zone. When data are collected and analyzed, the operator can adjust a zone to meet the required criterion. The frequency with which these data are collected is determined by the user from an office computer or an on-site terminal.

An RMU design is site specific. The design must specify the number of zones that will be monitored to correctly size the RMU. Units have been installed that monitor 16 zones, and greater numbers of zones are possible.

Normally, both the RMU and the modem are powered by the 120-volt AC power supplied to the rectifier. The enclosure that is normally used with an RMU has a NEMA Class 4 rating, which is both dust and water tight. If unusual environmental exposure conditions are expected, enclosures that immerse all electronic components under oil can be specified.

An RMU must include an office computer and printer. If these are not already available, they must be purchased as part of the system. Specifications should include installation at a designated site using a dedicated phone line. Various software packages are available to collect, store, and reduce the input data from the rectifier. Suppliers should be contacted to provide the hardware capability and software output to ensure the RMU meets the needs of the agency.

The zone voltage and current are normally provided to the computer terminal in real-time output each time a telephone call is made to the RMU. Data storage in the RMU is normally not provided. If desired, storage can be added to the RMU so that operating parameters are measured and retained at regular intervals between interrogations by the office computer.

The RMU can be designed to alert the operator, via the computer terminal, of a system malfunction such as interruption of AC power, excessive or zero DC current, and unusual reference electrode potential readings. This capability allows a malfunction in a zone to be identified as quickly as possible.

Estimating the Cost of Cathodic Protection

This guide is for estimating the construction cost of cathodic protection systems on bridges. The costs of patching and traffic control are not included, although, when cathodic protection is used, the patching cost can be minimized. Monitoring and maintenance costs are discussed.

Two types of estimates are possible given the data bases presently available. The order-of-magnitude estimate provides a quick "educated guess" for planning purposes. The system estimate provides a more detailed estimate based on the pay items in the specifications.

The procedures given below are based on data obtained from the literature, from actual monitored projects, and from the experiences of the authors. The user is urged to update unit cost estimates as new data become available and to compensate for inflation (the estimates provided are in 1992 U.S. dollars). Also, substructure cathodic protection costs can vary widely because of varying member sizes and access. The cost estimates provided here are averages. In special circumstances, additional costs will be incurred and should be evaluated on a case-by-case basis.

Order-of-Magnitude Estimate

The fastest and easiest cost estimate is commonly referred to as an "order-of-magnitude" estimate. When patching is not included in the estimate, the only information required is the approximate surface area of the anode on the structure. Once the anode system is chosen, the estimate involves the following two additional steps:

1. Selecting the unit cost per unit area of anode from **table 5**.

2. Multiplying the unit cost by the surface area of anode and the structure factor (**table 6**), which increases or decreases the unit cost.

The "structure factor" is a multiplier that adjusts for the size of the project. **Table 6** lists the recommended factors.

For example, assume that an order-of-magnitude cost estimate is wanted for a coke-asphalt system on an 82,000 ft.^{2} (7,600 m^2) bridge deck. From **table 5**, the estimated unit cost is $6

Table 5. Available Cathodic Protection Systems, Estimated Cost and Service Life

Anode System	Structures Protected	Estimated Cost in 1992 ($/ft.^{2})	Construction U.S. Dollars ($/m^2)	Estimated Service Life (years)[1]
Coke asphalt with bituminous overlay	Decks	6	65	20
Slotted conductive polymer grout	Decks	7	76	15
Mounded conductive polymer with concrete overlay	Decks	9	98	20
Titanium mesh with concrete overlay	Decks	9	98	35
Conductive paint	Substructures	7	76	5
Sprayed zinc without enclosure	Substructures	8	86	20
Sprayed zinc with enclosure	Substructures	14	151	20
Titanium mesh with shotcrete	Substructures	14	151	35

1. Based on expert opinions of the authors of the report.

Table 6. Structure Size Factors

Anode Area	Size Factor
Less than 4,000 ft.^{2} (370 m^2)	2.2
4,001 ft.^{2} to 10,000 ft.^{2} (371 m^2 to 925 m^2)	1.5
10,001 ft.^{2} to 30,000 ft.^{2} (926 m^2 to 2,775 m^2)	1.0
Greater than 30,000 ft.^{2} (2,775 m^2)	0.9

per square foot (S65 per m^2). The structure size is greater than 30,000 sq. ft. (2,775 m^2), so the factor, from **table 6**, is 0.9. Thus,

$$82{,}000 \text{ sq. ft.} * \$6/\text{sq. ft.} * 0.9 = \$442{,}800$$

is the order-of-magnitude estimate.

This type of estimate is helpful for general planning purposes; however, its accuracy is typically no better than plus or minus 20 percent.

System Estimate

Once a project advances beyond the initial stages, greater accuracy is usually needed. The procedure for providing a more detailed estimate is called a "system estimate." Using this approach, the unit and total costs of each pay item in the specifications are estimated.

First, questions about the structure need to be answered. Sample answers to each question are given in parentheses.

1. Is the bridge member a deck or substructure? **(deck)**
2. What type of anode system is preferred? **(coke-asphalt with bituminous overlay)**
3. What is the total surface area of the anode? **(82,000 sq. ft., 7,600 m^2)**
4. Is a remote monitoring system desired? **(yes)** If yes, should it include an office computer? **(yes)**
5. How far from the bridge are the necessary utilities (AC power and telephone service, if remote monitoring is desired)? **(1250 ft., 381 m)**
6. Will the rectifier be directly exposed to de-icers or seawater? **(no)**

Second, the individual pay items need to be defined. These typically include the following:

- Rectifiers.
- Reference cells.
- Wiring - AC and DC.
- Embedded metal continuity bonds
- Anode system.
- Corrosion engineering.
- Remote monitoring.

Third, the costs for available equipment and installation are defined. These relate to the cathodic protection design and typically include the following:

1. One rectifier circuit of 24 volts is needed to provide 10 amperes per zone plus one spare. Each circuit costs $1,000.

2. Four rectifier circuits per cabinet are required. Galvanized steel finish costs $1,010 per unit and stainless steel finish costs $2,110 per unit (materials and installation). The stainless steel finish is used when deicing salts will directly contact the cabinet.

3. Two embedded reference cells per zone are needed, and no other embedded monitors. Typically, each reference cell costs $150 and installation costs $185, for a total of $335.

4. The zone size will be 6,500 sq. ft. (600 m^2) for deck systems and 4,500 sq. ft. (420 m^2) for substructure systems. These sizes are the maximum specified in the appendix. For some structures, other zone sizes are appropriate.

5. Wiring costs include AC service, DC conduit and wiring, and the system negative connections to the reinforcing steel. The AC power service installation cost varies with distance **(table 7)**.

Table 7. AC Power Cost

Distance	AC Power Cost	
	U.S. $ per foot	U.S. $ per meter
Up to 100 ft. (30 m)	18	59
101 ft. to 300 ft. (31 m to 91 m)	13	43
301 ft. to 1000 ft. (92 m to 305 m)	10	33
Greater than 1000 ft. (305 m)	8	26

DC conduit costs are $3,500 per circuit. There will be two system negatives per circuit costing $100 each.

6. On average, two embedded metal continuity bonds will be installed per rectifier circuit at a cost of $100 each. These are metal-to-metal connections placed in the structure to ensure that the cathode network is electrically continuous. The connections could be reinforcing steel to reinforcing steel, reinforcing steel to drain, or reinforcing steel to expansion dam. The unit cost includes the cost of excavation, lead wire, lead wire connections (i.e., thermite welds on each end), and patching.

7. The protected area is assumed to be equal to the area covered by the anode. If an overlay or shotcrete is involved, its materials and installation costs are included as part of the anode system costs. Estimated anode system costs (materials and installation) for decks and substructures with anode areas of 10,001 sq. ft. to 30,000 sq. ft. (926m^2 to 2,775 m^2) are listed in **table 8**.

   Two estimated costs per square foot (with and without enclosure) are provided for the sprayed-zinc anode. On some projects, environmental requirements stipulate that a wholly contained enclosure be used, while in other instances this is not required. See the "Design" section of this manual for additional information.

   The size of the project affects the unit anode cost (the unit cost on small projects increases and the cost on larger projects decreases). The structure factor given in **table 6** can be used to adjust unit costs.

8. Corrosion engineering services can be subdivided into the following three areas that indicate the approximate level of effort:

    1. Design = 25 percent.
    2. Construction services = 50 percent.
    3. Activation = 25 percent.

   The unit price estimate for corrosion engineering is \$0.80 per square foot (\$8.65/m^2) for structures 10,001 sq. ft. to 30,000 sq. ft. (926 m^2 to 2,775 m^2). For structures of other sizes, the factors in **table 6** are used to adjust the unit price.

9. Remote monitoring systems are configured in modules, with one module recording the data from four rectifier circuits. Each module costs \$625, and there is a fixed cost of \$3,600 associated with installation, software, and training. Remote monitoring systems require a dedicated telephone line at a cost of about \$0.80 per linear foot (\$8.65/m^2). Therefore, the cost of the telephone line is equal to the distance between the existing service and the rectifiers multiplied by this unit price. If an office computer is desired with the remote monitoring system, add \$2,500.

From the above, the following equations result:

For decks: # circuits = 1 + (sq. ft./6,500 ft.^{2}), rounded to the next whole number (1)

For substructures: # circuits = 1 + (sq. ft./4,500 ft.^{2}), rounded to the next whole number (2)

Table 8. Anode System Costs

Anode System	Cost per (U.S. $/ft.²)	Unit Area (U.S. $/m²)
Deck Systems		
Coke-asphalt w/bituminous overlay	4.05	43.80
Nonoverlay slotted system	5.10	55.10
Conductive polymer mounds with portland cement concrete overlay	7.00	75.70
Titanium mesh w/portland cement concrete overlay	7.0	75.70
Substructure Systems		
Conductive coating	5.25	56.80
Thermally sprayed zinc		
without enclosure	6.00	64.86
with enclosure	12.00	129.70
Mesh anode with shotcrete	12.00	129.70

rectifiers = # circuits/4, rounded to next whole number (3)

Galvanized cabinet rectifier cost = ($1,000 * # circuits) + ($1,010 * # rectifiers) (4)

Stainless steel cabinet rectifier cost = ($1,000 * # circuits) + ($2,110 * # rectifiers) (5)

Reference cell cost = (2 * # circuits * $335) (6)

AC service cost = length * **table 7** unit cost (7)

DC conduit cost = # circuits * $3,500 (8)

System negative cost = 2 * # circuits * $100 (9)

Total wiring cost = AC service cost + DC conduit cost + system negative cost (10)

Embedded metal continuity bond cost = 2 * # circuits * $100 (11)

Anode cost = anode size * **table 8** unit cost * **table 6** factor
(Note: Anode Size = concrete surface area covered by the anode.) (12)

Corrosion engineering cost = anode size * $\$0.80/\text{ft.}^2$ * **table 6** factor (13)

# of remote monitoring (RM) modules = # circuits/4, rounded to next
whole number (14)

RM Cost = ($0.80 * length) + $3,600 + ($625 * # modules)
+ ($2,500 for computer) (Note: Length = telephone line installation distance in feet.) (15)

The total cost is the sum of the costs for each bid item, plus a contingency of 5 percent.

To illustrate the estimating procedure, the guide specifications in the appendix will be referenced and the sample answers to structure questions 1 through 6 (page 72) will be used. Sections 650.50 and 650.60 of the deck guide specifications and 655.50 and 655.60 of the substructure cathodic protection specifications define the method of measurement and the basis of payment.

The example structure is an 82,000-sq. ft. (7,600 m^2) bridge deck scheduled for a coke-asphalt cathodic protection system with bituminous overlay. A remote monitoring system with an office computer is desired. The utilities (AC power and telephone line) are available 1,250 ft. (381 m) away. The rectifiers will not be exposed directly to deicers or seawater.

To compile the system estimate, each item in the basis of payment is considered (the numbers after the section titles below refer to the applicable specification sections). The equations provided in the previous section are referenced by number. **Table 10** is a sample worksheet which is shown on pages 81 and 83.

Rectifiers (650.21, .23, .31, .33, and .50.01)

Section 650.50.01 states that "Rectifiers shall be measured when installed in place, including AC disconnect switches and grounding electrical, and demonstrated to be operational. Unit of payment will be on a per unit (each) basis."

The number of circuits is 14 (1 + [82,000/6500]) (equation 1), and the number of rectifiers is 4 (14/4) (equation 3). A standard galvanized cabinet is desired, and equation 4 gives the total rectifier costs as $18,040, which is then rounded to $18,000. The rounded unit rectifier cost is $4,500 ($18,000/4).

Reference Cells (650.22, .27, .32, and .50.02)

Specification section 650.50.02 states that "Reference cells shall be measured when installed in place and demonstrated to be operational. Unit of payment will be on a per unit (each) basis."

The unit reference cell cost is $335. The total reference cell cost according to equation 6 is $9,380 (i.e., $9,400).

Wiring (650.24 through .27, .34 through .36, and .50.03)

Specification section 650.50.03 states that "Wiring and conduit will be measured when installed in place. This item includes all conduit, junction boxes, AC service equipment, positive and negative cables, and reference cell cables. All equipment must be demonstrated to be operational and ready for commissioning. Unit of payment will be on a lump sum basis."

The AC service cost is determined using equation 7. The 1250 ft. (381 m) distance is multiplied by the $8 per foot ($26 per meter) listed in **table 7** (i.e., $10,000).

The DC conduit cost is determined using equation 8 and multiplying 14 circuits (equation 1) by $3,500 to yield $49,000.

The system negative cost according to equation 9 is $2,800 (2 * 14 circuits * $100).

The total wiring cost, per equation 10, is the sum of the AC service cost, DC conduit cost, and system negative cost, or $61,800.

Continuity Bonds (650.27, .37, and .50.04)

Specification section 650.50.04 states that "Continuity bonds will be measured when installed where required and demonstrated to be operational. Unit of payment will be on a per unit (each) basis."

The unit cost of a continuity bond is $100. The total cost of continuity bonding, using equation 11, is $2,800 (2 * 14 circuits * $100).

Anode Systems (650.28, .38, and .50.05)

Specification section 650.50.05 states that "Anode systems will be measured when furnished and installed in place and demonstrated to be operational. The protected area will be the area bounded by the anode and extending 6 in. outside the anode area or to any exposed steel closer than 6 inches from the anode. Unit of payment will be on a square yard of concrete installed basis."

From **table 8**, the cost of a coke-asphalt system is $4.05 per square foot ($43.80/m^2), while **table 6** provides a factor of 0.9. Equation 12 yields an estimated total anode system cost of $299,300. The unit cost per square yard is determined by dividing the total cost by 9,111 sq. yd. (i.e., 82,000 sq. ft./9).

Corrosion Engineering (650.40 and .50.06)

Specification section 650.50.06 states that "Detailed design shall be performed, construction services shall be provided and the entire system shall be activated, checked and adjusted and demonstrated to be operational within the parameters set forth in the specification. Unit of payment will be on a lump sum basis, with progress payments as shown in **table 650 3.**"

The corrosion engineering unit cost is \$0.80 per square foot (\$8.65/m^2) and **table 6** provides a factor of 0.9 for a structure of this size. Equation 13 yields an estimated corrosion engineering cost of \$59,040, which rounds to \$59,000.

Remote Monitoring (650.29, .39, and .50.07)

Specification section 655.50.07 states that "The remote monitoring system as described herein shall include the supply and installation of the remote monitoring unit, modem, enclosure (if applicable), wiring and conduit, telephone line, AC power to the RMU, software, documentation, testing, training and computer equipment (if applicable). The remote monitoring system shall be bid as a lump sum."

The number of remote monitoring modules is 4 (14 circuits/4, rounded to the next whole number) (equation 14). Using that information, the known line length of 1,250 ft. (381 m), and the known desire for a computer as part of the system, the remote monitoring cost is calculated using equation 15 as \$9,600.

Construction Cost Estimate Summary

The construction cost estimate summary (**table 9**) is merely a listing of all bid items and their unit and total costs. A listing is provided for the example structure.

Table 9. Construction Cost Estimate Summary

Bid Item	Unit	Quantity	Unit Cost (U.S. \$/sq. ft.)	Total Cost (U.S. \$/sq. ft.)
Rectifiers	Each	4	4,500	18,000
Reference cells	Each	28	335	9,400
Wiring	Lump sum	-	-	61,800
Continuity bonds	Each	28	100	2,800
Anode system	Sq. Yd.	9,111.11	32.81	298,890
Corrosion engineering	Lump Sum	-	-	59,000
Remote monitoring	Lump Sum	-	-	9,600

Total Estimated Cathodic Protection Construction Cost = \$459,550

The cost per unit area can then be determined by dividing by the anode surface area. For our example, the unit cost translates to \$5.60 per square foot and \$50.43 per square yard (\$60.47/m^2). It is often desirable to add a 5 percent contingency to these figures. With this contingency, the estimated total construction cost would be about \$482,527.

Cathodic Protection Monitoring and Maintenance Costs

Cathodic protection monitoring and maintenance costs will depend to some degree on the anode system and the environment. For the purposes of this estimate, "maintenance" refers to confirmation that equipment is functional, rectifier cleaning, and so on, rather than referring to repair of anodes or overlays. Thus, it is assumed that the anodes and overlays will NOT require maintenance during their service life. Monitoring costs also depend on the use of remote monitoring and structure size.

The monitoring and maintenance cost for structures of 10,001 sq. ft. to 30,000 sq. ft. (926 m^2 to 2,775 m^2) with remote monitoring is estimated as \$0.12 per square foot (\$1.30/m^2). This cost will double for structures without remote monitoring (i.e., \$0.24/ft.^{2}, 2.60/m^2). The factors in **table 6** are used to adjust this unit cost for structures of other sizes.

For the sample structure, the monitoring and maintenance cost per year is about \$8,900 (82,000 * \$0.12 * 0.9).

Patching Costs

Patching costs can be estimated using the data for portland cement concrete patches and the procedures given in the Strategic Highway Research Program (SHRP) Report, "Concrete Bridge Protection, Repair and Rehabilitation Relating to Reinforcement Corrosion - A Methods Application Manual." The total patch area can be estimated as the quantity of delamination and spalls times 1.15, a factor that accounts for the time lapse between the condition survey and repair and the need to square the patched areas. In the case of decks, lacking other data, it is reasonable to assume that approximately 5 percent of the patches will be full-depth patches while the others will be partial depth.

When cathodic protection is used, it is often possible to remove only the delaminated concrete, thus eliminating the need to remove sound concrete below the reinforcing steel. If this option is used, the estimated partial-depth removal unit costs should be reduced by about 50 percent.

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Table 10. System Cost Estimate: Sample Worksheet for Bridge Deck Cathodic Protection

Item	Description	Quantity	Unit	Unit Cost	Total Cost
1. Rectifiers	# Circuits = 1 + (total sq. ft./6,500) = 1 + (82,000 /6,500) (Round to next whole number.)	14	each	$1,000	$14,000
	# Units = # circuits/4 = 14/4 (Round to next whole number.)	4	each	$1,010	$4,040
	Total cost = ($1,000 x # circuits) + ($1,010 x # units) = ($1,000 x 14) + ($1,010 x 4) = $18,040 Unit cost = total cost/# units = $18,040/4 = $ 4,510				
	Total rectifier cost	**4**	**each**	**$4,510**	**$18,040**
2. Reference cells	# Reference cells = # circuits x 2 = 14 x 2 = 28				
	Total reference cell cost	**28**	**each**	**$335**	**$9,380**
3. Wiring	A. AC service cost = length of AC line x cost/ft.	1250	ft.	$8	$10,000
	B. DC conduit cost = # of circuits x $3,500/circuit	14	circuits	$3,500	$49,000
	C. System negative # System negatives = 2 x # circuits = 2 x 14 = 28				
	System negative total cost	28	each	$100	$2,800
	Total wiring cost (A + B + C)		**lump sum**		**$61,800**
4. Continuity bonds	# Continuity bonds = 2 x # circuits = 2 x 14 = 28				
	Total continuity bond cost	**28**	**each**	**$100**	**$2,800**

Table 10. System Cost Estimate: Sample Worksheet for Bridge Deck Cathodic Protection (Cont.)

Item	Description	Quantity	Unit	Unit Cost	Total Cost
5. Anode system	Sq. yd. of anode = sq. ft. of anode/9 = 82,000/9 = 9,111.11 Unit cost/sq. yd. = (unit cost/sq. ft.) * 9 * factor = $4.05 * 9 * 0.9 = $32.805 Anode cost = sq. yd. anode x unit cost = 9,111.11 * $32.805 = $298,890				
	Total anode cost	9,111.11	sq. yd.	$32.805	$298,890
6. Corrosion engineering	Enginerring cost = 82,000 sq ft * 0.80/sq ft * 0.9 = $59,040				
	Total corrosion engineering cost		lump sum		$59,040
7. Remote monitoring	# Modules (with 16 channels each) = # circuits/4 = 14 /4 (Round to next whole number.)	4	each	$625	$2,500
	Remote monitoring fixed cost		lump sum		$3,600
	Telephone line cost = length of line x cost/ft.	1250	ft.	$0.80	$1,000
	Computer	1	each	$2,500	$2,500
	Total cost = line + $3,600 + ($625 x # modules) + computer = $1,000 + $3,600 + ($625 x 4) + $2,500 =				
	Total remote monitoring cost		lump sum		$9,600
	Total Estimated Cathodic Protection Construction Cost				$459,550

Total Estimated Cathodic Protection Construction Cost with 5% Contingency $482,527

Other Estimated Costs:

8. Yearly monitoring & maintenance	Sq. ft. anode x (unit cost/sq. ft.) x factor 82,000 * $0.12 * 0.9 =	82,000	sq. ft.	$0.108	$8,856

4

Construction

This section discusses the construction of cathodic protection systems and describes the installation of the various types of systems that are commercially available today. The techniques for energizing and testing cathodic protection systems are also covered.

The information contained in this section is important regardless of the owner's involvement in the construction process. It will enable responsible parties to make sure that all components are installed properly and that the finished system operates as designed.

The guide specifications in the appendix require the contractor to prepare the detailed design prior to construction. The construction engineer monitors preparation of the design from the Design-Specifics Checklist, which is completed by the owner prior to project bidding. For decks, the checklist is in guide specification section 650.30.02; for substructures, it is in section 655.30.02.

Contractor Submissions

As with any bridge component, construction of a cathodic protection system requires that documentation be obtained defining the responsibilities of the contracting firm and identifying the materials and workmanship that will be employed. These records are indispensable for guaranteeing compliance with specifications. Therefore, the bridge project engineer should be aware of the common documents and specific items that must be addressed when installing a cathodic protection system.

Materials and Equipment

When a cathodic protection system is designed, certain electrical and hardware components are selected to meet stipulated performance and reliability requirements. Specification of these products is the responsibility of the structure's owner, who has the option of either require the use of specific components or of allowing an outside consultant to make the selections. Within the guide specification section 650.30, a checklist is provided to help the engineer designate which items in the cathodic protection system will be selected by the owner and which will be selected by outside firms. Some of these components are generically manufactured, such as wiring, and others may be sole source items, manufactured by only one firm.

Regardless of how the various items are selected, the engineer should obtain documentation about the components to be used. This documentation usually includes catalog cuts, manufacturers' performance data, shop or working drawings, and any warranties or guarantees that are offered. If any of the specified items are not available, an alternate must be supplied and documentation obtained verifying that the substituted items are of the same quality.

Detailed Design

In order for those constructing the cathodic protection system to meet all installation requirements, a detailed design with installation drawings and specifications must be produced by the owner, the installer, or their agents. The design should include electrical current, resistance, and voltage calculations, and drawings identifying the placement of various components. The location of all anodes, conductor bars, wiring, monitoring devices, and rectifiers must be clearly shown in these drawings. In addition, reinforced-concrete repairs required as a result of the findings of the condition survey must be indicated and cost calculations included when these repairs affect design parameters and project costs.

Activation Report

Once a system is installed and energized, an activation report defining the physical, electrical, and operational characteristics of each component should be produced. An activation report includes the results of electrical tests conducted on the anodes, monitoring cells, rectifiers, and all other electrical components of the system. If defects are discovered, the report should state corrective actions. Baseline data generated during activation are also included in the report since they can often be used to identify the source of any future operational problems.

Operation and Maintenance Manuals

Cathodic protection systems require routine maintenance, and an operation and maintenance handbook should be provided on any newly installed system. Items such as the manufacturers' operating instructions for equipment, the date the system was energized, as-built drawings, initial output settings, troubleshooting methods, and recommended intervals for all maintenance procedures must be included in this handbook. In addition, it is good practice to include copies of the project plans and specifications, project design memoranda, material records and certifications, and provisions for maintaining all future operation and maintenance records.

Anode System Installation

The anodes discussed in the design section have unique construction requirements. Knowledge of these requirements is vital to anyone involved in managing a successful system installation. The following discussion of anode system installation is separated into two parts - bridge decks and substructures.

Anode Systems for Bridge Decks

The deck is a large, horizontal plane area that easily lends itself to anode installation, and there are a number of anode systems available for deck protection. The following three anode systems are most commonly used on bridge decks:

- Coke asphalt.
- Non-overlay slotted.
- Distributed anode with concrete overlay.

The material that follows explains the system components and general installation methods used for these various systems. A copy of the guide specification for each is included in the appendix. Whenever possible, information provided in the text is referenced in parentheses to a corresponding guide specification number.

Coke Asphalt (651)

A schematic diagram of one type of coke-asphalt system is shown in **figure 26**. Two types of conductive asphalt concrete overlay systems are currently in use.

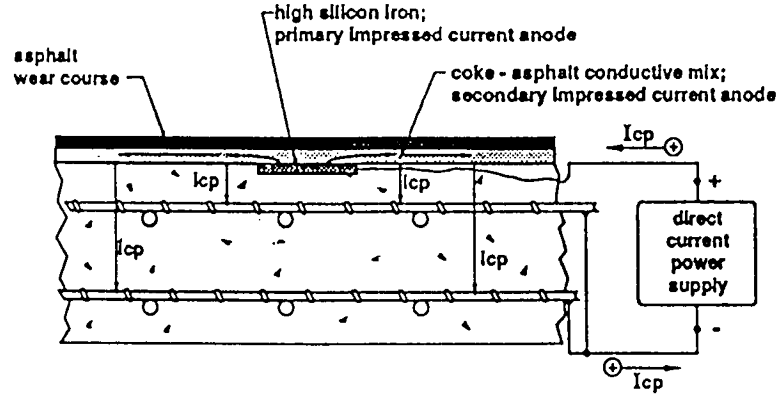


Figure 26. Conductive coke-asphalt overlay system.

The first type uses high-silicon cast-iron pancake anodes evenly distributed on the bridge deck surface to provide current to the conductive asphalt concrete. The anodes and wiring are attached to the deck with an epoxy adhesive. The deck is then covered with 2 in. of conductive asphalt concrete made with a 78 percent to 85 percent blend of 3/8-in. maximum-size aggregate coke breeze and 15 percent to 22 percent of AC-5 to AC-10 viscosity asphalt. The conductive asphalt concrete is overlaid with at least 2 in. of a standard asphalt concrete finish course.

The second conductive asphalt concrete overlay system, commonly used in Canada, utilizes a dry-materials blend of 40 percent course aggregate, 15 percent fine aggregate, and 45 percent coke breeze (1/4 in. maximum particle size) by weight, all mixed with 15 percent 85-100 penetration asphalt. This mixture is covered with an equal thickness finish course to produce a total overlay thickness of approximately 3 in. to 3 1/2 in. The anodes, monitoring instrumentation, and wiring are recessed flush with the deck to enable future replacement of the overlay without damaging these components.

Asphalt overlays are less commonly used in the United States than concrete overlays. The engineering characteristics of a conductive asphalt concrete overlay justify its consideration when a conventional asphalt concrete overlay is planned as part of a rehabilitation project.

Figure 27. Placing conductive coke asphalt over pancake anodes.

Non-Overlay Slotted (652)

The slotted anode system for bridge decks is comprised of copper-cored platinized niobium wire anodes and carbon filament strands that are placed into saw-cut slots made directly on the concrete bridge surface (**figure 27**). These slots are then filled with conductive polymer grout. Because the anodes are recessed into the deck, this system does not require an overlay. It is extremely important to determine during the survey of the bridge if there is sufficient depth of cover over the reinforcing steel to permit the use of a slotted anode system (**figure 28**).

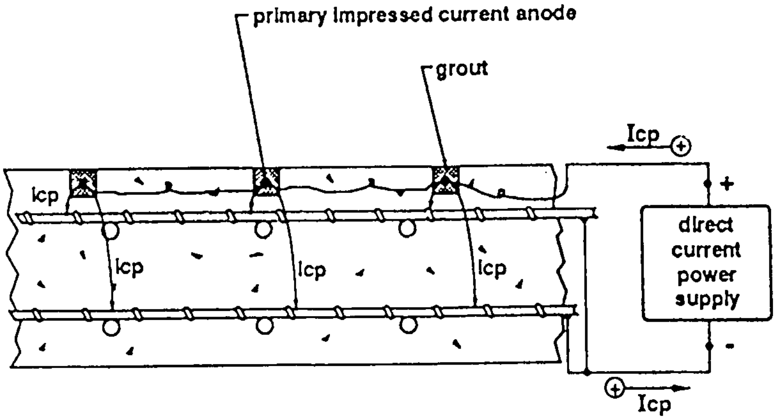


Figure 28. Slotted anode system.

Figure 29. **Prior to placement of any anode system, the deck should be checked for thin cover areas.**

Anodes and other electrical components for this system are placed in a series of closely spaced (typically 6 in. to 9 in.) parallel slots cut longitudinally in the deck with transverse slots cut at a spacing of 15 ft.to 40 ft. (center to center). Carbon filament strands and rigid conductive polymer concrete are placed in the longitudinal slots that serve as the main distributor of cathodic protection current to the reinforcing steel. Copper-cored platinized niobium wire and rigid conductive polymer concrete are placed into transverse slots. The transverse slots feed cathodic protection current to the longitudinal slots.

The sawed slots are typically 1/4 in. wide by 1/2 in. to 3/4 in. deep. After the slots are cut and cleared of debris, visual inspection is made to find any exposed rebar. If exposed rebar is found, it must be coated with either nonconductive polymer concrete or with epoxy. Electrical contacts between the anode and any other metallic items such as drains, scuppers, joint assemblies, guard rails, or light standards must be avoided. All slots should be terminated 3 in. from any metallic embedments in the deck other than rebar.

A concrete cover meter (**figure 30**) is used to detect rebar less than 1/2 in. from the bottom of each slot. Areas of shallow cover should be coated with epoxy or nonconductive polymer.

The carbon strand and platinized wire are placed into their respective slots with sufficient tension to keep them centered. Nonconductive spacers may be used to maintain the position of the strand or wire.

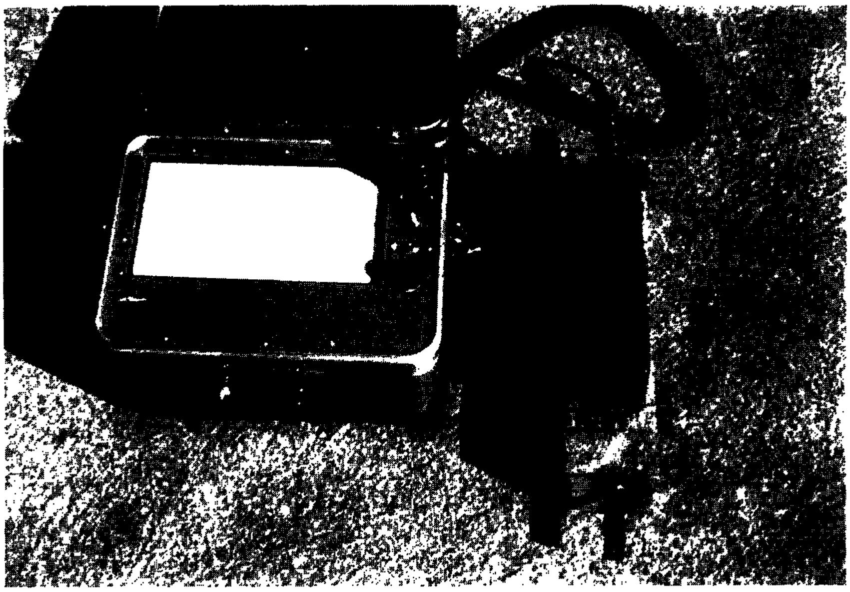


Figure 30. **The concrete cover meter is used to check areas of suspected thin cover more precisely.**

The conductive polymer requires special handling and care. Everyone involved with the placement of the conductive polymer should be familiar with the manufacturers' procedures for storing, mixing, and handling the material. The material must be stored at a temperature of between 50^0F and 80^0F. At each mixing area, an eyewash station should be provided. In addition, the working area should be a nonsmoking area and fire extinguishers should be provided.

A plan covering the proper handling, storage, and placement of the material should be provided and should include requirements for independent laboratory testing of material from each factory-produced batch used in the installation. The testing should verify that the material meets or exceeds the compressive strength, water absorption, and electrical resistivity level specified.

Before the conductive polymer is poured into the slots, all carbon strands and platinized niobium wire should be placed, and the niobium wire fed through drilled and plastic-sleeved deck holes to power connection junction boxes. All holes through the deck should then be completely sealed. The deck should be dry and the deck temperature should be above 40^0 F for at least four hours after polymer placement. If rain occurs during the four-hour curing period, the material must be covered and kept dry.

Normally, the pot life of the material after mixing is about 15 minutes at 77^0F. The material should be periodically agitated to prevent the components from separating. Any material not placed within the pot-life limit must be discarded.

For each cubic foot of material mixed, a sample should be taken for electrical resistivity testing.

Once in place, the carbon filler in the mixture begins to settle to the bottom of the slot and the resin tends to rise to the top. To aid in coloring and increase skid resistance, a fine, dry silica sand should be spread over the slots within 15 minutes of placement. After the conductive polymer has set, the excess sand is removed with oil-free compressed air or vacuum pickup.

Figure 31 is a schematic of a completed slotted system. **Figures 32 through 47** illustrate step-by-step installation techniques.

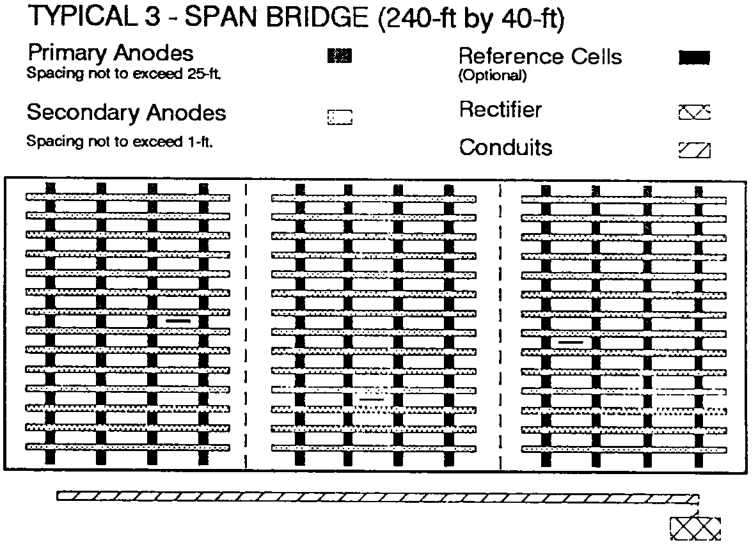


Figure 31. Diagram of complete slotted anode system.

Figure 32. Small single slot saw, often used for cutting transverse slots.

Figure 33. This heavy-duty machine can cut up to five slots in one pass.

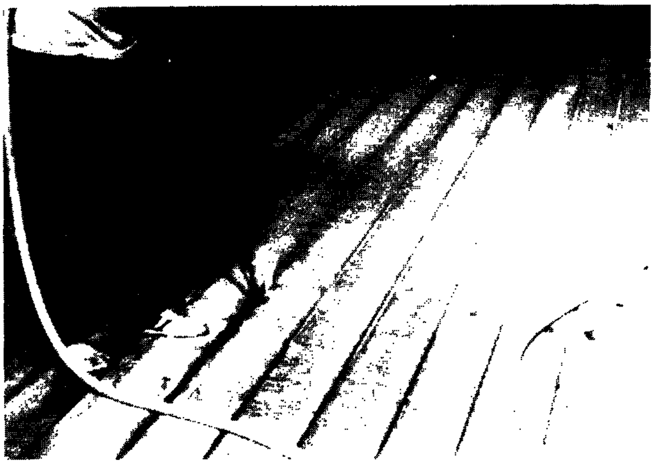


Figure 34. Air-blast cleaning the slots.

Figure 35. Water-blast cleaning the slots.

Figure 36. Slots ready for anode installation.

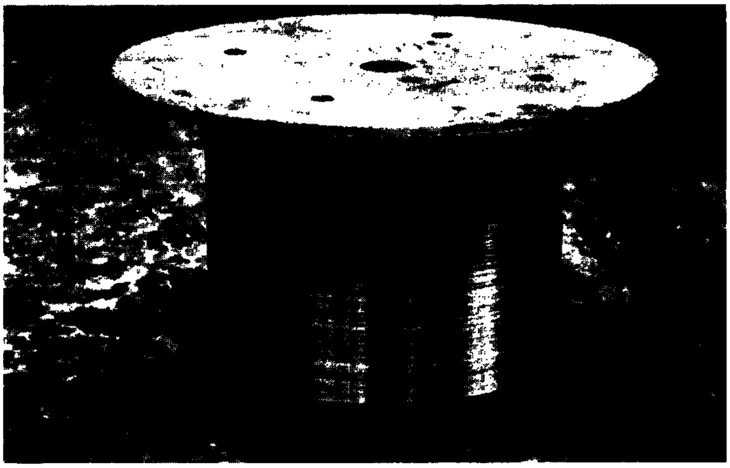


Figure 37. Platinum primary anode wire to be installed in transverse slots.

Figure 38. Pulling out carbon fiber strand to be placed in the longitudinal slots.

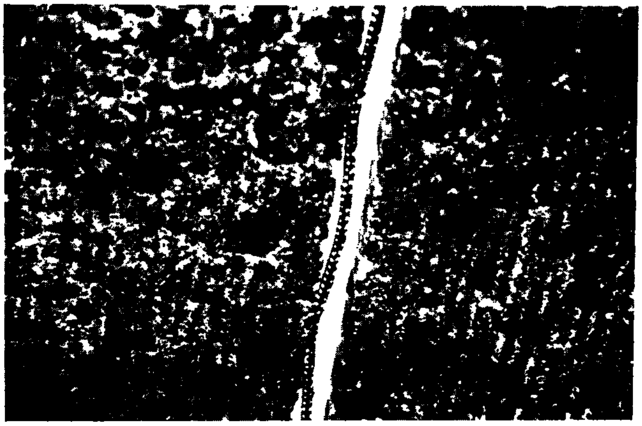


Figure 39. Close-up view of carbon strand in slot.

Figure 40. Conductive polymer with premeasured coke breeze in plastic mixing bags.

Figure 41. Mixing the catalyst with resin.

Figure 42. Pouring the catalyzed resin into the coke breeze.

Figure 43. Hand-placing the mixed FHWA conductive resin into the slots.

Figure 44. Dispenser for easier slot filling.

Figure 45. FHWA-sponsored research developed this automatic mixing and dispensing machine for the rigid conductive polymer anode material.

Figure 46. One lab sample of mixed polymer resin should be obtained from each cubic foot of mix.

Figure 47. Typical appearance of finished slotted system.

Distributed Anode Systems with Concrete Overlays (653)

Distributed anode systems with concrete overlays include the rigid conductive polymer mound system and the mixed metal-oxide mesh system. Both utilize anodes that are placed on the bridge deck and covered with a concrete overlay.

Rigid Conductive Polymer Mounds (653.25).

This system consists of longitudinal mounds placed 9 in. to 18 in. apart on the prepared deck surface. It is very similar to the slotted system, but instead of the anode being in slots, it is poured in mounds on the scarified deck (**figure 48**).

Figure 48. Conductive polymer mound system.

The mounds are typically 1 1/4 in. to 1 3/4 in. wide and about 3/8 in. high. Transverse mounds are placed on the deck surface at spacings from 25 ft. to 50 ft. in order to minimize voltage drop. The increased surface area of the mounds permits a wider spacing than is permitted in a slotted system.

After the scarified deck has been marked to indicate the locations of the anode mounds, a concrete cover meter or rebar locator set to detect rebar with less than 1/2 in. of concrete cover should be used to locate areas of insufficient cover. All of the areas with less than 1/2 in. of cover should be coated with nonconductive polymer or an epoxy compound compatible with the anode and immediately covered with a dry, fine silica sand to facilitate overlay bond.

The carbon strand and platinized niobium wire are fixed in place over the longitudinal and transverse marked lines using nonmetallic pins or spacers. Once in place, they should be protected from mechanical damage.

The polymer used in this system requires special handling and storage, as previously discussed. In addition, the same requirements for mixing, handling, temperature, moisture, placement time, and laboratory test sampling exist.

After placing the conductive polymer mounds, the carbon filler material will begin to settle to the bottom of the mound. Within 15 minutes of placement, carbon filler must be spread over the mounds to improve electrical contact between the top of the mounds and the overlay material. Any excess carbon should be removed using oil-free air or vacuum pickup after the polymer has cured. Once placed, the conductive polymer must be protected from rain for four hours after which the concrete overlay may be placed. Since the mounded system partially conducts current through the overlay, both the overlay material and bonding agent should have electrical resistivities after curing of less than 50,000 ohm-cm.

Figures 49 through 54 illustrate step-by-step installation techniques.

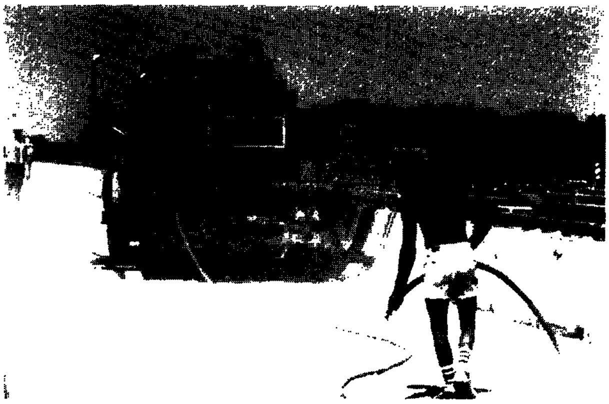


Figure 49. Final blast cleaning after scarification of deck surface and prior to placement of overlay anode system.

Figure 50. First machine used to place the mounded polymer overlay system.

Figure 51. Machine that places the carbon fiber filament and forms the polymer mound at the same time.

Figure 52. Top dusting the uncured polymer mounds with carbon particles.

Figure 53. Brushing in the bonding agent just prior to overlay placement.

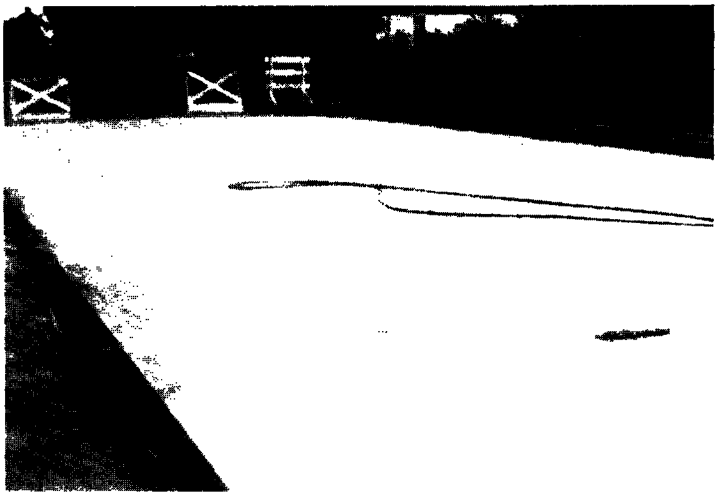


Figure 54. First completed FHWA mounded system near Minneapolis, MN.

Mixed Metal Oxide Mesh (653.26).

The mixed metal-oxide mesh anode is fabricated from an expanded mesh of titanium onto which a layer of precious metal oxides are sintered (**figure 55**). The anode mesh is supplied in rolls approximately 4 ft. wide by 250 ft. long. It is placed over the prepared deck surface and fastened in place with plastic anchors.

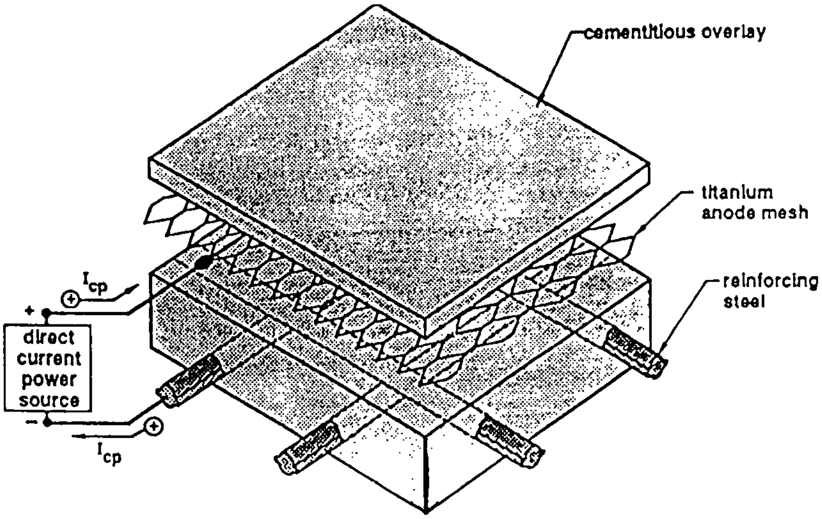


Figure 55. Mixed metal oxide mesh system.

Prior to placing the anode mesh on the concrete surface, the deck surface is prepared by scarification or other means suitable for ensuring adhesion of the overlay. The surface should be scanned with a rebar locator modified to detect reinforcing steel with less than 1/2 in. of concrete cover. Areas with less than 1/2 in. of cover should be coated with a nonconductive polymer or epoxy-coating system and immediately covered with a fine, dry silica sand.

The mesh is rolled out onto the deck surface and cut to panels of the desired length and width. These panels should not be placed more than 6 in. apart. A distance of 2 in. should be maintained between the mesh and any visible metallic components. The mesh is fastened to the deck with plastic anchors placed in drilled holes at a maximum 5-ft. intervals in both the longitudinal and transverse directions. Any dust created by the drilling should be removed by oil-free air blasting or vacuum pickup.

The mesh panels are interconnected with titanium current distribution strips that are resistance welded to the mesh panels. The strips are extended through the deck into junction boxes. These strips should be covered with heat-shrinkable tubing at the point where they go through the deck to prevent shorting to the rebar exposed in the drilled holes. The holes are patched with nonconductive grout.

The mesh has no special storage or safety considerations, except that it must not be cut by the sharp edges of the panels. Heavy work gloves are recommended when handling the mesh. Care must be taken to prevent mechanical damage to the mesh prior to and during overlay placement.

Figures 56 through 67 illustrate step-by-step installation techniques.

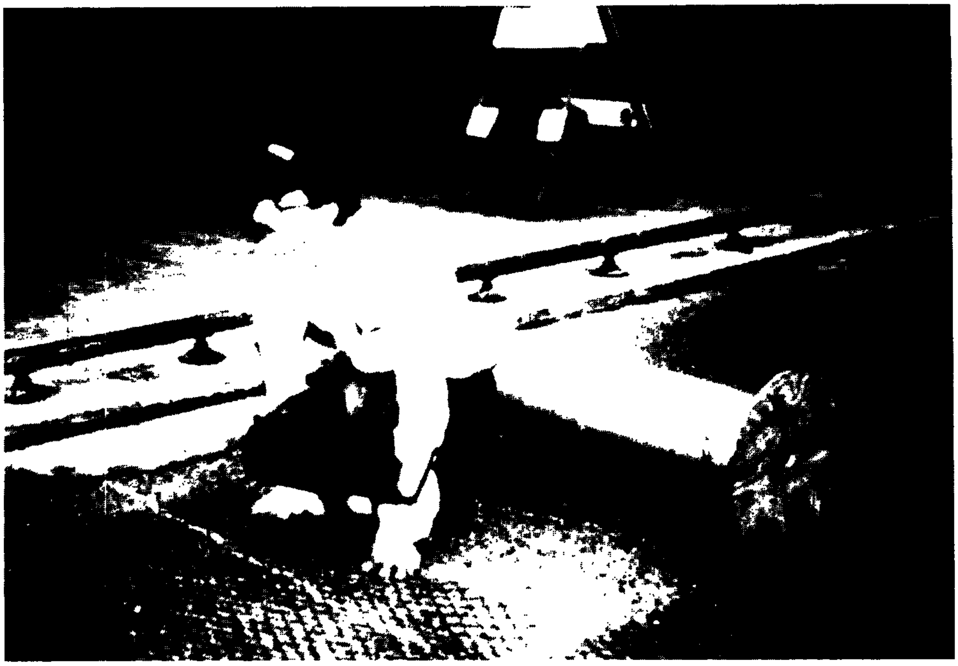


Figure 56. Rolling out the mixed metal-oxide mesh.

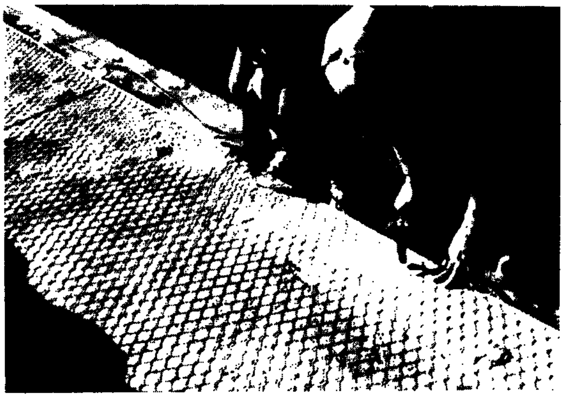


Figure 57. Pinning the mesh on a bridge sidewalk.

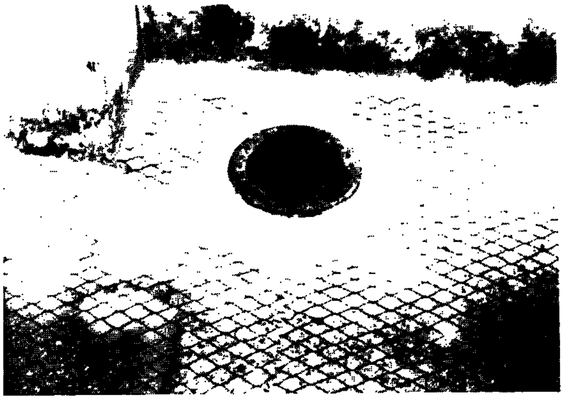


Figure 58. The mesh can be easily trimmed to fit around drains, etc.

Figure 59. The mesh panels are stopped approximately 3 in. from the metal expansion joint.

Figure 60. The transverse conductor bar electrically connects the 4-ft.-wide panels together.

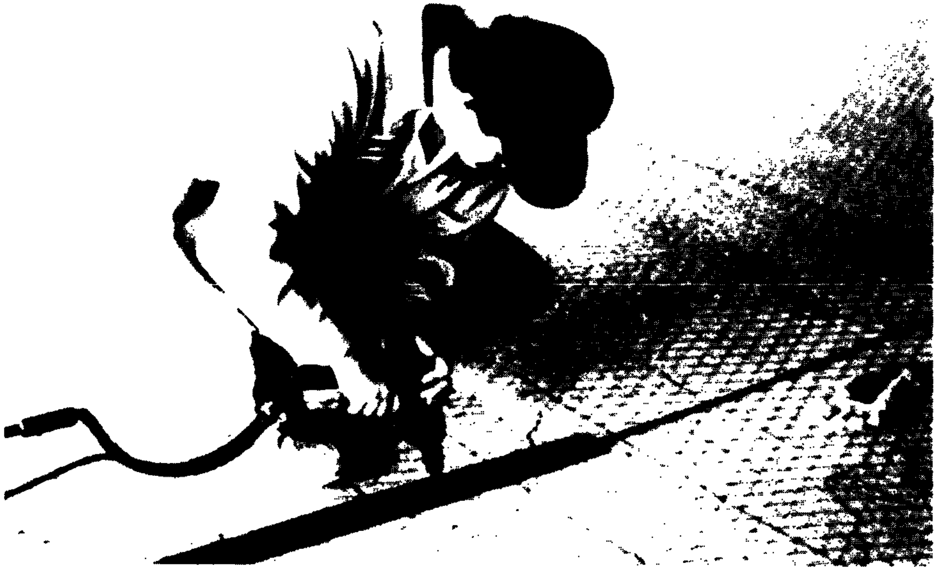


Figure 61. Welding the conductor bar to the metal mesh panels.

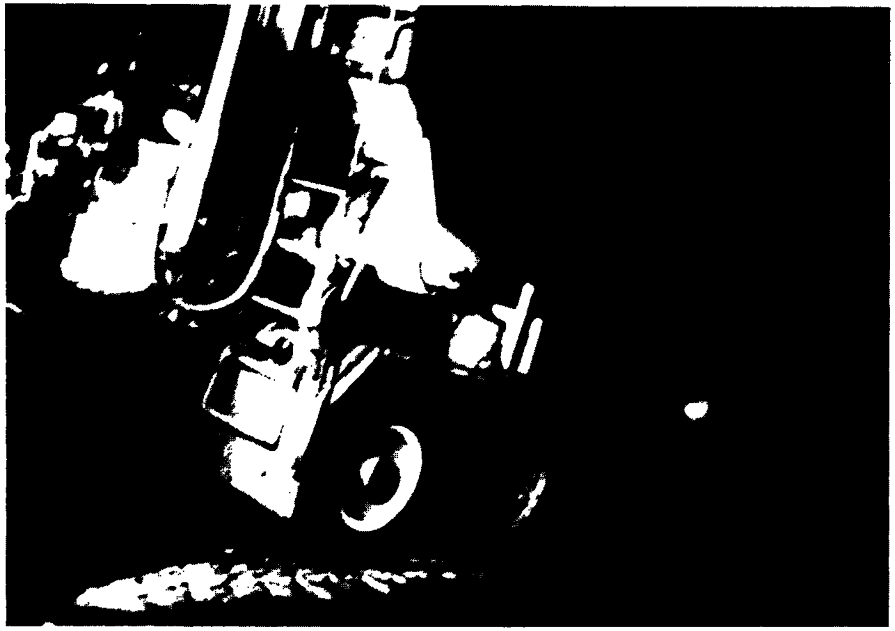


Figure 62. Mobile mixer delivers the concrete overlay.

Figure 63. Close-up view of the chute delivering the overlay material.

Figure 64. Brushing the grout through the concrete over the metal mesh.

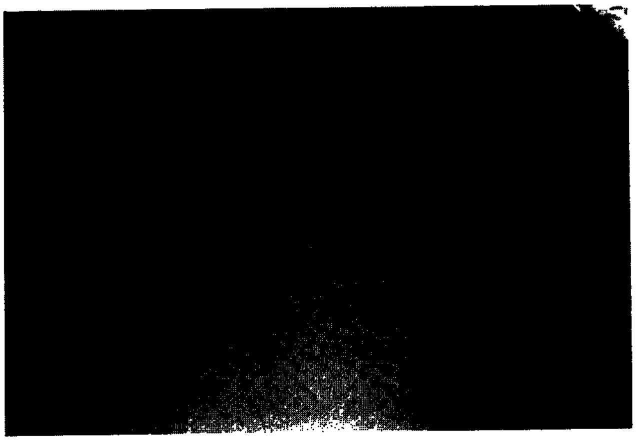


Figure 65. Spreading and finishing the concrete overlay.

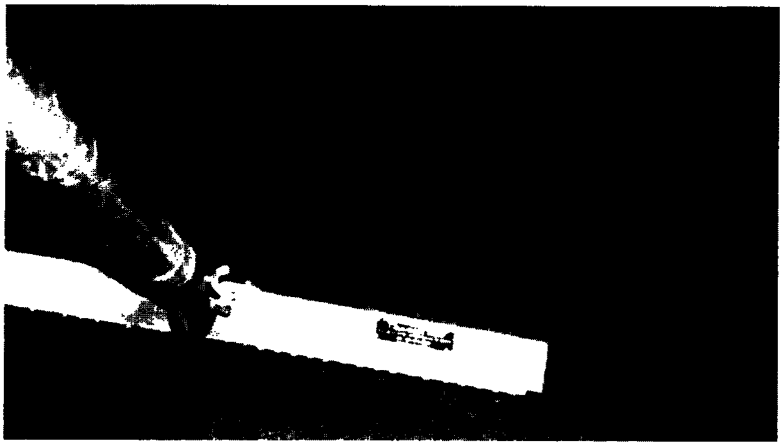


Figure 66. Final antiskid raking of the finished overlay.

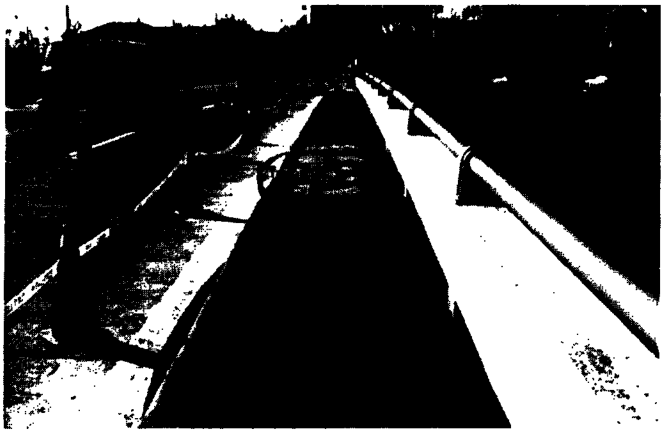


Figure 67. Finished mixed metal-oxide mesh system protects this sidewalk.

Substructure Systems

Nonwearing bridge components including piers, columns, beams, and barrier and retaining walls that are subject to corrosion require the application of specially designed impressed-current cathodic protection systems. Unlike bridge decks, these bridge components are usually vertical or overhead and have varying contours. Thus, anodes that can follow these contours and be reasonably mounted on the underside as well as the vertical surfaces of these components are usually required. Guide specifications are provided for these systems in the appendixes.

Conductive Coating (656)

A number of conductive-coating cathodic protection systems have been developed for substructures. The anode materials are all carbon-based paints or mastics. They are applied to the prepared concrete surface using brush, roller, or spray techniques. Since all of these materials are black in color, a cosmetic overcoat, commonly a latex-based paint, is applied over the conductive coating.

The conductive-coating system is comprised of primary anodes made of either copper-cored platinized niobium wire or precious metal-oxide-coated titanium strips combined with a conductive carbon anode coating (**figure 68**). The primary anodes discharge current through the anode-coating material to provide even and complete protection to a designated surface area. Using this anode combination, this system is capable of protecting areas with current densities of up to 2 mA/ft.^{2}.

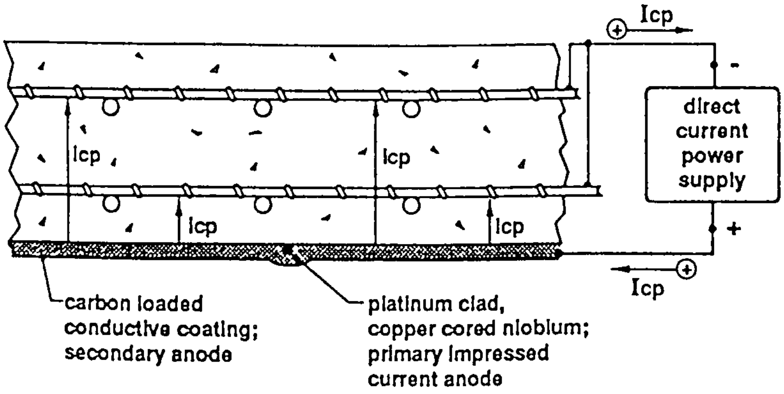


Figure 68. Conductive-coating installation.

The entire area to be protected using the conductive-coating system should be surveyed for damage and delaminations. These must be repaired before installing any component of the anodes.

Delaminated areas and previously patched regions that have high resistivities must be removed and replaced with a compatible concrete material. Tests should also be conducted to certify that there is at least a 1/4-in. cover over all embedded ferrous components.

To insure proper bond between the coating material and the concrete, the entire region to be protected should be thoroughly blast cleaned. When surface preparation is complete, the primary anodes are attached to the concrete using nonmetallic holders. The primary anodes are typically spaced 5 ft. apart, and there must be at least two primary anodes per zone. The conductive coating is applied by spray, brush, or roller to clean, dry surfaces. To insure proper current flow and durability, the coating must be applied uniformly to at least 16 mil dry-film thickness and must fully encapsulate the primary anodes. Regular adhesion and thickness tests are essential to confirm compliance with the specifications and to ensure the coatings' long-term durability. After the final coat of anode material has been allowed to cure for the time specified by the manufacturer, the system can be activated and tested.

As a final step, a vapor-permeable water-based paint may be used to cover the conductive material for aesthetic or safety reasons.

Thermally Sprayed Zinc (657)

Thermally sprayed zinc, applied directly to the prepared concrete surface, can be used as an impressed-current anode (**figure 69**). Either flame or arc-sprayed zinc can meet the specifications. Before the zinc is applied, all deteriorated and loose concrete must be removed and the concrete surface must be properly prepared by oil-free, dry-blast cleaning or other approved methods. Don't overclean and expose bare aggregate unnecessarily.

Figure 69. Thermally sprayed zinc installation.

The zinc system uses either 1/4-in. wide titanium strips or 1-in. brass plates as primary anodes. The titanium strips and brass plates are attached to the concrete using an insulating epoxy adhesive. A desired coating thickness of either 10, 15, or 20 mils is usually specified to ensure uniform current distribution and anode life. After application, the cooled zinc coating is inspected to identify any flaws. Lumps, blisters, coarse or loosely adhering particles should be removed, and cracks, pinholes, or chips filled. Regular adhesion and thickness tests to confirm compliance with the specifications are essential so that the coatings' long-term durability is ensured.

During application, the zinc must not come into contact with embedded steel, because such contact would create a short circuit. One method for avoiding contact that has had some success involves monitoring the direct current (DC) voltage between the zinc coating and the reinforcing steel. The voltage will typically range from 200 mV to 800 mV. A sudden drop in voltage or a potential difference of less than 150 mV indicates a possible short.

If the above procedure is not specified or the contractor wishes to perform a different test, the contractor must submit the detection plan to the engineer for approval. All shorts must be located immediately and eliminated prior to continuing the zinc application.

Thermally sprayed zinc systems should not exceed an operating anode current density of 2 mA/ft.^{2}.

Mesh Anode with Shotcrete Overlay (658)

Mesh anode material can be adapted for use on substructure components (**figure 70**). It can conform to a variety of shapes and is encapsulated with shotcrete.

Figure 70. Anode mesh with shotcrete installation.

Before installation, the area to be protected should be thoroughly cleaned to remove all paint, grease, and dirt. Deteriorated and loose concrete should also be removed, and the concrete surface abraded to allow a good bond to form between the substrate and the shotcrete. The surface should be prepared using wet or dry-blast cleaning, or a combination of these two methods.

The mesh panels are attached to the bridge surface with nonmetallic fasteners. To ensure that the shotcrete develops a good bond and completely encapsulates the mesh, these fasteners should be spaced 1 ft. apart and provide a 1/4-in. space between the concrete surface and mesh. Titanium distributor bars are installed to electrically connect the mesh panels in a zone.

Using a dry-mix shotcrete, samples should be produced so that corrections to the mix may be made prior to application. Excessive water in the mix can cause sagging. Not enough water in the mix will impair flow and cause excessive rebounding. The person charged with applying the material must demonstrate that it can be successfully applied with the mesh in place.

The shotcrete should be applied by holding the applicator nozzle at right angles to the surface. The nozzle must be slightly from this right angle to ensure the anode mesh is completely encapsulated. The gap between the mesh and concrete must be filled, and the outer surface of the mesh covered with the specified amount of shotcrete.

Because voids and delaminations may be formed, application of multiple layers of the shotcrete should be avoided. All rebound that does not fall clear of the work must be removed prior to curing. The shotcrete requires a temperature of 40^0F to 95^0F for proper curing and should be kept moist throughout the curing process, which takes seven days.

After the shotcrete is cured, the surface should be inspected. The shotcrete must be removed from areas that lack uniformity; exhibit segregation, honeycombing, or delamination; or contain dry patches, slugs, voids, or sand pockets. If necessary, the area should be properly scarified using a high-pressure water blast to provide a roughened surface that, after dampening, can be applied with new shotcrete. As a final step, the shotcrete should receive a cut finish.

Installation of Components

Regardless of the type of cathodic protection system being installed, a number of common components are required. Bonds to electrically discontinuous embedded steel, connections of DC negative wires to the reinforcing steel, and installation of monitors and reference cells must be made prior to installing the anodes. Once the anodes are in place, wiring can be completed and the system energized.

Installation of these components is critical to operating the system.

Discontinuous Reinforcing Steel

Electrical continuity of all embedded metallic components to be protected is necessary. Continuity of the embedded steel can be verified by electrical tests during either a condition survey or the construction process. Most reinforcing steel is electrically interconnected by wire ties and chair supports, but sometimes an isolated segment of steel is unconnected. Metallic components such as drains, railings, and expansion joints are often not connected to the steel reinforcing.

Continuity testing and electrical bonding to correct discontinuities can be most easily completed after loose and deteriorated concrete is removed but before repairs have been made. Thermite welding of wires between discontinuous members and adjacent electrically continuous rebar restores the electrical continuity. Additional information is provided in guide specification section 650.37.

The potential difference measurement technique is the most common continuity test used. If two embedded metals are electrically continuous, the potential difference between them should be zero. If two metal components are discontinuous, a potential difference will normally exist between them that can be measured.

The equipment needed to check continuity based on potentials consists of a high-impedance voltmeter (10 megohms or greater), a reel of insulated test-lead wire, and short lead wires with clips for connections. Tests may be made on metal exposed in repair areas or in excavations made for test purposes. Connections must be clean and free of corrosion. **Figure 71** presents a typical equipment setup for conducting a continuity test.

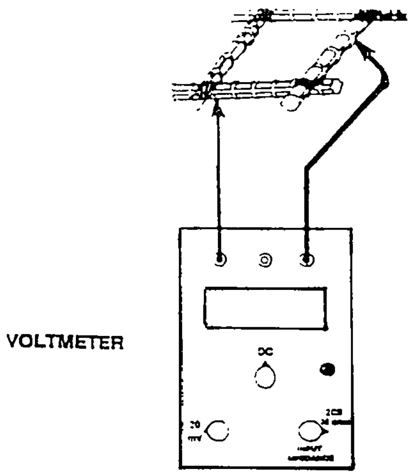


Figure 71. Equipment setup for continuity testing.

The test procedure consists of the following steps:

1. Thoroughly clean the reinforcing steel or metal component contact points to bright metal.
2. Connect voltmeter test lead to a reinforcing steel or metal component that is known to be electrically continuous. This contact will become the fixed test location.
3. Connect the other test lead to reinforcing steel or metal component to be tested for continuity. This contact will become the moving test location.
4. Measure and record the potential difference between these metallic components.
5. With the fixed test location unchanged, repeat step 4 for other reinforcing steel or metal components to be tested. Use the reel of wire for test locations that are far apart.
6. Repeat steps 1 through 5 as necessary.

The data gathered from the test procedure are divided into the following three categories:

1. Potential difference of less than 1 millivolt = electrical continuity probable.
2. Potential differences greater than 1 millivolt but less than 3 millivolts = electrical continuity uncertain (recheck for good contact).
3. Potential differences greater than 3 millivolts = electrical discontinuity probable.

Table 11 is an example of the results of a voltage-drop test for electrical continuity.

When the measurements in Table 11 are compared with the guidelines, locations 1,2,4,6, and 8 are the components with probable electrical continuity. Components with uncertain continuity are locations 5 and 7, while location 3 is electrically discontinuous.

Wire Connections to Reinforcing Steel

System negative and bond wire connections must be installed prior to anode placement. The wires must be thermite welded to the reinforcing steel (**figures 72 and 73**), and the completed thermite welds must be coated. The return wires can be routed in saw cut slots to the edge of the deck or to another convenient location at which point these are then fed through drilled holes into a junction box. Wires should be protected with a plastic sleeve or tube at points where they bend or where they feed through the deck to prevent nicks in

Table 11. Continuity Test Data Using the Voltage Drop Test Method

Fixed Contact = #6 Rebar at Southeast End

Location	Structure	Potential Difference (mV)
1	#4 rebar (SE)	0.0
2	#4 rebar (SW)	0.5
3	Storm drain	22.0
4	#4 rebar (S end)	0.3
5	#4 rebar (N end)	1.2
6	#4 rebar (NE)	0.0
7	#4 rebar (NW)	2.0
8	#6 rebar (NW)	0.1

the insulation or cuts in any of the conductors. Splices in the wires should be avoided. Damaged wires must be replaced. Saw slots and drilled holes are filled with nonconductive polymer containing sand or portland cement mortar.

Figure 72. Igniting thermite weld powder with flint gun.

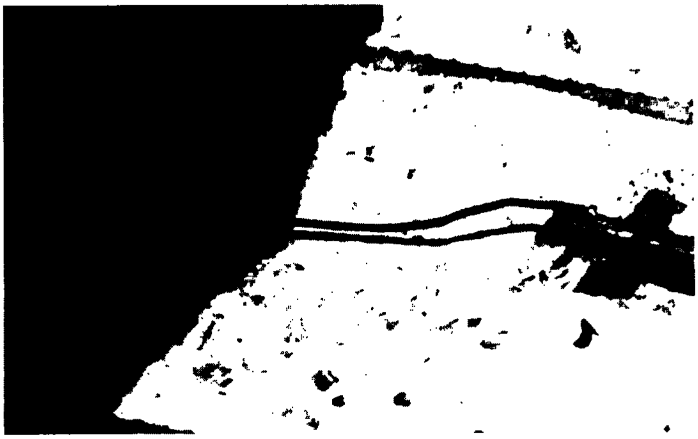


Figure 73. Completed thermite weld of copper lead wire to rebar.

Prior to patching the excavation areas, the quality of the thermite connections must be verified. The connection should withstand an impact test (sharp rap with a hammer). Electrical testing for continuity should be conducted and the results documented. Both potential and alternating current (AC) resistance measurements should be used to verify an effective negative connection and associated wiring. Further explanation of the method for making these connections is provided in guide specification section 650.27.

Installing Rebar Probes and Reference Cells

To verify the level of protection provided by the system, reference cells and rebar probes are installed in the structure prior to placement of the anodes. Typical installation of a reference cell and rebar probe are shown in **figure 74.**

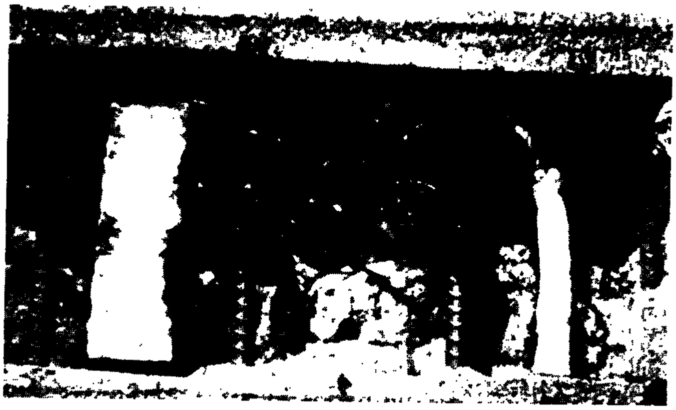


Figure 74. Silver-silver chloride reference electrode and rebar probe placed in a common excavation. Note the epoxy-coating material over the thermite connections. In this example, exposed rebar adjacent to the reference cell will be patched with chloride-containing cement. Normally, the rebar surrounding the reference cell <u>should not</u> be exposed while rebar adjacent to the corrosion probe is exposed, cleaned, and then patched with non-chloride-containing cement.

Reference cells are placed in specified locations in rectangular excavations of the concrete (typically 3 in. x 7 in. x 2 in. deep -- see also guide specification section 650.32). No reinforcing steel should be exposed in the excavation, and ground connection to the reinforcing steel should be made at a maximum of 5 ft. from the reference cell. The ground wire should be thermite welded to the rebar, and the weld area coated. The reference cell and the monitor ground wires are routed to junction boxes. The wires should be protected with sleeves at bends and at the access hole.

The excavations should be patched with concrete and cured for three days under wet burlap and a polyethylene covering.

The AC resistance between the ends of the reference cell lead wire and the reference cell ground wire should be less than 10,000 ohms. If values in excess of 10,000 ohms are measured, a defective wire or connection should be suspected. Potential measurements between the reference cell ground wire and the reference cell is a second way to check that the cell is functioning properly. The value measured should be between +100 and -700 mV. However, since most permanent reference cells are installed at highly anodic locations, cells providing positive values greater than +300 mV should be checked.

Macrocell rebar probes are usually located near an embedded reference cell. An excavation is made into the concrete to expose rebars on all four sides of the excavation. The bars are cleaned of scale and rust. A ground wire is thermite welded to an adjacent bar and then coated. The rebar probe is centered in the excavation parallel to the main reinforcement.

The probe, reference cell wires, and ground leads can be routed in common to junction boxes.

The rebar probe excavation must be patched with conventional portland cement concrete that contains no chlorides. The patch material must completely surround the rebar probe and be cured for three days under wet burlap with a polyethylene sheet cover.

Installing the Rectifier Controller

The rectifier-controller is usually installed concurrently with final system wiring. Rectifier units are designed for pole, wall, and concrete pad mounting that is adaptable to a variety of field conditions (see guide specification section 650.31).

Rectifiers typically run on 120-volt, 60-hertz, single-phase AC power, although other inputs are available. The owner identifies the source location and type of AC power to be furnished and arranges for the power to be made available. The contractor is responsible for bringing the power from the nearest location to the rectifier.

Making Final DC Wire Connections

Wiring is routed to the rectifier-controller location through a rigid schedule 80 Poly Vinyl Chloride (PVC) conduit. PVC is preferred over hot-dip galvanized conduit because of its superior corrosion resistance. Waterproof wire splices should only be permitted in junction boxes. Routing of the conduit is generally based on ease of construction and aesthetic considerations and should be shown on the drawings. Wiring, conduit, and power supply mounting are shown in **figures 75 through** 77. Additional information is provided in guide specification section 650.32.

Figure 75. Pole-mounted, air-cooled rectifier installed adjacent to the bridge.

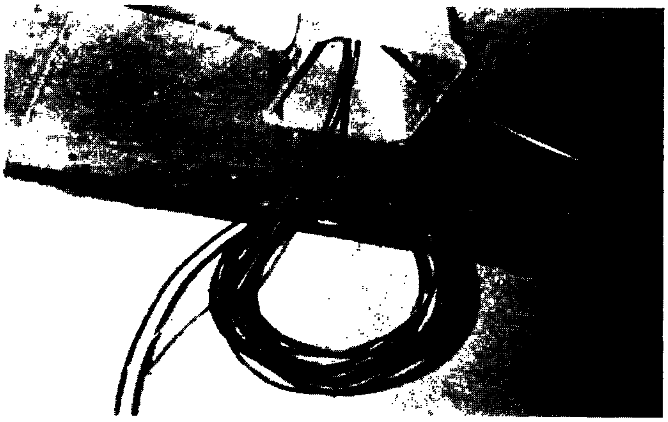


Figure 76. Plastic junction box and conduit beneath the deck . All splices are made in these types of junction boxes.

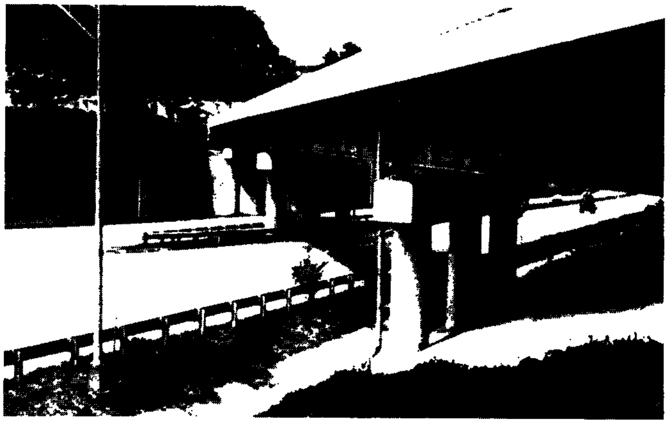


Figure 77. Conduit run underneath parapet to the rectifier power supply.

Setting the System for Operation

The specifications will set forth the operating performance criteria, methods of testing, and qualifications of testing personnel. Depending on the type of system, one or more methods of testing may be specified.

When the system is ready to be energized, a final check of the system components should be conducted. Anodes, monitors, and wiring should be tested to verify they are in good working order. The rectifier unit should be inspected for proper wiring and operation.

Several criteria for setting the system's output have been developed. In 1990, the National Association of Corrosion Engineers (NACE) published Recommended Practice RP-0290-90, "Cathodic Protection of Reinforced Steel in Atmospherically Exposed Concrete Structures."[3] In section 2 of RP-0290-90, NACE recommend using one or more of several criteria. The following are the two most commonly used recommendations:

> **100 mV Polarization Decay** -- The reinforcing steel, and any other metal embedments to be protected, shall de-polarize a minimum of 100 mV at anodic locations. When using the polarization decay method, the decay is determined by interrupting the protective current and monitoring the reinforcement's potential measured relative to a stable reference electrode. When the current is interrupted, an immediate voltage shift will occur. This voltage shift is the result of eliminating the IR drop and is not to be included in the polarization measurements. The potential of the steel immediately after that shift shall be used as the initial reading from where to measure polarization decay. The polarization decay equals the initial reinforcement potential after interrupting the current minus the reinforcement's final potential. Typically, the polarization criterion should be met within four hours.
>
> **The E Log I Analysis** -- The E Log I test is performed by incrementally increasing the cathodic protection current from the installed system. At each interval the IR drop free potential of the steel reinforcement is measured relative to a stable reference electrode. A plot of the steel reinforcement potential versus the logarithm of the current applied is called an E Log I plot.
>
> When performing the E Log I test, the reference electrodes are placed at anodic locations. Potential measurements recorded shall be free of cathodic protection current IR drop.
>
> The current required for cathodic protection is the value determined to occur at the beginning of linear behavior of the plot. It should be noted that this is a purely empirical approach that is not supported by the electrochemical theory of corrosion. Under certain conditions, including nature of the structure, exposure conditions, etc., the linear portion

of the plot may be difficult to determine. In these cases, alternative criteria should be applied.

The other criteria recommended by NACE, including statistical analysis and polarization gain, are seldom used and hence are not included in the guide specifications or in this document.

Polarization Decay Testing

Polarization (change in the energy level) of the reinforcing steel occurs over time when cathodic protection current is applied. Conversely, polarization decay occurs over time when the cathodic protection current is interrupted. Virtually no polarization change occurs if the cathodic protection current is only briefly interrupted (for less than one second). This briefly interrupted polarization measurement is commonly referred to as an instant-off measurement and is free of any IR drop error. IR drop is produced by the cathodic protection current (I) flowing through the resistive concrete media (R), which results in a corresponding voltage drop (E) in the concrete between the reference electrode and the reinforcing steel. This voltage drop is included in the potential reading, and values so measured are always more negative than the actual polarized potential of the reinforcing steel. The polarization change in the reinforcing steel is measured using an appropriate stable reference electrode and a high-impedance voltmeter (see "Design" section - "Reference Cells and Monitors").

The amount of polarization decay that occurs on a cathodically protected structure is measured by de-energizing the system and recording the IR drop free change in reinforcing steel polarization potential over time. If the potential decays (shifts in the positive direction) by a least 100 millivolts in four hours from the instant-off potential, the criterion is satisfied. The instant-off measurement should be made within one second of system output interruption. Results of a typical polarization decay test are shown in **figure 78**.

For structures that are either submerged or nearly water saturated, potential decay occurs much more slowly because of the lack of oxygen in the concrete. For these cases, the test time will have to be substantially increased. The four-hour time constraint for polarization decay is in the criterion because changing environmental conditions that can occur over longer time periods also change polarization values. The conditions near the reinforcing steel-concrete interface that affect the test include concrete temperature, moisture content, chemistry, and stray currents. As long as these conditions do not change significantly during the test, time is not critical. However, concrete chemistry changes are inevitable if the test period is extended for more than several days.

For reliable results, a number of measurements should be taken at different locations. At the very least, polarization decay data should be obtained for each permanently embedded reference electrode.

A potential contour plot survey over the entire structure's surface, in accordance with American Society for Testing Materials (ASTM) C876-90, should be made shortly before system installation (after all repairs are complete) to ascertain appropriate test locations. The resulting contour plot will identify the most anodic areas within each proposed anode zone, as well as locations for permanently embedded reference electrodes and locations for testing with portable reference electrodes.

E Log I Testing

E Log I tests can be performed using portable test equipment or the system rectifier. The equipment must have sufficient power and controls, including the following:

- Independent control of output for each zone being tested.
- Current control from 1 percent to 100 percent of circuit maximum-rated current capacity in 1 percent or smaller increments.
- Circuity that measures IR drop-free potential for each zone monitor being tested.

E Log I testing is usually performed on systems that have not been energized or on systems that have been turned off to allow full polarization decay or at least sufficient polarization decay to permit valid graphical solution. (Valid graphical solution occurs when the polarization decay level is more positive than the point at which the "second" linear E Log I relationship will initiate during the test. Further information describing the second linear region is provided in the following paragraphs.)

The test involves applying current in small steps for each zone. At the end of each step, the current and polarized instant-off potential are recorded. In the initial steps the current increases from 20 mA to 50 mA. Each current step is held for two or three minutes to allow the electrochemical reactions to stabilize. After the first 10 to 20 steps, the current steps are usually increased to 100 mA to 200 mA until the current or voltage capacity of the rectifier circuit is reached.

The data are plotted on a semilog graph with the current on the log scale and the potential on the linear axis. On a typical sample plot (**figure 79**), there are very small and relatively linear increases in potential initially. As current increases, the plot becomes curved and then goes linear. The current required to initiate this second linear portion of the plot is needed to provide cathodic protection for that zone (technically known as "I-protect"). Correspondingly, the potential achieved at this current level is the minimum polarized potential that provides corrosion control (technically known as "E-protect").

The plotting of these data can be somewhat arbitrary if plotted by hand. Even a small change in estimating where the second linear portion of the curve initiates can lead to a substantial

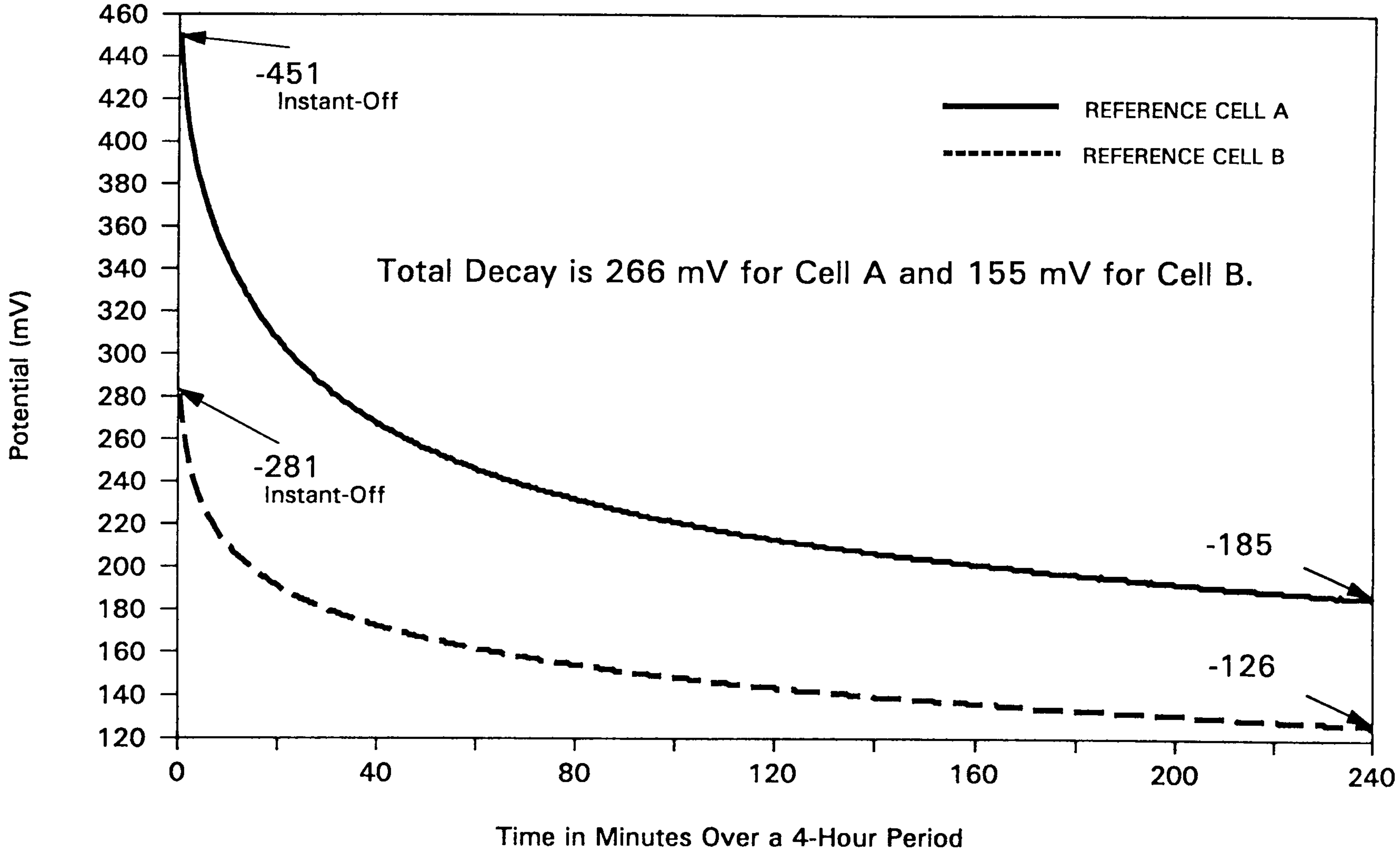


Figure 78. **Polarization decay test data. Reference cells - Zone 1.**

change in the current required for protection because the current is being plotted logarithmically. It is therefore usually preferable to use computer-generated graphical plots that can more accurately estimate the linear region using linear regression analysis methods. Most of the popular PC spreadsheet programs readily perform this kind of analysis.

The most common test for the linear relationship is to calculate the coefficient of determination ("R-Squared") for the computer-generated linear approximation versus the actual data measured. It is not unusual to obtain coefficients of 0.99 using 10 or more contiguous points from the graph (a perfect correlation would have a coefficient of 1.0). If either a lesser number of data values or a lower coefficient is obtained, the analysis may not be valid.

Criteria Discussion

The polarization decay test does not predict the system operating levels necessary to achieve cathodic protection. Instead, this test is used to evaluate the effectiveness of an operating system. Therefore, initial operating levels for the system have to be selected. Initial operating levels can be based on previous experience with similar structures in similar environments, short-term system activation results, or E Log I tests. If the estimated current does not provide 100 mV polarization decay after the system has operated for at least 24 hours, the system current output should be increased. The system should be operated at this new output level until the new polarization level has stabilized and then be tested. Similarly, if over protection is experienced, the current should be reduced and operated for a similar time interval before repeating the polarization decay test.

Polarization decay tests determine the operating parameters for the conditions existing at the time testing. Changes in these conditions can change these requirements. For example, both higher concrete temperatures and lower moisture contents increase current requirements. Therefore, these tests should be conducted during warmer, dryer seasons so that the output is set under the most arduous conditions. If the testing is performed during more mild conditions, the output should be set somewhat higher than indicated by the test.

Another test method involves operating the system in a constant voltage mode with the operating voltage set to provide the current required at the time of the test. As the temperature increases or decreases, the current output will correspondingly increase or decrease and provide more uniform protection levels. If this method is used, the system is usually set with a maximum current output. This current limit prevents acid attack from the system anode to concrete interface, excessive consumption rates on the anode material, and the rectifier capacity from being exceeded. Constant voltage control may not be applicable if the anode and reinforced steel are in significantly different moisture content environments (e.g., when anodes are directly exposed to the weather).

E LOG I COMPUTED CORROSION AND CATHODIC PROTECTION DATA
ZONE 1 - REFERENCE CELL B - 4,500 SQ-FT DECK

2nd linear region slope = 321.65 millivolts/decade
I-Corr = 1,032.96 milliamps
E-Corr = -386 millivolts
I-Protect = 3,024.13 milliamps (0.7 mA/sq.ft.)
E-Protect = -536.06 millivolts

Evaluation of Data for Tafel Line of Best Fit

Standard error of Y estimate = 0.68859
Coefficient of determination (R squared) = 0.99968
No. of observations used = 27

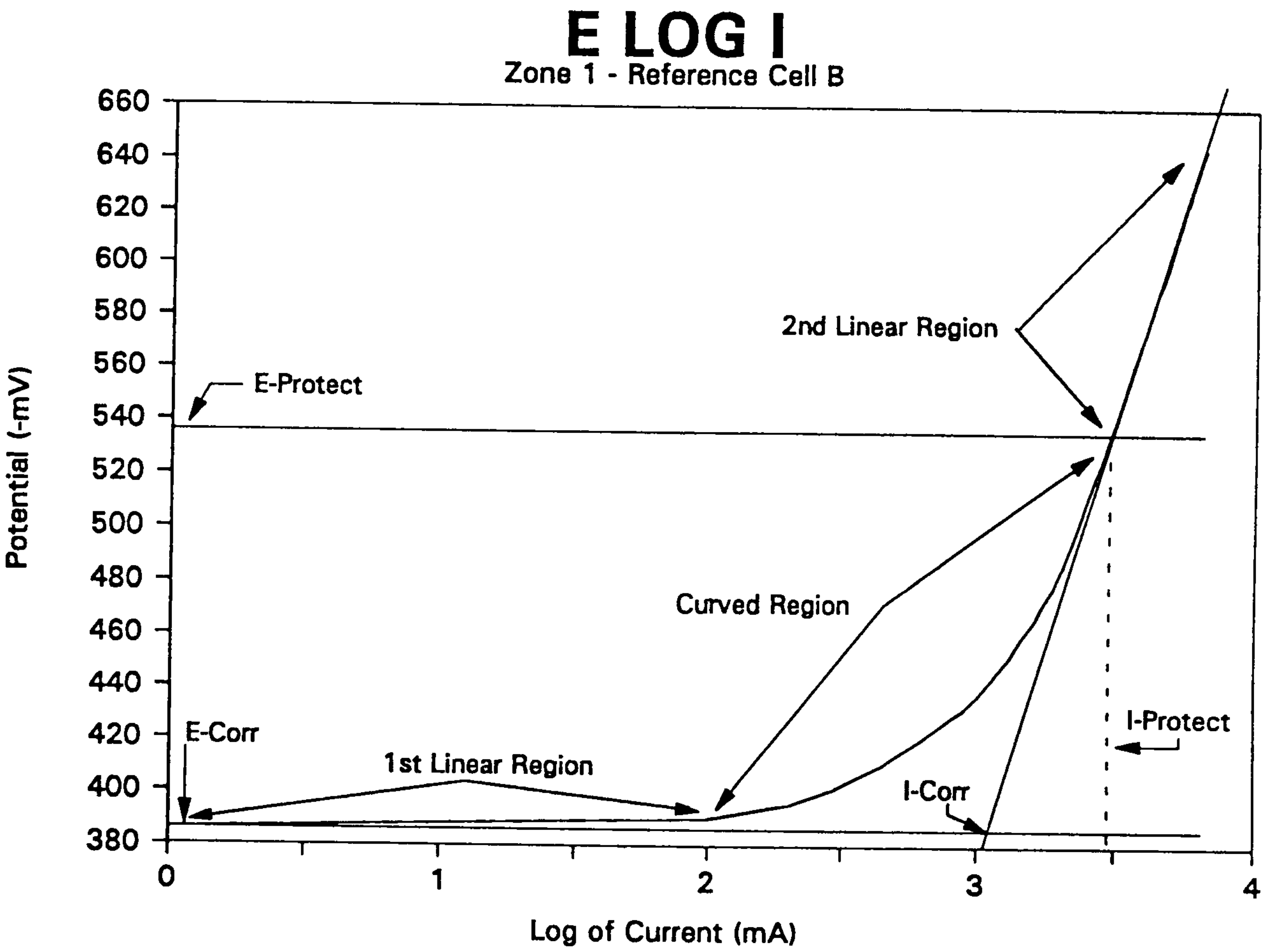


Figure 79. E Log I computed corrosion and cathodic protection data. Zone 1 - Reference cell B - 4,500-sq.-ft. deck.

Additional Testing Devices

Macrocells are indicators of the current required for cathodic protection. The macrocell is connected to the reinforcing steel through a 10-ohm resistor. The voltage across the resistor is proportional to the current flow through the resistor and can be calculated from Ohm's Law, $\underline{I} = \underline{E/R}$. In addition, the polarity indicates whether the direction of current flow is from the reinforcing steel to the macrocell or from the macrocell to the reinforcing steel.

When the macrocell is first connected to the reinforcing steel, the direction of current flow will be from the steel to the macrocell, which indicate that the macrocell is corroding. This reaction is a classic example of the galvanic corrosion cell. As the cathodic protection current is gradually increased in steps, the current flow from the reinforcing steel to the macrocell decreases. At a specific cathodic protection current, the macrocell corrosion current is nullified. Additional cathodic protection current reverses the direction of current flow, indicating that the macrocell is being protected. **Figure 80** is a typical example of macrocell data.

A variation of the macrocell described above is reported in SHRP-S-359 "Criteria for Cathodic Protection of Reinforced Concrete Bridge Elements". In this case, the macrocell is created by cutting a short piece of native rebar in the most anodic (corrosive) part of the structure. After isolating the bar and attaching a wire to it, the probe is used in the same way as the currently available macrocell. Although this technique appears promising, additional field testing is needed to verify its usefulness.

Project Documentation

At the conclusion of the job, the contractor must provide the owner with the following:

As-built drawings. These drawings are the complete record of construction on the project. They provide the history of the project for reference on future projects. Included with the drawings are all manufacturers' submittals regarding equipment incorporated into the contract.

Operation and maintenance manual. The manual contains all the wiring diagrams, drawings of system rectifier control and monitoring panel(s), location of physical components, initial operating parameters, and schedules for the first year of operation. A list of materials that should be readily available (extra rectifier fuses, electronic control cards, etc.) should be included. Manufacturers' troubleshooting and maintenance information should be provided for the appropriate components

Operator training. The contractor should provide a one-day maintenance-level course to familiarize personnel with the systems, including all key components and how to care for them.

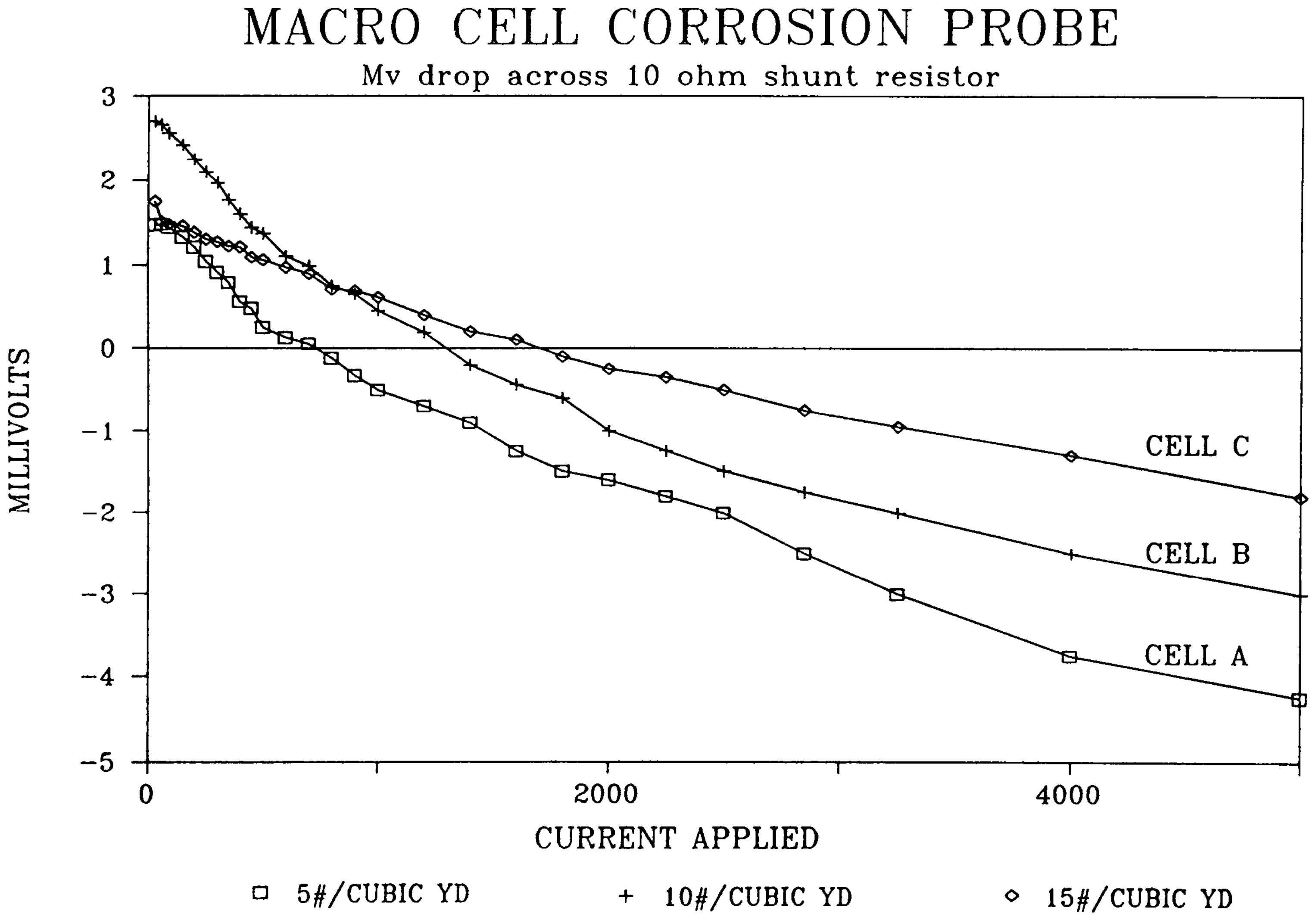


Figure 80. Plot of macrocell corrosion probe data.

5

Operation and Maintenance

To provide long-term corrosion protection, a cathodic protection system must operate continuously at proper operating levels, and therefore, the state highway agency responsible for the system must have a cathodic protection program to provide regular maintenance and performance evaluation.

Monthly monitoring (whether performed manually or by computer) and annual testing and adjusting of the system are fundamental to successfully preventing corrosion of reinforcing steel.

Cathodic protection has a major advantage over other bridge rehabilitation methods in that it can be easily monitored from readily available electrical parameters. Operational and maintenance procedures for any one cathodic protection system may vary slightly, depending on the type of anode system and rectifier used. However, most of the evaluation data are common to all systems. Diligent monitoring and maintenance will ensure proper operation and corrosion control.

Monitoring includes checking the systems monthly and performing a thorough annual inspection. If remote monitoring is installed, the required data can be obtained via telephone lines, which makes monthly and annual inspections even easier. Annual site visits are recommended to ensure that no deterioration, such as loose conduits, blocked rectifier vents, or failed lightning arresters, has occurred.

This section provides guidance for performing routine monthly monitoring and annual inspections. Troubleshooting and adjustment guidelines for typical cathodic protection systems are included.

Performing Monthly Monitoring of the System

To ensure that malfunctions are detected and repaired as soon as possible, systems must be checked at least once a month. Monthly monitoring involves going to each rectifier site, visually checking for physical damage and deterioration, and recording the rectifier output current and voltage for each circuit. This procedure only requires 5 to 10 minutes per rectifier and verifies that the system is providing continuous service. By tracking the data, performance irregularities and needed adjustments can be identified. A sample form for documenting routine monthly inspections is shown in **figure 81**. Agencies responsible for multiple installations often use local inspectors to gather data and send it to a central operations group for analysis.

If more time is available during the monthly check, visually inspecting all system components and taking embedded instrumentation data are recommended. It is also useful to obtain such information as temperature, weather conditions, kilowatt-hour meter readings, operational modes, and rectifier tap settings. See **figure 82** for an outline of a detailed monitoring program and monthly maintenance data form. A separate procedure is outlined for cathodic protection systems equipped with remote monitoring equipment.

Monthly Detailed On-Site Monitoring

A site-specific, detailed inspection report form should be developed as a guide for the inspector. As-built drawings including those showing the rectifier control and monitoring panel(s) will aid the inspector. The form typically has the following three sections:

> **Section One** - General Information. Bridge identification, rectifier type, location and rating, site condition, alternating current (AC) power usage, date, time, and the inspectors name are recorded. Also included are verification of items such as the rectifier tap settings, mode of operation, and other fixed adjustments that were made during the previous inspection as well as visual inspections and any general maintenance checks.
>
> **Section Two** - Operational Data. Data obtained for each circuit using the rectifier meter(s) are recorded, including the voltage and current levels, at a minimum. This section would also contain reference cell IR drop-free potential measurements and rectifier potential set points, if the rectifier has this capability.

Cathodic Protection
Rectifier Monthly Maintenance Log Sheet

Bridge Identification: ________________ Rectifier Model No.: ________ Rectifier S/N: ________

DATE	INSPECTOR	ZONE 1		ZONE 2		ZONE 3		ZONE 4		COMMENTS
		Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)	

Figure 81. Simplified cathodic protection system monthly report form.

Section Three - Embedded Instrumentation. Data acquired with an external portable voltmeter are recorded. This section includes macrocell, rebar probe, and voltage probe measurements that indicate the level of protection being provided by the system.

Typical front and side rectifier panel layouts for a four zone cathodic protection system are shown in **figure 83**.

Each of the four zones is energized by a separate circuit and has automatic and independent voltage and current control, manual override control, and IR drop-free reference cell measuring capability. Two embedded reference cells and two embedded macrocell probes are installed in each zone.

Step-by-step instructions to complete the inspection follow below. These instructions represent the most extensive monthly testing usually performed on a bridge cathodic protection system. Some rectifier units may not be equipped with all the described components.

Section One - General Information

Bridge Identification

Record the bridge name, number, and location. This information is permanently on the form.

Cathodic Protection Zone Identification

Identify each zone by its corresponding bridge component, location, circuit identification, and type of anode. This information is valuable for system inspection and troubleshooting and can be on the form permanently.

Rectifier Location

Record the location of the rectifier unit to assist other future inspectors. This information can be on the form permanently.

Cathodic Protection
Monthly Maintenance Data Sheet

[Section 1]

Bridge Identification: XXX ____________________

Cathodic Protection Zone Identifier:

Zone No.	Circuit No.	Bridge Component	Anode Type
1	1	XXX	XXX
2	2	XXX	XXX
3	3	XXX	XXX
4	4	XXX	XXX

Rectifier Location: XXX ____________________

Rectifier Model No.: XXX ______ Rectifier S/N: XXX ____________

Rectifier DC Rating: XXX ______ AC Kilowatt-Hour Meter: ____________

Date: __________ Time: __________ Inspector(s): ____________

Surface Condition: __________ Ambient Temperature: ____________

Visual Inspection:
Rectifier Unit: ____________
Cabinet: ____________
Ventilation: ____________
Protection Devices: ____________
Other: ____________
AC Power: ____________

Secondary Tap Settings:

Circuit No.	Course			
1	1	2	3	4
2	1	2	3	4
3	1	2	3	4
4	1	2	3	4

Control Mode:

Circuit No.				
1	G	Y	R	N
2	G	Y	R	N
3	G	Y	R	N
4	G	Y	R	N

G = Green (Potential); Y = Yellow (Voltage); R = Red (Current); N = None

Auto/Manual Switch Position:

Circuit No.		
1	Auto	Manual
2	Auto	Manual
3	Auto	Manual
4	Auto	Manual

Remarks: ____________________

____

[Section 2]

The following measurements are obtained from the rectifier meter.

Circuit Select Position	Meter Select Position	Rectifier Meter Reading
1	Voltage	______ Volts
1	Current	______ Amps
1	Instant-Off Ref. Pot. (A)	______ Volts
1	Instant-Off Ref. Pot. (B)	______ Volts
1	Potential (Set)	______ Volts
2	Voltage	______ Volts
2	Current	______ Amps
2	Instant-Off Ref. Pot. (A)	______ Volts
2	Instant-Off Ref. Pot. (B)	______ Volts
2	Potential (Set)	______ Volts
3	Voltage	______ Volts
3	Current	______ Amps
3	Instant-Off Ref. Pot. (A)	______ Volts
3	Instant-Off Ref. Pot. (B)	______ Volts
3	Potential (Set)	______ Volts
4	Voltage	______ Volts
4	Current	______ Amps
4	Instant-Off Ref. Pot. (A)	______ Volts
4	Instant-Off Ref. Pot. (B)	______ Volts
4	Potential (Set)	______ Volts

[Section 3]

The following measurements require a portable voltmeter.
Using an external meter, measure potentials across reference cell terminals (red and black) at rectifier

Circuit No.	Reference Cell No.	On Reference Potential
1	A	______ Volts
1	B	______ Volts
2	A	______ Volts
2	B	______ Volts
3	A	______ Volts
3	B	______ Volts
4	A	______ Volts
4	B	______ Volts

Using an external meter, measure potential across marcocell probe terminals (red and black) at rectifier

Circuit No.	Marcocell Probe No.	
1	1	______ mV divided by 10 = ______ mA
1	2	______ mV divided by 10 = ______ mA
2	3	______ mV divided by 10 = ______ mA
2	4	______ mV divided by 10 = ______ mA
3	5	______ mV divided by 10 = ______ mA
3	6	______ mV divided by 10 = ______ mA
4	7	______ mV divided by 10 = ______ mA
4	8	______ mV divided by 10 = ______ mA

Note: Above readings obtained with positive of meter to red terminal and negative of meter to black terminal
Record polarity (plus or minus) of reading.

Figure 82 Detailed cathodic protection system monthly report form.

Rectifier Information

Record the rectifier model number, serial number, and direct current (DC) rating for each circuit (they are printed on the rectifier front panel or door). This information can be on the form permanently.

AC Kilowatt-hour Meter

Rectifier units powered by local AC power will have an AC kilowatt-hour meter. Observe and record the meter reading. Calculation of the AC power used to operate the system during the time period can be used to determine rectifier efficiency as follows:

$$\frac{\text{Average DC Amps} \times \text{Volts} \times \text{Hours since last inspection}}{[(\text{AC power in KWH since last inspection}) \times 1000]} \times 100\% = \text{Percent Efficiency}$$

Date, Time, and Inspector

Fill in the date, time, and inspector(s) initials.

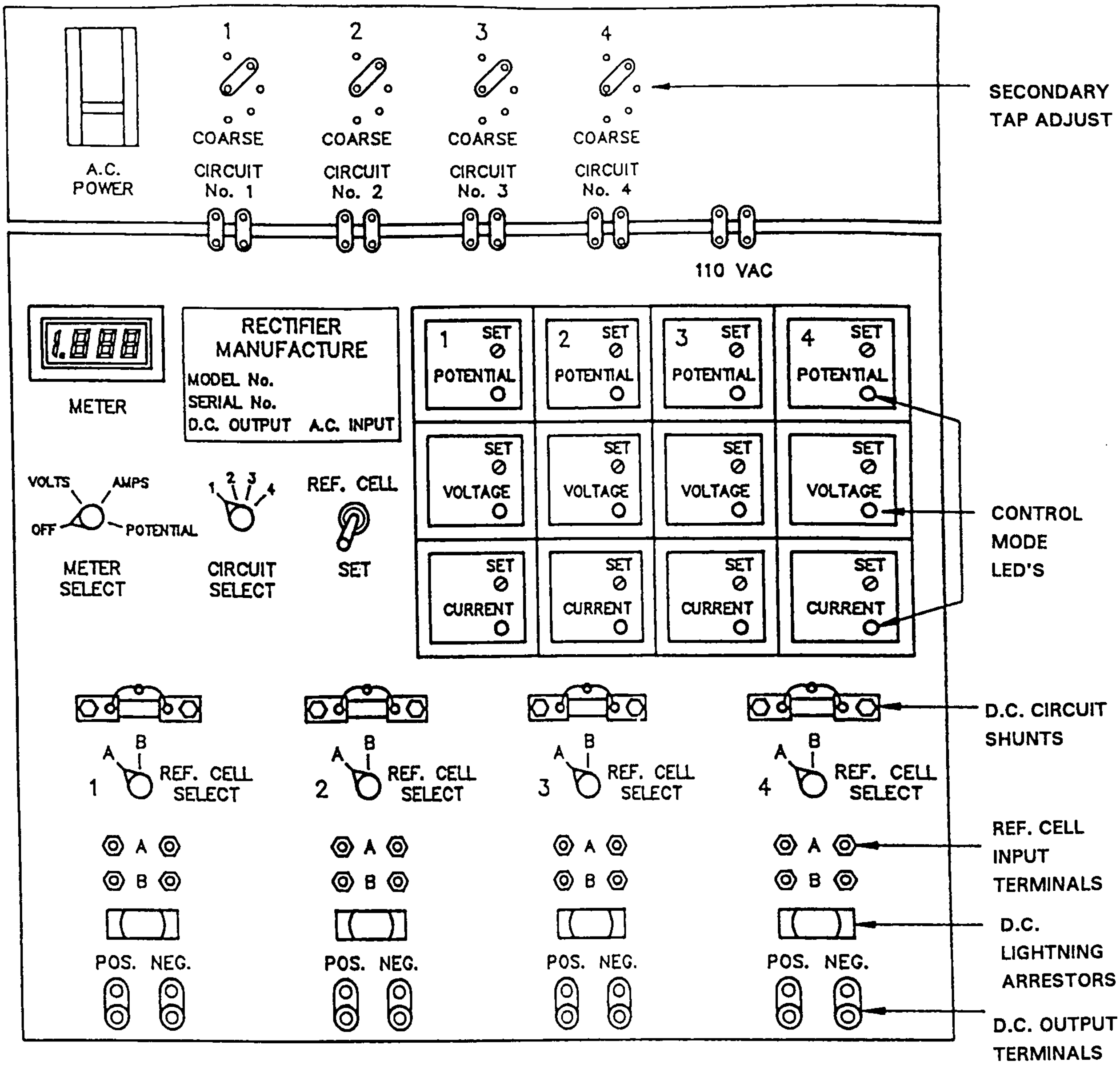
Site Conditions

Measure and record the ambient temperature and surface condition(s) (i.e., wet, dry, snow, ice covered). Note that these conditions can be different for different bridge components. This information will assist in the overall evaluation of the system's operation and will help determine the need for any system adjustment during the annual inspection review.

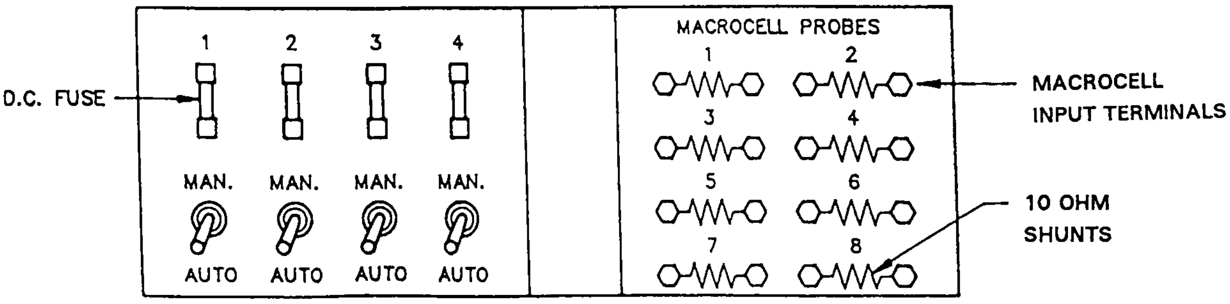
Visual System Inspection

The following list of areas should be viewed and appropriate comments documented on the inspection report form:

1. Rectifier unit. Observe cabinet condition and report if vandalized or damaged. Check for blocked or plugged cabinet vents (vents are typically located on the bottom and under the weather hood of the cabinet) and clear any obstructions. Note that failure to keep vents cleared can result in temperature rises that can damage the



RECTIFIER FRONT PANEL LAYOUT



RECTIFIER SIDE PANEL LAYOUT

Figure 83. Example of a typical rectifier panel layout.

electronics. Check lightning protection devices (usually located on the bottom of the front panel) and report any damage. Inspect inside the cabinet and report any damage. Replace any blown fuses and note the circuit and fuse replaced.

2. AC power. If the system is provided with the recommended AC power disconnect switch, check that it is secure and in the on position.

Secondary Tap Setting

Note the secondary tap settings, if provided, for each rectifier circuit and circle the operating setting. The secondary tap adjustments are normally located at the top of the front panel of the rectifier unit.

Control Mode

Observe the light-emitting diode display (LED) lights on each controller face plate located on the front panel of the rectifier unit. One light on circuits 1 through 4 should be brightly lit. Circle the color of the brightest light. If none are lit, leave blank.

Auto/Manual Switch Position

Observe the auto/manual switch located on the side panel of the rectifier unit. Record the position of the switch for circuits 1 through 4.

Remarks

Document anything unusual or any change from the last inspection period. Also document any changes to the settings or adjustments during this inspection.

Section Two - Operational Data

Rectifier Operating Parameters

These measurements can be obtained from the rectifier meter(s). It is also good practice to occasionally verify the accuracy of the rectifier meter by using a portable meter to make the same measurements. Typical locations of the meter select, circuit select, and reference cell switches are shown in **figure 83**.

Set the circuit select switch to 1.

Set the meter select switch to VOLTS. Read the voltage displayed on the meter and record the reading.

Set the meter select switch to AMPS. Read the current displayed on the meter and record the reading.

Set the meter select switch to POTENTIAL. Set the reference cell switch to embedded reference cell A, allow the meter reading to stabilize. The instant-off potential is displayed on the meter. Record the reading.

Set the reference cell switch to embedded reference cell B. Let the meter stabilize. Record the potential.

Return the reference cell switch to its original position.

Rectifiers with IR drop-free measuring capability have a potential set adjustment. With the meter select switch in the POTENTIAL position, press down on the potential REF. CELL/SET spring-loaded toggle switch that is located on the front panel. While continuing to hold it in the SET position, read and record the potential displayed on the meter. Release the toggle switch and it will spring back to the REF.CELL position.

For concrete applications, this potential set point adjustment is normally set higher than the system can achieve (typically -0.900 volts). If the reference cell potential does reach the set value, the controller will automatically override the other settings and reduce the output to a level that maintains the reference cell potential at the set potential value.

Repeat the procedure for zones 2, 3, and 4.

Return the meter select switch to the OFF position. Note that digital meters typically have a five year power ON operating service life. Failure to leave the meter in the power OFF mode while unattended will result in reduced meter service life.

Section Three - Embedded Instrumentation

All measurements for this section require a portable high-input impedance (10 meg-ohm minimum) voltmeter. Almost all modern digital multimeters meet this requirement. The terminal test points are labeled and are on the front and side panel of the rectifier (**figure 83**).

Reference Cell "ON" Potential Measurements

With the meter in the DC volts measuring mode, connect the positive meter lead to the red terminal (reference cell) and the negative to the black terminal (reinforcing steel) of reference cell A for zone 1. With the rectifier ON, record the voltage. This reading is the ON potential for reference cell A in zone 1.

Repeat the above procedure for reference cell B of circuit 1.

Repeat the above procedure for reference cells A and B in zones 2, 3, and 4.

Macrocell Current Measurements

With the digital meter in the DC millivolt mode, connect the positive meter lead to the red terminal (probe) and the negative to the black terminal (reinforcing steel) of the number 1 macrocell probe. Record the value (in millivolts) and polarity of the measurement. Divide the value by 10 (the shunt resistance value in ohms) to obtain the current in milliamps between the probe and the reinforcing steel. A positive reading indicates the probe is cathodic (i.e., noncorroding), and a negative measurement indicates the probe is anodic (i.e., corroding).

Repeat the above procedure for macrocell probes 2 through 8.

Remote Monitoring

If a cathodic protection system has a remote monitoring system, monitoring can be automated. Automated monitoring is very efficient and can be scheduled as frequently as desired. Some systems can be programmed to send the owner data if a problem occurs. The parameters for a typical remote monitoring system include the following:

1. Description overview. A real-time data interrogation system is installed for each rectifier. This unit can measure and record the status of each rectifier circuit and associated embedded instrumentation for each cathodic protection zone. The cathodic protection system can be remotely monitored via telephone line from a personal computer (PC) using two Hayes compatible modems to transmit data over ordinary telephone lines. Both modems should have auto-answer capability and must be compatible with the computer's communications software. Data stored in the field interrogation unit can be transferred to the office PC on request. The data can be readily viewed, analyzed, and stored in computer files.

2. Data interrogation system. Generally, the minimum, maximum, and average readings, should be recorded by the field interrogation system during each monitoring period. At a minimum, the system should be capable of collecting the following data for each zone:

   (a.) Zone voltage. The DC zone voltage should be measured and recorded to the nearest 0.1 volts.

   (b.) Zone current. The zone current is usually measured and recorded as a millivolt drop across a shunt installed in a series with DC (+) output for each zone. The value will generally range from 0 millivolts to 50 millivolts and should be measured to the nearest 0.1 millivolts if the shunt is rated at 1 ampere per millivolt.

   (c.) Reference electrode potential. Each reference electrode's On and instant-off potential should be measured and recorded. The values measured generally range between -300 millivolts and -1200 millivolts and should be recorded to the nearest millivolt.

   (d.) Macrocell current. The direction and amount of current to or from the macrocell rebar probe is generally measured as a millivolt drop across a 10-ohm shunt installed in a series between the probe and the reinforcing steel. The value will usually range from -10 millivolts to +10 millivolts. Both the polarity and value as measured to the nearest 0.01 millivolts should be recorded.

3. On-site interrogation system. The on-site interrogation system should have sufficient memory to store one month's readings. Software that allows the user to set the system interrogation parameters from a PC is suggested. These parameters can include the following:

    (a.) Integration time. The length of time over which the input signal is sampled to determine the average reading. The integration time typically used is between 100 milliseconds and 250 milliseconds, depending on whether the rectifier DC output is filtered, what the anticipated crest factor is if silicon controlled rectifier (SCR) output control is used, and what amount of superimposed AC ripple on the DC signal is being measured.

    (b.) Scan rate. The number to times per hour each zone's operating data will be read. The scan rate is generally 1 to 60 readings per circuit each hour.

    (c.) Monitoring Period. The interval for recording and storing the minimum, maximum, and average of the above scanned readings for each zone. The monitoring period normally ranges from 1 to 48 hours. Both the scan rate and monitoring period are constrained by the memory capacity of the on-site interrogation computer. A combination of a fast scan rate and long monitoring period will require the most memory. The system memory constraints for each of these parameters should be obtained from the manufacturer.

4. Data format and transfer. The data format is determined by the software. A well-written program for data acquisition will have a customized routine using a binary format for data storage and transmission. This method is much more space efficient than the American Standard Code for Information Interchange (ASCII) format and it thereby significantly reduces memory requirements and transmission times. Some systems only permit binary data acquisition and transmission when the data is converted to ASCII at the host PC computer. Other systems provide both ASCII and binary formats at the data collection point, thereby simplifying real-time monitoring. The report format is independent of the data format and may be available at the collection point or only at the host PC. Compatibility with other programs, such as spreadsheets and data bases, should be provided by a conversion routine that is part of the host PC software program. To ensure the integrity of the data that are transferred, the interrogation system should employ an error detection code during each transfer operation.

5. Desk top computer system. Even an 8088 microprocessor-based PC can be used for remote data acquisition, storage, and analysis, but for speed of data processing, the computer should be equipped with an 80486 microprocessor (or at least an 80386). At least 1 megabyte of random access memory (RAM) memory should be provided (8 megabytes are preferred). At least one high-density floppy disk (3 1/2 in. is preferred) and one 30 megabyte hard disk drive (200 megabyte is preferred) are usually required as well as a monochrome or color graphics monitor, serial and parallel ports, printer, and all necessary interface cables and connectors.

6. Computer software. To complete the interrogation system, an "off-the-shelf" integrated spreadsheet or data base program (i.e., Microsoft Excell, Lotus 1-2-3, or Microsoft Access preferably compatible with Microsoft Windows) is usually used to organize, store, and analyze the monitoring data.

Conducting Annual Inspections

Thorough annual testing of cathodic protection systems is advised as a standard practice by the National Association of Corrosion Engineers (NACE) Recommend Practice RPO390-90. This inspection provides greater assurance that the system is effectively protecting against bridge corrosion. The annual inspection should be conducted by qualified personnel familiar with cathodic protection of reinforced concrete structures. The benefits of this inspection are as follows:

1. The inspection verifies that the reinforcing steel is effectively protected.
2. It verifies the accuracy of embedded instrumentation, rectifier components, and remote monitoring equipment.
3. It ensures that operating levels are optimal.
4. It allows any problems to be corrected.

A typical annual inspection should include the following:

Review of Monthly Monitoring Data

This review should identify trends in the data such as changes in DC voltage to maintain a constant current, current changes in the constant voltage control mode, and embedded instrumentation responses to seasonal and system conditions. This review should also identify any changes and remedial repairs that were made to the systems. Any recurring repairs, such as blown fuses or failures of other protection devices, should receive extra attention.

Detailed Visual Inspection

The visual inspection should document the following:

1. AC power circuitry. Check that the AC power disconnect switch is secure and on. Check the power meter and all exposed conduit. Report any damage.

2. Cathodic protection zones. Check the physical appearance of the concrete and visible cathodic protection components (anodes, monitors, junction boxes, etc.) for each zone. Report any damaged and stained concrete areas, anode deterioration, and any damaged or missing components.

3. Rectifier unit. Observe the cabinet condition and report any vandalism or damage. Check for blocked or plugged cabinet vents and clear any obstructions. Check and replace, as necessary, all fuses and lightning protection devices. Carefully look at all other electrical components and connections and report all that are broken, cracked, scorched, burned, or vandalized.

   The meter is the most delicate component in the rectifier. Meters can be checked by comparing their readings to that of a good portable voltmeter that is connected across the appropriate terminals. The voltage across the ammeter shunt can be measured with a millivoltmeter and the current flow then calculated to verify the accuracy of the rectifier ammeter. Shunts used with cathodic protection ammeters are usually rated at 50 millivolts at full scale (e.g., a 10-ampere circuit is usually equipped with a 10-ampere/50 millivolt shunt such that each measured millivolt drop across the shunt indicates a current flow of 0.2 amperes). Millivolt and current ratings are stamped directly on the shunt. Current through a shunt is directly proportional to the millivolts measured; therefore, a ratio is established that allows the actual current to be calculated as follows:

$$I_{actual} = \frac{E_{measured}}{\frac{E_{shunt}}{I_{shunt}}}$$

where

I_{actual} = DC Current (amperes)

I_{shunt} = Shunt DC Current Rating (amperes)

$E_{measured}$ = Millivolt drop reading measured across a shunt (mV)

E_{shunt} = Shunt DC Millivolts (mV)

4. DC and monitoring circuitry. Check all conduit, wiring, and junction boxes for damage.

Polarized and Instant-Off Measurements

One method of evaluating that embedded instruments are operational is by checking their response to cathodic protection current. These measurements are obtained using high-input impedance digital voltmeters connected across the appropriate test-lead terminals.

Reference Cells

"On" potentials are generally between -350 millivolts and -2000 millivolts. The more negative the value the more IR drop in the value. Record the on and instant-off potentials, verifying that the potential decay is in the correct polarity (refer to the "Construction" section on "Polarization Decay Testing" for further information).

Macrocell Probes

It is common to measure values of -1 millivolt to +10 millivolts across the 10-ohm resistor with cathodic protection current applied. The macrocell current becomes less cathodic (or even anodic) when the current is momentarily interrupted. This interruption is a valid way to check that the macrocell probe is operational. Macrocells that immediately become anodic when the rectifier is first turned off are extremely powerful corrosion cells. With continuous cathodic protection current applied, the macrocell will in time become a less powerful corrosion cell and may not return to an anodic condition for weeks with the rectifier turned off.

Electrical Resistance Measurements

These measurements are made after the cathodic protection has been turned off (typically after a polarization decay test) and the embedded instrument and anode lead wires have been disconnected. The measurements are best analyzed by comparing them with previous measurements. The measurements must be made with an AC resistance meter (e.g., Nilsson 400 AC Resistance Meter) rather than with a DC ohmmeter since there are residual DC voltages in each of these circuits. Typical values and behavior for commonly installed cathodic protection anode systems and silver-silver chloride reference cells are as follows:

Anode to reinforcing steel. The resistance measurement will depend on the type of anode installed. The resistance value will vary with temperature (higher in colder seasons and lower in warmer seasons) and moisture condition (lower when wet and higher when dry). Resistance will gradually increase over the life of the system. Carbon-based systems typically experience the greatest increase in resistance. Zinc systems experience somewhat lower increases than carbon-based systems. Titanium-based systems experience only minor increases. Abrupt changes in resistance should be investigated for possible damage. For individual zones of approximately 5000 sq. ft., carbon-based anodes exhibit values between 1 ohm and 10 ohms while titanium-based anodes have values in the 0.5-ohm to 2-ohm range. Zinc anodes usually measure higher than titanium-based anodes but less than carbon-based systems.

Silver-silver chloride reference cells. The resistance between the reference cell and reinforcing steel will vary with concrete temperature and moisture content. The resistance value will generally have a significant increase within the first year or two of operation and then become more stable, varying by seasons, for its remaining service life. A range of 200 ohms to 2,500 ohms in the first year and 500 ohms to 10,000 ohms thereafter is common. Potential measurements obtained from reference cells with resistance over 50,000 ohms usually indicate a defective reference cell.

Performance Adjustment Testing

This testing includes the following:

1. Polarization decay test. This test evaluates system performance and provides information on the need for system readjustment. To determine if the system is providing corrosion control, criteria of 100-millivolt decay at a minimum has been recommended by NACE (RPO290-90). This is defined as the half-

cell potential difference between the instant-off (IR drop-free) and the last potential taken after four hours of continuous protection current interruption. Further details on the test procedures are in the "Construction" section under "Testing, Energizing, and Commissioning."

2. E Log I testing. This test is performed to determine the amount of current required for corrosion control. It must be performed after the system has been off at least overnight or long enough ensure that sufficient polarization decay has occurred to provide a valid test. Typically, if less than 3 millivolts of potential decay are measured on all zone reference cells over a 15-minute period, sufficient decay has occurred. Further details on the test procedures and analysis are in the "Construction" section under "Testing, Energizing, and Commissioning."

3. Macrocell testing. Macrocell millivolt drop and polarity are measured during polarization decay tests. The values obtained give some information on the effectiveness of the protection. The amount of cathodic protection current required to nullify corrosion of the probe can be measured during the E Log I polarization test. Further details on the test procedure and analysis are in the "Construction" section under "Testing, Energizing, and Commissioning."

Adjust System as Required

The system should be adjusted for optimum corrosion control based on the corrosion control effectiveness and anode current density limits described in the "Design" section of this manual. A reduction in cathodic protection current requirements for reinforced concrete bridge components under continuously applied cathodic protection current for several years is typical. In general, cathodic protection requirements were found to stabilize more quickly in relatively constant environments as opposed to environments with highly variable seasonal climates (two years versus five years).

Prepare Annual Inspection Report

The final report should include a tabulation and analysis of the data, as well as conclusions and recommended operating parameters. Any recommendations for repairs or modifications required to ensure the continued effectiveness of the system should also be included. The report should provide a ready reference for maintenance and management personnel.

Remedial Measures

Remedial measures should be taken whenever periodic inspections indicate that corrosion protection is no longer adequate. Repair, replacement and adjustment of components of the cathodic protection system should be made accordingly. Most remedial measures can be performed at the rectifier. These repairs are usually no more extensive than occasionally replacing a fuse or adjusting the output. Immediate repair ensures corrosion control, which minimizes bridge rehabilitation.

Basic Troubleshooting

Equipment

Equipment for basic troubleshooting is not elaborate but must be adequate to do the job. A quality digital multimeter, such as a Fluke Series 70 or a Beckman Series 200 meter, is relatively inexpensive and capable of making most measurements. An AC resistance meter, such as a Nilsson Model 400, is good for checking circuits external to the rectifier. In addition, portable reference electrodes, small tools including assorted screwdrivers and pliers, several jumper wires with alligator clips, and spare fuses will be useful.

Precautions

When troubleshooting at the rectifier, the following should be observed:

1. From the rectifier front panel, identify all rectifier and external circuit test terminals before starting any troubleshooting. One source of information to assist in this identification is the rectifier maintenance manual.

2. Turn the rectifier off when working in it. Open both the AC disconnect switch ahead of the rectifier and the internal AC circuit breaker.

3. Proceed with caution when testing with the rectifier on. Most rectifiers are designed with guards over high-voltage contacts to prevent accidental contact and injury.

4. Make sure meters are properly connected. A voltmeter must be connected across the circuit to be measured. An ammeter must be connected in a series with the circuit being tested. Check polarity when making DC measurements. The rectifier must be off when using ohmmeters. When measuring the resistance of external circuits using an AC resistance meter, disconnect the lead wires from the rectifier terminals.

General Guide

Visual inspection

Many problems are relatively obvious to the experienced technician looking for signs of overheating and sources of unusual noises. Loose connections, signs of electrical arcing, strange odors, enclosure or cabinet damage all indicate troubles that do not require elaborate test procedures to discover.

No DC current and voltage

Check the rectifier for AC power, a tripped AC circuit breaker, blown AC fuse, or bad meter. If the problem is not identified, check the input and output of the rectifying elements and the windings of saturable reactor units.

DC voltage and no DC current

Check the rectifier for a blown DC fuse, an open connection at the positive (anode) or negative (structure) terminals, or a bad ammeter. Check the anode-to-structure leads for open circuits.

DC current and no DC voltage

Check the rectifier for a shorted connection at the positive (anode) and negative (structure) terminals, or a bad voltmeter circuit. Check the anode-to-structure leads for a short circuit.

Low DC voltage or DC current

Check the rectifier meter(s) and controller. For rectifiers with IR drop-free control capability, check that the instant-off potential is lower than the "set" potential. Measure the circuit resistance between the anode and structure leads.

High DC voltage

Check the rectifier voltmeter and controller. Measure for high-circuit resistance between the anode and structure lead.

Rectifier operates but no automatic control

Check that all rectifier controller circuit cards are properly seated in their terminal strips. For rectifiers with IR drop-free control capability, check the reference cell terminals for open or loose connections. Check that the resistance between the reference cell and reference cell ground leads is within an acceptable value for the controller (typically less than 50,000 ohms).

Erroneous reference cell potential

Check the reference cell leads and the meter measuring circuit for proper connections. Verify meter accuracy. Check reference cell circuit resistance.

Erroneous macrocell current

Check the macrocell leads, shunt resistor, and meter measuring circuit for proper connections. Verify shunt resistance (typically 10 ohms) and meter accuracy. Check macrocell circuit resistance.

General Tips

Fuses are very easy to check. They have very low resistance when good and very high resistance when bad. Always remove a fuse from the circuit before checking it.

Lightning arrestors usually show physical damage when defective. The lightning arrestor can be disconnected and removed from the circuit and the rectifier can operate (unprotected) without them. If removed, they should be replaced as soon as possible.

If a rectifier is completely inoperative and the AC circuit breaker will not hold, the problem is likely a short in the transformer or rectifier elements.

For rectifiers with electronic voltage/current controller cards, have replacement cards for controllers on hand. If the controller card is the suspected cause of a DC output problem, verify by plugging it in to a good controller. If the DC output can be properly adjusted with the replacement controller, the original controller is bad.

For rectifiers with IR drop-free measuring or controlling capability, temporarily short the reference cell input with a jumper wire if the external reference cell circuit is the suspected cause of a DC output problem. If the rectifier output returns to normal, the reference cell circuit is bad.

For rectifiers with saturable reactor current control, disconnect the control current leads to the reactor and connect a heavy-gauge jumper wire to bypass the reactor power leads if the saturable reactor is the suspected problem. If the rectifier output goes to maximum voltage, the reactor is probably bad.

For rectifiers equipped with noise or efficiency filters, defective filter chokes usually fall open if there is no DC output. Connect a temporary heavy-gauge jumper wire across the choke and observe DC output. If the current output is restored, the choke is defective. If a capacitor fuse is blown and the replacement fuse also blows, a defective capacitor is the probable cause (the capacitor usually fails by shorting). Rectifiers can usually be operated with unfiltered output while replacement parts are on order.

References

1. American Concrete Institute, "Corrosion of Metals in Concrete," 222R-85 Committee Report, Detroit 1985.

2. Hull, T.J., "Economic Impact of the Corrosion Problem," Proceedings of Reinforced Concrete Bridge Decks, San Antonio, Texas, February 12-13, 1985.

3. Standard Recommended Practice, " Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete," National Association of Corrosion Engineers Standard RP0290-90, 1990.

Appendix A

Tentative Guide Specification for Cathodic Protection of Concrete Bridge Decks

AASHTO-AGC-ARTBA
TASK FORCE #29

650. BRIDGE DECK CATHODIC PROTECTION

650.10 DESCRIPTION: This document was prepared for the AASHTO-AGC-ARTBA Joint Committee by Task Force 29 of the Subcommittee on New Highway Materials. The goal of the Task Force is to delineate concise guidelines which can be used by highway agencies as standard specifications for Cathodic Protection of Reinforced Concrete Bridge Decks. The task force members dedicate this document and our efforts to the late Richard F. Stratfull. Dick worked for many years for the California Department of Transportation and was a pioneer in the areas of corrosion detection and prediction, and cathodic protection of concrete bridge decks.

The intent of these documents is to define standard specifications applicable to the Nation's bridges. It is recognized there are bridge structures which do not match the standard and would be subject to special study and design. The standard bridge deck is a reinforced, double mat rebar structure with a 6- to 9-inch thick slab. Standardization is expected to permit contractors to install these systems efficiently and, hence, provide an economic system to the bridge owner.

Cathodic Protection (CP) is the only known fully developed means of mitigating the corrosion of reinforcing steel in existing bridge decks caused by the presence of chloride ions. The routine use of CP for pipeline protection and underground structures prompted development of new technologies which would allow the successful application and operation of CP on bridge decks. The first installation of an impressed current CP system on a bridge deck took place in California in 1973, using high silicon cast iron anodes affixed to the deck and covered with a 2-inch lift of conductive coke breeze asphalt and topped with a 2-inch wearing course of asphaltic concrete. Since that pioneering effort, the field of cathodic protection for reinforced concrete bridge decks has matured into a proven technology with several design options available. It should be considered as a valuable engineering alternative for the rehabilitation of salt-contaminated bridge decks.

As in any new technology, advancement of state-of-the-art of bridge deck CP involves interaction among Federal and State government agencies with researchers, contractors, and private industry and governmental research agencies. In 1982, the Federal Highway Administration issued a position paper on Cathodic Protection Systems which promoted widespread implementation of CP as a rehabilitation technique for bridge decks. The intensive research and product development by private industry and governmental research agencies which followed, has led to a new generation of anodes and a substantial reduction in the cost of materials and installation. The final determinant for any technology, however, must be generated by successful performance under field conditions. Satisfactory operation of more than 350 systems in 37 States and 8 provinces in Canada give suitable testimony to the viability of CP.

The specifications listed below are the product of this ongoing effort to advance the reliability and refine the design, construction, and operation of CP on bridge decks. Those components specified have been subjected to extensive and exhaustive laboratory testing and have also provided a minimum of at least two years of adequate field performance. The specifications cover three different types of anode systems, but no recommendations as to the proper system for a given structure, either direct or implied, are intended. The available systems are:

- Coke-breeze asphalt conductive overlay system
- Conductive polymer systems
  - Slotted
  - Mounded in conjunction with an overlay
- Tack-down, manufactured anode systems
  - Catalytic titanium anode mesh with concrete overlay

At present, only one catalytic titanium anode mesh is included in these specifications. Similar systems by other manufacturers have been istalled and are being evaluated. These will be considered by this task group in the near future for inclusion in these specifications.

Other anode systems, such as sprayed zinc with asphaltic concrete overlays and catalyzed titanium ribbon slotted systems, are under development. Although these may become standards in the future, at present, the task force considers them experimental and thus they are not included herein. We hope, however, that all possible alternatives will continue to be studied and that these standards will be updated as appropriate.

General specifications for other components such as reference cells, rectifier, etc., are also included, as well as recommended installation and activation procedures. At present, a saturable reactor type ectifier is specified. Silicon controlled rectifiers (SCR's) have also been successful in some installations. These will be further considered by this task group in the manufactur for inclusion in these specifications. Items which were used in the research phase of cathodic protection of bridge decks, such as rebar probes, corrosometers, and multi-control mode rectifiers are not listed as they are not deemed necessary for routine operation.

In developing the specifications important reference materials were used. Several of the most pertinent documents are listed in the Annex item E in Section 650 on page 52.

The use of cathodic protection on the following structures is not recommended at this time:

- Prestressed or posttensioned bridge decks,
- Bridge decks whose concrete air void system has a spacing factor of less than 0.008 inches (ASTM C-457) for coke-breeze systems only (concrete overlay CP systems have been used successfully on decks with inadequate air void systems and thus are recommended).
- Bridge decks with alkali-reactive aggregate concrete.

Waterproofing (membranes mainly in the form of thin traffic toppings) has been used recently in concert with cathodic protection. The Task Force believes that such use of waterproofing should still be considered experimental.

Equally important to proper specifications is the selection of a qualified and experienced corrosion engineer to develop the final design details, and to provide quality control and assessment during construction and proper system activation. Guidelines are provided within the specifications that indicate the minimum qualifications recommended.

Section 650 is the main cathodic protection specification, and includes an Annex covering the qualification of new materials and systems, the recommended rectifier warranty check, test methods, and a glossary of terms. It is followed by sections relating to each anode system (651: *Conductive Coke Asphalt*; 652: *Non-Overlay Slotted* ; and 653: *Distributed Anode CP Systems with Concrete Overlays*).

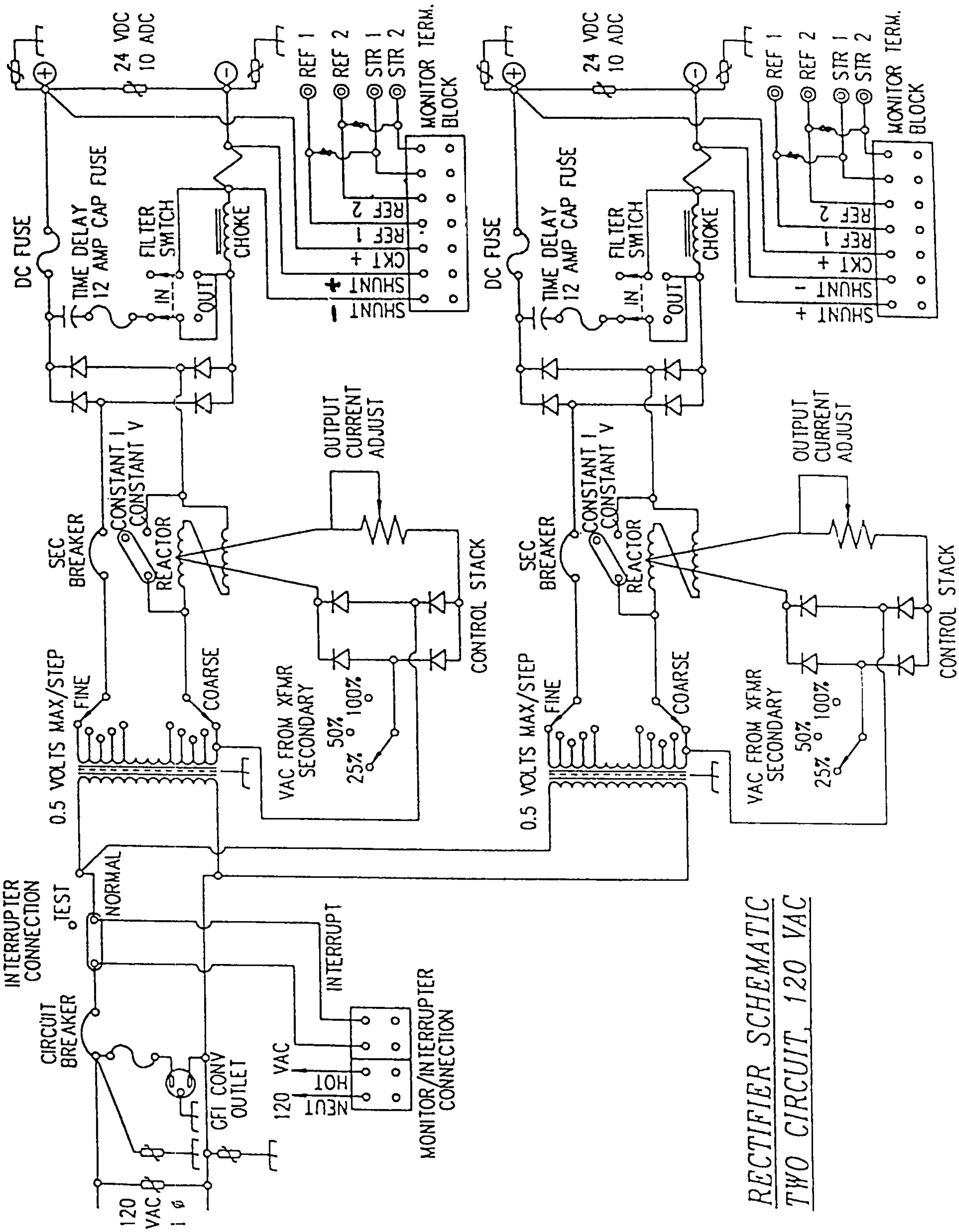
To implement this specification, it is necessary that the specifier complete the Design Specifics checklist in section 650.30.02. Detailed plans beyond those normally used on rehabilitation projects are not required. The detailed anode design and layout will be performed by the contractor and submitted as shop drawings prepared and signed by the Corrosion Control Consultant.

650.20 CATHODIC PROTECTION MATERIALS

650.21 CATHODIC PROTECTION RECTIFIER

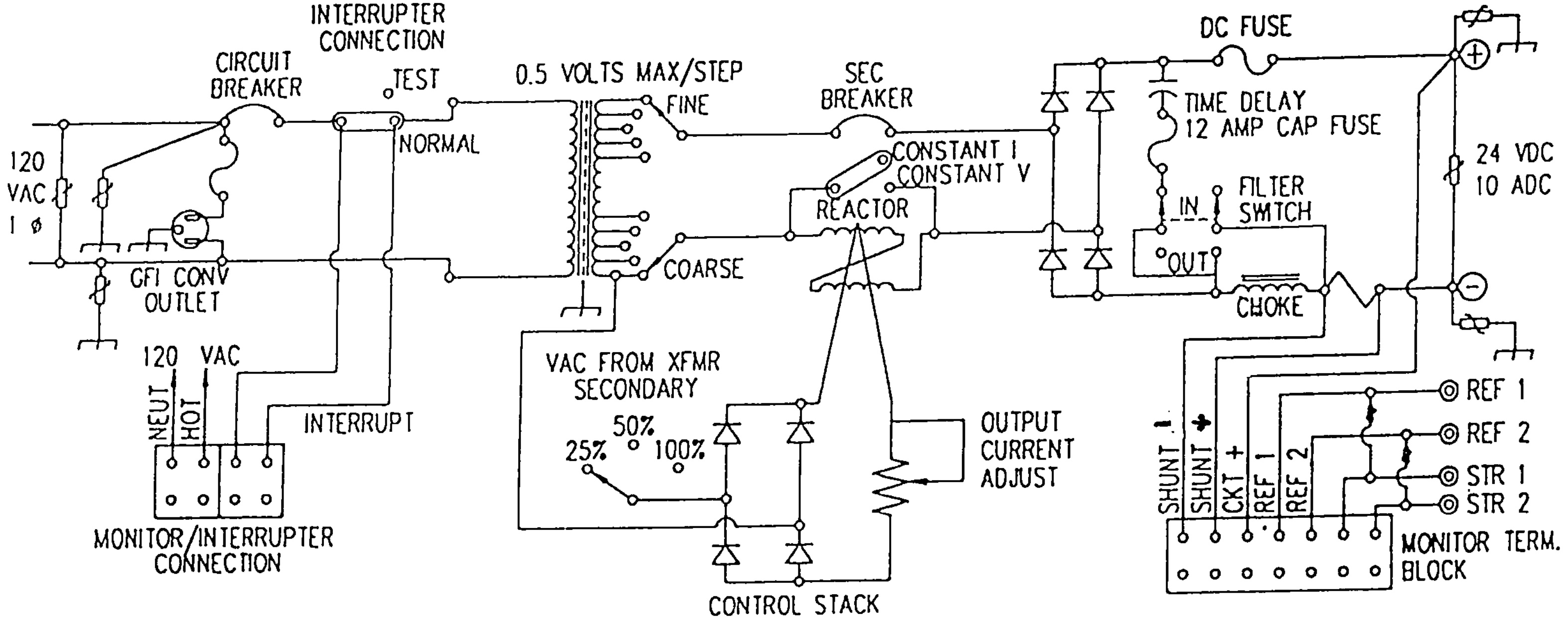
650.21.01 Description: This specification defines the requirements for manufacturing cathodic protection rectifiers for bridge deck protection. *The rectifier shall be the saturable reactor constant current type with the ability to change control to constant voltage.* The rated DC output of each circuit shall be 24 volts, 10 amperes. The rectifier shall be designed and constructed in accordance with the schematic shown in Figure 650-1 and the following specifications. Load (D.C. circuit) resistance will be variable and is expected to range from 0.25 ohms to 2.5 ohms.

Figure 650-1 (Sheet 1 of 3)



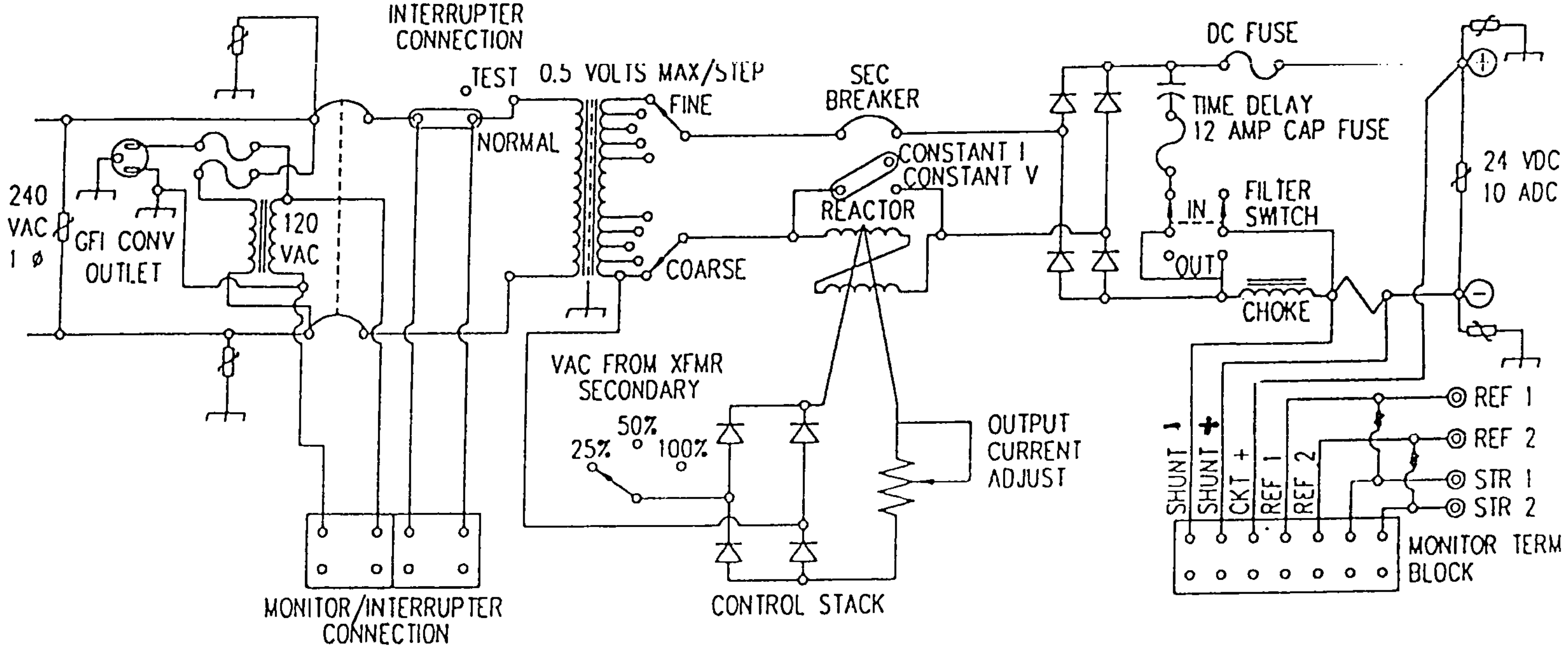
RECTIFIER SCHEMATIC
TWO CIRCUIT 120 VAC

Figure 650-1 (Sheet 2 of 3)



RECTIFIER SCHEMATIC
SINGLE CIRCUIT, 120 VAC

Figure 650-1 (Sheet 3 of 3)



RECTIFIER SCHEMATIC
SINGLE CIRCUIT, 240 VAC

If the zone to be protected is smaller than 1,000 square feet, the DC output current specified should be reduced.

Materials and equipment shall be designed, manufactured, and tested in accordance with the minimum applicable requirements of the latest editions of the following codes and standards referenced:

- National Electrical Code (NEC)
- National Electrical Manufacturers' Assoc. (NEMA)
- American Society for Testing and Materials (ASTM)
- Military Specifications (Mil Spec)
- American National Standards Institute (ANSI)

The material shall be installed outdoors and subjected to varying corrosive atmospheres with an ambient temperature of up to 50°C and relative humidity up to 100%. The expected operating life shall be in excess of 20 years.

Each rectifier supplied shall include two sets of the following as a minimum: a wiring schematic drawing, parts list, test results, and an operation and maintenance manual.

The rectifier shall be warranted for one full year after installation or 18 months after delivery (whichever comes first) against defects in design or workmanship.

The rectifier shall be supplied by a company established in and presently involved in the design and manufacture of cathodic protection rectifiers.

650.21.02 Enclosure: The enclosure shall be designed to meet NEMA type 3R, 4 or 4X requirements as outlined in NEMA Publication No. 250 and selected by the designer. It shall be constructed of 11 gauge minimum thickness material and shall provide for adequate convection cooling of internal components. The enclosure shall be designed for either pole, wall, or base mounting as required. Any opening designed for cooling and over 1/8" shall be screened to prevent entry of nest building insects. NEMA 3R enclosures shall have hinged removable front and side doors with bolts on adjustable stainless steel heavy-duty latches. NEMA 4 air cooled rectifiers shall have a single hinged front door with heavy duty, stainless steel latches. NEMA 4 air cooled enclosures shall include a thermostatically controlled fan with filter to provide adequate cooling. The fan and filter may be omitted if the designer can show that the rectifier will cool properly when operated at maximum output voltage and current and the maximum ambient temperature. When a NEMA type 4 oil cooled enclosure is specified the transformer and rectifier stack shall be mounted on separate removable racks. The enclosure shall have provisions for locking and protect the interior components from weather and vandalism. Entry for wiring shall be located in the bottom of the enclosure and be of adequate number and size to provide for input and output connections. A grounding lug shall be provided on the outside of the enclosure to accommodate a #6 AWG copper ground wire. A permanent manual holder shall be provided, attached to the inside of the cabinet door.

650.21.03 Transformer: The transformer shall be specifically designed for use in a cathodic protection rectifier, have separate, isolated primary and secondary copper windings and a grounded copper Faraday shield between primary and secondary windings. The transformer will be designed to operate continuously at rated load and will supply rated output at 5% low, 10% high line voltage without damage. The wire size of both windings is to be based on a minimum of 750 circular mils per amp. The transformer regulation shall not exceed 3% when measured at 1/4 load and full load. The transformer and materials will be designed and manufactured to meet the requirements of MIL E 917. The secondary will have a sufficient number of coarse and fine taps to allow adjustment of the output in 1/2-volt increments. All tap leads shall be sized for a minimum of 500 circular mils per ampere. These taps shall be brought out to link bar arrangements or a terminal block for adjusting the output of the rectifier and shall be located on the instrument panel.

The transformer shall be vacuum impregnated or preheated and immersed in Class F (150 degrees C) transformer varnish until all tapes, insulating materials, outer wrapping and coil windings have been completely saturated and then oven baked until dry. When completed and before installation into a rectifier, the transformer shall be tested and must be able to withstand 2000 volts for one minute without breakdown between the primary and core, secondary and core, and primary to secondary.

Each circuit shall have its own isolated secondary winding or individual transformer designed per the above requirements.

650.21.04 Rectifying Elements: The rectifying bridge shall have a forward average current rating of 25 amps minimum. Each diode shall have a minimum peak reverse voltage rating of 800 volts. Heat sinks shall be sized to provide continuous rectifier operation at rated ambient temperature and rated output. When block style rectifying elements are used, in addition to the above, they shall have 1200 volt minimum isolation.

650.21.05 Protective Devices: The entire unit is to be protected against overload and short circuit by a thermal magnetic type circuit breaker of the proper voltage rating and sized to hold 100% of the rated load current. It is to be connected between the AC supply and transformer primary. The circuit breaker shall be the manual reset type and must trip at between 110% and 125% of rated input current. The breaker shall be positioned and labelled to meet the requirements of the NEC article 240 sections 80 through 83C. In the case of multiple circuit rectifiers with individual transformers, each circuit shall have its individual AC supply protected by a properly sized fuse in addition to the breaker.

Rectifiers shall have a quick acting magnetic breaker rated at 120% of the circuit capacity placed in one leg of the AC secondary of each circuit.

650.21.06 Lightning and Surge Protection: The unit shall be equipped with properly sized AC and DC lightning protection. Each controlled output as well as every input to the rectifier shall be protected against voltage surges, using properly sized surge suppressors. Metal oxide varistors (MOV's) used to protect the AC input and DC output shall be rated at 500 joules and have a voltage rating which provide adequate protection to the internal circuitry. (See table 650-1 below.)

Table 650-1

VAC INPUT	MOV RATING(max)	DC OUTPUT	MOV RATING(max)
120	250 VRMS	24	130 VRMS
240	480 VRMS		

650.21.07 DC Panel Meters: Meters are not required, but when specified, shall have a minimum 2 1/2-inch scale, d'Arsonval pivot and jewel type movement, and have an accuracy of 2% of full scale. The meter circuit(s) will include a switch, hermetically sealed, which removes the meter(s) from the circuit when not in use. The ammeter shall be connected to an external shunt plainly marked to show ampere rating and millivolt drop. A single ammeter may be used in conjunction with a hermetically sealed selector switch to read each circuit's output. When a combination volt/ammeter is specified, the volt scale and ampere scale shall be clearly labeled.

When a digital meter is specified, it shall monitor the voltage and current output of each circuit of the rectifier using hermetically sealed switches to select the reading required. The selector switch shall have an off position which removes all input signals from the meter sense leads. A meter power on/off switch shall be supplied. The meter is to have an LCD (or LED) three and one half digit (minimum) display, have an accuracy of +/-0.05%, operate over a temperature range of -30 degree C to +65 degree C; and have a storage temperature range of -30 degree C to +80 degree C. The input impedance shall be 10 megohms minimum.

650.21.08 Shunts: Each output circuit shall have a DC shunt readily accessible for meter accuracy checks. They shall be mounted on the control panel and be marked. The shunt(s) shall be placed in the negative circuit rated at 50 mV and 120% of circuit current (maximum) and have uninsulated ring tongue terminals, positioned for easy connection of test equipment or meters, fastened to the calibrated test points. The negative circuits shall not be connected together.

650.21.09 Convenience Outlet: Units shall be equipped with a 115 VAC, Ground Fault Interrupter (GFI), grounded AC outlet mounted on the panel face. The outlet shall be fused for 15 amperes and be attached to the line side of the circuit breaker.

650.21.10 Terminals: A 600 volt AC input terminal block with "dead front" shall be located on the insulated control panel for connection of the input AC wiring. Solderless, compression lugs, spaced a minimum of 2 inches apart, sized to accommodate up to #6 AWG wire, shall be provided for the positive and negative output terminals of each circuit of the rectifier and be mounted on the control panel. Binding posts, suitable for attaching No. 10 AWG wire, shall be provided for each zone to accommodate two reference electrodes and structure test leads. Test jacks shall be provided to enable external monitoring of each voltage, current, or potential reading being taken. All terminals shall be clearly identified on the panel.

650.21.11 Output Control: Saturable reactors shall be used to provide constant current output for each circuit. Each circuit shall have its own reactor and control stack with individual adjustment so that adjustment of one circuit's output will not affect the output of any other circuit. Adjustment shall be by means of a potentiometer and voltage taps to enable smooth circuit output adjustment from 10% of maximum circuit current up to maximum circuit design current. The potentiometer shall be sized to handle 115% of the maximum RMS control winding current. The minimum capacity control stack shall be sized to provide 110% of maximum RMS control winding current with a junction temperature of 100°C. Both the control stack and potentiometer must be properly heatsinked as required to provide continuous operation at maximum control current and the ambient temperature specified. Current regulation from full load to short circuit may not exceed 115% on any circuit. The maximum hot spot temperature rise of any reactor must not exceed 75°C.

The constant current output shall remain within a range of +/- 5% of the set value over a change of resistive loading from 0.25 ohms to 2.5 ohms with the input AC voltage remaining constant. The constant current output may vary in proportion to changes in the AC line voltage input to the rectifier.

A link bar arrangement shall be provided to allow operation in constant voltage mode. When connected, the link bar will bypass the reactor, disabling constant current operation. This arrangement is to be located on the instrument panel of the rectifier and be properly labeled as to function.

650.21.12 Interrupter Connection: Provision for interrupting the input power to the rectifier with a portable interrupter shall be included. The hot line coming from the load side of the circuit breaker shall be connected to a stud and link bar arrangement. The studs are to be spaced 3 inches apart. The stud and link bar arrangement shall be "dead fronted" and labeled.

650.21.13 Wiring: All wiring and current carrying studs within the rectifier, except for meter circuits, shall be sized for not less than 500 circular mils per ampere. All current carrying bolts, terminals and connections shall be of copper, brass or bronze. Electrical connections made through the panel shall be either soldered to the bolt head or utilize the double nut method so as not to depend on the compression strength of the panel to maintain a tight connection. All connections shall be clear coated to prevent corrosion.

650.21.14 Nameplate: Each rectifier shall be provided with a stamped or engraved metal nameplate with the information shown in Figure 650-2::

Name of Manufacturer
Serial Number
AC Input Volts
No. of Phases
DC Output Volts
Maximum Ambient Temperature Designed to Operate In

Model Code
AC Input Amps
Frequency
DC Output Amps

Figure 650-2

650.21.15 Enclosure Finish: All welds shall be sanded and all sharp edges rounded before finishing. The entire enclosure shall be galvanized according to ASTM specification A123 and will have a minimum coating of 2.6 mils or 1.5 ounces of zinc per square foot of surface area. When painted, the enclosure will first be hot dip galvanized, and then all bare metal is to be chemically or steam cleaned followed by an air dry vinyl wash etching primer and a uniform undercoat of 1/2-mil of epoxy-based primer. The epoxy-base primer is to be applied over the entire surface and oven dried before applying two top coats of paint. The first top coat shall be a base enamel paint applied in a uniform coverage over the entire surface without holidays, spatter or runs. The DFT is to be 1/2-mil minimum. This coat is to be bake dried before applying the final top coat of baked enamel. The final coat shall be applied as above, bake dried and allowed to cool to room temperature before handling. The final DFT of all coats shall be no less than 1-1/2 mils.

650.21.16 Panel Material: The panel shall be constructed of 1/4-inch thick bakelite NEMA grade XX, or equal insulating material.

Panel Marking: All panel functions shall be legible and permanently labeled near the function being described using engraving techniques in the panel or bolt on engraved plates. Stick-on labels are not acceptable.

650.21.17 Remote Monitoring: A terminal block(s), suitable for connection of #18 AWG wire shall be provided to allow remote monitoring of output voltage, output current, and structure potentials of each circuit.

650.21.18 Filters: All single phase units shall include a filter. The output ripple of each circuit of the rectifier shall not exceed 5% of rated output voltage when measured at rated output voltage and current. The output ripple shall not exceed 5% of measured output voltage when measured at 25, 50 and 75 percent of rated output current. The filter must be removable, using switches and/or link bar arrangements, unless the filter is discharged completely when connected to the rated load, in less than 15 milliseconds after interruption of the input power. Choke designs shall meet the applicable requirements of the transformer specification (MIL E 917). The capacitor shall have a DC working voltage of twice the rated voltage output of the rectifier.

650.21.19 Disconnect Switch: The rectifier power input circuit shall be furnished with a switch and enclosure separate from the rectifier. The switch shall be a single-throw fuseable safety disconnect switch with solid copper neutral bus bar and shall be listed with the Underwriters Laboratory. The contractor will determine the proper switch rating required to supply the maximum voltage and current of the rectifier. The switch shall be lockable in both the on and the off positions. The switch enclosure shall be classified as a NEMA 3R type enclosure with a baked enamel finish.

650.21.20 Testing: Each completed rectifier shall be full load tested at low, high and nominal line voltage. The AC input voltage, current, ripple, watts, power factor, and the DC output voltage, current and efficiency shall be recorded at each input voltage. Each circuit shall be individually tested with all other circuits energized and loaded and the results recorded. Each circuit shall be tested for constant current at rated current output for expected variation in the load resistance (0.25 ohms to 2.5 ohms), but within the output voltage limits of the rectifier. Each rectifier or group of rectifiers shall be tested to show that they meet the requirements of this specification.

When required, testing may be witnessed by the customer at the manufacturer's location. The manufacturer shall certify compliance with the above test procedures.

650.21.21 Solar Power Supply: When section 650.30.02 so notes, the solar power supply shall be designed using the latest information concerning solar insolation for the area in which the power supply is to be installed as published by the Solar Energy Research Institute. If information is not published for the exact location of installation then the nearest location for which information is published shall be used. The array shall be sized using the least favorable mean daily direct normal insolation figures as the design parameter and shall be able to supply 120% of the maximum daily (24-hour) output ampere/hour rating of the power supply.

The unit shall include an electronic battery charge regulator set up to supply 2.35 volts per cell in series (lead acid type battery). The charge rate shall be temperature compensated at a rate of six millivolts per degree C per cell. Solderless pressure type terminals will be provided for solar array and battery connection. The unit shall include an output regulator complete with solderless pressure type terminals. Separate 50 millivolt shunts shall be provided for charge current and output current measurements. A meter shall be provided to read output voltage and current. An on/off switch shall be provided to remove the load from the output of the power supply. A blocking diode shall be installed in series with the solar array output to prevent battery leakage through the solar panels during sunless periods.

Battery capacity shall be determined by the daily ampere per hour requirement of the load as well as the minimum ambient temperature of the area of installation. Batteries shall be sized to provide a minimum of five additional days of reserve capacity and shall be maintenance free lead acid shallow discharge type. The total battery shall be sized using the 10-hour discharge rate as published by the battery manufacturer.

All current carrying power wiring shall be sized for a minimum of 1000 circular mils per ampere.

650.22 Reference Cells: The reference cells may be either silver-silver chloride or graphite. The same type of reference cells shall be furnished throughout the project. The cells shall be approved by catalog and data (2 years stability in concrete) submittals before being furnished to the project.

650.22.01 Silver/Silver Chloride: A silver/silver chloride cell shall consist of a silver metal element covered in silver chloride electrolyte and encased in a concrete compatible jacket. A single conductor lead wire shall be factory attached to the silver element. The single conductor wire shall be #14 AWG meeting 650.24 and colored black. The black conductor shall be connected to the silver element and sealed against moisture. A separate ground wire shall be supplied. It shall be #14 AWG meeting 650.24 and white in color. Both cell and ground leads shall be long enough to be routed without splices (except those housed in junction boxes) from the selected location in the deck to the terminal points in the rectifier. The manufacturer shall define the conversion factor for converting cell voltages to copper-copper sulphate equivalents.

650.22.02 Graphite Cells: A graphite reference cell shall consist of a non-impregnated graphite bar with a square cross-section of 1.5 inches (35 mm) on a side and 6.0 inches (150 mm) long with a factory attached lead wire. The lead wire shall have a firm mechanical connection to the graphite. The connection shall consist of a 3/8-inch diameter 1/2-inch long threaded brass rod with a drilled hole in the center of the rod of sufficient size to insert the lead wire. The lead wire shall be soldered to the inside of the rod. The brass rod shall be screed into the end of the graphite bar. The spaces between the lead wire, insulation and walls of the brass rod and hole shall be filled with a water tight flexible non-shrink seal. The cell shall be supplied with a #14 AWG wire meeting 650.24 and black in color. A separate ground wire shall be supplied. It shall be #14 AWG meeting 650.24 and white in color. Both cell and ground leads shall be long enough to be routed without splices (except those housed in junction boxes) from the selected location in the deck to the terminal points in the rectifier.

650.23 GROUND ELECTRODE: The grounding electrode and grounding conductor shall conform to the requirements of the NEC. In addition, the connection of the conductor and electrode shall be made with an exothermic weld. (650.27.01)

650.24 WIRE: Wire for anodes and system negatives, ground wires, and continuity bond wire used with exothermic welds shall be stranded copper conductors insulated with cross linked polyethylene listed by UL as RHH/RHW/USE or high molecular weight polyethylene of minimum insulation thickness of 3/32 inch. The conductor sizes of the anode and system negative wiring shall be as determined by the corrosion engineer in accordance with recommended practices of the NEC.

650.25 CONDUIT: The conduit for cathodic protection shall be either rigid ferrous metal or polyvinyl chloride (PVC) electrical conduit and shall include junction boxes, fittings, and attachment hardware. Rigid ferrous metal, electrical conduit and fittings shall be galvanized steel and shall conform to ANSIC 80.1, C80.4, and UL 6 for Type I rigid steel conduit. Each length of conduit shall bear the UL label. PVC conduit or EPL-40-PVC shall conform to NEMA standards Publication No. TC2 and shall be EPC-40-PVC. Conduit fittings shall meet NEMA TC3. Solvent cement for attaching fittings to the conduit shall be supplied or recommended by the conduit manufacturer.

Junction boxes used in a rigid conduit system shall be iron castings and hot-dipped galvanized in accordance with ASTM A 123 and conforming to NEMA ICS-6-Type 4 and UL 50. Junction boxes in a PVC conduit system shall be polyvinyl chloride with gasketed covers held by four screws. Junction boxes shall have a square 6 inch minimum opening and be a minimum of 4 inches deep.

Attachment hardware to attach conduit to bridge decks and abutments shall be rigid clamps formed to fit over the conduit with tables that fit flat on the deck or abutment, having holes for concrete penetrating screws or pins. Attachment hardware on a rigid conduit system shall be stainless steel or hot-dipped galvanized steel or malleable iron. Attachment hardware on a PVC conduit system shall be polyvinyl chloride coated steel and of sufficient size to allow movement of the conduit due to thermal expansion and contraction.

650.26 AC SERVICE EQUIPMENT: The material to be installed shall meet the National, State and local codes and be acceptable to the local electric company.

650.27 WIRE CONNECTIONS TO REBAR: Welding of reference cell ground wires and system negative wires to the reinforcing steel or other metal items shall be accomplished by a commercially available exothermic weld kit. Continuity bonding of discontinuous rebar may be accomplished by exothermic welding or resistance welding.

650.27.01 Exothermic Welding: The exothermic weld kit shall consist of a mold and powder charge of suitable size for the wire and reinforcing rod or item. The rod or item shall be cleaned before welding. The weld and wire shall be cleaned of oil and grease with a solvent and clean cloth. The mold shall rest on the rod or item and securely hold the wire in place. When ignited, the charge in the mold shall burn and result in a mechanically secure and electrically conductive weld of the wire to the reinforcing rod or item. The finished weld shall be cleaned of any slag. The weld and any exposed copper of the wire shall be coated. The coating for exothermic welds shall be a non-conductive, 100% solid, moisture and chemical resistant two-part epoxy paste. The epoxy shall initially cure in 20 minutes at 70°F and cure to an ultimate compressive strength of at least 8000 PSI in 24 hours at 70°F.

650.27.02 Resistance Welding: Discontinuous rebar may be bonded to continuous steel by resistance spot welding a 1/16-inch or 1/8-inch diameter steel tie wire to the steel. To make the weld, the rebar must be clean of all rust and oil. After cleaning, wrap the tie wire around the rebar when possible or lay the tie wire across the rebar, preferably on top of a rib. A resistance spot welder with modified hand tool is used to make the connection. The manufacturer's instructions shall be followed.

650.28 ANODE SYSTEM MATERIALS

650.28.01: The anode system shall be one of the following (as defined by the Owner):

- Coke asphalt: per Section 651
- Slotted system: per Section 652
- Distributed anode with overlay: per Section 653

650.29 REMOTE MONITORING SYSTEM

650.29.01 General

650.29.01.01: Supply all labor, materials and equipment necessary to furnish and install a remote monitoring system for the cathodic protection rectifier(s). The system shall consist of a remote monitoring unit (RMU), complete with integral telephone modem and operating software. The purpose of the remote monitoring system is to transfer rectifier operating data to a remote computer terminal, thus eliminating the need for monthly field inspections at the site.

650.29.01.02: The system shall monitor the status of the rectifier output voltage and current for each anode zone, and also have the capability of performing remote depolarization tests using each embedded reference cell (two per zone).

650.29.01.03: The system shall be designed for "real time monitoring" of the rectifier operating data, i.e. only the instantaneous data is transferred to the computer terminal at the time of the phone call.

650.29.01.04: The Contractor shall be responsible for supplying and installing a dedicated telephone line to each RMU, installing the RMU equipment at the rectifier site(s), and supplying operating software at the receiving end.

650.29.01.05: The remote monitoring system shall be warranted for one full year after installation or 18 months after delivery (whichever comes first) against defects in design and workmanship.

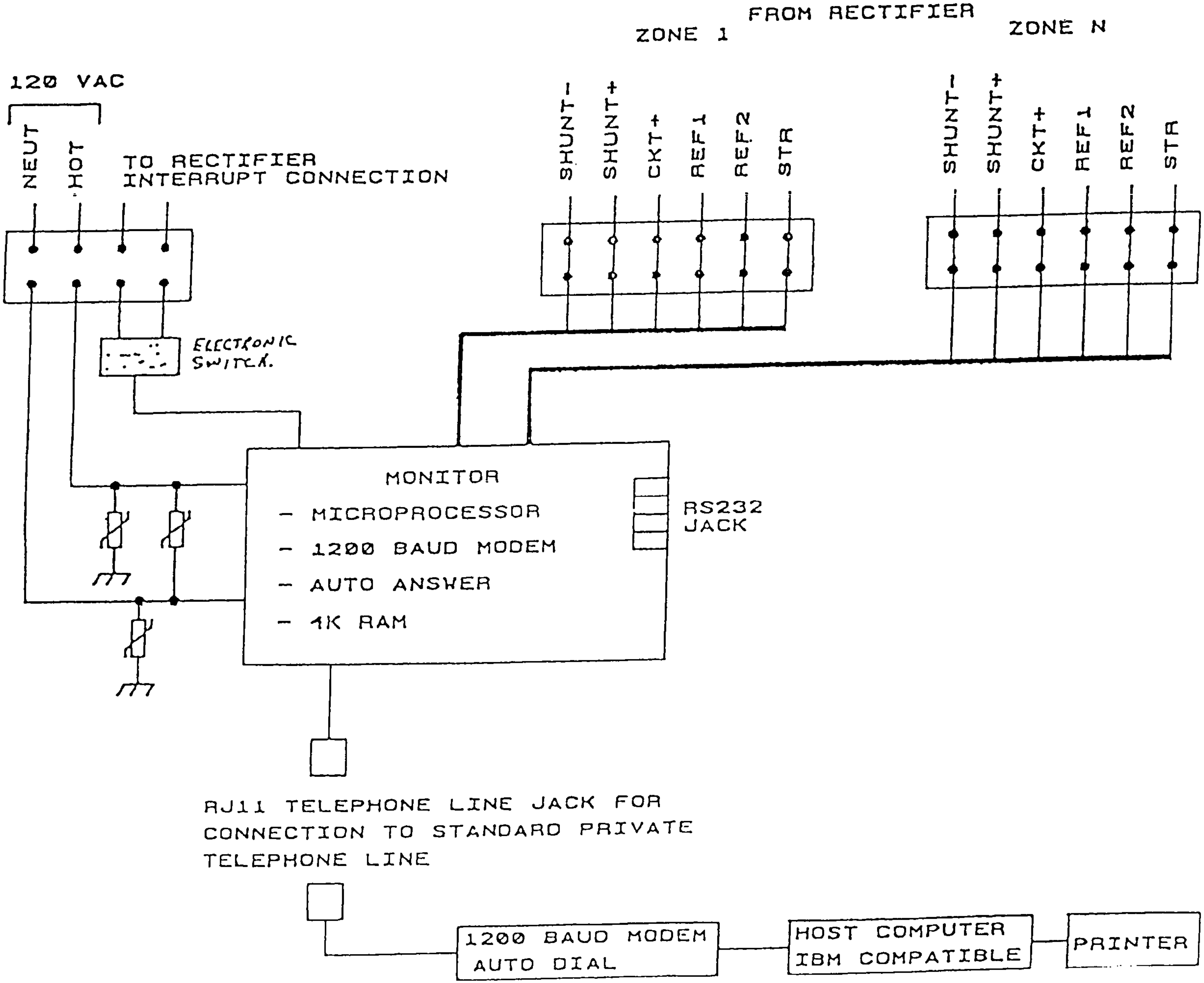
650.29.01.06: OPTIONAL: Contractor shall furnish and install computer equipment for receiving rectifier data at an office facility designated by the Owner.

650.29.02 Submittals: Prior to the installation the contractor shall submit to the Owner for approval, three sets of catalog cuts and material lists which completely detail the equipment to be supplied.

650.29.03 Hardware: A typical block diagram for the RMU configuration is shown in Figure 650-3. The system hardware shall conform to the following requirements:

650.29.03.01 *Environmental Parameters:* The RMU equipment shall be capable of operating in temperatures from -40°F to +185°F, and humidity ranging from 5% to 95% non-condensing. Printed circuit boards shall be silicon conformal coated to prevent dust and moisture intrusion. All inputs and outputs shall be provided with lightning protection.

Figure 650-3. Bridge Deck Monitor Unit



650.29.03.02 *Analog Input Parameters:* Analog input ranges for each zone shall be as follows:

- One input for measuring the anode current across a shunt capable of 0.1 amperes resolution,

- One input for measuring output voltage with a resolution of 0.1 V, and

- Two differential inputs for measuring reference cell potential data with 1 mV resolution. The input impedance for reference cell potential measurement shall be at least 10 megohms.

650.29.03.03 *Digital Output:* Should the RMU malfunction, the output current interrupt signal shall not interfere with normal operation of the rectifier.

650.29.03.04 *Data Communications:* A phone modem shall be provided with the RMU. The modem shall be capable of 1200 baud data transfer, with both answer and dial-up modes. The modem furnished shall have surge suppression and shall be fully compatible with the modem at the receiving end. The RMU shall have an integral RS-232 communications port, 7-bit ASCII, even/odd parity, and one stop bit.

650.29.03.05 *Analog to Digital Converter Resolution:* The resolution of the analog to digital converter shall be at least 10 bits (0.39%) at 0.5% accuracy.

650.29.03.06 *Timer:* The RMU shall be equipped with a timer which shall be used for depolarization tests.

650.29.03.07 *Interrupter:* An on/off interrupt "switch" shall be provided for conducting depolarization tests. The interrupt "switch" may be either electronic or electro-mechanical (relay) and must have opened the circuit within 10 milliseconds after the interrupt signal is given.

The "switch" must be capable of being driven by the monitoring unit microprocessor and shall be connected in the rectifier AC power supply as shown in Figure 650-1, Typical Rectifier Schematic.

650.29.03.08 *Data Storage:* The RMU shall have sufficient non-volatile CMOS RAM memory to store one set of depolarization values for each reference cell as specified under the "Software" Section. Storage for 500 total reference cell potential readings shall be provided (4 Kb minimum). The default setting shall be one per hour for 24 hours.

650.29.03.09 *Software:* The RMU shall be equipped with software which will enable the RMU to respond to commands and queries from the remote computer terminal as specified under the "Software" Section.

650.29.04 AC Power: The RMU and phone modem shall be powered by the rectifier 120 VAC power supply. If 220 VAC is used, a step down transformer shall be supplied.

650.29.05 Enclosure: The RMU may be mounted in the rectifier cabinet, if space is available, or installed in a separate RMU enclosure adjacent to the rectifier unit. The RMU enclosure shall have a NEMA 4 rating, with hinged gasketed cover and padlock feature. The enclosure shall be provided with mounting attachments and hardware. All exterior hardware shall be installed in conduit. Separate conduits shall be used for AC power and control wiring.

650.29.06 Wiring: All wiring interconnecting the RMU with the rectifier shall be Teflon insulated #18 AWG stranded copper wire. All other wiring used in the monitoring system shall be Teflon insulated #22 AWG. Cables providing AC power to the RMU shall be designed and installed to meet the National Electric Code. Wiring shall be neatly installed and secured within the enclosure using plastic wire ties.

650.29.07 Software: The software for the personal computer (PC) at the receiving end shall be user-friendly and easy to operate.

650.29.07.01 ***Telephone Dialing:*** The software shall have the capability of automatically dialing the RMU modem(s) from a phone number. The phone number file shall have the ability of being maintained and changed easily. For security purposes, a specific password will be required to access data at the RMU. The software shall have the capability of calling the RMU at any preselected date and time in the unattended mode. If the communication link cannot be established or the information received is not intelligible, the call shall be reiterated a maximum of three times. If after three tries data is still not received, an "error" message shall appear in the data file for that specific unit.

650.29.07.02 ***Data Storage:*** After dialing the RMU telephone number, the PC shall collect the rectifier operating data and store the information collected in an ASCII file. The data collected shall be accessible for use by other software programs. The software shall offer an option to print or store information as it is received.

650.29.07.03 ***Routine Monitoring:*** For routine monitoring the system shall measure the rectifier output voltage and current for each anode zone. Data files shall have a structure identification code, as well as the date and time that information is received. See Figure 650-4.

Structure: 1242
Date: 11/1/90
Time: 1:00 AM
Zone 1: Volts ____, Amps ____
Zone 2: Volts ____, Amps ____
Zone 3: Volts ____, Amps ____

Figure 650-4

650.29.07.04 ***Depolarization Testing:*** The depolarization test procedure shall be initiated by the PC. The software shall transmit a control character to the RMU which allows the rectifier output to be interrupted. The rectifier shall remain off until another control character is received from the PC or a period of 24 hours has passed, after which the rectifier is turned back on.

During the interrupted condition, the reference cell potentials shall be monitored on an hourly basis and the data stored in the local RAM for later retrieval by the PC. A separate control character shall retrieve the stored data. All data files shall have the structure identification code, as well as the date and time the test was initiated. The sequence for the depolarization test shall include the measurement of each reference cell "on" potential, IR free "instant off" potential, 1 hour off potential and so on. See Figure 650-5.

Structure: 1242
Date: 11/1/90
Start Time: 8:00 AM
Zone 1, RC1: "On" ____ mV
"Instant Off" ____ mV
1 Hr. off ____ mV
2 Hr. off ____ mV
3 Hr. off ____ mV
Etc.

Figure 650-5

The IR free "instant off" potential shall be measured between 100 and 1,000 milliseconds after the interrupt "switch" is opened. After the depolarization test has been completed and the rectifier is turned back on, the date, time, and voltage and current output for each zone shall automatically be recorded to verify system operation.

650.29.08 Dedicated Telephone Line: Contractor shall arrange for the supply and installation of a dedicated telephone line to each RMU. The telephone line installation and materials shall be in accordance with local utility and DOT standards. The Owner will pay for monthly telephone charges; however, the contractor shall be responsible for all costs associated with the initial installation.

650.29.09 Optional Computer Equipment: The contractor shall furnish and install a personal computer (PC) at an office facility designated by the Owner. The following equipment shall be provided:

- 386 100% IBM compatible computer, with keyboard, EGA color monitor, 1 Mb RAM, 2 serial ports, 1 parallel port, system clock with battery backup, 40 Mb hard disk drive, and 1.44 Mb 3 1/2-inch floppy disk drive.

- 200 baud Hayes compatible modem and all related communications software.

- Epson LQ 850 printer or equivalent.
- All cables required for complete operation of the system.
- One carton of printer paper suitable for the furnished printer.
- MS DOS 3.3 (or higher) operating system.

650.30 DESIGN AND CONSTRUCTION REQUIREMENTS:

650.30.01: The contractor shall design the cathodic protection system in accordance with these specifications and the selections of Section 650.30.02. The responsible design professionals shall meet the qualifications of 650.42 and shall sign the drawings and calculations. Five copies of detailed design and shop drawings, submittals, and appropriate calculations supporting the design shall be submitted to the Owner within 30 days of project start. Construction shall not begin until approval is received from the Owner in writing.

650.30.02 Design Specifics:

- Anode System (Owner will designate option(s)):

  651 Coke Asphalt ______

  652 Non-Overlay Slotted ______

  653.1 Conductive Polymer Mounds and Overlay ______

  653.2 ELGARD 150/210 Mesh and Overlay ______

- Rectifiers (Owner will designate options):

  Number of Rectifiers: #______

  Contractor Recommend: ______

  Cabinet: NEMA 3R ______

  NEMA 4 ______

  NEMA 4X ______

  Contractor Recommend: ______

Mounting: POLE _____

WALL _____

BASE _____

Contractor Recommend: _____

- Cabinet Material (Owner will designate one):

Stainless Steel (standard): _______

Hot Dip Galvanized Steel: ______

Paint Over Galv. _____ Color: _____

- Individual Circuits (24V, 10A each): Owner will designate number or contractor recommendation:

Total Number _____

Contractor Design _____

- Power Supply Type (Owner will designate one):

Rectifier - Constant Voltage/Constant Current Saturable Reactor _____

Solar Power _____

- Meters (Owner will designate one):

Contractor Recommend: ______

Combination Volt/Amp - Analog: _____

Separate Volt and Ammeter-Analog: _____

LCD Digital: _____

LED Digital: _____

NONE: _____

- Remote Monitoring (Owner will designate yes or no):

YES _____,
if YES- also supply office computer _____
(yes or no)
NO _____

650.30.03: All cathodic protection system designs shall meet the following criteria:

- Maximum Zone Size = 6500 square feet
- Design Current Density = 1.5 mA per square foot of deck surface
- Minimum of two anode leads per zone
- Minimum of two system negatives per zone
- Two embedded reference cells and corresponding rebar grounds per zone.

650.30.04: The anode system design designated in 650.30.02 shall meet all other requirements of these specifications and 651, 652 or 653 as applicable.

650.30.05: The contractor shall field measure all dimensions during construction and accurately record the dimensions on as-built drawings.

650.30.06: The contractor shall provide 8 copies of a project specific operation and maintenance manual. Items to be included as a minimum are:

- System Operating Procedures
- System Maintenance and Repair Procedures
- Rectifier Maintenance Log Sheets
- System Troubleshooting Guidelines
- Product Data Sheets
- As Built Drawings

650.30.07: The design professionals of item 650.30.01 and the manufacturers' technical representatives for all materials and components shall be available for consultation with the Owner by telephone upon request.

650.30.08: The contractor shall provide a technically qualified installation supervisor at the jobsite during all phases of the work.

650.31 RECTIFIER CONSTRUCTION REQUIREMENTS: The contractor shall install the rectifiers at locations approved by the engineer. The contractor shall furnish and install all hardware, brackets, poles and concrete necessary to mount the rectifier. If pole-mounted, the pole shall be embedded 3 feet in concrete. The rectifier shall be mounted at a comfortable working height for an average size person.

The contractor shall supply bronze padlocks to secure each rectifiers and each disconnect switches in the **ON** position and to prevent opening of the switch enclosure. All locks supplied on the project shall have the same key as the rectifier enclosure lock.

When solar power supply is required by the plans, the contractor shall determine the number of panels and batteries required in accordance with 650.21 and shall furnish and install the panels, panel mounting, and batteries. A power service disconnect switch shall not be required when solar power is required.

650.32 REFERENCE CELL CONSTRUCTION REQUIREMENTS: The contractor shall furnish and install two reference cells meeting 650.22 in each zone. Each cell shall be installed in an area of sound concrete which has half-cell readings in the highest (i.e. most negative) 10% of all readings in the sound concrete areas. Perform the half-cell survey after all patching has been completed in accordance with ASTM C876 and the reference cell sites shall be located by the contractor's corrosion engineer per section 650.43.02D.

At each site, the contractor shall excavate a slot between reinforcing bars about 3 inch wide, 7 inch long and 2 inch deep at the selected cell location. The excavation shall not expose reinforcing steel. The reference cell shall be placed in the bottom of the excavation following the manufacturer's recommended installation guidelines. The contractor shall drill an access hole in the excavation through the deck and into a junction box conduit system attached to the bottom of the deck. The reference cell lead wire shall be routed through the access hole and conduit system to the rectifier. The contractor shall attach the ground wire supplied with the reference cell to the reinforcing steel. The ground wire shall be attached by an exothermic weld meeting 650.27.01. The ground wire shall be attached 2 to 5 feet from the reference cell. The contractor shall perform all necessary excavation for the ground connection and provide an access hole to a junction box and conduit system attached to the bottom of the deck. The contractor shall route the ground wire through the junction box conduit system to the rectifier.

The contractor shall backfill the reference cell and ground wire sites with <u>salt-free</u> patching concrete (without purposeful addition of chloride unless otherwise recommended by cell manufacturer) to the level of the deck surface. After the backfill concrete is cured, the contractor shall measure the AC resistance and half-cell potential of each cell and ground wire circuit. Resistance readings shall not be more than 10,000 ohms and potential readings shall not be erratic (shall not vary by more than ± 0.02 volts in 10 minutes). If unacceptable readings are obtained, the contractor shall replace each unacceptable reference cell with a new cell.

650.33 GROUNDING ELECTRODE: The contractor shall install a grounding electrode system, no portion of which should be above 24 inches below the ground line. The electrode installation must conform to all applicable provisions of NEC, and must have a resistance to ground of less than 25 ohms.

Resistance to ground shall be measured by a commercially available ground tester which utilizes two reference ground rods and a Wheatstone bridge circuit with a null balancing meter. The ground tester shall be calibrated no more than 180 days before the earth resistance measurement.

The ground wire shall be attached to the top of the ground rod by exothermic welding and routed through 1/2-inch conduit to the rectifier cabinet where it shall be connected by a grounding lug to the cabinet. The exothermic weld shall be covered with epoxy meeting 650.27.01. The opening of the conduit shall be sealed.

650.34 WIRING CONSTRUCTION REQUIREMENTS: The contractor shall furnish and install the wiring for cathodic protection in the conduit junction box system between the bridge elements and the rectifier. All attachments to the reinforcing steel shall be by exothermic welds meeting 650.27.01. All connections to the anodes shall be by splice in a junction box or where permitted by the anode type by an approved splice or connection on the deck. The installed wiring shall run continuously from the anode or reinforcing steel to the rectifier terminal without splices (except in junction boxes with approved splice kits) or damage to the insulation. The contractor shall demonstrate to the engineer that the wiring is free of shorts and breaks. The wiring size shall be as determined by the corrosion engineer.

Electrical materials, equipment, and installations shall be in accordance with the current edition of the National Electrical Code and the National Electrical Safety Code.

All DC wiring terminated in junction boxes or at the rectifier shall be labeled with pre-marked heat shrink labels. A system wiring diagram with all wire labeling indicated shall be furnished to the Engineer.

650.35 CONDUIT CONSTRUCTION REQUIREMENTS: The contractor shall furnish and install conduit and junction boxes with hardware and concrete penetrating pins or expansion bolts in drilled holes to securely attach the conduit junction box system to the deck and abutment to route the anode, system negative, and reference cell wiring from the deck to the rectifier. Conduit routed underground shall be placed in trenches at least 2 feet deep and no more than 12 inches in width and backfilled. Changes in conduit direction of 90° or greater shall be accomplished by use of fittings with removable covers. Conduit diameter and routing shall be in compliance with NEC. Junction boxes shall be installed at each access hole on the bottom of the deck. A junction box shall be installed when the conduit changes in direction totalling 180°. Rigid conduit shall be attached to the deck and abutment with junction boxes and attachment hardware. The conduit shall be attached within 3 feet of each junction box or fitting and at least every 10 feet. Conduit connections between the bridge deck and abutment shall be flexible conduit or expansion coupling to allow for the thermal movement of the deck.

PVC systems shall be installed with at least one expansion coupling between junction boxes or other fixed points. Expansion coupling capable of a 6-inch maximum expansion shall be installed for every 100-foot length of conduit. For conduit runs of 35 feet or less, a 2-inch maximum expansion coupling may be installed. Expansion couplings are specified to compensate for temperature variations of 155°F (-35°F to +120°F). When installed at the lowest anticipated temperature, the coupling shall be adjusted proportionately. PVC systems shall be supported with attachment hardware within 3 feet of a junction box or other fixed point and at the maximum spacing shown in Table 650-2.

Table 650-2

Conduit Diameter (in.)	Attachment Spacing (ft.)
1-1/2	5
2	5
2-1/2	6
3	6
3-1/2	7
4	7

650.36 AC SERVICE: The disconnect switch shall be installed in the incoming electrical power circuit. The switch shall be mounted within 5 feet of the rectifier. The contractor shall furnish and install all necessary wiring and conduit from the utility power source identified in the plans to the disconnect switch and then to the rectifier. The completed electrical power service shall be installed in conduit buried at least 24 inches in soil where possible, and shall be installed in accordance with codes and electrical utility company requirements. The contractor shall select the size of wire and conduit appropriate for the anticipated maximum current load. The contractor shall furnish and install any equipment required by the utility company for connection of the power circuit to the electrical service.

650.37 CONTINUITY BOND CONSTRUCTION REQUIREMENTS: The contractor shall determine the electrical continuity of all steel rods in the top layer of bridge deck reinforcing steel and the continuity of scuppers, end dams, railings, and other similar metal items to the reinforcing steel. Electrical continuity exists between reinforcing bars or between reinforcing bars and other metal items when the millivolt difference between them is no more than 1.0 mV when measured with a high impedance (10 megohm minimum) voltmeter with a resolution of 0.1 mV. The meter shall be calibrated no more than 180 days prior to use. All bars in the top layer of reinforcing steel within a zone shall be considered continuous when the voltage differences between a minimum of six contact points on the perimeter reinforcing steel (within areas bounded by expansion joints) all show continuity. The points shall be located at the corners and middle of each deck area bounded by expansion joints.

The contractor shall locate all electrical discontinuances in the reinforcing steel and shall establish continuity by installing continuity bonds between all points of discontinuity. Discontinuities between the reinforcing steel and other metal items shall be located and bonded. A continuity bond shall consist of a #12 AWG wire welded to the two discontinuous items and embedded in the deck. The wire shall meet 650.24 and the welds shall meet 650.27. The contractor shall remove concrete as necessary to perform the continuity testing and install the bonds so that the wire and welds are embedded when the excavation is backfilled with concrete. The contractor shall backfill all continuity bond excavations with concrete to the level of the deck surface. After backfilling of the bond excavations, the contractor shall confirm the establishment of continuity by repeating the millivolt difference measurement.

650.38 ANODE SYSTEMS: Anode system construction shall be in accordance with the following, as appropriate:

Coke-asphalt: per Section 651

Slotted system: per Section 652

Distributed anode with overlay: per Section 653

650.39 REMOTE MONITORING CONSTRUCTION REQUIREMENTS: The contractor shall install the remote monitoring system at locations approved by the engineer. The contractor shall furnish and install all hardware, brackets, poles, software and telephone lines necessary for a fully functional remote monitoring system.

650.39.01 DOCUMENTATION AND TRAINING: Two (2) bound copies of a detailed operation and maintenance manual shall be provided. The manual shall include schematics of all circuitry, functional block diagrams, parts list and software tutorial. The contractor shall provide one (1) day of training to the Owner's personnel in the operation of the remote monitoring system.

650.40 CORROSION ENGINEERING SERVICES:

650.41 GENERAL: The contractor shall furnish the services of a consulting engineering firm specializing in the field of corrosion control for steel reinforced concrete bridge decks and substructures. This firm shall provide the engineering personnel and services detailed below for this bridge rehabilitation project. The corrosion engineering firm will report directly to the State Bridge Project Engineer (BPE), or the BPE designated representative. The corrosion engineering firm or their subsidiaries shall not be engaged in the manufacture or supply of corrosion control materials or equipment under this contract.

Each contractor shall provide the name of the corrosion engineering firm and the personnel to be assigned (names & resumes) proposed for work on this project as a part of the bid submission documents.

650.42 LEVELS OF EXPERTISE: The corrosion engineering firm shall provide the following levels of expertise on the project:

Project Principal Corrosion Engineer (PPCE): The PPCE shall be a Registered Professional Engineer or a National Association of Corrosion Engineer's (NACE) certified Corrosion Specialist or certified Cathodic Protection Specialist. The PPCE shall have a minimum of at least 8 years experience in corrosion investigation and evaluation, corrosion control system design, system installation, inspection, and commissioning of cathodic protection on steel reinforcing in concrete bridge structures. The PPCE shall be directly responsible for all corrosion engineering services provided by the consulting firm on the project and shall supervise and review all work performed by the project corrosion engineer(s). The PPCE shall review all corrosion control drawings and submittals detailing the system and equipment proposed for use on this project by the contractor. The PPCE shall be responsible for evaluating the performance of the installed corrosion control system and shall provide recommendations for long-term operation and maintenance. All conclusions and recommendations made by the PPCE shall be communicated in writing (verbal communication shall be confirmed in writing) to the BPE.

Project Corrosion Engineer (PCE): The PCE(s) shall have a minimum 5 years corrosion engineering experience as defined above on steel reinforced concrete structures and/or 10 years experience in evaluation of steel reinforced concrete structures. The PCE(s) shall also have served as the Project Engineer on at least one project of a similar magnitude and scope of work. If, due to the size of the project, more than one PCE is requested by the BPE during any phase of the rehabilitation work, the PPCE shall designate the segments of the project for which each PCE will be directly responsible.

The PCE(s) shall be "on-site" to supervise and/or perform all corrosion control inspection and testing required by the project specifications, and during all construction phases involving the installation of corrosion control system components which are permanently embedded in the concrete structure (e.g. anode systems, reference electrodes, and placement of cementitious overlay or grouts on anode materials). The PCE(s) shall evaluate and provide expert opinion (with review as necessary by the PPCE) to the BPE on all field modifications, additions or deletions proposed by the contractor for the corrosion control system(s). The PCE(s) shall perform or directly supervise the work of the corrosion engineering technicians.

Copies of all test data and written communications made by the PCE(s) involving the corrosion engineering work on this project shall be provided jointly to the PPCE and the BPE.

Corrosion Engineering Technician (CET): The CET(s) shall assist the PCE(s) in accomplishing field inspection and performing half-cell potential, electrical continuity, delamination and depth-of-cover testing, as well as commissioning of the corrosion control systems. The CET(s) shall have a working knowledge of, and at least 1 year of similar experience in performing the testing and inspection work required on this project.

Documentation of experience for PPCE, PCE and CET shall be submitted to the BPE.

650.43 ENGINEERING SERVICES: The consulting corrosion engineering firm shall provide the following services:

650.43.01 SUBMITTALS: Prepare the detailed design in concert with the Owner, the contractor and his material suppliers and in accordance with these specifications. Prepare and sign shop drawings showing anode layout, conduit and wiring, rectifier location and all details of this CP installation. Review all project corrosion control system drawings and submittals for compliance with the project specifications and good corrosion control practice on behalf of the Owner. The review shall include:

- CP system design
- Anode material and layout
- System DC power and monitor wiring and connections
- Embedded reference cells and grounds
- DC power and monitor conduit and junction boxes
- Rectifier power supply and controller

- Remote monitoring system
- All other miscellaneous corrosion control components

A signed written report detailing the conclusions and recommendations for the overall design and each submittal shall be submitted to the BPE.

650.43.02 On-Site Testing/Inspection: Any system component or device found to be defective or not in compliance with the project specifications by the PPCE or PCE during the bridge rehabilitation project shall be immediately replaced by the contractor, at the contractor's expense, if directed to do so by the BPE.

The following tests and inspection services shall be provided:

A. Continuity Testing - Electrical continuity tests shall be performed in accordance with 650.37 to ensure that steel reinforcing bars (both top and bottom mats) and all other embedded, or partially embedded metallic fixtures within each corrosion control zone are electrically continuous. This testing shall be performed on all bars exposed by the contractor during the project delamination removal process and on such other bar and metal embedments determined jointly by the PCE and the BPE as being necessary. Steel components which are determined to be electrically discontinuous shall be made continuous by the contractor in accordance with the project specifications.

Any embedded steel which was formally determined to be electrically continuous and then is made discontinuous by the contractor during the project repair and rehabilitation process shall be repaired by the contractor, using the method(s) provided for in the specifications at no cost to the Owner. Final determination as to the event which caused the discontinuity shall be made solely by the BPE.

B. Delamination Testing - A delamination survey shall be conducted utilizing the "chain drag" method. The boundaries of the delaminations will be marked by spray paint. This testing shall be performed on the entire deck to identify areas for patching.

C. Depth of Cover - The PCE or the CET shall randomly test the entire deck for depth of cover using a pachometer, rebar/metal locator or other similar equipment. This testing is to be performed after patch repair work and prior to anode placement. Minimum cover requirements and repair process to maintain these requirements shall be in accordance with the project specifications.

D. Technical Assistance During Construction - Field locate all embedded reference cells and rebar grounds. While the PCE is encouraged to provide technical assistance to the contractor during installation of the corrosion control system, this shall in no way relieve the contractor from his contractual obligations. Further, the PCE shall only lend assistance if it does not interfere with or extend the time necessary for performing the corrosion engineering technical services provided for in these specifications.

E. Inspection and Testing of Reference Cells - After all reference cells have been installed, and prior to any anode placement, each corrosion monitoring device shall be tested to determine if the device is functional as designed, per 650.32. Any monitors (or associated ground connections) which are determined to be defective shall be immediately repaired or replaced, if so directed by the BPE, at no cost to the Owner.

F. Anode/Steel Electrical Isolation Testing - Testing performed will depend on the type of corrosion control system installed:

- Rigid Conductive Polymer Anode Systems (in concrete overlays) - After the initial cure of the conductive polymer and before overlay placement (minimum 4 hours), testing shall be performed to ensure that the anode material is electrically separated from any embedded steel and to assure normal system performance. Any shorts or near shorts detected shall be cleared by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner.

- Pre-fabricated Anode Systems - Just prior to and during placement of the concrete overlay material, the anode system shall be tested and monitored to ensure that the anode material is sufficiently electrically separated from any embedded steel and to assure normal system performance. Any shorts or near shorts detected shall be cleared by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner.

- Slotted Systems - The anode system shall be tested and monitored after anode (and any slot filling materials) placement is complete to ensure that the anode material is sufficiently electrically separated from any embedded steel and to assure normal system performance. Any shorts or near shorts detected shall be cleared by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner.

G. System Energization, Testing and Adjustment - Upon completion of the corrosion control system installation, all electrical wiring, system power supplies, etc. will be checked for proper installation. Any defects detected shall be corrected by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner. Once this task is complete the system will be energized. The system shall be energized and adjusted in accordance with the E Log I and/or Depolarization Testing and Analysis procedures given in NACE Standard RP0290-90, Item No. 53072, "*Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*", approved April 1990. If E log I procedures are not used to define the initial operating parameters, the system shall be activated at 75 to 100 percent of design current for each zone, as determined by the PPCE and PCE. As a minimum, two anodic locations per zone shall be tested.

- E Log I Testing - The E Log I tests, when used, shall be performed on each zone as follows:

  -Prior to applying current to the anode material, record the potential values for all reference electrodes and the zone number, ambient temperature and deck condition (wet, dry, etc.)

  -The protection current shall be increased at approximately 3-minute intervals. The initial current applied shall be no greater than 1% of the anticipated protective current required. Sizes of current increments shall be determined by the PCE, depending on the shifts in steel potential at prior current increments, but shall not result in an average shift of more than 15 mV per current increment.

  -Just prior to increasing the protection current, the PCE shall record the following data at each current increment; 1) Applied current (A), 2) Instant "Off" potential of reference cell (mV), and 3) Voltage between the anode and reinforcing steel (V).

  -The PCE shall determine the initial current requirements based on analysis of the E Log I test data. The system shall be adjusted for continuous operation based on the E Log I test results and analysis.

- Depolarization Testing - After polarization of the reinforcing steel has occurred as a result of the applied protection current for a minimum of 30 days, a depolarization test shall be performed on each zone by the PCE and CET(s) as follows:

-Prior to initiating depolarization tests, measure and record the following:

- Zone number
- Ambient temperature (°F)
- Deck condition (dry, wet, etc.)
- Operating voltage (V)
- Operating current (A)
- Reference cell potential "on" (mV)

-Measure and record the "Instant-off" potential for each reference cell of each zone at the start of the test period.

-Measure and record all reference electrode-to-rebar potential data at a minimum of every 1, 4 and 24 hours.

-The PCE shall calculate and record the depolarization value and analyze the data. The system shall be adjusted to provide the optimum level of corrosion control based on results and analysis of the depolarization test. As a minimum, 100 mV of depolarization is desired on all embedded reference cells.

H. Final Report - This report, signed by both the PPCE and PCE, shall include all test data, analysis of data and operating settings, with conclusions and recommendations for long term system operation and maintenance.

I. Training of Owner's Personnel - The PCE shall conduct one 8-hour training course at the project site regarding the operation and maintenance of the cathodic protection system. The PCE shall provide 8 system operating manuals per 650.30.06 which shall be available for use by the personnel present at the training session.

650.50 METHOD OF MEASUREMENT: The cathodic protection system shall be measured and paid for as described below:

650.50.01 RECTIFIERS: Rectifiers shall be measured when installed in place, including AC disconnect switches and grounding electrical, and demonstrated to be operational. Unit of payment will be on a per unit (each) basis.

650.50.02 REFERENCE CELLS: Reference cells shall be measured when installed in place and demonstrated to be operational. Unit of payment will be on a per unit (each) basis.

650.50.03 WIRING: Wiring and conduit will be measured when installed in place. This item includes all conduit, junction boxes, AC service equipment, positive and negative cables, reference cell cables. All equipment must be demonstrated to be operational and ready for commissioning. Unit of payment will be on a lump sum basis.

650.50.04 CONTINUITY BONDS: Continuity bonds will be measured when installed where required and demonstrated to be operational. Unit of payment will be on a per unit (each) basis.

650.50.05 ANODE SYSTEMS: Anode systems will be measured when furnished and installed in place and demonstrated to be operational. The protected deck area will be the area bounded by the anode and extending 6 inches outside the anode area or to any exposed steel closer than 6 inches from the anode. Unit of payment will be on a square yard of deck installed basis.

650.50.06 CORROSION ENGINEERING: Detailed design shall be preformed, construction services shall be provided and the entire system shall be activated, checked and adjusted and demonstrated to be operational within the parameters set forth in this specification. Unit of payment will be on a lump sum basis, with progress payments as shown in table 650-3.

650.50.07 REMOTE MONITORING: The remote monitoring system as described herein shall include the supply and installation of the remote monitoring unit, modem, enclosure (if applicable), wiring and conduit, telephone line, AC power to the RMU, software, documentation, testing, training and computer equipment (if applicable). The remote monitoring system shall be bid as a lump sum.

650.60 BASIS OF PAYMENT: The accepted quantity for cathodic protection will be paid at the contract unit price when completely in place, tested, and accepted. Payment will be as shown in Table 650-3.

Table 650-3

Pay Item	**Pay Unit**
Cathodic Protection Rectifier	Each
Reference Cell	Each
Wiring	L.S.
Continuity Bonds	Each
Anode Systems	Sq.Yd. Deck
Corrosion Engineering	L.S. per listing below:
Section #'s	Progress Payments, % of Lump Sum
650.43.01	25%
650.43.02 A thru F	50%
650.43.02 G thru I	25%
Remote Monitoring	L.S.

651. COKE ASPHALT CATHODIC PROTECTION SYSTEM

651.10 DESCRIPTION: This bridge deck cathodic protection system employs a layer of conductive asphalt on the concrete deck surface, powered by high-silicon, cast-iron anodes. This work shall consist of one course of conductive asphalt concrete, containing coke breeze aggregate, and one course of conventional bituminous mixture constructed as a wearing course.

The asphalt surfacing of the system provides a good riding surface, is suitable for any deck geometry, and can be applied to decks with active cracks. The service life of the systems is generally limited by the life of the wearing course and for this reason, all cathodic protection hardware is embedded in the deck concrete to allow removal and replacement of the asphalt layers without damage to anodes, instrumentation, or system wiring. An important factor to consider in selection of structures in cold regions for repair with this system is the adequacy of the concrete air void system. The conductive asphalt mix is porous and has a tendency to retain moisture on the concrete surface. If the moist concrete is not properly air-entrained, and is subject to frequent freeze-thaw cycling, deterioration of the concrete may be accelerated.

651.20 MATERIALS:

651.21 ANODES: Anodes shall be DURCO Pancake Bridge Deck Anodes Type I manufactured by the Duriron Company, Inc. or equivalent.

Anodes shall be supplied with a lead wire attached. The length of wire attached shall be sufficient to reach from the anode to the curb without splicing. The connection between the lead wire and anode shall be secure and shall be sealed to prevent moisture ingress.

651.22 ELECTRICALLY CONDUCTIVE MIX: Coarse and fine aggregates shall conform to the requirements of AASHTO M43, grading #67 (coarse) and AASHTO M29, grading #1 (fine).

Coke breeze shall be produced from coal or shall be calcined petroleum coke breeze. Coke breeze produced from petroleum refining which is non-heat treated (non-calcined) is not acceptable. When Option "B" is utilized, the moisture content of the coke breeze to be used in the mix shall not be more than 1 percent by mass. Coke breeze shall meet the gradation shown in Table 651-1:

Table 651-1

Sieve Size	**% Passing**
3/8"	100
no. 3	92-100
4	80-85
8	57-82
16	40-65
30	27-48
50	14-30
100	5-15
200	3-8

Asphalt cement shall be penetration grade (85-100 or 150-200, depending on local availability and as defined by the Engineer), or viscosity grade equivalent approved by the Engineer.

Composition of the Mixture:

The mix proportions shall be as shown in Table 651-2:

Table 651-2

Material	**% by Mass**
Coke Breeze	45
Coarse Aggregate	40
Fine Aggregate	15
Asphalt Cement (% of Aggregate Mix)	15

The actual proportions shall be confirmed by mix design. With one composition of the aggregate and coke breeze conforming to the requirements of ASTM D 3515, 3/4 inch Mix (Table 1 - Dense Mixtures). The mix voids shall be set at 3%. The quantity of asphalt required is determined by multiplying the AC content specified in the contract by the actual amount of electrically conductive mix placed. The approved mixture shall have the following properties: Marshall stability (1200 min.) and Flow (6-16).

Resistivity:

The mix shall have a maximum resistivity of 3 ohm-cm when tested in accordance with 650A.C.02.

651.23 WEARING COURSE MIX: The materials and their use shall conform to the requirements of subsections 401.2 through 401.08. The composition shall conform to the requirements of ASTM D 3515, 1/2 inch or 3/8 inch Mix (Table 1 - Dense Mixtures).

651.24 VOLTAGE PROBES: Voltage probes shall be graphite reference cells in accordance with 650.22.02. A minimum of one probe per 6,500 square feet shall be provided.

651.30 DESIGN AND CONSTRUCTION REQUIREMENTS: The system shall be designed and constructed in accordance with this section. This work shall not commence until repairs to the bridge deck have been completed either fully or in sections, as approved by the engineer.

651.31 DECK ENTRY: A deck entry hole of 100 millimeters (4 inches) diameter shall be drilled through the deck at the locations indicated in the contract drawings. A 75 millimeters (3 inches) diameter PVC conduit end bell and support mechanism shall be installed and grouted in place as indicated. Care shall be taken to ensure that any leaking through these holes will not contact substructure elements.

651.32 ANODES: Anodes shall be placed in recesses on the deck surface. Anode spacing and other design requirements are as follows:

- Maximum anode spacing = 25 feet.
- Maximum deck area protected by one anode = 800 sq. ft.
- End anodes located no more than 10 feet from the deck end and each interior joint.
- Arrange anodes in "lines" of several leadwire connected strings. Each anode string shall typically contain 3 to 4 individual anodes and it is desirable that the feeder lines supply power to anodes which are widely separated on the deck (so that, in the event of loss of power in one feeder line, a large section of the deck is not left entirely without protection).
- When possible, the anodes shall be located in the curb areas of the deck.
- Additional information and typical designs are provided in SP-017, "Bridge Deck Rehabilitation Manual, Part Two: Contract Preparation", Ontario Ministry of

Transportation and Communications, April 1984.

The base and sides of each anode shall be given two coats of epoxy resin applied not less than 24 hours before the anode is to be placed in the structure.

Adhesive tape shall be applied to the top face of the anode before the anode is placed to protect the anode surface during installation. The adhesive tape shall be removed immediately prior to placement of the coke-mix.

Anode locations shall be accurately marked on the deck as indicated on the drawings. A pachometer shall be used to determine reinforcing bar locations. The final anode location may be moved up to 150 millimeters (6 inches) in any direction such that the minimum number of reinforcing bars will have to be cut in making the recess for the anode. Where the concrete cover over the reinforcing bars is greater than 50 millimeters (2 inches), the anode recesses do not require the cutting of reinforcing bars.

Anode recesses shall be cut by either of the following methods to provide a recess of 50 millimeters (2 inches) deep with as smooth a bottom as practical:

- Use a core drill and remove with a jackhammer; cut the reinforcing steel flush with the hole walls with a cutting torch; or use a concrete saw to form a square and remove the concrete within the square with a jackhammer. Cut the reinforcing steel, as above.

Immediately after cutting the anode recess, the ends of any cut reinforcing bars at the edges of the recess shall be coated with a thick layer of epoxy paste. Care shall be taken to cover all exposed steel.

The anode wire slot shall be cut from the anode recess to the curb as indicated in the drawings. All dust and debris shall be removed from the anode recess, and a 12 millimeters (1/2-inch) thick bed of epoxy paste shall be placed in the bottom of the recess. The anode shall be placed in the recess, and supported on non-conductive spacers to prevent settlement in the epoxy paste.

Spacers of glass, plastic, or other insulating materials shall be used; wood or metal spacers shall not be used. The anode shall be placed such that the top of the anode is flush with the deck surface, and the lead wire feeds directly into the slot in the deck.

It is extremely important to ensure that the anode is not in direct contact with the reinforcing steel. The resistance check (described in 651.36(1)) should be carried out at this time. If the resistance check indicates that there may be contact between the anode and reinforcing steel, the anode shall be removed and reset in fresh epoxy and the cut ends of any bars re-insulated with epoxy. The resistance check shall be repeated.

Once the resistance check for an anode indicates that there is not direct contact between the anode and the reinforcing steel, filling of the anode recess may proceed.

After the epoxy in the recess has set, the cavities around the anode shall be filled with mortar, flush with the deck. If a concrete saw was used to form the recess, all saw cuts beyond the recess shall be filled with epoxy paste, flush with the deck surface.

The anode lead wire shall be set in the slot such that it extends without splicing to the curb, and the slot shall be sealed with epoxy paste flush with the deck. It is necessary that all anode lead wires, for a given zone, come back to one rectifier output to provide redundancy.

651.33 REBAR GROUND CONNECTION: Install rebar grounds in accordance with 650.27.01.

651.34 VOLTAGE PROBES (GRAPHITE PROBE): Approximate probe locations shall be marked on the deck as indicated on the drawings. A pachometer shall be used to locate the closest reinforcing bars; the exact probe location shall be marked midway between the two bars. The probe is to be positioned such that it lies between the two bars, at the same depth as the bars, but does not contact them or any other reinforcing steel.

A recess and lead wire slot shall be cut in the deck as indicated in the drawings.

Before it is placed in the deck, the graphite probe shall be checked to ensure that the probe-lead wire connection is tight and well-sealed. If it is not, the probe shall be rejected.

A mortar bed shall be placed in the recess, the probe placed on it, and the top of the probe adjusted flush with the deck. It shall be ensured that the graphite probe does not contact any exposed reinforcing steel or anodes. Mortar shall then be used to fill the recess flush with the deck. At this time, the check described in 651.36(3) shall be carried out to ensure that the probe has been placed correctly.

Once this is done, the probe lead wire shall be placed in the slot between the recess and curb, and the slot be filled with epoxy paste flush with the deck. The exposed probe surface shall be cleaned, then covered with adhesive tape for protection. The tape shall be removed immediately prior to placing the conductive asphalt.

651.35 REFERENCE CELLS: Install reference cells in accordance with 650.32

651.36 SYSTEM CHECKS: Once anodes, ground connections, voltage probes, and reference cells are in place, the following checks shall be made and the results reported to the Engineer. These checks may be carried out as work proceeds.

1. **Anode-to-Reinforcing Steel Resistance.** The resistance between the anode lead wire at the curb, and the nearest rebar ground connection, shall be measured with an AC ohmmeter. If the indicated resistance is less than 30 ohms, a short circuit between the anode and the reinforcing steel may exist. In this case, the anode shall be removed and reset, and the reinforcing bars in the anode recess re-insulated with epoxy paste. The resistance tests shall be carried out before proceeding with connection of the anode lead wires to the anode

buses.

2. **Continuity.** The voltage between adjacent rebar ground connections shall be measured by placing a high impedance voltmeter between the ends of the lead wires. A voltage reading of 1.0 mV or less would be expected between rebar ground connections within the same physically continuous area of the deck (i.e. along the length of a single span structure, or between an adjacent joint of a larger structure). If this is the case, ground leads shall be connected to the ground bus wire and work shall continue.

Fluctuating or voltages in excess of 1 mV are indicative of a poor connection to, or a poor continuity of, the reinforcing steel, and must be investigated before work proceeds. To ensure that proper rebar continuity is achieved, the Engineer may direct that additional rebar ground connections be made. When fluctuating or non-zero voltages are measured between two rebar ground leads, the approval of the PCE is required before proceeding to connect the individual rebar ground leads to the ground buses.

3. **Graphite Probe-to-Reinforcing Steel Resistance.** The resistance between each graphite probe and the closest connection to the reinforcing steel shall be measured, using an AC ohmmeter. A resistance between the two lead wires of less than 5 ohms, could be indicative of a short circuit between the probe and the reinforcing steel, and shall be investigated before work proceeds. The voltage between the two lead wires shall also be recorded and reported.

If these checks indicate that any of the anodes or probes have been improperly placed, or connected, the contractor shall remove and replace them.

Work shall not proceed until the PCE has ascertained that all instrumentation has been installed and is operating properly, and a sufficient number of sound rebar ground connections have been provided to ensure continuity of the reinforcing steel. Once this has been done, hook-up of lead wires at the deck curb or edge may proceed.

651.37 CONNECTIONS AT CURB: The following lead wire connections shall be made at the deck's curb:

- **ANODE:** Individual anode lead wires, to anode bus (#10 Black anode lead wire to #6 Black anode bus).
- **REBAR GROUNDS:** Individual rebar ground connections to ground bus (#10 White lead wire to #6 White ground bus).
- **VOLTAGE PROBES:** Extend individual lead wires (#10 Red lead wire to #10 Red lead wire extension).
- **REFERENCE CELLS:**

  Probes - Extend individual lead wires (#10 lead to #10 Green lead wire extension).

Grounds - Extend individual half-cell ground wires (#10 White lead wire to #10 White ground wire extension).

All buses and extension wires shall be long enough to extend from the curb to the control panel without splicing.

All connections of #10 cable to #6 cable (anode and rebar grounds) shall be made with thermite weld connections. The connections shall be thoroughly electrically insulated and the connection area shall be wrapped in a double layer of electrical tape. The free end of each wire shall be labeled clearly with the number of the component as shown on the drawings. The marking system used shall be waterproof and durable.

651.38 WIRES ALONG CURB. Where wires run along the deck curb, they shall be bundled together using nylon cable ties. The cables shall be tied whenever a lead wire or bus joints the cable bundle, and at least every 10 feet along their length. The cable ties shall be fastened to the deck with an insulated anchoring device.

The anchored wire bundle shall be encased in a formed fillet strip or air-entrained concrete.

Care shall be taken not to impede the drainage of the deck surface by improper placement of the wire bundle and protective strip. Where bundled wires must be routed around deck drains which are adjacent to the curb, drainage shall be provided.

Wires shall be passed to the underside of the deck by means of a deck entry hole. Where the wires pass into the deck, they shall be protected from abrasion damage. The deck entry shall be sealed with a silicon plug, not less than 50 millimeters (2 inches) thick, level with the deck surface. The formed fillet strip shall be extended to cover the plugged deck entry hole.

651.39 FINAL DECK PREPARATION. The deck surface shall be checked carefully to locate any exposed reinforcing steel, or other metal such as wire ties, which may be continuous with the reinforcing steel, and which must be prevented from contacting the conductive asphalt overlay. These areas shall be marked, and shall be coated with two coats of epoxy resin. Care shall be taken to completely coat the exposed metal and to avoid spilling resin on the concrete deck surface.

651.40 PLACING OF ELECTRICALLY CONDUCTIVE MIX (COKE BREEZE). The construction requirements shall be as prescribed in subsections 401.09 through 401.22, (except for 401.14) of the AASHTO Construction Manual. In addition, the following are required:

- When electrically conductive mix is to be placed over concrete, the concrete surface shall not be tack-coated and shall be dry and free of debris.

- Just prior to paving, the adhesive tape on all cathodic protection anodes and voltage probes shall be removed. The anode top surfaces shall be thoroughly cleaned using a stiff wire brush.

- Electrically conductive mix shall not be placed within 150 millimeters (6 inches) of any metal appurtenance, i.e. deck drains, expansion joints, etc,; this space shall be filled with any other approved type of hot mix which does not contain conductive aggregates, i.e. either coke breeze or steel slag.

- Tarpaulins shall be used to cover coke breeze mixes in the truck boxes during transportation and laying.

The Contractor is given the following options in choosing a method of producing the conductive mix. A continuous mix plant or a batch plant shall be used with either option. Before selecting Option "B", the Contractor shall ensure that the moisture content of the coke breeze and the heating capacity of the asphalt plant are such that the mixing and placing temperatures can be achieved.

<u>Option "A"</u>

The Contractor shall:

a) Pass the coke separately through the dryer and store it in one of the hot bins;

b) Protect the coke in the hot bin from contamination by other materials;

c) Dry the stone and sand in the normal manner and store in their respective bins;

d) Proportion the components and mix as per conventional procedure.

<u>Option "B"</u>

The Contractor shall:

a) Ensure that the plant is equipped with a cold feed bin and conveyor belt to feed the coke breeze to the weigh batcher;

b) Super-heat the stone and sand so that the final mixture mixing and placing temperatures meet the specification requirements;

c) Direct the heated stone and sand into the weigh batcher;

d) Add the coke to the weigh batcher via the conveyor belt;

e) Direct the heated stone and sand and the coke into the pug mill and dry mix for one minute;

f) Add the asphalt cement and mix until all aggregates are coated.

The mix shall be laid to a 40 millimeters (1.5 inches) compacted depth and covered by the surface course within the same day.

Trial Batch

The Contractor shall demonstrate his ability to produce the desired mix before the initial placement of conductive mix on the contract. This shall be done at the plant by trial batching (in particular, conductivity) from a minimum of two batches of the size which will be used. Testing will take approximately 3 hours. After the testing period, the Contractor may start placing the mix on the road, providing the test mix is satisfactory. If the test mix is unsatisfactory, corrections shall be made and the testing procedure repeated.

Material from the trial batch shall not be incorporated in the work.

651.41 PLACING OF SURFACE COURSE: Placing of the 40 millimeters (1-1/2 inches) of surface course shall be according to the construction requirements prescribed in subsections 401.09 through 401.22.

652. NON-OVERLAY SLOTTED CATHODIC PROTECTION SYSTEM

652.10 DESCRIPTION

652.11 These specifications cover the design and installation of a slotted-anode cathodic protection system for reinforced concrete bridge decks.

652.12 This system requires that a minimum of 95% (preferably 100%) of the reinforced concrete deck have *at least* 1.0 inch of concrete cover over the top mat of rebar.

652.13 In this system, the protective D.C. current is distributed across the deck in each of several uniformly sized zones through primary wire and strand anodes, which are installed in transverse and longitudinal slots. These slots, which must be properly spaced and saw-cut into the surface of the concrete deck, are subsequently filled with a secondary anode material (conductive polymer grout). These systems are designed and installed such that the average current density at the surface of the conductive polymer grout does not exceed 5.0 mA per square foot.

652.20 MATERIALS

652.21 WIRE PRIMARY ANODE

652.21.01 The primary wire anode shall be a conductive wire that consists of a copper core, clad first with a layer of niobium, then with an outer layer of platinum. The wire shall have the properties shown in Figure 652-1.

Diameter in inches	0.031	or 0.062
Thickness of niobium cladding in inches	0.003	or 0.006
Thickness of platinum cladding in microinch	25	25
Linear resistance in milliohm/ft	16	4.2
Tensile strength (min.) in psi	90,000	103,000
Yield strength (min.) in psi	60,000	68,000
Percent elongation (max.)	2%	3%

Figure 652-1

652.22 STRAND PRIMARY ANODE

652.22.01 The strand anodes shall be strands of high purity pitch-based carbon filaments (no less than 99% carbon assay). Each strand shall be wrapped with braided Dacron threads (or equivalent threads), to minimize fraying, and shall possess the properties shown in Table 652-1.

Table 652-1

Filaments per strand	40,000
Electrical resistance (max.)	1 ohm/ft
Tensile strength (min.)	390,000 psi

652.23 CONDUCTIVE POLYMER GROUT

652.23.01 This anode backfill (i.e. secondary anode) shall be a pourable, electronically conductive, polymer grout (concrete). Its formulation shall be based on that of the material defined in U.S. Patent Application No. 346.428, which was filed in February 5, 1982, by the U.S. Department of Transportation. It shall contain all appropriate wetting and coupling agents and the resin utilized shall provide the maximum possible resistance to degradation by acid and chlorine.

652.23.02 The composition of the conductive polymer grout shall be as shown in Figure 652-2.

Components	Concentration
Vinyl Ester Resin (D-1115 Hetron, manufactured by Ashland Chemical Co., Columbus,Ohio, or approved equal.)	35% by wt. of total mixture
Coke Breeze DW1	65% by wt. of total mixture
Silane Coupling Agent (A-174)	1.0% by wt.of resin
Wetting Agent (S440)	1.0% by wt.of resin
Cobalt Naphthenate	0.5% by wt.of resin
Titanium Dioxide (RHD 6X)	1.0% by wt.of resin
Methyl Ethyl Ketone Peroxide	2.0% by wt.of resin

Figure 652-2

If the placement temperature will be 60°F or less, then dimethyl aniline shall be added to the resin at a rate of 0.5% by weight.

652.23.03 The conductive polymer grout shall have the properties shown in Figure 652-3.

Compressive Strength (min.)	4,000 psi, after 4 hours at 70°F
Resistivity (max)	10 ohm-cm
24-Hour Water Absorption	less than 0.5%

Figure 652-3

652.23.04 Prior to the initiation of any work on the project, the Contractor shall provide data that demonstrate successful use of the conductive polymer grout, as formulated by his supplier, on at least two previous bridge deck cathodic protection installations. These data shall include independent laboratory test reports documenting compliance with the above specifications on these bridges, an infrared spectrograph of the product and data on compressive strength and resistivity of the material made during field construction. If such demonstrated successful performance is not available or acceptable to the Owner, at least two separate lots of the conductive polymer concrete formulation to be used shall be prepared and evaluated by a qualified independent laboratory approved by the Owner. (Each lot shall be a minimum of 10 gallons.) The material shall be certified by the laboratory to be in full compliance with the above specifications. All data obtained on each lot, including infrared spectra and test methods used, shall be a part of the certification reports submitted to the Owner for approval prior to initiation of work.

652.23.05 The Contractor shall submit a material safety data sheet (MSDA) for each of the above-listed components that require one, and plans for the storage, handling, and placement of the materials prior to receiving them at the job site.

652.23.06 Mixing and handling instructions shall be contained in each separate package of the resin material delivered to the job site. All components (resin, catalyst, coupling agents, activator, and filler) shall be prepackaged such that when mixed together, each resulting batch of conductive polymer grout shall be approximately 0.25 cubic feet in volume, without the necessity of on-site weighing or volumetric measurement of the components.

652.23.07 An electrical resistivity sample shall be obtained from each fourth batch of the material produced in the job site, and evaluated to assure that the above requirement on resistivity is met. Each package of the resin material shall come complete with a resistivity cup that is calibrated by a qualified, independent laboratory, to facilitate testing of the polymer's resistivity.

652.23.08 Suppliers of conductive polymer grout typically require a 6-week notice prior to the desired shipping date. Furthermore, the shelf life of the polymer resin is only approximately nine weeks after shipping date. Therefore, the Contractor shall plan and coordinate the work schedule accordingly.

652.30 CONSTRUCTION REQUIREMENTS

652.31 DESIGN (LAYOUT OF ZONES)

652.31.01 The design of a slotted cathodic protection system for a reinforced concrete bridge deck consists of dividing the entire deck surface into several uniform and properly sized zones.

652.31.02 Each zone shall consist of at least two transverse slots and several longitudinal slots, that shall be cut into the concrete surface for the placement of the primary anode wire and the strands, respectively.

652.31.03 The maximum area of each zone shall not exceed 6500 square feet.

652.31.04 Spacing of Anode Slots and Primary Wire Size

652.31.04.01 The spacing between the two transverse slots for the primary anodes in each zone shall be no more than 25 feet if individual primary wire anodes are in the transverse slots only, or 50 feet if primary wire anode loops are used.

> NOTE: Primary wire anodes may be straight lengths of individual anode wires or may be anode wire loops. An anode wire loop typically runs completely around (i.e. on all 4 sides) of the zone or subzone it feeds. The loop is a continuous length of wire with power feeds on both ends.

0.031-inch primary anode wire shall be used only when the total length of an anode (portion in the deck) is less than 50 feet.

652.31.04.02 The spacing between the longitudinal slots for the strand anodes in each zone shall be no more than 6 inches.

652.31.05 Dimension of Slots

652.31.05.01 The width of each transverse or longitudinal slot shall be 0.25 +/- 1/8 inch.

652.31.05.02 The depth of each transverse, or longitudinal slot, shall be 0.75 +/- 1/8 inch.

652.32 CUTTING SLOTS

652.32.01 Before cutting, all areas of the deck in which the concrete cover over the reinforcing steel is less than 0.75 inch shall be identified. In these areas, the slot locations shall be moved up to 4 inches in either direction, as necessary, to maximize the thickness of concrete between the reinforcing steel and the bottom of the slots, after these are cut into the surface of the deck.

652.32.02 Slots shall be routed around all exposed steel components in the deck, such that no portion of the slot is closer than 3 inches to said components.

652.32.03 Each slot shall be terminated at 3 to 6 inches from any curb, parapet wall, expansion joint, or boundary of an adjacent zone.

652.32.04 These slots shall be thoroughly cleaned after sawing, and kept clean, so they are free of all foreign material throughout the subsequent placement of the anodes in these slots and the backfilling of the slots with the conductive polymer concrete. Proper surface preparation of the slots is critical to the bonding of the polymer concrete.

652.32.05 Reference cells shall be located parallel between slots.

652.33 INSTALLATION OF PRIMARY ANODES

652.33.01 Before placement of the primary wire and strand anodes, the anode slots shall be blown with compressed air to remove any loose contaminants or moisture. The compressed air system shall have a moisture trap and an oil trap to prevent contamination of the slots. The slots shall be free of moisture (i.e., visibly dry), dirt, grease, oil, asphalt, or other foreign material before placing any anode material. Any exposed steel shall be completely covered with a non-conductive vinyl-ester polymer.

652.33.02 Placement of Strand Anodes

652.33.02.01 It is preferable that the strand anodes (carbon strands) be placed in their slots prior to the placement of the primary anode wires. This would minimize the disturbance on the anode wires after their placement.

652.33.02.02 A carbon strand shall run along the entire length, and at the bottom of each longitudinal slot.

652.33.02.03 Each strand may be spliced by simply providing a 3-inch untied overlap, with no special connection.

652.33.02.04 The strand anode shall be shielded from electrical contact with any exposed reinforcing bar or other metallic components in the deck, by coating the steel on the bottom and the sides of the slot (to 3 inches from both ends of the exposed steel), with the non-conductive vinyl-ester polymer coating.

652.33.02.05 Where the carbon strands encounter a primary anode wire (i.e., where a longitudinal slot crosses a transverse slot), no mechanical connection between these strands and the primary anode wire is necessary.

652.33.03 Placement of Primary Anode Wires

652.33.03.01 The primary anode wire shall not be kinked or scored. Any such damages to the anode wire shall be grounds for rejection.

652.33.03.02 A primary anode wire shall be positioned in the lower half of each transverse sawed slot in the bridge deck. This may be done using non-metallic spacers or other methods, to be approved by the Owner.

652.33.03.03 No on-deck splicing of the primary anode wires shall be permitted. Each primary anode wire shall be of sufficient length to extend continuously, without splicing, from the farthest end of the slot in which it is to be placed in the deck, to its designated junction box below the deck.

652.33.03.04 The anode wires shall be electrically shielded from any exposed reinforcing bars or other metallic components in the deck, by completely coating these components with a non-conductive, vinyl-ester polymer coating. Care should be exercised not to coat the walls of any slot with this non-conductive coating.

652.33.03.05 Each anode wire shall be protected from abrasion damage, at where it is brought through the deck in a drilled hole, with a Kynar sleeve that runs through the full depth of the deck to a junction box.

652.33.03.06 Each anode wire shall be connected to a separate, continuous length of No. 10 AWG stranded copper wire with THHN insulation, that leads from the terminal box, using insulated compression connectors or terminal lugs.

652.33.03.07 The connection shall be sealed with a 3M Scotchcast #85-10 compression splice tape, or approved equivalent, and contained in a conduit junction box on the underside of the bridge deck.

652.33.03.08 Each anode lead shall be properly tagged, with permanent, corrosion-resistant identification tags, at the rectifier (and/or terminal box) to identify its function and its corresponding working zone in the deck.

652.34 INSTALLATION OF NON-CONDUCTIVE SEALANT

652.34.01 After all the lead wires for the primary anode wires, the reference cells, system negatives, and probes are in place and extended through the deck, in holes that are drilled through the deck, fill the holes with a non-conductive sealant.

652.35 BACKFILLING OF SLOTS WITH CONDUCTIVE POLYMER GROUT

652.35.01 The sawcut slots shall be visibly dry and free of dirt, grease, oil, asphalt or other foreign material when placing the polymer concrete.

652.35.02 Any exposed reinforcing bars and other metallic components in the slots shall be electrically insulated, by non-conductive vinyl-ester coating, to insure that they do not come in contact with the primary anodes and the conductive polymer grout. The coating shall cover each exposed steel and 3-inch of the slot's base and sides, from each end of the exposed steel.

652.35.03 The conductive polymer grout shall be placed in the slots only after the primary anodes are in place and all drill holes in the deck have been completely filled with a non-conductive material.

652.35.04 The conductive polymer grout shall be installed only when the deck temperature is in excess of 40°F and expected to remain above that temperature for at least 4 hours. Furthermore, no grout shall be placed when precipitation is forecast or expected within 4 hours.

652.35.05 The conductive polymer grout shall be mixed in strict accordance with the instructions provided, and shall be periodically agitated in the mixing or pour containers, during backfilling of the slots so that no significant separation of the filler and the resin occurs. The use of a portable paint mixer is recommended for the mixing operation.

652.35.06 The conductive polymer grout shall be poured into each slot to a level equal to 1/8 inch above that of the surrounding deck surfaces. The conductive polymer concrete shall not be spilled into other areas of the deck surface.

652.35.07 Within 15 minutes of the placement of the conductive polymer grout, dry, fine silica sand shall be spread generously over all backfill.

652.35.08 After the material has set sufficiently, any excess sand shall be removed from the deck surface using vacuum pick-up or by blowing with compressed air.

652.35.09 Vehicular traffic over the backfilled slots may be allowed after 4 to 5 hours.

653. DISTRIBUTED ANODE CP SYSTEM WITH CONCRETE OVERLAY

653.10 DESCRIPTION

653.11 This specification covers distributed anodes which are placed on a blasted, cleaned deck surface and then covered with a concrete overlay.

653.12 Approved anode systems are:

- Conductive polymer mounds
- ELGARD Mesh Anodes

653.12.01 Conductive polymer mounded systems consist of primary anode wires and strands which are placed on a prepared deck surface, covered with a secondary anode (conductive polymer grout), and overlaid with concrete to provide a new riding surface. These systems are designed and installed such that the average current density at the surface of the conductive polymer grout does not exceed 7.5 mA per square foot of grout surface area.

653.12.02 ELGARD Mesh Anode systems consist of expanded titanium mesh coated with a precious metal oxide catalyst which is fastened to a prepared deck surface and overlaid with concrete to provide a new riding surface. These systems are designed and installed such that the average current density at the surface of the anode does not exceed 10.0 mA per square foot.

653.20 MATERIALS

653.21 The Cementitious Overlay: The Cementitious overlay shall satisfy the following properties:

653.21.01 Maximum vacuum saturated volume resistivity of 50,000 ohm-cm as determined by AASHTO T-277 (modified - See 650A.C) at 28 days at 73°F plus or minus 2 degrees. The following concretes have been used successfully with cathodic protection for more than 2 years:

- Low slump concrete
- Latex modified concrete
- Conventional portland cement concrete

653.21.02 Minimum thickness of 1 1/2 inches for latex modified concrete and 2 inches for low slump concrete or conventional Portland Cement Concrete.

653.21.03 If latex modified concrete is used as the overlay material, prior bridge deck spall repair should not be performed with latex modified concrete.

653.22 EPOXY BONDING AGENTS

653.22.01 An epoxy bonding agent must not be used with a rigid overlay cathodic protection system.

653.23 PATCHING MATERIALS

653.23.01 Portland cement concrete - AASHTO M241, as specified.

653.23.02 Other patching materials should not have a volume resistivity exceeding 50,000 ohm-cm as determined by AASHTO T-277 (modified- see 650A.C) at 28 days at 73°F plus or minus 2 degrees.

653.24 HIGH PRESSURE WATER BLASTING

653.24.01 Prior to the concrete overlay operation, decks with ELGARD Anode Mesh may be blasted with water having pressures not exceeding 4,000 psi. Care shall be taken not to point the nozzle of the water blasting unit directly at the plastic fasteners on the deck.

653.25 CONDUCTIVE POLYMER MOUND ANODE

653.25.01 The primary anode wire shall be a conductive wire that consists of a copper core, clad first with a layer of niobium then with an outer layer of platinum. The wire shall have the properties shown in Figure 653-1.

Diameter in inches	0.031	or	0.062
Thickness of niobium cladding in inches	0.003	or	0.006
Thickness of platinum cladding in microinch	25		25
Linear resistance in milliohm/ft	16		4.2
Tensile strength (min.) in psi	90,000		103,000
Yield strength (min.) in psi	60,000		68,000
Percent elongation (max.)	2%		3%

Figure 653-1

653.25.02 The primary anode strands shall be strands of high purity pitch-based carbon filaments (no less than 99% carbon assay). Each strand shall be wrapped with braided Dacron threads (or equivalent threads), to minimize fraying, and shall possess the properties shown in Figure 653-2.

Filaments per strand	40,000
Electrical resistance (max.)	1 ohm/ft
Tensile strength (min.)	390,000 psi

Figure 653-2

653.25.03 The secondary anode shall be a pourable, electronically conductive, polymer grout. Its formulation shall be based on that of the material defined in U.S. Patent Application No. 346.428, which was filed in February 5, 1982, by the U.S. Department of Transportation. It shall contain all appropriate wetting and coupling agents and the resin utilized shall provide the maximum possible resistance to degradation by acid and chlorine.

653.25.04 The composition of the conductive polymer grout shall be as shown in Figure 653-3.

Components	**Concentration**
Vinyl Ester Resin (D-1115 Hetron, manufactured by Ashland Chemical Co., Columbus,Ohio, or approved equal.)	35% by wt.of total mixture
Coke Breeze DW1	65% by wt.of total mixture
Silane Coupling Agent (A-174)	1.0% by wt.of resin
Wetting Agent (S440)	1.0% by wt.of resin
Cobalt Naphthenate	0.5% by wt.of resin
Methyl Ethyl Ketone Peroxide	2.0% by wt.of resin

Figure 653-3

If the placement temperature will be 60°F or less, then dimethyl aniline shall be added to the resin at a rate of 0.5% by weight.

653.25.05 The conductive polymer grout shall have the properties shown in Figure 653-4.

Compressive Strength (min.)	4,000 psi, after 4 hours at 70°F
Resistivity (max.)	10 ohm-cm
24-Hour Water Absorption	less than 0.5%

Figure 653-4

653.25.06 Prior to the initiation of any work on the project, the Contractor shall provide data that demonstrate successful use of the conductive polymer grout, as formulated by his supplier, on at least two previous bridge deck cathodic protection installations. These data shall include independent laboratory test reports documenting compliance with the above specifications on these bridges, an infrared spectrograph of the product, and data on compressive strength and resistivity of the material made during field construction.

If such demonstrated successful performance is not available or acceptable to the Owner, at least two separate lots of the conductive polymer grout formulation to be used shall be prepared and evaluated by a qualified independent laboratory approved by the Owner. (Each lot shall be a minimum of 10 gallons). The material shall be certified by the laboratory to be in full compliance with the above specifications. All data obtained on each lot including infrared spectra and test methods used shall be a part of the certification reports submitted to the Owner for approval prior to initiation of work.

653.25.07 The Contractor shall submit a material safety data sheet (MSDS) for each of the above-listed components that require one, and plans for the storage, handling, and placement of the materials prior to receiving them at the job site.

653.25.08 Mixing and handling instructions shall be contained in each separate package of the resin material delivered to the job site. All components (resin, catalyst, coupling agents, activator, and filler) shall be prepackaged such that when mixed together, each resulting batch of conductive polymer grout shall have a volume of 0.25 cubic feet, without necessity of on-site weighing or volumetric measurement of the components.

653.25.09 An electrical resistivity sample shall be obtained from each fourth batch of the material produced at the job site, and evaluated to assure that the above requirement on resistivity is met. Each package of the resin material shall come complete with a resistivity cup that is calibrated by a qualified, independent laboratory, to facilitate testing of the polymer's resistivity.

653.25.10 Suppliers of conductive polymer grout typically require a 6-week notice prior to the desired shipping date. Furthermore, the shelf life of the polymer resin is only approximately 9 weeks after shipping date. Therefore, the Contractor shall plan and coordinate the work schedule accordingly.

653.26 ELGARD MESH ANODE

The ELGARD Mesh Anode may be either one of two types: ELGARD 210 anode designed to supply 2.1 mA per square foot of concrete, or ELGARD 150 anode designed to supply 1.5 mA per square foot of concrete.

653.26.01 ELGARD 150 Anode

The anode shall be a highly expanded titanium mesh, coated with a precious metal oxide catalyst with at least 2 years proven history on concrete bridge decks. The anode mesh shall conform to the approximate properties shown in Figure 653-5.

Nominal Anode Surface Area	0.15 ft^2/ft^2
Substrate Composition	Titanium, Grade 1
Catalyst	Mixed Precious Metal Oxide
Width of Roll	45 Inches
Length of Roll	267 ft.
Weight of Roll	26 lbs/1000 ft^2
Diamond Dimension	3" LWD x 1 1/3" SWD
Resistance Lengthwise (45" width)	0.026 ohms/ft.
Resistance Width (with current distributor)	0.008 ohms/ft.

Figure 653-5

653.26.02 ELGARD 210 Anode

The anode shall be highly expanded titanium mesh, coated with a precious metal oxide catalyst with at least 2 years proven history on concrete bridge decks. The anode mesh shall conform to the approximate properties shown in Figure 653-6.

Nominal Anode Surface Area	0.21 ft^2/ft^2
Substrate Composition	Titanium, Grade 1
Catalyst	Mixed Precious Metal Oxide
Width of Roll	48 inches
Length of Roll	250 Ft.
Weight of Roll	45 lbs/1000 ft^2
Diamond Dimensions	3 LWD x 1 1/3" SWD
Resistance Lengthwise (48" width)	0.014 ohms/ft
Resistance Widthwise (with current distributor)	0.005 ohms/ft

Figure 653-6

653.26.03 Current Distributor

Current shall be distributed to the anode system using current distributors of solid Grade 1 titanium strip, 1/2-inch wide x 0.035-inch thick.

653.26.04 Fastener

The anode shall be fastened to the deck using Fastex Part No. 354-260300-00-0078 plastic fasteners, or the equivalent.

653.26.05 Prior to the initiation of any work on the project, the Contractor shall provide accelerated lifetime data which demonstrate the ability of the anode lot, as formulated by the anode supplier, to survive a total charge of 700 A-Hr per square foot of concrete surface area.

653.30 DESIGN AND CONSTRUCTION REQUIREMENTS

653.31 DELAMINATED CONCRETE

All delaminated concrete shall be removed prior to installation of the anode system.

653.32 PREVIOUS PATCHES

All patches exceeding 2 square feet and materials with a volume resistivity of more than 50,000 ohm-cm (as determined by AASHTO T-277 modified - see 650A.C) shall be removed prior to installation of the cathodic protection system. This must result in a deck surface area with no more than 10% coverage of patches greater than 50,000 ohm-cm.

653.33 REPLACEMENT BARS

All replacement bars must be spliced to the remaining reinforcing bars to ensure electrical continuity.

653.34 EPOXY INJECTED AREAS

All epoxy injected repair areas exceeding 2 square feet in area must be removed.

653.35 PATCHING

In general, patching shall be done sufficiently in advance of the overlay operation so that the patch material stiffens enough to prevent deforming.

653.36 SCARIFICATION

The bridge deck surface should be scarified as required for satisfactory bonding of the overlay to the existing substrate prior to installation of the anode system.

653.37 REFERENCE CELLS

Reference cells shall be installed prior to installation of anode materials.

653.38 CONDUCTIVE POLYMER MOUND SYSTEM

653.38.01 The primary anode wires shall run perpendicular to the primary anode strands, except if a wire loop is used, in which case two of the four sides of the loop will be perpendicular to the strands.

> NOTE: Wire anodes may be straight lengths of individual anode wires or may be anode wire loops. An anode wire loop typically runs completely around (i.e. on all four sides) of the zone or subzone it feeds. The loop is a continuous length of wire with power feeds on both ends.

The maximum spacing of wire anodes shall be as follows:

- If loops are used: 50 feet
- If loops are not used: 25 feet

A 0.031 inch primary anode wire shall be used only when the total length of each anode in the deck is less than 50 feet.

653.38.02 There shall be at least two separate power feeds for each electrical zone.

653.38.03 Anode strands shall be placed at a maximum 12-inch center-to-center spacing.

653.38.04 There shall be a minimum of 1/2 inch of concrete cover between the anode and the reinforcing steel. Where less than 1/2 inch of cover exists, a non-conductive polymer shall be installed between the anode and reinforcing steel.

653.38.05 All foreign material shall be cleaned from the concrete surface prior to placing anode materials in a manner approved by the Engineer.

653.38.06 The anode wire shall be positioned using nonmetallic holders or other methods approved by the Engineer at the locations shown on the plans.

653.38.07 Each primary anode wire shall be sleeved with Kynar or approved equal where brought through the deck in a drilled hole. The hole shall then be filled with nonconductive polymer or approved equal.

653.38.08 All primary anode wires in a zone shall be connected to a continuous length of #10 AWG stranded copper insulated wire leading from the rectifier/controller. The connection shall be a compression type and shall be contained in a conduit junction box on the underside of the bridge deck.

653.38.09 Anode strands shall run continuously in a zone and may be interconnected by providing a 3-inch overlap. No positive connections between anode strands and other components of the anode system are required.

653.38.10 In no case shall the tension on the strands be excessive so as to cause the strand to rise above the deck surface. If necessary, the strand can be affixed to the deck with hot glue or other suitable means.

653.38.11 The secondary anode backfill shall be installed when the deck temperature is in excess of 40°F and expected to remain above that value for 4 hours.

653.38.12 The anode backfill material shall be placed after the primary anode wire and anode strands are in place and all drill holes in the deck have been completely filled with a non-conductive polymer.

653.38.13 The backfill shall be placed over all primary anode wire and anode strands so as to completely encapsulate them. Conductive polymer material shall be placed directly onto the deck surface so a mound of material 1.25 to 1.75 inches wide and approximately 3/8 inches thick results. Consistency of the material shall be such that excessive spread of the mound does not occur prior to set. Before applying to the deck the Contractor shall demonstrate to the Engineer the dispensing method and technique used to establish the finished mound.

653.38.14 The anode backfill shall be mixed in strict accordance with the instructions provided and shall be periodically agitated during placement such that no significant separation of the coke and the resin occurs within the mixing or pouring containers. The quantity of anode backfill mixed at any given time shall not exceed that which can be installed within 30 minutes.

653.38.15 Within 15 minutes of backfill placement, conductive carbon filler (DW1 or equivalent) shall be spread generously over the anode mounds. Excess carbon filler that does not bond to the mound shall be removed using oil free compressed air or a vacuum pick-up after the material has set (typically 4 hours) and prior to concrete overlay placement.

653.38.16 Testing for short circuits between the conductive polymer anode and the reinforcing steel shall be conducted after installation of the anode and before placement of the overlay. Testing shall also be conducted during placement of the conductive polymer mounds in order to locate short circuits as soon as possible. Short circuit testing shall be conducted using a high impedance digital DC voltmeter.

The voltage measurement shall be taken by connecting the anode to the positive terminal of the voltmeter, and the reinforcing steel to the negative terminal of the voltmeter. The millivolt reading displayed by the voltmeter is the difference in static or rest potential between the anode and the steel. A reading of less than 1.0 mV is indicative of a short circuit. Expected readings range from slightly positive to -500 mV. If there is uncertainty, a short circuit can be confirmed by powering the system with a portable power supply. A lack of response from the embedded reference electrodes is confirmation of a short circuit within the zone being tested. If a short circuit exists, it must be located and eliminated before placement of the overlay.

653.39 ELGARD MESH ANODE SYSTEM

653.39.01 The anode mesh and current distributor design shall be such that the anode IR drop shall not exceed 300 mV from the power feed point to the farthest point from the power feed.

653.39.02 Anode Mesh Layout

The panels of anode mesh shall be laid out to run either parallel or transverse with the deck. Spacing between adjacent mesh panels may vary from slight overlap to a maximum of 6 inches depending on deck width and construction staging. If necessary, a mesh panel may be cut lengthwise to accommodate system requirements. Distance between anodes in adjacent electrical zones shall be 4 to 6 inches.

653.39.03 Current Distributor Layout

Current distributors shall be laid out to run perpendicular to the panels of anode mesh. Current distributors shall be designed to extend from a junction box mounted beneath the deck, through an access hole and across the entire width of the electrical zone.

653.39.04 The anode mesh shall be designed to be installed not closer than 2 inches from any exposed steel on the deck.

653.39.05 There shall be at least two separate power feeds for each electrical zone.

653.39.06 Access Holes

Access holes shall be provided for current distributor bars (as well as system negatives and instrumentation wiring). These holes shall be a maximum of 1 1/2 inches in diameter by the thickness of the deck. All access holes shall be cored to prevent "pop-outs". After wiring has been installed, the access holes shall be filled with non-conductive epoxy.

653.39.07 Installation of Current Distributors

Current distributors shall be installed to extend down through the access hole, and shall be bent at a right angle to lay flat across the deck. If necessary, lengths of current distributor can be welded together by overlapping ends approximately three inches and making spot welds every 1/2 inch. If the resulting length is longer than required, the current distributor can be cut to fit with tin snips.

The current distributor running through the access hole shall be electrically insulated from any steel which may have been exposed by the coring operation. A length of heat shrink tubing equal to the depth of the access hole shall be applied to the current distributor running through this hole. The heat shrink tubing shall be Alpha FIT-700 or approved equal.

In lieu of extending the current distributor through the access hole, an insulated titanium connector may be installed. The connector consists of a titanium rod, 1/8-inch in diameter by 16-inches long, with a 10-inch current distributor strip factory welded to the rod. The current distributor shall overlap the titanium rod by approximately 2 inches, with spot welds at three locations. The spot welds shall be made at the factory using a high powered resistance welder. The exposed rod is insulated with heat shrink for approximately 12 inches, leaving 2 inches uncovered. The 10-inch strip is resistance welded to the current distributor bar on the deck by overlapping the strips by approximately 6 inches, and providing a minimum of three spot welds. The rod is extended through the access hole in the deck to facilitate connection to the anode lead wire from the rectifier.

653.39.08 Installation of Anode Mesh

The anode mesh shall be installed in accordance with the manufacturer's instructions. A general procedure is described below:

The first width of mesh is installed at the edge of the electrical zone. One end of the roll of anode mesh is fastened to concrete surface using plastic fasteners. The mesh is then unrolled, tensioned slightly and fastened to the surface about every 10 feet. At the edge of the zone, the mesh is cut and fastened in place. Before placing any more mesh, the current distributors are welded to the mesh. Each successive width of mesh is placed adjacent to the last and welded to the current distributors until the entire electrical zone is covered. After all the mesh has been installed, additional fasteners are installed as directed by the Engineer and the PCE. Mesh shall be fastened sufficiently to prevent significant movement during placement of the overlay, and so that it maintains a low profile with the concrete substrate.

653.39.09 Welding of Anode Mesh to the Current Distributors

All titanium-to-titanium electrical connections shall be metallurgical bonds made by resistance welding using equipment supplied by the anode manufacturer and in accordance with the manufacturer's instructions. Where anode mesh is welded to the current distributor, there shall be at least one weld for every three inches of current distributor.

653.39.10 Isolation from Exposed Steel

The anode must be prevented from contacting or very nearly contacting exposed steel such as scuppers and expansion joints. Anode mesh shall be installed not closer than 2 inches from exposed steel. Installed mesh may be cut from tin snips to meet this requirement, and the anode shall be securely fastened to meet and maintain this requirement during placement of the overlay.

653.39.11 Isolation from Shallow Steel

Following the depth-of-cover survey (section 650.43.02.C), any areas of shallow steel (0.25 inch or less concrete cover) shall be corrected by one of the following three methods.

- The anode mesh shall be cut out and fastened to the deck around the shallow steel. This method is preferred for small areas of shallow steel as well as for small exposed wire ties which often cannot be located with metal detectors, but can be located visually.
- A non-conductive epoxy can be applied to the concrete surface directly above the steel, and quartz sand shall be broadcast over the epoxy as it hardens. The maximum width of this application is two inches.
- A plastic spacer can be used to lift the anode off the deck surface. The spacer must be approved by the Manufacturer's Technical Representative and by the Engineer and the PCE.

653.39.12 Testing for Short Circuit Between Anode and Reinforcing Steel

Short circuit testing before, during, and after placing the overlay shall be conducted using a high impedance digital DC voltmeter. The DC voltage technique is preferred since the resistance of a properly installed system is normally a fraction of an ohm, making detection of a short circuit difficult using the resistance technique.

The voltage measurement shall be taken by connecting the anode to the positive terminal of the voltmeter, and the reinforcing steel to the negative terminal of the voltmeter. The millivolt reading displayed by the voltmeter is the difference in static or rest potential between the anode and the steel. A reading of zero to plus or minus 1.0 mV is indicative of a short circuit. Expected readings range from slightly positive to -500 mV. If there is uncertainty, a short circuit can be confirmed by powering the system with a portable power supply. A lack of response from the embedded reference electrodes is confirmation of a short circuit within the zone being tested. If a short circuit exists, it must be located and eliminated before the cathodic protection system can function properly.

653.39.13 Application of Bonding Grout

Ideally, the bonding grout, if required, should be applied using grout spray equipment. In general, scrubbing bonding grout into the concrete surface using a stiff-bristled broom is not recommended. Alternatively, a soft-bristled broom may be used to work the grout evenly.

653.39.14 Protection of Anode During Overlay Placement

During the placement of the overlay, the anode system shall be protected from concrete truck traffic by laying down sheets of 3/8-inch plywood. This protects the anode from possible mechanical damage and prevents oil from the truck from contaminating the concrete surface. Plywood sheets are removed as the placement of the overlay progresses.

653.39.15 Connection of Distributor Bar to Anode Lead Wire

A 1/4-inch diameter hole shall be punched or drilled near the end of the current distributor bar in the junction box beneath the deck. The anode lead wire, fitted with a ring or spade crimp connector, is then secured to the current distributor bar by a 10-32 x 3/8 inch bolt and matching nut. The connection shall then be insulated using a sealing electrical tape.

Splices made in junction boxes between the titanium rod connector and anode lead wire shall be mechanically connected (crimp connection) and insulated in an approved heat-shrinkable material.

APPENDIX TO SECTION 653

CALCULATIONS TO SUPPORT ITEM 653.39.01, VOLTAGE (IR) DROP REQUIREMENT

Anode mesh and current distributor design shall be such that the anode IR drop shall not exceed 300 mV from the power feed point to the furthest point from the power feed.

Sample calculations are given with the example design shown in Figure 653-7.

Anode voltage (IR) drop for the ELGARD system is calculated by adding the voltage drop in the current distributor to the voltage drop in the anode mesh along the longest current path in the anode structure. For the example design shown in Figure 653-7, total voltage drop is:

$$E_T = E_{AB} + E_{BC}$$

A. Calculate Current Distributor Voltage Drop (E_{AB})

The current distributor voltage drop is calculated by multiplying the current distributor resistance (see material specs) by the average current flow.

Where:

$$R_{AB} = 0.005 \text{ ohms/ft x } 12 \text{ ft.}$$

$$R_{AB} = 0.06 \text{ ohms}$$

The *average* current flow in the current distributor is

$$i_{AB} = \underline{0.002 \text{ A/ft}^2} \text{ X } \frac{(100)(12)\text{ft.}^2}{2}$$

$$i_{AB} = 1.2 \text{ A}$$

Total current is divided by 2 above since we are considering a distributing conductor. Now,

$$E_{AB} = i_{AB}\, R_{AB} = (1.2)(0.06)$$

$$E_{AB} = 0.072 \text{ V}$$

B. Calculate Mesh Voltage Drop (E_{BC})

The mesh voltage drop is calculated by multiplying the mesh resistance (see material specs) by the average current flow.

Where:

$$R_{BC} = 0.014\text{/ft. ohms x } 50 \text{ ft.}$$

$$R_{BC} = 0.70 \text{ ohms.}$$

The average current flow in this width of anode mesh is

$$i_{BC} = \underline{0.002A} \times \frac{(50)(4)\ \text{ft.}^2}{2}$$

$$i_{BC} = 0.20\ \text{A}$$

Again, total current is divided by 2 above since we are considering a distributing conductor. Now,

$$E_{BC} = i_{EC}\ R_{BC} = (0.20)\ (0.70)$$

$$E_{BC} = 0.140\text{V}$$

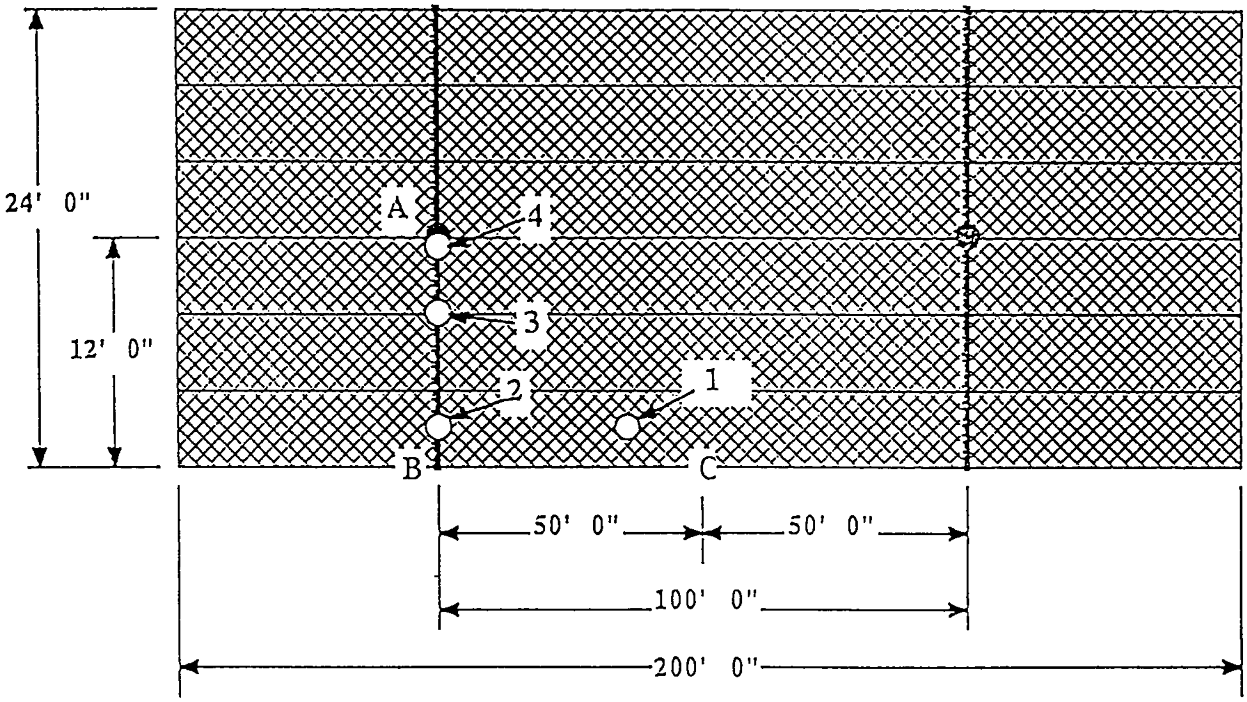
C. Calculate the Total IR Drop

$$E_T = E_{AB} + E_{BC}$$

$$E_T = 0.072 + 0.140$$

$$E_T = 0.212\ \text{V} = 212\ \text{mV}$$

Figure 653-7. ELGARD 210 ANODE MESH - PLAN VIEW OF ZONE



650A. BRIDGE DECK CATHODIC PROTECTION TENTATIVE SPECIFICATION ANNEX

A. INTRODUCTION OF NEW TECHNOLOGIES AND MATERIALS

650A.A.01 ANODES: Anode materials, whether applied as surface coatings or embedded in surface concrete or overcoats, can be expected to deteriorate with time under the combined effects of current transmission and environmental exposure. Current discharge taking place at the anode-concrete surface may also adversely affect the concrete environment.

These effects have been explored and quantified in field installations, for a number of anode materials. However, as an increasing number of anode materials are introduced, or as existing anode materials are changed significantly, there is a need for a simple and rapid means of performance evaluation.

This document outlines two laboratory tests which may be useful to the user/owner who wishes to gain a preliminary assessment of anode performance. These laboratory tests represent a minimum level of evaluation which would be expected to be carried out before an anode is considered for large-scale testing. The reader is cautioned that good performance of an anode in these tests does not ensure the success of a full-scale installation; however, failure of an anode to survive these tests would be an indication that the material might not perform as well as other anode materials presently in use.

The two tests described below examine the performance of an anode material operating in a range of solutions (Accelerated Anode Life Test), and the performance of all components of the anode system when powered in a small scale concrete specimen (Anode System Evaluation on Concrete).

650A.A.01.01 Accelerated Anode Life Test: The anode sample shall be subjected to a lifetime equivalent of 700 amp-hours/square foot. The sample size shall be the area of anode in contact with 1 square foot of concrete. Testing should be carried out over at least a 90-day period. For example, a sample operated at 0.162A would meet the 700 amp-hours/square foot criterion after 180 days (4,320 hours) of operation.

The anode shall be tested in aqueous solution. Test solutions should include 1.0N (40 grams per liter) sodium hydroxide solution, 30 grams per liter sodium chloride solution, and simulated pore water solution. Simulated pore water solution shall consist of 0.20% calcium hydroxide, 3.20% potassium chloride, 1.00% potassium hydroxide, and 2.45% sodium hydroxide.

During the period when the anode sample is powered, periodic weight measurement should be carried out to quantify any consumption of anode material which occurs.

Some anodes fail by loss of electrochemical activity without measurable loss of weight. In this case, anode failure can be determined by monitoring anode potential. It would also be appropriate to monitor any changes in the resistivity of the anode sample.

Although this test and suggested evaluation methods are not suitable for all anode materials (i.e., conductive surface coatings), it is hoped that they will provide a starting point. If this test is considered to be inappropriate for a candidate anode material, an alternative life test may be proposed by the anode supplier, but the test proposed shall not be less complete or rigorous than that described above.

650A.A.01.02 Anode System Evaluation on Concrete: The anode system shall be installed on a concrete specimen in accordance with the manufacturer's instructions, and shall be powered for a period of at least 1 year at the manufacturer's maximum recommended anode current density.

Concrete specimens shall provide a minimum of 10-inch by 12-inch surface to be powered. Bridge deck quality concrete shall be used, and a chloride content in the range of 10-15 pounds per cubic yard NaCl is recommended, or otherwise as required, to reflect chloride levels encountered in the field.

The specimen shall contain mild steel reinforcement with a minimum surface area of approximately 1 square foot configured to simulate bridge deck reinforcement.

Bars shall be interconnected to form an electrically continuous mat, either by securing intersecting bars with tie wires, or by providing welded connections.

The concrete shall be cured before anode application, and sides of the specimen shall be coated with a sealer to prevent excessive moisture loss during the test period.

Concrete surface preparation shall be as recommended by the manufacturer, taking into account typical highway agency requirements and practice.

The anode shall be applied to the concrete surface in the configuration which it will be used in the field. The same means to be used for connecting current supply leads to the anode, and any overcoat materials, etc. recommended for field use with the anode, shall be used for installation of the system on the test specimen.

One year is the minimum period of powering recommended, and the applied anode current density throughout the test period should be no greater than the maximum recommended by the manufacturer. When the sample is powered in a laboratory environment, care should be taken to avoid excessive drying of the specimen. Outdoor specimen exposure is also appropriate, and may provide a more accurate reflection of anode performance where climatic conditions or variations are extreme.

Excessive voltage increase, or the appearance of damage to the concrete at the interface with the anode is an indication that the anode may not perform as well as other anode materials presently in use.

650A.A.02 Embedded Reference Electrodes: The effectiveness of the cathodic protection system is generally assessed by measuring the potential of embedded steel within the structure. The embedded steel serves as an electrochemical half-cell, and its potential can be measured by using another half-cell, whose potential is well known, as a reference point. A half-cell used for this purpose is known as a reference half-cell, or reference electrode.

A satisfactory reference electrode should have the following properties:

- It should have a known potential which does not vary greatly with concentration of contaminants, temperature changes, or other environmental conditions.
- Its potential should be stable over a long period of time.
- It should not polarize with the passage of small amounts of current, either when these are anodic or cathodic.

- It should return to the same potential after polarization (no hysteresis effects).
- It should have a low internal resistance.
- It should not alter or contaminate the concrete in any way.
- It should be of a tough construction suitable for field construction practices.

It is possible to measure the potential of embedded steel using a portable reference electrode on the surface of the structure. This is sometimes accomplished by using a potential well to direct the measurement to steel below the surface. Using a surface reference electrode in this manner is inconvenient however, and measurement directly on the concrete surface may be inaccurate. For these reasons, permanent reference electrodes are usually embedded within the concrete, and are intended for use over a period of several years.

A number of reference electrodes have been suggested and explored for use with cathodic protection systems in atmospherically exposed concrete. These include zinc/zinc sulfate, silver/silver chloride, moly/moly oxide, graphite, and lead. Comparative studies of these different types of reference electrodes are very limited, but on the basis of some studies and practical experience, silver/silver chloride and graphite probes are accepted as the most reliable.

This document outlines two laboratory tests which may be useful to users to gain a preliminary assessment of new reference electrodes, or of proposed modifications to accepted reference electrodes. The reader is cautioned that acceptable performance in the tests does not guarantee the success of a reference electrode in the field service, but failure of a reference electrode to pass these tests would be an indication that it may not perform as well as the reference electrodes presently in use.

The two tests described below examine the short-term performance of a reference electrode during the passage of small amounts of current (Polarization Test), and the performance of an embedded reference electrode over a long period of time (Long-Term Stability Test).

650A.A.02.01 Polarization Test: All instruments for measuring potential require a transfer of electricity to operate. Although this quantity of electricity may be very small, this requirement will cause the reference electrode to polarize, or deviate from its equilibrium potential. The amount of polarization should be small, and it should not prevent the reference electrode from returning to its equilibrium potential quickly.

For this test, the reference electrode being tested is embedded in a concrete specimen together with a standard reference electrode. The standard reference shall be a silver/silver chloride electrode with a proven long-term history of use in cathodic protection systems for concrete structures. The two reference electrodes shall be installed parallel to each other, and within 1 inch of each other, but shall not be in direct contact. The concrete specimen shall be at least 4 inches square and 8 inches long, and shall be constructed of bridge deck quality concrete. The specimen shall contain no steel embeddment or chloride content, unless a particular chloride content is recommended by the reference electrode supplier.

For this test, the reference electrode being tested is made a working electrode, and is intentionally polarized away from its equilibrium potential. This is accomplished by placing the specimen in contact with a metal plate which serves as a third electrode. Contact can be conveniently made by placing the specimen on a wetted sponge which in turn is placed on the metal plate. The reference electrode being tested is first made to operate 2 mV anodic of its equilibrium potential, and the current flow is recorded in micro amps. The electrode potential is measured using the standard reference electrode, and current flow is measured between the electrode being tested and the steel plate. Similar data are collected up to 10 mV anodic of equilibrium potential. Data are then collected with decreasing potentials down to 10 mV cathodic of the equilibrium potential. Finally, data are collected with increasing potentials back to the equilibrium point, completing one cycle of data collection. This entire test should be done in not less than 2 minutes.

In the close vicinity of the equilibrium potential, the current passed by the electrode will form a linear plot against the displacement of potential from its equilibrium value. A steep slope of this plot is desirable since the electrode potential will then remain relatively constant during use (the slope is proportioned to exchange current). This slope should be greater than 0.1 micro-amp per mV.

Furthermore, data taken during increasing potentials should be very nearly the same as data taken during decreasing potentials, i.e. the plot should form a single straight line rather than two separate lines. A plot with two separate lines indicates a changing potential with the passage of time. This hysteresis effect is an indication that the electrode may not be sufficiently reversible.

650A.A.02.02 Long-Term Stability Test: It is usually intended that an embedded reference electrode will be used to control the cathodic protection system for several years. The long-term stability of a reference electrode is particularly difficult to predict and test.

For this test, a sample specimen is constructed identical to that described for the Polarization Test above. Again, it is recommended that no steel be included in the specimen.

The specimen is then placed outdoors in a northern climate (wet, freeze-thaw environment), and performance is monitored. During this time, the following data are recorded.

- Reference electrode under test versus standard reference electrode, mV.
- Reference electrode under test versus calibrated surface reference electrode, mV.
- Standard reference electrode versus calibrated surface reference electrode, mV.

Data are recorded at least weekly for 1 year.

Potential difference between the reference electrode under test and the calibrated surface reference electrode should not vary by more than 50 mV, and should exhibit no obvious long-term trends. Potential difference between the reference electrode under test and the embedded standard reference electrode should not vary by more than 20 mV, and should exhibit no obvious long-term trends.

650A.A.03 RECTIFIERS

650A.A.03.01 Description: This specification defines the requirement for the manufacture of new cathodic protection rectifiers for bridge deck protection.

New materials and equipment shall be designed, manufactured and tested in accordance with the minimum applicable requirements of the latest editions of the following codes and standards referenced:

- National Electrical Code (NEC)

- National Electrical Manufacturers' Assoc. (NEMA)
- American Society for Testing and Materials (ASTM)
- Military Specifications (Mil Spec)
- American National Standards Institute (ANSI)

The new material shall be installed outdoors and subjected to varying corrosive atmospheres with an ambient temperature of up to 50°C and relative humidity up to 100%.

Each new rectifier supplied shall include as a minimum: a wiring schematic, parts list, test results and an operation and maintenance manual.

The new rectifier shall be warranted for 1 year after installation or 18 months after delivery (whichever comes first) against defects in design or workmanship.

The new rectifier shall be supplied by an established company presently involved in the design and manufacturing of cathodic protection rectifiers.

650A.A.03.02 Enclosure: The enclosure shall be designed to meet NEMA type 3R, 4 or 4X requirements as outlined in NEMA Publication No. 250 and selected by the designer. It shall be constructed of steel, stainless steel, aluminum, anodized aluminum or plastic material of sufficient thickness to meet the outdoor requirements of the rectifier. The enclosure shall be designed for pole, wall or base mounting, as required. If air cooled, any opening designed for cooling and over 1/8 inch shall be screened to prevent entry of nest-building insects. The enclosure shall have ready access to the rectifying and controlling components through door(s) as listed in the rectifier manufacturer's submittal criteria. The enclosure shall be lockable to protect the interior components from weather and vandalism. Knockouts for wiring shall be conveniently located in the bottom of the enclosure and be of adequate number and size to provide for input and output connections. A grounding lug shall be provided on the outside of the enclosure to accommodate a #6 AWG copper ground wire.

If the cabinet is NEMA 4 Aluminum, external heat sink cooling fans shall be finished in hard coat anodizing. All other exterior sheet aluminum parts shall be suitably prepared and finished in 3 to 5 mils polyester fusion bond powder paint.

650A.A.03.03 New Standard Air Cooled Rectifiers: Any new standard air cooled rectifier has to meet the design criteria as set forth in Paragraphs 650.21.03 through 650.21.10. These rectifier(s) have to have demonstrated two (2) years of successful operation in a bridge deck environment.

650A.A.03.04 New Electronically Controlled Rectifiers: Individual, plug-in control cards (one per output circuit) shall be provided for constant voltage or constant current operation as required. The control circuit shall provide for continuous adjustment over the full range of the rated output voltage as well as continuous adjustment over the full range of output current. When operated in the constant current mode, the voltage must be permitted to fluctuate over the full output range. Variations of input line voltage over the design range shall not cause the output of the circuit to deviate from its set point. In multiple output rectifiers adjustment of one circuit's output shall not effect the preset output of any other circuit. Each circuit shall be able to operate at distinct and separate voltage and amperage settings depending on the mode of operation.

Control cards are to be wave soldered, tested, burned in for a minimum of 100 hours, and be retested before being placed into a unit. After testing, accepted control cards will be conformal coated to protect against the environment.

Meters shall be digital LED with + or -0.5% and be fully temperature compensated from -30°C to +65°C. The meter(s) shall have environmentally sealed switches to select the reading required. A selector switch will be provided which will have an "**OFF**" position that removes the meter from the circuit.

New electronic controllers have to have demonstrated successful operation for 2 years in a bridge deck environment.

650A.A.03.05 Other Provisions: Paragraphs 650.21.12 through 650.21.16 (except as otherwise noted), and 650.21.17, if applicable, shall be adhered to.

B. WARRANTY CHECK ON RECTIFIER

It is common for the rectifier to have a manufacturer's warranty covering manufacturing defects and design errors. Before the warranty period is over, the rectifier should be inspected for possible problems that would be covered by the warranty.

650A.B.01 ENCLOSURE: The enclosure should show no signs of rusting or blistering due to poor application of galvanizing, paint, or other coating. All doors and latches should work smoothly. (NOTE: The manufacturer cannot be held responsible for damage if the type of enclosure or finish is not suitable for the environment in which it is placed.)

650A.B.02 TRANSFORMERS, REACTORS, CHOKES: If the unit was properly maintained, and there is no obstruction to air flow, these devices should have no signs of overheating or rusting; tap wires should show no signs of overheating.

650A.B.03 METERS: The meters should be readable, function properly, and accurately.

650A.B.04 CIRCUIT OPERATION: Each circuit should be easily adjusted and perform as it did when installed. If there are printed circuit boards in the rectifier, turn off the rectifier and inspect each one for signs of overheating components. Contacts in the printed circuit board connector should not be sprung or discolored. If the rectifier has rheostats in the output for adjustment, inspect the rheostat and its mounting for signs of overheating and discoloration.

650A.B.05 RECTIFYING ELEMENTS: The heat sinks that the main rectifying elements are attached to should each be approximately the same temperature if each circuit is operating at the same current output. If there is uneven heating or discoloration of the heat sinks, they may be undersized, or the rectifying element itself may be undersized. Any signs of overheating may be an indication that the component is not properly sized for the application and should be reported. These items may be covered by the manufacturer's warranty if the rectifier was properly installed, maintained, and operated within its specified limits.

C. TEST METHODS

650A.C.01 ESTIMATED ELECTRICAL RESISTIVITY OF CONCRETE MATERIALS

650A.C.01.01 Obtain three fully cured core or cylinder samples at least 4 inches in diameter and 2 inches long. The samples shall be completely representative of the concrete to be studied.

650A.C.01.02 Perform Rapid Permeability tests on each of the three samples in accordance with the procedure of AASHTO T277-83I "Rapid Determination of the Chloride Permeability of Concrete", except add the following:

650A.C.01.03 Immediately prior to connection of the 60-volt power supply leads, record the two pin AC resistance between the two cell halfs, measured with a Nilsson 400 or equivalent.

650A.C.01.04 Calculate estimated resistivity by multiplying the measured AC resistance by 16.8.

650A.C.01.05 Report the estimated resistivity (73 degrees F, vacuum saturated) as the value obtained in 650A.C.01.04 for each specimen. Average the findings for the three individual specimens and also report the average and the range.

650A.C.02 RESISTIVITY TESTING OF COKE-ASPHALT MIXTURES

1. SCOPE

1.1 This method describes the procedure for the measurement of electrical resistance of an asphalt briquette prepared using Marshall compaction and testing apparatus.

2. RELEVANT DOCUMENTS

2.1 ASTM Designation D1664-80 *Standard Test Method for Coating and Stripping of Bitumin-Aggregate Mixtures.*

2.2 AASHTO T245-82 *Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus.*

2.3 AASHTO T166-78 *Bulk Specific Gravity of Compacted Bituminous Mixtures.*

2.4 AASHTO T209-82 *Maximum Specific Gravity of Bituminous Paving Mixtures.*

2.5 AASHTO T269-80 *Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures.*

3. APPARATUS

3.1 AC OHMETER: One capable of measuring to .01 ohms is preferred as this instrument is best suited for both laboratory testing and at field installations, or,

3.2 AC or DC OHMETER: Capable of measuring to .01 is acceptable for laboratory measurements.

NOTE: Two models of the recommended AC ohmeters are; (a) Vibroground, Associated Research Inc., and (b) Neilson 400.

3.3 "C" CLAMP: 100-mm size, one required.

3.4 PLEXIGLASS DISCS: 98-mm diameter by 6.35 mm thick, two required.

3.5 COPPER SHEET: 101-mm diameter by 0.8 mm thick, as required.

3.6 VERNIER CALIPER: With 0.025 mm accuracy, one required.

4. TEST PROCEDURES

4.1 Use MTO Test Method LS-261 for the preparation of the Marshall specimens with the following exceptions:

4.1.1 Determine the mass and the thickness of the two copper plates being used.

4.1.2 Place one copper plate in the bottom of the compaction mold.

4.1.3 Weigh in a mass of approximately 900 g of mixture to produce a briquette with a desired compacted volume ranging from 510 to 520 mL.

4.1.4 Rod the mixture as outlined in MTO Test Method LS-261, place the other copper plate on the rodded mixture, and compact in the normal manner.

4.2 Using the Vernier calipers, measure the diameter and the height of the briquettes at four different locations. An average value for each is then computed. If the copper plates are attached to the briquettes, subtract the thickness of the plates from the height dimensions.

4.3 Subtract the mass of both copper plates, and calculate the bulk relative densities of the briquettes.

4.4 Place a plexiglass disc against each of the copper plates leaving sufficient area of the copper plates exposed so that the ohmeter lead terminals can contact each copper plate.

4.5 Center the "C" clamp on each plastic disc, and apply a small compressive force to hold the discs on the copper plates. Place an ohmeter lead terminal on each copper plate.

4.6 After each 1/8-turn of the "C" clamp, measure the resistance of the sample between the copper plates and record the value. The resistance value should decrease as the applied compressive force is increased. Apply pressure in increments by means of the 1/8-turn of the "C" clamp until the resistance no longer decreases. The lowest resistance achieved is recorded for the final calculations, and should be obtained before the sample has noticeably deformed.

5. REPORT

5.1 The resistivity for each sample is determined using the following formula:

$$P = \frac{R \times A}{L}$$

where: P = resistivity - ohm cm

R = resistance - ohm

A = area of briquette - cm^2

L = length of briquette
between copper plates - cm

5.2 Maximum allowable resistivity is 3 ohm cm.

6. GENERAL NOTES

If the resistivity is greater than 3 ohm cm, alter the mix proportions by replacing a portion of the sand with a maximum of 5 percent by mass of additional coke breeze.

D. GLOSSARY OF CORROSION AND CATHODIC PROTECTION RELATED TERMS

Alternating Current - Electric current which repeatedly reverses direction on a periodic cycle, usually at a frequency of 60 cycles per second (60 Hz).

A.C. Service - Alternating current supply to the rectifier; usually 120 or 240 volts A.C.

Anode - The electrode at which oxidation reactions (i.e. corrosion reactions) occur, and to which negatively charged ions migrate when an electric current is passed through an electrolyte. In a bridge deck cathodic protection system, the anode is an inert material which is used to distribute protective current to the reinforcing steel.

Anode Manufacturer's Installation Supervisor (IS) - Representative of the anode manufacturer who is familiar with all aspects of the product and its installation. The IS shall give advice to the contractor in the field regarding the product installation and perform all necessary field tests to ensure proper installation of the anode system. The IS shall have a minimum year of relevant experience on bridge deck cathodic protection systems.

Anode Mesh CP System - An anode mesh system used for cathodic protection of reinforced concrete structures. The system consists of a catalyzed titanium anode mesh, current distributors and plastic fasteners. The anode mesh CP system is used in conjunction with a rigid concrete overlay.

Anode Zone - An isolated anode circuit on the concrete deck occupying an area not exceeding 6,500 square feet.

ASCII - Computer code given numerical equivalent of characters and numbers.

ASTM A123 - Standard for hot dip galvanizing of steel.

ASTM C876-91 - Standard for measurement and interpretation of half-cell potentials of reinforcing steel in concrete.

Attenuation - Electrical losses in a conductor caused by current flow in the conductor.

BPE - State Bridge Project Engineer, also referred to as the "Engineer" or Owner's representative.

Carbon Strand - An anode conductor used in conductive polymer slot and mounded CP systems. The material consists of multiple high purity carbon strand filaments wrapped with dacron fiber.

Cast Iron Anode - A primary anode used in coke asphalt CP systems. The anode consists of high silicon iron cast into a flat disc or pancake, with attached lead wire.

Cathode - The electrode at which reduction occurs, and to which positively charged ions migrate when an electric current is passed through an electrolyte. In a bridge deck CP system, the cathode is the embedded steel.

Cathodic Protection (CP) - Reduction or elimination of corrosion by making the metal (reinforcing steel) a cathode. CP of reinforced concrete is usually accomplished by means of an impressed D.C. current.

Cell - An electrochemical system consisting of an anode and a cathode in metallic contact and immersed in an electrolyte. The anode and cathode may be different metals.

Circular Mils - A measurement of cross sectional area, typically used in describing the size of copper conductors.

Coarse Taps - Large interval adjustment settings placed along the secondary of a transformer in a rectifier. The taps produce voltages corresponding to the number of turns at which they are connected.

Coke Asphalt CP System - A type of anode system for cathodic protection of reinforced concrete bridge decks. The system consists of one coarse of conductive asphalt containing coke breeze, powered by embedded cast iron anodes, and one coarse of conventional bituminous mixture constructed as a wearing surface.

Conductive Polymer Grout (Concrete) - A conductive polymer anode material used with mounded or slotted CP systems. The material consists of three components (promoted resin binder, catalyst and carbon filler), which are premeasured and mixed on site.

Constant Current - An operating mode in a rectifier in which the current is set at a fixed level, and the voltage varies. Variations in the rectifier output voltage and current will occur with the changes in the bridge deck resistance and AC line voltage and is limited by the tap settings of the transformer.

Constant Voltage - An operating mode in a rectifier in which the voltage is set at a fixed level, and the current varies. Variations in the rectifier output voltage and current will occur with the changes in the bridge deck resistance and AC line voltage and is limited by the tap settings of the transformer.

Corrosion - The natural tendency of a metal to revert to its native state because of a reaction with its environment. In order for corrosion to occur there must be an anode, a cathode, an electrolyte and a metallic path between the anode and cathode.

Corrosion Engineering Technician (CET) - An approved technician from the corrosion engineering firm, who shall assist in the field inspection and testing of the cathodic protection system. The CET shall have at least one year of similar experience on bridge deck CP installations.

Corrosion Product - Product resulting from a corrosion reaction. The term may apply to a solid compound (rust), gases or ions.

Corrosion Rate - The speed at which corrosion progresses, often expressed as a constant loss or penetration per year (mils per year, for thickness changes) or in units of milligrams per square decimeter per day (mdd), for weight change. 1 mil = 0.001 inch, 1 milligram = 0.001 gram.

Current - A movement of electricity through a solid or solution; commonly measured in amperes or milliamperes (1 ampere = 1,000 milliamperes). In a cathodic protection system, the direct current flow is ionic (through the electrolyte) and electronic (through the metallic paths).

Current Density - The current per unit area of surface of metal or concrete. A common unit is mA/sq.ft. (milliamperes per square foot).

Current Distributor - An uncoated strip of titanium (0.5 inches wide) which is used with the anode mesh CP systems. The purpose of the current distributor is to feed current to the anode mesh system and connect adjacent rolls of mesh together electrically. The current distributor is typically placed across the deck and welded to the mesh using a portable resistance welder.

Dead Front - Isolated panel used to shield electrical components.

Delamination - A separation along a plane parallel to the concrete surface, frequently found in reinforced concrete structures as a result of corrosion of reinforcing steel.

Depolarization Test - An acceptance test used for cathodic protection of reinforced concrete structures. The depolarization is determined by interrupting the protective current and measuring the potential decay between the reinforcing steel and a calibrated reference cell. The potential decay should be monitored for a minimum 4-hour period. The depolarization equals the final potential minus the initial interrupted potential (IR drop free). A minimum 100-millivolt depolarization shift is a commonly used criterion for cathodic protection of reinforcing steel in concrete.

Design Specifications - A set of documents that, in aggregate, will form the nucleus for well-founded, understandable and equitable contract documents. These documents include written specifications and/or drawings.

Diode - An electrical device in a rectifier that allows passage of current in only one direction. The diode is used to convert A.C. current to D.C. current. Silicon and selenium are common diodes.

Direct Current (D.C.) - Electric current that flows in only one direction.

Disconnect Switch - A device used for breaking the flow of electric current.

D.C. Wiring - All insulated conductors necessary for connecting the anode zones, reinforcing steel, reference cells and other instrumentation with the rectifier and/or junction box.

Efficiency - One measure of the quality of a rectifier indicating the amount of input power reaching the output. The efficiency of rectifiers may range from 50% to over 90%.

Electrode - A metal in contact with an electrolyte which serves as a site where electrochemical reactions occur.

Electrical Continuity - A closed circuit (unbroken electrical path) between metal components under consideration. For cathodic protection of bridge decks, continuity typically refers to the electrical connection of reinforcing steel.

Electrical Discontinuity - The physical separation between metal components under consideration. For cathodic protection of bridge decks, electrical discontinuity typically refers to discontinuous reinforcing steel, or isolation of the anode from the cathode (reinforcing steel).

Electrolysis - Chemical changes in an electrolyte brought about by the passage of an impressed electric current.

Electrolyte - Any medium which serves as a conductor for the passage of ionic current (i.e. concrete, soil and water).

E-Log I Test - An acceptance test for cathodic protection (CP) of reinforced concrete. The E-Log I test is performed by incrementally increasing the CP current from the installed system. At each interval, the IR drop free potential of the steel reinforcement is measured relative to a stable reference cell. A plot of the reinforcing steel potential versus the logarithm of the current applied is then made. The current required for cathodic protection is the value determined to occur at the linear behavior of the plot (tafel slope).

Energizing - (turn on) The process of initially applying power to a cathodic protection system.

Engineer - The owner's representative or project engineer, also referred to as the BPE.

Exothermic Weld - (thermite weld) A fusion weld of a copper wire to a metal surface (reinforcing steel). Exothermic welds for cathodic protection use a special alloy to provide minimum heat effect on the steel.

Filter - A device used to increase the conversion efficiency of a rectifier. Filters typically consist of an inductor or choke, which is used to reduce the ripple component in the D.C. output.

Fine Taps - Low interval adjustment settings placed along the secondary of a transformer in a rectifier. The taps produce voltages corresponding to the number of turns at which they are connected.

Ground Electrode - (ground rod) Electrical contact with earth ground.

Half-Cell - A single electrode in contact with an electrolyte and which, in contact with another half-cell, forms a full electrochemical cell. This term is sometimes used to designate a reference electrode or reference cell.

Heat Shrink - A heat shrinkable tube used to insulate a bare conductor.

Impressed Current System - The type of cathodic protection system in which an externally supplied direct current is forced between the anode and cathode by means of an external source, such as a rectifier.

Instant Off - The polarized half-cell potential of an electrode (embedded reinforcing steel) taken immediately after the protective current is turned off. The instant off potential closely approximates the IR drop free value when there was current flow.

Interrupting - The on and off cycling of a power supply (rectifier).

Interrupter - A device used for interrupting current flow. The interrupter may be internal within the rectifier or portable.

Ion - An atom or group of atoms that have lost or gained one or more electrons, and have therefore acquired an electric charge (i.e. Cl^-, OH^-, H^+, Na^+).

IR Drop - The voltage drop in a conductor caused by current flow and resistance within that conductor. IR drop occurs in both metallic and electrolytic conductors.

LCD - (Liquid Crystal Display) Display on a digital meter which requires light from an external source.

Lead Acid - A type of battery used for solar power supplies.

LED - (Light Emitting Diode) Display on a digital meter that can be read well in low light, but which is very difficult to read in bright light such as indirect sunlight.

Lightning Arresters - Devices which are used to protect electrical components from voltage surges. Lightning arresters are typically placed on the A.C. and D.C. sides of a rectifier.

Link Bar - A metal strap which connects two terminals in an electrical device. In a rectifier, link bars are typically used to connect and adjust transformer tap settings.

Macro Cell - A corrosion cell with a large anode to cathode relationship. A macro cell is sometimes used to designate a rebar probe.

Metal Oxide Varistor - (MOV) A lightning arrester used to protect silicon diodes, SCR's, and other sensitive electronic components from voltage surges. MOV's are voltage sensitive resistors which react quickly to voltage surges and can conduct large amounts of currents for short periods of time.

Meters - An instrument which is used for measuring and recording such as in the case of rectifier voltage, current and reference cell potential. Rectifier meters may be analog or digital.

Micro Cell - A corrosion cell with a small anode to cathode relationship.

Mounded CP System - A type of cathodic protection system in which conductive polymer concrete is placed in longitudinal and transverse mounds on the surface of the deck and covered with a concrete overlay.

NACE RPO290-90 - NACE standard which deals with cathodic protection of reinforcing steel in atmospherically exposed concrete structures.

NEMA Grade XX - NEMA rating for insulating panel materials.

NEMA Type 3R Enclosure - Type 3R enclosures are intended for outdoor use primarily to provide a degree of protection against falling rain, sleet, and external ice formation.

NEMA Type 4 Enclosure - Type 4 enclosures are intended for indoor or outdoor use primarily to provide a degree of protection against wind blown dust and rain, splashing water, and hose directed water.

NEMA Type 4X Enclosure - Type 4X enclosures are intended for indoor or outdoor use primarily to provide a degree of protection against corrosion, wind blown dust and rain, splashing water, and hose directed water.

Nonconductive polymer concrete - A nonconductive polymer consisting of three components (resin binder, catalyst and sand), which are premeasured and mixed on site. Nonconductive polymer concrete is typically used with conductive polymer concrete CP systems, to insulate the anode material from contacting exposed or partially embedded steel.

Ohm's Law - The relationship between voltage, current and resistance (E = IR).

Oxidation - A chemical or electrochemical reaction involving the loss of electrons. Corrosion of metal at an anode is an example of oxidation.

pH - A value taken to represent the acidity or alkalinity of a solution. A pH of seven is considered "neutral", with lower numbers representing solutions which are acidic and higher numbers solutions which are basic or alkaline.

Platinized Niobium Copper Core Wire - A primary anode conductor (.031 or .062 inch diameter) used in conductive polymer slot and mounded CP systems. The wire consists of a copper core, clad with a layer of niobium and then a thin outer layer of platinum.

Polarization - The shift in potential of an electrode away from its open circuit potential resulting from the passage of current. In a cathodic protection system, polarization refers to the protective film that develops on the surface of the cathode (reinforcing steel).

Polarization Decay - The decrease in electrode (reinforcing steel) potential with time, resulting from the interruption of applied current.

Potential - A voltage measurement (i.e. half-cell potential).

Potential Survey - Obtaining half-cell potentials at multiple locations on the surface of a structure.

Potentiometer - An instrument used for measuring voltage. Also a variable or adjustable resistor.

Primary Anode - Any anode material which acts as a contact medium for the secondary anode and distributes current from the power supply line to the secondary anode.

Project Principal Corrosion Engineer (PPCE) - An approved engineer from the corrosion engineering firm who shall review all work performed by the project corrosion engineer. The PPCE shall be a registered Professional Engineer or a National Association of Corrosion Engineers (NACE) certified Corrosion Specialist or certified Cathodic Protection Specialist. The PPCE shall have at least 8 years of related experience on bridge deck CP systems.

Project Corrosion Engineer (PCE) - An approved engineer from the corrosion engineering firm who shall be on-site to supervise and/or perform all inspection and testing as outlined in the project specifications, and provide expert opinion regarding field modifications, additions and/or deletions. The PCE shall have at least 5 years of related experience on bridge deck CP systems and/or 10 years experience in evaluation of steel reinforced concrete structures.

Protective Device - A device used to protect electrical components from voltage surges, such as a lightning arrester or MOV.

Rebar Probe - A monitoring probe used to evaluate cathodic protection performance. The probe consists of a segment of reinforcing bar which is attached to an insulated wire and cast into a salty mortar block (Chloride content is typically 15 pounds per cubic yard). The high chloride content simulates the most anodic location in the deck. A macro cell is sometimes used to designate a rebar probe.

Reduction - A chemical or electrochemical reaction involving the gain of electrons; as when a metal ion in solution goes to the metallic state at a cathode.

Reference Cell - (Reference electrode) A half-cell of reproducible potential (i.e. Ag/AgCl, $Cu/CuSO4$ and Graphite). A standard against which the potentials of other electrodes can be measured and compared. Reference cells may be portable or permanently embedded in the concrete deck.

Reference Cell Ground - Wire connected to the reinforcing steel used for obtaining reference cell potential measurements.

Remote Monitoring System - A device used to collect and transfer rectifier operating data to a remote computer terminal, thus eliminating the need for monthly field inspections at the bridge. The remote monitoring system typically consisting of a data recorder, modem, telephone service and personal computer at the receiving end.

Resistance - Opposition offered by a conductor to the passage of electrical current; measured in ohms.

Resistivity - The electrical resistance of a substance (i.e. concrete, water and soil) commonly measured in ohm-centimeters (ohm-cm). Concrete of lower resistivity is likely to be more corrosive than concrete of higher resistivity.

Rectifier- A device used to convert alternating current to direct current. In a cathodic protection system the rectifier is used to control the voltage and current output to each zone.

Rectifying Element - A device which is used to pass current in one direction and to block it in the opposite direction. Fabricated from either silicon or selenium (see diode).

Ripple - percent ripple = Ripple Voltage (RMS)/volts DC x 100. Ripple voltage shall be measured across the output terminals of the rectifier with a true RMS AC voltmeter. Volts DC shall be measured across the output terminals of the rectifier with a DC voltmeter.

R.M.S. - (Root Mean Square) The R.M.S. value represents both the D.C. and A.C. components of a rectifier waveform and is 70.7% of the peak value and 111% of average D.C. value.

Rusting - Corrosion of iron or iron-based alloys to form a reddish brown product known as rust, which is primarily iron oxide. A term properly applied only to ferrous alloys.

Saturable Core Reactor - A type of rectifier that provides constant current output. A saturable core reactor is a transformer type device in which the A.C. voltage is regulated by a D.C. current flowing on the iron core.

Secondary Anode - Any anode material that distributes the cathodic protection current to the entire surface of the structure under cathodic protection.

Shunt - A calibrated resistor used to measure D.C. current flow in a metallic conductor. The current is calculated by measuring the millivolt drop across the shunt, and multiplying this value by the calibration factor for the shunt (Amps/mV).

Sliding Terminal Blocks - A type of terminal block in an electrical circuit that allows "through" connections (from one side to the other) to be easily made or broken.

Slotted CP System - A non-overlay cathodic protection system consisting of a series of saw cuts placed in the concrete deck. Primary and secondary anode conductors are then placed in these slots and backfilled with a conductive polymer concrete.

Solar Power Supply - An alternate power source which is used in remote areas where electric service is not available. A solar power supply consists of a photovoltaic solar array, battery bank and system controller/regulator.

Spalling - The cracking and separation of concrete caused by corrosion induced stresses.

Stray Current Corrosion (interference corrosion) - Corrosion caused by direct current from external sources through paths other than the intended circuit. Accelerated corrosion may result if such current is collected by a structure and leaves to enter the electrolyte.

System Negative Connection - Cable connection to the reinforcing steel from the rectifier negative (-) output.

Transformer - One or more coils of wire wound around a laminated iron core. Its purpose is to step a voltage up or down, and to isolate the D.C. circuit from its source in a rectifier.

Voltage - Difference of potential expressed in volts or millivolts (1 volt = 1,000 millivolts).

Voltage Probe - Graphite reference cell placed in contact with coke asphalt and used only with coke asphalt cathodic protection system in accordance with Section 651.

E. SELECTED REFERENCES

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5. Stratfull, R.F., Editor, *"A Manual for the Corrosion Control of Bridge Decks"*, Report No. FHWA-CrENG-1, Federal Highway Administration, February 1983 (not published).

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9. *State of the Art Report - Cathodic Protection of Reinforced Concrete Elements"*, SHRP S-337, Strategic Highway Research Program, National Research Council, Washington D.C., 1993, p. 89.

10. *"Cathodic Protection of Reinforced Concrete Bridge Decks"*, Proceedings of the Conference on Cathodic Protection of Reinforced Concrete Bridge Decks, San Antonio, Texas, February 12-13, 1985, published by National Association of Corrosion Engineers.

11. *"Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete"*, C876-91, American Society of Testing and Materials.

12. *"Maintenance and Rehabilitation Considerations for Corrosion Control of Existing Steel Reinforced Concrete Structures"*, RP-0390, National Association of Corrosion Engineers, 1990.

13. *"Design Considerations for Corrosion Control of Reinforcing Steel in Concrete Structures"*, RP0187/90, National Association of Corrosion Engineers, 1990.

Appendix B

Tentative Guide Specification for Cathodic Protection of Concrete Bridge Substructures

655. BRIDGE SUBSTRUCTURE CATHODIC PROTECTION

655.10 DESCRIPTION: This document was prepared under the SHRP C102D Contract "Manual, Model Specifications and Cost Information on Cathodic Protection of Reinforced Concrete Bridge Elements". The goal of this document is to delineate concise guidelines which can be used by highway agencies as standard specifications for Cathodic Protection of Reinforced Concrete Bridge Substructures. It is recognized there are bridge structures which do not match the standard and would be subject to special study and design. Standardization is expected to permit contractors to install these systems efficiently and, hence, provide an economic system to the bridge owner.

Cathodic Protection (CP) is the only known fully developed means of mitigating the corrosion of reinforcing steel in existing bridge elements caused by the presence of chloride ions. The routine use of CP for pipeline protection and underground structures prompted development of new technologies which would allow the successful application and operation of CP on bridge elements. The first installation of an impressed current CP system on a bridge deck took place in California in 1973, using high silicon cast iron anodes affixed to the deck and covered with a 2-inch lift of conductive coke breeze asphalt and topped with a 2-inch wearing course of asphaltic concrete. Since that pioneering effort, the field of cathodic protection for reinforced concrete bridge elements has matured into a proven technology with several design options available. It should be considered as a value engineering alternative for the rehabilitation of salt-contaminated bridge elements.

As in any new technology, advancement of state-of-the-art of bridge element CP involves interaction among Federal and State government agencies with researchers, contractors, and private industry and governmental research agencies. In 1982, the Federal Highway Administration issued a position paper on Cathodic Protection Systems which promoted widespread implementation of CP as a rehabilitation technique for bridge decks. The intensive research and product development by private industry and governmental research agencies which followed, has led to a new generation of anodes and a substantial reduction in the cost of materials and installation. The final determinant for any technology, however, must be generated by successful performance under field conditions. Satisfactory operation of more than 350 systems in 37 States and 8 provinces in Canada give suitable testimony to the viability of CP.

The specifications listed below are the product of this ongoing effort to advance the reliability and refine the design, construction, and operation of CP on bridge elements. Those components specified have been subjected to extensive and exhaustive laboratory testing and have also provided a minimum of at least two years of adequate field performance. The specifications cover three different types of anode systems, but no recommendations as to the proper system for a given structure, either direct or implied, are intended. The available systems are:

- Conductive coating
- Thermally sprayed zinc
- Catalytic titanium anode mesh with shotcrete overlay

At present, only one catalytic titanium anode mesh is included in these specifications. Similar systems by other manufacturers have been installed and are being evaluated.

We hope that all possible alternatives will continue to be studied and that these standards will be updated as appropriate, as new anode systems with adequate field performance become available.

General specifications for other components such as reference cells, rectifier, etc., are also included, as well as recommended installation and activation procedures. At present, a saturable reactor type rectifier is specified. Silicon controlled rectifiers (SCR's) have also been successful in some installations. Items which were used in the research phase of cathodic protection of bridge elements, such as rebar probes, corrosometers, and multi-control mode rectifiers are not listed as they are not deemed necessary for routine operation.

In developing the specifications important reference materials were used. Several of the most pertinent documents are listed in the Annex item E in Section 650A.

The use of cathodic protection on the following structures is not recommended at this time:

- Prestressed or posttensioned bridge substructures,
- Bridge substructures with alkali-reactive aggregate concrete.

Equally important to proper specifications is the selection of a qualified and experienced corrosion engineer to develop the final design details, and to provide quality control and assessment during construction and proper system activation. Guidelines are provided within the specifications that indicate the minimum qualifications recommended.

Section 655 is the main substructure cathodic protection specification, and includes an Annex covering the qualification of new materials and systems, the recommended rectifier warranty check, test methods, and a glossary of terms. It is followed by sections relating to each anode system (656: *Conductive Coating*; 657: *Thermally Sprayed Zinc*; and 658: *Anode Mesh with Shotcrete Overlay*).

To implement this specification, it is necessary that the specifier complete the Design Specifics checklist in section 655.30.02. Detailed plans beyond those normally used on rehabilitation projects are not required. The detailed anode design and layout will be performed by the contractor and submitted as shop drawings prepared and signed by the Corrosion Control Consultant.

655.20 CATHODIC PROTECTION MATERIALS

655.21 CATHODIC PROTECTION RECTIFIER

655.21.01 Description: This specification defines the requirements for manufacturing cathodic protection rectifiers for bridge substructure protection. *The rectifier shall be the saturable reactor constant current type with the ability to change control to constant voltage.* The rated DC output of each circuit shall be 24 volts, 10 amperes. The rectifier shall be designed and constructed in accordance with the appropriate schematic shown in Figure 655-1 and the following specifications. Load (D.C. circuit) resistance will be variable and is expected to range from 0.25 ohms to 2.5 ohms. If the zone to be protected is smaller than 1,000 square feet, the DC output voltage and current specified should be reduced.

Materials and equipment shall be designed, manufactured, and tested in accordance with the minimum applicable requirements of the latest editions of the following codes and standards referenced:

- National Electrical Code (NEC)
- National Electrical Manufacturers' Assoc. (NEMA)
- American Society for Testing and Materials (ASTM)
- Military Specifications (Mil Spec)
- American National Standards Institute (ANSI)

The material shall be installed outdoors and subjected to varying corrosive atmospheres with an ambient temperature of up to 50°C and relative humidity up to 100%. The expected operating life shall be in excess of 20 years.

Each rectifier supplied shall include two sets of the following as a minimum: a wiring schematic drawing, parts list, test results, and an operation and maintenance manual.

The rectifier shall be warranted for one full year after installation or 18 months after delivery (whichever comes first) against defects in design or workmanship.

The rectifier shall be supplied by a company established in and presently involved in the design and manufacture of cathodic protection rectifiers.

655.21.02 Enclosure: The enclosure shall be designed to meet NEMA type 3R, 4 or 4X requirements as outlined in NEMA Publication No. 250 and selected by the designer. It shall be constructed of 11 gauge minimum thickness material and shall provide for adequate convection cooling of internal components. The enclosure shall be designed for either pole, wall, or base mounting as required. Any opening designed for cooling and over 1/8" shall be screened to prevent entry of nest building insects. NEMA 3R enclosures shall have hinged removable front and side doors with bolts on adjustable stainless steel heavy-duty latches. NEMA 4 air cooled rectifiers shall have a single hinged front door with heavy duty, stainless steel latches. NEMA 4 air cooled enclosures shall include a thermostatically controlled fan with filter to provide adequate cooling. The fan and filter may be omitted if the designer can show that the rectifier will cool properly when operated at maximum output voltage and current and the maximum ambient temperature. When a NEMA type 4 oil cooled enclosure is specified the transformer and rectifier stack shall be mounted on separate removable racks. The enclosure shall have provisions for locking and protect the interior components from weather and vandalism. Entry for wiring shall be located in the bottom of the enclosure and be of adequate number and size to provide for input and output connections. A grounding lug shall be provided on the outside of the enclosure to accommodate a #6 AWG copper ground wire. A permanent manual holder shall be provided, attached to the inside of the cabinet door.

655.21.03 Transformer: The transformer shall be specifically designed for use in a cathodic protection rectifier, have separate, isolated primary and secondary copper windings and a grounded copper Faraday shield between primary and secondary windings. The transformer will be designed to operate continuously at rated load and will supply rated output at 5% low, 10% high line voltage without damage. The wire size of both windings is to be based on a minimum of 750 circular mils per amp. The transformer regulation shall not exceed 3% when measured at 1/4 load and full load. The transformer and materials will be designed and manufactured to meet the requirements of MIL E 917. The secondary will have a sufficient number of coarse and fine taps to allow adjustment of the output in 1/2-volt increments. All tap leads shall be sized for a minimum of 500 circular mils per ampere. These taps shall be brought out to link bar arrangements or a terminal block for adjusting the output of the rectifier and shall be located on the instrument panel.

The transformer shall be vacuum impregnated or preheated and immersed in Class F (150 degrees C) transformer varnish until all tapes, insulating materials, outer wrapping and coil windings have been completely saturated and then oven baked until dry. When completed and before installation into a rectifier, the transformer shall be tested and must be able to withstand 2000 volts for one minute without breakdown between the primary and core, secondary and core, and primary to secondary.

Each circuit shall have its own isolated secondary winding or individual transformer designed per the above requirements.

655.21.04 Rectifying Elements: The rectifying bridge shall have a forward average current rating of 25 amps minimum. Each diode shall have a minimum peak reverse voltage rating of 800 volts. Heat sinks shall be sized to provide continuous rectifier operation at rated ambient temperature and rated output. When block style rectifying elements are used, in addition to the above, they shall have 1200 volt minimum isolation.

655.21.05 Protective Devices: The entire unit is to be protected against overload and short circuit by a thermal magnetic type circuit breaker of the proper voltage rating and sized to hold 100% of the rated load current. It is to be connected between the AC supply and transformer primary. The circuit breaker shall be the manual reset type and must trip at between 110% and 125% of rated input current. The breaker shall be positioned and labelled to meet the requirements of the NEC article 240 sections 80 through 83C. In the case of multiple circuit rectifiers with individual transformers, each circuit shall have its individual AC supply protected by a properly sized fuse in addition to the breaker.

Rectifiers shall have a quick acting magnetic breaker rated at 120% of the circuit capacity placed in one leg of the AC secondary of each circuit.

655.21.06 Lightning and Surge Protection: The unit shall be equipped with properly sized AC and DC lightning protection. Each controlled output as well as every input to the rectifier shall be protected against voltage surges, using properly sized surge suppressors. Metal oxide varistors (MOV's) used to protect the AC input and DC output shall be rated at 500 joules and have a voltage rating which provide adequate protection to the internal circuitry. (See the table below.)

VAC INPUT	MOV RATING(max)	DC OUTPUT	MOV RATING(max)
120	250 VRMS	24	130 VRMS
240	480 VRMS		

655.21.07 DC Panel Meters: Meters are not required, but when specified, shall have a minimum 2 1/2-inch scale, d'Arsonval pivot and jewel type movement, and have an accuracy of 2% of full scale. The meter circuit(s) will include a switch, hermetically sealed, which removes the meter(s) from the circuit when not in use. The ammeter shall be connected to an external shunt plainly marked to show ampere rating and millivolt drop. A single ammeter may be used in conjunction with a hermetically sealed selector switch to read each circuit's output. When a combination volt/ammeter is specified, the volt scale and ampere scale shall be clearly labeled.

When a digital meter is specified, it shall monitor the voltage and current output of each circuit of the rectifier using hermetically sealed switches to select the reading required. The selector switch shall have an off position which removes all input signals from the meter sense leads. A meter power on/off switch shall be supplied. The meter is to have an LCD (or LED) three and one half digit (minimum) display, have an accuracy of +/-0.05%, operate over a temperature range of -30 degree C to +65 degree C; and have a storage temperature range of -30 degree C to +80 degree C. The input impedance shall be 10 megohms minimum.

655.21.08 Shunts: Each output circuit shall have a DC shunt readily accessible for meter accuracy checks. They shall be mounted on the control panel and be marked. The shunt(s) shall be placed in the negative circuit rated at 50 mV and 120% of circuit current (maximum) and have uninsulated ring tongue terminals, positioned for easy connection of test equipment or meters, fastened to the calibrated test points. The negative circuits shall not be connected together.

655.21.09 Convenience Outlet: Units shall be equipped with a 115 VAC, Ground Fault Interrupter (GFI), grounded AC outlet mounted on the panel face. The outlet shall be fused for 15 amperes and be attached to the line side of the circuit breaker.

655.21.10 Terminals: A 600 volt AC input terminal block with "dead front" shall be located on the insulated control panel for connection of the input AC wiring. Solderless, compression lugs, spaced a minimum of 2 inches apart, sized to accommodate up to #6 AWG wire, shall be provided for the positive and negative output terminals of each circuit of the rectifier and be mounted on the control panel. Binding posts, suitable for attaching No. 10 AWG wire, shall be provided for each zone to accommodate two reference electrodes and structure test leads. Test jacks shall be provided to enable external monitoring of each voltage, current, or potential reading being taken. All terminals shall be clearly identified on the panel.

655.21.11 Output Control: Saturable reactors shall be used to provide constant current output for each circuit. Each circuit shall have its own reactor and control stack with individual adjustment so that adjustment of one circuit's output will not affect the output of any other circuit. Adjustment shall be by means of a potentiometer and voltage taps to enable smooth circuit output adjustment from 10% of maximum circuit current up to maximum circuit design current. The potentiometer shall be sized to handle 115% of the maximum RMS control winding current. The minimum capacity control stack shall be sized to provide 110% of maximum RMS control winding current with a junction temperature of 100°C. Both the control stack and potentiometer must be properly heatsinked as required to provide continuous operation at maximum control current and the ambient temperature specified. Current regulation from full load to short circuit may not exceed 115% on any circuit. The maximum hot spot temperature rise of any reactor must not exceed 75°C.

The constant current output shall remain within a range of +/- 5% of the set value over a change of resistive loading from 0.25 ohms to 2.5 ohms with the input AC voltage remaining constant. The constant current output may vary in proportion to changes in the AC line voltage input to the rectifier.

A link bar arrangement shall be provided to allow operation in constant voltage mode. When connected, the link bar will bypass the reactor, disabling constant current operation. This arrangement is to be located on the instrument panel of the rectifier and be properly labeled as to function.

655.21.12 Interrupter Connection: Provision for interrupting the input power to the rectifier with a portable interrupter shall be included. The hot line coming from the load side of the circuit breaker shall be connected to a stud and link bar arrangement. The studs are to be spaced 3 inches apart. The stud and link bar arrangement shall be "dead fronted" and labeled.

655.21.13 Wiring: All wiring and current carrying studs within the rectifier, except for meter circuits, shall be sized for not less than 500 circular mils per ampere. All current carrying bolts, terminals and connections shall be of copper, brass or bronze. Electrical connections made through the panel shall be either soldered to the bolt head or utilize the double nut method so as not to depend on the compression strength of the panel to maintain a tight connection. All connections shall be clear coated to prevent corrosion.

655.21.14 Nameplate: Each rectifier shall be provided with a stamped or engraved metal nameplate with the following information:

Name of Manufacturer
Serial Number Model Code
AC Input Volts AC Input Amps
No. of Phases Frequency
DC Output Volts DC Output Amps
Maximum Designed Operating Ambient Temperature

Figure 655-2. Nameplate

655.21.15 Enclosure Finish: All welds shall be sanded and all sharp edges rounded before finishing. The entire enclosure shall be galvanized according to ASTM specification A123 and will have a minimum coating of 2.6 mils or 1.5 ounces of zinc per square foot of surface area. When painted, the enclosure will first be hot dip galvanized, and then all bare metal is to be chemically or steam cleaned followed by an air dry vinyl wash etching primer and a uniform undercoat of 1/2-mil of epoxy-based primer. The epoxy-base primer is to be applied over the entire surface and oven dried before applying two top coats of paint. The first top coat shall be a base enamel paint applied in a uniform coverage over the entire surface without holidays, spatter or runs. The DFT is to be 1/2-mil minimum. This coat is to be bake dried before applying the final top coat of baked enamel. The final coat shall be applied as above, bake dried and allowed to cool to room temperature before handling. The final DFT of all coats shall be no less than 1-1/2 mils.

655.21.16 Panel Material: The panel shall be constructed of 1/4-inch thick bakelite NEMA grade XX, or equal insulating material.

Panel Marking: All panel functions shall be legible and permanently labeled near the function being described using engraving techniques in the panel or bolt on engraved plates. Stick-on labels are not acceptable.

655.21.17 Remote Monitoring: A terminal block(s), suitable for connection of #18 AWG wire shall be provided to allow remote monitoring of output voltage, output current, and structure potentials of each circuit.

655.21.18 Filters: All single phase units shall include a filter. The output ripple of each circuit of the rectifier shall not exceed 5% of rated output voltage when measured at rated output voltage and current. The output ripple shall not exceed 5% of measured output voltage when measured at 25, 50 and 75 percent of rated output current. The filter must be removable, using switches and/or link bar arrangements, unless the filter is discharged completely when connected to the rated load, in less than 15 milliseconds after interruption of the input power. Choke designs shall meet the applicable requirements of the transformer specification (MIL E 917). The capacitor shall have a DC working voltage of twice the rated voltage output of the rectifier.

655.21.19 Disconnect Switch: The rectifier power input circuit shall be furnished with a switch and enclosure separate from the rectifier. The switch shall be a single-throw fuseable safety disconnect switch with solid copper neutral bus bar and shall be listed with the Underwriters Laboratory. The contractor will determine the proper switch rating required to supply the maximum voltage and current of the rectifier. The switch shall be lockable in both the on and the off positions. The switch enclosure shall be classified as a NEMA 3R type enclosure with a baked enamel finish.

655.21.20 Testing: Each completed rectifier shall be full load tested at low, high and nominal line voltage. The AC input voltage, current, ripple, watts, power factor, and the DC output voltage, current and efficiency shall be recorded at each input voltage. Each circuit shall be individually tested with all other circuits energized and loaded and the results recorded. Each circuit shall be tested for constant current at rated current output for expected variation in the load resistance (0.25 ohms to 2.5 ohms), but within the output voltage limits of the rectifier. Each rectifier or group of rectifiers shall be tested to show that they meet the requirements of this specification.

When required, testing may be witnessed by the customer at the manufacturer's location. The manufacturer shall certify compliance with the above test procedures.

655.21.21 Solar Power Supply: When section 655.30.02 so notes, the solar power supply shall be designed using the latest information concerning solar insolation for the area in which the power supply is to be installed as published by the Solar Energy Research Institute. If information is not published for the exact location of installation then the nearest location for which information is published shall be used. The array shall be sized using the least favorable mean daily direct normal insolation figures as the design parameter and shall be able to supply 120% of the maximum daily (24-hour) output ampere/hour rating of the power supply.

The unit shall include an electronic battery charge regulator set up to supply 2.35 volts per cell in series (lead acid type battery). The charge rate shall be temperature compensated at a rate of six millivolts per degree C per cell. Solderless pressure type terminals will be provided for solar array and battery connection. The unit shall include an output regulator complete with solderless pressure type terminals. Separate 50 millivolt shunts shall be provided for charge current and output current measurements. A meter shall be provided to read output voltage and current. An on/off switch shall be provided to remove the load from the output of the power supply. A blocking diode shall be installed in series with the solar array output to prevent battery leakage through the solar panels during sunless periods.

Battery capacity shall be determined by the daily ampere per hour requirement of the load as well as the minimum ambient temperature of the area of installation. Batteries shall be sized to provide a minimum of five additional days of reserve capacity and shall be maintenance free lead acid shallow discharge type. The total battery shall be sized using the 10-hour discharge rate as published by the battery manufacturer.

All current carrying power wiring shall be sized for a minimum of 1000 circular mils per ampere.

655.22 Reference Cells: The reference cells may be either silver-silver chloride or graphite. The same type of reference cells shall be furnished throughout the project. The cells shall be approved by catalog and data (2 years stability in concrete) submittals before being furnished to the project.

655.22.01 Silver/Silver Chloride: A silver/silver chloride cell shall consist of a silver metal element covered in silver chloride electrolyte and encased in a concrete compatible jacket. A single conductor lead wire shall be factory attached to the silver element. The single conductor wire shall be #14 AWG meeting 655.24 and colored black. The black conductor shall be connected to the silver element and sealed against moisture. A separate ground wire shall be supplied. It shall be #14 AWG meeting 655.24 and white in color. Both cell and ground leads shall be long enough to be routed without splices (except those housed in junction boxes) from the selected location in the deck to the terminal points in the rectifier. The manufacturer shall define the conversion factor for converting cell voltages to copper-copper sulphate equivalents.

655.22.02 Graphite Cells: A graphite reference cell shall consist of a non-impregnated graphite bar with a square cross- section of 1.5 inches (35 mm) on a side and 6.0 inches (150 mm) long with a factory attached lead wire. The lead wire shall have a firm mechanical connection to the graphite. The connection shall consist of a 3/8-inch diameter 1/2-inch long threaded brass rod with a drilled hole in the center of the rod of sufficient size to insert the lead wire. The lead wire shall be soldered to the inside of the rod. The brass rod shall be screed into the end of the graphite bar. The spaces between the lead wire, insulation and walls of the brass rod and hole shall be filled with a water tight flexible non-shrink seal. The cell shall be supplied with a #14 AWG wire meeting 655.24 and black in color. A separate ground wire shall be supplied. It shall be #14 AWG meeting 655.24 and white in color. Both cell and ground leads shall be long enough to be routed without splices (except those housed in junction boxes) from the selected location in the deck to the terminal points in the rectifier.

655.23 GROUND ELECTRODE: The grounding electrode and grounding conductor shall conform to the requirements of the NEC. In addition, the connection of the conductor and electrode shall be made with an exothermic weld. (655.27.01)

655.24 WIRE: Wire for anodes and system negatives, ground wires, and continuity bond wire used with exothermic welds shall be stranded copper conductors insulated with cross linked polyethylene listed by UL as RHH/RHW/USE or high molecular weight polyethylene of minimum insulation thickness of 3/32 inch. The conductor sizes of the anode and system negative wiring shall be as determined by the corrosion engineer in accordance with recommended practices of the NEC.

655.25 CONDUIT: The conduit for cathodic protection shall be either rigid ferrous metal or polyvinyl chloride (PVC) electrical conduit and shall include junction boxes, fittings, and attachment hardware. Rigid ferrous metal, electrical conduit and fittings shall be galvanized steel and shall conform to ANSIC 80.1, C80.4, and UL 6 for Type I rigid steel conduit. Each length of conduit shall bear the UL label. PVC conduit or EPL-40- PVC shall conform to NEMA standards Publication No. TC2 and shall be EPC-40-PVC. Conduit fittings shall meet NEMA TC3. Solvent cement for attaching fittings to the conduit shall be supplied or recommended by the conduit manufacturer.

Junction boxes used in a rigid conduit system shall be iron castings and hot-dipped galvanized in accordance with ASTM A 123 and conforming to NEMA ICS-6-Type 4 and UL 50. Junction boxes in a PVC conduit system shall be polyvinyl chloride with gasketed covers held by four stainless steel screws. Junction boxes shall have a square 6 inch minimum opening and be a minimum of 4 inches deep.

Attachment hardware to attach conduit concrete members shall be rigid clamps formed to fit over the conduit with tables that fit flat on the concrete surface, having holes for concrete penetrating screws or pins. Attachment hardware on a rigid conduit system shall be stainless steel or hot-dipped galvanized steel or malleable iron. Attachment hardware on a PVC conduit system shall be polyvinyl chloride coated steel and of sufficient size to allow movement of the conduit due to thermal expansion and contraction.

655.26 AC SERVICE EQUIPMENT: The material to be installed shall meet the National, State and local codes and be acceptable to the local electric company.

655.27 WIRE CONNECTIONS TO REBAR: Welding of reference cell ground wires and system negative wires to the reinforcing steel or other metal items shall be accomplished by a commercially available exothermic weld kit. Continuity bonding of discontinuous rebar may be accomplished by exothermic welding or resistance welding.

655.27.01 Exothermic Welding: The exothermic weld kit shall consist of a mold and powder charge of suitable size for the wire and reinforcing rod or item. The rod or item shall be cleaned before welding. The weld and wire shall be cleaned of oil and grease with a solvent and clean cloth. The mold shall rest on the rod or item and securely hold the wire in place. When ignited, the charge in the mold shall burn and result in a mechanically secure and electrically conductive weld of the wire to the reinforcing rod or item. The finished weld shall be cleaned of any slag. The weld and any exposed copper of the wire shall be coated. The coating for exothermic welds shall be a non-conductive, 100% solid, moisture and chemical resistant two-part epoxy paste. The epoxy shall initially cure in 20 minutes at 70°F and cure to an ultimate compressive strength of at least 8000 PSI in 24 hours at 70°F.

655.27.02 Resistance Welding: Discontinuous rebar may be bonded to continuous steel by resistance spot welding a 1/16-inch or 1/8-inch diameter steel tie wire to the steel. To make the weld, the rebar must be clean of all rust and oil. After cleaning, wrap the tie wire around the rebar when possible or lay the tie wire across the rebar, preferably on top of a rib. A resistance spot welder with modified hand tool is used to make the connection. The manufacturer's instructions shall be followed.

655.28 ANODE SYSTEM MATERIALS

655.28.01: The anode system shall be one of the following (as defined by the Owner):

- Conductive coating: per Section 656
- Thermally sprayed zinc: per Section 657
- Mesh anode with shotcrete overlay: per Section 658

655.29 REMOTE MONITORING SYSTEM

655.29.01 General

655.29.01.01: Supply all labor, materials and equipment necessary to furnish and install a remote monitoring system for the cathodic protection rectifier(s). The system shall consist of a remote monitoring unit (RMU), complete with integral telephone modem and operating software. The purpose of the remote monitoring system is to transfer rectifier operating data to a remote computer terminal, thus eliminating the need for monthly field inspections at the site.

655.29.01.02: The system shall monitor the status of the rectifier output voltage and current for each anode zone, and also have the capability of performing remote depolarization tests using each embedded reference cell (two per zone).

655.29.01.03: The system shall be designed for "real time monitoring" of the rectifier operating data, i.e. only the instantaneous data is transferred to the computer terminal at the time of the phone call.

655.29.01.04: The Contractor shall be responsible for supplying and installing a dedicated telephone line to each RMU, installing the RMU equipment at the rectifier site(s), and supplying operating software at the receiving end.

655.29.01.05: The remote monitoring system shall be warranted for one full year after installation or 18 months after delivery (whichever comes first) against defects in design and workmanship.

655.29.01.06: OPTIONAL: Contractor shall furnish and install computer equipment for receiving rectifier data at an office facility designated by the Owner.

655.29.02 Submittals: Prior to the installation the contractor shall submit to the Owner for approval, three sets of catalog cuts and material lists which completely detail the equipment to be supplied.

655.29.03 Hardware: A typical block diagram for the RMU configuration is shown in Figure 655-3. The system hardware shall conform to the following requirements:
655.29.03.01 ***Environmental Parameters:*** The RMU equipment shall be capable of operating in temperatures from -40°F to +185°F, and humidity ranging from 5% to 95% non-condensing. Printed circuit boards shall be silicon conformal coated to prevent dust and moisture intrusion. All inputs and outputs shall be provided with lightning protection.

655.29.03.02 ***Analog Input Parameters:*** Analog input ranges for each zone shall be as follows:

> One input for measuring the anode current across a shunt capable of 0.1 amperes resolution,
>
> One input for measuring output voltage with a resolution of 0.1 V, and

Two differential inputs for measuring reference cell potential data with 1 mV resolution. The input impedance for reference cell potential measurement shall be at least 10 megohms.

655.29.03.03 *Digital Output:* Should the RMU malfunction, the output current interrupt signal shall not interfere with normal operation of the rectifier.

655.29.03.04 *Data Communications:* A phone modem shall be provided with the RMU. The modem shall be capable of 1200 baud data transfer, with both answer and dial-up modes. The modem furnished shall have surge suppression and shall be fully compatible with the modem at the receiving end. The RMU shall have an integral RS-232 communications port, 7-bit ASCII, even/odd parity, and one stop bit.

655.29.03.05 *Analog to Digital Converter Resolution:* The resolution of the analog to digital converter shall be at least 10 bits (0.39%) at 0.5% accuracy.

655.29.03.06 *Timer:* The RMU shall be equipped with a timer which shall be used for depolarization tests.

655.29.03.07 *Interrupter:* An on/off interrupt "switch" shall be provided for conducting depolarization tests. The interrupt "switch" may be either electronic or electro-mechanical (relay) and must have opened the circuit within 10 milliseconds after the interrupt signal is given.

The "switch" must be capable of being driven by the monitoring unit microprocessor and shall be connected in the rectifier AC power supply as shown in Figure 655-1, Typical Rectifier Schematic.

655.29.03.08 *Data Storage:* The RMU shall have sufficient non- volatile CMOS RAM memory to store one set of depolarization values for each reference cell as specified under the "Software" Section. Storage for 500 total reference cell potential readings shall be provided (4 Kb minimum). The default setting shall be one per hour for 24 hours.

655.29.03.09 *Software:* The RMU shall be equipped with software which will enable the RMU to respond to commands and queries from the remote computer terminal as specified under the "Software" Section.

655.29.04 AC Power: The RMU and phone modem shall be powered by the rectifier 120 VAC power supply. If 220 VAC is used, a step down transformer shall be supplied.

655.29.05 Enclosure: The RMU may be mounted in the rectifier cabinet, if space is available, or installed in a separate RMU enclosure adjacent to the rectifier unit. The RMU enclosure shall have a NEMA 4 rating, with hinged gasketed cover and padlock feature. The enclosure shall be provided with mounting attachments and hardware. All exterior hardware shall be installed in conduit. Separate conduits shall be used for AC power and control wiring.

655.29.06 Wiring: All wiring interconnecting the RMU with the rectifier shall be Teflon insulated #18 AWG stranded copper wire. All other wiring used in the monitoring system shall be Teflon insulated #22 AWG. Cables providing AC power to the RMU shall be designed and installed to meet the National Electric Code. Wiring shall be neatly installed and secured within the enclosure using plastic wire ties.

655.29.07 Software: The software for the personal computer (PC) at the receiving end shall be user-friendly and easy to operate.

655.29.07.01 ***Telephone Dialing:*** The software shall have the capability of automatically dialing the RMU modem(s) from a phone number. The phone number file shall have the ability of being maintained and changed easily. For security purposes, a specific password will be required to access data at the RMU. The software shall have the capability of calling the RMU at any preselected date and time in the unattended mode. If the communication link cannot be established or the information received is not intelligible, the call shall be reiterated a maximum of three times. If after three tries data is still not received, an "error" message shall appear in the data file for that specific unit.

655.29.07.02 ***Data Storage:*** After dialing the RMU telephone number, the PC shall collect the rectifier operating data and store the information collected in an ASCII file. The data collected shall be accessible for use by other software programs. The software shall offer an option to print or store information as it is received.

655.29.07.03 ***Routine Monitoring:*** For routine monitoring the system shall measure the rectifier output voltage and current for each anode zone. Data files shall have a structure identification code, as well as the date and time that information is received. See example below:

Structure: 1242
Date: 11/1/90
Time: 1:00 AM
Zone 1: Volts ____, Amps ____
Zone 2: Volts ____, Amps ____
Zone 3: Volts ____, Amps ____

655.29.07.04 ***Depolarization Testing:*** The depolarization test procedure shall be initiated by the PC. The software shall transmit a control character to the RMU which allows the rectifier output to be interrupted. The rectifier shall remain off until another control character is received from the PC or a period of 24 hours has passed, after which the rectifier is turned back on.

During the interrupted condition, the reference cell potentials shall be monitored on an hourly basis and the data stored in the local RAM for later retrieval by the PC. A separate control character shall retrieve the stored data. All data files shall have the structure identification code, as well as the date and time the test was initiated. The sequence for the depolarization test shall include the measurement of each reference cell "on" potential, IR free "instant off" potential, 1 hour off potential and so on. See example below:

Structure:	1242	
Date:	11/1/90	
Start Time:	8:00 AM	
Zone 1, RC1:	"On"	___ mV
	"Instant Off"	___ mV
	1 Hr. off	___ mV
	2 Hr. off	___ mV
	3 Hr. off	___ mV
	Etc.	

The IR free "instant off" potential shall be measured between 100 and 1,000 milliseconds after the interrupt "switch" is opened. After the depolarization test has been completed and the rectifier is turned back on, the date, time, and voltage and current output for each zone shall automatically be recorded to verify system operation.

655.29.08 Dedicated Telephone Line: Contractor shall arrange for the supply and installation of a dedicated telephone line to each RMU. The telephone line installation and materials shall be in accordance with local utility and DOT standards. The Owner will pay for monthly telephone charges; however, the contractor shall be responsible for all costs associated with the initial installation.

655.29.09 Optional Computer Equipment: The contractor shall furnish and install a personal computer (PC) at an office facility designated by the Owner. The following equipment shall be provided:

> 386 100% IBM compatible computer, with keyboard, EGA color monitor, 1 Mb RAM, 2 serial ports, 1 parallel port, system clock with battery backup, 40 Mb hard disk drive, and 1.44 Mb 3 1/2-inch floppy disk drive.
>
> 1200 baud Hayes compatible modem and all related communications software.
>
> Epson LQ 850 printer or equivalent.
>
> All cables required for complete operation of the system.
>
> One carton of printer paper suitable for the furnished printer.
>
> MS DOS 3.3 (or higher) operating system.

655.30 DESIGN AND CONSTRUCTION REQUIREMENTS:

655.30.01: The contractor shall design the cathodic protection system in accordance with these specifications and the selections of Section 655.30.02. The responsible design professionals shall meet the qualifications of 655.42 and shall sign the drawings and calculations. Five copies of detailed design and shop drawings, submittals, and appropriate calculations supporting the design shall be submitted to the Owner within 30 days of project start. Construction shall not begin until approval is received from the Owner in writing.

655.30.02 Design Specifics:

Anode System (Owner will designate option(s)):

656 Conductive Paint ______

657 Thermally Sprayed Zinc ______

658 ELGARD 150/210 Mesh and Shotcrete Overlay ______

Rectifiers (Owner will designate options):

Number of Rectifiers: #______

Contractor Recommend: ______

Cabinet: NEMA 3R ______

NEMA 4 ______

NEMA 4X ______

Contractor Recommend: ______

Mounting: POLE ______

WALL ______

BASE ______

Contractor Recommend: ______

Cabinet Material (Owner will designate one):

Stainless Steel (standard):

Hot Dip Galvanized Steel

Post. Fab (standard): ______

Stainless Steel: _____

Paint Over Galv. _____ Color: _____

Individual Circuits (24V, 10A each): Owner will designate number or contractor recommendation:

Total Number _____

Contractor Design _____

Power Supply Type (Owner will designate one):

Rectifier - Constant Voltage/Constant Current Saturable Reactor _____

Solar Power _____

Meters (Owner will designate one):

Contractor Recommend:

Combination Volt/Amp - Analog: _____

Separate Volt and Ammeter-Analog: _____

LCD Digital: _____

LED Digital: _____

NONE: _____

Remote Monitoring (Owner will designate yes or no):

YES _____,

if YES- also supply office computer _____
(yes or no)

NO _____

655.30.03: All cathodic protection system designs shall meet the following criteria:

Maximum Zone Size = 4500 square feet

Design Current Density = 1.5 mA per square foot of reinforcing steel surface within eight (8) inches of the anode

Minimum of two anode leads per zone

Minimum of two system negatives per zone

Two embedded reference cells and corresponding rebar grounds per zone.

655.30.04: The anode system design designated in 655.30.02 shall meet all other requirements of these specifications and 656, 657 or 658 as applicable.

655.30.05: The contractor shall field measure all dimensions during construction and accurately record the dimensions on as- built drawings.

655.30.06: The contractor shall provide 8 copies of a project specific operation and maintenance manual. Items to be included as a minimum are:

System Operating Procedures

System Maintenance and Repair Procedures

Rectifier Maintenance Log Sheets

System Troubleshooting Guidelines

Product Data Sheets

As Built Drawings

655.30.07: The design professionals of item 655.30.01 and the manufacturers' technical representatives for all materials and components shall be available for consultation with the Owner by telephone upon request.

655.30.08: The contractor shall provide a technically qualified installation supervisor at the jobsite during all phases of the work.

655.31 RECTIFIER CONSTRUCTION REQUIREMENTS: The contractor shall install the rectifiers at locations approved by the engineer. The contractor shall furnish and install all hardware, brackets, poles and concrete necessary to mount the rectifier. If pole-mounted, the pole shall be embedded 3 feet in concrete. The rectifier shall be mounted at a comfortable working height for an average size person.

The contractor shall supply bronze pad locks to lock the rectifiers and the disconnect switches in the **ON** position and to prevent opening of the switch enclosure. All locks supplied on the project shall have the same key as the rectifier enclosure lock.

When solar power supply is required by the plans, the contractor shall determine the number of panels and batteries required in accordance with 655.21 and shall furnish and install the panels, panel mounting, and batteries. A power service disconnect switch shall not be required when solar power is required.

655.32 REFERENCE CELL CONSTRUCTION REQUIREMENTS: The contractor shall furnish and install two reference cells meeting 655.22 in each zone. Each cell shall be installed in an area of sound concrete which has half-cell readings in the highest (i.e. most negative) 10% of all readings in the sound concrete areas. Perform the half-cell survey after all patching has been completed in accordance with ASTM C876 and the reference cell sites shall be located by the contractor's corrosion engineer per section 655.43.02D.

At each site, the contractor shall excavate a slot between reinforcing bars about 3 inch wide, 7 inch long and 2 inch deep at the selected cell location. The excavation shall not expose reinforcing steel. The reference cell shall be placed in the bottom of the excavation following the manufacturer's recommended installation guidelines. The reference cell lead wire shall be routed through the junction box and conduit system to the rectifier. The contractor shall attach the ground wire supplied with the reference cell to the reinforcing steel. The ground wire shall be attached by an exothermic weld meeting 655.27.01. The ground wire shall be attached 2 to 5 feet from the reference cell. The contractor shall perform all necessary excavation for the ground connection. The contractor shall route the ground wire through the junction box conduit system to the rectifier.

The contractor shall backfill the reference cell and ground wire sites with <u>salt-free</u> patching concrete (without purposeful addition of chloride unless otherwise recommended by cell manufacturer) to the level of the original concrete surface. After the backfill concrete is cured, the contractor shall measure the AC resistance and half-cell potential of each cell and ground wire circuit. Resistance readings shall not be more than 10,000 ohms and potential readings shall not be erratic (shall not vary by more than ± 0.02 volts in 10 minutes). If unacceptable readings are obtained, the contractor shall replace each unacceptable reference cell with a new cell.

655.33 GROUNDING ELECTRODE: The contractor shall install a grounding electrode system, no portion of which should be above 24 inches below the ground line. The electrode installation must conform to all applicable provisions of NEC, and must have a resistance to ground of less than 25 ohms.

Resistance to ground shall be measured by a commercially available ground tester which utilizes two reference ground rods and a Wheatstone bridge circuit with a null balancing meter. The ground tester shall be calibrated no more than 180 days before the earth resistance measurement.

The ground wire shall be attached to the top of the ground rod by exothermic welding and routed through 1/2-inch conduit to the rectifier cabinet where it shall be connected by a grounding lug to the cabinet. The exothermic weld shall be covered with epoxy meeting 655.27.01. The opening of the conduit shall be sealed.

655.34 WIRING CONSTRUCTION REQUIREMENTS: The contractor shall furnish and install the wiring for cathodic protection in the conduit junction box system between the bridge elements and the rectifier. All attachments to the reinforcing steel shall be by exothermic welds meeting 655.27.01. All connections to the anodes shall be by splice in a junction box or where permitted by the anode type by an approved splice or connection on the concrete surface. The installed wiring shall run continuously from the anode or reinforcing steel to the rectifier terminal without splices (except in junction boxes with approved splice kits) or damage to the insulation. The contractor shall demonstrate to the engineer that the wiring is free of shorts and breaks. The wiring size shall be as determined by the corrosion engineer.

Electrical materials, equipment, and installations shall be in accordance with the current edition of the National Electrical Code and the National Electrical Safety Code.

All DC wiring terminated in junction boxes or at the rectifier shall be labeled with pre-marked heat shrink labels. A system wiring diagram with all wire labeling indicated shall be furnished to the Engineer.

655.35 CONDUIT CONSTRUCTION REQUIREMENTS: The contractor shall furnish and install conduit and junction boxes with hardware and concrete penetrating pins or expansion bolts in drilled holes to securely attach the conduit junction box system to the substructure to route the anode, system negative, and reference cell wiring from the substructure to the rectifier. Conduit routed underground shall be placed in trenches at least 2 feet deep and no more than 12 inches in width and backfilled. Changes in conduit direction of 90° or greater shall be accomplished by use of fittings with removable covers. Conduit diameter and routing shall be in compliance with NEC. A junction box shall be installed when the conduit changes in direction totalling 180°. Rigid conduit shall be attached to the substructure with junction boxes and attachment hardware. The conduit shall be attached within 3 feet of each junction box or fitting and at least every 10 feet. Any conduit connections between the bridge deck and substructure or other substructure elements shall be flexible conduit or expansion coupling to allow for the thermal movement.

PVC systems shall be installed with at least one expansion coupling between junction boxes or other fixed points. Expansion coupling capable of a 6-inch maximum expansion shall be installed for every 100-foot length of conduit. For conduit runs of 35 feet or less, a 2-inch maximum expansion coupling may be installed. Expansion couplings are specified to compensate for temperature variations of 155°F (-35°F to +120°F). When installed at the lowest anticipated temperature, the coupling shall be adjusted proportionately. PVC systems shall be supported with attachment hardware within 3 feet of a junction box or other fixed point and at the following maximum spacing:

Conduit Diameter (in.)	Attachment Spacing (ft.)
1-1/2	5
2	5
2-1/2	6
3	6
3-1/2	7
4	7

655.36 AC SERVICE: The disconnect switch shall be installed in the incoming electrical power circuit. The switch shall be mounted within 5 feet of the rectifier. The contractor shall furnish and install all necessary wiring and conduit from the utility power source identified in the plans to the disconnect switch and then to the rectifier. The completed electrical power service shall be installed in conduit buried at least 24 inches in soil where possible, and shall be installed in accordance with codes and electrical utility company requirements. The contractor shall select the size of wire and conduit appropriate for the anticipated maximum current load. The contractor shall furnish and install any equipment required by the utility company for connection of the power circuit to the electrical service.

655.37 CONTINUITY BOND CONSTRUCTION REQUIREMENTS: The contractor shall determine the electrical continuity of all steel rods in the layer of reinforcing steel adjacent to the concrete surface and other similar metal items to the reinforcing steel. Electrical continuity exists between reinforcing bars or between reinforcing bars and other metal items when the millivolt difference between them is no more than 1.0 mV when measured with a high impedance (10 megohm minimum) voltmeter with a resolution of 0.1 mV. The meter shall be calibrated no more than 180 days prior to use. All bars in the top layer of reinforcing steel within a zone shall be considered continuous when the voltage differences between a minimum of four contact points in a zone all show continuity. The points shall be located at the extreme boundaries of the zone.

The contractor shall locate all electrical discontinuances in the reinforcing steel and shall establish continuity by installing continuity bonds between all points of discontinuity. Discontinuities between the reinforcing steel and other metal items shall be located and bonded. A continuity bond shall consist of a #12 AWG wire welded to the two discontinuous items and embedded in the concrete. The wire shall meet 655.24 and the welds shall meet 655.27. The contractor shall remove concrete as necessary to perform the continuity testing and install the bonds so that the wire and welds are embedded when the excavation is backfilled with concrete. The contractor shall backfill all continuity bond excavations with concrete to the original level of the surface. After backfilling of the bond excavations, the contractor shall confirm the establishment of continuity by repeating the millivolt difference measurement.

655.38 ANODE SYSTEMS: Anode system construction shall be in accordance with the following, as appropriate:

Conductive coating: per Section 656

Thermally sprayed zinc: per Section 657

Mesh anode with shotcrete overlay: per Section 658

655.39 REMOTE MONITORING CONSTRUCTION REQUIREMENTS: The contractor shall install the remote monitoring system at locations approved by the engineer. The contractor shall furnish and install all hardware, brackets, poles, software and telephone lines necessary for a fully functional remote monitoring system.

655.39.01 DOCUMENTATION AND TRAINING: Two (2) bound copies of a detailed operation and maintenance manual shall be provided. The manual shall include schematics of all circuitry, functional block diagrams, parts list and software tutorial. The contractor shall provide one (1) day of training to the Owner's personnel in the operation of the remote monitoring system.

655.40 CORROSION ENGINEERING SERVICES:

655.41 GENERAL: The contractor shall furnish the services of a consulting engineering firm specializing in the field of corrosion control for steel reinforced concrete bridge decks and substructures. This firm shall provide the engineering personnel and services detailed below for this bridge rehabilitation project. The corrosion engineering firm will report directly to the State Bridge Project Engineer (BPE), or the BPE designated representative. The corrosion engineering firm or their subsidiaries shall not be engaged in the manufacture or supply of corrosion control materials or equipment under this contract.

Each contractor shall provide the name of the corrosion engineering firm and the personnel to be assigned (names & resumes) proposed for work on this project as a part of the bid submission documents.

655.42 LEVELS OF EXPERTISE: The corrosion engineering firm shall provide the following levels of expertise on the project:

> **Project Principal Corrosion Engineer (PPCE):** The PPCE shall be a Registered Professional Engineer or a National Association of Corrosion Engineer's (NACE) certified Corrosion Specialist or certified Cathodic Protection Specialist. The PPCE shall have a minimum of at least 8 years experience in corrosion investigation and evaluation, corrosion control system design, system installation, inspection, and commissioning of cathodic protection on steel reinforcing in concrete bridge structures. The PPCE shall be directly responsible for all corrosion engineering services provided by the consulting firm on the project and shall supervise and review all work performed by the project corrosion engineer(s). The PPCE shall review all

corrosion control drawings and submittals detailing the system and equipment proposed for use on this project by the contractor. The PPCE shall be responsible for evaluating the performance of the installed corrosion control system and shall provide recommendations for long-term operation and maintenance. All conclusions and recommendations made by the PPCE shall be communicated in writing (verbal communication shall be confirmed in writing) to the BPE.

Project Corrosion Engineer (PCE): The PCE(s) shall have a minimum 5 years corrosion engineering experience as defined above on steel reinforced concrete structures and/or 10 years experience in evaluation of steel reinforced concrete structures. The PCE(s) shall also have served as the Project Engineer on at least one project of a similar magnitude and scope of work. If, due to the size of the project, more than one PCE is requested by the BPE during any phase of the rehabilitation work, the PPCE shall designate the segments of the project for which each PCE will be directly responsible.

The PCE(s) shall be "on-site" to supervise and/or perform all corrosion control inspection and testing required by the project specifications, and during all construction phases involving the installation of corrosion control system components which are permanently embedded in the concrete structure (e.g. anode systems, reference electrodes, and placement of cementitious overlay or grouts on anode materials). The PCE(s) shall evaluate and provide expert opinion (with review as necessary by the PPCE) to the BPE on all field modifications, additions or deletions proposed by the contractor for the corrosion control system(s). The PCE(s) shall perform or directly supervise the work of the corrosion engineering technicians.

Copies of all test data and written communications made by the PCE(s) involving the corrosion engineering work on this project shall be provided jointly to the PPCE and the BPE.

Corrosion Engineering Technician (CET): The CET(s) shall assist the PCE(s) in accomplishing field inspection and performing half-cell potential, electrical continuity, delamination and depth-of-cover testing, as well as commissioning of the corrosion control systems. The CET(s) shall have a working knowledge of, and at least 1 year of similar experience in performing the testing and inspection work required on this project.

Documentation of experience for PPCE, PCE and CET shall be submitted to the BPE.

655.43 ENGINEERING SERVICES: The consulting corrosion engineering firm shall provide the following services:

655.43.01 SUBMITTALS: Prepare the detailed design in concert with the Owner, the contractor and his material suppliers and in accordance with these specifications. Prepare and sign shop drawings showing anode layout, conduit and wiring, rectifier location and all details of this CP installation. Review all project corrosion control system drawings and submittals for compliance with the project specifications and good corrosion control practice on behalf of the

Owner. The review shall include:

CP system design

Anode material and layout

System DC power and monitor wiring and connections

Embedded reference cells and grounds

DC power and monitor conduit and junction boxes

Rectifier power supply and controller

Remote monitoring system

All other miscellaneous corrosion control components

A signed written report detailing the conclusions and recommendations for the overall design and each submittal shall be submitted to the BPE.

655.43.02 On-Site Testing/Inspection: Any system component or device found to be defective or not in compliance with the project specifications by the PPCE or PCE during the bridge rehabilitation project shall be immediately replaced by the contractor, at the contractor's expense, if directed to do so by the BPE.

The following tests and inspection services shall be provided:

A. Continuity Testing - Electrical continuity tests shall be performed in accordance with 655.37 to ensure that steel reinforcing bars (all layers) and all other embedded, or partially embedded metallic fixtures within each corrosion control zone are electrically continuous. This testing shall be performed on all bars exposed by the contractor during the project delamination removal process and on such other bar and metal embedments determined jointly by the PCE and the BPE as being necessary. Steel components which are determined to be electrically discontinuous shall be made continuous by the contractor in accordance with the project specifications.

Any embedded steel which was formally determined to be electrically continuous and then is made discontinuous by the contractor during the project repair and rehabilitation process shall be repaired by the contractor, using the method(s) provided for in the specifications at no cost to the Owner. Final determination as to the event which caused the discontinuity shall be made solely by the BPE.

B. Delamination Testing - A delamination survey shall be conducted by sounding with a blunt metallic instrument. The boundaries of the delaminations will be marked by spray paint. This testing shall be performed on the entire concrete surface to identify areas for patching.

C. Depth of Cover - The PCE or the CET shall randomly test the entire concrete surface for depth of cover using a pachometer, rebar/metal locator or other similar equipment. This testing is to be performed after patch repair work and prior to anode placement. Minimum cover requirements and repair process to maintain these requirements shall be in accordance with the project specifications.

D. Technical Assistance During Construction - Field locate all embedded reference cells and rebar grounds. While the PCE is encouraged to provide technical assistance to the contractor during installation of the corrosion control system, this shall in no way relieve the contractor from his contractual obligations. Further, the PCE shall only lend assistance if it does not interfere with or extend the time necessary for performing the corrosion engineering technical services provided for in these specifications.

E. Inspection and Testing of Reference Cells - After all reference cells have been installed, and prior to any anode placement, each corrosion monitoring device shall be tested to determine if the device is functional as designed, per 655.32. Any monitors (or associated ground connections) which are determined to be defective shall be immediately repaired or replaced, if so directed by the BPE, at no cost to the Owner.

F. Anode/Steel Electrical Isolation Testing - Testing performed will depend on the type of corrosion control system installed:

> Conductive Paint Anode Systems - After the conductive paint cures, testing shall be performed to ensure that the anode material is electrically separated from any embedded steel and to assure normal system performance. Any shorts or near shorts detected shall be cleared by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner.
>
> Thermally Sprayed Zinc Anode Systems - The anode system shall be tested and monitored during the application of zinc coating to ensure that the anode material is sufficiently electrically separated from any embedded steel and to assure normal system performance. Any shorts or near shorts detected shall be cleared by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner.
>
> Pre-fabricated (Mesh) Anode Systems - Just prior to and during placement of the shotcrete overlay material, the anode system shall be tested and monitored to ensure that the anode material is sufficiently electrically separated from any embedded steel and to assure normal system performance. Any shorts or near shorts detected shall be cleared by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner.

G. System Energization, Testing and Adjustment - Upon completion of the corrosion control system installation, all electrical wiring, system power supplies, etc. will be checked for proper installation. Any defects detected shall be corrected by the contractor using methods approved by the BPE. This repair work shall be performed by the contractor at no additional cost to the Owner. Once this task is complete the system will be energized. The system shall be energized and adjusted in accordance with the E Log I and/or Depolarization Testing and Analysis procedures given in NACE Standard RP0290-90, Item No. 53072, "*Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*", approved April 1990. If E log I procedures are not used to define the initial operating parameters, the system shall be activated at 75 to 100 percent of design current for each zone, as determined by the PPCE and PCE. As a minimum, two anodic locations per zone shall be tested.

E Log I Testing - The E Log I tests, when used, shall be performed on each zone as follows:

-Prior to applying current to the anode material, record the potential values for all reference electrodes and zones numbers, ambient temperature and deck condition (wet, dry, etc.)

-The protection current shall be increased at approximately 3-minute intervals. The initial current applied shall be no greater than 1% of the anticipated protective current required. Sizes of current increments shall be determined by the PCE, depending on the shifts in steel potential at prior current increments, but shall not result in an average shift of more than 15 mV per current increment.

-Just prior to increasing the protection current, the PCE shall record the following data at each current increment; 1) Applied current (A), 2) Instant "Off" potential of reference cell (mV), and 3) Voltage between the anode and reinforcing steel (V).

-The PCE shall determine the initial current requirements based on analysis of the E Log I test data. The system shall be adjusted for continuous operation based on the E Log I test results and analysis.

Depolarization Testing - After polarization of the reinforcing steel has occurred as a result of the applied protection current for a minimum of 30 days, a depolarization test shall be performed on each zone by the PCE and CET(s) as follows:

-Prior to initiating depolarization tests, measure and record the following:

(1) Zone number

(2) Ambient temperature (°F)

(3) Substructure condition (dry, wet, etc.)

(4) Operating voltage (V)

(5) Operating current (A)

(6) Reference cell potential "on" (mV)

-Measure and record the "Instant-off" potential for each reference cell of each zone at the start of the test period.

-Measure and record all reference electrode-to-rebar potential data at a minimum of every 1, 4 and 24 hours.

-The PCE shall calculate and record the depolarization value and analyze the data. The system shall be adjusted to provide the optimum level of corrosion control based on results and analysis of the depolarization test. As a minimum, 100 mV of depolarization is desired on all embedded reference cells.

H. Final Report - This report, signed by both the PPCE and PCE, shall include all test data, analysis of data and operating settings, with conclusions and recommendations for long term system operation and maintenance.

I. Training of Owner's Personnel - The PCE shall conduct one 8- hour training course at the project site regarding the operation and maintenance of the cathodic protection system. The PCE shall provide 8 system operating manuals per 655.30.06 which shall be available for use by the personnel present at the training session.

655.50 METHOD OF MEASUREMENT: The cathodic protection system shall be measured and paid for as described below:

655.50.01 RECTIFIERS: Rectifiers shall be measured when installed in place, including AC disconnect switches and grounding electrical, and demonstrated to be operational. Unit of payment will be on a per unit (each) basis.

655.50.02 REFERENCE CELLS: Reference cells shall be measured when installed in place and demonstrated to be operational. Unit of payment will be on a per unit (each) basis.

655.50.03 WIRING: Wiring and conduit will be measured when installed in place. This item includes all conduit, junction boxes, AC service equipment, positive and negative cables and reference cell cables. All equipment must be demonstrated to be operational and ready for commissioning. Unit of payment will be on a lump sum basis.

655.50.04 CONTINUITY BONDS: Continuity bonds will be measured when installed where required and demonstrated to be operational. Unit of payment will be on a per unit (each) basis.

655.50.05 ANODE SYSTEMS: Anode systems will be measured when furnished and installed in place and demonstrated to be operational. The protected area will be the area bounded by the anode and extending 6 inches outside the anode area or to any exposed steel closer than 6 inches from the anode. Unit of payment will be on a square yard of concrete installed basis.

655.50.06 CORROSION ENGINEERING: Detailed design shall be performed, construction services shall be provided and the entire system shall be activated, checked and adjusted and demonstrated to be operational within the parameters set forth in this specification. Unit of payment will be on a lump sum basis, with payments as outlined in 655.60.

655.50.07 REMOTE MONITORING: The remote monitoring system as described herein shall include the supply and installation of the remote monitoring unit, modem, enclosure (if applicable), wiring and conduit, telephone line, AC power to the RMU, software, documentation, testing, training and computer equipment (if applicable). The remote monitoring system shall be bid as a lump sum.

655.60 BASIS OF PAYMENT: The accepted quantity for cathodic protection will be paid at the contract unit price when completely in place, tested, and accepted. Payment will be as follows:

Pay Item	**Pay Unit**
Cathodic Protection Rectifier	Each
Reference Cells	Each
Wiring	L.S.
Continuity Bonds	Each
Anode Systems	Sq.Yd.
Corrosion Engineering Section #'s	L.S. per listing below: Progress Payments, % of Lump Sum
655.43.01	25%
655.43.02 A thru F	50%
655.43.02 G thru I	25%
Remote Monitoring	L.S.

655A. BRIDGE SUBSTRUCTURE CATHODIC PROTECTION SPECIFICATION ANNEX

Refer to AASHTO-AGC-ARTBA Task Force #29, Tentative Bridge Deck Cathodic Protection Specifications, Section 650A.

656. CONDUCTIVE COATING ANODE CATHODIC PROTECTION SYSTEM

656.10 DESCRIPTION: This cathodic protection system consists of a primary anode, a secondary anode which is a carbon anode coating and an optional over coat for decorative or safety requirements. This system is designed for places in which current density at the surface of the anode does not exceed 6 mA/ft^2.

656.20 MATERIALS

656.21 PRIMARY ANODE: Primary anodes should be wires made of platinum coated niobium or strips made of precious metal oxide coated titanium.

656.21.01 The primary anode wire shall consist of a copper core, covered by niobium with an outer layer of platinum. The wire shall have the following properties:

Diameter	**0.031 inch**	**OR**	**0.062 inch**
Thickness of niobium (inches)	0.003		0.006
Thickness of platinum (μ inch)	25		25
Linear resistance (m ohm/ft)	16		4.2
Tensile strength (psi)	90,000		103,000
Yield strength (psi)	60,000		68,000
Percent elongation (max)	2%		3%

656.21.02 The primary anode strip shall be solid ASTM A 265 Grade I titanium with a precious metal oxide coating. The strips are typically 0.50" wide x 0.025" thick with a linear resistance of 21 m ohm/ft. The titanium shall have the following properties:

Intensive Properties of Titanium	
Density:	0.163 lb/in^3
Melting Point:	3040°F
Coefficient of thermal expansion:	.0000048 in/in/°F
Modulus of elasticity:	14,900,000 PSI
Thermal conductivity:	9.0 BTU/hr/ft^2/°F/ft
Specific heat:	0.124 BTU/lb/°F
Electrical resistivity:	000056 ohm-cm
Tensile strength:	35,000 PSI min
Yield strength:	25,000 PSI min
Elongation:	24% min
Weldability:	Good

656.22 SECONDARY CONDUCTIVE ANODE: Conductive coatings are of light weight addition to reinforced concrete adding weight at only 0.1 lb ft^2 (0.5 kg/m^2) of surface coated. For systems exposed to sunlight or moisture it may be advantageous to overcoat with a light color to reduce solar gain and coating deterioration respectively. Conductive coatings are not particularly abrasion resistant and shall not be applied for wearing surfaces. Conductive coatings are normally designed in excess of 25 years at 2 mA/ft^2 anode current density. Life is likely to be determined by failure of the cohesive bond between the concrete and the coating which may be accelerated by acid formation at the concrete/coating interface. The conductive coatings typically have the following physical properties:

Tensile strength:	> 250 psi
Volume Solids:	42% ± 3%
Pigment:	Carbon
Color:	Black
Shelf life:	Minimum of 9 months
Electrical resistivity:	< 10 ohm-cm

656.23 OVERCOAT: A single component, water based overcoat compatible with the conductive coating substrate, the overcoat shall be (variable) in color with the ability to completely hide the black substrate color. The material shall be permeable to allow moisture and vapor transmission of the cathodic protection reactions. The material shall provide excellent durability to its environment exposure.

656.30 CONSTRUCTION REQUIREMENTS

656.31 SURFACE PREPARATION REQUIREMENTS

656.31.01 DELAMINATED CONCRETE: All delaminated concrete shall be removed prior to installation of the anode system. Concrete shall be reinstated to its original profile using cementitious materials, surface treatments shall not be applied.

656.31.02 PREVIOUS PATCHES: All patches exceeding 2 sq. ft. in area repair materials with a volume resistivity of more than 50,000 ohm-cm (as determined by AASHTO T-277 modified -- see 650A.C) shall be removed prior to installation of the cathodic protection system. Concrete shall be reinstated to its original profile using cementitious materials, surface treatments shall not be applied.

656.31.03 REINFORCEMENT: Reinforcement exposed after the removal of concrete shall have all loose rust or scale removed. All replacement bars must be spliced to the remaining reinforcing bars to ensure electrical continuity.

656.31.04 EPOXY INFECTED AREAS: All epoxy injected areas exceeding 2 sq. ft. in area must be removed.

656.31.05 FERROUS COMPONENTS AT SURFACE: Any tying wires, nails, chairs or other ferrous components visible on the surface of the concrete shall be cut back or covered with cementitious patch material to insure not less than 1/4" cover from the surface. Deliberately exposed ferrous components shall be masked.

656.31.06 EMBEDDED MONITORS: All embedded monitors shall be installed prior to installation of anode materials.

656.31.07 MASKING: Cathodic protection anode materials shall not make direct contact to any ferrous component of the concrete substructure. All ancillary steel or deliberately exposed reinforcing steel must be masked before anode application. Areas of concrete to be used for future surface half-cell potential measurements can be achieved by simple masking tape.

656.31.08 PATCHING: Concrete shall be reinstated to its original profile using cementitious materials. Surface treatments and curing membranes shall not be applied. In general, patching shall be done sufficiently in advance to the anode installation so that the patch material fully cures.

656.31.09 SCARIFICATION: The concrete surface should be scarified as required for satisfactory bonding of the anode components. The surface should be cleaned and abraded by dry grit blasting or other approved techniques.

656.32 CONDUCTIVE COATING CONSTRUCTION REQUIREMENTS

656.32.01 Prior to the initiation of any work the Contractor shall provide all technical and data sheets that demonstrate successful use of the conductive coating as formulated by his supplier or previous bridge substructure cathodic protection installations. This data shall include test reports documenting compliance with these specifications. If such data is not available two separate areas of the conductive coating to be used shall be prepared and evaluated by a qualified independent consultant.

656.32.02 The Contractor shall submit a material safety data sheet for any hazardous component that includes plans for storage, handling, and placement of the material, prior to receiving the material at the job site.

656.32.03 Mixing, recoat time, application and handling instruction shall be contained in each separate package delivered to the job site.

656.32.04 There shall be a minimum of 0.25 inch of concrete cover between the anode and the reinforcing steel where less than 0.25 inch of cover exists, a non conductive polymer or masking shall be installed between the anode and reinforcing steel.

656.32.05 All foreign material shall be cleaned from the concrete surface prior to placing anode materials in a manner approved by the Engineer.

656.32.06 The primary anode wire strip shall be positioned using nonmetallic holders, fiber mesh or other methods approved by the Engineer at the locations shown on the plans. Typically primary anode spacing is approximately 8 ft. for coatings applied at 16 mils thickness. However, the maximum spacing should not exceed 25 ft. and a minimum of two primary anodes are designed per zone.

656.32.07 Each primary anode shall be sleeved with kynar or approved equal if brought through pre-drilled holes in the concrete. The hole shall then be filled with nonconductive polymer or approved equal.

656.32.08 All primary anode wires in a zone shall be connected to a continuous length of #10 AWG stranded copper insulated wire leading from the rectifier/controller. The connection shall be a compression type and shall be contained in a conduit junction box.

656.32.09 The conductive coating anode shall be applied by spray, brush or roller techniques in a uniform manner approved by the Engineer. If two coats are needed the second coat shall not be applied until a minimum of 4 hours of cure time at 70°F or as specified by the manufacturers data sheet. At higher temperatures the coating shall not be applied unless the substrate temperature is at least 5°F above the dew point. Anode material is applied at approximately 16 mils thick or at the thickness specified by the Engineer

656.32.10 Short Circuit Testing: After the conductive coating cures a voltage measurement shall be taken by connecting the primary anode lead to the positive terminal of a voltmeter, and the reinforcing steel to the negative terminal of a voltmeter. The voltage reading displayed is the difference in static or rest potential between the anode system and the steel. A reading of less than 1.0 mV is indicative of a short circuit. If there is uncertainty, a short circuit can be confirmed by powering the system with a portable DC power supply. A lack of, or poor response from the embedded monitors is confirmation of a short circuit within the zone being tested. If a short circuit exists, it must be located and eliminated.

656.32.11 The Contractor shall allow a minimum of 24 hours cure time between installation and energization or in accordance with the manufacturer's data sheet.

656.32.12 A platform which provides efficient and safe access for workers, supervisors and inspectors to all work areas shall be provided.

656.32.13 The Contractor shall provide a plan for collecting and disposing of all project wastes. Waste includes scrap metal, concrete and concrete dust and blasting materials.

657. THERMALLY SPRAYED ZINC ANODE CATHODIC PROTECTION SYSTEM

657.10 DESCRIPTION: This cathodic protection system consists of a primary anode connection of titanium strips or brass plates and a high purity zinc coating which may be covered with a decorative or protective coating. The optimum design current limits have not yet been identified, but it is recommended the design does not exceed ~~10~~ **2 mA/ft^2 of concrete surface**

657.20 MATERIALS

657.21 PRIMARY ANODE CONNECTION: Primary anode connection to the zinc coating shall be made of titanium strips or brass plates. These shall be fixed to the concrete surface with an insulating bed of epoxy prior to spraying the zinc coating.

657.21.01 The titanium strips shall be made of solid ASTM A 265 Grade I titanium. The titanium strips are typically 0.50" thick by 0.040" wide and 6.0" long.

657.21.02 Brass plates shall be made from brass conforming to UNS number C21000 or C22000 as specified in ASTM Standard B 36. **The Contractor shall submit a mill certificate verifying compliance with ASTM Standard B 36 to the Engineer. The brass plates are typically 2 1/2" in diameter and 1/8" thick. The bolts shall be a 1/4"-20 UNC x 1" of brass. One bolt shall be affixed perpendicular to the plate by brazing with a silver alloy filler material conforming to procedures in the AWS "Brazing Manual".**

657.21.03 Epoxy adhesive for attaching primary connections to concrete shall be Concresive *AEX* 1419 as manufactured by Adhesive Engineering Co., DP-420 by 3M Co., or an approved equal.

657.22 ZINC ANODE: The anode material consists of pure (99.9%) zinc coating which may be overcoated. The Contractor shall have an independent laboratory certify the purity of all zinc wire to be used on the project and list the percentage of each impurity. The physical **properties of the zinc are similar to those of a conductive coating, being only a light weight addition to the reinforced concrete. The zinc is applied by arc or flame spray to the external concrete surface to a thickness of approximately 10 to 20 mils. Zinc is not suitable for**

wearing surfaces. The durability of zinc coating is minimal on wet surfaces were corrosion of the zinc will occur. An overcoat in this case will increase the life of the anode.

657.30 DESIGN AND CONSTRUCTION REQUIREMENTS

657.31 SURFACE PREPARATION

657.31.01 DELAMINATED CONCRETE: All delaminated concrete shall be removed prior to installation of the anode system. Concrete shall be reinstated to its original profile using cementitious materials. Surface treatments shall not be applied.

657.31.02 PREVIOUS PATCHES: All patches exceeding 2 sq. ft. in area repair materials with a volume resistivity of more than 50,000 ohm-cm as determined by AASHTO T-277 shall be removed prior to installation of the cathodic protection system. Concrete shall be reinstated to its original profile using cementitious materials, surface treatments shall not be applied.

657.31.03 REINFORCEMENT: Reinforcement exposed after the removal of concrete shall have all loose rust or scale removed. All replacement bars must be spliced to the remaining reinforcing bars to ensure electrical continuity.

657.31.04 EPOXY INFECTED AREAS: All epoxy injected areas exceeding 2 sq. ft. in area must be removed.

657.31.05 FERROUS COMPONENTS AT SURFACE: Any tying wires, nails, chairs or other ferrous components visible on the surface of the concrete shall be cut back or covered with cementitious patch material to insure not less than 1/4" cover from the surface. Deliberately exposed ferrous components shall be masked.

657.31.06 EMBEDDED MONITORS: All embedded monitors shall be installed prior to installation of anode materials.

657.31.07 MASKING: Cathodic protection anode materials shall not make direct contact to any ferrous component of the concrete substructure. All ancillary steel or deliberately exposed reinforcing steel must be masked before anode application. Areas of concrete to be used for future surface half-cell potential measurements can be achieved by simple masking tape.

657.31.08 PATCHING: Concrete shall be reinstated to its original profile using cementitious materials. Surface treatments and curing membranes shall not be applied. In general, patching shall be done sufficiently in advance to the anode installation so that the patch material fully cures.

657.31.09 SCARIFICATION: The concrete surface should be scarified as required for satisfactory bonding of the anode components. The surface should be cleaned and abraded by dry grit blasting or other approved techniques.

657.32 THERMALLY SPRAYED ZINC CONSTRUCTION REQUIREMENTS

657.32.01 The Contractor shall prepare the concrete and primary connection surfaces for zinc anode application by abrasive blasting these surfaces to remove all surface contaminants.

657.32.02 The Contractor shall apply the zinc anode before the surfaces can become re-contaminated.

657.32.03 There shall be a minimum of 0.25 inch of concrete cover between the anode and the reinforcing steel. Where less than 0.25 inch of cover exists, a non conductive polymer or masking shall be installed between the anode and reinforcing steel.

657.32.04 All foreign material shall be cleaned from the concrete surface prior to placing anode materials in a manner approved by the Engineer.

657.32.05 Titanium strips or brass plates shall be used as the primary anode connections. These connection shall be fixed onto the concrete surface with an insulating bed of epoxy prior to coating. A minimum of two anode connections shall be designed for each zone.

657.32.05.01 The primary connection shall be mechanically connected to a #10 AWG size which will terminate at the rectifier/controller.

657.32.06 The zinc anode shall be thermally sprayed using flame or arc spray techniques per the specified thickness. Typically 10 to 20 mil thickness is designed. The Contractor shall allow a minimum of one hour between installation and energization.

657.32.07 The Contractor shall submit the manufacturer's zinc spraying equipment specification and recommended operational procedures for the Engineer's review. Approval shall be made by successful demonstration in a trial area.

657.32.07.01 Bond strength and thickness uniformity must be demonstrated during the application using a hand controlled spray gun. Feed wire rate, spray distance, rate and path of travel, overlaps distances and time between successive overlap and number of overlaps shall be established and maintained throughout the project by the Contractor.

657.32.08 Short Circuit Testing: During the application of the zinc coating, electrical shorting of the zinc to any metallic member of the substructure that is electrically **continuous to the reinforcing steel can be immediately detected. One detection plan which has been successful consists of monitoring the DC voltage between the zinc coating and the reinforcement steel. Expected voltage will range from 100 to 500 mV. A sharp drop in voltage is a definite indication of a short. The Contractor shall submit a detection plan to the Engineer for approval. All shorts identified shall be immediately located and corrected to eliminate the short prior to continuing the zinc application.**

657.32.09 Visual Inspection: The zinc anode shall be visually inspected using a lens with a magnification of 10. To be acceptable, the coating shall have uniform appearance and follow the form of the concrete surface. The coating shall not contain any lumps, blisters, coarse texture or loosely adhering particles, nor shall it contain any cracks, pinholes, or chips which expose the concrete substrate.

657.32.10 Adhesion Testing: Adhesion test shall be conducted using aluminum or steel test discs. These discs shall be cemented to the test area and after curing the test discs shall be pulled from the test area with a calibrated pull off tester as specified by the Engineer. To be acceptable, the adhesion strength shall be greater than 150 psi. Adhesion test areas shall be recoated with zinc to the specified thickness after scraping any loose or delaminated zinc caused by the adhesion test.

657.32.11 Thickness Testing: Thickness measurements shall be performed for each zone. Measurement locations and frequency shall be determined by the Engineer. The zinc coating thickness at each location shall be ± 2 mils of the specified thickness.

657.32.12 A platform which provides efficient and safe access for workers, supervisors and inspectors to all work areas shall be provided by the Contractor. This platform shall be enclosed by a structure with heating and ventilation system which provides for oper**ational efficiency, occupational health and safety and environmental conditions which promote high zinc to concrete bond strength and protection of the external environment from contamination by noxious materials.** ***The ventilation system which filters and recirculates enclosure air shall be designed to prevent dusts, vapors and gases in the enclosure from accumulating in concentrations which are explosive or otherwise hazardous to personnel.***

657.32.13 The Contractor shall provide a plan for collecting and safely disposing of all project wastes ***in accordance with environmental regulations.*** Waste includes scrap metal, concrete and concrete dust, blasting material and zinc dust .

658. MESH ANODE CP SYSTEM WITH SHOTCRETE OVERLAY

658.10 DESCRIPTION

658.11 GENERAL

658.11.01 This work shall consist of furnishing and installing all materials and equipment for the cathodic protection of underside slabs, beams and columns.

658.11.02 Cathodic protection system shall utilize Elgard CP anode mesh or equivalent.

658.11.03 Cathodic protection system shall consist of:

1. Elgard anode mesh or equivalent in all areas. Shotcrete to be used as encapsulant material.

2. Elgard current distributor bars or equivalent per drawings and specifications.

3. Direct current power supplies (rectifiers) installed at locations shown in drawings.

4. Reference cells and reinforcing bar ground connections at select locations per drawings. Also, system negative rebar connections.

5. Junction boxes, conduit runs and associated wiring to the rectifiers.

658.11.04 Anode mesh and current distributor design shall be such that the anode IR drop shall not exceed 300mV from the feed. This criterion shall still be met in the event of a four inch diameter core removed from any location within the anode system. The Contractor shall submit shop drawings showing the anode mesh layout and exact locations of current distributor bars.

658.11.05 The work set out in this specification document also includes all labor, materials and equipment for preparation for shotcreting, including sand-blasting or hydrojet removal of deteriorated or microfractured surface concrete in areas to be shotcreted.

658.11.06 Supply, application, curing and quality control of all shotcrete work.

658.11.07 DEFINITION OF TERMS:

The following definitions refer to words and terms used in this section. For definitions not covered in this section, refer to Section 650A.D in this document, ACI 506R-90 and ACI 506.2-90.

1. *Acceptable, approved or permitted:* Acceptable to, approved by, or permitted by the Engineer.

2. *Bench Gunning:* The practice of shooting thick members of full section by shooting from the bottom up.

3. *Blow pipe:* Air jet operated by nozzleman's helper in shotcrete gunning to assist in keeping rebound and overspray out of work.

4. *Dry-Mix shotcrete:* Shotcrete in which most of the mixing water is added at the nozzle.

5. *Ground Wire* (also called *Screed Wire* or *Shooting Wire*): Small gauge, high strength wire used to establish line and grade to guide shotcrete work.

6. *Gun:* Shotcrete delivery equipment.

7. *Gunning* (also called *Shooting*): The act of applying shotcrete.

8. *Nozzleman:* Worker on the shotcrete crew who manipulates the nozzle, controls water addition to the dry-mix shotcrete, and controls final deposition of the material.

9. *Overspray:* Shotcrete material deposited away from the intended receiving surface.

10. *Pre-Dampening* or *Pre-Moisturizing:* The addition of water to the dry-mix shotcrete, prior to introduction into the shotcrete gun, to bring the shotcrete to a moisture content usually in the range of 3 to 6 percent.

11. *Rebound:* Shotcrete material leaner than the original mixture which ricochets off the receiving surface and falls to accumulate on the ground or other surfaces.

12. *Rod:* Sharp-edged cutting screed used to trim shotcrete to forms or ground wires.

13. *Shotcrete:* Mortar or concrete pneumatically projected at high velocity onto a receiving surface.

14. *Sloughing* (also called *Sagging*): Subsidence of shotcrete, due generally to excessive water in the mix or placing too great a thickness of shotcrete in a single pass.

658.11.08 Shotcrete shall be applied in accordance with good construction practice as detailed in ACI 506R-90 Guide to Shotcrete, except as modified in this specification.

658.12 SUBMITTALS

658.12.01 Submit 5 copies of literature for manufactured equipment and products, including manufacturer's specifications, test reports and installation instructions.

658.12.02 Submit 5 copies of shop drawings:

1. Rectifier wiring diagram and front/side face plate layout.

2. Anode and current distributor bar layout and assemblies.

3. Junction boxes and conduit layout and assemblies.

658.12.03 Submit 5 copies of Project Specific submissions required by this section.

658.12.04 Contractor-Furnished Mix Design: Submit for approval by the Engineer the mix design for each strength of shotcrete mix included in the work.

1. Control: Establish the strength quality of the shotcrete as set forth in this document by tests made in advance of operations. If data from previous experience is not available or approved, prepare trial mixtures for preconstruction testing. Submit proposed trial mixture proportions to Engineer for review and approval prior to start of preconstruction testing.

2. Preconstruction Test Panels: Fabricate a separate test panel for each design being considered, for each shooting position to be encountered, and for each nozzleman. At least part of the panel shall contain the same reinforcement, if any, as the structure. The panel shall be not less than 30 inch square and 4 inch deep. Shotcrete test panels shot shall be of the same thickness as the structure, but not less than 4 inch thick.

3. Test Specimens: Test two specimens at seven days, three at 28 days for compressive strength. Cores for compressive strength test shall have a minimum diameter of 3 inches with length to diameter ratio preferably 2:1 and not less than 1:1. Convert measured compressive strengths for cores to equivalent 2:1 length to diameter ratio core strengths, using strength correction factors in ASTM C42. Take two cores from the panel and test for chloride permeability per the requirements of AASHTO-T277-83I (see Section 650A.C).

Diamond-saw cut test panels with reinforcing steel so the Engineer can examine the adequacy of encasement of reinforcement. All cored, cut or broken surfaces shall be dense and free from laminations and sand pockets.

-- Construct test panels with sealed plywood or other suitable forming material and provide 45 degree sloped edge form boards, to prevent entrapment of rebound.

-- Shoot at least one test panel for each 10 cubic yard of shotcrete placed or each shift, whichever is more frequent.

-- Shoot construction test panels by the same nozzleman doing the work.

-- Orientation of the test panels as shot should be representative of the production work.

-- Field cure test panels in the same manner as the work for 24 hours prior to moving to the test laboratory. Cure in the test laboratory in a moist room at 73°F ± 3° and 98% ± 2% relative humidity environment as prescribed in ASTM C192, until the time of testing, except that test panels are not to be removed from wooden form before *three* days.

658.12.05 Certified Test Reports: Test reports shall be accompanied by notarized certificates from the manufacturer certifying that the tested material is of the same type, quality, manufacturer and make as that proposed to be supplied. Submit certified test reports for the following:

1. aggregates
2. admixtures, if any
3. reinforcement, if any
4. materials for curing concrete, if any
5. portland cement
6. mix water

658.12.06 Delivery and Storage:

1. Cement: Store cement in weather-tight enclosures to protect against dampness and contamination.

2. Aggregates: Prevent segregation and contamination of aggregates by proper arrangement and use of stockpiles.

3. Admixtures: Store admixtures in a manner that will prevent contamination, evaporation, freezing or other damage.

658.12.07 Chloride Permeability Testing: Shotcrete shall be tested for chloride permeability as per AASHTO T277-83I (see section 650A.C). Specimens to be used for testing shall be obtained by core drilling. Two cores per test panel shall be taken 7 days after shotcreting. Random test locations will be selected by the Engineer or his representative. The cores shall be tested between 8 and 12 days of age. Cores shall undergo an accelerated boil cure per ASTM C684 and then be tested for chloride permeability. Test results shall be reported in writing to the Engineer and shotcrete supplier within 5 days after tests are completed. Refer to 658.26.07.01 in this section for desired properties.

658.12.08 Resume of Shotcrete Crew: Submit resumes of individuals in the shotcrete crew. Also list past experience in similar overhead shotcrete projects.

658.13 JOB CONDITIONS

658.13.01 The Contractor shall field measure all dimensions.

658.13.02 Quantities of rectifiers and reference cells are as shown on the drawings and specifications.

658.13.03 Quantities of anode mesh, current distributor bars, conductor leads and conduit lengths, and accessories are approximate only.

658.13.04 The Contractor shall maintain and keep in the field office a working set of Record Drawings. The Record Drawings shall be provided to the Engineer prior to Final Completion of the project. The Record Drawings shall indicate the following:

1. All deviations from the Contract Drawings.

2. Exact locations (measured from a known reference point) of installed reference cells and all reinforcing bar connections.

3. Exact location of all junction boxes and conduit.

4. Conductor wire identification scheme.

658.13.05 If requested, the Contractor shall furnish samples of materials for testing and inspection. Material may be accepted by the Engineer on the basis of the manufacturer's certification that the material has been sampled, tested and inspected by an independent laboratory approved by the Engineer or in the manufacturer's laboratory and certified by an independent inspector approved by the Engineer for compliance with the specifications. A copy of the independent laboratory reports which shall document test methods and findings shall accompany said certification. The Engineer reserves the right however, to accept or reject any material on the basis of his own tests and inspections.

658.13.06 All reinforcing steel to lead wire connections shall be accomplished using brazing or equivalent, in accordance with the manufacturer's instructions. Specific attention shall be directed to the process of connecting lead wires to reinforcing steel. Each project brazing shall be made to the satisfaction of the Engineer and may be hammer impact tested. The connection shall be completely coated with a 100% solids liquid epoxy which is inert in concrete and approved by the Engineer in writing. Alternate connection techniques shall be approved by the Engineer in writing.

658.13.07 Anode material shall be placed onto a clean surface after all concrete patching, sand blasting and cleaning has been completed.

658.13.08 All conductors and cables shall be identified at the rectifier end and in all junction boxes with the identification letters and numbers shown in the drawings. Labels to identify each conductor or cable shall be plastic or cloth adhesive tape which can be embossed or printed with letters and numbers, and wrapped around each conductor or cable.

658.13.09 No wire splices shall be permitted that are not housed in junction boxes or authorized by the Engineer in writing.

658.13.10 All connections and wire splices housed in junction boxes shall be of permanent compression type approved by the Engineer in writing; shall be completely sealed to prevent moisture intrusion; and shall be electrically insulated from other connections, wires and the junction box.

658.13.11 The cathodic protection system shall be installed in conformance with applicable federal, state, and local codes.

658.13.12 Preparation of shop drawings and cathodic protection installation, activation and adjustment of zones, preparation of maintenance manual, and as-built drawings shall be performed under the direct supervision of a consulting engineering firm per section 655.40.

658.13.13 Unless adequate protection is provided and approved, do not place shotcrete during rain, sleet, or snow. Mix and place shotcrete only when the temperature is at least 40°F and rising.

658.13.14 Protection: Precautions should be taken to avoid damage to any surface near the work zone due to mixing and handling of the materials.

658.13.15 Shotcrete manufacturer shall be a company specializing in the type of materials specified in this specification with not less than 5 years of experience. Applicator shall be acceptable to the manufacturer.

658.14 QUALITY ASSURANCE

658.14.01 Codes and Standards: Refer to the following codes. Comply with relevant part applicable to this section except where more stringent requirements are specified in this document. The publications listed below form a part of this specification to the extent referenced. The publications are referred to in the text by the basic designation only.

1. American Concrete Institute (ACI) publications:

a.	ACI 301-84	Specifications for Structural Concrete for Buildings
b.	ACI 506R-90	Guide to Shotcrete
c.	ACI 506.2-90	Specification for Materials, Proportioning, and Application of Shotcrete
d.	ACI 222R-85	Corrosion of Metals in Concrete
e.	ACI 117-90	Standard Tolerance for Concrete Construction and Materials

2. American Society for Testing and Materials (ASTM) publications:

a.	C33-90	Specifications for Concrete Aggregate
b.	C42-87	Test Methods for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
c.	C87-90	Test Method for Effect of Organic Impurities in Fine Aggregate on Strength of Mortar
d.	C94-90	Specification for Ready-Mixed Concrete
e.	C109-86	Test Method for Compressive Strength of Hydraulic Cement Mortars
f.	C150-89	Specification for Portland Cement
g.	C192-90A	Practice for Making and Curing Concrete Test Specimens in the Laboratory
h.	C260-86	Specification for Air-Entraining Admixtures for Concrete
i.	C309-8	Specification for Liquid Membrane Forming Compounds for Curing Concrete

j. C494-86	Specification for Chemical Admixtures for Concrete
k. C642-82	Test Method for Specific Gravity, Absorption and Voids in Hardened Concretes
l. C684-89	Test Method for the Making of, Accelerated Curing, and Testing of Concrete Compression Test Specimens
m. C685-86	Specification for Concrete made by Volumetric Batching and Continuous Mixing

3. American Association of State Highway and Transportation Officials (AASHTO) publications:

a. AASHTO T277-83I	Rapid Determination of the Chloride Permeability of Concrete

b. AASHTO-AGC-ARTBA Task Force #29 Guide Specification for Cathodic Protection of Concrete Bridge Decks

4. National Association of Corrosion Engineers (NACE) publications:

a. RP0290-90	Standard Recommended Practice - Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures

658.20 MATERIALS

658.21 RECTIFIERS

658.21.01 Refer to section 655.21.

658.22 REFERENCE CELLS

658.22.01 Refer to section 655.22.

658.23 ANODE SYSTEM

The anode may be either one of two types: ELGARD 210 anode designed to supply 2.1 mA per square foot of concrete, or ELGARD 150 anode designed to supply 1.5 mA per square foot of concrete.

658.23.01 ELGARD 150 Anode

The anode shall be a highly expanded titanium mesh, coated with a precious metal oxide catalyst with at least 2 years proven history on concrete bridge decks. The anode mesh shall conform to the approximate properties shown below:

Nominal Anode Surface Area	0.15 ft^2/ft^2
Substrate Composition	Titanium, Grade 1
Catalyst	Mixed Precious Metal Oxide
Width of Roll	45 Inches
Length of Roll	267 ft.
Weight of Roll	26 lbs/1000 ft^2
Diamond Dimension	3" LWD x 1 1/3" SWD
Resistance Lengthwise	
(45" width)	0.026 ohms/ft.
Resistance Width	
(with current distributor)	0.008 ohms/ft.

658.23.02 ELGARD 210 Anode

The anode shall be highly expanded titanium mesh, coated with a precious metal oxide catalyst with at least 2 years proven history on concrete bridge decks. The anode mesh shall conform to the approximate properties shown below:

Nominal Anode Surface Area	0.21 ft^2/ft^2
Substrate Composition	Titanium, Grade 1
Catalyst	Mixed Precious Metal Oxide
Width of Roll	48 Inches
Length of Roll	250 ft.
Weight of Roll	45 lbs/1000 ft^2
Diamond Dimension	3" LWD x 1 1/3" SWD
Resistance Lengthwise	
(48" width)	0.014 ohms/ft.
Resistance Width	
(with current distributor)	0.005 ohms/ft.

658.23.03 Current Distributor

Current shall be distributed to the anode system using current distributors of solid Grade 1 titanium strip, 1/2-inch wide x 0.035-inch thick.

658.23.04 Fastener

The anode shall be fastened to the deck using Fastex Part No. 354-260300-00-0078 plastic fasteners, or the equivalent.

658.23.05 Prior to the initiation of any work on the project, the Contractor shall provide accelerated lifetime data which demonstrate the ability of the anode lot, as formulated by the anode supplier, to survive a total charge of 700 A-Hr per square foot of concrete surface area.

658.24 CONDUCTORS

658.24.01 Refer to section 655.24.

658.25 CONDUIT AND JUNCTION BOXES

658.25.01 Refer to section 655.25.

658.26 SHOTCRETE: The overlay material shall be shotcrete as specified below.

658.26.01 Cement: Cement to be portland cement conforming to ASTM C150, Type I.

658.26.02 Normal Weight Aggregate: Use normal weight aggregate conforming to ASTM C33, with the combined gradation conforming to the following:

Gradation Limits for Combined Aggregate

Sieve Size U.S. Standard Square Mesh	Percent by Weight Passing Individual Sieves (Gradation 1)
3/4 in	-
1/2 in	-
3/8 in	100
No. 4	95-100
No. 8	80-100
No.16	50-85
No. 30	25-60
No. 50	10-30
No. 100	2-10

658.26.03 Mixing Water: Use mixing water that is fresh, clean, and potable. Mortar specimens made in accordance with ASTM C87 shall show no unsoundness or marked change in setting, and the compressive strength at 28 days shall be at least 95 percent of the compressive strength of mortar specimens made with water of known satisfactory quality in conjunction with the same sand and cement. Make strength comparison on mortar cubes in accordance with ASTM C109.

658.26.04 Curing Water: Water used for curing shall be free of elements which could cause unsightly staining.

658.26.05 Admixtures: Use accepted admixtures meeting the requirements listed in 658.26.07.01, if admixtures are permitted. Except as otherwise accepted, dissolve soluble admixtures in water before introduction into the mixture. Agitate liquid admixtures which settle.

658.26.06 Masterpatch 230 VP: Use Masterpatch 230 VP or equivalent for all hand patching.

658.26.07 PERFORMANCE CRITERIA

658.26.07.01 Performance Requirements: Shotcrete must conform to the following performance requirements:

Serial No.	Property	Standard	Values for Plain Concrete
1	Compressive strength, psi	C42-87 at 7 days at 28 days	 3600 5800
2	Boiled Adsorption, wt. %	C642-82	8-10
3	Volume of Permeable voids, %	C642-82	17-21
4	Concrete - Shotcrete interface bond, psi	--	150
5	Chloride permeability, coulombs	AASHTO T277-83I	1500

NOTE: The above values are all "minimum" acceptable limits.

In the absence of a suitable mix proportioning experience, start with the following nominal trial mix proportions.

WET MIX

Serial No.	Material	Quantity
1	Cement	755 lb/cu.yd.
2	Sand	2771 lb/cu.yd.
3	Water	300 lb/cu.yd
4	Water Reducer	as required
5	Superplasticizer	---
6	Water to cementitious ratio	≤ 0.4

DRY MIX

Serial No.	Material	Quantity
1	Cement	755 lb/cu.yd.
2	Sand	2771 lb/cu.yd.
3	Water	275 lb/cu.yd.

NOTE: Shotcrete trial mix proportions given above are based on saturated surface dry (SSD) aggregates and estimated water demands and air contents. Adjust mix proportions as appropriate to produce correct yield for specific aggregates being used and actual water demands and air contents achieved.

If using dry bagged shotcrete materials, adjust aggregate proportions to allow for absorption in aggregates.

IMPORTANT NOTE: The adoption of these trial mix proportions does not relieve the contractor of the responsibility to meet the performance requirements of the specification.

658.26.07.02 Adjustment to Shotcrete Mixes: Minor mix design adjustments may be requested by contractor when characteristics of materials, job conditions, weather, test results or other circumstances warrant; at no additional cost to the client and as accepted by the engineer. It shall be the option of the engineer to require laboratory test data for revised mix design and strength results.

658.26.07.03 Shotcrete Delivery Equipment:

1. Dry-mix shotcrete delivery equipment to conform to the recommendations of ACI 506R-90, "Guide to Shotcrete". Equipment to be capable of discharging the shotcrete mixture into the delivery hose and delivering a continuous smooth stream of uniformly mixed material to the discharge nozzle at the proper velocity.

2. Recommendations of the equipment manufacturer to be followed for the type and size of compressor, hose, water, ring, nozzle and accelerator dispensing system to be used.

3. Discharge nozzle to be equipped with a manually operated water injection ring capable of ready adjustment to produce an even distribution of water through the delivered mixture.

4. Air added to the gun to be free from moisture, oil or other contaminants and adequate for maintaining sufficient nozzle velocity at all parts of the work.

658.26.08 BATCHING, MIXING, AND DELIVERY

658.26.08.01 Dry-mix shotcrete may be batched, mixed and supplied using any of the following systems:

1. Dry-bagged premix.

2. Volumetric/weight batching.

658.26.08.02 Dry-Bagged Premix:

1. Dry-bagged shotcrete to contain premix of all shotcrete ingredients.
2. Dry-bagged shotcrete to be "bone dry" at time of discharge into pre-dampener. Bagged material to be protected from moisture during shipping, storage and delivery to points of application. Bagged shotcrete which has prehydrated or formed lumps due to exposure to moisture to be discarded.

3. Dry-bagged shotcrete to be applied within 15 minutes of mixing with water in pre-dampener.

658.26.08.03 Volumetric/Weight Batching:

1. Provide a dependable batching plant suitable for volumetric/weight batching.

2. Cement permitted to be added by the bag. Sand shall be either weight or volume batched, provided volumetric batching is checked for conformance with the requirements of ASTM C685 by using a weight batch check of the volumetric proportioning.

3. Weight batch checks of volumetric proportioning to be conducted at the start of every shift or for every 10 cu. yds. of shotcrete batched, whichever is more frequent.

4. Batching and mixing equipment to be cleaned thoroughly at least once per shift to prevent accumulations of aged material.

5. Equipment to be capable of homogeneously mixing materials in sufficient quantity to maintain shotcreting continuity.

6. All mixed shotcrete material to be applied within 15 minutes of mixing. Aged material to be discarded.

658.27 NON-CONDUCTIVE EPOXY

658.27.01 Non-Conductive epoxy shall be 100% solids liquid epoxy. It shall be inert in concrete and approved by the Engineer in writing.

658.28 AC SERVICE EQUIPMENT

658.28.01 Install in accordance with section 655.26.

658.29 ELECTRICAL BOND WIRES

658.29.01 This shall be #12 AWG stranded copper wire per section 655.24 or section 655.27.02.

658.30 CONSTRUCTION DETAILS

658.31 GENERAL

658.31.01 The CP installation shall be performed in concert and coordinated with concrete repair and in accordance with the drawings and specifications.

658.31.02 Before installation of the CP system, all concrete repair work shall be completed in each zone of interest.

658.31.03 Each CP zone and its respective components shall be electrically isolated from all other CP zones.

658.31.04 Installation of reference cells, system negative connections, all concrete repair and patching shall be completed and the area thoroughly cleaned prior to anode and shotcrete placement.

658.32 RECTIFIERS

658.32.01 Install in accordance with section 655.31.

658.33 REFERENCE CELLS

658.33.01 Install in accordance with section 655.32.

658.34 SYSTEM REBAR NEGATIVES

658.34.01 System rebar negatives shall be installed at the approximate locations shown on the drawings. The Engineer will define each exact location. There shall be two system negatives per zone.

658.34.02 The rebar negatives shall be installed in the structure at the level of the reinforcing steel mat near the surface where cathodic protection system is being installed.

658.34.03 Excavate and expose rebar sufficiently for brazing at each location.

658.34.04 Cut 1/2" by 1/2" slots to the appropriate junction box in the deck.

658.34.05 Attach system negative lead wire per 658.13.06 and route wire via 1/2" x 1/2" slot and terminate in the appropriate junction box.

658.34.06 Backfill slots with Masterpatch 230 VP mixed and placed in accordance with the manufacturer's instructions.

658.34.07 Connect the system negative to the rectifier ground header cable per 658.13.10 in the appropriate junction box after installation of conduits and junction boxes and routing of cables as per 658.40.

658.35 SURFACE PREPARATION FOR SHOTCRETING

658.35.01 Remove all loose and unsound material to the satisfaction of the Engineer.

658.35.02 Remove paint, oil, grease, dirt or other contaminants deleterious to good shotcrete bond using wet grit sandblasting, dry sandblasting, or a combination of these methods. The surface prepared shall exhibit a saw tooth structure for proper bonding of shotcrete. As a minimum, the required "saw tooth structure" is defined as that obtained using a deep sandblast.

658.35.03 Remove all loose particles from any exposed reinforcing steel by vigorously scrubbing with a wire-bristle brush. Heavy, loose layers of rust on exposed reinforcement shall be removed by wire brushing or scraping. Remove dust and similar fine particles by sweeping and blowing with compressed air. Reinforcing steel must be mechanically cleaned and be free of rust, grease, oil and other bond inhibiting matter. The depth of concrete chipped behind the rebar, wherever necessary, shall be equal to or greater than one inch.

658.35.04 The edges of the delaminated area shall be cut with power saws for the initial 1/2 inch depth to achieve a uniform edge and shall not be feathered. Edges shall be slightly undercut to key the patch into existing concrete surface.

658.35.05 The surface to be shotcreted shall be free from running surface water and in a saturated surface dry condition at the time of application of shotcrete.

658.35.06 The enclosure shall be designed and erected by the contractor to contain rebound within the work area and to protect walls from rebounds. The Contractor shall be responsible for cleaning the place to its original condition.

658.36 ANODE SYSTEM

658.36.01 Anode mesh and current distributor design shall be such that the anode IR drop shall not exceed 300 mV from the power feed point to the farthest point from the power feed. This criterion shall still be met in the event of a 4-inch diameter core removed from any location within the anode system (see sample calculations in the Appendix to Section 658).

658.36.02 Anode Mesh Layout

The panels of anode mesh shall be laid out to run either parallel or transverse with the concrete surface. Spacing between adjacent mesh panels may vary from slight overlap to a maximum of 6 inches depending on width of the area and construction staging. If necessary, a mesh panel may be cut lengthwise to accommodate system requirements. Distance between anodes in adjacent electrical zones shall be 4 to 6 inches.

658.36.03 Current Distributor Layout

Current distributors shall be laid out to run perpendicular to the panels of anode mesh. Current distributors shall be designed to extend from a junction box mounted on the overlay surface through an access hole and across the entire width of the electrical zone.

658.36.04 The anode mesh shall be designed to be installed not closer than 2 inches from any exposed steel on the deck.

658.36.05 There shall be at least two separate power feeds for each electrical zone.

658.36.06 Access Holes

Access holes shall be provided for current distributor bars (as well as system negatives and instrumentation wiring)in the overlay. These holes shall be a maximum of 1 1/2 inches in diameter by the thickness of the overlay. After wiring has been installed, the access holes shall be filled with non-conductive epoxy.

658.36.07 Installation of Current Distributors

Current distributors shall be installed to extend down through the access hole, and shall be bent at a right angle to lay flat across the concrete surface. If necessary, lengths of current distributor can be welded together by overlapping ends approximately three inches and making spot welds every 1/2 inch. If the resulting length is longer than required, the current distributor can be cut to fit with tin snips.

The current distributor running through the access hole shall be electrically insulated from any steel. A length of heat shrink tubing equal to the depth of the access hole shall be applied to the current distributor running through this hole. The heat shrink tubing shall be Alpha FIT-700 or approved equal.

In lieu of extending the current distributor through the access hole, an insulated titanium connector may be installed. The connector consists of a titanium rod, 1/8-inch in diameter by 16 inches long, with a 10-inch current distributor strip factory welded to the rod. The current distributor shall overlap the titanium rod by approximately 2 inches, with spot welds at three locations. The spot welds shall be made at the factory using a high powered resistance welder. The exposed rod is insulated with heat shrink for approximately 12 inches, leaving 2 inches uncovered. The 10-inch strip is resistance welded to the current distributor bar on the concrete surface by overlapping the strips by approximately 6 inches, and providing a minimum of three spot welds. The rod is extended through the access hole to facilitate connection to the anode lead wire from the rectifier.

658.36.08 Installation of Anode Mesh

The anode mesh shall be installed in accordance with the manufacturer's instructions. A general procedure is described below:

The first width of mesh is installed at the edge of the electrical zone. One end of the roll of anode mesh is fastened to concrete surface using plastic fasteners. The mesh is then unrolled, tensioned slightly and fastened to the surface about every 10 feet. At the edge of the zone, the mesh is cut and fastened in place. Before placing any more mesh, the current distributors are welded to the mesh. Each successive width of mesh is placed adjacent to the last and welded to the current distributors until the entire electrical zone is covered. After all the mesh has been installed, additional fasteners are installed as directed by the Engineer and the PCE. Mesh shall be fastened sufficiently to prevent significant movement during placement of the overlay, and so that it maintains a low profile with the concrete substrate. In addition, non-metallic spacers shall be used at a maximum of one-foot intervals such that the mesh is spaced 1/4" to 3/8" from the prepared concrete surface.

658.36.09 Welding of Anode Mesh to the Current Distributors

All titanium-to-titanium electrical connections shall be metallurgical bonds made by resistance welding using equipment supplied by the anode manufacturer and in accordance with the manufacturer's instructions. Where anode mesh is welded to the current distributor, there shall be at least one weld for every three inches of current distributor.

658.36.10 Isolation from Exposed Steel

The anode must be prevented from contacting or very nearly contacting exposed steel such as scuppers and expansion joints. Anode mesh shall be installed not closer than 2 inches from exposed steel. Installed mesh may be cut from tin snips to meet this requirement, and the anode shall be securely fastened to meet and maintain this requirement during placement of the overlay.

658.36.11 Isolation from Shallow Steel

Following the depth-of-cover survey (section 655.43.02.C) any areas of shallow steel (0.25 inch or less concrete cover) shall be corrected by one of the following three methods.

> The anode mesh shall be cut out and fastened to the concrete surface around the shallow steel. This method is preferred for small areas of shallow steel as well as for small exposed wire ties which often cannot be located with metal detectors, but can be located visually.
>
> A non-conductive epoxy can be applied to the concrete surface directly above the steel, and quartz sand shall be broadcast over the epoxy as it hardens. The maximum width of this application is two inches.
>
> A plastic spacer can be used to lift the anode off the deck surface. The spacer must be approved by the Manufacturer's Technical Representative and by the Engineer and the PCE.

658.36.12 Testing for Short Circuit Between Anode and Reinforcing Steel

Short circuit testing before, during and after placing the overlay shall be conducted using a high impedance digital DC voltmeter. The DC voltage technique is preferred since the resistance of a properly installed system is normally a fraction of an ohm, making detection of a short circuit difficult using the resistance technique.

The voltage measurement shall be taken by connecting the anode to the positive terminal of the voltmeter and the reinforcing steel to the negative terminal of the voltmeter. The millivolt reading displayed by the voltmeter is the difference in static or rest potential between the anode and the steel. A reading of less than 1.0 mV is indicative of a short circuit. Expected readings range from slightly positive to -500 mV. If there is uncertainty, a short circuit can be confirmed by powering the system with a portable power supply. A lack of response from the embedded reference electrodes is confirmation of a short circuit within the zone being tested. If a short circuit exists, it must be located and eliminated before the cathodic protection system can function properly.

658.36.13 Application of Bonding Grout

Ideally, the bonding grout, if required, shall be applied using grout spray equipment. In general, scrubbing bonding grout into the concrete surface using a stiff-bristled broom is not recommended. Alternatively, a soft-bristled broom may be used to work the grout evenly.

658.36.14 Protection of Anode During Overlay Placement

During the placement of the overlay, the anode system shall be protected from possible mechanical damage.

658.36.15 Connection of Distributor Bar to Anode Lead Wire

A 1/4-inch diameter hole shall be punched or drilled near the end of the current distributor bar in the junction box. The anode lead wire, fitted with a ring or spade crimp connector, is then secured to the current distributor bar by a 10-32 x 3/8 inch bolt and matching nut. The connection shall then be insulated using a sealing electrical tape.

Splices made in junction boxes between the titanium rod connector and anode lead wire shall be mechanically connected (crimp connection) and insulated in an approved heat-shrinkable material.

658.37 SHOTCRETE APPLICATION

658.37.01 Shotcrete to be applied in accordance with good practice as detailed in ACI 506R-90 "Guide to Shotcrete".

658.37.02 Only use nozzleman and crew experienced and competent in the application of shotcrete. Submit a summary of crew's experience with similar projects to the engineer for approval.

658.37.03 Use shooting wires where appropriate to control line and grade.

658.37.04 Direct the shotcrete nozzle at right angles to the surfaces being shotcreted, except as required for building coves, filling joints and corners or encasing large diameter steel.

658.37.05 Avoid construction of multiple layers of shotcrete where possible. If multiple layer shotcrete construction is necessary, rigorously follow the surface preparation procedures for existing shotcreted layers as prescribed in ACI 506R-90.

658.37.06 Remove all rebound which does not fall clear of the work prior to hardening. Do not incorporate rebound and hardened overspray in the shotcrete work.

658.37.07 Fill all corners and any other area where rebound cannot escape or be blown free, with sound material before proceeding elsewhere.

658.37.08 Hold nozzle at such distance and angle as to ensure the placing of material behind the reinforcement before shotcrete accumulates in front. Do not place shotcrete through more than one layer of reinforcing steel rods in one application unless preconstruction tests have demonstrated that the steel is properly encased thereby.

658.37.09 Ensure that the anode mesh is encapsulated by the shotcrete by keeping the anode mesh at least 1/4 inch away from the existing concrete surface. The anode mesh shall not be left exposed anywhere.

658.37.10 Testing for short circuit between anode and reinforcing steel during shotcrete application shall be performed in accordance with Section 658.36.12.

658.37.*11* REPAIR OF SURFACE DEFECTS

658.37.*11*.01 In areas which lack uniformity; exhibit segregation, honeycombing or lamination; or which contain dry patches, slugs, voids or sand pockets remove the shotcrete. Broom scarify the area, if necessary, with high pressure water blast to provide a roughened surface which, after dampening, shall receive the new shotcrete. Do not repair holes created by the removal of test cores by shotcreting, but as provided in Chapter 9 of ACI 301.

658.37.*12* FINISHING

658.37.*12*.01 Provide a cut finish as a final surface finish. Scrape or cut surfaces to remove high spots only after the shotcrete has become stiff enough to withstand the pull of the cutting device. For thin sections of shotcrete, commence moisture curing at once after finishing the shotcrete surface.

658.37.*13* TOLERANCE AND VARIATIONS

658.37.*13*.01 Tolerances are generally expressed in terms of their negative and positive components.

658.37.*13*.02 If no tolerances are stated for any individual element, structure, or feature in the corresponding drawings, then refer to ACI 117-90 for permissible variations. No tolerance indicated shall be construed to permit encroachment of the structure beyond legal property boundaries.

658.37.*13*.03 Increase tolerance for shotcrete other than gun finished surfaces by a factor of 1.5.

658.37.*13*.04 Preconstruction meetings shall be held for the purpose of reviewing critical tolerances, methods of making measurements, and the basis for acceptance/rejection of completed work to avoid misunderstandings at the time of final inspection.

658.37.*14* CURING AND PROTECTION

658.37.*14*.01 Throughout the curing process, keep the shotcrete at a temperature range of 40° to 95°F and in a moist condition.

658.37.*14*.02 Initial curing: Keep the shotcrete continuously moist for 7 days after being placed by continuous steam or mist.

658.37.*15* SAFETY MEASURES

658.37.*15*.01 Adequate safety measures should be taken to protect shotcrete crew and all personnel from rebound materials and alkalis in portland cement.

658.37.*15*.02 Shotcrete crews should wear appropriate masks, gloves, eye protection, and protective clothing. Eyebaths and wash facilities should be available in immediate vicinity of the shotcrete application.

658.37.*16* ACCEPTANCE

658.37.*16*.01 Delaminations either within shotcrete or at substrate/shotcrete interface constitute cause for shotcrete rejection. Extent of delaminations should be evaluated by sounding with a blunt metal instrument and, where necessary, verified by coring.

658.37.*16*.02 Engineer is the final authority of the acceptability of shotcrete as determined by visual examination and necessary testing.

658.37.*16*.03 Before successive layers of shotcrete is placed, the preceding layer should be checked for defects. Remove and repair all defective shotcrete prior to placement of a successive shotcrete layer at no cost.

658.37.*16*.04 Engineer should inspect and approve prepared repair areas prior to placement of shotcrete.

658.37.*17* HAND APPLIED

658.37.*17*.01 Hand patching is recommended wherever shotcreting is impossible as per the specification set forth in this section. Use Masterpatch 230 VP or equivalent material for hand patching to encapsulate the anode mesh.

658.38 CONDUIT AND JUNCTION BOXES

658.38.01 Install in accordance with section 655.35.

658.39 WIRE IN CONDUIT AND CONNECTION TO RECTIFIER

658.39.01 Install in accordance with section 655.34.

658.40 AC SERVICE

658.40.01 Install in accordance with section 655.36.

658.41 CONTINUITY BONDING

658.41.01 Install in accordance with section 655.37.

658.42 DOCUMENTATION AND TRAINING

658.42.01 Refer to section 655.39.01.

658.50 METHOD OF MEASUREMENT

658.50.01 Refer to section 655.50.

658.60 BASIS OF PAYMENT

658.60.01 Refer to section 655.60.

APPENDIX TO SECTION 658

CALCULATIONS TO SUPPORT ITEM 658.36.01, VOLTAGE (IR) DROP REQUIREMENT

Anode mesh and current distributor design shall be such that the anode IR drop shall not exceed 300 mV from the power feed point to the furthest point from the power feed. this criterion shall be met in the event of a 4-inch diameter core removed from any location within the anode system.

Sample calculations are given with the example design shown in Figure 658-1.

Anode voltage (IR) drop for the ELGARD system is calculated by adding the voltage drop in the current distributor to the voltage drop in the anode mesh along the longest current path in the anode structure. For the example design shown in Figure 653A, total voltage drop is:

$$E_T = E_{AB} + E_{BC}$$

1. Voltage Drop for Standard System as Designed

A. Calculate Current Distributor Voltage Drop (E_{AB})

The current distributor voltage drop is calculated by multiplying the current distributor resistance (see material specs) by the average current flow.

Where:

$$R_{AB} = 0.005 \text{ ohms/ft} \times 12 \text{ ft.}$$

$$R_{AB} = 0.06 \text{ ohms}$$

The average *current* flow in the current distributor is

$$i_{AB} = \frac{0.002A/ft^2 x (100)(12) ft^2}{2}$$

$$i_{AB} = 1.2 \text{ A}$$

Total current is divided by 2 above since we are considering a distributor conductor. Now,

$$E_{AB} = i_{AB}R_{AB} = (1.2)(0.06)$$

$E_{AB} = 0.072$ V

B. Calculate Mesh Voltage Drop (E_{BC})

The mesh voltage drop is calculated by multiplying the mesh resistance (see material specs) by the average current flow.

Where:

$R_{BC} = 0.014$ ohms/ft x 50ft

$R_{BC} = 0.70$ ohms

The average current flow in this width of anode mesh is

$$i_{BC} = \frac{0.002A/ft^2 x (50)(4) ft^2}{2}$$

$i_{BC} = 0.20$ A

Again, total current is divided by 2 above since we are considering a distributing conductor. Now,

$E_{BC} = i_{BC}R_{BC} = (0.20)(0.70)$

$E_{BC} = 0.140V$

C. Calculate the Total IR Drop

$E_T = E_{AB} + E_{BC}$

$E_T = 0.072 + 0.140$
$E_T = 0.212$ V = 212mV

2. Calculate the IR Drop with a Four Inch Core Removed from the Anode System.

There are several possible locations to consider, represented by numbers 1-4 in Figure 1.

2.1 Location No. 1

The removal of a 4-inch core from location No. 1 (mesh) increases the resistance so slightly it is not measurable. Total anode IR drop remains 212mV.

2.2 Location No. 2

In this case, removal of a 4-inch core increases the resistance of the current distributor, R_{A3}, by the following amount.

ELGARD-210:	0.0041 ohms
ELGARD-150:	0.0071 ohms

These numbers have been determined experimentally. In the case of this example, E is then determined as follows:

$$R_{AB} = 0.06 + 0.0041$$

$$R_{AB} = 0.0641 \text{ ohms}$$

$$E_{AB} = i_{AB}R_{AB} = (1.2)(0.0641)$$

$$E_{AB} = 0.077 \text{ V}$$

$$E = E_{AB} + E_{BC}$$

$$E = 0.077 + 0.140$$

$$E = 0.217 \text{ V} = 217 \text{ mV}$$

Anode IR drop is increased only slightly.

2.3 Location No. 3

In this case, the 4-inch diameter core is removed from the current distributor precisely at the point between widths of anode mesh. This might seem unlikely since there are only eight such points in this example zone. If this is a concern, the current must be supplied from the other current distributor, and the anode design will not meet the 300 mV criterion.

One possible solution is to install a parallel current distributor bar spaced at least 4 inches from the primary distributor bar. In this case the distributor bar resistance, R_{AB} will be half that of the standard design and,

$$R_{AB} = 0.06/2 = 0.03 \text{ ohms}$$

Proceeding with the calculations as in 4.0.1,

$$E_{AB} = 0.036\text{V}$$

$$E_T = 0.036 + 0.140$$

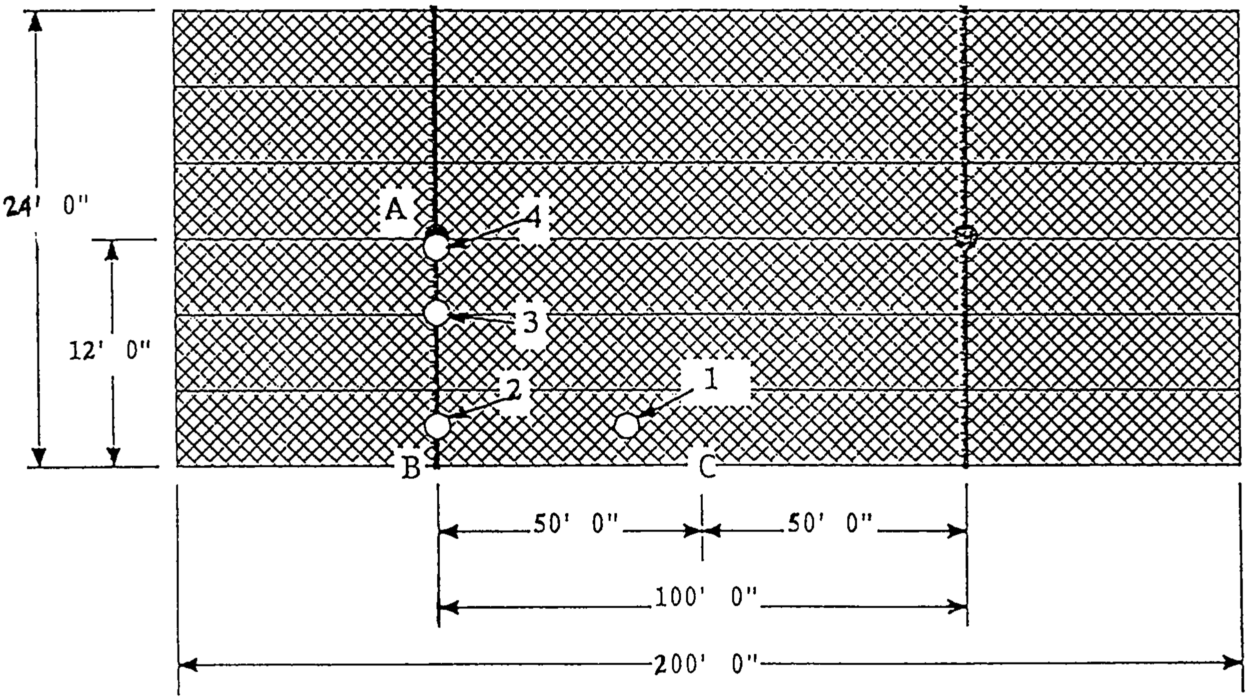
$$E_T = 0.176V = 176 \text{ mV}$$

With a double conductor bar in place, a 4-inch diameter core through any place along AB will cause a negligible resistance increase, and the total voltage drop will remain 176 mV. This would be insurance against a rare occurrence which some may consider unnecessary. The area to sever the conductor bar at location No. 3 represents 0.06% of the total area of the zone.

2.4 Location No. 4

In this case, the 4-inch diameter core is removed precisely from the power access hole. The system would then not meet the 300 mV Criterion. The area required to sever the system at location No. 4 represents only 0.01% of the total area of the zone; however, and the manufacturer believes this is an unnecessary consideration. If this a concern, then additional power feeds must be specified to each zone.

Figure 658-1. ELGARD 210 ANODE MESH - PLAN VIEW OF ZONE



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