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Cathodic Protection of Reinforced Concrete Bridge Elements: A State-of-the-Art Report

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Abstract

This report describes the evolution of cathodic protection of reinforced concrete bridges and its current state-of-the-art. It discusses how cathodic protection works, and the effectiveness of the technique. An extensive history of cathodic protection of reinforced concrete is included that covers all aspects of completed projects. There are sections on condition surveys, remedial action, anode systems, design aspects, operation and maintenance, and research and development needs. All of the various types of anode systems are characterized in detail as they have been designed and constructed. The ancillary equipment common to all systems such as power supplies and monitoring equipment are reviewed. Research and development needs are addressed to bring to light the essential research work that is required to further the development and use of cathodic protection of reinforced concrete structures.

Executive Summary

Since the first cathodic protection systems were used in the 1970s, many advances have been made in the system components and test procedures. Techniques are available today to assess the extent and rate of corrosion, as well as the performance of cathodic protection systems.

Although there is no doubt that cathodic protection mitigates the corrosion of reinforcing steel in concrete, the effects of passage of current through concrete is still not fully understood. Presently there must be a compromise between the complexities of concrete and cathodic protection, and the need for a simple and functional cathodic protection system. This report is intended to be a concise review of the history of cathodic protection and its current status for protection of highway structures.

Examination of several structures has shown that cathodically protected areas have less corrosion than nearby unprotected areas or structures. Also, extensive studies have proven that cathodic protection stops corrosion of the embedded reinforcing steel. Thus, there is no question that properly installed and activated cathodic protection systems halt corrosion and corrosion induced damage in salt-contaminated above-ground reinforced-concrete structures.

Cathodic protection was first used in 1824 to protect steel in seawater. The first uses on concrete began prior to 1955 on prestressed concrete water pipelines. These applications involved the use of the soil or water to apply and distribute the current, and are not pertinent to this report. However, the above-ground concrete field developed from these efforts.

Cathodic protection controls the corrosion of steel in concrete by applying an external source of direct current to the surfaces of the embedded steel. This is referred to as impressed current cathodic protection. Such a system requires the following components:

- External DC Power Source (Rectifier)
- Current Distribution Hardware (Anode)
- Conducting Electrolyte (Moist Concrete)
- Protected Metal (Reinforcing Steel)
- Completed Circuit (Wiring)
- Evaluation and Control Devices (Probes, Reference Cells, Controllers)

Cathodic protection has been used primarily as a rehabilitation technique to extend the life of structures that already are deteriorated. Although this is cost effective, studies have shown that installation of cathodic protection prior to extensive corrosion-induced damage can be even more cost effective because the high cost of concrete removal and repair is avoided. More than 275 structures have been cathodically protected in North America. Missouri has over 100 installations and Ontario has nearly 50. A recent survey indicated that 90% of the installations were operating satisfactorily as designed.

Several types of anode systems have been developed. The first was a conductive coke-asphalt overlay for bridge decks that operated successfully. Then slotted systems were developed and used. Next, distributed anodes with concrete encapsulation were used. Conductive paints and mastics have been used for non-traffic bearing areas as well as flame-sprayed zinc. Other types of anode systems being investigated include conductive portland cement concrete, conductive ceramics, and conductive rubber.

The anticipated lifetimes of the systems is from 5 to 40 years depending on the type of anode system. These systems cost $6.00 to $14.00 per square foot ($65 to $150 per square meter) in place. By 1989, the total of above ground concrete surface area protected was about 9 million square feet (0.84 million square meters). Today it is estimated that over 350 structures are cathodically protected with the surface area exceeding 10 million square feet (0.94 million square meters).

Prior to rehabilitation, it is a standard procedure to conduct a condition survey of the structure to determine the extent of damage, cause of the damage, and the economic feasibility of rehabilitation options. Procedures for conducting the surveys have been developed by the FHWA and many states. The results of the tests along with some condition assessments used for cathodic protection design provide the necessary information needed for selecting the cathodic protection rehabilitation option.

Depending on the level of distress and degradation of a particular bridge, the remedial repairs may be of greater cost than the cathodic protection system. Conversely a bridge that is less deteriorated may require only a minor amount of remedial repair work prior to installation of a cathodic protection system. It is important to recognize that remedial repairs must be compatible with cathodic protection systems.

Commonly used design guidelines and criteria have been developed that are similar for most of the anode systems in use. The unique design aspects of each anode type must be taken into account, so that a cathodic protection system will provide enough current to satisfy the protection criteria for the design life of a system. Anode current density is particularly important to prevent the buildup and concentration of acidic reaction products around the anode. Current distribution is another important factor that must be analyzed during design.

Monitoring devices are available to measure the effectiveness of a system. Embedded reference electrodes are used to measure the potential of the reinforcing steel in determining the system effectiveness. The silver-silver chloride electrode has evolved in the U.S. as the most commonly used reference electrode for embedment in concrete. Embedded macrocell probes, small lengths of reinforcing steel, are also used to measure the current in a system. When the probes indicate that the flow of current is net cathodic, cathodic protection is being achieved.

A power supply (rectifier) is necessary to provide a source of direct current for the operation of a cathodic protection system. Power supplies must be simple in design, rugged, and easy to maintain. Remote monitoring units are now available to monitor current, voltage, reference cell potentials, and instant-off potentials. Full remote control of a cathodic protection system is also available as an option.

Effective operation and maintenance of cathodic protection systems are vital for the continuous service that is required to extend the service life of a highway bridge structure. After eighteen years' experience in applying cathodic protection to bridges, it has become apparent that one of the areas that needs substantial improvement is effective operation and maintenance. Each system must be monitored, adjusted, and repaired as required. Cathodic protection systems are designed and installed to remain in constant operation during their design life. If the systems are not routinely monitored, problems may develop that leave the reinforcing steel unprotected. Ideally, cathodic protection systems should be monitored on a monthly basis.

Several areas are in need of addition research and development in the field of cathodic protection of embedded steel in concrete. Research is needed on the kinetics of the process of corrosion of steel in concrete, and how the kinetics are affected by cement content and type, oxygen and moisture content, and temperature. The various techniques for measurement of the corrosion rate of steel in concrete also need to be studied. Corrosion rate studies need to be extended to cathodically polarized steel. If the corrosion rate of polarized steel could be measured directly, any question of the appropriate cathodic protection criteria could be resolved. This remains the single most important issue in cathodic protection today.

1

Introduction

This report describes the evolution of cathodic protection (CP) of reinforced concrete bridges and the current state of the art. The evolution of reinforcing steel corrosion and the Research and Development and field efforts made to combat this problem are first presented as background material.

The massive highway system that has been constructed in the United States has been an important element in the economic development of the nation. A key component of this infrastructure is steel reinforced concrete. A primary reason for the good long-term performance of this composite is that concrete provides an alkaline environment which causes the steel to "passivate", or become covered with a protective oxide film.[1] Unfortunately, with the advent of a widespread bare pavement policy in the early 1960s and significant coastal construction, a widespread corrosion problem began to occur at an increasing rate. In spite of the alkalinity of the concrete, it was determined that chloride ions, contained in deicing salt, in seawater, or added to the fresh concrete, could destroy the concrete's ability to keep the steel in a passive state. Hausmann[2] reported that if chloride to hydroxyl ion ratios exceed 0.6, embedded steel corrosion could occur, and such has been confirmed in recent investigations.[3] For bridge structures, it has generally been found that a concrete chloride content in the range of 1.0 to 1.4 pounds chloride per cubic yard (0.6 to 0.8 kg per cubic meter) is the critical value above which steel corrosion in concrete can occur.[4,5,6] The resultant rust occupies more volume than the parent iron and this exerts tensile stresses on the surrounding concrete. When these stresses exceed the tensile strength of the concrete, cracking develops. This cracking often interconnects between reinforcing bars and the common undersurface fracture, or delamination, develops. As corrosion continues, the concrete cover breaks up and a pothole or spall is formed, frequently accelerated by additional stress from freezing and thawing and traffic pounding.

By the early 1970s, it was obvious that something had to be done to increase bridge structure life. The use of positive protective systems was initiated. Higher quality concrete, improved construction practices, increased concrete cover over the reinforcing steel, surface sealers, waterproof membranes, coated reinforcing steel, specialty concretes, corrosion inhibiting admixtures and other special treatments have been evaluated and used extensively in new bridge construction. It is generally agreed that new reinforced concrete bridges constructed using select protective systems will exhibit a long life. Many structures built prior to the 1980s remain salt contaminated, however, and continue to deteriorate at an alarming rate.

While researchers and designers actively studied the problem and debated its causes, maintenance engineers were faced with the need to repair the damage on existing decks. The most expeditious repair, that of removing loose concrete and filling the hole with a patch material, was also the least satisfactory. Patching in this manner becomes a never-ending process because of continued, and usually accelerated deterioration of the concrete around the patch. Deterioration was usually accelerated since areas of chloride-contaminated and chloride-free concrete were immediately adjacent to each other. This results in maximum driving potential and minimum electrical resistance for the corrosion cell. Low permeability concrete overlays have been used since the mid 1950s, and when properly constructed, were found to extend life, but reinforcement corrosion continued beneath the overlays because of salt contaminated concrete left in place.[7]

Today the nation's bridges continue to deteriorate at an alarming rate. In a recent report to Congress, the Federal Highway Administration (FHWA) reported that of the nation's 577,000 bridges, 226,000 (39% of the total) were deficient, and that 134,000 (23% of the total) were classified as structurally deficient.[8] Structurally deficient bridges are those that are closed, restricted to light vehicles only, or that require immediate rehabilitation to remain open. The damage on most of these bridges is caused by corrosion. The United States Department of Transportation has estimated that $90.9 billion will be needed to repair the damage on these existing bridges.[9]

In the early 1970s, it was recognized that concrete is an ionic conductor and capable of supporting a small flow of electric current. It was further recognized that this current could be used to alter the energy state of the reinforcing steel surface, and thus mitigate the corrosion process by the use of cathodic protection. This theory was first put into practice by R.F. Stratfull and co-workers in the California Department of Transportation on the Sly Park Road Bridge in June, 1973.

Since those early days, many advances have been made in cathodic protection system components and test procedures.[10] Anode systems have been developed with improved performance and lifetime. A variety of techniques are available today to assess the extent and rate of the corrosion process, as well as the performance of cathodic protection systems. By the early 1980s, the FHWA recognized cathodic protection as a technology which could make a significant impact on the otherwise progressive corrosion induced deterioration of bridge structures. In an official policy statement issued in April, 1982, R.A. Barnhart of the FHWA stated that cathodic protection is ".... the only rehabilitation technique that has proven to stop corrosion in salt-contaminated bridge decks regardless of chloride content of the concrete." FHWA estimates show that up to $50 billion in repair costs could be saved over the next 30 years by the use of cathodic protection.[11]

Much work remains to be done, however. Although there is no doubt that the process of cathodic protection does mitigate the corrosion of reinforcing steel in concrete, the understanding of the complexities involved is still incomplete. This is largely a result of the complexity of concrete as an electrolyte. Concrete is very non-uniform, not only from structure to structure, but also within a given structure. Important variations include chloride concentration, moisture and oxygen content, and the carbonation of concrete after prolonged exposure to the atmosphere. Such variations can affect the distribution of current by changing concrete resistance, and can also create extraneous potentials within the concrete that make measurement and analysis very difficult. Other physical factors, such as varying depth-of-concrete-cover and steel density, and the presence of previously placed patch materials, further complicate the situation.

Since it is not possible to cope with all these complexities in an ideal way, the challenge for the cathodic protection engineer is to make the system as simple and functional as possible, while providing adequate corrosion protection for the structure. This compromise between simplicity and adequate performance must not be done by ignoring the complexities of the structures, however, but rather with a thorough understanding of their implications.

This report is not intended to be an all-inclusive review of the technology of cathodic protection. Other, more extensive documents are being prepared for that purpose. It is rather intended to be a concise statement of the history and status of cathodic protection as applied to highway bridge structures: its attributes and usefulness, and its difficulties and shortcomings. This report will first review the history of cathodic protection as applied to reinforced concrete bridges. It then discusses the condition survey techniques used to determine the extent of corrosion damage and the feasibility of using cathodic protection as a rehabilitation technique. Aspects of system design and the nature of different anode types are then followed by the operation and maintenance items necessary to properly adjust and maintain a system once installed. Finally, the writer's view of current research and development needs is discussed.

2

Does it Work?

Many engineers have requested positive proof that cathodic protection will halt deterioration of salt-contaminated reinforced concrete structures. Such requests have resulted in the removal of several CP systems several years after installation and evaluation of the structures (in comparison to unprotected nearby structures or portions of the same structure). Corrosion probes (macrocell current measurements and resistance probes) have also been used to monitor corrosion current flow and corrosion-induced metal loss.

The first bridge deck CP system installed by the California Department of Transportation (Caltrans) covered only a portion of the deck. After several years, the protected deck section was compared to the unprotected portion and it was conclusively shown that the CP system prevented new delaminations from forming (except in epoxy-injected areas), and that the unprotected deck continued to deteriorate.[12,13] The Ontario Ministry of Transportation performed a similar investigative study and found similar results (i.e. cathodic protection prevented continued delamination due to rebar corrosion in salt-contaminated concrete).[14]

Probes have shown, in a different way, that cathodic protection works. Resistance probes record the increase in probe resistance as the metal cross section is decreased due to corrosion. In both laboratory and field studies, corrosion of properly installed probes (i.e. probes which were corroding prior to CP) has been halted by cathodic protection, whereas, the corrosion continued when CP was not applied. Some difficulty has been encountered in causing all probes to always corrode when surrounded by salty concrete. This can be minimized if the probe is made the macroanode of a macrocell, with the structure reinforcing steel as the macrocathode. Macrocell probes measure the electrons produced by the corrosion process on rebar embedded in concrete slabs and structures. CP that "works" causes the rebar to receive electrons rather than lose them (i.e. the current flow changes direction). In hundreds of test slabs and in over 25 field structures, this current reversal (to a noncorroding condition) has been confirmed, thus proving that the cathodic protection stopped the corrosion.

In fact, it has been found that even underpowered cathodic protection systems will minimize deterioration. In 1985, Kenneth C. Clear, Inc. applied low-power CP to two salt-contaminated test slabs and compared their deterioration to that experienced by similar unprotected slabs. These CP systems were purposely activated at power levels less than that needed for full protection (i.e. less than 100 mV depolarization and less than the current indicated by E log I). After two years, the unprotected slabs were badly cracked, rust stained and delaminated; the CP slabs showed no increased deterioration. Furthermore, the CP system had a beneficial effect on the natural corrosion situation and after that period of protection, the original low current was found to be sufficient to meet the accepted criteria. After six years, the cathodically protected specimens remain undamaged, while the unprotected controls have literally "fallen apart" as a result of rebar corrosion induced damage.

A similar significant reduction in corrosion as a result of cathodic protection was found in National Cooperative Highway Research Program project 12-19B.[15] A large test slab with select salt-contaminated areas and two independent mats of reinforcing steel was monitored for mat-to-mat natural corrosion current flow (the top rebar in salty concrete was anodic and the bottom rebar in salt-free concrete was cathodic). The slab was then cathodically protected for 1.2 years using a conductive paint anode system applied to the top surface. No new delaminations developed during the period under CP and the existing delamination (prior to CP) did not increase in size. Near the end of the effort, the CP system was then turned off and several months passed. When the natural corrosion current was remeasured, it was found to be only one-third of that before cathodic protection. Thus, the cathodic protection system not only halted corrosion when activated, it influenced the overall corrosion state of the structure such that, even when the system was off, natural corrosion was much less (probably due to the migration of chloride away from the steel). This can only result in greatly extended life without major maintenance. During this test period, nearby slabs which had been rehabilitated using patching and concrete overlays (i.e. no CP) were also monitored. These slabs experienced no significant reduction in natural macrocell corrosion during the test period.

Thus, there is no question that properly installed and activated cathodic protection systems halt corrosion and corrosion induced concrete damage in "salt-contaminated" above-ground reinforced concrete structures. In fact, the evidence shows that even underpowered systems are beneficial and that cathodic protection has a long term beneficial effect. Even if the system is turned off (after a year or more), the natural corrosion state of the structure will be less than it would have been, had the cathodic protection never been applied.

3

History of Cathodic Protection

Introduction

Cathodic protection of steel in seawater was first used in 1824 by Sir Humphrey Davey.[16] During the past 50 years, it has been extensively and successfully used for the protection of steel in water and soils. The earliest applications of cathodic protection to reinforced concrete were to prestressed concrete water pipelines.[17,18] Applications were made before 1955 to buried reinforced concrete water tanks, to steel reinforcement and linings of nuclear reactor containment vessels, and to concrete coated pilings.[19,20] In the early 1980s, the Minnesota Department of Transportation installed cathodic protection on four lane-miles of continuously reinforced concrete pavement. This system used both vertical and horizontal anodes (in coke backfill) buried in the median to provide protection to the reinforcing steel via the soil and slab underside.[21] Sacrificial anodes have been used to protect concrete members underwater.[22]

All of these applications involved the use of the soil or water to apply and distribute the current, and thus are outside the scope of this state-of-the-art report. The reader is referred to the references for additional details on these conventional systems. The above-ground concrete CP field did, however, develop from this field and thus, it is appropriate to discuss the principles of CP prior to discussing above ground systems.

Cathodic protection controls corrosion of steel in concrete by applying an external source of direct current to the surfaces of the embedded steel. Corrosion is an electrochemical process in which the energy gained in the conversion of iron ore to steel is released in the form of a direct current. The resulting combination of the ferrous ions with chloride and water (at the anode) produces the scale (corrosion products which occupy more volume than the parent steel) which exerts the detrimental tensile forces in the concrete. This anodic reaction is balanced by a reduction reaction combining the released electrons, oxygen and water to form hydroxyl ions (at the cathode). Cathodic protection supplies an external energy to the steel surface to prevent the formation of ferrous ions by forcing all reinforcing steel to function as a current receiving cathode.

Cathodic protection can be applied either by using an impressed current or a sacrificial anode. An impressed current cathodic protection system requires only a few basic components.

- External DC Power Source (Rectifier)
- Current Distribution Hardware (Anode)
- Conducting Electrolyte (Concrete)
- Protected Metal (Reinforcing Steel)
- Completed Circuit (Wiring)
- Evaluation and Control Devices (Probes, Reference Cells, Controllers)

Of the above components, items 1 and 5 were in common use in other fields of cathodic protection and did not require much modification for use on bridge decks and other above-ground concrete members. Items 3 and 4 are inherent in the structure, but it must be emphasized that the effect of the cathodic protection system on these items is a very important, in fact a limiting parameter, in most instances. The items which required the most adaptation or modifications were the current distribution hardware (item 2) and the evaluation and control devices (item 6). In tests, the area affected by an anode was found to be confined, and the ability to "throw" current through concrete was limited.[20,23]

Cathodically Protected Structures

Cathodic protection has been used in the reinforced concrete field primarily as a method to extend life of structures that are already deteriorated. It has most often been applied to badly deteriorated structures after patching. Although this is cost effective, studies have shown that installation of CP prior to extensive corrosion- induced damage can be even more cost effective because the high cost of extensive concrete removal and repair is avoided. Also, in recent years, CP has been used in new construction (i.e. CP installed, and left in place to be activated when needed) on a number of large civil projects with uncoated reinforcing steel. Most notable of these are large bridge structures in Italy.[24] In most bridge deck rehabilitation cases, only deteriorated concrete (i.e. delaminations) is removed prior to CP installation and the anode is placed in or on the repaired, original top deck surface. However, in some instances (such as in Utah), all concrete has been removed around the top mat steel and the anode has been placed beneath the top mat prior to concrete placement. Also, most installations have involved placement of the anode on the top of salt-contaminated concrete with the steel in most need of protection closest to the anode. Attempts to place the anode on salt-free concrete remote from the steel to be protected (e.g. deck underside when the top mat rebar is surrounded by salty concrete, but the bottom mat rebar is in salt-free concrete) have met with only limited success and are still considered developmental.

A 1988-89 survey conducted by Battelle indicated that more than 275 bridge structures in the United States and Canada have been cathodically protected and that the total concrete surface under cathodic protection was almost nine million square feet (840,000 square meters).[25] About 99 percent of the protected area is on bridge decks, with the remainder on piers, pier caps and beams. Most of the bridges were 20 to 35 years old when cathodic protection was applied. Ninety percent of the protected structures are located in deicing salt regions and 10 percent are in marine environments. One highway agency (Missouri) has over 100 installations, another (Ontario) has nearly 50, and four states have 5 to 25 (California, Florida, Ohio and New Jersey). It is known that this survey underestimated actual CP usage since at least three states shown with zero installations (Utah, Pennsylvania and Virginia) have several installations each.

The Battelle survey indicated that 90 percent of the installations were operating satisfactorily "as designed" and that monthly monitoring by an in-house electrician was the most common monitoring method. E log I and hundred millivolt shift (polarization or depolarization) procedures were most commonly used for activation, adjustment and monitoring. Rectifier types in use included constant current (most common), constant voltage and constant potential control (least common).

Conductive Overlays

To provide a solution to the current distribution difficulty and to satisfy the constraints of an anode system for bridge deck use, a conductive overlay anode system was developed. This anode, consisting of a mixture of asphalt and metallurgical coke from coal (in place of a conventional aggregate), in conjunction with commercially available high silicon cast iron primary anodes, was first placed on a reinforced concrete deck in June 1973. Throughout this document the terms primary and secondary anodes are used in line with the American Association of State Highway and Transportation Officials TG 29 draft specification for cathodic protection of concrete bridge decks and are defined as follows:

- 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.

- Secondary Anode: Any anode material that distributes the cathodic protection current to the entire surface of the structure under cathodic protection.

Some believe these terms are misnomers and prefer "anode conductor" in lieu of "primary anode", and "anode" in lieu of "secondary anode".

The coke-asphalt system was developed and first used on the Sly Park Road Overcrossing bridge deck of U.S. Route 50 by Mr. Richard F. Stratfull and co-workers in the Caltrans. It consisted of direct placement of the primary anodes and wiring on the deck surface.[23,26,27] A continuous, 2-inch (5 cm) layer of the coke-asphalt mixture was then placed over the anodes and deck. A conventional asphaltic concrete overlay was finally placed as a wearing course. The primary, high silicon cast-iron anodes were powered by a constant-voltage rectifier.

After almost eleven years of operation, the system continued to function with the only major change being the substitution of a constant current rectifier for the original power source. The coke-asphalt overlay provided uniform current distribution over the deck surface, extended the primary anode life, protected the primary anode and instrumentation from traffic flow, and was economically justifiable. No evidence of acid or other chemical attack of the underlying portland cement concrete has been found.

As a follow-up, Caltrans installed seven additional coke-asphalt overlay systems in 1974-1975[26] and the FHWA established Demonstration Project No. 34 in 1975 to promote and fund projects involving cathodic protection of reinforced concrete structures. Over the period 1975-1980, the Demonstration Project funded a total of fourteen additional coke-asphalt overlay cathodic protection systems. Reference 28 summarizes this work and other reports are also available.[29,30,31] Twenty-two such systems were installed in eleven States by 1984. Usage since that time in the United States has been minimal. In 1985, it was reported that six coke-asphalt cathodic protection systems had been effectively operating on California bridge decks for over 11 years.[12] The physical condition of all six systems was reported to be excellent. The only maintenance was the addition of a 1 inch (2.5 centimeter) thick asphalt concrete wearing surface to the Sly Park deck due to cracks at the paving seam and wear as a result of tire chain traffic. No evidence of continued corrosion distress was observed on the cathodically protected portions of any of these structures.

The coke-asphalt overlay functions excellently as a secondary anode, but has exhibited some structural degradation in a number of instances. In addition, the added dead load limited the candidates for this type of system and the added height required modifications in drains, expansion joints, approaches, and curbing. Also, freeze-thaw deterioration of improperly air-entrained deck concrete beneath the overlay has limited its use to decks with proper air-void systems.

The Ontario Ministry of Transportation and Communications, recognizing the advantages of the coke-asphalt system, installed its first deck CP system in 1974. Ontario refined the original concept to improve structural stability and to permit replacement of the overlay without damaging primary anodes, wiring or instrumentation. The addition of some conventional aggregate to the coke-asphalt mix produced an overlay with higher stability and resistance to traffic loading with only a slight increase in resistivity. The conductive layer thickness is commonly 1.5 inches (37 mm) and is followed by 1.5 inch (37 mm) wearing course of conventional asphaltic concrete. Two problems were minimized; the premature deterioration of the original mix and the added dead load. Also, to protect primary anodes, cables and instrumentation during normal resurfacing, these items were placed in cut-outs in the portland cement concrete deck.[32,33,34]

The modified coke-asphalt overlay cathodic protection system became, in 1978, one of three procedures utilized in Ontario, Canada for bridge reconstruction.[35,36] A total of thirty such cathodic protection systems were constructed through 1984 in Ontario and use has continued (four structures are scheduled for 1992). At least one other conductive overlay system exists in other parts of Canada.

The evolution process with respect to conductive coke-asphalt overlays has slowed greatly in the last few years, to the point of virtual non-use within the United States. This may be undesirable. The basic anode system is efficient and time proven. The Ontario mix design yields increased stability of the wearing course and decreased dead load. A low cost sealer, which is expected to be compatible with CP, and will minimize freeze-thaw deterioration of the deck concrete beneath asphaltic overlays at low cost, has been defined.[37] Also, lower-cost, rapidly deployed primary anode systems (such as widely spaced platinized wire in slots backfilled with FHWA conductive polymer concrete, followed by a coke-asphalt overlay) deserve consideration.[38] These points suggest that this system deserves greater attention in the future.

An alternative conductive overlay was used experimentally on a bridge deck in Virginia in 1987.[39] This system involved overlaying the entire surface with 0.5 inch (1.25 cm) of the FHWA conductive polymer grout discussed below (1.25 centimeters thick) and is under evaluation.

Slotted Systems

Although coke-asphalt overlays have inherent advantages, the added weight, added height, time to replacement, and the danger of freeze-thaw deterioration of improperly air entrained concrete accelerated the development of other anode types. Slotted-cathodic protection systems for bridge decks were developed starting in the mid-1970s. The same requirements of durability, design life, minimal adverse effect on the electrolyte and economics hold for a slotted anode system. The primary anode material was commercially available in the form of platinized wires. These materials provide a reasonable design life, but must be closely spaced to effectively distribute protective current over the deck surface. Wire sizes of 0.031 inches (0.79 mm) diameter and 0.062 inches (1.57 mm) diameter are commonly available and permit the placement of the anode in small slots saw cut into the deck. Platinum layer thicknesses are typically 25-50 microinches (0.6-1.2 microns). Although a few installations have utilized wire with a solid niobium core, most projects involved niobium-clad, copper-core wire in which at least 35 percent of the cross sectional area is niobium. Testing by FHWA and others indicated that a spacing of no more than one foot (30.5 cm) was required for effective current distribution.[40,41,42] A slotted system with a platinized wire anode placed in a slot required the use of a backfill material which was conductive and would withstand traffic and the environment. The initial tests of slotted systems in 1977 used portland cement mortar around the platinized wire and a cap of polymer modified mortar was used as backfill material.[40] The backfill failed because of attack by the gases and acid which are produced at the wire surface. A backfill involving a proprietary "conductive" cementitious non-shrinking grout was defined and installed in 1979 on a Toronto, Canada bridge deck.[43] That same year the FHWA tested the "conductive" grout mixture on deck sections at its Virginia research center. The material also was used on at least one bridge deck in the United States. The grout exhibited adequate strength and freeze-thaw durability, but was attacked by the acids produced at the anode during the testing. Subsequent inspection of the Toronto bridge and other work in Ontario yielded similar results with respect to premature acid attack and deterioration of the backfill.[40,41] It was determined that the "conductive" grout was not electronically conductive and thus does not appear to be the ideal backfill required for an effective slotted cathodic protection system using platinized wire.

A backfill consisting of fine, calcined petroleum coke and topped with a flexible sealant was proposed by one industry supplier. This system was installed on FHWA test slabs in 1979 and on a deck in 1980 and functioned with no evidence of acid attack. However, the durability of the calcined petroleum coke-filled slot has been poor in some instances. The flexible sealant has also evidenced failure under traffic.[28,40] Thus, the coke-filled slot concept does not appear to be a viable alternative for deck surfaces.

Because of the shortcomings of the proprietary grouts and coke-filled slots and the attractive civil engineering aspects of the non-overlay systems, FHWA research was initiated in the late 1970s to define an improved backfill material.[40,44,45] The desired characteristics of the material included: high and rapid strength development, resistance to acid attack, resistance to chlorine attack, electronic conductivity, good bond to concrete, high freeze-thaw durability and good abrasion resistance.

The FHWA research efforts resulted in the development of a conductive polymer grout (concrete) material with a compressive strength in excess of 4000 psi in 4 hours, a resistivity of less than 10 ohm-cm, and excellent bond to concrete and freeze-thaw durability. The material included a vinyl ester resin with appropriate additives and coke breeze as the conductive filler.

Fifteen slotted bridge deck cathodic protection systems were installed between 1979 and 1984 in eleven States, and by 1989 more than 100 such systems were in place and operational. Most installations involved the use of the FHWA conductive polymer concrete, with the Missouri DOT having the most systems. The majority of the slotted systems in Missouri included the placement of an overlay after installation of the slotted cathodic protection system. The largest slotted CP system was installed on a 282,000 square foot (26,200 square meters) elevated box girder bridge deck in Charleston, West Virginia. It involved closely spaced, narrow slots with platinized wire loops as primary anodes and carbon strands as secondary anodes. This system was installed and activated in the mid 1980s without daytime lane closure. Reports on several other installations are available.[46,47]

Several modifications have evolved in the primary anode layout and materials. A grid of both longitudinal and transverse anode lines was instituted to provide redundancy among the anode lines as insurance against the failure of a connection point or failure due to cracking, and to increase the uniformity of the current distribution. High tensile strength, multi-filament carbon strands were approved as a partial replacement for the platinized wire. The lower cost carbon strand appeared to be a viable anode material when the platinized wire anodes were utilized for supplying the current to the carbon strand. Also, slot sizes were first increased, to decrease current density at the conductive polymer grout concrete interface and thus minimize acid attack, and then decreased to minimize degradation due to thermal cycling and traffic. Closely spaced, small slots provided the best performance. Design current densities were reduced from 10 to 5 mA/square foot (110 to 55 mA/square meter) of conductive polymer grout surface as a means of extending life.[48] Also, automated grooving and slot backfill equipment has been developed and field tested.[49]

An alternative slot anode material, titanium ribbon with a precious metal mixed oxide coating, was developed in the late 1980s and extensively tested in outdoor exposure and on parking decks. This material (1/4 or 1/2 inch width) is centered in slots with non-metallic spacers and the slot is backfilled with cementitious non-shrink grout.[50] Field trials on bridge decks are underway.

Distributed Anodes with Concrete Encapsulation

The excellent structural properties of the FHWA conductive polymer concrete material and its short time to achieve a 4000 psi compressive strength promoted the concept of mounded cathodic protection systems with non-conductive overlays.[40,44,45,51] The rigid overlays are used in deck restoration because of several good civil engineering considerations: extended deck life, minimal additional salt penetration, minimal freeze-thaw deterioration in underlying concrete, and a new, skid resistant riding surface.

In 1981, FHWA researchers began to consider a mounded grid anode cathodic protection system in conjunction with latex modified and conventional concrete overlays. The structural characteristics of the conductive polymer permits minimal disruption of the overlay process, and permits the overlay operation to be completed without damage to the anode grid. After removing unsound concrete, patching and scarifying the deck, the platinized wire and carbon strand anodes are placed on the deck surface and the conductive polymer concrete is mounded over the anode wires and strands.

The use of cathodic protection under conventional rigid overlays was completed on one bridge in 1983 (Minnesota DOT) and five others in 1984, as well as on a 200,000-square-foot (18,580-square-meters) five-level parking deck, and on over 75,000 square feet (6970 square meters) of another parking deck. Since that time, at least 10 other systems have been installed. Both conventional concrete and latex modified concrete overlays were involved in these efforts. The installation of the cathodic protection systems did not greatly interfere with the rigid overlay operation. All these systems included the use of FHWA conductive polymer concrete applied over a grid of platinized wire anodes and high purity carbon strand. Typically, carbon strand anodes were spaced at 1.5 feet (46 cm) in one grid direction and crossed periodically (every 25 to 50 feet) by platinized wire anodes in the other direction. Both types of primary anodes were then covered by mounds of conductive polymer concrete. These cathodic protective systems appeared to be more efficient and resistant to acid attack than slotted systems. Evidently, the moisture at the anode level remained high and more stable, and much reserve alkalinity was provided by the new concrete. Also, current discharges from all surfaces of the mound compared to three sides of a slot, and thus current density could be limited to low values (about 7.5 mA/ft^2 per square foot of anode surface). The effective size of the anode could be controlled by varying the dimensions of the mound, thus minimizing current density and acid attack.

An alternative anode (Raychem Ferex) for use in conjunction with rigid overlays and shotcrete or other forms of concrete encapsulation became available in 1984.[38,51,52] This anode utilized copper conductor surrounded by a flexible polymeric anode material which does not require an electronically conductive backfill. Woven into a mesh, the anode material was placed on the deck or substructure member and covered with a conventional rigid overlay or shotcrete. The mesh uniformly covered the member in an attempt to distribute the current evenly to the rebar and insure proper anode current density. Demonstration projects were constructed in Alberta, Canada on the Entwhistle Bridge and on about 50 U.S. bridge decks. Conductive cleats (small plastic clips which hold two conductive wires) were devised as a means of providing redundancy and were supplemented in some instances with platinized wire and the FHWA conductive polymer grout. By 1990, several field installations were exhibiting problems with anode degradation and embrittlement due evidently to local hot spots. Thus, this anode is not widely used today.

The mixed metal oxide mesh anode was developed in about 1985 for cathodic protection of reinforcing steel in concrete. It is composed of a mixed metal oxide catalyst sintered to a titanium mesh and has been successful in both decks and substructures.[38,51,52,53] Testing indicates that this anode has the following characteristics: long life, uniform current distribution, oxygen specific, stable, and sufficiently redundant.[54] Also, this anode operates below the chlorine discharge potential (1.03 V CSE) in most concrete environments.

One hundred mesh anode cathodic protection systems were installed between 1985 and 1990 in nineteen states. Three mesh manufacturers have supplied material for laboratory and field testing, but only one (Elgard) is presently active in the U.S. marketplace. Today, over four million square feet (370,000 square meters) of above ground reinforced concrete structures are cathodically protected using titanium mesh anode systems in North America. The anode installation involves rolling out the mesh onto the concrete surface, fastening the mesh onto the concrete surface with plastic fasteners and welding titanium strips onto the mesh. These titanium strips, also called current distributors, are bent through holes previously drilled in the deck for connection to copper wiring in a conduit system. For substructure applications the titanium strips terminate directly into junction boxes. The encapsulant concrete (conventional or latex modified overlay or shotcrete) is then placed. This anode has become the most widely used system in recent years.

Conductive Coatings

Conductive paints and mastics were investigated and used on concrete members not subject to traffic beginning in the late 1970s.[15,38,52,54-58] These secondary anode systems used several forms of carbon dispersed in solvent or water based paints; and typically covered the entire concrete surface to be protected. The primary anode was typically platinized wire and the connection between the wire and the paint was made using the paint, a conductive paste or FHWA conductive polymer grout. The black-colored paint was typically overcoated with a lighter colored material. Initially, conductive paints designed for use in other applications (ex. television tubes) were used, but in the last eight years materials designed solely for concrete members have become available. Durability problems in wet, freeze-thaw and splash-zone environments were common with the earlier materials. Tests did show conclusively however, that a properly designed, constructed and activated conductive paint system could adequately protect steel in concrete in humid environments.[15,52,54-56] Conductive polymer coatings have also been investigated for use on substructures.[38,49]

An alternative conductive coating for concrete members was developed in 1983 by California Department of Transportation researchers.[59,60] This material, flame-sprayed zinc, functions as a secondary anode covering virtually the entire concrete surface. It has performed well in several trials when shorting problems could be avoided. An advantage is its "concrete-like" color.[38,52,61] Typical zinc thickness has been in the range of 8 to 20 mils (0.2 to 0.5 millimeters), depending on design life. The development and use of arc spray techniques has resulted in faster, lower cost applications and the ability to apply thicker coating with fewer passes.[38] With the original flame-spray equipment, up to eight passes were required to deposit the desired zinc thickness and production rates were slow (only a few square feet per hour). Arc spray is much faster, and equipment size has increased from the 200 amp guns used in Norfolk, Virginia in 1986 to 600 amp guns in Big Spring, Texas in 1988.[38] It is possible to achieve a production rate of 50-70 square feet (4.65-6.5 square meters) per hour at 20 mils (0.5 millimeters) thickness on a concrete substrate with a 600 amp arc spray gun. The largest zinc systems to date have been installed by the Oregon DOT on the Cape Creek and Yaguina Bay Bridges. These installations have led to several recent technical advances in the installation and use of sprayed zinc as an anode.

Recently, sprayed zinc has also been investigated for use as a sacrificial anode cathodic protection system on substructure members in hot, moist, coastal environments.[62] The zinc was sprayed directly on the exposed reinforcing and the surrounding concrete after blast cleaning. A textured overcoat (cement and polymer) is also being studied to minimize environmental self-corrosion of the zinc and for aesthics. Performance after three years is encouraging. Some zones of the Cape Creek Bridge in Oregon are also operating sacrificially.

Other Anode Systems

Other anode systems have and are today being investigated for use in cathodic protection of above-ground reinforced concrete members. They include conductive portland cement concrete, conductive ceramics and conductive rubber.[56,63] Conductive rubber has been used by the Florida DOT in marine, substructure applications with reported success, and it is available commercially. Conductive ceramics are proported to tolerate high current densities without acid attack of the surrounding concrete because of their composition and high permeability. However, this has not been conclusively confirmed. Trials are in process in Europe. Also, surface mounted precast conductive polymer anodes (both rigid and flexible) have been studied and used in limited trials. These systems have not yet advanced beyond laboratory or experimental use.

Of the above systems, conductive portland cement concrete has received the most attention. Attempts have been made to make portland cement mortars and concretes conductive by addition of carbon in various forms. This includes addition of acetylene black; use of conductive, lightweight, carbonaceous aggregate or a petroleum coke mixture; use of marconite aggregate—a carbon by-product of oil refining; and use of carbon black and carbon fibers.[55,56,64,65,66] High range water reducers can offset the increased water demand caused by some of the carbon materials, but questions exist as to the effect of many of these materials on air entrainment and the subsequent freeze-thaw durability. Another technical issue involves the amount and the effect of CP-generated acid on the conductive concrete. With additional research and field studies, it may be possible to produce an electronically conductive portland cement mortar or concrete without sacrificing the required mechanical and durability properties.

Probes and Criteria

Instrumentation consists of reference cells, corrosion rate measuring probes, and current pick-up probes. As the various projects progressed in the last fifteen years, the instrumentation has remained relatively constant, but the method of installation has evolved. In the early installations, data obtained were often of minimal value because of the placement procedures used with the various probes.

Instances in which measured corrosion rates or currents of the probes in salty concrete were zero regardless of whether or not the cathodic protection system was on, were not uncommon. This problem can be avoided by precasting the probe in salty concrete, excavating field concrete around bars on all four sides of the probe and then patching with salt-free concrete. Reference cell installation on the other hand, has evolved to the point that the cells are installed at anodic locations without exposing structure rebar in their vicinity, to insure the cell is monitoring the proper rebar (i.e. anodic steel in old, salty concrete).[45,48]

Reference electrodes of many types have been utilized. Among the types are:

- zinc-zinc sulphate
- copper-copper sulphate
- silver-silver chloride
- molybdenum-molybdenum oxide
- graphite
- lead

Of these, none has remained completely stable. The silver-silver chloride and graphite cells have the steadiest record to date in the United States.[45,57,59,67] Manganese dioxide reference cells were developed and reported to be stable in concrete in European studies[68]

Controllers for regulating cathodic protection current have ranged from a simple resistor circuit to sophisticated microprocessor control of the rectifiers. Because of the reference cell instability and reliability problems, potential control has given over to constant current or constant voltage control. Sophisticated, electronic rectifier/controllers were used during much of the 1980s and reliability problems were common. Recently, a back-to-basics approach has been emphasized.

It is paramount that all potential measurements on reinforced concrete structures be made using procedures which eliminate "IR error". This has been accomplished using the special rectifier/controllers discussed above, by using an unfiltered rectifier and an oscilloscope operating in the nulling mode, or by switching off the power for a short period (typically 0.06 to 1 second), either manually or via AC or DC interrupters.

Attempts to achieve and maintain specific polarized potentials, such as -850 or -700mV versus Copper Sulfate Electrode on above-ground concrete cathodic protection systems have been made.[20,69] However, in structures where much of the steel is naturally cathodic and thus in a passive state, and the dissolved oxygen content is far higher than in most buried structures, the application of such criterion has been found to result in very high unneeded power requirement. This may cause premature deterioration of the anode and surrounding concrete, and raises concerns about the long-term effect of the CP currents on reinforcing steel bond.[26,31,42,45,58] Also, half-cell potentials of the reinforcing steel have been found to be highly variable with changing moisture and oxygen content. As a result, the use of a specific half-cell potential criterion has decreased (especially in light of the reference cell stability problems discussed above). Rather, the use of E log I testing has become common.[38,42,45] In this procedure, half-cell potential is plotted versus the log of current, and the graph is analyzed to define the cathodic protection current requirements on each specific structure. Recently, however, much discussion concerning the use of short-term potential shift has occurred, and this has become the most commonly used type of criteria.[25] Most discussion centers on criterion of 100 to 150 mV polarization or depolarization in periods from 4 hours to several days.[70,71] National Association of Corrosion Engineers Recommended Practice for Cathodic Protection of Above-Ground Reinforced Concrete Members was finalized in 1990.[72] This document permits use of E log I or depolarization (100 mV) for activation, as well as a third statistical analysis method which is not widely used or proven.

Additional criteria related studies are now being conducted under SHRP contract, and these may have impact on evaluation and monitoring of CP systems in the future.

Alternate Cathodic Protection Power Sources

The impressed current cathodic protection systems discussed above normally require a source of commercial AC power to operate the rectifier and controllers. Many concrete structures that might benefit from cathodic protection do not have commercial AC power within the vicinity. Consequently, alternate cathodic protection power sources have been evaluated.

Sacrificial anode cathodic protection systems which utilized zinc anodes placed in saw cut slots in the deck or on the deck followed by an overlay have been studied. A natural galvanic potential exists between the zinc and steel rebar. Although limited to about 0.5 volts driving voltage, cathodic protection current using this natural voltage will flow from the zinc to the rebar, and no external power is needed. Several evaluation projects have met with limited success.[57,58,73,74] The effective spread of the cathodic protection currents was limited to a few inches from the anode since the fixed natural voltage is too low to throw the current through the concrete for greater distances. This, coupled with the problem generated by the expansive corrosion products of the zinc, have led to minimal use of sacrificial anode systems. Recently, however, zinc applied by arc spray has been investigated as a sacrificial anode for substructure members in hot, moist marine environments (such as the Florida Keys). Concrete in this environment is relatively low in resistivity and the zinc can be placed over the entire surface without being encapsulated in concrete. Results through three years are encouraging.[62]

A variable voltage source for cathodic protection which does not require commercial power is a solar photoelectric panel used in conjunction with DC batteries.[45,75] The cost per watt of power is high, but this can be offset by the zero power and AC line installation costs. A solar electric unit was installed in 1977 to power a conductive overlay anode system for a bridge on the George Washington Parkway in the Washington, DC area.[75] Solar power could be the solution to providing an economical power source for remote bridge locations.

Effect of Cathodic Protection on Bond

The effect of cathodic protection currents on bond/pullout strength of reinforcing steel in concrete has been extensively investigated. Although some researchers have stated "Hydrogen evolution can seriously damage the rebar bond", a thorough study of available data indicates that this concern is not justified.[76] As early as 1913, studies showed that a detectable softening of the concrete occurred near the cathode when reinforcing steel was made cathodic.[77] Subsequent studies have shown that this is caused by the gradual concentration of calcium, sodium and potassium ions (i.e. alkali hydroxides) near the steel.[107] Any decrease in bond strength has been found to be related primarily to the total charge passed (i.e. current times time) rather than current density, voltage or other factors.[77-80] Significant excess bond strength normally exists, and at the low current densities used in cathodic protection, hundreds of years would be required to affect bond strength sufficiently to be a concern to the integrity of most structures. Thus, today, this area is normally not considered a limiting factor in the use of cathodic protection. A limited number of laboratory studies have indicated a potential problem when cathodic protection is used on reinforced concrete structures constructed with aggregates which are alkali reactive.

Service Life of Cathodic Protection Systems

Cathodic protection systems used during the past 18 years on highway structures have exhibited variable service lives as a result of the developmental nature of the field and the variety of systems studied. Conclusive data are not yet available on all systems (SHRP is studying this area further), but experiences defined in the literature and opinions of the authors are summarized below.

The service life is defined as the time to major maintenance. All cathodic protection systems must be monitored and periodically adjusted to maximize service life, but this is not major maintenance. With major maintenance, the cathodic protection systems are expected to continue in operation and thus, a structure's additional useful life could exceed the values given below. It must be emphasized that these estimates are optimal values for systems which are properly designed, installed and maintained.

Coke-Asphalt Deck Systems

Anode life will be very long from an electrical standpoint (40 years or more) and system life can be expected to be in excess of 20 years with a single replacement of the nonconductive asphaltic overlay required during that time for civil engineering reasons.

Slotted Systems

These systems (narrow, closely spaced slots) have an expected life in excess of 15 years without major maintenance. Life could be longer with proper system adjustment.

Systems with Concrete Encapsulation

FHWA mounded conductive polymer distributed anodes with low slump or latex-modified concrete overlays are expected to have service lives in excess of 20 years.

Titanium mesh systems with concrete overlays or encapsulation will have very long service lives probably limited only by the life of the concrete encapsulation. Thus, with proper construction, the service life can be expected to be in the range of 35 to 40 years (or more) in most environments.

Conductive Paint Systems

These systems have a time to major maintenance of about 5 to 10 years in moderate environments. However, the life can then be further extended by paint removal and repainting.

Sprayed Zinc

Impressed current sprayed zinc systems have an expected service life of 10 to 20 years depending on the thickness of zinc applied and the environmental exposure.

Cathodic Protection System Costs

As with service life, construction costs of cathodic protection systems have been difficult to define because of the developmental nature of most installations. The varying work included (some estimates include traffic control, patching and overlays, while others do not) and the "training curve" experienced by contractors and others involved also adds to the difficulty. For this reason, SHRP is further studying this area. In spite of the above, the following general information can be provided. None of the estimates given below include the cost of traffic control, patching or structural repair.

Coke-Asphalt Deck Systems

Stratfull reported the cost of the 1973 installation at Sly Park to be $3.00 per square foot ($32.00 per square meter). The costs of installations constructed under Demonstration Project 34 between 1975 and 1980 generally range from $2.00 to $12.00 per square foot ($21.50 to $129.00 per square meter) and average about $6.00 per square foot ($64.00 per square meter). Published figures from the Ontario Ministry of Transportation in 1977 indicated a cost of about $4.00 per square foot ($43.00 per square meter) and later experiences indicated that the "standard" Ontario systems were being constructed for less than $3.00 per square foot ($32.00 per square meter). These data also indicated that the cathodic protection system costs were only about one-third of the total rehabilitation costs, with the remainder being spent for traffic control, new joints and deck patching.

An estimate for coke-asphalt deck systems (in 1991 U.S. dollars) is $6.00 per square foot ($64.00 per square meter).

Slotted Systems

Reported costs for slotted system (mainly FHWA conductive polymer grout, platinized wire and carbon strand) have typically ranged from $4.00 to $16.00 per square foot ($43.00 to $172.00 per square meter). The best information is that available from the 280,000 square feet (26,000 square meters) West Virginia DOT elevated box girder bridge deck which was cathodically protected between 1984 and 1986 using small, closely spaced slots. The cost of the system, not including traffic control, was about $4.50 per square foot ($48.00 per square meter).

In present dollars, a rough estimate for a slotted system would be $6.00 per square foot ($64.00 per square meter).

Distributed Anodes with Concrete Encapsulation

Several FHWA conductive polymer mound deck systems have been constructed at a cost in the range of $3.50 per square foot ($38.00 per square meter), not including the cost of traffic control or the overlay, while others have experienced costs as high as four times that value. It is believed that the higher cost structures were greatly influenced by the "learning curve".

The cost of titanium mesh anode systems have typically been in the same range when traffic control and the overlay are not included (i.e. $3.00 to $5.00 per square foot or $32.00 to $54.00 per square meter).

When a concrete overlay is used to encapsulated the anode, the overlay cost has typically been in range of $4.00 per square foot ($43.00 per square meter). When shotcrete is to encapsulate mesh anodes, the cost of the shotcrete is often estimated at $9.00 per square foot ($97.00 per square meter).

Thus, a rough estimate for a distributed anode deck system including the concrete overlay would be $9.00 per square foot ($97.00 per square meter), and a similar estimate for a substructure system including shotcrete would be $14.00 per square foot ($151.00 per square meter).

Conductive Paint Systems

Reported construction costs vary from less than $10.75 per square meter to about $129.00 per square meter. A rough estimate for substructure conductive paint systems constructed today is $54.00 per square meter.

Sprayed Zinc Systems

Reported costs range from $1.00 per square foot ($10.80 per square meter) to about $12.00 per square foot ($130.00 per square meter) for these systems on substructures and on deck surfaces (the latter covered with an asphaltic concrete overlay). In nonexperimental use, it is estimated that these systems could be constructed today for about $9.00 per square meter ($97.00 per square meter).

Summary

Cathodic protection for reinforced concrete members began in earnest with the Sly Park installation of 1973. In the eighteen years since, the materials and techniques have evolved to better suit the requirements of the civil engineer and the corrosion engineer. Cathodic protection for bridge decks and other concrete members has grown from an experimental concept to a viable rehabilitation procedure.

The evolution of above-ground concrete cathodic protection systems has resulted in the development of several techniques and materials solely for the reinforced concrete field. Today, the bridge deck cathodic protection field is further developed than cathodic protection for substructures, although systems are available for both types of members. To compare the available systems and techniques in order to define the best system would be inappropriate. Each of the four basic anode systems—conductive overlays, slotted systems, distributed anode systems encapsulated in concrete, and conductive coatings—serves a particular purpose. Table 1 summaries the available systems and their costs (for large installations) and service lives.

Table 1. Available CP Systems and Estimated Costs and Lives

Anode System	Structures Protected	Estimated Construction Cost, 1991 U.S. S/square foot ($/meter square)	Estimated Service Life, years per meter square
Coke-Asphalt Overlay	Decks	$6 ($65)	20
Slotted Conductive Polymer Grout	Decks	$6 (S65)	15
Mounded Conductive Polymer w/ Concrete Overlay	Decks	$9 ($97)	20
Titanium Mesh w/ Concrete Overlay	Decks	$9 ($97)	35
Titanium Mesh w/ Shotcrete	Substructures	$14 ($150)	35
Conductive Paint	Substructures	$5 ($54)	5
Sprayed Zinc	Substructures	$9 ($97)	15

With a growing interest and technology in cathodic protection of above-ground reinforced concrete structures, evolution will continue and new and composite cathodic protection systems will become routine. A milestone in CP of above-ground reinforced concrete was reached in 1984. Over one million square feet (93,000 square meter) of cathodic protection had been installed or was in the design and construction process on above-ground reinforced concrete bridges, parking garages, and buildings, with the total number of structures in the range of 75. By 1989, the number of individual projects was about 275 and the total above ground concrete surface area protected was about 9 million square feet (840,000 square meters). The vast majority of these systems were reported to be functioning adequately.[25] Today, it is estimated that over 350 structures are cathodically protected, with the surface area under protection exceeding 10 million square feet (930,000 square meters).

4

Condition Survey

A condition survey is generally performed prior to rehabilitation. Condition survey is a general term that is often meant to include collecting data which indicates the presence of spalls, delaminations, electrical potential levels of the reinforcing steel and the chloride content in the concrete. Table 2 shows a suggested correlation between condition survey results and the general bridge rating. Cathodic protection has typically been used in bridges that are rated two, three and four. A substantial economic advantage could be enjoyed if CP rehabilitation were applied more frequently to structures rated five through eight. These are structures that could accommodate CP prior to major concrete remedial repairs being required.

Before any rehabilitation can be considered, a complete condition survey of the bridge is conducted to determine the extent of damage, cause of damage, and the economic feasibility of rehabilitation options. The tests used to rate a structure's deterioration are corrosion condition surveys that range from a simple visual inspection of the corrosion damage to an in-depth laboratory analysis of concrete samples. Many programs and manuals have been developed by FHWA and State Highway Agencies for detecting and assessing corrosion conditions.[51,81] Results of these tests, in combination with some condition assessments used for CP design provide the necessary information needed for selecting the CP rehabilitation option. All the essential tests are briefly outlined in this section.

Tests Used For Assessing the Bridge Structure Condition

Visual Inspections

When conducting a condition survey, a visual inspection of the structure is in order. A complete visual inspection should include recording the location, size and shape of cracks, spalls and stained areas. All signs of patch work to the deck and substructure should be noted. This information provides insight to the degree of damage which has occurred to a structure. The information can also be used to aid in the selection of areas to be further sampled and evaluated as well as plotting damage progress in the future.

Table 2. Concrete Bridge Component Deterioration Chart

		Condition Indicators (% deck area)			
Category	Rating	Spalls	Delaminations Half-cell Potential (copper sulfate electrode)	Electrical (Volts)	Chloride (Pounds per Cubic Yard)
Category #3	9	None	None	None more negative than - 0.20	None
Light	8	None	None	None more negative than - 0.35	None more than 1.0
Deterioration	7	None	Less than 2%	45% more negative than - 0.35	None more than 2.0
Category #2	6	less than 2% spalls or sum of all deteriorated and/or contaminated deck concrete less than 20%.			
Moderate Deterioration	5	less than 5% spalls or sum of all deteriorated and/or contaminated deck concrete to 20 and 40%			
Category #1	4	less than 5% spalls or sum of all deteriorated and/or contaminated deck concrete 40 to 60%.			
Extensive Deterioration	3	more than 5% spalls or sum of all deteriorated and/or contaminated deck concrete more than 60%.			
	2	Deck structural capacity grossly inadequate.			
Structurally Inadeq. Deck	1	Deck has failed completely repairable by replacement only.			
	0	Holes in Deck - danger of other section of deck failing.			

Delamination Surveys

Using visual inspection alone, one cannot detect the full extent of damage that has occurred to a bridge structure. Before a spall is formed, the bond between the reinforcing steel and concrete will crack, creating a delamination. In these areas, the surface concrete may still be in place, making visual detection impossible.

To determine an accurate estimate of the areas requiring remedial action, delamination tests should be performed on all parts of the bridge structure. Delaminated areas produce a distinctive hollow sound when the concrete is mechanically stimulated with a hammer, chain, steel rod or other similar device. Chain dragging is commonly used to detect delaminated areas on top of horizontal surfaces and a common hammer is often used on vertical or underside surfaces. To effectively survey large deck areas, Delamatech and chain roller type machines have been utilized. Procedures for determining delamination in concrete by sounding techniques are defined in American Society for Testing and Materials designation D4580-86.[82] Once a delaminated area is located it is typically outlined on the structure using chalk or paint. The area of delamination and spalls is then visually available to record and estimate the amount of existing damage.

Both the FHWA and State Highway Agencies are investigating the use of infrared and radar technology to detect delaminations. These technologies typically provide graph recorded data which require interpretation to estimate the amount of existing damage.

Electrical (Half-Cell) Potential

To determine the possibility of corrosion activity in visibly good and sound areas of concrete, half-cell potential surveys are performed. Half-cell measurements allow a comprehensive corrosion survey to be performed in a relatively short period of time. The results obtained from this type of survey reveal the potential differences present in the reinforced concrete structure. Contour mappings of these potential levels can be used to easily identify corrosion activity of the reinforcing steel in concrete. Half-cell potential mapping, in combination with the tests described previously, provide a clear picture of existing and near future corrosion damage to a bridge structure.

As the passive oxide film on the reinforcing steel becomes destroyed by high concentrations of chloride ions, the electrochemical corrosion process begins. It is during this process that an energy imbalance between and within reinforcing steel is naturally adjusted through the release of iron ions and electron movement. The methodology for this measurement and guides for interpreting the results are described in ASTM C876-89.[83] The variation in energy levels produce voltage gradients which indicate corrosion activity and are measurable with voltmeters, reference electrodes and lead wires. Besides identifying areas that have a high probability for corrosion activity, attention should also be given to locations where large differentials in values exist. Even if the half-cell values do not suggest a high probability for corrosion, large differences in values suggest areas where corrosion may occur.

During SHRP interviews, many engineers said that measuring half-cell potentials was costly to collect in terms of manpower.[84] To aid in the collection of large numbers of potential readings, several devices have been developed. Data acquisition units with built-in voltmeters can store large amounts of readings, and substantially reduce the time required to record potentials. These types of devices also make the development of contour plotting easier, by directly entering the readings into computer programs specifically designed to create the contour maps. Other devices were developed to make the task of taking potential readings even faster, such as the M.C. Miller Four Cell Array. This piece of equipment can record four readings simultaneously, greatly reducing survey time. Other multiple cell and moving-wheel type half-cell devices, such as the Potential Wheel developed by Taywood Engineering, are commercially available.

Chloride Concentration Analysis

Chloride ions are well recognized as the major cause of corrosion of steel reinforcements in bridge structures. Chloride ions concentrations in excess of 1.0 lb/cubic yard (0.16% by weight of cement) of concrete have been determined to destroy the passive oxide film which is formed on reinforcing steel embedded in concrete.[5] Varying levels of chloride ion concentrations are known to form macrocells, which ultimately result in delaminated and spalled areas. A chloride ion concentration analysis indicates the extent of chloride ion contamination at specific locations.

Chloride concentration analysis begins by obtaining concrete powder samples or cores from various locations on the bridge. Careful selection of the sample sites should be conducted in order to obtain a true representation of chloride contamination. Obviously, the greater the number of samples taken, the better the test results will mirror reality. In practical terms, however, the costs involved with obtaining and analyzing the samples limits the number which are taken. A general guide for obtaining samples is three samples per location with a minimum of one location per 2,500 square feet (230 square meters) of concrete surface area.[51] Samples are collected at various depths to develop a profile of the penetration of chloride ions. The different sample depths are typically 0-1 inch, 1-2 inch, and 2-3 inch (0 to 2.5 centimeters, 2.5 to 5 centimeters and 5 to 7.6 centimeters) from the surface. The process for the proper removal of field test samples and how to conduct chloride content of concrete, potentiometric titration laboratory method, is outlined in the AASHTO Standard T260.[85] A rapid field determination of chloride content of concrete was developed by SHRP "Standard Test Method Using the Specific Ion Probe."[86]

Once the results of the chloride analyses are known, a plan view of the extent of contamination to the bridge can be developed and location of possible macro-cells can be identified. Using the test results, projections can also be made for the expected level of chloride concentration in future years.[87] Thus, if the chlorides have not yet exceeded the threshold level for corrosion at the rebar depth, the future time when this will occur can be reasonably estimated based on Fick's diffusion laws.

Condition Tests Used for Assessing the Option of Cathodic Protection

After the corrosion condition survey results are analyzed, the structure is classified and rated. The method of rehabilitation is then determined. If CP is considered, a further assessment of existing conditions is made to determine the economic viability of CP, the type of cathodic protection most appropriate and the need for any other additional remedial measures. The four essential assessment conditions include electrical continuity, depth of cover, concrete resistivity and quality of concrete.

Electrical Continuity

The electrical continuity of the embedded reinforcement is a prime concern for CP performance. The electrical continuity of the reinforcement must distribute the CP electrical current and must be sufficiently intact to prevent electrolyte corrosion from the CP. For the vast majority of bridges considered for CP, good electrical continuity within bridge components has been found and can be expected. Isolated cases where continuity was not found is usually where previous repairs or rehabilitations were made (see Remedial Action Section of this report) and between bridge components. Typically original construction has sufficient wire ties, chair supports and reinforcing bars to ensure good electrical continuity. However, if isolated metals are suspected, electrical continuity testing is in order.

To determine whether continuity exists in a structure, it is always recommended that a sufficient number of tests be made prior to the completion of the project specifications to confirm general continuity. This usually consists of contacting all existing exposed metallic members as well as a statistically significant number of embedded rebars (e.g. 10 to 20 locations) to assure a high probability that all rebar is continuous. Other metallic components such as railings, scuppers, etc., are often not continuous but are easily bonded into the system during rehabilitation. This testing can also be performed during the construction phase exclusively, but this generally results in higher costs since the contractors bidding the contract are dealing with an unknown quantity of continuity bonds and type required. The sampling method suggested above can accurately predict the amount of bonding required except for that required when excavating existing concrete from around the rebars breaks the wire ties which would otherwise provide continuity. The restoration of this continuity is usually required of the contractor at no additional cost since his work methodology will either prevent or cause these discontinuities.

To determine electrical continuity and locate electrically discontinuous embedded metal within a bridge structure, electrical tests are commonly used separately or in conjunction with one another for higher assurance of test results. "Potential Difference", "AC Resistance", "DC Resistance" and "Half-Cell Potential" measurements have all been used successfully for bridge structure continuity testing.[51,81] The two more commonly used measurements are described as follows:

Potential Difference Measurements

Electrically continuous metallic components embedded in an electrolyte such as concrete, should have no potential difference or voltage drop between them. Due to this fact, two embedded metals can be easily checked for electrical continuity using a voltmeter. To perform this test, the voltmeter is connected across the embedded metal components in the bridge structure via point probes. If the potential difference between the components is near zero, it can be assumed that the two embedded metals are electrically continuous to each other. Using this relatively simple approach, an entire bridge structure can be tested for electrical continuity rather quickly.

This test procedure is typically repeated for all embedded steels (reinforcing steel, scuppers and expansion joints), which are exposed before and during rehabilitation of a concrete structure. If a sufficient number of locations are not exposed, location and excavation of embedded steel may be necessary. As a general rule, specifications require that at least five locations are tested for every 1000 square feet (93 square meters) of surface area on each bridge component, (i.e. deck, sidewalk, abutment, etc.).

As a guide, the following criterion can be used to evaluate results of the potential difference test:

1. Potential difference between O mV and 1 mV = electrical continuity highly probable.

2. Potential difference > 1 mV = electrical discontinuity highly probable.

If any uncertainty exists, the AC resistance technique, described below, can be used to provide additional information. It is also advisable to conduct measurements by a second technique where a small sample of measurements are being extrapolated to the entire project, and therefore have a major influence on cost.

AC Resistance Measurements

The interconnections between two continuous metallic components have a finite electrical resistance which is of relatively low value. A measurement of the resistance indicates the degree of electrical continuity. When performed in conjunction with the potential difference measurements, one can determine with a fair degree of certainty the electrical continuity of the embedded metal components.

To perform this test, wire connections are made between two exposed metal areas and the four terminal posts of an AC resistance meter (Nilsson Model 400, for example). By measuring the resistance with the meter in the four terminal mode, mechanical connections and other extraneous causes of resistance can be eliminated, allowing only the resistance between the two components to be measured. The resistance is measured by nulling the indicating meter and reading from a calibrated dial. Since a finite resistance exists between two electrically continuous metals, a zero resistance value cannot be expected. The following is a guide for categorizing test results:

1. AC resistance less than 0.10 ohms = electrical continuity highly probable
2. AC resistance between 0.10 and 0.50 ohms = electrical continuity uncertain
3. AC resistance > 0.50 ohms = electrical discontinuity highly probable

For cathodic protection rehabilitation, all embedded metals found to be discontinuous must be repaired. This has been successfully done by using various bonding techniques, such as thermite welding, arc welding and brazing. Lead wires or direct bonding between discontinuous metal to continuous metal has been used. FHWA conductive polymer grout also has been successfully used to establish continuity where a large number of bonds must be made.

Depth of Cover

Selection of a CP system is dependent on the amount of concrete cover over the reinforcing steel. Insufficient depth of cover may limit CP options or possibly eliminate CP as an economically practical rehabilitation. When the depth of cover between the anode and the reinforcing steel is 0.5 inches or more, good distribution of the cathodic protection current has been found. Proper depth of cover also allows surface applied anode materials to be installed without electrical shorts. Systems have been installed with less cover but additional work is required. One of the most sensitive areas for poor cover is the bottom side of bridge components where the reinforcing chain support tips are near or at the surface. When sufficient cover exists (e.g. 1 inch or 2.5 centimeters or more over 95 percent of the structure surface to be protected) anodes installed in slots have been used.

To detect the depth of cover over reinforcing steel, electromagnetic induction type instruments (pachometers) have been developed. By sweeping the transmit/pick-up coils of these meters over the concrete surface, measurements of the concrete cover over the reinforcing bars can be obtained. The units also can be put into an alarm mode, alerting the operator to areas where preselected conditions are not met. Another device routinely used to perform depth-of-cover investigations is a common metal detector. While this type of instrument is not capable of determining the exact depth of cover, it can be used to determine if a predetermined cover is present. This is accomplished by adjusting the metal detector's sensitivity against a known standard. This type of instrument is also valuable in locating surface metals such as nails and tie wires that can short the CP anode to the reinforcing steel.

Petrographic Analysis

To gain a comprehensive understanding of the physical make-up and quality of concrete used in a bridge structure, a petrographic analysis is performed. A qualified petrographer can examine core samples obtained from the structure to determine in detail the existing condition of the concrete and probable future performance of the concrete. Standard laboratory tests are performed to measure the concrete's density, paste quality, air void system, compressive strength, depth of carbonation and type(s) of aggregate.[88] For example, an air void analysis is essential if a coke-asphalt CP system is designed for a deck subject to freeze/thaw conditions. A deck with a poor air void system must have a concrete sealer applied prior to the asphalt cover to ensure a long lasting rehabilitation.[38]

The information provided by this type of analysis allows for a thorough understanding of the quality of concrete in the bridge structure. While this type of test is not always performed as part of the CP rehabilitation, the knowledge gained greatly aids in the total analysis of the structure, and warns the rehabilitation design engineer of distress other than corrosion to which the structure may be prone that can ultimately effect its service life.

Concrete Resistivity

In order to know if the existing concrete or any patching material is compatible the with CP system, the resistivity of the material is determined. Resistivity is the physical property of a material to resist the conduction of electricity and is measured in ohm-centimeters. A material with a high resistivity is a poor conductor of electricity and vice versa.

Using the Wenner Four-Electrode Method, field tests are conducted to determine the resistivity.[89] Measurements are made in concrete after locating the reinforcement steel and positioning the probe as far as possible from the reinforcement. Measurements should not be made directly over reinforcing steel. Materials with resistivities which remain in excess of 50,000 ohm-cm are not considered compatible with cathodic protection.

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Remedial Action

Cathodic Protection (CP) is designed to be installed in conjunction with concrete and asphalt overlays, embedded into concrete and on concrete surfaces. Since the first CP installation in 1973 it has become evident that remedial repair work is integrated into nearly every CP project. In fact, in many cases CP is simply a minor part of a bridge rehabilitation project. Depending on the level of distress and degradation of a particular bridge, the remedial repair component may be of greater cost than the CP system, where conversely a bridge that is less deteriorated may require a minor amount of remedial repair work. As part of this process it has been learned that there are various repair measures which may hinder or make uneconomic or unfeasible the use of CP as part of the overall repair. Therefore, it is important to recognize what sort of remedial repairs are required in conjunction with the design and installation of CP. That is, if CP is a candidate for future rehabilitation, the remedial repair work must be compatible with CP.

A bridge structure exposed to salt can expect corrosion of the embedded steel during its service life. CP has proven itself as the only permanent repair of existing corroded steel reinforced concrete.[90] Therefore CP must not be considered separately, but as a part of a complete rehabilitation program. This section describes what has been learned about the remedial repair work and how it affects a CP installation.

Incompatible Concrete Materials

For a CP system to function properly, the CP anode and the reinforcing steel must be embedded in or in contact to a common conductive material. Typically, this material is a cementitious concrete which is sufficiently conductive to be compatible with a CP system. Incompatible areas in a reinforced concrete structure are often the result of previously installed high resistivity patch materials which are often polymer or epoxy based. Areas of carbonated concrete may be incompatible with CP. Dry carbonated concrete makes it difficult to impress current because of its high electrical resistivity.[91]

The concrete in which the CP system is installed should have a relatively uniform and low to medium resistivity. To measure the concrete's resistivity on site, the Wenner Four Probe Array method is often adapted[89] The proper spacing varies from a minimum of the concrete's coarse aggregate to a maximum of the reinforcement cover. Measurements are made after locating the reinforcement steel and positioning the probes as far as possible from the reinforcement steel. From these measurements, the resistivity is calculated which generally is in the range of 5,000 to 50,000 ohm-cm.[92] Areas where resistivity of the concrete or patch material is greater than 50,000 ohm-cm or vary greatly from that of the parent concrete are removed and patched with a more compatible cementitious concrete mix. Patch materials should be cementitious and not have electrically conductive materials (carbon or metal particles) added as conductivity must be ionic, not electronic. Concrete resistivity can also be determined from cores using the AASHTO 277, Rapid Permeability Test Method, with AC resistance measurements.

Recently silica fume concrete overlays have become popular because of their high density and reduced chloride penetration rate. Silica fume concrete is a portland cement concrete with silica fume added. Silica fume is an extremely fine pozzolan, 100 times finer than cement. When added to a concrete mix, silica fume produces a dense, high-strength concrete with increased impermeability.[93] Typically dosage rates of silica fume in concrete range from 3.75 to 16 percent silica fume by weight of cement.[94] The higher the ratio of silica fume to cement, the lower its electrical conductivity at a given water/cementitious ratio.[95] A concrete containing a high percentage of silica fume may be incompatible with CP.

Electrical Continuity

The electrical interconnection of the metallic components within a bridge structure influences the use of CP as a rehabilitation method.[51] Any electrically discontinuous metallic components that are embedded in concrete will not be protected by the CP system may and at least in theory, be adversely affected. Although electrical discontinuities of reinforcing steel and metallic components can be found and corrected during the structural rehabilitation process, often times during previous rehabilitation or repair, electrical discontinuities are created. Typically, bridge structures with uncoated reinforcing steel have good electrical continuity.

Electrical discontinuities are often created during the removal of spalled and delaminated concrete. Once a reinforcing bar is more than 50% exposed, the concrete around the reinforcing bar is completely removed to a specified minimum clearance. During this repair process, the electrical continuity between the reinforcing bars can be broken. To be certain that these reinforcing bars remain electrically continuous, electrical continuity testing should be performed on exposed bars prior to any concrete patching material placement. Other discontinuous metals which are created as part of the rehabilitation process are often the result of core drilling. Core holes drilled through and near the end of a reinforcing bar, isolate the shorter portion of the remaining reinforcing bar. When a reinforcing bar is cut, both remaining bar sections should be checked for electrical continuity. Isolated reinforcing bars have also resulted when part of the structure is removed. It is common to remove and replace barrier walls as part of a bridge's safety upgrade. During the demolition of these walls, the reinforcing bars that tie the walls into the bridge deck are often cut or burnt flush with existing concrete surface. The reinforcing bar which remains in the concrete are often found to be discontinuous.

Some discontinuous embedded metals are installed in the bridge as part of a rehabilitation. Examples of these discontinuous metals are anchor bolts, welded wire fabric, spliced reinforcing bars and reinforcing bars which are doweled into the original concrete. If these items are specified as part of a rehabilitation process, precautions should be taken to assure that these items are made electrically continuous to the reinforcing steel. These precautions may include: installing bonding wires; requiring a minimum number of tie wires between elements; cleaning of reinforcing steel (for better contact); and welding. If welding is used, careful attention to proper preparation as well as subsequent welding procedures and controlled cooling is essential.[96]

Scarification

To obtain adequate bonding for concrete overlays, it is often necessary to have the original concrete surface scarified. Specifications for repair of existing bridge decks often specify that the scarifying equipment remove not less than 1/4 inch (6 mm) from the original bridge deck surface. To meet this specification, contractors often well exceed the 1/4 inch (6 mm) concrete removal without much regard for maintaining minimal concrete cover over the reinforcing steel. This often results in large areas of reinforcing bars being exposed or having insufficient concrete cover to provide separation from the CP system's anode. Typically, anode installations require a minimum of 1/2 inch (12 mm) of concrete cover, to reduce possibilities of electrical shorts and assure adequate CP current distribution to the reinforcing steel.

Although the minimal concrete cover cannot always be met, a contractor can often save extra work by taking additional precautions to control the depth of the scarification. If the reinforcing steel is exposed or the minimal cover is not met, the following procedures have been used successfully to provide adequate clearance between the anode material and the reinforcing steel:

- Patch the areas with concrete in a similar manner to which the spalled areas are patched, making sure the concrete patch provides adequate cover.

- For rigid polymer CP systems, locate and cover the individual reinforcing bars with a minimum 1 inch (2.5 cm) wide nonconductive polymer sand mix placed directly on the concrete surface and over any partially exposed reinforcing bars where the anode will be placed.

- For titanium mesh CP systems, placement of plastic spacer mesh over exposed and shallow reinforcing steel prior to the anode installation. This spacer mesh is very similar to plastic safety fence.

- If the embedded metal or reinforcing bar is not a necessary component, the design engineer and contractor may elect to remove the metal component instead of using the above procedures.

Sandblasting

Prior to placing concrete in repair areas, sandblasting is commonly used to remove rust scale and old concrete from reinforcing bars, and to prepare a good bonding surface. This operation is completed prior to installing any electrical wires for the CP system negative connections or any bonding wires for electrical continuity. When wires are in place prior to sandblasting, the wire insulation and thermite weld coating are protected to prevent damage during the sandblasting process.

Sandblasting of the existing concrete surface is typically required prior to overlaying. It should be completed just prior to installing the anode material. Sandblasting with the anode material in place may damage the material. Proper planning and surface protection after anode installation may be necessary to prevent the necessity of re-sandblasting after the anode material is installed (this is less a concern for rigid polymer CP systems). The following are some recommended precautions:

- Install the anode material just prior to the overlay placement, limiting the amount of time that the prepared concrete surface is left exposed.

- Cover prepared areas with plastic sheets until ready to overlay.

- Continue protecting prepared surface areas during overlay process where foot and equipment traffic is expected. On titanium mesh CP systems where mixing trucks are permitted to drive on the anode, plywood sheets have been placed beneath the truck's tires. Plastic sheets have been used beneath the truck itself to catch any oil or grease which may drip from the truck.

- Prior to placing a zinc or conductive coating CP system on a vertical or bottom surface bridge member, sandblasting to remove contamination will improve bonding characteristics. The optimum surface profile for long-term CP operation has not yet been established and therefore is usually obtained from the contractors, suppliers or manufacturers and incorporated into in the project specifications.

Concrete Bonding Agents

Bonding agents are often specified for patch areas and overlay placements. The bonding agents are typically a cement-sand mix or an epoxy formula. A cement sand mix is compatible with CP, but epoxy bonding agents are not. Epoxy materials between the anode and reinforcement function as a shield preventing the CP current from passing through. As a result, reinforcing steel beneath repair areas or overlays with a epoxy bonding agent cannot receive protection from the CP system.

Epoxy Injection

Epoxy injection is a repair technique often used for rebonding cracked concrete. If the crack is a delamination resulting from corroded reinforcing steel, this method not only fails to eliminate the cause of the problem, it also deters the use of CP. Similar to the shielding caused by epoxy bonding agents, epoxy injection, when used to bond a concrete plane parallel to the concrete's surface, will shield the reinforcing steel beneath that plane from receiving CP current. Epoxy injecting concrete cracks perpendicular to the concrete surface, which can result from concrete stress relief as an example, is compatible with CP because it does not shield the reinforcing steel from CP current.

6

Anode Systems

Many different anode systems have been proposed, researched and used for cathodic protection of above-ground reinforced concrete structures. These were discussed in general terms in Chapter 3: History of Cathodic Protection. In this section, details are provided on the most widely used systems. Also, commonly used design guidelines and design criteria are presented in cases where a consensus has developed. Most of the anode systems are of the impressed current type, although sacrificial systems are also mentioned.

It must be noted that the anode system is only one part of the cathodic protection system. Therefore, rectifiers, embedded reference cells, system negatives and other components are always used in concert with each of these systems. These aspects are not however, discussed in this chapter unless they are specifically related to a particular anode system.

Conductive Coke-Asphalt

This bridge deck cathodic protection system employs a layer of electrically conductive asphaltic concrete on the repaired portland cement concrete surface to distribute the protective current evenly to the reinforcing steel. The protective current is delivered to the conductive asphalt via leadwires and high silicon cast iron primary anodes placed at select locations on the deck. Typically, this system includes the following:

- Pancake shaped high-silicon cast iron anodes with leadwires (anode-leadwire connection well sealed) are spaced at about 25 foot (7.6 meters) intervals and recessed into the deck surface. One anode is provided for every 500 to 800 square feet (45 to 75 square meters) of deck surface, the anodes are arranged in "lines" of several leadwires connected in strings. End anodes are located no more than 10 feet (3 meters) from the deck end and each interior joint. Each anode string typically contains 3 to 4 individual anodes. 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 are located in the curb areas of the deck. The recessing involves cutting a 2 inch (5 cm) deep and one foot (30 cm) square "hole" in the deck surface between reinforcing bars (or cutting and removing bars if necessary). The bottom of the "hole", any exposed bar ends and the bottom and sides of the anode are coated with epoxy. Leadwire slots are cut, and after placing the anode and leadwires, the holes and slots are backfilled with mortar. The recessing is done to allow replacement of the asphaltic concrete in the future without the need to replace the primary anodes. When completed, the top surface of the anode is flush with the concrete deck surface.

- Voltage probes (graphite probes - about 6 inches (15 cm) long and 1 inch (2.5 cm) square, with leadwires) are installed which are used in monitoring system performance. These probes with leadwires are recessed in the deck in a manner similar to that described for the primary anodes except that the probe and the "hole" are not coated with epoxy. When completed, the top surface of the probe is flush with the top of the deck.

- Thorough electrical checks are conducted to ensure all embedded items are properly installed and functioning correctly.

- Leadwire connections are made at the curb. Wires are bundled along the curb, and the bundle is encased in air-entrained concrete or in a formed fillet strip.

- The deck surface is examined to identify and coat (two coats of epoxy) any areas of exposed reinforcing steel, tie wires or other metal which could contact the coke-asphalt.

- A 1.5 inch (17 mm) (compacted depth) layer of conductive coke-asphalt is placed on the entire deck surface, except within 6 inches (15 cm) of any metal appurtenances (drains, dams etc. - these areas are filled with non-conductive asphaltic hot mix). The conductive coke-asphalt mix utilizes coke breeze from coal refining with a specific gradation range, 3/8 inch (10 mm) and 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 actual proportions are confirmed by mix design. The approved mixture exhibits the following properties: Marshall stability: 1200 minimum; Flow: 6 to 16; and Electrical Resistivity: 3 ohm-cm maximum. Options are available for producing the conductive plant mix. In the first option, the coke is dried and stored in a hot bin. Stone and sand are also dried and stored separately in their respective bins. Proportioning and mixing are done as per conventional procedure. In the second option, stone and sand are superheated and mixed with cold coke breeze (delivered by a conveyer belt) in the weigh batcher.

- A 1.5 inch (17 mm) thick non-conductive asphaltic concrete is placed as a wearing course.

Because water is trapped in the asphaltic overlays, it is generally recommended that this system not be used on decks in which the concrete does not have an adequate entrained air void system. However, laboratory and outdoor exposure research has identified a penetrating sealer which can be applied prior to coke-asphalt placement. This will minimize adverse freeze-thaw effects even on non-air entrained concrete, but still allow the protective current to pass. A single experimental trial experienced construction problems, but these were probably related to the application of too much sealer. A set quantity cannot be defined for all structures. The concrete should rather be allowed to "take" only that material which it will readily absorb by brushing. This research also showed that platinized wire and FHWA conductive polymer grout primary anodes in slots could be used in concert with the coke-asphalt secondary anode.

Distributed FHWA Conductive Polymer Anode Systems

Cathodic protection systems of two types are included in this section: non-overlay slot systems, and mounded conductive polymer systems involving the use of a portland cement concrete overlay. Both systems utilize similar materials and involve the construction of a grid of primary and secondary anodes in or on the portland cement concrete surface.

The primary anode is platinized wire, typically 0.031 or 0.062 inches (0.8 or 1.6 mm) diameter copper core, niobium clad (35 percent niobium in the cross-sectional area), with a minimum of 25 microinches (0.6 micron) of platinum. The smaller wire 0.031 inches (0.8 mm) is typically used only when the individual primary anodes do not exceed 50 feet (15 m) of wire embedded in the deck. Spacing of the primary anodes is normally limited to a maximum of 25 feet (7.5 m) if individual straight lengths of wire are used or 50 feet (15 m) if primary anode "loops" are used. 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. At least two separate power feeds are provided to each zone in all cases.

The secondary anodes are typically carbon strands composed of 40,000 high purity pitch-based carbon filaments (no less than 99% carbon assay). The carbon strand exhibits a maximum electrical resistance of 1 ohm per foot (3.3 ohm per meter), a tensile strength of 390,000 psi (27,000 Kg per square centimeter) minimum and is wrapped with a braided Dacron thread to prevent fraying. No positive electrical connections are required between the primary and secondary anodes or between different lengths of secondary anodes. The materials are simply overlapped and the conductive polymer grout "automatically" makes the electrical connection.

The FHWA conductive polymer grout (or "concrete" as it is sometimes called) is an electronically conductive polymer concrete as defined in U.S. Patent Application No. 346.428 filed February 5, 1982 by the U.S. for the additive adjustments given below). The composition is as follows:

Components	Concentration
Vinyl Ester Resin (D-115 Hetron, manufactured by Ashland Chemical Co., Columbus, Ohio, or approved equal.)	35 percent by weight of total mixture
Coke Breeze DWI	65 percent by weight of total mixture
Silane Coupling Agent (A-174)	1.0 percent by weight of resin
Wetting Agent (S440)	1.0 percent by weight of resin
Cobalt Naphthenate	0.5 percent by weight of resin
Titanium Dioxide (RHD 6X)	1.0 percent by weight of resin
Methyl Ethyl Ketone Peroxide	2.0 percent by weight of resin

If the placement temperature will be 60°F (15°C) or less, then dimethyl aniline shall be added to the resin at a rate of 0.5 percent by weight.

The conductive polymer exhibits the following properties:

Maximum Compressive Strength = 4,000 psi
(280 Kg per square meter) at @ 70°F (21°C)

Maximum Electrical Resistivity = 10 ohm-cm

Maximum 24-hour Water Absorption = 0.5 percent

The titanium dioxide imparts a gray color, but also increases resistivity slightly. It is used only when the material is to be placed in slots (i.e. it is not included in the formulation for material to be used as "mounds"). The placement consistency of the material can be adjusted by small additions or deletions of coke breeze and is typically described as pourable for slot use and slightly stiffer for use as mounds. As with all polymer concretes, safety precautions are a must and disposal of unused material must comply with the appropriate standards. Shelf life of the polymer resin is typically only nine weeks after shipping. Suppliers typically require six weeks' notice to formulate this specialty material.

Concrete cover over the reinforcing steel is an important consideration in the choice of cathodic protection anodes. If a slotted system is to be used, with slot depths of 3/4 inch (19 mm), then most, if not all reinforcing steel should have a cover of at least 1 inch (2.5 cm.) The slots (and the deck surface in the case of a mounded system) must be thoroughly checked for exposed steel and such areas coated with at least two coats of epoxy or vinyl ester resin prior to placement of the conductive polymer grout. Further, slots and mounds are normally routed around exposed metal items such as drains and allowed no closer than 3 inches (7.5 cm) to such items. Electrical testing to ensure anode system conductance and to detect any anode/rebar shorts is normally done during or shortly after conductive polymer placement. In the case of mounded systems, all shorts, if any, must be located and eliminated prior to overlay placement.

Specifics related to the grid design of each system are as follows:

Slotted Systems

The average anode current density should not exceed 5 mA per square foot (54 mA per square meter) of conductive polymer grout surface in contact with deck concrete. For example, the design current density is 1.5 mA/square foot (16 mA/square meter) of concrete surface, use slots 0.25 inch (6 mm) wide and 0.75 inch (19 mm) deep with a secondary anode slot spacing of 6 inches (15 cm). Wide slots are not recommended because of long term durability requirements.

After the conductive polymer is placed in the dry, cleaned slot, dry silica sand is broadcast in excess to absorb all bleeding excess resin and provide a visually acceptable, gritty riding surface.

Mounded Systems

The average anode current density should not exceed 7.5 mA/foot square (80 mA/square meter square) of conductive polymer surface in contact with the existing and new overlay concretes. For example, when the design current density is 1.5 mA/foot square (16 mA/square meter square) of concrete surface, use secondary anode mounds 1.25 to 1.75 inches (30 to 45 mm) wide and approximately 3/8 inch (10 mm) thick which are spaced 12 inches (30 cm) on center.

After placement of the mound on the dry, scarified and blasted deck surface (i.e. a dry, cleaned surface, ready for overlay), coke breeze is broadcast in excess to absorb all bleeding resin and maintain the conductive, gritty surface.

The deck surface is normally not recleaned prior to placement of the bonding grout and concrete overlay. Experience has shown that the mounds can be placed quickly without damage to the remaining cleaned surface. However, if recleaning is necessary in the event of rain or other delays, sandblasting or waterblasting can be performed without damaging the cured conductive polymer grout. Cementitious bonding grouts can be broom or spray applied over the mounds, and construction traffic (i.e. power buggies and trucks) can travel directly over the cured anode system during overlay placement.

Catalyzed Titanium Mesh Anodes

Catalyzed titanium mesh anode systems consist of expanded titanium mesh with a mixed precious metal oxide catalyst applied to the surface. The anode is fastened to the patched and prepared concrete surface using nonmetallic fasteners and then overlaid or otherwise encased in portland cement concrete. These systems are normally designed and installed such that the average anode current density does not exceed 10 mA/square foot (110 mA/meter square) of anode surface. Power is delivered to the mesh via leadwires and current distributor bars. The most commonly available system utilizes titanium (solid, Grade 1) current distributor bars about 0.5 inches (12 mm) wide and 0.040 inches (1 mm) thick. The distributor bars are run perpendicular to the mesh and are attached to the mesh using resistance welds (i.e. direct titanium to titanium metallurgical bonds) at a maximum spacing of 3 inches (7.6 cm). Other systems involving niobium distributors and crimps have been investigated but are presently not widely available in the United States.

Such systems function well because of the mixed precious metal oxide coating on the titanium, and thus, the composition and integrity of this coating are of prime importance. It is known that small coating breaks will not compromise effectiveness or cause premature failure of the anode, however. Because the specific composition of the available coatings are proprietary, it is not possible to specify such a system generically. Rather, only those anode systems which have been extensively tested in accelerated life tests and in concrete are normally specified for use. These are specified by product name and certified by the manufacturer. An accelerated life test is provided in the draft AASHTO Task Group #29 specifications for bridge deck cathodic protection and the following mesh systems are included in those specifications: Elgard 210 (0.21 area of anode surface per area of mesh), and Elgard 150 (0.15 area of anode surface per area of mesh).

These anode meshes are supplied in rolls about 250 feet (76 m) long and 45 inches (115 cm) wide for the 150 mesh, and 42 inches (120 cm) wide for the 210 mesh. The mesh weighs 45 pounds per 100 square foot (22 Kg per 100 square meters) for the 210 material, and 26 pounds per 1,000 square feet (13 Kg per 100 square meters) for the 150 material. Typical specifications require that the lot of mesh for use on each project be subjected to accelerated life testing and proven to survive a total charge of 700 A-Hr/square foot (7500 A-Hr/square meter) of concrete surface area.

Electrical connection between the current distributors and leadwires is normally done in a junction box. The current distributor is sleeved with heat shrink tubing to prevent possible shorting in any access holes drilled in the concrete. At least two separate power feeds are provided to each zone. The anode mesh is attached to the concrete with non-metallic pins spaced as required; typically 1-4 feet (0.3 to 1.2 m) on center depending on the member. The anode is installed no closer than 2 inches (5 cm) to exposed steel and is often cut with tin snips to meet this requirement. The mesh is isolated from shallow reinforcing steel by the cutting method, by coating the steel with nonconductive epoxy, or by use of a plastic spacer depending upon the extent of the area involved. Short circuit testing is performed prior to and during grout and concrete placement and any detected shorts are eliminated.

The majority of these systems constructed to date have involved bridge decks and have utilized latex modified or low water cement ratio concrete overlays. Bonding grout, if required, is best applied using grout spray equipment. The mesh is protected during overlay placement using sheets of 3/8 inches (10 mm) plywood. There have however, been a number of substructure systems involving anode encapsulation using cast-in-place concrete or shotcrete. Although these systems have performed well electrically (i.e. stopped corrosion), some problems with shotcrete bond have occurred. An ongoing effort to improve performance has identified a number of factors which effect bond. These factors include complete surface preparation (deep sandblasting), the use of nonmetallic spacers to hold the mesh at least 0.25 inches (6 mm) off the cleaned surface, conditioning of the surface to saturation by wetting prior to shotcreting, and 7-day fog curing.

Conductive Carbon Based Coatings

Conductive paints, mastics and sprayable conductive polymer grouts have been utilized as anodes for reinforced concrete cathodic protection systems not subject to traffic wear. These anode systems use carbon in one form or another in a solvent, resin or water base, as the secondary anode which typically covers the entire concrete surface to be protected. The primary anode is typically 0.031 inches (0.8 mm) diameter platinized wire or platinized ribbon. The connection between the primary and secondary anodes has been accomplished using FHWA conductive polymer grout and with thickened forms of the paints or mastics coupled sometimes with non-metallic mesh or tape. Surface preparation prior to application of this anode system is typically light sandblasting or medium to high pressure water blasting as recommended by the manufacturer. Generally, water blasting is not used when solvent borne or vinyl ester resin coatings will be applied.

The most common uses of such systems in the highway industry have been for substructures (piers, piles, columns and caps). They have also been used on the undersides of bridge and parking decks. The materials are almost always black in color and therefore are most often overcoated with a decorative latex paint (off-white or beige in color). The overcoat also performs several other functions. It protects the underlying conductive material from environmental deterioration, permits the venting of gases formed at the anode/concrete interface, and influences the moisture content of the thin layer of concrete immediately beneath the conductive coating. Much work remains to identify ideal overcoats.

Spacing of the primary anodes is dependent upon conductivity and thickness of the secondary anode, and no standards have yet evolved. However, at typical thickness 8 to 10 mils (0.2 to 0.25 mm) dry film thickness, good current distribution has been obtained on small members such as columns and piers when the distance between primary anodes was 10 feet (3 m) or less; and when a single primary anode (connected on both ends) powered a distance of no more than 5 feet (1.5 m) on either side. Greater spacings are undoubtedly possible with the proper choice of material and thickness. Computer programs based on transmission line models are available to predict current distribution for specific materials of known conductivity and thickness on concretes of known characteristics. Also, it is quite easy to determine voltage gradient (and thus estimate current distribution) in a conductive paint system by simply contacting the paint and measuring the system voltage at various locations perpendicular from the primary anode. Some have used a sponge-encased half cell as a viable contact probe, while others have used direct electrical contact (point probes). Generally speaking, the voltage drop within the conductive paint in a properly designed and constructed system should not exceed 10 percent of the voltage measured between the primary anode and the reinforcing steel.

Conductive paint cathodic protection systems are low first cost systems with relatively short maintenance-free lives in many exterior environments. Because of durability concerns, they are not in widespread use in splash zone areas or freeze-thaw areas with direct exposure to water and salt. Conductive paint systems also have experienced difficulty when they were placed on underside surfaces that are not chloride contaminated and the paint is not subjected to direct wetting. Such usage was most often an attempt to protect top steel in salty concrete with an anode placed on the underside. In these cases, it appears that the thin layer of concrete immediately beneath the paint dried out and thus became very resistive. In some cases, the resistance increased greatly and the desired protective current could not be delivered even at rectifier voltages of 50 volts.

Excessive anode current density can cause bond loss and deterioration of conductive paint CP systems in a year or less. Studies have shown that even when the average anode current density is relatively low, 1.5 mA/square foot (16 mA/square meter), hot spot areas of high current density can develop and induce localized deterioration of the paint. Although such is unsightly, repair is relatively inexpensive and easy (scrape and repaint the local area). In general, these systems will perform best when the anode current density remains at or below 1 mA/square foot (11 mA/square meter) of conductive coating surface.

The conductive coating and overcoat technology is still developing, and improved, longer lasting materials may be available in the future. These systems are most effective when placed on the concrete surface receiving chloride contamination and when aimed at protecting the reinforcing steel nearest the anode. Projects in which the conductive paint is placed on an uncontaminated surface, or when another mat of reinforcing steel is located between the anode and the steel to be protected should be considered experimental.

Sprayed Metallic Coatings

Sprayed zinc has been investigated and used since 1983 as a secondary anode on reinforced concrete substructures and decks (on the top surface and covered with a conventional asphaltic concrete overlay, or on the underside soffit). The process of zinc metallizing involves the melting of the zinc in the form of wire by one of several methods and the spraying of the liquid metal onto the concrete surface by means of compressed air. Overspray is often collected using vacuum systems and the actual zinc applied to the surface is typically 50 to 70 percent of the melted total for flame spray and as high as 90 percent for arc spray. Precautions are taken to protect workers and the environment during the spraying operations. Typically, these have included enclosures and air-fed respirator masks for workers within the enclosures. Waste materials (sandblast and zinc residue collected by vacuum systems) are funnelled into hazardous waste barrels which are taken to an authorized hazardous waste site for disposal. Of the two metallizing techniques most commonly used, flame-spray and arc-spray, the latter is preferred by most because of the higher production rates, the ability to apply a thicker coating per pass and less waste. The optimum system used to date is an arc spray system involving a 600 amp gun and a 20 mil (0.5 mm) thick production rate of about 50 to 70 square feet (4.6 to 6.5 square meters) per hour. Production rates are improving further as a result of recent developments.

Adhesion is achieved by mechanical bond to the prepared (sandblasted or shotblasted) concrete surface. Most such systems constructed to date have been impressed current systems. In this case, power is delivered to the zinc secondary anode via leadwires and primary anodes placed prior to application of the zinc. The primary anodes (commonly called primary distributors or connectors) have included small 2 inch by 2 inch by 1/16 inch to 3/8 inch (5 cm x 5 cm x 1.5 to 10 mm) copper, brass, steel or stainless steel plates with wire attachment bolts epoxied to the concrete surface. Titanium current distributor bars, as described in the section on titanium mesh anodes, have also been used as primary anodes. Guidelines for primary anode spacing are not yet developed, and thus, spacing must be based on previous successful experiences or calculations. The primary anode spacing is dependant on the thickness of zinc applied and can be calculated or determined experimentally. Generally, a minimum of two primary anodes per zone are used and the spacing can be much greater than that used with conductive paint systems.

The zinc thickness applied on early projects was typically 8 mils (0.2 mm) and the design life of the coating at that thickness is believed to be about 10 years. In other installations, the thickness has been increased to 15 to 20 mils (0.4 to 0.5 mm) to obtain longer life. Voltage requirements to deliver cathodic protection currents of about 1.5 mA/square foot (16 mA/m^2) have typically been less than 10 volts for systems where the anode/concrete interface was moist, to 40 to 50 volts when the zinc was applied to soffits (low chloride and not subject to wetting).

Some problems with shorting have occurred with impressed current sprayed zinc systems (the zinc directly contacts tie wires or rebar). These problems require close monitoring during zinc application. The voltage difference between the zinc and the rebar is monitored and if this value falls to zero, the spraying operation is stopped until the short is located and cleared. Also, one could consider separating the system into multiple subzones by leaving strips of concrete uncoated between subzones and/or consider the application of a thin cementitious coating on the concrete surface prior to zinc application. Overall, there is presently much interest in sprayed zinc impressed current systems for substructures.

Sprayed zinc also can be used as a sacrificial anode for cathodic protection systems in which the concrete resistivity is sufficiently low (typically, hot and moist coastal members). Trials by the Florida DOT during the past three years have provided encouraging results. In the Florida Keys, the zinc was applied to concrete and exposed reinforcing steel from slightly above the high tide mark to levels about 6 feet above the water line. This use is presently under development and must be considered experimental.

Other Anode Systems

In addition to the above systems, several other anodes are being actively pursued on above ground reinforced concrete members. One such system is a slot system involving the use of mixed-precious-metal-oxide-coated titanium ribbon and a non-shrink cementitious grout (such as Masterflow 713 and Set grouts) as the slot backfill material. Several large scale parking garage trials and installations have been completed in the last year and outdoor exposure studies have been in progress for over 4 years. These systems have typically utilized 0.25 or 0.50 inch (12 or 18 mm) ribbon 50 mils (1.3 mm) thick. Ribbons are placed vertically in 1/2 inch by 1/2 inch or 3/4 inch (12 mm by 12 or 18 mm) deep slots and held in place with non-metallic spacers. The catalyzed coating, current distributor bars and design details have been similar to that described previously for the catalyzed titanium mesh anodes, with the exception that design current densities up to 20 mA/square foot (215 mA/square meter) of anode surface have been used. Anode slot spacings in the range of 7 to 18 inches (18 to 45 cm) have been investigated.

The eventual failure mode of such a system has been confirmed to be acid attack of the concrete at the anode concrete interface. Hot spot problems at areas of high current density in very heterogeneous situations (such as delaminations not repaired, variable and very low cover), have resulted in the use of lower design current densities (typically 110 or 160 mA/m^2 of anode surface). Close anode spacings (typically 15 to 23 cm) have been used in recent efforts, as well as repair of all deteriorated areas prior to system installation. Work also is in process on the use of this system in concert with waterproof membranes.

A flexible conductive polymeric wire anode (Ferex) for use in concert with rigid concrete overlays was investigated and used in the latter 1980s. The conductive wire includes a copper conductor surrounded by a flexible conductive polymeric compound. The wire was woven into mats and attached to the prepared concrete surface using non-metallic inserts. The design current density on such systems was typically 10 mA/square foot (110 mA/square meters) of anode surface. It was known that the material would deteriorate rapidly if overpowered, but could provide long life if the anode current density was limited to the design value. To provide redundancy in overlay systems, conductive cleats (connectors) were used to allow current to pass between individual strands of wire, and in some instances, the FHWA conductive polymer grout and platinized wire were also used for added redundancy. The Ferex wire was also used in some slot systems that were backfilled with cementitious grout. Although initial tests were promising and a number of field systems were installed, this material has proven somewhat susceptible. Breaks in the wire (mainly at bends), subsequent corrosion of the metallic conductor, and also embrittlement at locations of high current density (i.e. localized hot spots) have resulted in system failures. Its use is very limited at present, although existing systems continue to be monitored.

Conductive ceramic anodes have been investigated on a laboratory and trial scale, but not developed to the stage of field use.

Conductive rubber anodes are being studied by the Florida DOT for use in impressed current cathodic protection of piles and similar marine structures.

Zinc, magnesium and aluminum anodes have been studied for their applicability as sacrificial anode systems on reinforced concrete structures. Both aluminum and zinc bulk anodes have been used successfully to cathodically protect the portions of reinforced concrete structures that are below the seawater line in hot, marine environments (Florida, Saudi Arabia). Zinc anodes have been tried in above-ground concrete structures as well, and these tests have shown that under moist conditions and close anode spacing, some protection can be achieved. Typically, the zinc, in the form of perforated sheets or ribbon (diamond shaped with a steel core) was embedded in chloride-laden, very high air content portland cement concrete, shotcrete or asphaltic concrete. However, such systems have only a very low driving voltage and thus, the protective current falls off rapidly if the concrete dries out (i.e. its resistivity increases). Another major factor that has minimized consideration of such systems has been concern regarding effect of the zinc corrosion products on the encapsulating material. It is unknown whether or not the use of high air content in the concrete would provide sufficient volume for the zinc corrosion products. These products may crack and spall the encapsulant concrete, thus simply transferring the problem to another location. More recently, metallized zinc has been investigated for direct application to the cleaned concrete and metal surfaces (no concrete encapsulant required).

7

Design Aspects

A cathodic protection system must be designed so that it will supply enough current to satisfy the protection criteria for the design life of the system. This simple statement is often difficult to achieve, because of the complexities of concrete and concrete structures. Various important aspects of cathodic protection system design are classified and discussed in this section.

Current Requirements and Distribution

Since the level of current needed cannot be determined until commissioning tests are conducted, system design is usually conservative. A number of guidelines have been used in the past to estimate design current requirement, and these have generally proven to be satisfactory. One rule-of-thumb is to provide 1.5 mA/square foot (16 mA/square meter) of steel surface that is within 8 inches (20 cm) of the anode. For conventionally reinforced bridge decks, a design current of 2 mA/square foot (21 mA/square meter) of concrete often has been used. Based on recent experience, this sometimes may be reduced to 1.5 mA/square foot (16 mA/m^2) of concrete.

While these guidelines have been generally acceptable, the designer needs to be aware that the current required is dependent on many complex factors. Current requirements have been reported ranging from 0.1 to 4.0 mA/square foot (1 to 43 mA/square meter) of concrete, depending on steel and concrete conditions. As experience is gained in the future, it may be possible to establish more accurate guidelines.

Concrete composition and condition can affect both the requirement and distribution of current to the steel. High salt concentration and moisture content both increase the conductivity of concrete, and unless these are uniformly present, they may cause uneven current distribution. One such example is a substructure subjected on one side to deicing salt run-off through a leaking joint. Some designers argue that this focus of current on such areas is appropriate, since areas high in salt and moisture content are most in need of protective current. This seems reasonable in a qualitative sense. Actual current distribution which results in such cases has not been rigorously established, however.

It is also important to consider the effect of patching practices on current requirement and current distribution. The removal of loose and delaminated concrete, followed by patching of the area to restore the original surface plane, is the most frequently used method of rehabilitation today. From a theoretical point of view, it would be ideal if this patch material perfectly matched the surrounding concrete in composition, but this is seldom the case in practice. Whenever adjacent areas of concrete contain different electrolyte chemistry (chloride concentration, for example), a concentration cell will develop. This cell will accelerate corrosion of steel near the boundary of the patch. This accelerated corrosion soon leads to further deterioration, and patching becomes a never-ending process.

If patch material is of very low conductivity, it is unlikely that steel within the patch will experience significant corrosion. Examples of such materials include those containing epoxy or a high content of silica fume. Such patching materials will also reduce the flow of current to the steel, and steel located beneath the patch may be unprotected. It is for this reason that most designers specify the removal of non-conductive patches prior to installation of the cathodic protection system.

The configuration and condition of the steel reinforcement is also an important factor which affects distribution of current. In order for steel to be protected, it must be electrically continuous. It is probably not uncommon for some steel to be discontinuous in cathodically protected structures, since the only way to verify that *all* steel is continuous is to actually test *all* the steel in the structure. As a practical matter, this is seldom done. A reasonable number of bars are usually tested for continuity, and, based on these results, a generalization can be made about electrical continuity within the structure. If discontinuous steel is found, it should be made continuous by connecting it to the cathodic side of the electrical circuit. This may be done using several techniques, including thermite welding, resistance welding, brazing, drilling and tapping, and other mechanical means. A concern is sometimes expressed that the heat generated by arc welding changes the metallurgy of the steel, and thus affects the mechanical properties of the bar. Arc welding should therefore be used with care where this might cause concern. Regardless of technique, the connection should be covered with a non-conductive insulator, such as epoxy, in order to prevent galvanic corrosion by dissimilar metals.

It is sometimes asked whether the application of cathodic protection will accelerate the corrosion of discontinuous steel. This is theoretically possible for certain situations. If, for example, a discontinuous steel element is located between the anode and cathodic steel, and if the voltage gradient is high enough, the element may become bipolar. In this case, current will enter the steel element near the anode causing it to become cathodic, and will leave the steel element near the cathode causing it to corrode. There seems to be relatively little evidence of this problem in the field, however.

Depth-of-steel is another factor which affects the distribution of current to the steel. Steel that is deeply embedded in the concrete will tend to receive less current than steel which is nearer to the anode. This is logical since the resistive path is greater for deeply embedded steel, and the flow of current must obey Ohm's Law. Current distribution in a double mat reinforcement typical of highway bridge deck construction, has been found to be about 70 percent-top mat and 30 percent-bottom mat. This is usually considered acceptable since it is the top mat most often contaminated by chloride, and therefore most often in need of protection. If it is considered necessary to fully protect the bottom mat of reinforcement, this will be difficult without overprotecting steel closer to the anode, and operating the anode at an excessive level of current. Such effects are difficult to predict with certainty, making an on-site test of the structure desirable at times.

Reinforcing steel surface area is another factor which can influence the flow of current. An area of high steel surface area will tend to receive more total current per unit area of concrete, so care must be taken not to exceed limitations of the anode at that point. Current received per unit area of steel surface will likely be lower, however, so that protection criteria may be more difficult to achieve. Some designers place more anode surface adjacent to areas of high steel surface area for this reason, and this offers some degree of compensation. The quantitative effect of steel surface area on current distribution and protection criteria has not been rigorously established, however.

Finally, the subject of delamination within the concrete and its effect on current distribution warrants consideration. It seems logical that the presence of a horizontal delamination would hinder the flow of electrical current. Studies suggest that this is not the case, however. Test results show that steel beneath even extensive delamination can receive enough current to meet protection criteria. This apparently occurs when the delamination plane is still in contact, and is moist enough to support the flow of cathodic protection current. This surprising result has, in special cases, caused designers to install cathodic protection systems without complete removal of delaminations. This can not be recommended as a general practice.

Anode Considerations

A wide variety of anodes have been developed for cathodic protection of concrete structures, and these are described in detail elsewhere in this report. There are, however, a number of general design principles which must be considered regardless of the anode chosen.

Because concrete has a high resistivity, usually about 5,000 to 50,000 ohm-cm, current will not be distributed long distances within a concrete structure. Early attempts to protect large areas of structure from small widely-spaced anodes were ample proof that protection cannot be delivered more than a few inches from the anode surface. The ideal anode configuration is often therefore one which uniformly covers the entire surface of the concrete. In this case, current is delivered to the reinforcement with maximum uniformity. Examples of this type of anode include conductive coatings and conductive overlays. In practice, this same uniformity is closely approximated by titanium mesh anodes of small diamond dimension (i.e. 1 to 3 inches (2.5 to 7.5 cm). Other discrete anode configurations may result in less uniform distribution of current.

Figure 1 is an idealized illustration of the current distribution achieved by discrete anodes in slots (shown in cross-section) spaced several inches apart. For such systems, a 12 inch (30 cm) center-to-center spacing has been found to be generally acceptable, whereas a 18 inches (45 cm) or greater spacing has usually been determined to be unacceptable.

An actual anode current density (considering all active surfaces of the anode) of 10 mA/square foot (110 mA/square meter) is usually specified as a design maximum. Operation at higher anode current densities may result in damage to the concrete due to the concentration of anode reaction products, particularly acid. There is experimental evidence that certain types of anode are less prone to cause acid damage and may therefore be able to operate at higher current densities than other anode types. This may be a result of anode geometry, or electrode kinetics, or both. It has been suggested that an anode comprised of small diameter wires, for example, results in better access of anode reaction products to a greater volume of alkalinity within the concrete. Finally, it is a thermodynamic reality that all carbon-based anodes react to slowly form carbon dioxide, which may have an effect on long-term performance. It is generally acknowledged that carbon anodes should be operated at lower current density than titanium-based anodes. This derating of carbon anodes does not impact conductive coatings or overlays which always operate at a very low current density.

No matter which anode is chosen, it is generally recognized that an uneven current distribution will result because of the resistance present within the anode itself. This will tend to cause a higher current to flow nearest to the point of electrical feed, and lower current farthest from the point of electrical feed. Several consultants and manufacturers recommend a maximum of 300 mV IR drop across the anode structure. Likewise, if wires in parallel are used to distribute current to the same electrical zone, care should be taken in sizing the wires so that differences in resistance will not create uneven current distributions. Whatever criterion is selected, it should be the same regardless of anode type, and should be recognized as an important factor in system design.

A final consideration for anode design is ruggedness and redundancy. The anode should not be easily damaged, either from construction practice during installation, or from future events. The design of the anode should include a redundancy of current-carrying pathways, so that future cracking or careless coring will not render the system inoperative.

Monitoring Devices

Embedded reference electrodes are important elements of a cathodic protection system, and, unfortunately, have often proven unreliable. It is only by measuring the potential of the steel that the effectiveness of the protection system can be evaluated. Since cathodic protection systems are intended to function for several years, the potential measurements must be reliable and accurate over long periods of time. During brief site visits to 49 cathodic protection systems conducted under SHRP Contract C-102B[97], six cases were reported where

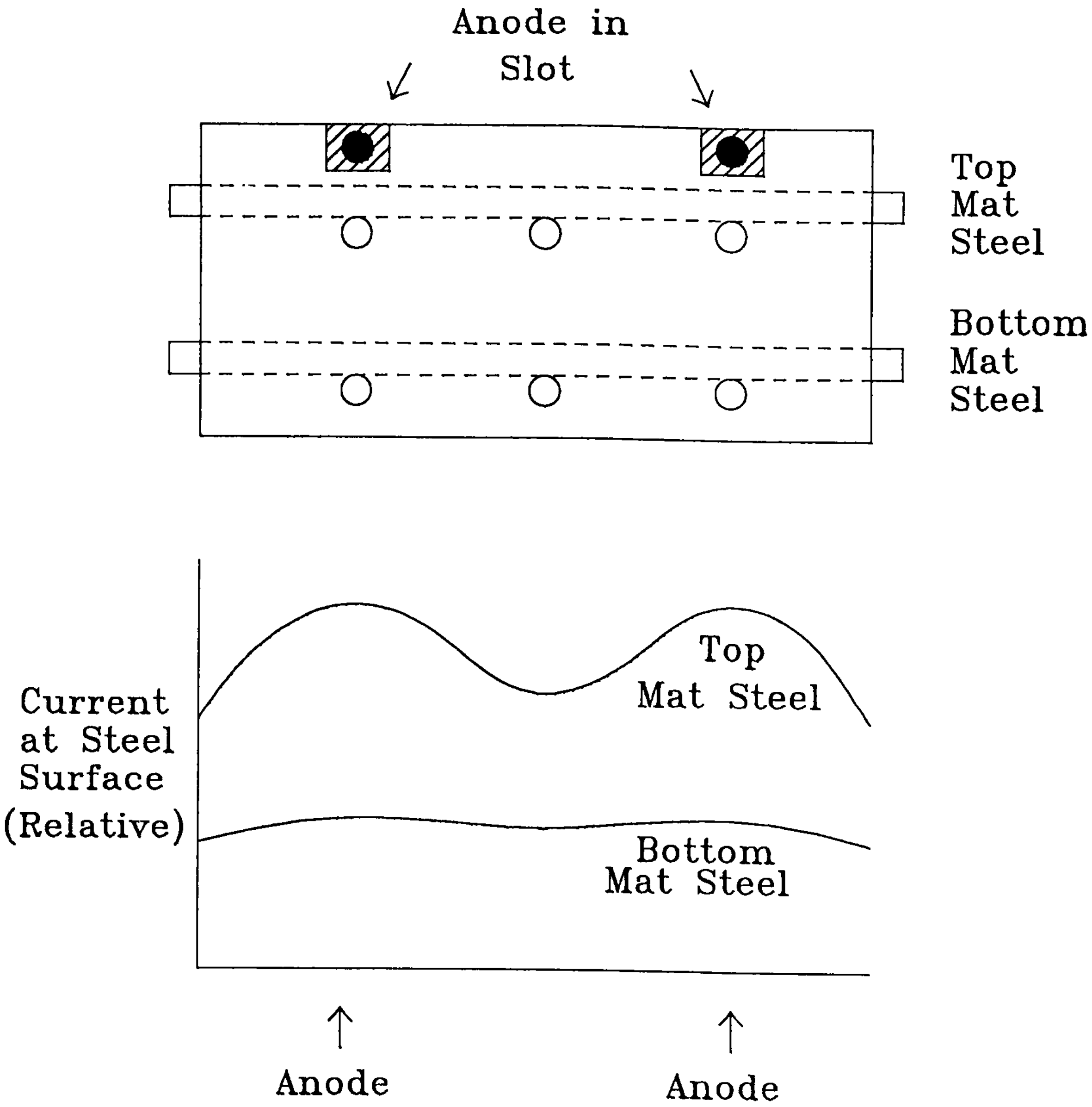


Figure 1. Current distribution due to anode position

reference half cells were not working. Considering the importance of potential measurements, this is a record which needs to be improved.

A reference electrode is one whose potential is known and is relatively constant, and against which the potential of another electrode may be measured. Any observed change in potential between the reference electrode and the electrode under observation is therefore due to the electrode under observation. The act of measuring its potential must cause no significant departure from equilibrium conditions. In order for this to be true, a reference electrode must possess certain electrochemical properties: low polarizability, high exchange current, minimum hysteresis, low impedance, and minimum response to changes in temperature and impurities.[98] For use in concrete, a reference electrode must also function well at high pH, be rugged enough to survive field construction practice and freeze-thaw cycling, and lend itself to reproducible fabrication. It must also work in the high resistance environment of dry concrete.

Several types of reference electrodes have been proposed and tested for use in concrete. These include "true" reference electrodes such as copper-copper sulfate, silver-silver chloride, calomel (mercury-mercurous chloride), molybdenum-molybdenum oxide and possibly manganese dioxide (details of construction are unknown). These may be regarded as "true" reference electrodes in that 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, which 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 such electrodes may remain stable in certain situations, their potential is dependent upon species in contact with their surface, and is subject to change as their environment changes. Calculation of the potential of such electrodes is usually difficult or impossible.

In order to choose a reference electrode, the designer must first decide the purpose of the electrode within the system. If the reference electrode is only intended to provide a stable potential for a 4-hour depolarization test, then several choices are possible. If however, the reference electrode is needed to determine actual steel potentials accurately over long periods of time, the choice will be more difficult. Various reference electrodes, or half-cells, which might be used in concrete are discussed below.

The copper-copper sulfate electrode (CSE) has been widely used in the cathodic protection industry, particularly in soil applications, and this has led to its extensive use for concrete applications as well. In particular it is the standard for potential measurements made from the concrete surface. The CSE is easy to construct, rugged and relatively cheap. Despite its popularity, however, the CSE is a questionable choice for use with concrete. Ives and Janz[98] and Uhlig[99] both report it to have poor reproducibility and objectionable polarization. This electrode is especially sensitive to contamination by chloride, which causes a substantial variation in its potential. Hydroxide ion contamination also causes a problem, since cupric hydroxide is highly insoluble, leading to plugging of the porous plug and covering of the electrode surface. The CSE should be carefully calibrated against an electrode known to be accurate both before and after testing is conducted.

The silver-silver chloride electrode has evolved in the U.S. as the most commonly used reference electrode for embedment 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 used (see Figure 2), but once constructed it should remain relatively stable. Unfortunately, silver-silver chloride electrodes are sometimes supplied with glass elements inside, and this has led to breakage and failure in field applications.

The graphite reference electrode was extensively tested and used by the Ontario Ministry of Transportation.[67] Graphite is not a true reference electrode, but is more properly called a pseudo-reference electrode. Its potential cannot be calculated easily, since it is dependent on the species in contact with its surface. Experience has shown its potential to be relatively stable in concrete however, as shown on Figure 2. The graphite reference is considered sufficient to conduct short-term depolarization tests, but should not be used to measure the true potential of the steel.

Other inert pseudo-reference electrodes, such as platinum, and mixed metal oxide have also been proposed as references. These also have an indefinite absolute potential, and, in view of their lack of extensive field experience, they should be used with caution.

Molybdenum-molybdenum oxide, lead, and zinc are other electrodes which have sometimes been proposed and used as reference electrodes in concrete. The accuracy of each of these can be questioned on a theoretical basis, and erratic results have been reported for each one. These also should be treated with caution.

Manganese dioxide, a true reference electrode developed at the Korrosionscentralen in Denmark, should also be mentioned. It is reported to have a potential of +160 mV vs SCE, and is reported to be long-term stable. It has been used fairly extensively in Europe but has not been utilized to any degree in the U.S.

In summary, although several electrodes have been proposed as embedded references, only silver-silver chloride and graphite have a proven history of use in the United States. Of these two, only silver-silver chloride can be considered a true reference capable of establishing actual steel potentials.

The location of the embedded reference electrodes is chosen to best represent the operation of the entire electrical zone. They are normally placed in areas of high steel surface area and concrete cover. The designer usually specifies the reference electrode to be installed in a

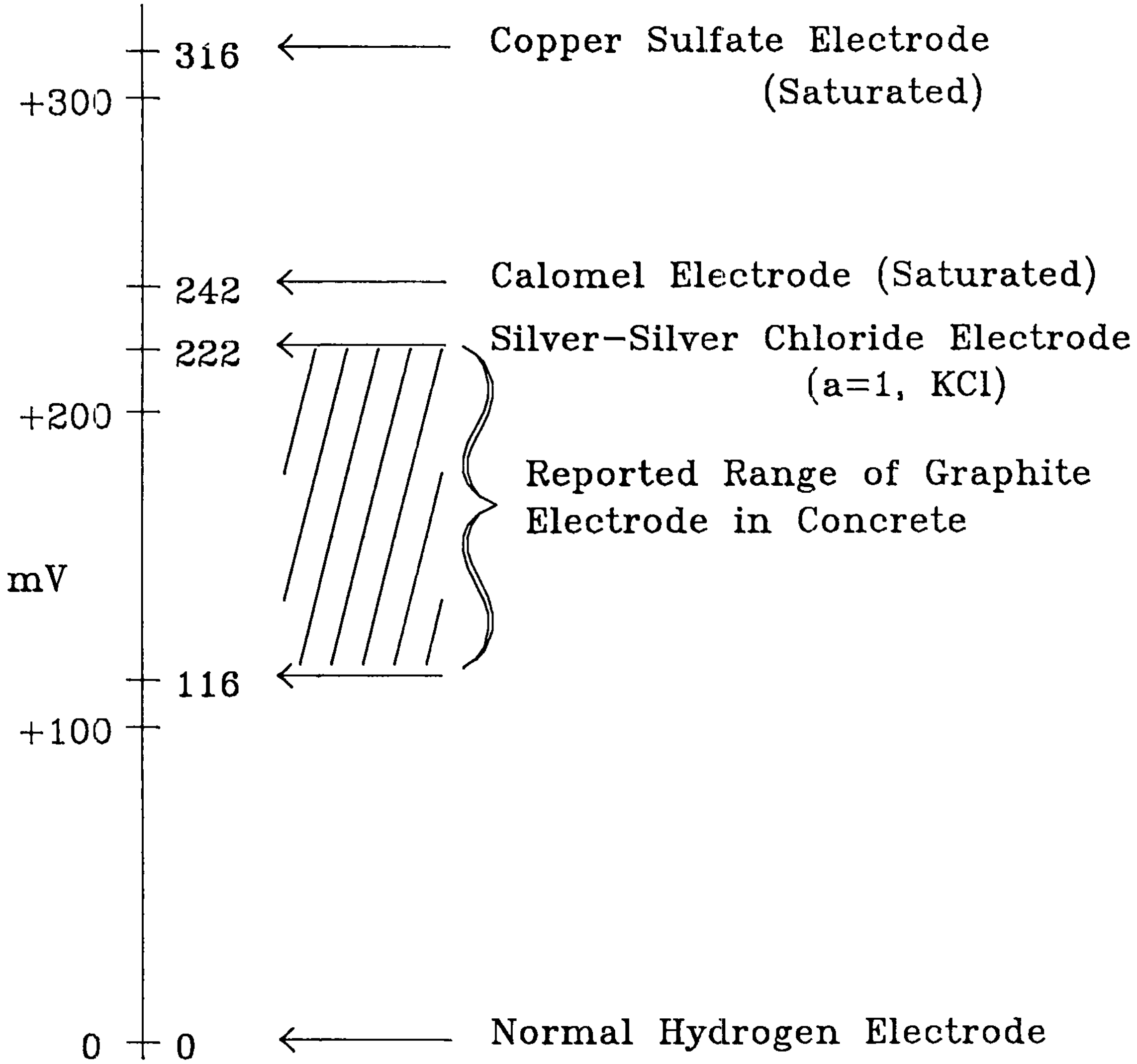


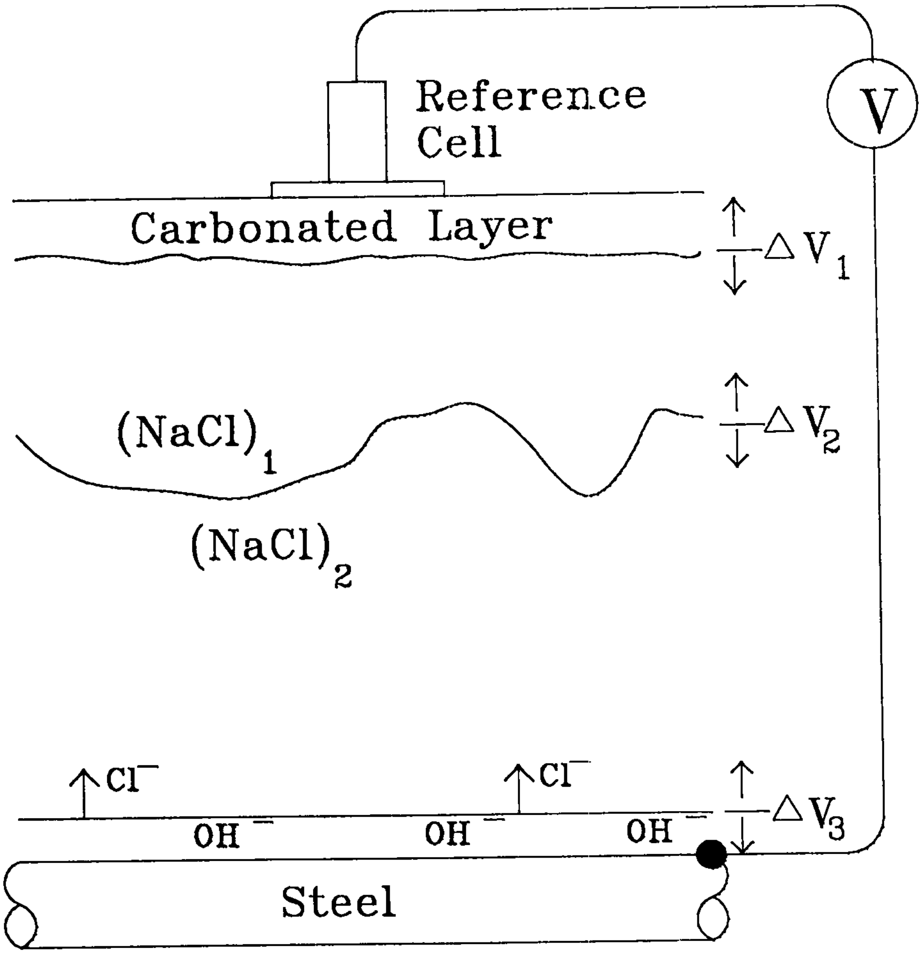
Figure 2. Relative position of selected reference electrodes

corrosive, or most anodic location, according to a potential survey. This will insure that even the most corrosive location will meet the chosen protection criterion. It is ideal to install the reference electrode with the measuring tip adjacent to the steel, but while leaving the steel in original sound concrete. The reference electrode should, in theory, be backfilled with concrete containing chloride at a concentration approximating that of the surrounding concrete in order to minimize junction potential. Some designers also choose to install the reference electrode furthest from the anode power feed, to insure that even the area receiving the least current is properly protected. Unfortunately, it is usually impossible to satisfy all these location criteria. For example, the most corrosive area will seldom have sound concrete around the bar, and is unlikely to be located by chance at a point farthest from the power feed. In such cases, the designer must make a choice based on his understanding of the importance of these factors.

It also is perfectly valid to measure steel potentials using a potential well and portable reference electrode at the surface. In this case, a hole is drilled down to the steel surface, the hole is fitted with a plastic sleeve, and filled with mortar or grout. The steel potential can then be taken at the opposite exposed end of the potential well. This technique is often used for structure testing. It has the advantages that it is cheap and that the reference electrode is always accessible and therefore easy to verify and change. The obvious disadvantage is the need to manually test at that location on the structure.

If an attempt is made to measure steel potential from the concrete surface, errors due to junction potential can result.[100] These errors are not possible to calculate, but may be very large. If the composition of pore water throughout the concrete were constant, junction potential error would not exist, but this is very seldom the case. Various compository differences which exist within a cathodically protected structure are illustrated in Figure 3. After a period of operation, the concrete near the protected steel may be depleted of chloride ion and rich in hydroxide ion. Chloride concentration differences are likely to exist elsewhere in the concrete, and the outside surface may be carbonated. Junction potentials which develop as a result of sodium chloride or pH differences may be especially large, in some cases over 200 mV. For this reason, it is important to minimize junction potential error by placement of the reference electrode or potential well very close to the steel surface. Even then, the measurement will contain some error. It is important to recognize that this error relates only to the absolute potential of the steel, however, and does not invalidate the results of depolarization or E-log I testing.

Finally, the practice of embedding small lengths of rebar that can be monitored separately is worth consideration. Such bars, commonly called macrocell probes, are normally monitored for current, and when the flow of current is net cathodic, they may be assumed to be protected. It is usual to cast macrocell probes in backfill containing a high concentration of salt, therefore creating a "most anodic site". If such a probe is protected, it is an indication that the rest of the structure may be protected as well. Macrocell probes are not alone sufficient as a cathodic protection criterion, but provide useful supplemental start-up data.



$$V_{Meas.} = (V_{Steel} - V_{Ref.}) + \Delta V_1 + \Delta V_2 + \Delta V_3$$

Figure 3. Junction potential error

Power Supply

A power supply is necessary to provide a source of direct current for the operation of a cathodic protection system. This power supply should meet certain requirements to insure safe, reliable, long-term operation. Reliability problems and complexity of many existing cathodic protection power supplies indicate the need for a power supply that is simple in design, rugged, and easy to maintain. A survey conducted by Battelle indicated that rectifiers were the leading cause of cathodic protection failures.

There are a number of power supply designs on the market ranging from simple tapped transformer/diode configurations to complex switch-mode designs providing a multitude of control and monitoring schemes.

In general, the power supplies in use today can be grouped into four main types:

1. A simple rectifier comprising typically a tapped transformer and silicon diode to convert the AC to an unregulated pulsating DC.
2. A saturable core reactor design wherein a special transformer forms a self-saturating magnetic amplifier that is capable of regulating the power to a load.
3. Thyristor designs where SCRs are used with feedback elements to operate as regulated constant-voltage or constant-current sources, and
4. Switch-mode designs where high speed transistors operating as switches are controlled by a feedback element to vary the on/off periods (duty cycle) of the switching elements. This process provides the means necessary to provide constant-current or constant-voltage control.

The table below lists some of the advantages and disadvantages of each type.

Table 3. Advantages and Disadvantages of Various Power Supplies

Simple rectifier	High reliability, simple, low cost, rugged	Unregulated, voltage control only
Saturable core reactor	High reliability, rugged, simple, regulated output	High distortion, less precise regulation, limits on range adjustments
SCR	Low cost, small size, high efficiency, regulated output	High ripple and noise, high distortion
Switchmode	High efficiency, smaller size and weight, regulated output	Generates EMI, noise and ripple, low reliability, high circuit complexity

At its present state of development, experience indicates that simplicity, ruggedness, and reliability appear to be the most important qualities that a power supply should have.

Since cathodic protection zone size may range from about 1,000 to 10,000 square feet (100 to 1000 square meters), power supply output is typically 2-20 amps. When coupled with a relatively low output voltage, typically 24 volts DC, this results in a very modest power requirement: perhaps 50 to 500 watts per zone.

The proper control mode is still a matter of debate. It would be ideal to control the power supply based on steel potential, but this assumes that potential measurements will be accurate and reliable long-term. This is not yet the case, and early experience has shown that potential control is not appropriate. This leaves the designer with the option of either constant current or constant voltage control. Constant current has the advantage of more closely controlling the electrochemistry which occurs at the steel surface. It is therefore more directly related to steel potential. But, since current requirements vary with environmental conditions, it may, result in overprotection (during winter, for example). Constant voltage control has the advantage that current will naturally reduce during very dry or cold periods when protection requirements are low. Although this seems reasonable in a qualitative sense, there is no evidence that this variation is quantitatively correct. A major disadvantage of voltage control is that current fluctuations may occur as a result of changes at places removed from the steel, such as at the anode, and this is not appropriate. Most designers today specify a power supply capable of operation by either constant current or constant voltage. Either control mode can then be used, based on future developments.

Finally, many designers today are specifying remote monitoring as a means of looking after systems and minimizing future maintenance costs. Items monitored include current, voltage, reference cell potentials and instant-off potentials. Full remote control is used less often, and here again, as with the power supply itself, the advantage of simplicity and reliability cannot be overemphasized.

Hydrogen Embrittlement

The normal reaction at the cathode surface during application of cathodic protection is oxygen reduction. But if overprotection occurs, it is possible for steel potentials to be driven more negative than -1.05 V vs. CSE. This is the thermodynamic threshold for hydrogen evolution at pH 12.5[101] The first step of this process involves the generation of monatomic hydrogen which can diffuse rapidly into the metal lattice. Hydrogen in this form will collect at grain boundaries and result in the phenomenon of "hydrogen embrittlement", particularly in certain high strength steels.

It is generally acknowledged that embrittlement is not a problem for conventional reinforcement, but for this reason, little cathodic protection has been installed on structures containing prestressed or post-tensioned steel. Whether or not this caution is justified is a matter of opinion.[102,103,104,105] A current FHWA research contract (Contract

No. DTFH61-91C-00030) "Cathodic Protection Developments for Prestressed Components", should help to resolve this issue.

8

Operation and Maintenance

Effective operation and maintenance of the CP systems are vital for the continuous service that is required to be effective and extend the service life of a highway bridge structure. However, the history of the first eighteen years of applying CP to bridges show that one area that needs substantial improvement is effective operation and maintenance of CP systems. The type of maintenance is readily defined: monitor, adjust and repair as required. However, the extent and time required for maintenance largely depends on location of the structure and the CP components installed. CP systems are designed and installed to remain in constant operation during their design life. Experience has shown that state personnel rather than consultants or service firms are monitoring the installed systems while consultants are often providing the annual inspection and adjustments of the systems.

"Cathodic Protection of Reinforced Concrete Structures," SHRP contract C-102B identified that 88 to 90 percent of the CP systems are performing properly from a questionnaire report from the SHA. Field investigation of supposedly functioning CP systems found an additional 10 percent failure, suggesting an overall 20 percent failure. However, many systems failed for trivial reasons such as switched-off power or blown fuses.[106] This in itself speaks well for CP components, as many of the state highway agencies reported infrequent monitoring of their systems. However, 10 to 12 percent of the systems not operating properly must be addressed.

Specifications are commonly written to require the contractor to supply an operation and maintenance manual. These manuals typically include CP components, operations, and minor troubleshooting techniques as well as a recommended monitoring program. Common types of system operations, which are basically determined by the type of rectifier, and maintenance programs are given below.

Types of Rectifier Operation

Since the rectifier is the heart of the system and must react to all changes in the system operation, it is important to understand its operation in order to maintain the CP system. The type of rectifier control selected for a CP system depends on the environment and any special requirements of the system. Currently two types of rectifier control are commonly specified providing either voltage adjustment or constant voltage and/or constant current control.

Manual voltage control rectifiers are the least complicated and hence the least expensive type of rectifier used. Rectifiers which are controlled by manually adjusting AC transformer taps or "variacs" are more a form of voltage limit type control since the setting determines maximum output voltage available. For this type of control, both voltage and current output will vary depending on the circuit resistance. Circuit resistance varies due to moisture, temperature, and physical or chemical alterations to any of the components of the circuit. This type of control is more acceptable if the environment and structure condition is relatively constant.

Constant voltage rectifiers allow the voltage output to remain constant regardless of change to the circuit resistance. Much tighter control of the DC voltage is possible with this type of rectifier than with the manual type. The output current is therefore controlled by changes in the circuit resistance only. Electronic voltage control is normally achieved through the use of silicon-controlled rectifiers (SCRs) or switchmode technology. To determine proper voltage setting for constant voltage control, analysis of historical system operational data is needed.[38]

A constant current control rectifier allows the output current to remain constant regardless of change to the circuit resistance up to the maximum voltage or current capability of the rectifier.[51] Such changes in circuit resistance are common in bridge structures since variations in moisture and temperature are inherent with weather changes on both a daily and seasonal basis. The methods of current control include saturable reactors, SCRs or switchmode technology. A saturable reactor operates by varying the magnetic flux saturation in an iron core, that resembles a transformer, through the use of a variable DC source. SCR use solid-state electronics which compare voltage signals and control the AC phase angle which regulates the DC output. Switchmode rectifiers use high-frequency switching power supplies whose outputs are regulated by an electronic signal from a synchronous detector switch. A schematic diagram of all these circuits to aid in understanding operation and field troubleshooting is supplied by the manufacturers or is available through consultants.

Since the amount of protection current needed to maintain CP varies with the environment of the structure and polarized condition of the reinforcing steel, periodic adjustment of the rectifier can extend the life of the CP system. Researchers have shown reduction in chloride levels after several years of operation and suggest that the CP current demand will decrease with time.[70,106,107] It is believed that many CP systems today can be operated at lower power levels, extending the service life of both the CP system and structure.

Test Requirements and Monitor Schedule

CP systems have been adversely affected by construction, lightning, vandalism, and AC power surges resulting in a loss of the protective current and hence, an interruption of the corrosion control. The sooner the malfunction is identified the sooner the system is returned to operation and any corrosion activity is held to a minimum. Thus, it is necessary that periodic inspections of the CP system are performed to allow for timely repairs and that periodic adjustments of the rectifier are performed to maintain corrosion control and ensure optimum life of the system. NACE Standard RPO290-90 recommends that all impressed current CP systems be checked at intervals of one month or at such intervals as necessary to insure effective operation and that annual surveys are conducted to verify that the system is meeting protection criterion.[72]

Monthly Monitoring

CP systems should be checked monthly. In practice 35 percent of the systems are monitored less frequently and some are never monitored.[25] A monthly operational inspection program should take little time, be simple, practical and cost effective. Monthly inspections allow malfunctions to be identified and repaired prior to the occurrence of extensive corrosion.[38] The monthly operational inspection should include only general data, visual inspection of the system and basic readings at the rectifier. All monthly inspection data should be recorded on a standardized form to insure that all necessary data is recorded. A standard form also simplifies evaluation of the data.

General Data

Normally the general data includes a structure description, rectifier information, and setting of the rectifier switches and controls.

The structure description includes the location and name of the structure, weather condition, date and time of the inspection. It is important that the temperature and deck condition (e.g. wet, snow-covered) be recorded since these directly affect the operation of the CP system.

Rectifier information includes the make, model, serial number, and output rating(s). This information aids in the analysis of any problems and, when necessary, ordering of replacement parts.

The setting of the rectifier switches and controls are also important. Typically, this includes the voltage tap setting or dial control position, auto/manual switch position, breaker switch, and indicator lights, if present. This information aids in the identification of problems and allows for corrective adjustments to be prescribed. It also is a check list to assure that all adjustments and settings are in proper position at the conclusion of the inspection.

Visual Inspection

Each exposed component of the system is visually inspected to ensure that it is not damaged and is in good operating condition. Conduits, junction boxes, rectifier and monitor stations are easily visually inspected. Damaged components may not affect system performance at that time; however, they can cause premature failure and reduce system life if they are not repaired.

Rectifier Meter Readings

Currently, most rectifiers are equipped with a meter used to read the output voltage and current. Some rectifiers also are equipped with an hour meter that indicates cumulative operating hours and others have meter capabilities to display instrumentation measurements such as (reference cell potential, temperature, corrosion probe currents, etc). All readings which are readily obtained can be recorded during the monthly inspection.

Start-Up Testing and Annual Survey

Although the monthly inspection of the CP system allows for minor problems to be identified, corrective repairs to be scheduled and operational data to be recorded, it is not intended to determine the absolute effectiveness of the CP system. To evaluate the CP system performance and make adjustments for optimum service, depolarization tests, E Log I tests, and electrical resistance measurements should be performed at start-up and thereafter annually. Criteria for achieving CP and providing corrosion control for reinforcing steel embedded in atmospherically exposed concrete is defined in NACE Standard RPO290-90.[72] The NACE Standard includes three criteria. However, only two are currently being used by the state highway agencies and these are discussed here.

For both of these tests, it is important to accurately measure the "IR-free" or "instant-off" potential of the steel. This is the potential without the voltage component due to concrete resistance. It is taken by measuring potential immediately (typically 0.06 to 1.0 sec.) after shutting current off, and may be taken manually, by using current interrupters, or by using special rectifiers designed to measure IR-free potential.[70,108]

Depolarization Test

The most popular NACE criterion is the 100 mV polarization development/decay of the structure with respect to a reference cell as it is the most practical to perform and simplest to analyze. This polarization criterion should be met within four hours of testing. The highway industry typically uses the polarization decay method, which is performed after the CP system has been energized and the structure polarized by the protective current. This criterion is only a guideline that was adapted from limited field experience and was designed for economic field use. It has been suggested that 100 mV is too low or too high and that four hours is too long or too short[38,70,71]. As more field data becomes available (through research work such as SHRP C-102F, "Field Activities and Data Collection of Existing Cathodic Protection Installations", and C-102D, "Cathodic Protection of Reinforced Concrete Bridge Elements") the optimum potential shift and time required may be better understood for practical application. At the time of this writing, the authors of this report believe that at least 100 mV of polarization should be achieved, and that hypotheses that much less polarization is adequate have not been proven. It is further recognized that polarization decay will take longer if the availability of oxygen is restricted, such as in the case of the concrete saturated with water.[70] It has also been reported that polarization decay becomes slower with an increase in operational life of the CP system.[109]

A common method used by consultants for recording the polarization decay data is through the use of an automatic voltmeter recorder or data logger. This allows for the potentials to be automatically stored at close time intervals over the test period (a task that would be extremely tedious by hand). This data is then loaded into a computer where it is easily graphed for evaluation and analysis. With many data points, the curve of the graph can easily be viewed and abnormalities identified.

E Log I Test

The E Log I test is most commonly performed by consultants or service firms specializing in CP to initially energize the CP system. This test has also been used during the CP service life after allowing sufficient depolarization to provide valid E Log I data. This NACE criterion is used to determine the existing corrosion parameters and CP requirements. To perform the test, protective current to the structure is gradually increased and the resulting structure-to-reference cell potential is recorded for each current increment. The reference cell potential verses the logarithm of the applied current are plotted and a Tafel diagram is generated and analyzed. The current required for cathodic protection is the value determined to occur at the beginning of linear behavior of the plot. Since interpretation of the data is subjective, consultants typically use computer programs to generate the plot and algorithms to analyze the data.

The E Log I test is best performed in the field using existing embedded reference cells and a test rectifier designed specifically for E Log I testing. The test rectifier reads an IR drop free potential and has a finely adjustable current output. Service rectifiers designed to perform this test also have been installed at bridge structures.

CP system adjustments based on both E Log I and depolarization test analysis provide optimum corrosion control. However, effective corrosion control has been demonstrated using either criterion alone. The question that is often raised is how much corrosion must be stopped to economically extend the service life of the bridge structure. Research work is currently underway to evaluate structures with existing CP systems under (SHRP C-102F), and work is being conducted to investigate and improve CP criteria (SHRP C-102D).

Electrical Resistance Measurements

The measurement of the resistance between various components of the CP system can aid in identifying component problems and system effectiveness. The two most common measurements are the anode-to-structure and structure-to-reference cell resistance. Increasing anode-to-structure resistance can be a signal that the anode is depleting or that portions of the anode are no longer in the circuit. Conversely, if the anode-to-structure resistance is low, an electrical short between the anode and steel reinforcement may be present. A change in structure-to-reference cell resistance can indicate a reference cell malfunction or other circuit problem. The most common method for measuring resistance is with an AC resistance meter.

Remote Monitoring

The most advanced and cost effective method of evaluating CP systems today incorporates the use of remote monitoring. The Remote Monitoring System (RMS) basically consists of a Data Recorder Unit (DRU), a modem and a PC computer in the office. Many options have become commercially available and are being utilized by state highway agencies.

The RMS may be real-time (what is happening at that moment) or it may store the data until it is retrieved by an operator at location or via the modem. The system also can turn the rectifier "on" and "off" and adjust the current or voltage output. These options can further be processed along with the data storage to perform E Log I and depolarization tests. Virtually any signal which can be converted to digital format can be collected, stored or transmitted via a RMS. The systems may also be programmed with an alarm that identifies data out of a pre-designed range or automatically initiate communications between the office, console and rectifier. Of additional interest is the New Jersey DOT's use of their remote monitoring to monitor deck temperature and, based on the data obtained, determine when to send out salt trucks in the winter.

CP System Failures

Ideally, once a CP system has been designed and installed, it will operate flawlessly for the design life of the system. Unfortunately, the reality is that component failures due to physical damage, environment causes or equipment malfunction necessitate remedial repair work. As the technology of CP of steel reinforced concrete continues to advance, the frequency of equipment related system failures has declined. However, occasional failures of reference cells, anode materials and rectifiers have occurred. A general description of more common problems will be offered here.

Commercially available reference cells have relatively short service lives when compared to the remainder of the CP system. This is due to the difficulty involved with keeping the reference cells stable over a long period of time. Temperature, moisture, resistance and ion concentration are all variable in concrete and affect the stability of a fixed reference cell. Over the short term, typically needed for CP criterion testing silver/silver chloride and graphite cells have shown the best performance to date.

The rectifier is often noted as the source of system failure. However, often the rectifier is only reacting to changes in system operation. Rectifiers stop operating because of blown fuses or tripped circuit breakers caused by power surges, lightning, or other external causes. Occasionally, the rectifier malfunction is more serious, such as a burned-out rectifier element, transformer or meter. If the problem is a fuse or circuit breaker, this can be repaired by field personnel when found and the rectifier is returned to operation quickly. Major malfunctions are typically referred to a professional trained in repairing that specific rectifier. If a problem reoccurs, it should be diagnosed by someone familiar not only with the rectifier but the entire CP system to determine if the problem is caused by the rectifier, the system design, or the environment.

Physical damage to the CP system can result from vandalism, accidents or construction activities. If the anode is damaged, the CP current distribution is affected and portions or whole zones of the CP system may not be controlling corrosion to the steel. Construction crews or vandals also may cause damage to rectifiers, junction boxes or other exposed CP components. Safety precautions such as locking of the rectifier or mounting the rectifier in a safe place, can minimize these mishaps. Since CP is a long-term repair, new construction may expose the rectifier or other components to environmental hazards that were not taken into consideration during the original design. A simple relocation of the component can ensure continued good performance.

9

Research and Development Needs

Although the basic processes of steel reinforcement corrosion and concrete deterioration are well understood, and the theory of cathodic protection is well known, there remain a number of related issues in need of research and development. These issues are unlikely to be studied in depth by private industry, since they are not directly related to the sales and profits of proprietary products. Support for such research instead come from publicly-funded institutions, such as the FHWA and SHRP.

Research is needed on the kinetics of the process of corrosion of steel in concrete, and how the kinetics are affected by cement content and type, oxygen and moisture content, and temperature. Further studies also need to be conducted on the various techniques for measurement of corrosion rate of steel embedded in concrete. Corrosion rate studies need to be extended to cathodically polarized steel. If the rate of corrosion of polarized steel could be directly measured, any question of the appropriate cathodic protection criteria could be resolved. This remains the single most important issue in cathodic protection today. It is generally accepted that the passage of cathodic protection current will migrate chloride away from the steel surfaces, increase hydroxide concentration, and cause the steel to repassivate. If this is true, then cathodic protection criteria should be dynamic, and change with time. Understanding this issue could have an important impact on the use of intermittent cathodic protection, the use of sacrificial anodes and the service life of cathodic protection systems.

Possible hydrogen embrittlement of high-strength steels is now being addressed by ongoing FHWA research contracts.

Other important issues involve concrete, and the changes which occur during the passage of electric current through concrete. A better understanding is needed of the concentration gradients which develop with time, particularly near the anode and steel surfaces. The problem of new concrete bonding to old is very important for cathodic protection. Technical improvements are especially needed in the area of cathodic protection system overlays applied to vertical and overhead surfaces.

Certain anode issues also are in need of research, and even here it is unlikely that enough will be done by private industry alone. It is recognized that all anodes in concrete generate acid, but the effect of that acid on concrete adjacent to the anode surface is not well understood. Different anode types produce different amounts of competing reaction products, such as chlorine, oxygen and carbon dioxide. How this mix may effect service life is not well known. Other factors, such as current density, temperature and moisture content, are probably important in determining the extent of damage due to anode reaction products, but studies along these lines have not been reported. It is possible that sacrificial anodes, such as zinc, may be appropriate for protection of certain structures without the need for externally impressed current. The use of sacrificial anodes in such cases is off to a slow start, primarily because no company has a protected, proprietary interest to promote. For the same reason, research and development of these systems has been slow. New and innovative anode configurations need to continue to be developed, particularly for substructures.

Reference electrodes and their use for the measurement of potentials in concrete are in need of further study. Without accurate, reliable measurement of the potential of steel in concrete, it is impossible to assess its rate of corrosion and the effectiveness of protection systems. The importance and shortcomings of existing reference electrodes are recognized, but the factors which affect their use in concrete are not as well appreciated. Errors due to junction potentials, for example, can be much larger than previously believed, and as yet cannot be predicted quantitatively.

Unfortunately, cathodic protection in the U.S. has so far been considered a salvage technique, to be used as a last resort on badly deteriorated structures. More consideration needs to be given to the incorporation of cathodic protection into original construction, as has been done on several structures in Europe and the Middle East. Likewise, the use of cathodic protection in tandem with coated reinforcing steel needs to be investigated. The various structural factors that influence distribution of current also need detailed examination.

Finally, a systematic review and refinement of the electrical components used for cathodic protection power supplies is in order. Different modes of electronic control need to be compared for use and reliability, and constant voltage vs constant current control needs continued investigation.

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