

Cathodic Protection for Life Extension of Existing Reinforced Concrete Bridge Elements

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NCHRP SYNTHESIS 398

**Cathodic Protection for Life
Extension of Existing Reinforced
Concrete Bridge Elements**

A Synthesis of Highway Practice

CONSULTANT

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SUBJECT AREAS

Bridges, Other Structures, Hydraulics and Hydrology, and Maintenance

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, “Synthesis of Information Related to Highway Problems,” searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, Synthesis of Highway Practice.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

*By Jon M. Williams
Program Director, IDEA
and Synthesis Studies
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Cathodic protection is the only technology that can directly stop corrosion in reinforced concrete structures. This report examines the use of cathodic protection by state transportation agencies for controlling corrosion on existing reinforced concrete bridge elements. There are descriptions of different types of systems and case studies of states using these systems. As well, there is analysis of reasons that public agencies may or may not employ cathodic protection.

Information was gathered through a literature review and a survey of U.S. state transportation agencies and Canadian provincial transportation agencies, augmented by selected interviews.

Ali Akbar Sohahngpurwala of CONCORR, Inc., Sterling, Virginia, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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CATHODIC PROTECTION FOR LIFE EXTENSION OF EXISTING REINFORCED CONCRETE BRIDGE ELEMENTS

SUMMARY Over the past three decades significant attention has been focused on the condition of the nation's aging highway bridge infrastructure. As the cost of maintenance and replacement continues to increase, many agencies are looking for materials and technologies to preserve their infrastructure and extend their service life. To address the corrosion problem on reinforced concrete structures, a research and development effort was initiated by both the private and the public sectors in the early 1970s. Numerous different technologies were introduced to repair damage caused by corrosion and to prevent or minimize further damage from occurring. During this time cathodic protection, one of the most effective technologies to stop corrosion, was adapted for implementation on reinforced concrete structures. In 1982, an FHWA Policy Statement reported that cathodic protection is the only technology that can directly stop corrosion in reinforced concrete structures and this statement is still valid today.

Since its first application on a bridge deck in 1973, many different types of systems have been developed and a significant amount of literature on their performance is available. Certain types of cathodic protection systems are projected to provide service-life extensions in the range of 25 to 50 years, and presently there are systems that have been in operation for 20 or more years.

The primary goal of this synthesis is to examine the utility of this technology for controlling corrosion on reinforced concrete structures and determine, if possible, why public agencies do or do not use this technology and explore how to encourage expanded appropriate use of this technology. To accomplish the goals of this project a survey of state and provincial departments of transportation (DOTs) and the industry was conducted. A total of 37 responses were received from public agencies, 32 of which were from U.S. state DOTs and 5 were from Canadian provincial DOTs. Responding states include all with 10 or more cathodically protected bridge decks, according to the National Bridge Inventory. A literature survey was also performed to obtain information on practices and experience with the use of this technology. The results of this exercise are documented in this report.

Agencies that have adopted this technology as one of the tools for bridge preservation and have developed in-house procedures, protocols, and acquired the technical skills to implement it have experienced reductions in maintenance frequency and costs and have achieved significant service-life extensions. In some cases, service-life extensions of more than 20 years have already been achieved, and those structures are not expected to have corrosion-induced damage as long as the cathodic protection systems are functional. However, only three states in the United States—Florida, Missouri, and Oregon and three Canadian provinces—Alberta, New Brunswick, and Ontario, have adopted this technology and are actively implementing it. Many other agencies have experimented or implemented the technology on select projects and have not made a commitment to implement it on a larger scale.

Some agencies' experience with the technology has not been satisfactory. Often, these agencies did not have the expertise or resources to evaluate, select, design, install, and monitor and maintain the systems. Many of these systems were not properly selected, had deficient design, substandard installation, and insufficient or no monitoring and maintenance. At

least one agency has indicated that although they had actively installed cathodic protection systems on their bridge structures in the 1980s, currently they do not have an inventory of the systems or any information on the status of the systems; those systems have been forgotten. Some failures were simply a result of the expansive growth the industry experienced in the late 1970s and the 1980s, and it took the marketplace some time to weed out the less-effective and less-durable systems. The survey data suggest that insufficient or no monitoring and maintenance is being performed by many agencies and it is the most important reason for the disappointing performance of many of the systems.

There are many agencies that can benefit from this technology but have not adopted it primarily owing to the high initial cost, inadequate resources to monitor and maintain the systems, lack of understanding of the technology, and lack of innovation and competition. Of the agencies that have never used or have not used cathodic protection since 2003, 18 indicated that they would consider it in the future. These agencies may need Standard Specifications for selection, design, and construction of these systems and protocols for monitoring and maintenance. Their staff may need to be trained in the implementation of the technology. The FHWA or the National Association of Corrosion Engineers may need to develop a document that public agencies can use to properly implement the technology. The National Association of Corrosion Engineers and/or the National Highway Institute may need to develop and conduct training classes to ensure that agencies have staff with the requisite skill sets. In addition, innovation and competition in the marketplace is lacking and the industry needs to determine a way to provide innovative products at competitive prices. Many agencies appear to favor the galvanic systems that require comparatively less monitoring and maintenance than the impressed current systems, and innovation in this area would be beneficial for the growth of the industry.

INTRODUCTION

As of 2002, the National Bridge Inventory (NBI) Database, maintained by the FHWA, contained a total of 587,964 bridges. The average age of the bridge structures in this database is 40 years, and 41% are at least 40 years old. Over the past three decades, significant attention has focused on the condition of the nation's aging highway bridge infrastructure. Several independent evaluations of the condition of the nation's infrastructure, based on condition ratings contained in the database, have been performed (1–3). These studies ascertained that 14% of the bridges were rated structurally deficient and the primary cause of the deficiency was corrosion of reinforcing steel. The cost to maintain the nation's bridges during the 20-year period from 1999 to 2019 is estimated to be \$5.8 billion per year, and the cost to improve and eliminate deficiencies over the same period is \$10.6 billion (1). A cost-of-corrosion study determined that the annual cost of corrosion to all bridges (including steel bridges) is \$8.29 billion and this does not include indirect cost incurred by the traveling public as a result of bridge closures (2).

To address the corrosion problem on reinforced concrete structures, a research and development effort was initiated by both the public and the private sectors in the early 1970s. Numerous different technologies were introduced to repair damage caused by corrosion and to prevent or minimize further damage from occurring. In addition, strategies were also developed to delay the initiation of corrosion on new structures, thereby increasing their service life. These were generally categorized as “Prevention.” Strategies, technologies, and materials developed to repair the damage induced by corrosion are generally referred to as “Repairs” and the term “Rehabilitation” is used if the project either eliminates or controls the cause or interferes with the process of deterioration to stop, control, or minimize it.

On new structures there are many techniques available to delay the initiation of corrosion, which include the increase of clear concrete cover, installation of overlays, reduction in the permeability of the concrete (by the use of latex modifiers and replacement of cement by silica fume or fly ash), admixing of corrosion inhibitors, use of alternative reinforcements (such as epoxy-coated rebars, galvanized rebars, and corrosion-resistant rebars), and controlling the ingress of moisture and chloride ions (with the application of sealers, membranes, and waterproofing materials). In very corrosive environments, such as those encountered in the Middle East,

cathodic protection systems are installed on new structures and are referred to as cathodic prevention.

Patching of damaged concrete, replacement of deck concrete, and encasement and jacketing of substructure elements generally fall in the Repair category. These methods do not do anything to prevent future corrosion-induced damage; they are primarily designed to restore the concrete element to an acceptable level of service, its original form or dimension, or its design structural capacity. Under certain circumstances, repair may accelerate the corrosion process and may result in its premature failure.

In a Rehabilitation effort, in addition to repair of the damaged concrete, one or more of the following may be included to control corrosion:

- Remove and replace all chloride-contaminated concrete;
- Reduce the concentration of and change the distribution of chloride ions by using electrochemical chloride extraction;
- Stop or slow the ingress of future chloride ions by using a less permeable cementitious overlay comprised of latex, silica fume, or fly ash-modified concretes;
- Stop or slow the ingress of future chloride ions by using sealers, membranes, and waterproofing materials;
- Repair cracks to prevent chloride ion contamination;
- Apply barrier coatings on the reinforcing steel in the repair areas;
- Apply corrosion inhibitors in the repair or over the entire concrete element to either interfere with the corrosion process or modify the characteristics of the in-place concrete; and
- Apply a cathodic protection system.

Among all strategies and techniques discussed previously, *cathodic protection is the only technology that can directly stop corrosion*, even in the most corrosive environment, if designed, installed, and applied correctly (4). As long as the cathodic protection system is operational at the required level, corrosion will not occur. Recognizing that this technology offered a mechanism to stop corrosion, the California Department of Transportation (DOT) (Caltrans) was the first to experiment with it as early as 1959 (5). It was not until 1972 that the first full-scale system was installed on the Sly Park Bridge in Placerville, California (6). Following the success of this experiment, Caltrans and the Ontario Ministry of

Transportation (MTO) started to install cathodic protection systems on bridge decks. By 1975, the FHWA became involved and initiated a Demonstration Project. This project provided funds to the state DOTs to experiment with and test the various materials and systems that were being developed at the time. In addition, it also controlled the application of the technology and ensured that the systems were installed in accordance with the best practice of the time. By 1978, cathodic protection had become one of the three standard rehabilitation techniques used by the Ontario MTO. By 1989, a total of 275 bridge structures in the U.S. and Canada had been cathodically protected (7). It is reported that by 1989, slotted cathodic protection systems had been installed on more than 100 bridge decks, and the state of Missouri had the highest number of such systems installed (8). By 1990, the technology had matured and many different types of anode materials and system configurations were available. By 1994, there were 350 operational cathodic protection systems in the United States and Canada (9).

The results of the survey conducted in this effort indicated that the responding public agencies have a total of 586 bridge structures with cathodic protection systems installed. The actual number is probably higher than this as not all public agencies responded to the survey. Several states, including California, Florida, Missouri, and Oregon, and provinces including Alberta, New Brunswick, and Ontario, have made cathodic protection a standard bridge preservation tool. Of the 586 bridges in North America, 464 are located in these 7 jurisdictions. Several existing cathodic protection systems have been operational for more than 20 years. Although no formal studies have been performed, in interviews several states using cathodic protection systems indicated that it has stopped corrosion and reduced bridge maintenance costs, especially in very corrosive environments. The TRB Corrosion Committee has estimated that 30,000 more bridges are at risk and could be candidates for installation of galvanic cathodic protection systems. In 1985, a National Association of Corrosion Engineers (NACE) publication reported that 300,000 of the 500,000 bridge decks in the United States are candidates for cathodic protection (10).

Corrosion is an electrochemical process in which electrical energy is associated with chemical reactions. There are two types of reactions that occur in an electrochemical process, anodic and cathodic. Metal loss (i.e., corrosion) results from the anodic reaction. A cathodic protection system impresses an electrical field on to the surface of the corroding reinforcement such that it favors the cathodic and deters the anodic reaction. If the applied electric field is strong enough, it will shut down the anodic reaction on the surface of the metal being protected and, thereby, stop corrosion. The protective electric field in a cathodic protection system is impressed by an anode. The anode is the primary component, and generally a cathodic protection system is defined by the anode material it uses. Many different types of anode materials have been developed for this purpose.

There are two different types of cathodic protection systems; the galvanic (or Passive System) and the impressed current (or Active System). In a galvanic system, an anode, a material that naturally is more electro-negative than the steel to be protected in the environment of use, is connected to the reinforcing steel to be protected. The difference in electrical potential between the anode and the reinforcing steel drives an electrical current that flows through concrete to the surface of the steel to be protected. In an impressed current cathodic protection system, the electrical potential is provided by an external source such as a rectifier (a device that provides unidirectional or direct current electrical current) and the anode delivers the current through the concrete to the surface of the steel to be protected. All anodes, galvanic or impressed current, are consumed during the transfer of current to the concrete, some at a slower rate than others.

Cathodic protection systems are capable of providing a significantly larger extension in service life compared with other corrosion mitigation systems. This is possible because they completely stop the corrosion process. As cathodic protection directly interferes with the process of corrosion, it does not matter if corrosion was initiated by the presence of chloride ions, carbonation of the concrete, dissimilar metals, or presence of stray currents. Generally, the extension in service life is dependent on the service life of the anode material and the maintenance of the system. Although the installation costs can be capital intensive, the life-cycle costs, when compared with other corrosion mitigation systems, are generally lower. The primary impediment to the use of this technology is the higher levels of monitoring and maintenance that are required, which can be burdensome for public agencies that do not have the resources. This technology is not well understood by the transportation community and has not been standardized for large-scale application.

The goals of this synthesis are to examine the extent of use of cathodic protection technology for controlling corrosion on reinforced concrete structures, ascertain why public agencies do or do not use this technology, and explore how to encourage the appropriate use of this technology. In their 1978 report, Battelle Columbus Laboratories estimated that 30% of the \$82 billion cost of corrosion to the U.S. economy in 1975 could have been avoided by effective application of known science and technology (11). Once again a similar question is being raised; is a technology as effective as cathodic protection being optimally used to minimize bridge preservation costs?

To accomplish the goals of this project, two questionnaires were developed to try and gain insight into the use of this technology on reinforced concrete bridge structures. The first was targeted toward public agencies that own, operate, and maintain bridge structures in North America, and the second was targeted toward the industry dealing with the cathodic protection technology. The first questionnaire was sent to all members of AASHTO and the industry questionnaire was sent to the major players in the field as determined by the author of the synthesis. A total of 37 responses were

received from public agencies, 32 of which were from U.S. state DOTs and 5 from Canadian provincial DOTs. The state of Ohio only provided a verbal response with regard to its experience with cathodic protection. A detailed response to the survey questions was not available. Only five responses were received from private industry. A literature survey was also performed to obtain information on practices and experience with the use of this technology. The results of this exercise are documented in this report.

The following chapter (chapter two) provides a primer on the cathodic protection technology, and the history of use of the technology is documented in chapter three. The results of the survey and the literature review with regard to policies and practices are summarized in chapter four. The problems encountered with the use of the technology are presented in chapter five and the long-term performance of the technology is presented in chapter six. Conclusions and best practices are noted in chapter seven.

CATHODIC PROTECTION TECHNOLOGY

There are two distinct types of chemical reactions that occur on the surface of metals embedded in concrete, anodic and cathodic. These reactions are electrochemical in nature and, as the name suggests, electrical energy is associated with these chemical reactions. These reactions occur at the metal/concrete interface. The loss of metal (i.e., corrosion) occurs as a result of the anodic reaction. The rate of these reactions is controlled by the magnitude and the direction of the local electric field and other factors. A cathodic protection system applies an electric field such that it favors the cathodic and deters the anodic reactions. When the magnitude of the applied electric field exceeds the threshold for the local environment, the anodic reactions stop; that is, corrosion stops.

The material that imposes the electric energy on the metal to be protected is called an anode. It is the primary component and, generally, a cathodic protection system is described by the anode material it uses. The strength of the electric field and the resistance of the system control the magnitude of the electric current that flows in the system. The principal requirement of the anode material is that it have the capacity to transfer the electrical charge from its surface to the electrolyte. The electrolyte is a conductive solution, such as pore water in concrete, through which the cathodic current flows to the surface of the metal to be protected. In the process of transferring the current, the anode will corrode (i.e., will be consumed). Therefore, the slower the consumption rate of the anode per unit of cathodic current, the longer it will last. In addition, the anode must be durable in the environment it is to be used in and be able to withstand the loading it may be subjected to. For example, the anode material placed on the deck of a bridge must be capable of withstanding the weather and the traffic. The lower the electrical resistivity of the anode material, the larger the surface area of the concrete element it can uniformly distribute the current to.

There are two different ways of imposing an electrical field on the metal to be protected. The one termed impressed current uses an external electrical power source to drive a current through the anode toward the metal to be protected. In the other method, galvanic cathodic protection, another metal (anode), which is more electronegative than the metal to be protected is placed in its vicinity and electrically connected to it. The difference in the natural electrical potential between the two materials in the given environment generates an electrical field to drive the protective current that flows from the anode to the surface of the metal to be protected.

IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM

Impressed current cathodic protection is achieved by driving a low voltage direct current from a relatively inert anode material through the concrete to the reinforcing steel. Direct current of sufficient magnitude and direction is applied to shut down the anodic reaction and support the cathodic reaction on the steel surface. The direct current is supplied by an external power source, most often a rectifier that converts alternating current to direct current. Recently, solar power and specially designed batteries have been successfully used as an external power source (12). The direct current is distributed to the reinforcing steel by the anode. Figure 1 shows the basic layout required for impressed current cathodic protection systems.

There are various different materials and configurations that can be used as anodes in impressed current cathodic protection systems. In some systems only one anode material is used and in others more than one is used. When more than one anode material is used, the material that receives power from the external power source is called the primary anode. It is important that the primary anode have as low an electrical resistivity as possible so that current can be distributed to longer distances with minimal loss. The secondary anode, which has a much larger surface area, receives current from the primary anode and distributes it uniformly over the area to be protected.

There has been an evolution in anode materials for use on reinforced concrete structures. During the developmental process, some of the anodes did not perform as expected and were eventually eliminated. Unfortunately, agencies initially experimenting with the cathodic protection systems used some of these underperforming anodes and were left with an unfavorable impression of the cathodic protection technology. Listed here and defined are anodes that have been used in impressed current cathodic protection systems.

Platinum niobium wire: This anode is comprised of a copper core, a niobium substrate, and a platinum cladding. Platinum forms the surface of the wire and is an excellent anode material with a very low corrosion rate and does not form an insulating layer in most electrolytes. The niobium substrate is used to provide dimensional stability and the copper core is used for its high conductivity and lower price. As

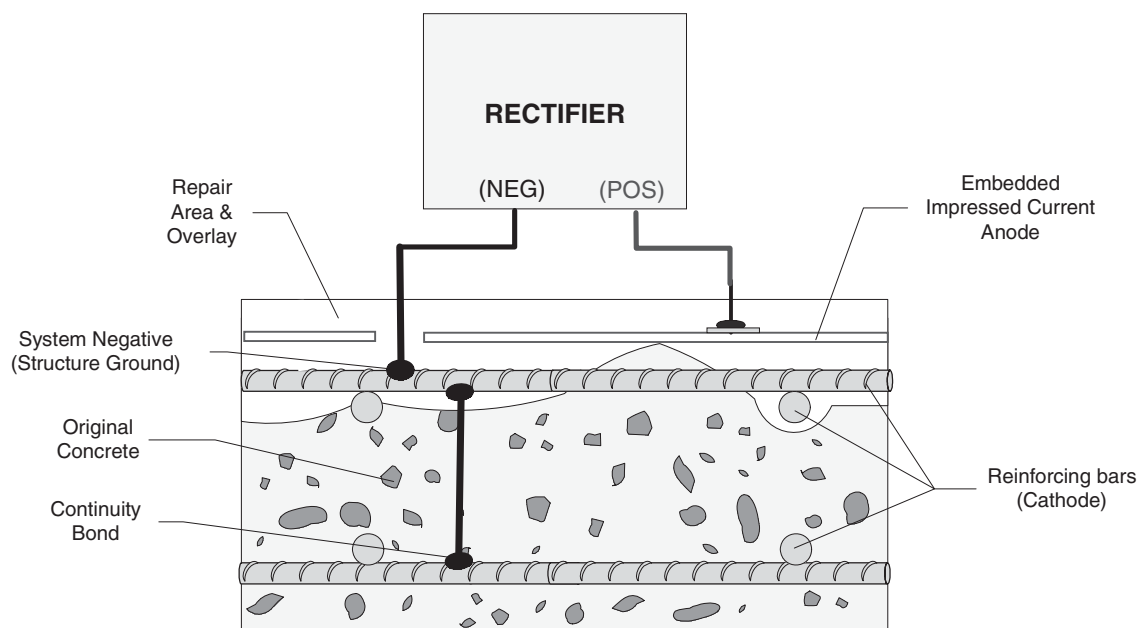


FIGURE 1 Basic layout of an impressed current cathodic protection system.

the dimensions of this anode are very small (see Figure 2), it requires either a very conductive electrolyte or a secondary anode to distribute current over larger areas.

Carbon fiber: A fiber comprised of graphite, which is very similar in application to the platinum niobium wire, except its conductivity is not as good (see Figure 3).

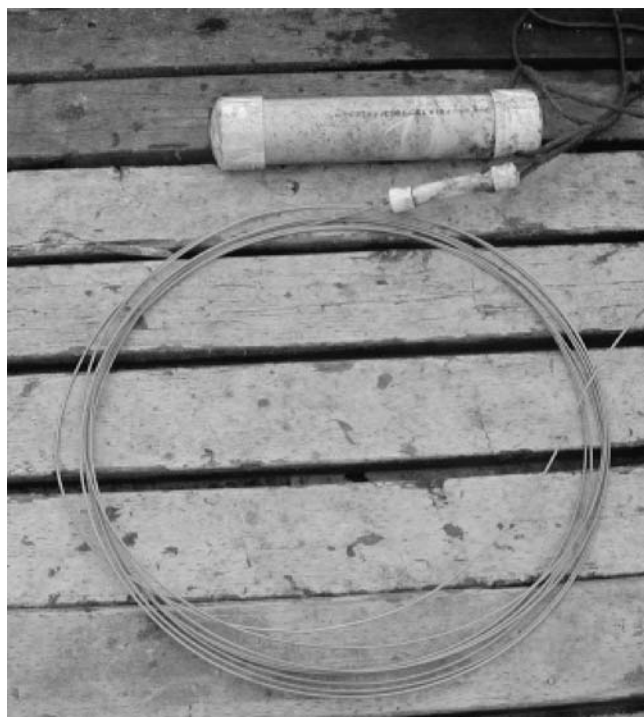


FIGURE 2 Platinum niobium wire anode.

Zinc: It is one of the most widely used anode materials and can be used as either an impressed current or a galvanic anode. Although zinc is available in many different configurations, in impressed current systems it has generally been applied to the concrete surface as a thin metallic coating using the arc spray technique.

Aluminum–zinc–indium alloy: This alloy can be used as an impressed current anode. It is applied to the entire surface of the concrete element using arc spray technique.

Mixed metal oxide: This uses titanium as a dimensionally stable base material, which is protected by thin, self-healing, tightly adherent oxide films. It is acid resistant and resists the passage of current in the anodic direction. The mixed metal oxide coating functions as the anode. The mixed metal oxides, formed on the surface of titanium through a process

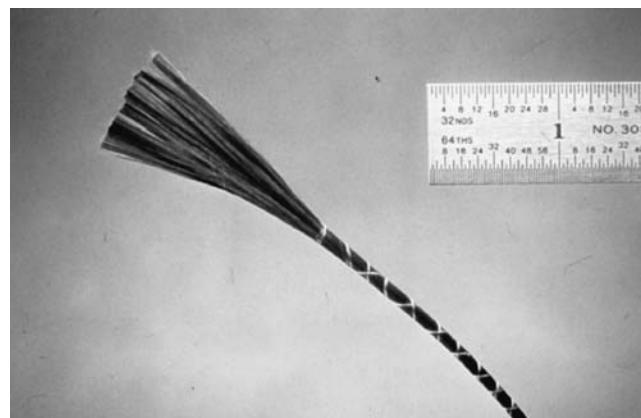


FIGURE 3 Carbon fiber anode.

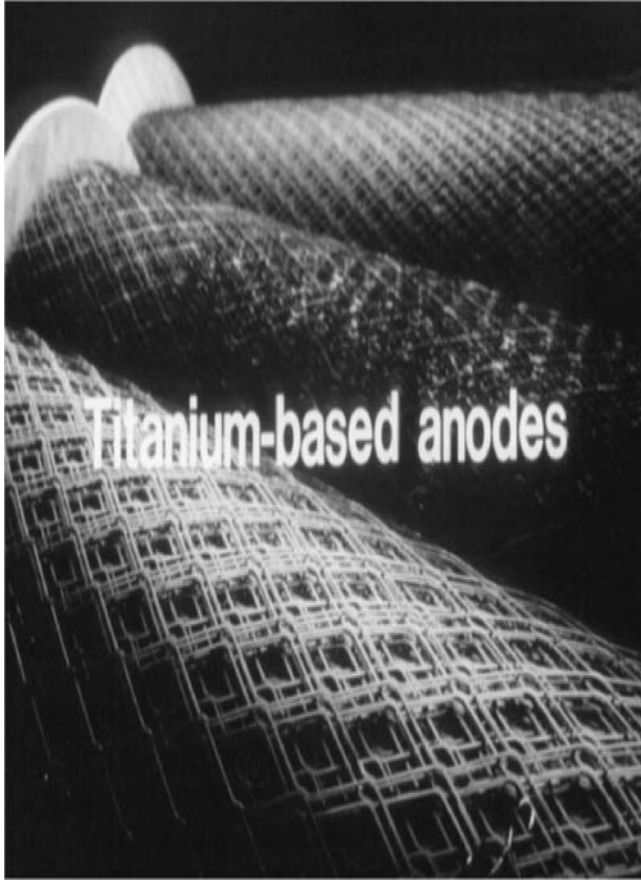


FIGURE 4 Mixed metal oxide mesh anode.

of thermal decomposition, have good electrical conductivity and anodic properties. The wear rate of these anodes is extremely low, uniform, and constant over all current densities. These anodes are supplied as expanded mesh (see Figure 4) and ribbon. A solid ribbon is also available.

Cast iron anodes: High silicon cast iron in various geometric shapes has been used as an anode material. These anodes were only used in the asphalt coke breeze overlay systems and are not used anymore.

Conductive rubber: The conductive rubber anode is manufactured from ethylene–propylene–diene monomer containing 25% by volume acetylene black conductive carbon and is produced as sheets with corrugation on one face.

Ceramics: These are supplied as tubular anodes and are manufactured from ceramic/titanium composite (see Figure 5). These anodes are designed to provide protection in a local area and do have good characteristics as an anode material.

The following have been used as secondary anodes on reinforced concrete structures:

Conductive polymer grout: This material was developed by the FHWA and is manufactured with vinyl ester resin with



FIGURE 5 Ceramic tubular anodes.

appropriate additives and coke breeze as the filler material. It has excellent freeze–thaw durability, bonds to concrete, and has electrical resistivity in the 10 ohm-cm range.

Conductive coatings: These coatings are essentially paints with graphite added to improve conductivity.

The available anode materials can be used in various combinations and configurations to meet the requirements of the structure. Combinations of anodes and configurations that have been used to date are discussed here.

On bridge decks, the configurations used to date can be categorized as follows:

1. Conductive overlay systems.
2. Non-overlay slotted.
3. Non-conductive overlay.

The only type of conductive overlay that has been promoted to date is the coke breeze overlay. Conductive coke breeze overlay systems use silicon–cast iron plate anodes placed on the deck surface or in recesses on the concrete deck surface. A conductive asphalt overlay is then placed. This is followed by placement of a conventional bituminous mixture, which serves as the wearing course.

The slotted non-overlay system requires sawing slots into the concrete, which form a uniform grid over the entire surface (see Figure 6). Anodes are then placed in the slots, which are backfilled with a conductive material. Several different anodes can be used in the slots and they include platinum niobium wire, carbon fiber, and mixed metal oxide ribbon. The slots are backfilled with an FHWA conductive polymer material when the primary anode is the platinum niobium wire or the carbon fiber. A cementitious backfill material can be used with the mixed metal oxide ribbon anodes. The older systems



FIGURE 6 Slotted non-overlay system (Platinum niobium wire anode and FHWA conductive polymer).

in Missouri were overlaid with a wearing surface of asphalt and the newer ones are overlaid with concrete.

Several different combinations of anodes and configurations have been used with a non-conductive overlay. One of the earlier designs used a grid of anodes on the concrete surface, usually platinum niobium wire or carbon fiber encapsulated with a mound of conductive polymer to increase the surface area of discharge. A cementitious overlay was then placed to restore the wearing surface. This configuration is not used any more. The other alternative involves placing a mixed metal oxide mesh anode on the surface of the deck as shown in Figure 7 and overlaying it with either a portland cement or latex modified concrete.

On the underside of the deck and other superstructure elements such as beams, girders, diaphragms, hammer heads, and caps the surface-applied systems are generally used. The surface-applied systems involve application of an anode



FIGURE 7 Placement of mixed metal oxide mesh on a deck surface. A cementitious overlay is normally placed on the mesh anode.

material over the entire surface of the concrete. The most common surface-applied anodes are conductive paint and thermally sprayed zinc. The conductive paint anode is applied by spray or roller and a decorative overcoat is then applied, if desired, for aesthetic purposes (see Figure 8). A thin layer of zinc is applied to the concrete surface, often using the arc spray technique. On hammerheads and caps, mixed metal oxide anode encapsulated in shotcrete has been attempted. In one application, the mixed metal oxide anode was placed on the underside of a roadway of a tunnel and encapsulated with shotcrete. In another, mixed metal oxide mesh was installed on the top and bottom surfaces of historic arches and encapsulated with shotcrete. The aluminum–zinc–indium alloy has also been installed using the arc spray method.

On bridge substructure elements the configurations used can be categorized into:

1. Surface applied,
2. Encapsulated, and
3. Non-encapsulated.



FIGURE 8 Conductive paint systems with decorative overcoat on hammerheads and columns.

The surface-applied systems are primarily applicable to columns that are exposed to deicing salt spray and are not used in tidal zones in marine environments. In tidal zones, the consumption rate of arc sprayed zinc can be very high and will not provide an acceptable service life, whereas the conductive paints are not very durable in such an aggressive environment. The zinc mesh anode, when used in tidal zones, is used in combination with a bulk zinc anode. In the encapsulated category, the mixed metal oxide and zinc mesh anodes are generally used. The anodes are encapsulated in a cementitious material most often held in place inside a fiberglass jacket. Mixed metal oxide anodes in a cementitious encapsulation without an outer jacket have also been used. The conductive rubber anode has been used in marine tidal zones without any encapsulation. The anode is placed on the surface of the concrete and held in place using fiberglass panels and compression bands. The conductive saltwater present in the tidal zone improves the electrical contact provided by the mechanical contact of the rubber with the concrete surface.

GALVANIC CATHODIC PROTECTION SYSTEMS

Galvanic cathodic protection is based on the principles of dissimilar metal corrosion and the relative position of specific metals in the Galvanic Series. A more electronegative metal is placed in the vicinity of the metal to be protected and is electrically connected to it. A typical installation is shown in Figure 9. No external power source is needed with this type of system and much less maintenance is required.

Zinc is more electronegative than low carbon steel, especially in the presence of chloride ions, and is the anode material of choice on reinforced concrete structures. It has been used in many different configurations such as arc sprayed, expanded mesh, perforated sheets, foil with adhesive, ribbon, pucks, and a solid rectangular mass (bulk anode). A typical installation of arc sprayed zinc and foil with adhesive is shown in Figure 10. The consumption rate of zinc is higher than that of the other primary anodes and limits its service life. However, zinc anodes can be easily replaced or replenished in

several configurations, thereby extending the service life of the system.

The ability to provide protective current is controlled by the resistivity of the concrete and the activation of the anode. The resistivity of the concrete can be maintained in a favorable range by the presence of moisture in the concrete or exposure to high humidity. Zinc may passivate or stop acting as an anode under certain conditions. To keep zinc active, high alkalinity or halide ions (chloride, bromide, or fluoride) are required. The alkalinity of concrete is generally high, although the surface is usually carbonated and pH is much lower than that observed in the interior. The aluminum–zinc–indium alloy was developed to avoid or minimize passivity in the application environment and provide a more negative potential to drive current through higher resistivity concrete. The majority of the zinc anode applications are in the marine environment where sufficient exposure to moisture maintains lower resistance and chloride ions are available to keep the zinc active. In non-marine environments, materials specifically designed to keep zinc active can be used for encapsulation.

Similar to the impressed current systems, the configurations used in the galvanic systems can be categorized as follows:

1. Surface applied,
2. Encapsulated, and
3. Non-encapsulated.

Zinc and aluminum–zinc–indium alloy can be surface applied using the arc spray technique. Zinc was also available in the form of a foil with adhesive that could be applied to the surface of the concrete. The surface-applied systems are generally used on the underside of bridge decks and superstructure elements such as beams, girders, diaphragms, and caps and substructure elements such as piles (above tidal zone), struts, columns atop footers, etc.

Expanded zinc mesh encapsulated in a cementitious material and contained in a fiberglass jacket that is installed

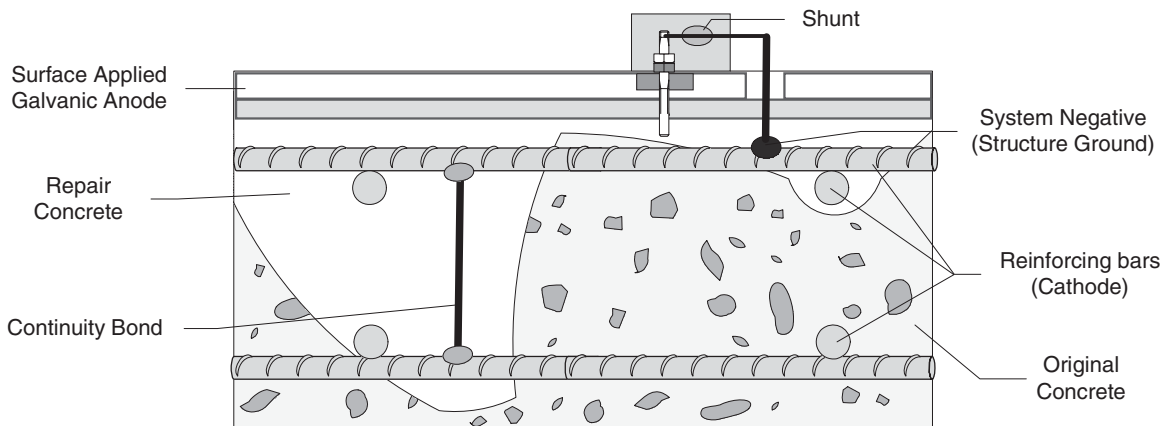


FIGURE 9 Schematic of a galvanic protection system.



FIGURE 10 Zinc foil and arc sprayed zinc systems.

around piles is an example of an encapsulated system. A representation of such a system is presented in Figure 11. The majority of the installations of such systems are on marine piles in tidal zones. These jackets in most instances are not limited to the tidal zone but are also used to protect the area just above the tidal zones. More recently, zinc anodes encapsulated in proprietary material designed to keep the zinc anode active (activated anodes) have also been used inside fiberglass jackets backfilled with cementitious material in non-tidal zones. The activated anodes are available in various shapes and sizes and have zinc at its core surrounded by the proprietary material.

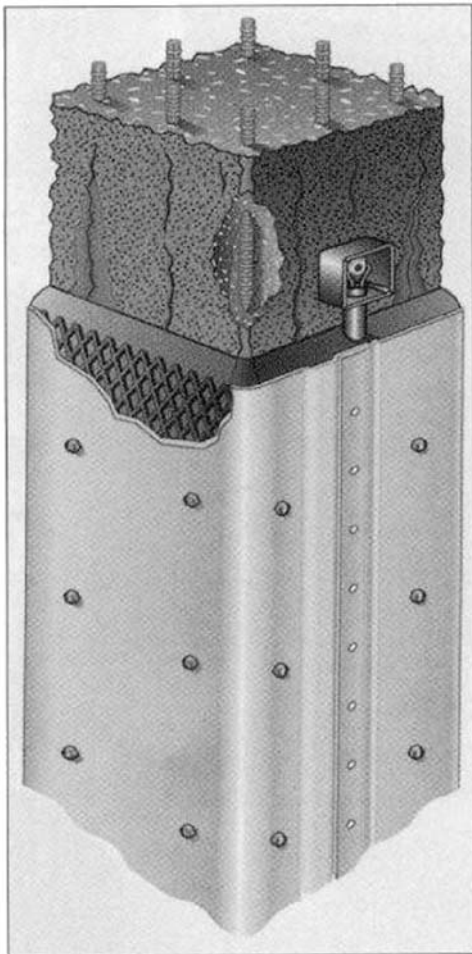


FIGURE 11 Expanded zinc mesh in jacket.



FIGURE 12 Hockey puck anode installation in repairs.



FIGURE 13 Expanded zinc mesh system without encapsulation with a zinc bulk anode.

owing to differences in pH and chloride ion concentration between existing concrete and the patch repair. A cylindrical configuration of this anode can be installed in excavations in concrete to provide local cathodic protection.

Perforated sheets, expanded mesh, and bulk anodes have been used in the marine environment without any encapsulation. In some instances, the perforated zinc or the expanded mesh anode were sandwiched between fiberglass or a recycled material panel and the concrete of the pile and held in place by compression bands (see Figure 13). The bulk anode is generally installed under water to supplement the protection provided by any of the other zinc anode configurations used on marine piles. The current requirement in the tidal zone can be very high and perforated sheets and expanded mesh zinc anodes, encapsulated or not, have a very high consumption rate in this region and need the bulk anode to keep their consumption rate to acceptable levels.

INSTRUMENTATIONS

The impressed current systems require a rectifier to provide power to the system. The rectifiers convert alternating current to direct current and supply it to the system. They also need circuitry to control the output, which can be regulated either by controlling the output voltage or the current. The current controlled systems are preferred. Some rectifiers also have potential control, whereby the potential of the reinforcement is measured and the output of the rectifier adjusted to maintain the potential or keep it under a given limit.

Most modern rectifiers come equipped with remote monitoring and control systems. These are used to remotely monitor the operation and the health of the system and control the output. Only remote monitoring systems are used in galvanic cathodic protection systems as these systems inherently cannot be controlled. The modern remote monitoring and control units can be accessed by means of telephone connection, cell phone, or the Internet and are capable of sending alarms when any of the system parameters stray out of the normal operating values.

Newer hybrid rectifiers can use an alternating current source, a battery, or solar power as input and provide controlled direct current output to the system. They have a built-in remote monitoring and control system and can also be used on galvanic systems for monitoring purposes.

Half-cell reference electrodes, specifically silver–silver chloride, are generally embedded in the concrete to monitor the potential of the protected steel. The shift in the potential of the protected steel owing to the application of the current is an indicator of the level of protection achieved. A NACE Standard Practice requires a 100 mV shift in the potential for complete stopping of corrosion (13).

Current probes and corrosion null probes can also be used to monitor the amount of cathodic current reaching the monitored area from the cathodic protection system. By measuring the current picked up by these probes, one can determine if sufficient current is distributed to monitored areas.

SELECTION AND DESIGN OF CATHODIC PROTECTION FOR REINFORCED CONCRETE BRIDGE STRUCTURES

The cathodic protection system must be matched to the structure material, its corrosivity (presence of chloride ions or carbonation), geometry, and the environment of use. The application of cathodic protection current results in the generation of alkalinity at the steel/concrete interface and is directly proportional to the current applied. This may accelerate the alkali–silica reaction if the aggregate is susceptible to it. Compared with an impressed system, a galvanic system is less likely to affect the alkali–silica reaction. When applying cathodic protection to high strength steels, caution must be exercised. If not properly designed and controlled, hydrogen gas can be generated at the metal surface which, when adsorbed in sufficient quantity, results in hydrogen embrittlement and subsequent failure of the steel. In impressed current systems, potential controlled rectifier systems are required when high strength steel is cathodically protected to avoid hydrogen embrittlement. Certain galvanic anodes such as zinc, which do not polarize the steel to hydrogen evolution potential, can be safely used on high strength steel. The reinforcement and all embedded metals to be protected must be electrically continuous or made so during installation as discontinuous metals can corrode owing to the discharge of current from their surface.

Chloride contamination of sound concrete is an important factor in selecting cathodic protection as an alternative. If the concentration and distribution of chloride ions in sound concrete is likely to result in corrosion initiation in the future, then none of the barrier systems are effective. Stopping additional ingress of chloride ions does not necessarily delay the initiation of corrosion as sufficient ions are already present. Electrochemical chloride extraction and cathodic protection are the only techniques that will not require removal of chloride contaminated concrete, which can result in significant cost savings.

Therefore, it is imperative that a concrete and corrosion condition survey be conducted to obtain the necessary information to match the appropriate cathodic protection to the structure.

As important as ascertaining the compatibility of cathodic protection is the selection of the appropriate type of system. The type and geometrical configuration of the anode is one of the most critical components in the success of a system. A particular application may preclude the use of some of the available anode materials. It is important that the selection of an anode material and configuration not impact the overall durability or the operating capacity of the structure; for example, it should not cause acid attack of the concrete or aggravate freeze–thaw damage, nor should it add additional dead load, which could result in reduction of its overall live load capacity or operating clearances.

Typically, a cathodic protection system is subdivided into smaller sections called zones to simplify control of the sys-

tem. It also permits the control of the system to be more responsive to actual corrosion conditions in various sections of the reinforced concrete elements and makes it easier to locate any problems that may occur. Standards limit a zone on a bridge deck to a maximum of 604 square meters (6,500 square feet) of concrete surface (9). In the case of bridge substructure systems, a single beam, piling, etc., may comprise a complete zone regardless of the concrete surface area. Each zone represents an independent cathodic protection system consisting of anode material, wiring, an external power source (if an impressed current cathodic protection system is used), connections to the reinforcing steel, and appropriate monitoring devices. When a rectifier is used in an impressed current system, it may be equipped with a control card so that the current, voltage, or potential in each zone can be controlled independently. The pre-design survey of the structure might include obtaining information that may affect the development of cathodic protection zones, installation and location of system components.

APPLICATION OF CATHODIC PROTECTION

BRIEF HISTORY OF USE IN NORTH AMERICA

The very first application of cathodic protection to reinforced concrete elements was reported in 1959 by Caltrans (5). During the late 1940s and the 1950s, Caltrans had spent more than \$1 million in repairing damage caused by corrosion on the 7-mile San Mateo–Hayward Bridge located in San Francisco and were forced to look for ways to control or stop corrosion. An experimental system was installed on the reinforced concrete beams of this structure. It used carbon rods and a conductive backfill, which were placed in wooden troughs and attached on to the concrete beams. Later, in 1972, based on this proof of concept, Caltrans installed a full-scale cathodic protection system on the deck of the Sly Park Bridge near Placerville, California (6). This system used silicon iron anodes embedded in a layer of coke breeze (see Figure 14). The coke breeze was used as a conductor to distribute the current uniformly over the bridge deck. As the coke breeze mix did not have the requisite material properties to serve as the riding surface, an overlay of asphalt was placed on top of the coke breeze. Based on the initial success at the Sly Park Bridge, Caltrans installed seven more asphalt–coke breeze overlay cathodic protection systems during 1974 and 1975. An evaluation of these seven bridge deck cathodic protection systems was performed and its report in 1981 established the feasibility of using such a system on bridge decks for mitigating corrosion (14).

With the application of the first system on Sly Park, the cathodic protection industry for reinforced concrete structures was born. Several concurrent efforts for developing new technologies and implementing the one demonstrated at Sly Park were initiated in the 1970s. A majority of these efforts focused on the implementation of cathodic protection on bridge decks. FHWA led the way with Demonstration Project 34 (DP-34), *Cathodic Protection for Reinforced Concrete Bridge Decks*, which began in 1975 and funded the installation of 14 asphalt–coke breeze systems by 1982 (15). Other reports indicated that by 1984 a total of 22 systems were operational in 11 states (16).

In 1976, MTO reported installation of asphalt–coke breeze systems on two structures; one was a ramp at a major interchange in Ontario and the other was the Duffins Creek Bridge. Ontario improved on the original design developed by Caltrans by changing the mix design of the coke breeze layer and making it more stable. In addition, they installed the anodes

and the wirings in cut outs on the reinforced concrete deck, thereby reducing their susceptibility to damage during replacement of the asphalt riding layer. By 1978, the asphalt–coke breeze overlay system had become one of the three standard procedures that MTO used for rehabilitation of reinforced concrete bridge decks and as many as 30 systems were installed by 1984 (17,18).

Although the basic concept of the asphalt–coke breeze system was sound and the systems (especially the designs employed by Ontario) were working well, the focus of the cathodic protection industry shifted to other materials and methods of installation, and these systems fell out of use in the United States. Recently, MTO also discontinued the use of this type of system. As slots cut on the deck surface provided a convenient mechanism to install anodes without adding any additional dead load, the focus of research and development shifted to anode and backfill materials that would be used in slots.

In the late 1970s, two separate efforts evaluated the application of zinc anodes in the form of ribbons and sheets in Illinois. The first effort evaluated zinc ribbons placed in longitudinal slots on the deck and backfilled with cementitious mortar and was conducted by the Illinois DOT. The anode spacings evaluated in this effort were 24 and 48 in., and this study concluded that the zinc ribbons were only capable of throwing the protective current to a distance of 3 in. on either side of the slot (19). The second effort was performed under NCHRP and it evaluated the zinc ribbons in the slot and zinc sheets on the surface of the deck. This effort was unable to come to any conclusions on the feasibility of using zinc on bridge decks as a cathodic protection anode material (20).

The platinum niobium wire that was commercially available became the next material of choice as the primary anode. It provided the necessary electrical properties, was durable, and could provide a reasonable service life. Research by FHWA and others indicated that spacing between slots not exceed 12 in. for effective current distribution by this anode material (21–23). The first evaluation of this system in 1977 used portland cement mortar as the backfill material and topped it off with a polymer modified mortar (21). The backfill material failed owing to the generation of gasses and acid at the platinum wire, which resulted in acid attack. Several other materials, such as a proprietary conductive cementitious non-shrink grout (24) and a conductive grout mixture,



FIGURE 14 Conductive coke breeze system with pancake anodes.

were tested and they too could not withstand the acid attack. An industry supplier proposed a calcined petroleum coke back-fill topped with a flexible sealant. Although this combination was able to withstand the acid attack it was not durable enough for use on bridge decks (15,21). Continued FHWA research led to the development of the conductive polymer grout, which was able to meet all the requirements needed of the backfill material (21,25).

From 1979 to 1984, slotted systems were installed on a total of 15 bridges distributed over 11 states. With the development of the FHWA conductive polymer grout, the number of bridges increased to more than 100 by 1989 (16). Missouri

led with the maximum number of installations. In Missouri, the earlier slotted systems were overlaid with asphalt. Later, the asphalt overlays were replaced by cementitious overlays. In 1985, one of the largest slotted cathodic protection systems was installed on the elevated sections of I-64 in Charleston, West Virginia. The system is still operational and the last time it was evaluated in 2005 it was found to provide adequate protection against corrosion (26). Figure 15 documents the installation of one such system.

The successes of the conductive polymer grout in the slots led to the development of the mounded system. The conductive polymer grout was laid out in a grid on the surface of the



FIGURE 15 Various stages of construction of a slotted FHWA conductive polymer cathodic protection system.



FIGURE 16 Construction of mounded conductive polymer cathodic protection system.

deck after deteriorated concrete was removed and patched and the deck was scarified (see Figure 16). The platinum wire was encapsulated in the grout in one direction of the grid and carbon fibers were used in the other direction of the grid. Carbon fiber was used to reduce the cost of the system. Latex-modified concrete or a conventional concrete overlay was then placed over the grid to provide a riding surface. The first such system was installed in 1983 on the 42nd Street Bridge in South Minneapolis, Minnesota. This system was monitored for five years under an FHWA research program and was found to be operational until July 1996. The evaluation in May 1998 suggested that the system had fallen into disrepair and was powered down (27). A few more of these systems were installed on bridge decks and one was installed in a parking garage.

For applications on concrete elements that are not subjected to traffic, conductive paint and mastics were developed in the late 1970s (28–31). The conductive coating type anode system completely covers the concrete surface and provides efficient current distribution. It is easy to install using a variety of common installation methods (spray, roll, or brush) and its low initial cost makes it a desirable system. The conductive coating is black, and a decorative overcoat latex paint is often required for safety and cosmetic purposes. NCHRP Project 12-19 identified several commercially available conductive paints that showed promise. The trial was conducted at a U.S. Army Corp of Engineers building at Ft. Lee, Virginia (31). The paint was used as a secondary anode and the platinum wire was used as the primary anode with the FHWA conductive polymer providing the electrical contact between the platinum wire and the paint. Since 1975, the Florida DOT (FDOT) has been involved in conductive paint and mastic cathodic protection work on pilings, piers, caps, beams, and deck undersides and its work also indicated that conductive paints and mastics can be a viable anode material (32). A follow-up NCHRP effort, Project 12-19B, was charged with further evaluation of conductive paint cathodic protection systems (28). This effort identified another conductive coating that was

judged as the best paint material tested and was used in a field application. In the early 1980s, MTO also conducted feasibility tests using different conductive coatings (33). At first, the conductive paints developed for other applications such as television tubes were used. Later, paints were specifically developed for use on reinforced concrete structures. The service life of the paint system is limited by the durability of the paint and its ability to weather. The durability of the paint in wet, freeze–thaw, and splash zones was a significant concern and was evidenced by the Ontario study in which the paint started to weather in 3 to 6 years. Conductive paint systems installed on two bridges in Virginia started to exhibit significant deterioration of the paint within 10 years of operation (27–34); however, properly designed and well-installed systems have provided adequate protection in humid environments (28,30,33). Conductive paints have performed much better in parking garage structures (35).

Arc sprayed zinc was developed as a conductive coating anode by Caltrans in 1983 and was used as an impressed current anode in the first field trial on Pier 4 of the Richmond–San Rafael Bridge located in San Francisco Bay, California (36). Using the arc spray technique, the application rate was significantly increased over the older flame sprayed method. In the arc sprayed technique, an electrical arc between two zinc wires is used to melt the metal, which is applied to the concrete surface by a stream of air. As this coating is a metal, it is very conductive and a limited number of electrical contact points to the power supply are required if used as an impressed current anode. Unlike the conductive paints, the zinc coating is comparable in color to concrete and requires no decorative overcoat. The second largest application of arc sprayed zinc is the Yaquina Bay Bridge in Oregon (37), where it has been used as an impressed current anode. Oregon was instrumental in the development of good specifications for the application of arc sprayed zinc systems and quality control. The section of the structure that was receiving the arc sprayed zinc was enclosed to control the environment for the application of the zinc coating and to contain the dust generated during concrete repair (see Figure 17). In the response to a survey question, the state of Oregon stated that “In Oregon, impressed current cathodic protection with arc sprayed zinc anodes appears to fill a niche market for the preservation of our historic bridges along the Pacific coastline. The effective life of the zinc anodes and the requirements for renewal or replacement of anodes is the subject of on-going research.” With the completion of ongoing construction, Oregon will have 1.17 million square feet of concrete under arc sprayed zinc cathodic protection making it the largest user of this type of system in North America.

FDOT started to use it on sub- and superstructure elements as a galvanic anode. By 2002, it had been applied to 13 bridges with a combined protected concrete surface of approximately 350,000 square feet (38). In a typical application, the system is installed without any concrete restoration and the connection to steel is achieved by applying the zinc directly on to



FIGURE 17 Yaquina Bay Bridge, Newport, Oregon, has the largest arc-sprayed zinc-impregnated current cathodic protection system.

the exposed reinforcement. The most common uses include structures where the deterioration is several feet above the tidal zone and on structures where only isolated areas need to be provided with corrosion control. The service life of this galvanic anode has been observed by FDOT to range from 5 to 10 years depending on the environmental conditions at the site, location above water level, and the type of reinforcement being protected.

The ferex anode became available in 1984. This anode used a copper conductor covered by a flexible polymer anode material. Woven into a mesh, the anode was placed on the deck or the substructure element and encapsulated by a cementitious overlay material. Up to 50 systems were installed on bridge decks. However, by 1990 many of these systems were exhibiting anode deterioration and the anode is no longer used (16). There were several reasons for the failure of this anode material, ranging from deficient system design to inability to withstand the high alkaline environment in the concrete.

FDOT developed the concept of conductive rubber and the rubber industry was able to manufacture it for use as an anode material. This rubber was produced as sheets with corrugation on one face and could be positioned on the pile surface and held in place by a compression jacket manufactured from fiber-reinforced polyester. The compression jacket used stainless steel bands to produce the requisite pressure to hold the system in place (see Figure 18). The first such system was installed in 1987 on the piles of a bridge carrying US-90 over the Intracoastal Waterway in Jacksonville, Florida. Results of 2 years of monitoring indicated uniform distribution of current on marine pilings (39). An update in 2002 reported that this system had been installed on three bridges and the systems were providing adequate protection (38). This system is no longer used owing to the availability of better alternatives.

The mixed metal oxide anode was developed in 1985 and has been used on both bridge decks and substructure elements.

This anode is composed of a titanium base upon which proprietary mixed metal oxides are sintered. The mixed metal-oxide catalyst is specific to the evolution of oxygen rather than chlorine, and the operating voltage is 0.5V below the theoretical voltage required to drive the oxidation of chloride ions to chlorine gas (40). This reduces acid attack on the concrete as a result of the generation of chlorine gas at the anode/concrete interface. The anode is supplied primarily in two forms: mesh and ribbon. In the mesh form, a titanium expanded mesh with diamond-shaped openings is used as a base and the mixed metal oxides are sintered on all exposed surfaces of the titanium. The mesh is supplied in 4-ft wide rolls, and can be installed on a horizontal or a vertical surface and is usually encapsulated in a cementitious overlay material. Power is supplied to the anode by means of titanium conductor bars welded to the anode at appropriate locations. The ribbon is available as either a solid ribbon or an expanded mesh ribbon and is usually installed in slots, which are then backfilled with a cementitious material. The first experimental bridge decks were constructed with this system between 1986 and 1987. Its first use on a substructure was in Ontario, Canada, where it was encapsulated with an acrylic polymer-modified



FIGURE 18 Conductive rubber anodes.

gunitite. Between 1985 and 1990, approximately 100 mixed metal oxide systems were installed on bridge decks and more than 3.9 million square feet of concrete surface area were protected (16). Field evaluation of the various mixed metal oxide mesh anodes on twin structures in Virginia was reported after approximately 7 years of operation. The authors concluded that these anodes most likely could have a service life in the range of 60 to 90 years based on the normal current densities required for reinforced concrete bridge decks (41).

In 1991, FDOT reported the use of perforated zinc sheets as galvanic anodes, which could be installed in the same fashion as the conductive rubber system (42). The zinc anodes were effective in providing the cathodic protection current; however, the high consumption rate of the zinc at high tide was unacceptable. To overcome this drawback at the next installation, on the B. B. McCormick Bridge in Jacksonville, Florida, a bulk zinc anode was added under the low water line to provide the majority of the current during high tide. Based on the success of this system, a full-scale installation was designed and installed in 1993 on the Bryant Patton Bridge (43). In 1996, FDOT reported on another improvement to the system by embedding the zinc perforated sheet in a cementitious material and creating a jacket. The expanded zinc mesh in a fiberglass jacket has been commercially available since then and is a standard system of use in Florida. To date these jackets have been used in 51 projects in Florida and have been installed on 1,782 piles. According to the material supplier, this system has been installed on more than 4,000 piles in the state of Florida, most of which are installed on structures that do not belong to FDOT. A more recent effort evaluated the performance and the condition of jacketed cathodic protection systems in Florida and found some evidence to suggest that this system can be expected to provide cathodic protection for approximately 20 years (44).

In 1996, a zinc foil with adhesive system was developed and was later marketed commercially (45). Arc sprayed titanium with a mixed metal oxide coating was first applied on the Depoe Bay Bridge located in Depoe Bay, Oregon, around 1996. This was an attempt to apply a successful anode material in a different form. The conductive ceramic anodes were developed in the United Kingdom and are now available in North America. Under an FHWA research project, the aluminum-zinc-indium alloy for use in galvanic cathodic protection systems was developed around 1998 (46). Around the same time, the activated zinc anodes became available commercially. These anodes use zinc as the core and encapsulate it with proprietary material. This ensures that the zinc remains active throughout its service life. They come in several different geometries for application in various different reinforced concrete components. The smaller anodes, designed for use in concrete repairs commonly known as hockey pucks, are increasingly being used in bridge repairs. Other geometries such as the cylindrical anodes for use in larger repair areas, as depicted in Figure 19, are now available.



FIGURE 19 Activated cylindrical anodes used for a repair.

FHWA provided funding for the installation of many of the experimental and trial cathodic protection systems through DP-34. It controlled the implementation of the technology from the early stages until the mid-1980s. After the joint committee of AASHTO, Association of General Contractors of America (AGC), and American Road and Transportation Builders Association (ARTBA) started the Guide Specification for Cathodic Protection of Concrete Bridge Decks in 1989, DP-34 ended. The guide specification prepared by this committee was published in 1994. While the FHWA was involved in the implementation of the cathodic protection, it mandated a certain level of design quality, quality control and assurance during installation, and provided technical assistance, after which, state DOTs became responsible for the design, installation, monitoring and maintenance of the systems. Several states such as California, Florida, Missouri, and Oregon developed in-house expertise in this technology and have been effectively using it to control their maintenance costs. Similarly, the provinces of Alberta, New Brunswick, and Ontario are also using this technology to control corrosion-induced damage on their reinforced concrete bridge structures.

In 1990, NACE developed a Standard Recommended Practice for Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures. The Strategic Highway Research Program (SHRP) published the SHRP-S-337 “Cathodic Protection of Reinforced Concrete Bridge Elements: A-State-of-the-Art-Report” in 1993 (16).

PRESENT USE OF CATHODIC PROTECTION IN NORTH AMERICA

A 1992 SHRP report documented the growth of the cathodic protection industry from 1973 until 1989, which is presented in Figure 20. Their survey results tallied a total of 287 cathodic protection systems applied to 200 bridges in North America (8). They estimated that the agencies that had not

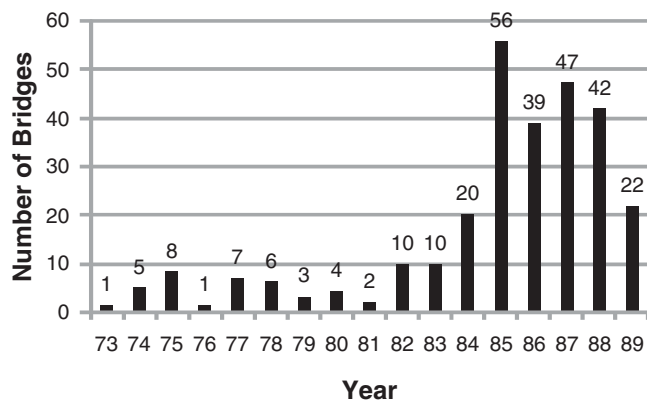


FIGURE 20 Number of cathodic protection system installations per year (1973–1989).

responded to the survey had an additional 20 systems installed on their bridges. In 1989, five states, California, Florida, New Jersey, Ohio, and Pennsylvania had between 6 and 20 cathodic protection systems installed and two agencies, Missouri and Ontario had more than 20 cathodic protection systems. Missouri had the most with 121 systems, and was followed by Ontario (44), New Jersey (18), California (17), and Ohio (14).

To determine the extent of use of cathodic protection systems at the time of this synthesis, two approaches were used; in the first approach, the NBI database was queried, and the second approach was to request the inventory of cathodic protection systems from the public agencies in the survey. It may be noted that the NBI only contains information on structures located in the United States. Item 108C of the NBI database requires the deck protection type to be listed. One of the several deck protection types that can be coded for is cathodic protection. The code for cathodic protection in this database for Item 108C is 4. Only cathodic protection systems installed on bridge decks can be input into the NBI database; systems installed on any other elements are not accounted for.

The results of the NBI query and the response of the survey are combined in Table 1. Of the 36 states in the United States which are known to have a cathodic protection system in the NBI database, 24 responded to the survey. Eight states that did not have any cathodic protection systems listed in the NBI database also responded. The state of Ohio responded; however, it did not have any information on inventory to provide.

A total of 375 deck cathodic protection systems are listed in the NBI database for structures located in the United States. The number of deck cathodic protection systems listed in the NBI database for states that responded to the survey is 309. However, the states in the survey reported a total of 279 deck cathodic protection systems. The difference in the numbers may be accounted for by cathodic protection systems that have been decommissioned, have failed, or the bridge decks have been replaced. For the state of New Jersey, the NBI database

has 22 bridges with a deck cathodic protection system; however, the survey response lists no bridges with cathodic protection systems. Similarly, for Illinois, the NBI lists 25 bridges with a deck cathodic protection system and the state reports 8 for the bridge decks. Missouri has 32 more deck systems than the listing in the NBI database. Ohio has coded a total of 29 bridges in the database. However, the state DOT at present does not have any information on the status of any impressed current cathodic protection system installed. At present they only use localized anodes in repairs. It is possible that some of the localized anodes installed in repairs have been coded as cathodic protection systems. There is no simple way to judge which of the two sets of numbers is more accurate, the NBI listing or the numbers reported by the states in the survey. It is assumed that the state responses are more accurate and that the coding in the NBI database may not reflect the actual conditions on the ground.

A total of 586 structures have cathodic protection systems installed in North America with 389 located in the United States and 197 in Canada. Of the 586 structures, 375 have cathodic protection systems installed on decks, 47 on superstructure elements such as beams and girders, 49 on caps, 83 on columns, 107 on piles, and 15 on footers. Twenty-five of the 36 respondents have cathodic protection systems installed on bridge structures. One respondent has no information available on the installed systems and, therefore, is not included in the count.

According to survey responses, Missouri has the highest number of bridges with deck cathodic protection systems, 161 of 375 (43%) and Ontario, New Brunswick, and Alberta have 40, 35, and 20 bridges, respectively. For superstructure elements, Oregon has 11 bridges and Alberta and Ontario have 10 bridges each out of a total of 47. Cathodic protection has been installed on caps of 49 structures, 10 of which are located in Alberta and 9 in Oregon. On piles, Florida has the most with 50 bridges (46%), followed by New Brunswick with 40 bridges (37%) out of a total of 107 bridges reported. Also, on footers, Florida has the most with 10 bridges out of the total 15 (67%).

Over the next 5 years, 159 new cathodic protection systems are being planned for installation by the responding agencies.

Table 2 provides the number of agencies that have a cathodic protection system on each type of bridge component. Bridge decks and columns appear to be the elements on which the vast majority of agencies have installed cathodic protection systems. These are followed by caps, superstructure elements, piles, and footers in descending order.

The distribution of the use of the various types of cathodic protection systems on various bridge components is listed in Table 3. This table documents the number of respondents using the particular system on each type of bridge element. In the impressed current category, the titanium mesh was found

TABLE 1
NUMBER OF CATHODIC PROTECTION SYSTEMS IN EACH STATE OR PROVINCE

State/Province	State Code	Responded to Survey	NBI	Reported Total	Deck	Superstructure	Caps	Columns	Piles	Footers
Alabama	AL	No	0							
Alaska	AK	No	2							
Arizona	AZ	Yes	0	1	0	0	0	0	0	0
Arkansas	AR	Yes	0	0	0	0	0	0	0	0
California	CA	Yes	6	20	12	1	0	6	1	1
Colorado	CO	Yes	13	6	6	0	0	1	0	0
Connecticut	CT	Yes	12	13	12		1			
Delaware	DE	No	1							
District of Columbia	DC	No	0							
Florida	FL	Yes	1	71	3	5	6	10	50	10
Georgia	GA	No	0							
Hawaii	HI	Yes	0	0	0	0	0	0	0	0
Idaho	ID	No	2							
Illinois	IL	Yes	25	15	8	3	2	1	1	0
Indiana	IN	Yes	20	15	15	0	0	0	0	0
Iowa	IA	Yes	13	6	3	2	0	1	0	0
Kansas	KS	No	5							
Kentucky	KY	No	0							
Louisiana	LA	No	0							
Maine	ME	No	1							
Maryland	MD	Yes	13	15	14	0	0	1	0	0
Massachusetts	MA	No	3							
Michigan	MI	No	5							
Minnesota	MN	No	1							
Mississippi	MS	Yes	1	0	0	0	0	0	0	0
Missouri	MO	Yes	129	167	161	0	0	2	0	0
Montana	MT	Yes	1	0	0	0	0	0	0	0
Nebraska	NE	No	8							
Nevada	NV	No	0							
New Hampshire	NH	No	2							

(continued)

TABLE 1
(continued)

New Jersey	NJ	Yes	22	0	0	0	0	0	0	0
New Mexico	NM	Yes	1	0	0	0	0	0	0	0
New York	NY	Yes	2	4	3	0	0	1	0	0
North Carolina	NC	Yes	0	3	0	0	2	2	1	2
North Dakota	ND	Yes	0	0	0	0	0	0	0	0
Ohio	OH	Yes	29							
Oklahoma	OK	Yes	2	0	2	0	5	15	0	0
Oregon	OR	Yes	8	11	9	11	9	7	0	0
Pennsylvania	PA	Yes	12	11	11	0	0	1	0	0
Puerto Rico	PR	No	0							
Rhode Island	RI	No	0							
South Carolina	SC	Yes	0	0	0	0	0	0	0	0
South Dakota	SD	Yes	3	12	8	0	3	1	0	0
Tennessee	TN	Yes	7	0	0	0	0	0	0	0
Texas	TX	Yes	8	1	1	4	5	5	3	2
Utah	UT	Yes	0	2	2	0	0	0	0	0
Vermont	VT	Yes	0	1	0	0	1	1	0	0
Virginia	VA	Yes	6	12	7	0	4	7	1	0
Washington	WA	Yes	3	3	2	1	0	0	0	0
West Virginia	WV	No	4							
Wisconsin	WI	No	3							
Wyoming	WY	Yes	1	0	0	0	0	0	0	0
Prince Edward Island, Canada	PEI-CA			2	1		1	1		
New Brunswick, Canada	NB-CA			85	35			10	40	
Nova Scotia, Canada	NS-CA									
Ontario, Canada	ONT-CA			60	40	10		10		
Alberta, Canada	AL-CA			50	20	10	10	0	10	0
Totals			375	586	375	47	49	83	107	15

Note: Table based on results of Questions 20 and 21 of the survey and data mined from the NBI Database.

TABLE 2
USE OF CATHODIC PROTECTION
ON VARIOUS BRIDGE COMPONENTS

Cathodic Protection Installed on Bridge Components	No. of Respondents
Deck	22
Superstructure	9
Caps	12
Columns	19
Piles	8
Footers	4

Note: Table based on results of Question 21 of the survey.

to have been used on all bridge components by the greatest number of agencies. Arc sprayed zinc was reported as the second most used system. However, more applications of it are found to be on caps and columns. The conductive paint has been used on all bridge components, with the exception of the bridge deck and is the third most used system.

The point zinc anodes (hockey pucks) lead the galvanic cathodic protection category by a wide margin and have been used on all bridge components, most often on columns, caps,

and decks. Arc sprayed zinc comes in a distant second and also has been used on all bridge components, most often on columns. The third contender is the arc sprayed aluminum–zinc–indium alloy and it also has been used on all bridge components. The zinc foil has been used on all components other than the struts and the footers.

INTERNATIONAL USE OF CATHODIC PROTECTION

Around 1984, European countries started to recognize the magnitude of the corrosion problem and, in 1985, the United Kingdom began an evaluation of the technology. Since then, 2.15 million square feet of concrete surface has been protected using various different types of cathodic protection systems. In Northern Europe, Denmark leads with more than 60 installations, with 8 to 10 installations added each year. At present, the majority of the cathodic protection systems are being installed on swimming pools. Two manufacturers of remote monitoring and control systems for cathodic protection are located in Denmark, and one of them is also an anode supplier. Conductive coating systems are a norm in Norway and four bridge structures have been protected in the last 8 years. In Norway, the installation activity is more focused on parking structures. Several tunnels and bridges have received cathodic protection in Switzerland and the area protected in 1997 was estimated to be more

TABLE 3
TYPES OF CATHODIC PROTECTION SYSTEMS USED BY RESPONDENTS

Bridge Elements	Impressed Current Cathodic Protection										Galvanic Cathodic Protection						
	Arc Sprayed Zinc	Arc Sprayed Titanium	Arc Sprayed Alloys	Conductive Paint	Ferex Anode	Ceramic Anode	Conductive Polymer	Titanium Mesh	Titanium Ribbon	Other	Arc Sprayed Zinc	Arc Sprayed Alloys	Hockey Puck Zinc Anodes	Zinc Foil Anodes	Jackets with Expanded Zinc Mesh	Zinc Bulk Anode	Other
Bridge Decks	2	1	0	0	0	3	5	12	5	2	1	1	7	1	0	1	3
Beams, Girders, and Diaphragms	1	1	0	1	0	0	1	2	0	0	4	3	4	3	1	1	0
Caps	5	0	1	3	0	0	1	3	0	0	4	4	9	3	0	0	0
Columns	5	0	1	3	0	1	1	4	0	0	8	5	12	4	2	2	0
Piles	0	0	0	1	0	0	0	1	1	1	2	2	2	2	3	7	1
Struts	1	0	0	2	0	0	1	1	1	0	3	1	3	0	0	0	0
Footers	1	0	0	2	0	1	1	1	1	0	2	1	1	0	0	2	1

Note: Table based on results of Question 22 of the survey.

than 107,000 square feet. Italy has installed cathodic protection on 1.6 million square feet of deck surface of new bridges containing prestressing elements. The British Standard Institute has developed a standard for the use of cathodic protection technology in Europe.

As early as 1996, Australia and Hong Kong started to use cathodic protection. In Australia, a number of bridges, wharves, and other structures, including the supports of the Sydney Opera House, have received cathodic protection. With Hong Kong's large coastal exposure, several bridges

and wharves have received cathodic protection. South Korea, Singapore, and Japan also have a few installations. China began using cathodic protection on structures built for the 2008 Olympics. Some activity is also underway in India.

One of the largest reinforced concrete cathodic protection systems to be installed in the Middle East is the titanium mesh anode system installed in Yanabu, Saudi Arabia, in 1987. Since then, many new and old structures in the Middle East have received cathodic protection. The total protected area is estimated to be in excess of 5.4 million square feet.

CATHODIC PROTECTION USE: POLICIES AND PRACTICES

To obtain a more complete understanding of the use and the application of cathodic protection technology, the corrosivity of the environment, the decision-making process, and the application and use of cathodic protection systems need to be analyzed. As cathodic protection technology is relatively more expensive than the other alternatives, with the exception of electrochemical chloride extraction, the perception of corrosivity of the environment is very important in justifying its use. Similarly, if the decision-making processes for repair and rehabilitation either are not sophisticated enough or do not include cathodic protection as an alternative, then the use of the technology would be limited. The design, installation and quality control, and monitoring and maintenance practices have a significant impact on the experience of use of this technology. The survey conducted in this effort focused several questions in these areas. A summary of the responses is presented here.

MAGNITUDE OF THE PROBLEM

A summary of responses to the question regarding the magnitude of the corrosion problem faced by the agency is presented in Table 4. Mississippi is the only state among the respondents that does not have a corrosion problem on its reinforced concrete bridge structures. Four respondents (Arizona, Indiana, New Jersey, and Wyoming) indicated that it was a minor problem. A majority of respondents consider it to be a moderate problem. Eight respondents, Connecticut, New York, Oklahoma, Oregon, Pennsylvania, Utah, Vermont, and Virginia, consider it to be a major problem.

Table 4 indicates that corrosion is at least a moderate problem for 30 of 36 respondents. Considering that many states and several Canadian provinces that experience severe winters did not respond to this survey, the actual corrosion problem must be much more severe than that suggested by the responses received in this effort.

Interestingly, the top five users of the cathodic protection technology, Missouri, New Brunswick, Florida, Ontario, and Alberta have classified their corrosion problem as moderate. Thus, it is reasonable to conclude that cathodic protection could be an applicable tool for a majority of the agencies, based on the magnitude of their corrosion problem. However, many agencies now use epoxy-coated rebar and at least one state has questioned the applicability of cathodic protection on the rebars.

The perception of the magnitude of the corrosion problem correlates reasonably well with their deicing salt use. From the four agencies that indicated that corrosion was a minor problem, two have salt use in the range of 0 to 5 tons and two in the range of 6 to 10 tons per lane-mile per year. Eight of the respondents that indicated that corrosion is a moderate problem use 0 to 5 tons per lane-mile per year. Of the remaining, 4 agencies use 6 to 10, 4 agencies use 11 to 15, and 2 agencies use 16 to 20 tons per lane-mile per year of deicing salts. Four respondents did not provide their deicing salt usage and one only has marine exposure. Three of the eight respondents that consider corrosion to be a major problem, Connecticut, Oklahoma, and Oregon, have salt use in the range of 0 to 5 tons per lane-mile per year. Oregon's primary exposure condition is the marine environment along the Pacific Coast. Of the agencies that indicated it was a major problem, the state of Virginia uses 6 to 10, Utah and Vermont use 11 to 15, and New York and Pennsylvania use more than 20 tons per lane-mile per year of deicing salt.

A summary of salt usage agencies is presented in Table 5. The majority of the respondents, 17 of the 32 agencies that provided salt usage information, have average salt usage in excess of 5 tons per lane-mile. The manner in which the *SHRP Methods Application Manual* (47) categorizes salt use implies that salt use of more than 5 tons per lane-mile is the highest category of use. Based on the *SHRP Manual*, a majority of the respondents are in the high usage category.

The relationship between deicing salt use and the magnitude of the problem can be a simple one. However, the analysis is difficult to perform because (1) deicing salt data available from various sources are often incomplete; (2) data are often not compiled in a uniform manner; (3) deicing salt use varies from one part of the state to another; (4) the number of bridges vary from one part of the state to another; (5) the exposure is a combination of deicing salts and marine environment; and (6) some of the states or portions of the states may be using non-chloride-bearing deicing salts. The climatic conditions can also have a significant impact on the rate of corrosion and the diffusion of chloride ions into the concrete and thereby influence the relationship between deicing salts and magnitude of the problem. For example, in every cold environment, although salt usage is much higher, the colder temperatures maintain corrosion at much lower levels.

TABLE 4
MAGNITUDE OF THE
CORROSION PROBLEM

Magnitude of Corrosion	No. of States
Not a Problem	1
Minor	4
Moderate	23
Major	8
Total	36

Note: Table based on results of Question 4 of the survey.

TABLE 5
SALT USAGE

Tons Per Lane-Mile Per Year	No. of Respondents
None	1
0 to 5	14
6 to 10	7
11 to 15	6
16 to 20	2
>20	2

Note: Table based on results of Question 7 of the survey.

EXPOSURE CONDITIONS

For bridge decks the primary chloride exposure is deicing salts. Twenty-one respondents indicated that more than 70% of decks are exposed to deicing salts and 13 of those stated that all of their decks (100%) are exposed to deicing salts. A summary of exposure environments is presented in Table 6. The province of Prince Edward Island listed 100% of its bridges in the “Both” category; that is, exposed to both the deicing salts and the marine environment. Only Mississippi has more than 90% of its decks categorized as “Neither,” which correlates well with their perception of the corrosion problem.

Understandably, the substructure exposure to deicing salts is lower than that of the bridge decks; only 6 of the 13 respondents (with 100% of bridge decks exposed to deicing salts) reported that all of their bridge substructures are exposed to it. The deicing salt exposure to substructure elements comes in two forms: (1) leakage of chloride-contaminated water through joints and (2) drains and splashing of the contaminated solution onto the substructure elements by vehicles in the underpass. The substructure elements confront a

more corrosive exposure when they are located in a marine environment. It may be noted that for the purpose of the survey, marine exposure was defined to persist 2 miles around a saline body of water. In addition to Mississippi, Washington State has more than 90% of its substructures listed as “Neither.”

PROCESS FOR SELECTION OF CORROSION MITIGATION ALTERNATIVES

To ascertain the compatibility and the cost-effectiveness of a cathodic protection system on a reinforced concrete structure, among other things, it is important that the severity of exposure, the presence of chloride ions in sound concrete, the presence of electrical continuity, the susceptibility of the concrete to alkali-silica reaction and freeze-thaw damage, and the presence of corrosion activity in sound areas be known. Analysis of test methods used by respondent agencies during Routine Bridge Inspection and corrosion condition evaluation was performed and is summarized in Table 7.

TABLE 6
DISTRIBUTION OF BRIDGES BASED ON EXPOSURE CONDITION

% of Bridges	Bridge Deck Exposure				Substructure Exposure			
	Marine Exposure	Deicing Salt Exposure	Both	Neither	Marine Exposure	Deicing Salt Exposure	Both	Neither
5-9	26	6	32	21	24	8	33	14
10-19	2	1	1	2	4	1	1	1
20-29	4	0	1	1	5	2	0	1
30-39	0	3	0	2	0	5	0	0
40-49	0	1	0	1	0	4	0	3
50-59	2	2	0	2	2	4	0	2
60-69	0	2	0	1	0	1	0	3
70-79	0	2	0	1	0	0	0	3
80-89	0	1	0	2	0	2	0	2
90-99	0	2	0	1	0	2	0	4
100	1	16	1	1	1	7	1	2

Note: Table based on results of Questions 5 and 6 of the survey.

TABLE 7
TEST METHODS USED

Test Method	No. of Respondents	
	Routine Bridge Inspection	Corrosion Condition Evaluation
Visual Survey	36	29
Crack Survey	19	16
Delamination Survey	21	29
Chloride Ion Content Analysis	4	28
Half-cell Potential Survey	4	23
Carbonation Testing	0	3
Electrical Continuity Testing	2	6
Corrosion Rate Measurement	0	2
Concrete Resistivity Testing	1	3
None	0	1
Other	0	2

Note: Table based on results of Questions 8 and 9 of the survey.

All agencies perform a visual survey during the Routine Bridge Inspection and a majority of them perform delamination and crack surveys. Only a few perform chloride ion content analysis, half-cell potential survey, electrical continuity testing, and concrete resistivity measurements. The testing protocol used by the majority of the agencies would provide a good measure of the symptoms of corrosion, rust staining, cracking, delamination, and spalling, and would reasonably indicate the overall condition of the structure and provide a basis for more in-depth evaluation. During an in-depth survey or corrosion condition evaluation, the vast majority of the agencies perform a visual survey, delamination survey, chloride ion content analysis, and half-cell potential survey. Thus, information on the extent of chloride contamination and the presence of active corrosion is also being determined during these evaluations. Only a few agencies conduct electrical continuity; three perform carbonation testing, one considers petrographic analysis on select projects, and one uses corrosion rate measurements. North Dakota does not perform corrosion condition evaluation and only performs the visual survey during the Routine Bridge Inspection. Generally reinforcing steel on a bridge deck is electrically continuous, and therefore, electing to test for continuity during the installation of the cathodic protection system is acceptable. However, ascertaining the susceptibility to alkali-silica reaction could be performed during the selection process, unless based on materials used in standard concrete mixes the susceptibility is already known. Similarly, susceptibility to freeze-thaw could be ascertained during the selection of the alternative corrosion mitigation systems.

A majority of the agencies have standard procedures, protocols, or methodologies for conducting corrosion condition evaluations, analyzing the data collected during the evaluations, and selecting repair and corrosion control alternatives

based on the data collected during the evaluations. Sixteen agencies include cathodic protection as an alternative in their selection process (see Table 8). Of the agencies that cited the corrosion problem as a major one, four, Connecticut, New York, Oregon, and Pennsylvania, include cathodic protection as one of the options, but Oklahoma, Utah, and Virginia do not. Eight respondents stated that their agencies included cathodic protection as an alternative because it provides service-life extension desired for many of the high use structures and/or its agency staff has significant success in the use of the technology. The province of New Brunswick includes it, as it does not have any alternatives for the severe exposure conditions its structures have to withstand.

The quantity of damage was reported by 16 agencies to be the determining factor for the selection of a corrosion control system and the cost of application and repair was identified by 6 agencies (see Table 9). Only four agencies reported that the presence of chloride ions would be the determining factor and, for three respondents, the extension in service life was the determining factor. All other choices in the list were picked by two or fewer respondents. These responses suggest that the procedures, protocols, and methodologies used by these agencies may not be effectively using the data obtained during surveys to properly select a corrosion mitigation system. The quantity of damage signifies the magnitude of the problem and not its cause. It is more appropriate for the selection of the repair; however, it would have to be the presence and distribution of chloride ions in the remaining sound concrete that would control which corrosion control system would be the most effective and viable in that application.

Twenty-three agencies have or would consider cathodic protection for its ability to prevent future damage and to substantially extend the service life (Table 10). Recommendations of their own agency research and development efforts have encouraged the use of cathodic protection for many agencies. The cost of other alternatives, the level of chloride

TABLE 8
USE OF PROCEDURES, PROTOCOLS, AND METHODOLOGIES

Questions	Yes	No
Are there agency-wide standard procedures, protocols, or methodologies for conducting corrosion condition evaluations of reinforced concrete structures?	18	18
Does your agency have procedures, protocols, or methodologies to analyze the data collected during condition evaluation?	20	16
Does your agency have procedures, protocols, or methodologies to select repair and corrosion control alternatives based on data collected from condition evaluations?	20	16
If your agency has procedures, protocols, and/or methodologies to select repair and corrosion control alternatives, does it include cathodic protection?	16	17

Note: Table based on results of Questions 10 to 12 and 14 of the survey.

TABLE 9
FACTORS MOST LIKELY TO DETERMINE WHICH
CORROSION CONTROL SYSTEM WILL BE SELECTED

Factors	No. of Respondents
Quantity of Damage	16
Presence of Chloride Ions	4
Extension of Service Life	3
Life-Cycle Costs	2
Cost of Repair and Rehabilitation	6
Disruption in Bridge Operation	0
Structure Type	0
Funds Available	1
Consultant Familiarity with Corrosion Control System	0
Past Experience with Corrosion Control System	2
Agency Practice	2
Agency Research Findings	0

Note: Table based on results of Question 13 of the survey.

ion contamination, and the location of the structure were also considered by several agencies as reasons for its use. The summary in Table 11 indicates cathodic protection has been used when service life in excess of 20 years was desired if the structure was located in a very aggressive environment, if no other alternatives are available, or if it is located in a marine environment.

TABLE 10
REASONS FOR WHICH CATHODIC PROTECTION
WAS CONSIDERED

Reason	No. of Respondents
Quantity of Concrete Damage	9
Level of Chloride Ion Contamination	12
Cost of Other Alternatives	13
Prevention of Future Damage	22
Agency Research and Development Recommendation	13
Funding Available from Other Sources such as FHWA or Congressional Mandate to Use Cathodic Protection	10
Location of Structure	11
Structure Type	8
Severity of Exposure	11
Extension of Service Life Provided by Cathodic Protection	23
Life-Cycle Cost Analysis	6
Consultant Recommendation	1
FHWA Recommendation	3
Experience with Cathodic Protection	7
Other	4

Note: Table based on results of Question 18 of the Survey

TABLE 11
CATHODIC PROTECTION USED FOR THE FOLLOWING
REASONS

Reason	No. of Respondents
Marine environment where exposure is very corrosive and no other corrosion control system provides service life extension of more than 5 years	8
Deicing salt exposure that has resulted in high and uniform chloride ion contamination and no other corrosion control system is expected to provide service life extension of more than 5 years	9
Life-cycle cost of cathodic protection system was lower than any other corrosion control system	3
Cathodic protection system was expected to provide service life extension in excess of 20 years	13
Location of the structure required use of an aggressive corrosion protection system	10
Type of structure	7
Other	6

Note: Table based on results of Question 29 of the survey.

Funding from other sources has encouraged the use of the technology for some agencies and their experience with the technology only encouraged its use in seven agencies. This last response raises a question; what has been the experience of user agencies with cathodic protection systems? The summary of responses in Table 12 provides some answers to this question; nine agencies do not include cathodic protection as an alternative corrosion mitigation system in their procedures, protocols, and methodologies for selecting repair and corrosion control alternatives owing to disappointing past experience and eight agencies do not use it because it is more

TABLE 12
REASONS FOR NOT INCLUDING CATHODIC PROTECTION
AS AN ALTERNATIVE CORROSION CONTROL SYSTEM

Reason	No. of Respondents
Exposure environment is not sufficiently corrosive to warrant the use of cathodic protection	4
Cathodic protection technology is relatively more expensive than other options available	8
Engineers and contractors that serve the agency do not have any experience with the technology	5
Cathodic protection is too complicated and the agency does not have sufficient understanding to use it	3
Past experience with cathodic protection has been disappointing	9

Note: Table based on results of Question 15 of the survey.

expensive than the other options available. Some agencies do not have the requisite expertise and a few others find the technology too complicated. Of the agencies that have never used or have not used cathodic protection in the last 5 years, 18 responded in the affirmative that they would consider it in the future, whereas 7 responded in the negative.

CORROSION MITIGATION TECHNOLOGIES IN USE

The survey also tried to identify what other corrosion mitigation technologies the respondents are using. Table 13 summarizes the various kinds of corrosion control systems that agencies use on new and existing structures. Sealers and concrete overlays are used by a majority of the agencies on both new and existing structures. Waterproofing with asphalt overlay is primarily used on new structures and waterproofing membranes are used on both. Admixed corrosion inhibitors, galvanic cathodic protection, and surface-applied inhibitors are used by a decreasing number of agencies, especially for new structures. Impressed current cathodic protection is used by a single agency as a prevention technology. On existing structures, localized zinc point anodes, galvanic cathodic protection, impressed current cathodic protection, admixed corrosion inhibitors, and surface-applied corrosion inhibitors are used by a decreasing number of agencies. The trend indicates that agencies are choosing the simplest options with minimal or no monitoring and maintenance requirement. Electrochemical chloride extraction is used by five agencies. Four technologies were listed in the “Other” category for new structures: polyester concrete overlay, thin-bonded

TABLE 13
CORROSION CONTROL SYSTEMS USED BY RESPONDENTS

Corrosion Control Technologies	No. of Respondents	
	Used on New Structures	Used on Existing Structures
Waterproofing Membranes	16	18
Waterproofing with Asphalt Overlay	17	
Sealers	27	28
Concrete Overlays	23	29
Specialty Concrete		9
Coatings on Rebars in Repair Areas		12
Admixed Corrosion Inhibitors	12	13
Surface Applied Corrosion Inhibitors	6	10
Localized Zinc Anodes (hockey pucks)		19
Impressed Current Cathodic Protection	1	13
Galvanic Cathodic Protection	7	15
Electrochemical Chloride Extraction		5
Other	4	2

Note: Table based on results of Questions 16 and 17 of the survey.

overlay, epoxy-coated rebars, and fiberglass-reinforced polymer reinforcing bars. Although not included as an option, epoxy-coated reinforcing bars are also a corrosion control system and are primarily used in new structures; however, a few agencies indicated it is the other option for both new and existing structures. Wyoming also uses crack healers and sealers on existing structures.

IMPLEMENTATION OF CATHODIC PROTECTION SYSTEMS

As indicated in Table 14, only six agencies have standards for design and/or construction specifications governing the use of cathodic protection on reinforced concrete structures. Designs of cathodic protection systems are generally performed by agency staff and some of the respondents obtain assistance from a consultant. Some of the agencies that indicated that they use in-house staff to design cathodic protection systems may not have staff with sufficient qualifications, and at least one has indicated that all systems they have installed have failed. A NACE-certified Cathodic Protection Specialist is involved in the design of the cathodic protection system through a consultant only for a few agencies and some agencies use consultants who work in conjunction with the material manufacturer or supplier. Rarely is a consultant asked to design a system based on Agency Standards and Construction Specifications or a contractor/installer charged with design responsibilities. For cathodic protection systems to perform as desired it is imperative that the design be performed by qualified and experienced personnel using current recommended or standard practice. NACE has a Standard Practice, NACE SP0290-2007, available and it recommends that such activities be performed under the direction of a registered professional engineer or a certified NACE corrosion specialist or cathodic protection specialist. It is important that

TABLE 14
DESIGN PROTOCOLS AND DESIGN RESPONSIBILITY

	Yes	No
Does your agency have any standards for design and/or construction specifications governing the use of cathodic protection on reinforced concrete structures?	6	18
Design of cathodic protection systems are normally performed by:		
Agency Staff	13	
Consultant—Engineering Firm with Access to NACE-Certified Cathodic Protection Specialist	6	
Consultant—Engineering Firm with Assistance from Manufacturer and/or Installer	8	
Consultant—Engineering Firm Based on Agency Standards and Construction Specifications	1	
Contractor or Installer	1	
Agency Staff in Conjunction with Consultant	8	

Note: Table based on results of Questions 23 and 24 of the survey.

the designer's professional experience include suitable experience in cathodic protection of reinforced concrete structures. Although manufacturers and installers of the systems have an intimate knowledge of their products, design by third parties is preferred to allow for a more robust analysis of the suitability of the various systems available for the subject project and the avoidance of any conflict of interest issues. As is the practice in the design of civil structures, it is important that the manufacturer's and installers be consulted and their assistance used by the third-party designers to ensure that the full knowledge of the system is brought to bear on the design.

All cathodic protection systems on bridge structures in Washington State (a total of 3) have been installed using design-build contracts. Colorado, with six reported systems, has used design-build contracts on 50% (3) of them. One of the major users of this technology, New Brunswick, uses such contracts on 20% of its projects and another large user, Florida, uses it on 2% of its projects. This survey result appears to be in contrast to the responses received from the industry, which indicated that 50% of the cathodic protection projects are design-build. In general, the design-build contracts are awarded to general contractors with cathodic protection materials supplier and/or installer as a subcontractor (Table 15). To obtain the desired performance it is imperative that the design-build contractor be required to possess or have access to the skill sets and experience described by the NACE SP0290-2007 Standard Practice.

Table 16 shows that the responsibility for quality control during installation is often carried out by the agency staff and less frequently by the contractor, manufacturer, or installer. An independent NACE-certified or a qualified inspector or a NACE-certified inspector hired through a consultant is used infrequently. Agency staff performing the quality control is most desired; however, agency staff must have the requisite qualification and experience to do the job. Quality control by a contractor, manufacturer, or installer is not desirable unless they are required to provide an independent qualified and experienced inspector who can certify that the project was installed in accordance with the project specifications.

TABLE 15
FREQUENCY OF DESIGN-BUILD CONTRACTS

	Yes	No
Cathodic Protection Projects Bid Out as Design-Build	5	19
Projects Generally Awarded to:		
Cathodic Protection Materials Provider and/or Installer	0	
General Contractors with Cathodic Protection Materials Supplier and/or Installer as Subcontractor	6	
General Contractor with an Independent Cathodic Protection Consultant	1	
Other	2	

Note: Table based on results of Questions 25 and 26 of the survey.

TABLE 16
QUALITY CONTROL DURING INSTALLATION

Performed By	Yes
Agency Staff	18
Consultant—Engineering Firm with NACE-Certified Personnel	4
Consultant—Engineering Firm	1
Contractor, Manufacturer, Installer	8
Independent NACE-Certified or Qualified Cathodic Protection Inspector	3
No One	0

Note: Table based on results of Question 27 of the survey.

Connecticut, Florida, Indiana, Vermont, and Prince Edward Island monitor all cathodic protection systems under their jurisdiction as depicted in Table 17. The California, Missouri, Ontario, and Oregon DOTs monitor a majority of the systems. New Brunswick indicated that it does monitor its cathodic protection systems, but did not indicate how many of its systems it does monitor. All other responding agencies do not monitor the cathodic protection systems they have. Monitoring of the systems is absolutely imperative to its continued performance, as unmonitored systems essentially mean non-performing systems.

Table 18 suggests that the majority of the agencies that monitor their cathodic protection systems use agency staff for that purpose. In some agencies, agency staff and a contractor monitor the systems. Nine agencies have at least one trained person to monitor and maintain their systems and seven agencies believe that they have sufficient personnel to perform the job (Table 19). Seven agencies have a program in place to monitor and maintain their cathodic protection systems and five use consultants on a regular basis. Remote monitoring units are used by eight agencies. The frequency of remote monitoring; that is, remotely connecting to the system and obtaining a status report, might be performed at least once a month for impressed current cathodic protection systems. The remote monitoring system is to be set to obtain system parameters at

TABLE 17
NUMBER OF BRIDGES BEING MONITORED

Agencies	No. Monitored	No. of Systems
Prince Edward Island, Canada	2	2
New Brunswick, Canada	N/A	85
California	10	20
Connecticut	13	13
Florida	71	71
Indiana	15	15
Missouri	96	167
Ontario, Canada	40	60
Oregon	9	11
Vermont	1	1

N/A = not available.

Note: Table based on results of Question 32 of the survey.

TABLE 18
CATHODIC PROTECTION MONITORING

Performed By	Yes	No
Agency Personnel	14	22
Contractor	1	35
Both	6	30

Note: Table based on results of Question 33 of the survey.

least once a day. The results in Table 20 show that only three agencies meet this criterion. The frequency for galvanic systems can be as little as once a year. The recommended frequency for site visits to ascertain the condition of impressed current systems is once a year and galvanic cathodic protection systems about once every 5 years. Ten agencies meet the impressed current criteria.

CASE HISTORIES

Several agencies have adopted cathodic protection technology as one of several bridge preservation tools. Five case studies are presented in this section. These case studies highlight various mechanisms that agencies have used to successfully implement corrosion mitigation technologies, not just cathodic protection, thereby reducing their maintenance costs and increasing the average service lives of their bridge structures.

Missouri

In Missouri all bridge decks and 35% of substructure elements are exposed to deicing salt. The state's corrosion problem is characterized as moderate and its average salt usage rate is the range of 0 to 5 tons per lane-mile per year. Their initial experience with cathodic protection technology was gained in the 1970s during the installation of three conductive coke breeze cast iron anode cathodic protection systems. These cathodic protection systems were installed during ongoing regular construction projects and were funded by

TABLE 19
RESOURCES FOR MONITORING AND MAINTENANCE
OF CATHODIC PROTECTION SYSTEMS

	Yes	No
Does your agency have any personnel trained to monitor and maintain cathodic protection systems?	9	15
Does your agency have sufficient trained personnel to monitor and maintain all cathodic protection systems under your jurisdiction?	7	17
Does your agency use consultants on regular basis to monitor and maintain cathodic protection systems?	5	19
Does your agency have a program in place to monitor and maintain the cathodic protection systems?	7	17
Are remote monitoring units used to monitor some or all of the cathodic protection systems?	8	16

Note: Table based on results of Questions 34 to 38 of the survey.

TABLE 20
FREQUENCY OF MONITORING

Remote Monitoring		Site Visits	
Once a week	2	Once every three months	0
Once a month	1	Once every six months	5
Twice a year	1	Once every year	5
Once a year	4	Once every two years	8
		Once every five years	1

Note: Table based on results of Questions 39 and 40 of the survey.

DP-34. These systems were based on the Caltrans design of the same era. Two engineers in the Missouri DOT (MDOT) became familiar with the technology. One of them specialized in the construction/electrical area and the other in the materials engineering field. The success of these first installations sufficiently impressed the DOT's Bridge Engineer to champion the use of this technology. The department's policy was modified to include the use of cathodic protection technology. At present, there are 167 bridge structures in the state with operational cathodic protection systems. The oldest operating system in the state, slotted with platinum-niobium wire anode, is 23 years old.

MDOT created a formal team to handle cathodic protection technology under their Materials Group. This team was charged with the selection, design, installation, and operation of all cathodic protection systems in the state. For training purposes, the DOT sent personnel to a cathodic protection training course conducted by a private organization. The DOT staff also received in-house training and additional training from workshops conducted under the SHRP Showcase Program and Demonstration Project 84. In 2000, as the districts acquired many of the required skill sets in the use of this technology, the formal team was dissolved. The Research Group and the Central Bridge Design Office now have one expert each in this technology area. In the districts, there are approximately 12 full-time dedicated personnel for monitoring the installed systems. Personnel from diverse technical backgrounds such as Traffic Signal Electricians, Traffic Engineers, Bridge Maintenance Engineers, and Construction Inspectors have acquired cathodic protection expertise. The Traffic Engineers and Signal Electricians use electrical and electronic systems quite similar to those used in impressed current cathodic protection systems and, therefore, are easily trained to perform monitoring and maintenance tasks. The Bridge Maintenance Engineers handle the regular maintenance required on the systems and the Construction Inspectors provide quality control and assurance during installation. This philosophy has allowed MDOT to use their available in-house resources to implement the cathodic protection technology. Funding for all cathodic protection work comes from the general maintenance fund and all research on cathodic protection is performed in-house.

Design of all cathodic protection systems is also done in-house. The state has developed Standard Specifications based on the AASHTO Guidelines. Design and installation specifica-

tions have also been developed. The condition of the concrete superstructure, availability of power, chloride ion content, and half-cell potential survey results are used for ascertaining the need for a cathodic protection system on a bridge deck. A Special Provision is added to every contract that requires installation of a cathodic protection system. Construction inspectors trained by personnel from Research perform inspections during installations and Traffic Signal Electricians conduct acceptance testing on rectifiers. All maintenance work on the cathodic protection systems is done in-house.

Almost all of the cathodic protection systems, 161 of 167, are installed on bridge decks, with the remaining systems installed on substructure elements. A majority of the deck systems are slotted and use the platinum–niobium anode wire. The oldest titanium-mixed metal oxide anode-based system in the state is 19 years old. In the last 8 years, all deck systems installed have been mixed metal oxide anode systems. The current Contract Specifications provide a choice between slotted and mixed metal oxide; however, the mixed metal oxides have been preferred.

With more than three decades of use, the state has experienced much success, but some failures as well. The ferex anode-based systems installed on two dozen bridges failed in fewer than 5 years and had to be replaced. MDOT believes that the choices available in the marketplace are limited and that monopoly is stifling innovation. There are only two experienced contractors in the state. They would prefer to see more cathodic protection systems on substructure elements; however, they believe innovation is necessary for large-scale adoption.

Florida

Florida has 6,000 bridges located in the marine environment and corrosion of the substructures is observable within 12 years of construction. The collapse of the Anclote River Bridge in Pinellas County on December 17, 1968, and the accompanying loss of life led to an investigation that concluded that the failure had resulted from corrosion of the reinforced concrete bridge components. To ensure that the corrosion problem was properly managed, the state hired a corrosion expert who started the FDOT corrosion program. Now the state has a Corrosion Laboratory housed in the Central Office of FDOT, which is a part of the Materials Office. The Corrosion Laboratory has nine full-time personnel, various contract workers, and two consultants to assist it in carrying out its mission. Initially, the corrosion program trained personnel in-house. Later, they hired people with formal training in corrosion. Its personnel receive training from NACE programs and keep current with the corrosion technology through attendance at various conferences. The Corrosion Laboratory, funded by the State Material Office Budget, is fully equipped to perform much of the material testing and conduct research efforts in corrosion-related areas. The laboratory is also capable of executing condition evaluation,

research installation, and monitoring and maintenance of cathodic protection systems or other corrosion mitigation technologies.

FDOT has a very robust research and development program in the area of corrosion mitigation. It has developed many of the technologies currently in use on substructure elements. The corrosion group has been involved in the development of various cathodic protection systems since the early 1970s. Initially, all research was performed by the corrosion group. Later, the program was expanded, and several Florida universities were contracted to perform both theoretical and field research. Consultants are also used in some of the research efforts. The use of zinc penny sheets, conductive rubber, zinc mesh in jackets, arc sprayed zinc above the tidal zones, and bulk anodes on marine pilings have all been outcomes of these research efforts.

As would be expected in any such undertaking, the Corrosion Laboratory initially experienced failures in some of the earlier systems. Owing to a lack of confidence, many of the districts were initially reluctant to implement the technology developed or adopted by the Corrosion Laboratory. As they started to experience success and bridge inspection teams recognized the reduction in inspection and maintenance needs, districts adopted the technologies and procedures developed and started to implement cathodic protection technology on all of its structures.

The Corrosion Laboratory provides a complete corrosion package. It can evaluate the structure and ascertain the need for corrosion mitigation, provide options for corrosion control, provide quality control and quality assurance services and assistance during construction, and monitor and maintain the cathodic protection systems. The Corrosion Laboratory does not limit itself to cathodic protection technology; it uses all corrosion mitigation technologies depending on their applicability and the need for extension in service life. Considering the number of structures in need of maintenance and the size of the staff, the Corrosion Laboratory uses consultants as and when needed, and districts also have begun to use local consultants for the same purpose.

FDOT has a formal policy for the use and application of cathodic protection system technology. Standards have been developed for several different types of cathodic protection systems that are a part of the *Bridge Repair Manual*. The bridge owners hire local consultants for the repair and rehabilitation programs, who use FDOT standards to design cathodic protection systems for the project. The Corrosion Laboratory reviews all cathodic protection systems designed for implementation on state-owned structures. Many of the local bridge consultants in the state have acquired sufficient expertise to design cathodic protection systems and there are several Corrosion Consultants who either provide services to the bridge consultants, the districts, or to the Corrosion Laboratory. This policy of allowing consultants to design cathodic

protection systems has created a significant pool of skilled manpower that the state can access for the implementation of this technology. The installation of the cathodic protection systems can be done by any qualified contractor. However, each project is required to have the services of an independent NACE-certified Cathodic Protection Specialist to provide quality control and quality assurance services. The independent specialist not only provides inspection services, but also trains and provides guidance to the contractors with the installation of the cathodic protection system. Because many contractors in the state have acquired experience in the installation of the cathodic protection systems, competition in the marketplace has been maintained.

Monitoring and routine maintenance of all cathodic protection systems is performed by the Corrosion Laboratory. If a major repair is required, then either the bridge crew or a contractor is used. As the inventory of cathodic protection systems in the state grows, FDOT is finding it difficult to manage all the systems in-house and is starting to use consultants for this purpose. The galvanic cathodic protection systems are monitored once a year. When the work load cannot be handled by the manpower available, the best performing systems are temporarily dropped from the monitoring program. The impressed current systems are monitored using remote monitoring technology. There is only one impressed current system in the inventory that does not have a remote monitoring unit and the Corrosion Laboratory staff visit the system once each month. Data from the remote monitoring systems are reviewed weekly. To ensure that it is able to properly monitor the impressed current cathodic protection systems, a remote monitoring unit was specifically designed for their needs.

The Corrosion Laboratory, in an interview, indicated that because of its experience and expertise in the area of corrosion, it is not subject to extensive sales and marketing efforts. Many of the products used in the state are first evaluated by the Corrosion Laboratory. The anode materials available in the marketplace do address their present needs; however, innovation and more competition in the anode marketplace would be welcome.

With the use of cathodic protection technology, FDOT has experienced a reduction in maintenance costs. Its inventory includes impressed current systems that have been in operation for 20 years and galvanic systems that have been operational for 10 to 15 years.

Oregon

Oregon has many historic structures and much of their corrosion problem stems from exposure to the marine environment. Its need to protect superstructure elements on many of its marine structures has resulted in the state being the largest users of surface-applied cathodic protection systems such as arc sprayed zinc. With the completion of ongoing construction, Oregon will have 1.17 million square feet of concrete

under cathodic protection. They pioneered the practical application of cathodic protection for preservation of existing major historic coastal bridges.

The historic Alsea Bay Bridge suffered significant corrosion-induced damage and had to be replaced. The public process for the replacement was difficult and it cost the Oregon DOT (ODOT) \$24 million more than the simpler bridge it had planned to use for replacement. This prompted it to search for technologies to preserve its other historic bridges and avoid replacement for as long as possible. One of the crews in the DOT had electrical and mechanical engineers who were familiar with cathodic protection technology used on pipelines, marine vessels, and offshore oil platforms, and they proposed its use on reinforced concrete structures. At that time, Caltrans had just completed a research project to test thermal-sprayed zinc as an anode on the surface of the reinforced concrete components. Oregon selected the arc sprayed zinc anode for application on historic structures and completed its first application on the Cape Creek Bridge in 1990. Including the ongoing project on Coos Bay South Approaches, there are a total of 11 bridges with cathodic protection systems in the state. Although the number of bridges is not large, the surface area protected is.

ODOT has a Bridge Preservation Group that includes structural, electrical, geotechnical, hydraulics, and corrosion positions and is charged with the preservation of all bridge structures in the state. There are two corrosion positions: Corrosion Protection Engineer and Corrosion Design in the group. This group has developed specifications for design and application of the arc sprayed cathodic protection systems, and has also experimented with various other surface-applied anodes. Corrosion consultants are used in conjunction with their in-house staff for design and to provide quality control during installation. Monitoring and maintenance is done in-house.

California

Caltrans was the pioneer in the application of cathodic protection to reinforced concrete structures. It was the first to install cathodic protection systems on bridge decks. Cathodic protection is best suited for its marine structures. Deicing salt exposure is limited to the mountainous regions of the state, where the overlay systems on bridge decks are often damaged by the chains on heavy trucks during the winter and are not preferred in those applications. Cathodic protection is considered to be last option and is used only when the exposure environment is such that no other corrosion control system will provide the desired service-life extension. Caltrans developed the coke breeze cathodic protection system and experimented with several coating systems including arc sprayed zinc. It has also experimented with a conductive polyester concrete bridge deck cathodic protection system.

The Caltrans Corrosion Technology Branch (CTB) is currently staffed by four engineers and two technicians. The exist-

tence of the CTB can be traced back to the time of Richard Stratfull who pioneered cathodic protection application on reinforced concrete structures. Stratfull was instrumental in developing the awareness of corrosion and the importance of having DOT staff receive training in cathodic protection. At present, three staff members are experienced and are well-versed with cathodic protection technology; they primarily control the implementation of the technology. In-house-developed technology and research projects funded by the FHWA provided them with much of the experience. CTB staff has also received training from NACE educational programs. Funding for the corrosion laboratory is allocated through the Office of Testing and Technology Services, which is a sub-branch of the Division of Engineering Services. CTB provides its services to the headquarters and the districts.

The maintenance groups and structure design engineers decide on the repair and/or rehabilitation strategies. The design of the cathodic protection systems, when used, is done by the CTB. Caltrans does not have any standards; they use the specifications from previous projects and the experience of the staff in designing the systems. Also, it does not interact with the cathodic protection industry and has generally used systems developed in-house. Quality control functions are done by in-house personnel. Monitoring and maintenance of the cathodic protection systems is performed by CTB. Caltrans believes that if better guidelines become available and if its confidence in the newer product is established, it is likely to increase its use of the technology.

Connecticut

In the 1990s, the Connecticut DOT (ConnDOT) initiated a research study to ascertain the effectiveness of cathodic pro-

tection systems in controlling corrosion of its reinforced concrete bridge elements. The study was lead by a ConnDOT Principal Investigator and the cathodic protection systems were installed under subcontracts in construction projects. A total of 13 structures received cathodic protection under this project. From 1989 to 1993, cathodic protection systems were installed on the decks of 12 bridge structures. In the 1996–1997 time frame, cathodic protection was installed on the caps of one more bridge. All cathodic protection systems installed under this program are impressed current type with titanium-mixed metal oxide mesh or ribbon anodes.

The selection and design of the cathodic protection systems were performed in-house by the Research Group with assistance from the FHWA and NACE. The installation specifications were developed by the Research Group in conjunction with their consultants and they in turn received input from system material suppliers and installers. The material suppliers provided a manufacturer's representative during the installation to ensure that the systems were installed in accordance with the project specifications and requirements.

Since installation, all systems have been monitored by the Research Group and are performing satisfactorily. Although they do not have formally trained personnel, the Research Group has acquired sufficient skills to monitor and maintain the systems. All bridges included in the study are within a few hours' drive of ConnDOT offices and site visits are regularly made to monitor and maintain the systems.

When asked to categorize their experience with the cathodic protection systems, it stated that "ConnDOT's experience has been highly satisfactory for corrosion prevention and control."

PROBLEMS ENCOUNTERED WITH CATHODIC PROTECTION SYSTEM APPLICATION

Problems with cathodic protection system application have been experienced in all aspects of the application process, from selection of the appropriate system through installation to the regular monitoring and maintenance of the systems. Each phase of the application process is discussed in this chapter to ascertain the areas in most need of improvement.

SELECTION OF A CATHODIC PROTECTION SYSTEM

The results of the survey conducted in this effort indicate that, in general, agencies do perform visual, crack, and delamination surveys during routine bridge inspection, which provides them with information to determine if corrosion has been initiated in their structures and whether it needs attention. Once corrosion-induced damage reaches a certain threshold, which is probably different for each state, a corrosion condition evaluation is performed that generally includes chloride ion content analysis and half-cell potential testing. Such data would provide a good idea of susceptibility to future corrosion in sound areas. If chloride ion distribution at the steel depth has either exceeded or is close to the threshold and the top layer of the sound concrete has high levels of chloride ion concentration, the reinforced concrete element is a good candidate for cathodic protection. However, judging from the response to survey questions, it appears that the quantity of damage is considered by most agencies to be the determining factor. Although the quantity of damage is a good indicator of what is happening, waiting for a certain level of damage to occur increases the total cost of repair. If instead of quantity of damage chloride ion content is used, the structures would be prioritized earlier for installation of a cathodic protection system and would result in lower total cost of repair.

Between 55% and 60% of the responding agencies have some form of standards, procedures, protocols, or methodology for conducting corrosion condition evaluations, analyzing the data, and using the data to select alternatives for repair and rehabilitation. This means that a good number of them either do not need or do not have a standardized procedure for implementing this or other technologies. It is reasonable to expect that the standards, procedures, and protocols used by the agencies vary; whereas some may be in need of an update, others may be the state of the art. Several attempts have been made to develop a protocol or a decision matrix that can be used to identify alter-

natives that are likely candidates for the particular project based on corrosion condition survey results. The latest in the series is the *Manual* developed under an NCHRP study that documents a methodology for conducting corrosion condition evaluations and selecting alternatives based on its results (48).

In addition to determining the applicability of cathodic protection for a particular structure, it is also necessary that the corrosion condition data provide information on whether galvanic or impressed current cathodic protection will be required. The results of the survey indicate a trend toward the use of galvanic cathodic protection systems. Galvanic cathodic protection systems have a current delivery limit that is controlled by the type of anode and the environment and may not provide sufficient current in certain applications. At the start of the industry, in the 1970s, the E Log I test was used to determine the current requirement. Owing to equipment and time requirements, this test is rarely used today. Experienced practitioners use all or some combination of chloride ion distribution, severity of the environmental exposure, half-cell potential survey results, corrosion rate measurements, electrical conductivity measurements, and quantity of damage information to ascertain if galvanic or impressed current systems will be required. Therefore, it is imperative that agencies either use in-house personnel with appropriate skill sets or hire a consultant with the requisite qualifications and experience to make the selection decision.

DESIGN OF SYSTEM

Proper design of a cathodic protection system is paramount. Good design guidelines and criteria will ensure that system designs meet some minimum standard. The available guidelines and criteria for cathodic protection on reinforced concrete structures are not sufficient. At present the following two documents are available:

1. NACE SP0290-2007 Standard Practice for "Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures," developed by the National Association of Corrosion Engineers, published in 2007.
2. Guide Specification for Cathodic Protection of Concrete Bridge Decks, developed by a joint committee of AASHTO, AGC, and ARTBA, and was published 1994.

The NACE standard is the more recent document and provides broad guidelines as to what might be considered during design and relies on professional experienced personnel to make the decisions. The AASHTO document does go into design detail for each type of system; however, many of the newer systems are not included and some of the included systems are no longer used. Neither of the documents provides a basic template for project specifications that might be used as a basis by designers. Only six agencies from among those that responded to the survey have a standard for design and/or construction specifications governing the use of cathodic protection on reinforced concrete bridge elements. Another document that is presently being developed by NACE is a Recommended Practice for Sacrificial Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures. The Europeans in 2000 have recently published the standard EN 12696:2000 for implementation of cathodic protection technology. The state of Missouri identified the need for a new guide specification and suggested that if one could be provided that the DOTs could ratify the use of NACE standards and recommended practices.

Once a decision has been made as to which type of cathodic protection system is to be used, the anode material and configuration needs to be selected. Based on the results of the survey, it is clear that for a majority of the agencies, agency staff designs these systems. Some agencies are assisted by a consultant, although fewer require a consultant to design the system with assistance from either a NACE-certified Cathodic Protection Specialist or the material manufacturer or supplier. Even for agencies that have a well-established and experienced staff to handle cathodic protection issues, good information on all materials and configurations may not be available and when a need arises for a material or configuration other than what they have previously used, they must rely on information from material manufacturers and suppliers. Information from material manufacturers and suppliers can be valuable; however, the agency must have the expertise to evaluate that information. FDOT stated that "many agencies are reluctant to accept the technology because there have been too many overzealous sales representatives and they do not have in-house expertise to evaluate the proposed systems." Texas reported that they do not have the requisite skill sets and "all we really know is what the sales people tell us." A consultant stated that designers allow "material or other commercial considerations to push design." That would only be possible if the designer is not an independent party and has commercial interests in the materials or supplies for cathodic protection systems. Some earlier specifications required that the designer not have any vested interest in the manufacture or supply of cathodic protection materials.

When the first applications of cathodic protection started, FHWA and local DOTs were performing research and experimenting with various anode materials and configurations. As funding for such research dried up, users depended more on information provided by the material suppliers and manufac-

turers, which may not always be considered from an independent source. For many of the newer materials, very little information from independent sources is available. A well-defined test method or guidelines for evaluating anode materials and their various configurations is required. The evaluation of the anode materials and configurations might be done by the agencies themselves or by independent research and testing groups. At present, the primary indicator of success used by many sales groups is the number of applications of the particular material and its acceptance by other agencies. Often, there are no hard data or sufficient length of operation to ascertain the performance and the long-term durability of the material. Therefore, this method of acceptance of an anode material based on sales figures can be flawed. Not only might the performance and durability of the anode material be considered but its applicability to the subject project could be evaluated.

In an interview, the Manager of DP-34 Cathodic Protection for Reinforced Concrete Bridge Decks stated that after FHWA involvement in the cathodic protection industry was reduced in 1989, many agencies had not yet acquired sufficient expertise in the technology and became dependent on vendors and material suppliers for all aspects of the use of the technology. He stated that "It was a free for all and many materials which were not ready for use were pushed into the marketplace." He also indicated that the lack of competition in the industry is a problem. He presented the example of the ferex anode. As soon as the material was identified as having good properties to serve as an anode material, the sales and marketing teams pushed the material on numerous bridge structures (at least 50) without verifying the performance or the durability of the material in concrete. Almost of all of these systems failed. Missouri reported them failing between 0 to 5 years, California reported that they failed between 6 to 10 years, and in South Dakota the systems failed immediately after installation. A consultant involved in the use of this system believes that the ferex anode failed because it becomes brittle in concrete, subsequently cracks and the inner copper core becomes exposed. The copper core is not a satisfactory anode material and it corrodes rapidly at the application of current and the anode quickly fails. Missouri concurred with this observation and stated that this anode material was not suited for use in concrete. The manager of DP-34 believes that some of the newer anode materials making their way into the marketplace may have similar problems.

Even when well-established anode materials and configurations are selected, the design parameters need to be properly established. The present design protocols only require the design to limit the voltage drop along the anode material; they do not provide any mechanism for or require the calculation or estimation of other system parameters. Mathematical models are currently available for such calculations and estimations (49). The design of the cathodic protection system on the Benjamin Franklin Bridge in Philadelphia did not properly estimate the system requirements. The overall resistance of the system came out to be too high and the rectifiers specified

for the project cannot provide the required current. To reduce the resistance of the circuit and keep the system partially operating, the owner has to regularly spray water on the underside of the approach slabs to reduce system resistance.

Design could also include the impact of other systems present on the structure. For example, the cathodic protection system on the bridge carrying I-64 in Norfolk, Virginia, cannot be operated owing to supposed interference between the rectifiers and other electrical systems on the bridge. This system was installed to protect approximately 400,000 square feet of the deck surface area. Upon energization of the system, it was observed that the rectifier cards were failing within weeks. When operational, the system was providing adequate protection. The cause of the burnout of the rectifier cards was not confirmed; however, several theories were put forth by the involved parties including short circuits, grounding problems, interference from alternating current on the bridge for lighting, etc. (34). A review of the impact of the cathodic protection system into the bridge electrical grid was never conducted. In another example, an impressed current cathodic protection system on a bridge deck or decks in New Jersey failed to provide corrosion control because the designers had not included the impact of corrugated metallic forms present at the bottom of the bridge deck(s). Owing to its large surface area, a majority of the cathodic protection current was received by the corrugated forms and an insufficient amount was received by the reinforcement. The failure of the zinc foil with adhesive anodes on the hammer heads of the James River Bridge and the Route 58 eastbound lane over Leatherwood Creek (both in Virginia), was attributed to the orientation of the panels of zinc in the vertical direction, which allowed water to flow along the joints and enter the space between the anode and the adhesive resulting in disbondment (34).

Placement of rectifiers on bridge decks where they are susceptible to lightning strikes required the Virginia DOT to keep replacing several control cards every year on the James River Bridge when the conductive paint system was installed on the hammerheads. The rectifiers had alternating current and direct current lightning arrestors; however, these arrestors were destroyed after the first lightning strike and the control cards were damaged during subsequent strikes. The project manager for DP-84 indicated that in several projects in which DP-84 was involved, rectifiers suffered damage from lightning strikes. Thus, design could also include a careful selection of the placement of the rectifiers and protection against lightning and vandalism.

In addition to good design, a detailed set of specifications is required for installation. The specifications would take into account the actual condition of the structure. In one project in Florida, the zinc expanded mesh system in a jacket failed to provide adequate cathodic protection. Analysis of the failure indicated that the project specifications did not provide any instructions to remove the existing jacket and the new jacket

had been installed on top of the existing jacket and therefore the cathodic protection system was unable to function.

INSTALLATION AND QUALITY CONTROL

Proper installation is necessary for the success of any system. Therefore, qualified individuals must be used to install cathodic protection systems. If qualified installers are not available, then the installers might be required to obtain assistance from qualified consultants who can provide guidance and quality control.

A qualified quality control and quality assurance provider must be included in the installation process. There are several examples of systems that are nonoperational from the time of installation. On the underside of the roadway of the Brooklyn Battery Tunnel, a mixed metal oxide mesh anode was installed and encapsulated with shotcrete. Improper installation resulted in the shotcrete disbonding from the underside of the roadway at many locations. The problems were not identified during installation. This multimillion dollar system had to be discarded as it was not fully functional (50). A similar problem was encountered on the Queen Isabella Causeway in Texas; however, owing to good quality control, the encapsulation was properly installed after three attempts and the system functioned as expected. Similarly, during installation of a mixed metal oxide mesh system on the top and the bottom surface of the historic arches of the Jefferson Street Memorial Bridge in Fairmont, West Virginia, a trained and experienced inspector was able to detect the slight variation in the color of the anode, which implied that the mixed metal oxide had not been sintered to the titanium expanded mesh. The supplier denied it at first and had the contractor install the defective material. Testing of the suspect mesh verified the lack of mixed metal oxide on the mesh and it cost the contractor \$500,000 to correct the problem. The last reported inspection, after 5 years of operation, indicated that the system is functioning as designed.

Electrical shorts between the anode and the reinforcing steel are the most common problems encountered in the installation of these systems. A rigorous testing schedule must be maintained to ensure that there are no shorts, especially in impressed current systems. Many systems have failed as a result of the presence of shorts.

MONITORING AND MAINTENANCE

The respondents in the survey have made it clear that monitoring and maintenance of the cathodic protection system is too burdensome and that most agencies are finding it difficult to cope with this process. Initial cost and monitoring are the factors that discourage the application of cathodic protection systems. Of the twenty-four respondents who have at least one cathodic protection system, only 10 monitor them as summarized in Table 17 in chapter four. Therefore, 14 agencies do not monitor their cathodic protection systems. Among the respon-

dent states, only five monitored all of the systems, with another four monitoring only some. The province of Ontario indicated that owing to downsizing of the government and the outsourcing of maintenance, it is concerned about its ability to monitor and maintain impressed current systems and are more inclined to use galvanic systems in the future. Texas does not believe it can monitor and maintain the systems and therefore does not use them. Utah had a total of seven systems, all of which failed because they were not able to monitor and maintain them and also because personnel involved with those projects are no longer with the department and very little if any information is now available. Only nine agencies indicated that they have at least one person to monitor their cathodic protection systems and five believed that they had sufficient staff to monitor all of their systems. Monitoring and maintenance being a significant burden was selected by the most respondents (12) as a reason for not selecting cathodic protection systems in the future as noted in Table 21. Ohio, which had started to use cathodic protection systems in the 1980s, has lost all personnel who were familiar with the systems and at present even status information on these systems is not available to the agency.

TABLE 21
NOT INCLINED TO USE CATHODIC PROTECTION
IN THE FUTURE

Reason	No. of Respondents
Cathodic protection system did not work at all	3
Cathodic protection did not stop corrosion and concrete repairs were required after cathodic protection installation within the first 5 years	0
Cathodic protection components failed and could not be maintained	7
Monitoring and maintenance was a significant burden	13
The agency does not have the resources to monitor and maintain the cathodic protection system	7
The technology is not well understood by the agency	3
The consultants are not well versed in the technology to recommend it to the agency	1
Applicators and contractors that do business with the agency do not have any experience with the technology	2
Experience of other agencies suggest cathodic protection is too complicated, does not work, is too expensive, and requires significant monitoring and maintenance	1
Agency staff with experience in cathodic protection has retired or have been promoted and new staff have no experience with cathodic protection	2
Cost of cathodic protection was relatively higher than other options	10
Other	3

Note: Table based on results of Question 31 of the survey.

TABLE 22
STATUS AND OPERATION OF CATHODIC PROTECTION
SYSTEMS

Question	Yes	No
Is the current status of operation of all or some of the cathodic protection systems available to the agency?	11	11
While they were operational, did the cathodic protection systems stop corrosion and extend the remaining service life of the reinforced concrete component?	15	2
If not, has a cause been determined?	4	2

Note: Table based on results of Questions 41, 44, and 45 of the survey.

Site visits by the SHRP team before 1992 uncovered some systems that were believed by the agencies to be operational, but had either failed or were powered off (51). The owners did not have the correct information on the systems in their jurisdiction. Under FHWA Demonstration Project 84, similar experiences were discovered in several states. Agencies believed that their systems were operational when, in actuality, they were not. In one instance, the present staff of the agency did not even know that they had a cathodic protection system in their jurisdiction. Table 22 summarizes the responses to the question that asked if the agency was aware of the status of the cathodic protection systems they have.

Seven of the 22 respondents to Question 42 (Table 23) indicated that they had less than 5% of their cathodic protection systems operational. In Question 47 (Table 24), most respondents believed that the failure of their cathodic protection systems could be attributed to insufficient current output by the system owing to improper settings. Improper current settings are a symptom of inadequate monitoring and maintenance and can be easily rectified and not be a reason for the inadequate performance.

Many of the disappointing experiences have resulted from failure of systems as a result of insufficient monitoring and maintenance; many agencies simply do not have the resources. Some agencies installed systems for non-technical reasons. As their understanding of the technology and their confidence in its ability to provide protection were inadequate, sufficient motivation did not exist to allocate the necessary resources. In some instances, the agencies did not appreciate

TABLE 23
PERCENT OF SYSTEMS OPERATIONAL

% Cathodic Protection Systems	No. of Responses
5	7
20	0
40	2
60	2
80	4
100	7

Note: Table based on results of Question 42 of the survey.

TABLE 24
REASONS FOR FAILURE OF CATHODIC PROTECTION SYSTEMS

Reasons for Failure	No. of Responses
Failure of cathodic protection components resulted in the system being not operational for more than 20% of the time	8
Cathodic protection system not putting out sufficient current owing to improper design	0
Cathodic protection system not operational owing to failure of one or more components	1
Cathodic protection system not putting out sufficient current owing to improper settings	10
Cathodic protection system did not operate owing to deficient design	2
Cathodic protection system not installed as designed	1
Anode not appropriate for the application	0
Vandalism damaged system components	5
Not identified	5

Note: Table based on results of Question 47 of the survey.

the need for monitoring and maintenance. The Technical Committee of NACE reported that “In many cases the way CP [cathodic protection] is sold today, the client/owner is not informed of the need for future maintenance of the CP System. The client/owner must know up front that an inspection/monitoring program is required. This must be addressed in the scope of work. This area should be addressed in a NACE document” (52).

PERFORMANCE AND DURABILITY OF SYSTEM COMPONENTS

Performance and durability of the anode materials is crucial to the overall success of the cathodic protection systems. All anodes have some performance and durability limitations; for example:

- Conductive polymer material used as secondary anodes is susceptible to acid attack,
- Conductive paint can weather within 5 to 10 years depending on the exposure conditions,
- Mixed metal oxide anodes when operated above 10 mA/ft² of anode surface area can generate chlorine, which can result in acid attack of the concrete,
- Zinc anodes can passivate in certain environments,
- Ceramic anodes can have low contact resistance and if the gasses are not vented properly can result in acid attack,
- Adhesive in the zinc foil anodes can dissolve and loss of bond can occur if water infiltrates,
- Coke breeze systems can suffer from high resistance due to loss of coke around anodes and corrosion of wire connectors, and
- Arc sprayed zinc and aluminum–zinc–indium alloy may experience bond problems, etc.

Therefore, anode materials and the configurations in which they are used must be selected, designed, and installed in accordance with the best practice and the system operated within safe operating ranges.

The survey queried the respondents on time to failure of most commonly used cathodic protection systems. The primary reason for this question was to try and ascertain the experience agencies have had with cathodic protection. The question did not distinguish between premature failure and end of service life. Therefore, some agencies reported both and some responded only if the systems were considered to have failed prematurely.

In reviewing the durability of anode materials, it is important to understand that whereas some agencies have reported failures for certain systems others have very successfully applied them. Many failures of cathodic protection systems occurred when (1) experimenting with new systems; (2) agencies installed systems without requisite experience and knowledge; (3) systems were not matched to the structure or the environment, improperly designed, or incorrectly installed; and (4) systems were not monitored or maintained appropriately. A distinction must be made between designed consumption or weathering of an anode and durability. For example, when arc sprayed zinc is completely consumed, it does not signify failure of the system; it is simply time to replace the anode. However, if the anode debonded or became passive then it would be considered a failure.

As discussed in chapter four, the ferex anode systems did not exhibit sufficient durability for use in reinforced concrete structures and failed within 5 years, which was reported by several respondents. Missouri reported failure of conductive polymer systems at 0 to 5 years when carbon fibers were used as the primary anode. However, the conductive polymer anode systems using platinum as the primary anode have lasted between 21 and 25 years. Missouri now only uses platinum as the primary anode in conjunction with conductive polymer anodes.

Failure of the conductive coke asphalt system was reported by four agencies, Missouri (11 to 15 years), North Carolina and Virginia (0 to 5 years), and Ontario (6 to 10 years). The failure in Virginia was judged to have resulted from acid generation at the anode. In addition, coke asphalt systems are susceptible to damage during replacement of the riding surface (some operational systems have been lost during replacement of the asphalt riding surface). This is an inherent flaw in the design of this type of system and it is not used any more.

Failure of a zinc foil with adhesive system was reported by five agencies; three had experienced failure in the 0- to 5-year time frame and two in the 6- to 10-year time frame. Florida, Illinois, and Missouri reported failure of the adhesive and loss of bond. High rate of anode consumption at the edges was

TABLE 25
LENGTH OF OPERATION OF
CATHODIC PROTECTION SYSTEMS

Length of Operation	No. of Responses
Less than 1 year	2
1 to 5 years	3
5 to 15 years	15
Greater than 15 years	3

Note: Table based on results of Question 43 of the survey.

reported by Oregon. Missouri indicated that in year 1 the bond failure was noted, and by year 4 the anode was consumed. This anode is no longer available.

Florida reported failure of the localized (hockey puck) zinc anodes in 0 to 5 years, as the anodes did not provide adequate protection in their application.

Most agencies indicated that on average cathodic protection systems were operational for 5 to 15 years. Three agencies, New Brunswick, Missouri, and Washington State, indicated that their systems lasted more than 15 years. A summary of the responses to this question is provided in Table 25. It may be noted that with a few exceptions, not many agencies have systems old enough to have been operational for more than 15 years.

The rectifier on an impressed current system can often be the weakest link and requires the most maintenance. Several agencies that reported failure of various kinds of systems indicated that the failure had occurred as a result of the failure of the rectifier. It was selected by the greatest number of respondents to require the most maintenance (Table 26). Cables, wiring, and conduits were also identified by the same number of respondents. However, the rectifier is easy to repair or replace and is not a fatal flaw. The cable, wiring, and conduit failure, where they are embedded in concrete, could turn out to be a fatal flaw. A maintenance frequency of once a year was experienced by the most number of respondents as the summary in Table 27 indicates.

TABLE 26
CATHODIC PROTECTION COMPONENTS THAT REQUIRE
THE MOST MAINTENANCE

Component	No.
Rectifier	6
Remote Monitoring Unit	3
Anode	1
Cable, Wiring, and Conduit	6
Reference Cells	1
Current Probes	0
Concrete Overlay or Backfill Material Used to Encapsulate the Anode	1

Note: Table based on results of Question 48 of the survey.

TABLE 27
FREQUENCY OF CATHODIC
PROTECTION COMPONENT
MAINTENANCE

Frequency	No.
Once a week	0
Once a month	1
Once a quarter	0
Once every six months	2
Once a year	7
Once every two years	2
Once every five years	4

Note: Table based on results of Question 49 of the survey.

The durability of the rectifier is dependent on several factors. As discussed earlier, lightning strikes on a rectifier are a significant problem and 10 agencies noted that to be one of the most important problems. The rectifying element, the control cards, and the remote monitoring units were identified by the agencies to be the components most susceptible to failure in the rectifier. Their responses to this question are tabulated in Table 28. In the interview, Missouri indicated that certain rectifiers have performed better than others and have been operational for the entire service life of the system.

Vandalism is also an issue that must be considered during design. Placing system components out of reach of vandals is essential. At least one agency has reported the failure of a system as a result of vandalism. In one instance, it was found that homeless people living under a bridge had cut the conduit and wires for the cathodic protection system in an effort to obtain power for their heaters and television sets.

North Carolina installed five different types of impressed cathodic protection systems, the mixed metal oxide mesh, conductive paint, conductive polymer, conductive coke breeze, and aluminum-zinc-indium alloy, on five different bents and all of them failed within one year. The mode of failure for each of the five systems was listed as "whole system failed." In the rectifier experience section they indicated that they had problems with the rectifier and the control cards. They also commented that these systems were not considered "tough

TABLE 28
RECTIFIER COMPONENTS MOST SUSCEPTIBLE
TO FAILURE

Component	No.
Rectifying Element Failure	8
Control Card Failure	7
Lighting Strikes	10
Remote Monitoring Unit Failure	6
Other	6

Note: Table based on results of Question 52 of the survey.

enough for severe bridge environments.” This is in contrast with the experience of other states such as California, Florida, Missouri, and Oregon and in Canadian provinces such as Alberta, New Brunswick, and Ontario, who among them have a total of 464 bridge structures with cathodic protection systems. A majority of all systems in Florida are in the marine environment. Many of the systems in the northeastern provinces of Canada are in very aggressive marine and deicing salt environments. Missouri itself has mixed metal oxide and conductive polymer anode systems that have been operational for at least 19 years.

Many of the problems and failures of cathodic protection systems discussed previously are symptomatic of the evolution of anode materials and the process of learning the material interactions and limitations. With the exception of the conductive coke asphalt, ferex anode, and the zinc foil anode, all other anodes are still successfully being used. Several different types of systems, both galvanic and impressed current, have been in operation for approximately 20 years.

INITIAL AND LIFE-CYCLE COST

A majority of the respondents indicated that the initial cost of the cathodic protection systems is relatively high. Many are not convinced that the cost-benefit ratio is favorable. Some agencies indicated that they would like to see documentation of performance for each type of cathodic protection system and a listing of both initial and operating costs. Some indicated that the quality of the products available needs to be improved and the cost lowered for cathodic protection to be an attractive alternative for them. Several also indicated that more innovation and competition in the marketplace is desired.

The second generation of bridge structures (bridges built after the 1970s) include improvements to design such as an increase in cover, lower permeability concrete, use of epoxy-coated rebars, use of admixed corrosion inhibitors, etc. California uses a polyester concrete wear surface on bridge decks that can be expected to provide a reasonably good level of waterproofing and it can also be replaced overnight with minimal traffic delays. These techniques do provide a reasonable extension in service life. Therefore, on this generation of structures, the need for cathodic protection will occur at a much later date. If we use the solution to Fick’s Second Law of Diffusion and estimate the impact of cover and diffusion coefficient on time-to-corrosion initiation, we find that the increase in cover results in an exponential increase in time to corrosion. Similarly, the impact of improving the permeability, and to some extent diffusivity, also increased time-to-corrosion initiation exponentially. When both are combined the impact is more dramatic.

Most agencies are very comfortable with barrier systems such sealers, concrete overlays, and waterproofing membranes. The initial costs of cathodic protection will generally be higher compared with these technologies. The

distinguishing factor between cathodic protection systems and barrier systems is that at the end of the service life of the cathodic protection system there is no corrosion-induced damage. Whereas barrier systems gradually fail and at the end of their service life, some chlorides have migrated into the concrete and corrosion-induced damage has occurred.

CATHODIC PROTECTION MARKET

The size of the present cathodic protection market is not sufficient to generate competition and drive innovation. There are only a few vendors and they do not necessarily focus on the same market segment and therefore competition is virtually non-existent. The sale of the system is dependent on the owners already having faith in their products or their sales people convincing them of the benefits of its use. Even the consulting arena is quite limited as manufacturers and installers find it easier to sell design-build projects. The lack of demand for post-installation services also is not very helpful to the growth of the industry. The majority response from the industry indicated that the industry is in decline. However, one vendor noted that they expect to install cathodic protection systems on 200 bridges in the next five years. They also indicated that they have been involved with either the supply of materials, installation of the systems, or providing consulting and engineering services for cathodic protection on 1,350 bridges since 1980. Because the number of structures reported by state and provincial agencies is less than half that figure, it is assumed that many of those structures are located outside of North America or are not owned by state and provincial agencies. As this vendor is a large international corporation, their sales figures and future projections are a clear indication of where the

TABLE 29
FACTORS THAT WILL ENCOURAGE APPLICATION
OF CATHODIC PROTECTION SYSTEMS

Factors	No. of Responses
Better understanding of the technology by agency staff	15
Education of the consultants	4
Trained applicators and contractors	4
Reduction in cost of the cathodic protection system	22
Availability of consultants to monitor and maintain cathodic protection systems	9
Improved technology to monitor and maintain systems	20
Improved quality of the system components that would reduce the frequency of repair and maintenance of cathodic protection components	17
Improved design	11
Technical assistance in selection of appropriate cathodic protection systems for each application	13
All of the above	8

Note: Table based on results of Question 53 of the survey.

rest of the world is going with this technology. In North America, the cathodic protection industry for bridge structures is somewhat weak. These numbers also provide insight into the marketplace in terms of monopoly and lack of competition.

When agencies were questioned as to which factors will encourage the application of cathodic protection technology, reduction in cost was cited by the greatest number of agencies. In the summary of the responses presented in Table 29, reduc-

tion in cost is closely followed by improved technology to monitor and maintain, improved quality of system components, improved understanding of the technology, and technical assistance in selection of appropriate cathodic protection systems. Thus, for the growth of the market, more innovation and competition is required to reduce costs and improve the monitoring systems and quality of the components. The industry and technical associations will have to do more to provide better direction in the selection process and design of the systems.

LONG-TERM CATHODIC PROTECTION SYSTEM PERFORMANCE

To date, more than 500 bridge structures in North America have had cathodic protection systems installed. Many of the early systems were experimental and their design, installation, and operation for a certain period have been documented. To obtain a good understanding of the long-term performance, a history of performance for at least half or more of its projected service life should be available. This would allow one to reasonably ascertain if the claims made with regard to extension in service life are realistic. As there are various types of cathodic protection systems, the long-term performance is dependent on the materials and components used. When reviewing the performance of cathodic protection systems, it is important to ascertain the impact of design and the installation quality on its performance. Cathodic protection systems of the same type on various different installations have provided a varied performance and sometimes performance has been limited by inadequate design, improper installation, or inadequate monitoring and maintenance.

In 1995, as a continuation of SHRP, the FHWA initiated an effort (FHWA-54) to monitor for 5 years the performance of various different types of cathodic protection systems on highway structures that were operational at that time and/or were just installed. Various materials in various configurations had been used as anodes resulting in various different types of cathodic protection systems. The selection of the anode material and its configuration is paramount to the success of the system. The primary objective of this study was to determine the effectiveness of various materials and configurations when used as anodes on highway structures through a long-term evaluation. In this effort, a total of 20 highway structures (19 bridges and one tunnel) protected by one or more types of cathodic protection system(s) were included. The structures were located in 11 states and 1 Canadian province. These structures were protected by a total of 19 impressed current and 5 galvanic cathodic protection systems. There were 9 different types of anode materials and configurations used in impressed current and 3 different types of anode materials and configurations used in galvanic cathodic protection systems. The length of time the systems had been in operation at the end of the program varied from 1 to 15 years. The results of this effort were published in 2000 (27). The findings of this report are briefly reviewed along with the response of various public agencies to the survey conducted in this effort. Where possible, information on long-term performance available in literature for systems that

have moved beyond research and experimentation and have become mainstream systems is also included.

IMPRESSED CURRENT CATHODIC PROTECTION SYSTEMS

Slotted Non-Overlay—Conductive Polymer Backfill

One of the largest slotted conductive polymer non-overlay cathodic protection systems was installed on the bridge carrying I-64 in Charleston, West Virginia, which was energized in 1985. This system was still operational at the time of this report and although the system has undergone repairs, no concrete repairs have been required since the start of operation. This system was monitored under the FHWA-54 program and monitoring and maintenance appeared to be a major problem for the owners. A consultant was hired to monitor and maintain the system and it had a documented history of satisfactory operation until 2005 when it was last monitored. The anode material in a few slots experienced acid attack and the conductive polymer material had failed. The primary anode, platinum niobium wire, and the secondary anode, carbon fiber, were exposed to the traffic and were damaged. These were repaired after approximately 7 years of operation. The West Virginia system uses platinum as the primary anode in the longitudinal slots and carbon fibers in the transverse slots. This system does not have an overlay and the conductive polymer in the slots is exposed to loading from vehicular traffic.

Missouri has the largest inventory of slotted cathodic protection systems. Its oldest system has been in operation for 23 years. Of its 161 bridge deck systems, 38 are mixed metal oxide titanium systems, 8 have platinum and carbon wire, and the remainder of the systems uses platinum wire as the anode material. It should be noted that all slotted systems in Missouri have an overlay. Only 10 slotted bridge deck systems have asphalt overlay; all others have a concrete overlay. The cathodic protection systems on the bridge decks prevent corrosion of the embedded reinforcement and its electric field also forces the chloride ions to migrate away from the reinforcement toward the positive anode material, thereby reducing the chloride ion content in the deck concrete. Recently, when the bridge decks with cathodic protection systems had to be widened, the chloride ion distributions in the decks were evaluated. When the chloride content at the

top mat steel depth was in excess of 2 pounds per cubic yard, a cathodic protection system was reapplied after widening; otherwise, a dense concrete overlay was used. In two projects for bridge widening, a total of 27 bridge decks were evaluated. These bridge decks had been protected by cathodic protection systems for a minimum of 10 years. A total of 10 bridge decks did not require reapplication of the cathodic protection system; on 15 bridge decks the cathodic protection was reapplied and 2 bridge decks were replaced.

The experiences of Missouri clearly indicate that the application of cathodic protection not only extends the service life of the reinforced concrete structure but can revert it to a chloride contamination state, which does not require cathodic protection. No other corrosion mitigation system, with the exception of electrochemical chloride extraction, can do that.

Mixed Metal Oxide

Six mixed metal oxide systems were monitored under the FHWA-54 project; the mesh form of the anode was used in five and the ribbon was used in one. The mesh anodes were installed on the decks of three bridge structures. The deck systems had been operational for 6 to 12 years by the end of the evaluation and were judged to be operating satisfactorily. The ribbon anode was installed on a bridge deck and was documented to be performing well after 9 years of operation, and in the survey it was reported to be operational at the age of 16. The mesh anode has been installed on marine substructure elements of several bridges in Florida and is either encapsulated in gunite or installed in a jacket system. The oldest of these is the gunite encapsulated system, which was in operation for 19 years at the time of reporting and had only minor repairs to correct failed gunite (53). The authors of the Florida report expect this type of system to provide a service life extension in the range of 50 years. The oldest operational system in Missouri was installed in 1989 and was operating satisfactorily after 19 years. Since 1990, Ontario has been using the mixed metal oxide mesh anodes on bridge decks with a cementitious overlay and waterproofing and has had significant success with this system. Service life is projected to be in the range of 25 to 30 years. Connecticut has 12 bridge deck systems that have been operational for 15 to 18 years. This anode material has proven to provide the longest extension in service life and has one of the highest current discharge capacities among other available materials.

Arc Sprayed Zinc

The second largest application of arc sprayed zinc in Oregon is on the Yaquina Bay Bridge and protects 283,300 square feet of concrete surface area. This system was energized in 1996 and was monitored under the FHWA-54 effort until 1998. The installation of the system on the arch spans was completed in 1991 and on the south approach spans in 1995.

Up until 1996, the systems were operated as a galvanic cathodic protection system. At the start of the operations as an impressed current system there were issues with the remote monitoring and remote control of the system and many zones were not outputting sufficient current to meet the 100 mV shift criteria. The problems with the remote monitoring and control systems were worked out and the systems were outputting current density of 2.2 mA per square foot of concrete surface area (54). The oldest operational system in Oregon is on the Cape Creek Bridge, which has been operational since 1989.

Conductive Paint

A conductive paint system had been operational on the Yaquina Bay Bridge for 17 years when reported in 2004 (54). Two conductive paint systems were monitored by the FHWA-54 project and both of them were located in Virginia. One was installed on the hammerheads of the bridge carrying I-95 over the James River in Richmond and the other was on the hammerheads of the bridge carrying I-81 over the Maury River in Lexington. Both systems provided adequate protection while they were operating. The conductive paint was deteriorating owing to exposure to the elements and the system on the I-95 bridges had reached the end of its service life after 9 years of operation, and the system in Lexington was exhibiting signs of paint deterioration after 5 years of operation. The systems on the bridges of I-95 were replaced and the Lexington Bridge was replaced. Although the conductive paints may have a shorter service life, especially when exposed to the elements, it is fairly inexpensive to reapply the paint and extend the remaining service life.

GALVANIC CATHODIC PROTECTION SYSTEM

There is a tendency for many agencies to use the galvanic cathodic protection systems because they do not need the level of monitoring and maintenance that impressed current cathodic protection systems require. These are finding application on marine substructure elements and superstructure elements exposed to deicing salts.

Arc Sprayed Zinc

Arc sprayed zinc is being used primarily on marine substructure and superstructure elements. Research has indicated that the resistance of the system can be maintained within acceptable limits if sufficient moisture is available. Direct wetting of the zinc system is most effective in maintaining the delivery of adequate current by the system (55). This anode is suitable for application above the tidal zone. On the drier superstructure elements where direct wetting of the system is not possible, the zinc anodes suffice because corrosion rates are generally lower in these locations and the galvanic systems are able to provide adequate cathodic current. In Florida

alone, arc sprayed zinc has been applied in 36 projects and protects 677,053 square feet of concrete surface area. The oldest such system was installed in 1989 on the Niles Channel Bridge and was operational for 17 years.

Three systems were evaluated under the FHWA-54 program and all of them were installed on marine substructure elements. The experimental system on the Queen Isabella Causeway in Texas was only 1 year old at the end of the project and was performing well. The Howard Frankland Bridge in Tampa and the Seven Mile Bridge in the Florida Keys had arc sprayed zinc systems that were 5 and 7 years old, respectively, at the end of the evaluation. The Howard Frankland Bridge system was performing well; however, the Seven Mile Bridge was providing less than adequate protection. The Seven Mile Bridge has epoxy-coated rebar and the cathodic protection system was installed to provide protection to the epoxy-coated rebar.

Over the last five years, Ontario has increasingly used arc sprayed zinc and the aluminum–zinc–indium alloy as cathodic protection anodes on piers, girders, and caps and their monitoring data indicate good performance to date.

Zinc Mesh Anodes in a Jacket

The zinc mesh anodes in a jacket have been used in Florida since 1994. To date, these types of galvanic cathodic protection systems have been used on 51 projects and installed on approximately 1,782 piles. At least 16 structures have these systems, which have been in operation for more than 10 years. FDOT has a program to monitor and maintain them and their data to date indicate that, in general, these systems are providing adequate protection.

Overall Long-Term Performance

Cathodic protection systems that are properly designed, installed in accordance with standard practice and good workmanship, and adequately monitored and maintained have performed well. The agencies that have committed to the use of this technology and have made resources available have reaped the long-term benefits and have reduced their overall maintenance costs. Several different types of cathodic protection systems have been demonstrated to provide service life extension of at least 20 years, and are expected to continue to provide protection.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

CONCLUSIONS

Based on the results of the survey and the discussions presented in this report the following conclusions can be drawn:

1. Agencies that have successfully implemented cathodic protection technology have experienced a reduction in the frequency and cost of bridge maintenance and an increase in the service life of their bridge structures. To accomplish this they had to acquire a good understanding of the technology and expertise in the technology.
2. Cathodic protection is accepted as a viable corrosion control technology by some agencies. However, the use of this technology is limited.
3. The use of cathodic protection technology has been declining. From 1970 to 1989 approximately 275 bridges were outfitted with cathodic protection systems; in the next 20 years, almost 240 bridges had been added to the inventory of 21 agencies. However, there is some promise of growth during the next 5 years. The technology is actively used only by the states of Florida, Missouri, and Oregon and the provinces of Alberta, New Brunswick, and Ontario.
4. The primary disadvantages to the use of cathodic protection technology are the initial cost and the burden of monitoring and maintaining the systems. Past disappointing experience has also slowed the implementation of this technology. Many of the disappointing experiences resulted from the use of the previous generation of materials and inappropriate implementation of the technology. In addition, most agencies do not have the resources to implement the cathodic protection technology and have chosen not to make a commitment toward developing such resources.
5. Galvanic cathodic protection is becoming more attractive than impressed current owing to lower monitoring and maintenance requirements. Future research and development might be focused in this direction.
6. Competition and innovation are required in the industry to improve the quality of products and services.
7. Corrosion is, at a minimum, a moderate problem for the majority of the departments of transportation in North America, although for some it is a severe problem. Several agencies that are expected to experience severe corrosion problems did not respond to the survey. In many

states and provinces where cathodic protection would be an appropriate technology to implement, deicing salt usage is sufficiently high, more than 5 tons per lane-mile per year. For coastal states and provinces, marine exposure is also a significant cause of corrosion on reinforced concrete structures.

8. A majority of agencies have standard procedures, protocols, or methodologies for conducting corrosion condition evaluations, analyzing the data, and selecting alternatives. The test methods used by the agencies in corrosion condition evaluations appear to be adequate; however, no information on the quality of these evaluations is available.

REQUIREMENTS FOR IMPLEMENTATION OF CATHODIC PROTECTION TECHNOLOGY

Based on the results of the survey and the literature review, the following would improve the quality of the implementation and increase the confidence in the technology, thereby resulting in an increase in its use.

1. Dissemination of information on the cost benefits of using cathodic protection systems and success stories from user agencies by either the National Association of Corrosion Engineers (NACE) or FHWA, or both.
2. It would be useful if training in the technology were offered by a national program such as NACE or the National Highway Institute.
3. Development of standards and specifications for selection, design, installation, and monitoring and maintenance of the systems. It is important that user agencies adopt a standardized protocol for corrosion condition evaluation, analysis of data, selection of alternatives, design of the system, specifications for installation, and protocols for monitoring and maintenance.
4. Departments of transportation might acquire at least one individual, if not more, with expertise in cathodic protection technology. Although the individual may not be able to perform all of the necessary tasks, he or she would be knowledgeable enough to supervise others or manage consultants. It would be desirable for the individual to possess the NACE Cathodic Protection Specialist Certification.
5. It is best to use anode materials and configurations that are prequalified, meet a certain performance and

durability criteria, and have a documented history of field performance, unless an experimental system is being installed.

6. Quality control and assurance may be provided by either the agency or an independent third party with trained and qualified personnel who have experience in similar systems.
7. Each agency might develop a database to track and inventory all cathodic protection systems. This database can also be used to track the status of the system and manage monitoring and maintenance program.

FUTURE RESEARCH NEEDS

1. Research and development of newer anode material may help to provide a larger selection for the user agencies and expand the application of the technology. Development of more effective and efficient galvanic anodes would increase the acceptance of the technology as it requires less monitoring and maintenance. Also, an increase in the service life of galvanic anodes is desirable.
2. Better information is needed on life-cycle costs and initial costs, in comparison with other corrosion treatments.

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Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation