CATHODIC PROTECTION FOR
REINFORCED CONCRETE BRIDGE DECKS
LABORATORY PHASE
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AREAS OF INTEREST:
BRIDGE DESIGN
CONSTRUCTION
GENERAL MATERIALS
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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.
This report is recommended to bridge design engineers, construction engineers, materials engineers, and others concerned with the preservation of concrete bridge decks. Laboratory studies and model testing employed to determine the feasibility of preventing corrosion of reinforcing steel in bridge decks cathodically by the application of direct current are reported. Two approaches are available for attaining cathodic protection: an impressed current system and a sacrificial anode system. Both systems were investigated, and both were determined to hold promise for protecting bridge decks. A plan for an in-service evaluation of study findings is proposed.

The premature occurrence of spall and pothole damage in bridge decks caused by corrosion of the reinforcing steel in the presence of moisture and deicing chlorides is well known to highway engineers charged with the preservation of the highway physical plant. Numerous studies directed toward the solution of the problem have been made within the National Cooperative Highway Research Program and elsewhere, and significant gains have been accomplished. Nevertheless, general agreement exists that further substantial improvement in the control of the problem is desirable and possible. One of the most significant of completed recent studies is described in NCHRP Report 165, “Waterproof Membranes for Protection of Concrete Bridge Decks—Laboratory Phase.” A follow-on field-evaluation phase of the study is in progress. These two studies are directed at controlling deck deterioration through the use of a waterproof-membrane layer on the bridge-deck surface, over which a wearing course is placed. Accomplishments to date indicate that the membrane approach will prove to be successful, especially where previous salt contamination is not present. The fact that there exists a large number of salt-contaminated decks in need of protection has inspired research into other control procedures, including cathodic protection. The cathodic-protection approach to corrosion control is well established and widely employed in connection with buried structures, including steel-reinforced concrete pipe.

In the study reported herein, USS Engineers and Consultants, Inc., researchers examined a variety of impressed-current and sacrificial-anode approaches to cathodic protection in the laboratory and in prototype testing. Among the impressed-current approaches, a method previously developed by the California Department of Transportation was examined in depth and concluded to offer the most promise of any of the cathodic-protection systems studied. This design con-
sists of an inert anode placed in a conductive overlay covering the surface of the
deck. The conductive overlay is made of asphaltic concrete containing coke
particles. Direct current supplied from an outside source serves to neutralize cor-
rosive action on the reinforcing steel. A sacrificial-anode design using zinc ribbons
in combination with an essentially nonconductive asphaltic concrete overlay also
was determined to hold promise if problems associated with low driving voltage
and expansion of anode corrosion products can be overcome. Accomplishment of
the study should be of value to any field evaluation studies of cathodic protection
of bridge decks that are undertaken. With the California Department of Trans-
portation in the forefront, several agencies are now conducting field evaluations
of the impressed-current approach to cathodic protection. The sacrificial-anode
approach is the subject of an on-going NCHRP study (Project 12-13A). The field
evaluations should provide answers to the questions being asked about the long-
term effectiveness of the systems in protecting steel against corrosion, the resistance
of the systems to physical damage, and the possible adverse effect of the bituminous
concrete overlays on the durability of the underlying concretes.

The report contains a number of recommendations that have received general
support from the advisory panel established to guide the project. An exception is a
recommendation that the steel polarized potential be limited to a maximum of
$-1100mV_{CuSo}_4$ to preserve bond between the reinforcement and the concrete. This
recommendation is based primarily on experience and judgment of the researchers
and minimally on project results. At least one expert in the field of cathodic pro-
tection believes that this may prove to be an unnecessarily restrictive limitation
disadvantageous to the application of cathodic protection to bridge decks.
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Other investigators include the following individuals from the U. S. Steel Research Laboratory who assisted in the project work and reduction of the data in the areas indicated: Dr. B. E. Wilde, Section Supervisor, and E. Williams, Senior Research Engineer, both of the Corrosion Technology Division, Appendix E, Electrochemical Studies; J. D. Swan, Senior Research Engineer, Corrosion Technology Division, and Dr. J. F. McDermott, Senior Research Engineer, Applications Research Division, Appendix E, Cathodic-Protection Exposure Tests. In addition, Dr. McDermott assisted throughout this project by providing information relating to various civil engineering aspects. T. D. Drexler, Senior Research Engineer, Mathematics Division, conceived and developed the mathematical model detailed in Appendix G.

Gratitude is also extended for the assistance of R. I. Osterholm, Research Engineer, and H. G. Augustine, Associate Chemist, both of the Chemicals Division, who planned and performed the electrically conductive asphaltic concrete studies described in Appendix F.
SUMMARY

The objective of the research reported herein was to develop a technically and economically feasible cathodic-protection method for steel-reinforced-concrete bridge decks.

Studies were made of factors affecting the cathodic protection of steel reinforcement in concrete and of possible methods of using this approach to control corrosion on highway bridge-deck reinforcement. Both laboratory and model tests were conducted.

Laboratory studies of the electrochemical behavior of steel in simulated concrete environments, with and without chloride, demonstrated that corrosion can be controlled by the application of cathodic current to corroding steel. Under all conditions tested, it was found that corrosion was stopped at a steel-polarized potential of $-770 \text{ mV}_{\text{Cu/CuSO}_4}$ measured to a copper-copper sulfate ($\text{Cu/CuSO}_4$) reference half-cell. Other studies showed that, at a potential of $-1170 \text{ mV}_{\text{Cu/CuSO}_4}$, hydrogen gas bubbles form at the steel surface.

Bond studies indicated that the application of a cathodic-protection current to rebars in concrete can decrease bond strength between the steel and the concrete. Evaluation of the results in relation to the anticipated conditions of cathodic protection applied to a bridge deck pointed out that the decrease in bond strength would be slight and would not give reason to reject the use of cathodic protection on bridge decks. The results also confirmed the finding of the state-of-the-art review that overprotection of steel in concrete should be avoided. This can best be done by limiting the maximum steel-polarized potential to a value of $-1100 \text{ mV}_{\text{Cu/CuSO}_4}$.

Two basic approaches to cathodic protection, the impressed-current and sacrificial-anode methods, were thoroughly investigated by using an analog model of a typical, reinforced bridge-deck section. This investigation showed that the essential electrical parameter for cathodic protection of a bridge deck in either approach is uniform current flow of appropriate value from a well-distributed anode system located on the deck surface. Exhaustive tests on an impressed-current system using a soffit-anode arrangement showed that this method is not economically practical because of the close spacing of anodes needed for adequate current distribution.

The most promising design consists of an inert anode placed in a conductive overlay covering the surface of the deck. The concept for this type of system was originated by the California Highway Department. The system developed gave complete protection of the top rebar mat with low impressed voltage and total current. Asphaltic concrete made conductive by mixing coke particles within the concrete mix is the practical answer to providing a conductive layer for bridge decking. Tests with coke breeze as aggregate in asphalt show that this material, while marginal with respect to stability, should meet the durability requirements.
of this application when it is provided with a wearing cover to protect it from traffic abrasion and to distribute wheel loads.

A demonstration of the conductive-layer system on a full-scale prototype of a typical deck section proved successful. In this work, several different combinations of conductive-layer thicknesses and types of anodes were used. In general, a 2-in.-thick layer of conductive asphalt worked best. However, a reduction in layer thickness was shown to be practical when the anode system is extended to give better distribution of current. A small-diameter platinized-wire anode was found to be suitable for this purpose.

It also became apparent from prototype tests that bridge-deck potentials measured with the half-cell placed over the conductive layer are in error. Drilling through the conductive layer and placing the half-cell directly on the concrete is the practical solution to this problem. When surveying a deck with a conductive layer, this procedure is necessary at several select locations to adjust potential readings measured in the normal way.

The sacrificial-anode approach investigated in this study was found promising. A mock-up demonstration showed that problems associated with low driving voltage and expansion of anode-corrosion products might be overcome by proper design and installation. In view of this, the requirements are identified for sacrificial-anode type, spacing, surrounding materials, and installation methods.

The various phases of this investigation were also concerned with the development of a mathematical model. This model uses a computer program to simulate cathodic-protection designs on a bridge deck and will predict the resultant rebar potentials for various applied voltages. The model was tested and verified during the cathodic-protection studies on the prototype deck. The model in its final form was used to develop a chart that predicts current distribution (in terms of rebar potentials attained) for various parameters of a conductive-layer design. A second chart was prepared that predicts the applied voltage and total current of the system.

On the basis of the results of this investigation, it is concluded that the cathodic-protection method of corrosion control can be successfully adapted to bridge decking. Both the sacrificial-anode and impressed-current methods show promise. Design criteria, applicable materials, and proper installation and checkout methods have been developed; the next step is a service evaluation on an actual bridge deck. The mathematical model developed during this project will be useful in evaluating localized conditions to aid in the actual field implementation.
CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

The increased use of deicing salts for removal of snow and ice from highways has resulted in premature deterioration of concrete bridge decks. Previous research has identified chloride-induced corrosion of the reinforcing steel in the bridge decks as the major cause of the deck deterioration. A number of alternative solutions are being investigated to determine their relative effectiveness for controlling or eliminating this corrosion. The purpose of the present research has been to investigate one of these solutions; namely, the use of cathodic protection as a method of suppressing bridge-deck corrosion.

DISCUSSION OF PROBLEM

It is generally recognized that the increased use of highway deicing salts (chlorides) is the principal contributing factor associated with the corrosion of steel reinforcement in bridge decks (1, 2). The riding quality of a bridge deck is most seriously impaired when there is a separation and removal of the surface concrete; that is, spalling resulting from a combination of physical stress and corrosion. The physical stresses from shrinkage, temperature change, or applied loading cause cracks in the concrete over the topmost rebars, and these cracks eventually permit access of moisture and deicing salts to the underlying steel. This, in turn, induces corrosion and eventually spalling. Even where there are no cracks, there is evidence that water and salts can permeate the concrete (1).

In any case, concentrations of salts or moisture at the steel surface result in destruction of the inherent passivity normally exhibited by steel in concrete (2, 3). Anodic and cathodic regions develop which induce galvanic corrosion cells. Because the corrosion products formed have about 2.2 times the volume of the steel they replace, the expansion causes pressure, which contributes significantly to the spalling of the concrete. Once spalling initiates, road salts and moisture have an even greater access to the reinforcing bars; and this leads to increased corrosion of the bars.

Several alternative methods for controlling or eliminating the corrosion of reinforcing steel in concrete are under investigation. Alternatives being investigated include: (1) impervious membranes to keep chlorides out of the concrete, (2) epoxy coating of the reinforcing steel itself in order to protect the steel from the influence of the chlorides, (3) use of galvanized rebars, (4) development of a non-corrosive deicer, (5) improvement of impermeability of the concrete cover, (6) neutralization of the effect of chlorides that have already entered the concrete, and (7) application of cathodic protection. It is with the last of these alternatives, cathodic protection, that this investigation is concerned.

The electrochemical principles for cathodic protection are well established, and this method of corrosion prevention is extensively employed in a wide variety of applications with great success. The principal application of cathodic protection for steel-reinforced concrete has been for buried pipelines, where it has been proven to be effective against the corrosive effects of soil and water. The method often has been used to save severely damaged pipelines. However, the use of cathodic protection for bridge decks presents certain problems not encountered with buried structures. Foremost among the problems is the lack of space and suitable environment for the anode. Nevertheless, at the outset of this research program, it was considered possible that a cathodic-protection method could be developed that not only would protect new bridge decks, but also would suppress active corrosion in existing salt-contaminated decks and, thereby, extend their useful life.

RESEARCH APPROACH

The over-all objective of the research described in this report is to develop a technically and economically feasible cathodic-protection method for steel-reinforced-concrete bridge decks. Effective cathodic protection must provide proper current distribution and achieve protective polarization potentials of the reinforcing steel. The principal objective of this research is to develop the design criteria and optimum design for cathodic-protection systems that meet these requirements and, thereby, can arrest or control corrosion of reinforcing steel in concrete bridge decks, particularly in existing structures. In pursuing these goals the investigation was divided into a number of parts, consisting of:

1. A review of pertinent past work concerning the application of cathodic protection for steel reinforcement in concrete.
2. Experiments to identify the electrochemical conditions under which steel in simulated concrete-bridge-deck environments will evolve hydrogen and be protected from corrosion.
3. Tests to determine whether cathodic protection can cause adverse effects on the concrete-to-rebar bond and on the concrete itself.
4. Determination of the essential electrical and physical parameters for cathodic protection of concrete bridge decks, using a physical analog and mathematical simulation methods.
5. Verification of laboratory-developed designs and criteria by controlled testing on a reinforced-concrete prototype specimen of a bridge-deck slab.
6. Development of information concerning applicable materials, procedures for installation, adjustment, and operation of proposed cathodic-protection systems.
7. Proposal of a method for evaluating the performance of selected cathodic-protection system(s) on a bridge deck under service conditions.
CHAPTER TWO

FINDINGS

Over-all, the findings of this investigation demonstrate that the cathodic-protection method of corrosion control can be successfully adapted to bridge decking. The sacrificial-anode and impressed-current methods were tested and show promise of meeting the requirements for practical and economical systems. The information needed for immediate implementation to decks for service evaluation has been developed. In addition, a mathematical model was developed which will be useful in evaluating localized conditions to aid in the field adaptation.

IMPLEMENTATION STUDIES

Perhaps the most significant result of the 18-month study was the finding that the sacrificial-anode method of applying cathodic protection shows promise of meeting the requirements for a technically and economically feasible way of eliminating corrosion of the reinforcing steel in bridge decks (Appendix H). The use of sacrificial anodes in the present application is not without problems, however. Results of the analog studies (Appendix F) show that, because of the low attendant driving voltage between the anode and the cathodically protected steel, a well-distributed anode arrangement will be essential. Other studies (Appendix F) indicated that, because of the expansive nature of the sacrificial-anode corrosion products, physical damage to the material surrounding the anode is possible. Despite these determinations, the results of prototype tests (Appendix H) prove that these problems might be overcome with proper design and installation methods.

Electrochemical studies (Appendix D) demonstrate that, in moist concrete containing some chloride, both magnesium and zinc anodes are capable of providing cathodic-protection current. However, the sacrificial-anode system found to be most promising in a mock-up test consists of using a flexible zinc ribbon, approximately 0.062 in. sq, placed on the concrete surface every 6 in. across the deck. The anodes and the deck are covered in the usual manner with asphaltic concrete, preferably one with an open-graded aggregate. Analyses by simulation, using the mathematical model developed during this project (Appendix G), show that this arrangement, with the anodes placed every 12 in. across the deck, should provide cathodic protection for the top rebar mat. Further, a prototype test (Appendix H) indicates that the sacrificial-anode method would be effective during all but prolonged dry weather periods.

Scale-model tests of the type described in Appendix F showed that the bridge-deck rebar network will meet requirements of electrical continuity and that the essential parameter of a cathodic-protection design is a well-distributed anode arrangement located over the top rebars. In addition to the aforementioned zinc anode arrangement, a design utilizing an electrically conductive overlay is also an effective means of meeting this requirement. Conductive pavement has been used for snow-melting systems, R. F. Stratfull of the California Department of Transportation (Appendix A) proposed using it for cathodic protection. The conductive-overlay design consists essentially of an anode in contact with an electrically conductive asphaltic concrete spread uniformly over the deck. It is used in conjunction with the impressed-current method of cathodic protection.

Tests of the type described in Appendix F showed that asphaltic concrete can be made electrically conductive by incorporating a carbonaceous material (coke breeze) within the concrete. This material has properties that, although marginal, indicate it should perform satisfactorily, with respect to resistance to rutting or shoving, when it is provided with a wearing-course overlay. Prototype model studies (Appendix H) showed that the cathodic protection was most efficient when a 2-in.-thick electrically conductive overlay was used; however, depending on the anode arrangement, this thickness could be reduced to as low as 0.5 in.

Two types of anodes were found to be suitable for use with the conductive-overlay design. One was a disk-shaped, 12-in.-diameter silicon-iron type; the other was prepared from a continuous platinum-surfaced niobium wire of 0.062-in. diameter. Neither of these anodes had any important deteriorating effect on the overlay system. In contrast, a test with the platinized wire anode embedded in concrete showed that anodic reactions caused considerable damage to the concrete.

During studies (Appendix E) with the conductive-overlay system, it was discovered that bridge-deck potentials measured with the half-cell placed on or over the conductive layer (containing coke breeze) were in error. From a laboratory investigation (Appendix D) of this problem, a theoretical expression was derived for computing true rebar potential from “topside” reference measurements. Later work with this system on the prototype deck showed that the true potential is obtained with the half-cell in contact with the concrete under the conductive layer.

Studies, described in Appendix F, with a solfit-anode impressed-current system showed poor current distribution to the top rebar mat. An area less than twice the anode-backfill contact area was protected by using maximum impressed voltage. Pulsing the impressed voltage lowered the current to maintain this protected area, but it did not improve current distribution and thereby increase the protected area.
**POTENTIAL CRITERIA**

Studies, described in Appendix D, with corrosion cells similar to those that might occur in a concrete-bridge-deck environment indicate that cathodic protection is achieved in all cases considered at a rebar polarized potential of \(-770 \text{ mV measured against a copper-copper sulfate reference half-cell} \ (mV_{CuSO_4})\). From polarization studies it was found that under certain conditions the rebar might be subject to pitting. However, the data show that the application of the aforementioned potential will cathodically protect against this attack as well as against general corrosion.

The investigation (Appendix E) to determine whether cathodic protection can cause adverse effects showed that the application of a cathodic-protection current to reinforcing bars in concrete can result in a decrease in bond strength between the steel and the concrete. It should be noted, however, that the current levels that produced the loss of bond were appreciably higher than would be used in a normal cathodic-protection application. A total applied current of 3460 amp hr/sq ft, applied at current densities as high as 960 mA/sq ft, produced about a 10-percent reduction in ultimate bond stress in these tests. Doubling the total applied current resulted in a further reduction in bond stress. There was relatively little effect shown between the applied current density and ultimate bond strength. Also, the bond stress required to produce a 0.01-in. loaded-end slip did not show a relationship to either current density or total applied current.

**MATHEMATICAL-MODEL DEVELOPMENT**

A mathematical model has been developed (Appendix G) to determine steady-state current flow in a bridge deck employing cathodic protection. This model, which uses a digital computer to carry out the calculations, can be used to calculate the area of bridge deck protected with a cathodic-protection system provided that various parameters of the system and the deck are known. To use the model, such parameters as the resistivity of the concrete and the type of anode system, along with the various physical aspects of the deck and cathodic-protection method, must be known. Given these parameters and the applied potential, the computer determines the current flow for each point in the deck and the current density at the rebar surfaces. In turn, an empirical relationship between the current density and the rebar potential is used to calculate the polarized potential of the rebar as measured in practice.

The mathematical model was developed and verified with data gathered from tests on the analog and prototype models used in this program.

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**CHAPTER THREE**

**INTERPRETATION, APPRAISAL, AND APPLICATION**

**INTERPRETATION**

The state-of-the-art review and the work conducted in this investigation clearly show that cathodic protection is effective against corrosion when applied to steel reinforcement in concrete bridge decks. A demonstration of cathodic protection, applied to a prototype model of a bridge-deck section, shows that it is a viable solution to the bridge-deck corrosion problem. Although the use of cathodic protection will require unique implementation, it will be equally adaptable to existing and new bridge decks. A measure of a minimum protection potential of the rebars is the parameter that will be used in the field to ensure that reliable protection has been attained.

From studies with steel reinforcement exposed to the same conditions as bridge decks, it has been established that corrosion is stopped by application of direct current after attainment of a minimum electrical potential of 0.77 V negative to a copper-copper sulfate reference half-cell. This electrical measurement is the simple, nondestructive test presently employed by many highway engineers to give a quantitative evaluation of the corrosion state of the deck steel. To determine the cathodic-protection effectiveness, a systematic survey of the electrical potential of the steel reinforcement will be made to ensure that the minimum protection potential exists over the deck surface.

The results of cathodic-protection exposure tests show that the application of a cathodic-protection current to reinforcing bars in concrete can result in a decrease in bond strength between the steel and the concrete. It should be noted, however, that the objective of the present tests was to observe the effects of very high currents. The 6920 amp hr/sq ft of current that was applied is far in excess of any reasonable level of cathodic-protection current that would be applied to a bridge structure. The 6920 amp hr/sq ft is equivalent to about 75 years of protection at a very high level of current density.

Bond stresses generally are not critical in the design of the reinforced-concrete slabs of bridge decks because the span-to-depth ratios of the slabs are relatively large. In fact, the AASHTO bridge specification does not require the computation of bond stresses in the design of bridge decks. Therefore, a moderate decrease in ultimate bond stress, such as 10 percent or possibly 20 percent, should not jeopardize
the ultimate safety of a deck slab. In the case of bond stress to produce a 0.01-in. loaded-end slip, no significant effect was noted.

The results of the cathodic-protection exposure tests confirm the findings of the state-of-the-art review (Appendix A) that overprotection should be avoided. Although the present study was not set up to quantitatively define the acceptable limits of potential for application of cathodic protection to steel reinforcement in concrete, the findings of this study indicate that this can be done by limiting the maximum rebar polarized potential to $\text{E}_{\text{cathodic of steel}}$. This potential permits operational latitude and also limits current density (see Fig. G-1) to a value well below the minimum that caused adverse effects on bond stress (Figs. E-6 and E-7). Coincidentally, the potential, $-1.1 \text{ V}_{\text{cathodic of steel}}$, is somewhat lower than the hydrogen-bubble potential of steel in concrete, which was determined in the laboratory to be $1.17 \text{ V}_{\text{cathodic of steel}}$. As judged by the results of splitting tensile tests on concrete cylinders containing no reinforcing steel, there is no effect on concrete strength from the application of a cathodic-protection current in the ranges covered in this study (2.5 to 10.0 mA/sq ft).

With reference to the electrical requirements of a bridge-deck cathodic-protection system, it was shown that the electrical continuity of the reinforcing network of most bridge decks should be suitably continuous and should have a sufficiently low resistance to ground. Also, the only possible way to obtain the uniform cathodic current flow to the top rebar mat, where it is needed to prevent deterioration of the bridge deck, is to provide a well-distributed anode over the top mat; that is, on the deck surface.

Exhaustive testing with a softf-anode impressed-current system showed that this approach is not likely to be economically practicable because of the close spacing of the anodes that is required for adequate current distribution. Similar testing of a surface system of impressed-current design indicated that a conductive overlay is required as part of the system for adequate current distribution. A distributed pattern of platinitized wire, alone, used for this purpose, did not work well. The most promising way found to spread the current is to place small anodes in a layer of coke breeze spread uniformly on the deck. The anode introduces the cathodic-protection current into the coke layer. Because the coke is a good conductor (electronic), it permits the current to be distributed and introduced uniformly into the deck concrete. In fact, the coke is a secondary anode with the attendant electrochemical reactions occurring at the points of current discharge.

The key to the implementation of this design was proposed by Stratfull (Appendix A) and relates to the use of coke breeze as aggregate in asphaltic concrete. This material was found to have properties that, although marginal, indicate it should perform well when protected by a conventional wearing course to distribute wheel loads and take the abrasion. From tests with this material on a prototype deck, it was learned that a 2-in.-thick layer of the conductive asphalt gave best current distribution. However, depending on the anode arrangement used to introduce the current into the conductive layer, this thickness may be reduced to a smaller value. Two anodes were found to work well with this system. They are a silicon-iron anode and a platinitized-wire anode. Both types met requirements for installation, life, and dependability for this application. Further selection of the anode type relates more to the thickness of the conductive layer than to other considerations. The anodic electrochemical reactions had no important deteriorating effect on either the conductive-overlay system or the anodes in this study.

A design for providing the cathodic protection, by using sacrificial anodes, is proposed, in which the rebars in the concrete deck are connected to the anode to produce a battery action for the purpose of generating the cathodic-protection current. During this investigation, magnesium and zinc alloys were considered for the anode metal. However, as a result of the findings of this test, zinc is the preferred material for the bridge-deck cathodic-protection system. As in the impressed-current tests, it was found that the best sacrificial-anode design is to place the anodes over the top rebar mat.

As opposed to the electrically conductive asphaltic overlay, distribution of the sacrificial-anode current was achieved by using long, ribbon-like anodes that are placed in a rather comprehensive pattern over the deck. This arrangement, combined with the use of permeable asphaltic concrete to accommodate anode corrosion products and permit ingress of water, worked well in a laboratory test. Once the asphalt becomes wet with chloride-bearing water, the zinc anodes become self-activate and the cathodic-protection current begins to flow and provides corrosion control until the anode metal is consumed by corrosion. However, field tests are needed to establish that, in actual practice, the permeable asphalt mix will not be choked with fine materials, from traffic abrasion of the pavement surface and other sources, which will fill up the voids that were provided to accommodate corrosion products and provide needed moisture. The useful life of an anode system can be readily calculated on the basis of an estimate of the average current produced by the anodes. Other results of the sacrificial-anode study show that, although dependent on moisture to function, it can be effective during all but prolonged dry weather periods.

The problems of cathodically protecting bridge-deck reinforcement are varied, and each bridge will always present original and unusual aspects. For these reasons, the mathematical model (Appendix G), developed and validated in this project, will have great significance in the final implementation of cathodic protection to existing bridges. The present computer program provides a basis for the development of a computer design system to evaluate various aspects, such as resistivity of the concrete, design of the reinforcement, type of anode system, and other physical aspects of the deck and cathodic-protection method under consideration. The computer program can be used to calculate the extent of protection achieved with the system.

As an example of one way the mathematical model will be used, the nomograms in Figures 1 and 2 were prepared on the basis of the results of mathematical-model analysis of the conductive-overlay design for an impressed-current anode system (described in Appendix H). The chart in Figure 1 is used to predict the polarized potentials of a
Figure 1. Polarized rebar potential, at a specific distance from the anode, for different conductive-layer parameters.

Figure 2. Cathodic-protection current and voltage for various deck-surface areas and conductive-layer parameters.
rebar in the top mat, at various distances from a single, disk-shaped silicon-iron anode, for different combinations of conductive-overlay resistivity and layer thickness. Figure 2 is used to determine the rectifier voltage and current for protection of various surface areas. The conditions used in the development of the data for these nomograms are those on the prototype deck during the model-verification study.

APPRAISAL

It is anticipated that the findings of this research will result in a viable method of applying cathodic protection to reinforcement bars in concrete bridge decks. The method will be adaptable to existing bridges throughout the United States, and it can be readily applied to new bridge decks. The criteria for the cathodic protection of steel reinforcement in concrete exposed to the same conditions as bridge decks have been established. Electrical requirements of a bridge-deck cathodic-protection system are clearly defined. Two promising cathodic-protection systems have been developed. Applicable materials, installation methods, and checkout and adjustment procedures to be used with each are described. A mathematical model has been developed to evaluate localized conditions and bridge geometry to aid in the actual field implementation of the recommended systems. These systems are immediately applicable to a service evaluation on actual bridge decking.

COST OF CATHODIC PROTECTION

The following estimates have been prepared on the basis of information developed during the experimental work with the two possible approaches of cathodic protection for bridge decks. It should be recognized that the costs of providing the conductive paving and AC power supply will vary greatly from location to location; each design approach could vary greatly to accommodate local conditions. Nevertheless, it was desirable to develop these estimates in order to make an economic evaluation of these methods of corrosion protection as compared with alternative methods.

The cost estimates are for a deck surface, 5000 sq ft, and do not include engineering costs (design or checkout) or the cost of deck reconditioning. The significant cost elements and the average cost for the proposed approaches to cathodic protection are as follows:

**Impressed-Current Approach: (10-Year Minimum Life)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Range of Cost (Installed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paving</td>
<td>$2000 to $3000</td>
</tr>
<tr>
<td>Anodes &amp; wiring (10 each)</td>
<td>$1000 to $1500</td>
</tr>
<tr>
<td>Rectifier (10 amp &amp; 10 V)</td>
<td>$500 to $2500</td>
</tr>
<tr>
<td>AC power supply</td>
<td>$500 to $2000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$4000 to $9000</strong></td>
</tr>
<tr>
<td><strong>Average cost per sq yd</strong></td>
<td><strong>$7.20 to $16.20</strong></td>
</tr>
</tbody>
</table>

**Sacrificial-Anode Approach: (10-Year Minimum Life)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Range of Cost (Installed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paving</td>
<td>$1000 to $1500</td>
</tr>
<tr>
<td>Zinc anode (ribbon)</td>
<td>$1500 to $2000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$2500 to $3500</strong></td>
</tr>
<tr>
<td><strong>Average cost per sq yd</strong></td>
<td><strong>$4.50 to $6.30</strong></td>
</tr>
</tbody>
</table>

In addition to the obvious cost advantage of the sacrificial-anode system over the rectifier approach, it should be noted that rectifiers have a continuing power expense and require more maintenance than the sacrificial anodes.

On the basis of a direct comparison by using 1974 costs, it would appear that the cathodic-protection approach ranks highest among the available ways to prevent corrosion of rebars in bridge decks. For example, the cost of cathodic protection (up to $16/sq yd) is well above estimated costs, which have been published in *Engineering News Record* (July 4, 1974), of either epoxy-coated or galvanized rebars ($10 and $5/sq yd, respectively), and it is higher than the reported cost of $9/sq yd for membrane systems. However, these approaches are not applicable to salt-contaminated bridge decks. In this light, the extra cost of cathodic protection may be warranted because it is the only available method (others are under development) for existing bridge decks.

It must be recognized that costs are subject to considerable fluctuation, and that cost relationships must always be viewed in the environment of current prices.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

From the results of this investigation, the following general conclusions are drawn:

1. Cathodic protection is a viable method of corrosion prevention for steel reinforcement in concrete bridge decks.

The method will be adaptable to existing bridges and can be readily applied to new bridge decks.

2. There are two possible methods of cathodic protection. In one method, the anode is a sacrificial metal such as zinc or magnesium, and the flow of current is induced by galvanic action. The second is one in which a current...
An anode that is not sacrificial in nature is impressed between the reinforcement and an exterior anode that is not sacrificial in nature.

3. An essential parameter with either cathodic-protection method is an anode arrangement over the top rebar, which gives a uniform current flow of appropriate value to the rebar mat.

4. An impressed-current cathodic-protection design consisting of an inert electrode in contact with an electrically conductive asphaltic concrete spread uniformly over the surface of the deck shows the greatest promise for the cathodic protection of bridge decks in the near future. The asphaltic concrete is made electrically conductive by incorporating a carbonaceous material within the concrete mix. The cathodic protection is most effective with a 2-in. thickness of conductive asphaltic concrete; however, by extending the electrode arrangement for introduction of the current into the conductive layer, a thickness of less than 2 in. can be used.

5. The electrically conductive asphaltic concrete has properties that, although marginal, should give satisfactory performance with respect to resistance to rutting or shoving when provided with a wearing-course overlay.

6. The sacrificial-anode method of cathodic protection also shows promise. This design will use a continuous-length anode of zinc that will be installed over the top rebar mat on the concrete and covered, in the usual manner, with asphaltic concrete overlay, preferably one with an open-graded aggregate.

6. It has been established that a minimum polarization potential value of -0.77 V to copper-copper sulfate reference is a suitable cathodic-protection potential criterion for corroding rebars in a reinforced-concrete bridge deck.

8. The overprotection of steel in concrete can lead to loss of bond between rebars and concrete. To avoid overprotection, the maximum polarized potential value with the rebars in the bridge deck should be limited to -1.1 V to copper-copper sulfate reference.

SUGGESTIONS FOR FURTHER RESEARCH

Research is still needed to determine whether the cathodic-protection method of corrosion protection for steel reinforcement in concrete bridge decks will perform satisfactorily under prolonged exposure to adverse weather and heavy traffic conditions. To answer this question, it is recommended that the following Phase II research program be initiated.

PHASE II—RESEARCH PLAN FOR SERVICE EVALUATION OF CATHODIC PROTECTION FOR REINFORCED CONCRETE BRIDGE DECKS

Objective

The over-all objective of the Phase II research program is to conduct a service evaluation of the cathodic-protection systems developed in the present investigation (Phase I) for steel-reinforced-concrete bridges. Two basic designs will be evaluated: (1) the sacrificial zinc-anode system with porous overlay, and (2) the impressed-current system with electrically conductive overlay. Each system will be installed and evaluated on a full bridge deck. The test bridges will be of typical size and with exposure and traffic conditions corresponding with those that cause bridge-deck deterioration. The test bridges are to be provided by NCHRP by arrangement with state highway departments.

The research will include a preliminary field survey to establish the “before” test condition of the bridge decks. Upon completion of this task, the state highway department will perform a rehabilitation of the decks. Concurrent with this work, the research tasks of providing necessary instrumentation in the decks and finalization of cathodic protection designs (using the mathematical model developed in the Phase I investigation) will be performed. After deck restoration and preparation of cathodic-protection designs, the research will include supervision of the installation of the cathodic systems (work to be performed by state highway department), followed by an 18-month field investigation of the systems' performance.

Preliminary Field Survey

A field survey of the bridge decks will be conducted to determine their condition and also to develop background information that would be helpful in evaluating the effectiveness of cathodic protection in preventing deck deterioration. This work will include an electrical potential survey as well as documentation of areas requiring repair. Other information concerning design, construction, and past maintenance will be recorded. The concrete resistivity and the electrical resistance of the rebar network will be obtained for use in the mathematical model study.

Deck Instrumentation

Each test deck will be instrumented with 10 electrical-resistance probes for measuring corrosion and evaluating the effectiveness of the cathodic protection. Eight probes will be equally spaced along the deck length at locations most remote from the cathodic-protection anodes. Two probes will be placed near anode sites on the deck. These probes will be used to accurately measure the cathodic current density at these points. The flat surface probe (Corrosometer Probe Model 60472) will be used. This probe has an exposed surface area of 10 sq in.; this larger surface area is needed to measure current densities on the probe. All probes will be embedded in concrete with chloride added to create a corrosive environment. The probes will be placed on the deck with the exposed metal facing up and at an elevation corresponding to the top mat. Each probe will be connected electrically to the deck steel at an accessible point along the side of the bridge. The corrosion rate of the probes will be measured periodically by disconnecting them from the deck steel and by using the Corrosometer Model CK-2. Because the probes are normally connected to the deck, they too will be under cathodic protection. Accordingly, a change in their resistance, which is indicative of their corroding, would indicate lack of cathodic protection in the deck steel near the probe area. The purpose of measuring the current density on the probes is to substantiate that the current density values associated with the potential criterion on actual concrete bridge decks.
are in the order of those estimated in the Phase I investigation.

**Cathodic-Protection Design**

After completion of the essential predesign tasks, the two cathodic-protection methods, developed during Phase I, and actual bridge information will be analyzed to determine the best designs for each method on the test bridges. It is proposed to use the mathematical-model computer program, developed in the Phase I study, for preparation of the specific cathodic-protection-design details. On the basis of these results, a design consisting of an electrically conductive asphaltic-concrete overlay and appropriately spaced inert anodes will be prepared. This design will consist of two parts: (1) a 2-in.-thick overlay with silicon-iron anodes and (2) a ½-in.-thick overlay with platinized wire anodes. (See Appendix H for anode details.) The two parts will be installed equally over the deck surface.

In the second case, an analysis will be made to determine anode spacing for a sacrificial-anode design using a continuous-length ribbon zinc anode placed on the concrete and covered with asphaltic concrete. This design will also have two parts: (1) using an asphalt overlay with an open-graded aggregate fraction and (2) using a normal, wearing-course asphaltic-concrete mixture.

In all cases, good electrical and cathodic-protection engineering practice, much of which is discussed in Appendix C, will determine the selection of electrical conductors and the various hardware, such as conduit fitting, as well as the method of installation and attachment of these items to the bridge deck. The connection of smaller wires will be made by the Thermit process or compression fittings, whereas the connection of larger cables and the connection to the steel core of the zinc ribbon will require use of a mechanical joint, such as a split-bolt connector.

A commercially available rectifier will be used with the impressed-current design. A convection air-cooled unit with rectifier elements of either selenium or silicon will be satisfactory. The rectifier current capacity will be determined from the model study. The operating voltage will also be determined by the model. However, the rectifier unit voltage is to be about 50 percent higher to provide for higher than anticipated circuit resistance.

In relation to durability, the “new and usual” materials are the electrically conductive asphalt concrete with the impressed-current system and the open-graded asphaltic concrete with the sacrificial-anode system. From the results of tests of stability and flow conducted with the electrically conductive asphalt concrete (Appendix F), it has been concluded that it should be provided with a wearing-course overlay. The sacrificial-anode overlay will be prepared with aggregate fractions corresponding to an acceptable open-graded mixture. Table F-4 gives information concerning these materials as they were prepared for the Phase I study.

**Installation of Cathodic Protection**

The installation will consist of positioning the anodes in accordance with the specifications prepared from the computer analysis. They will be installed in accordance with the procedures developed during the Phase I investigation.

The construction of the overlay, for the most part, will be consistent with usual practices and specifications for this type of work. The anode wiring arrangement will include a separate wire to each inert anode and provision to measure the current flow to them. This is done by measurement of a voltage drop across a shunt installed in series between each anode and the rectifier. For the zinc anode (sacrificial), the current-measuring shunt will be installed in series between a given length of the zinc ribbon and its connection to the deck steel.

**Field Investigation**

After the cathodic-protection systems have been installed, but before the rectifier has been turned on and before the zinc anodes are attached to the deck steel, a systematic survey of the electrical potential of the steel reinforcement will be made by using a reference electrode and appropriate electrical instrumentation. On the deck with the conductive overlay, a limited number of small holes must be drilled through the overlay in order to make check readings with a reference electrode contacting the deck under the overlay (see Appendix H). This result will indicate an adjustment value to be applied to potential readings obtained nearby and with the reference placed in the usual manner.

The cathodic-protection rectifier will be turned on and adjusted to the current value required to provide the cathodic protection (indicated by the computer analysis). Also, the zinc anodes on the second test bridge will be connected to the deck steel. Approximately one month after activating the cathodic protection, all readings (electrical-resistance probe-corrosion rate and the total current flow to each probe, anode current readings, and steel reinforcement potential measurements) will be obtained. These measurements, along with information concerning the physical condition of the bridge decks and cathodic-protection equipment (visual observations), will be obtained once each month thereafter. During this test, adjustment of the current from the various anodes used with the impressed-current system may be necessary to maintain the steel-reinforcement potential within the range, \(-0.77\) to \(-1.10\) V, shown in the Phase I study to be a suitable potential criterion. This adjustment is best made by installing resistance in the anode circuit. No adjustment will be required in the zinc-anode system because of the self-limiting potential value.

**Evaluation of Systems**

After these systems have been in operation for 18 months, critical analyses of their performance will be made. The analyses will be based on the results of the electrical-resistance probe readings, the ability of the systems to maintain the steel potentials in the required protective range, and the physical condition of the bridge decks and the cathodic-protection hardware and equipment at the end of the test. In addition, the information developed during the evaluation will be used to prepare a detailed manual for highway engineers and administrators to aid in the design and immediate implementation of the new methods to prevent deterioration of concrete bridge decks. The manual will
cover the use of the computer program for development of
design details, the proper selection of materials and equip-
ment, methods of activation, checkout and adjustment, and
maintenance of bridge-deck cathodic-protection systems.

**Time Requirements**

All work on Phase II will be completed within 27 months
after the effective date of the contract. The PERT diagrams
of Figure 3 and the associated activity description given in
Table 1 present the schedule of the Research Plan, includ-
ing the time when each task will begin and its anticipated
duration.

![PERT diagram for Phase II](image)

**Figure 3. PERT diagram for Phase II.**

| TABLE 1 |
| PERT DESCRIPTION TABLE |

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Begin</th>
<th>End</th>
<th>Activity Description</th>
<th>Time Duration</th>
</tr>
</thead>
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<td></td>
<td></td>
<td>Months</td>
</tr>
<tr>
<td>Begin</td>
<td>End</td>
<td></td>
<td></td>
<td>Begin</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td></td>
<td>Preliminary Field Survey</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td></td>
<td>Cathodic Protection Design Analyses</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td></td>
<td>Rehabilitation and Instrumentation of Decks</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td></td>
<td>Installation Cathodic Protection Systems</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td></td>
<td>Field Investigation</td>
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<td>6</td>
<td>7</td>
<td></td>
<td>Evaluation of Systems and Preparation of Field Manual</td>
<td>24</td>
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<tr>
<td>7</td>
<td>8</td>
<td></td>
<td>Review of Report</td>
<td>27</td>
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</tbody>
</table>
REFERENCES


APPENDIX A

STATE OF THE ART, CATHODIC PROTECTION FOR STEEL REINFORCEMENT IN CONCRETE

INTRODUCTION

The first task of the research program was to prepare a state of the art to determine how much was already known about cathodic protection for reinforced-concrete bridge decks and to identify those systems, materials, and procedures that offer promise of controlling corrosion in this application. Because only one earlier application of cathodic protection to reinforced-concrete bridge decks was known to have been made, and because many of the same principles, techniques, and other aspects of the practice of cathodic protection for steel in concrete (usually in soil and water) are applicable, the scope of the review was enlarged to include also those phases of the cathodic protection of steel in concrete that appeared specially pertinent to the bridge-deck application.

In the review that follows, no attempt is made to discuss every application of cathodic protection to steel in concrete that has been reported. Instead, the review is presented in the form of a summary of the present state of knowledge, with pertinent references inserted when needed to indicate information sources.

The summary was prepared specifically for the bridge engineer. Accordingly, the basic considerations of both the corrosion process and the cathodic protection process are discussed initially. This is followed by a historical review of the general use of cathodic protection and the methods of applying cathodic protection of steel reinforcement in concrete. Other facets of the corrosion problem that are reviewed include design considerations, cathodic-protection criteria, analog models, and cathodic protection of bridge decks.
BASIC CONSIDERATIONS

Why Metal Corrodes

The fundamental reason metal corrodes is that the corrosion products are thermodynamically more stable than the metals themselves. It is generally recognized that the ordinary corrosion observed is electrochemical in nature and that, for steel in concrete, the electrochemical reactions result from salt-laden moisture in contact with the steel (3, 4). For such reactions to occur, there must exist areas of different electrical potential that are electrically connected. When these conditions are met, corrosion occurs through the transfer of metal ions to the moisture, leaving electrons behind. By definition, this is an anodic reaction and the areas that corrode are called anodic. The remaining electrons move through the metal from the anodic areas to non-corroding locations, where they react with either water or oxygen. By definition, this is a cathodic reaction and the locations at which it occurs are called cathodes. The electrons neutralize cations in the electrolyte, thus completing an electrical circuit. This corrosion is, in effect, an electrolytic battery.

How Cathodic Protection Works

The basic hypothesis of cathodic protection is that all galvanic corrosion on a structure has been halted when all points on its surface have been polarized to a potential equal to, or more anodic than, the open-circuit potential of the most anodic point on the structure (5).

In this condition, all points on the surface of a structure are at the same potential. Since there are no potential differences between points on the structure surface, no galvanic currents are flowing and no galvanic corrosion is occurring. This can be visualized by referring to the potential-current diagram shown in Figure A-1. The current applied, \( I_a \), when of a proper value, causes the corrosion potential, \( E_{corr} \), to be changed to coincide with anode potential, \( E_{an} \), on the threatened structure. Therefore, the essential factor in cathodic protection is met and no corrosion current can flow.

History of Cathodic Protection

Most authorities credit the English scientist Sir Humphry Davy with the earliest example of a practical application of cathodic protection, when in 1824 he initiated the use of zinc to control corrosion of copper bottoms of ships (6). From this work, it is evident that the electrolytic theory of corrosion and certain present-day problems of galvanic corrosion and corrosion prevention were partly anticipated by Davy.

In 1903, some 80 years after Davy's work, the electrochemical principles of corrosion were expressed in their most useful form by Whitney (7). Whitney's work provided the basic structure for modern methods of corrosion control by demonstrating that the corrosion of iron in water is electrochemical in nature.

At about this same time, extensive systems of underground metal pipelines were being constructed throughout the United States. By the 1920's, corrosion leaks began to occur on these pipelines with alarming frequency. Prior to about 1930, the principal cause of the corrosion on these pipelines was reportedly stray current from trolley cars operated with direct current (8). Because the stray-current effects greatly overshadowed other causes of corrosion, they were generally considered to be the sole cause. Reflecting this concern for the stray-current problem, the National Bureau of Standards, in 1913, conducted extensive experiments to investigate the damage caused by stray currents to structures embedded in concrete (9). This was the first reported interest in the corrosion of steel in concrete. This work clearly established that, under certain conditions of cathodic reaction on the steel, a loss of bond strength between the concrete and steel was possible.

After 1930, a move to discontinue operation of the trolley cars began; however, the corrosion of buried metals continued at an intensified rate (10). This produced the realization that stray current from the trolley system, while creating an adverse effect at various locations on underground cables and pipelines, was also providing a beneficial cathodic-protection effect at other locations on these cables and pipes. Interestingly, in some cities, movements were started to set up large-current generators to create earth currents to continue these benefits. Consequently, the major pipeline and telephone-cable owners began anticorrosion steps to protect the exteriors of their pipes and metallic cables.

Initially, the anticorrosion measures consisted mainly of providing various types of protective coatings for the metal. Extensive use was made of cement as a protective coating for pipelines (11), even though the protective value of cement coating in areas of stray currents was regarded as questionable at best. The use of cement protective coatings declined with the increased use of cathodic protection. At present, cement coatings are used under certain circumstances as protection for underground gas lines (12).
The use of cathodic protection grew rapidly with the development, in the mid-1930's, of a new source of direct current, known as the copper oxide rectifier. These earliest cathodic-protection applications were very successful; and it was apparent that the cathodic-protection method of corrosion control gave the following advantages:

1. When properly applied, corrosion is completely stopped.
2. The effectiveness of cathodic protection in arresting corrosion can be measured by a simple, nondestructive electrical measurement.
3. The cost of applying cathodic protection is a fraction of the replacement cost of the threatened structure, and cathodic protection is clearly the least expensive means of providing long-term, maintenance-free service life for metal structures in corrosive environments.

Shortly after the end of World War II, corrosion problems developed with large-diameter, prestressed-reinforced-concrete water pipelines in Europe, Israel, and North Africa (13, 14, 15, 16). During the 10-year period between 1945 and 1955, the use of cathodic protection to prevent such corrosion became widespread. Other cathodic-protection applications for steel in concrete include underground portions of concrete water-storage tanks, steel reinforcement and liner plate of concrete nuclear-reactor containment vessels, and concrete-coated piling; however, the use of cathodic protection in these applications has not reached major proportions.

How Cathodic Protection is Applied

The cathodic protection of metal is applied by causing a flow of current from any source to the metal (5). Two methods are generally used to transmit the protective current (17, 18, 19). In one, the threatened structure is made the cathode of an electrolytic corrosion cell with a more active metal as an anode. In the second, the threatened structure is made to react as a cathode by using an external power source.

**Electrolytic-Cell Method (Sacrificial-Anode Systems)**

To obtain cathodic protection by the electrolytic-cell method, a metal electrode that is anodic to the metal of the structure is connected to the structure by a metallic conductor and is placed in the electrolyte with the structure, as shown in Figure A-2. In this arrangement, the structure and the anode operate as a bimetallic corrosion cell. The anode electrode is sacrificed: thus, the name “sacrificial-anode system.” In effect, the corrosion is transferred from the structure to the anode, which is expendable and may be easily replaced. The driving potential for the current is the natural potential difference between the metal of the structure and the anode. Some typical potential relationships are shown in the limited tabulation of the practical galvanic series of metals given as follows (19):

<table>
<thead>
<tr>
<th>Typical Metal</th>
<th>Potential, volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium alloy (6% Al, 3% Zn, and 0.15% Mn)</td>
<td>-1.60</td>
</tr>
<tr>
<td>Zinc</td>
<td>-1.1</td>
</tr>
<tr>
<td>Aluminum alloy (5% Zn)</td>
<td>-1.05</td>
</tr>
<tr>
<td>Mild steel (rusted)</td>
<td>-0.2 to -0.5</td>
</tr>
<tr>
<td>Mild steel in concrete</td>
<td>-0.2</td>
</tr>
<tr>
<td>Copper</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

*Typical potential normally observed in neutral soils and water, measured to the copper sulfate reference.

From this listing, it is obvious that the magnesium offers cathodic protection to any of the other metals listed, whereas copper does not. In practice, alloys of magnesium, aluminum, and zinc are used as sacrificial anodes, although only magnesium and zinc are generally used for the cathodic protection of steel reinforcement in concrete.

**External-Power Approach (Impressed-Current Systems)**

The external-power approach to cathodic protection is shown in Figure A-3. This system operates in the same
manner as the sacrificial-anode system, except that external power is provided to drive or impress the current into the structure receiving protection. Because the current flow does not depend on the relative potentials of the anode and the metal of the structure, the anodes are selected on the basis of their capability to conduct current and transmit it to the electrolyte with a minimum amount of corrosion to the anode. Carbon and high-silicon cast iron are the anode materials most often used. Although carbon is not a metal, it has excellent electrical properties and does not corrode while transferring the current.

The protective current for impressed-current systems may be obtained from several possible sources. Batteries and wind-driven generators have been used in remote locations with no alternating-current power. However, the most common source is the rectifier, which converts alternating-current power to direct-current power. The cathodic-protection rectifier can be adjusted to produce a range of voltages, so that the necessary current can be provided under various conditions.

**Comparison of Systems**

Although the two different systems of cathodic protection—the sacrificial-anode system and the impressed-current system—perform the same function, there are inherent advantages and disadvantages to each.

The primary limiting factor in the use of sacrificial anodes is their low driving voltage, since they rely on the inherent galvanic potential. This is particularly true of zinc, which has a driving potential of about 250 millivolts (mV) when coupled to a protected steel structure. This limitation restricts the use of sacrificial anodes to environments of relatively low electrical resistivity. The impressed-current system, on the other hand, can be designed to deliver large amounts of current at high voltage and, therefore, can be used in almost any environment. However, these higher voltages and currents establish an extensive current field in the earth, which is more likely to produce interference on any nearby structure. Also, the use of high current and voltage may result in nonuniform potentials and possible overprotection, which, for steel reinforcement in concrete, may cause an adverse effect on the bond between the concrete and the steel.

Another advantage of the sacrificial-anode system is that, when properly installed and left undisturbed, it may be expected to operate continually without maintenance for the life of the anodes. Because the driving voltage is inherent and the currents and voltages involved are relatively small, there is little chance of system failure. The equipment used with the impressed-current method is subject to some deterioration and does require periodic maintenance and inspection to ensure its continued operation. Also, the nature of the impressed current is such that any flaw in the anode cable insulation can result in an interruption of the current flow. The cathodic protection might also be interrupted by power failure or by inadvertent or ill-advised disconnection from the power source.

* Interference is a form of stray-current corrosion in which the offending current is from a cathodic-protection system.

**Design Considerations**

The present practice for the cathodic protection of steel reinforcement in concrete includes the use of sacrificial-anode and impressed-current approaches. The principal use for cathodic protection is to prevent corrosion of steel reinforcement in concrete water pipelines buried in the soil. Also, the methods, procedures, materials, and equipment used with these applications are largely the same as those used with purely metallic pipelines. Appendix C contains a review of the practices associated with these applications. The discussion in the following paragraphs relates to certain inherent characteristics of reinforced-concrete structures that necessitate special consideration in the planning of the use of cathodic protection.

**Electrical Continuity**

The successful use of cathodic protection for steel reinforcement in concrete requires electrical continuity between the various metallic members of the reinforcement (20). If one segment of the reinforcement is electrically isolated from the remainder and from the point of protective current drainage, it will receive little or no protective current and could be damaged by cathodic interference. In one example, axial current flow on a reinforced-concrete pipeline is reported to have caused serious corrosion when the current was forced to bypass a high-resistance pipe coupling through the earth. A potential difference of 100 mV or more has been measured at this type of pipe joint. Experience shows that originally suitable continuity at pressure contacts, as at mechanical pipe couplings, can act erratically and change for no apparent reason. This erratic performance, as well as causing cathodic interference, makes systematic investigation of galvanic corrosion impossible. Therefore, it is a common procedure to provide bonding between all of the various elements when the use of cathodic protection is anticipated. For cast-in-place reinforced concrete, the bonding is usually accomplished by welding the reinforcement during construction. However, because welding of prestressed steel is not recommended, mechanical connections are usually provided for prestressed-concrete structures. The bond must always have effective metallic connection to the structures involved.

**Potential Attenuation**

Large prestressed-concrete pipe sections and concrete tanks contain long lengths of prestressing steel wire. The protective current flow through this wire may result in excessive attenuation of potential when the structure is placed under cathodic protection (21). This problem is further aggravated with cement-coated steel because the current requirements for cathodic protection are somewhat higher than for an organic-coated steel, and, reportedly, are somewhere between the requirements of bare steel and organic-coated steel in the soil (15). Therefore, a second impor-
tant electrical parameter for the cathodic protection of steel reinforcement in concrete structures is to maintain a low conductivity along the length of the reinforcement networks to avoid excessive potential attenuation (21). This problem is overcome on concrete pipe by providing intermediate bond to increase the frequency of drainage connections, often through the use of an exterior shunt cable connected to the pipeline at frequent intervals along its length. Robinson (22) reduced the potential attenuation along 11,800 ft of No. 6 wire on prestressed pipe by a factor of six by using intermediate bonds between the wire and the pipe cylinder. These steps are necessary to avoid extreme nonuniform potentials on the structure and to minimize the current requirements for cathodic protection.

Cathodic-Protection Criteria

Potential Criterion

Early investigators established that the most highly anodic areas on steel will have a potential of about $-0.80\ V$ as measured to a copper sulfate reference contacting the environment reasonably near the anodic area (23). Accordingly, the practical potential value of $-0.85\ V$ has been adopted as an indication that a cathodically protected structure has been polarized to a potential equal to, or more anodic than, the most anodic point on the structure. This is the most widely used criterion for cathodic protection of steel in soil and water exposure (24). The criteria for the cathodic protection of steel in concrete are not as clearly established. For example, Scott (25) has shown that the cathodic protection of steel, with a damaged concrete coating, was obtained with a polarized potential in the range $-0.71$ to $-0.81\ V$ to the copper sulfate reference. This potential range is somewhat more negative than the potential of iron in equilibrium with a saturated ferrous chloride solution. Hausmann (26) suggested a criterion for the cathodic protection of steel in concrete that is somewhat different. His criterion is dependent on whether the steel is corroded or uncorroded. He recommends a minimum value of $-0.50\ V$ to copper sulfate reference for uncorroded steel in concrete and a minimum value of $-0.71\ V$ to copper sulfate reference for corroded steel. The Scott and the Hausmann criteria both relate to cement-coated steel in a chloride environment.

Although the corrosion of cement-coated steel may be arrested at potentials substantially less negative than the usual steel-in-soil criterion of a minimum value of $-0.85\ V$ to copper sulfate reference, this criterion is, nevertheless, generally employed for cathodic protection in concrete. This criterion is accepted on the basis that, at locations where the concrete is grossly damaged or seriously deteriorated, the open-circuit (anodic) potential of the steel may reach $-0.80\ V$ to the copper sulfate reference as on any corroding bare-steel surface.

Overprotection

A major difference between the steel-in-soil and steel-in-concrete potential criteria for cathodic protection is that the maximum potential value with the cement-coated steel must be limited to about $-1.1\ V$ to copper sulfate reference (25, 26). It has been recognized, for some time, that to maintain the steel potential at or beyond $-1.1\ V$ results in hydrogen evolution at the steel surface. This practice is wasteful, because most of the current is expended in the electrolysis of water. However, with steel-in-soil applications, where it is expedient, potentials well above those resulting in hydrogen evolution are permitted. Experience and testing with concrete and cement-coated steel show that, although the passage of current through concrete has no detrimental effect on the concrete itself, certain reactions are possible at the cathodic steel surface that may result in a loss of bond between the concrete and the steel (9, 15, 25, 27 through 30).

Bureau of Standards’ tests in 1913 first showed that a definite softening of the concrete occurred near the cathode when reinforcing steel was made cathodic (9). This softening resulted in the loss of the bond between the smooth reinforcing steel and the concrete, and was, reportedly, due to the gradual concentration of sodium and potassium ions near the cathode by the passage of the current. Although the area of softening increased with time (as far as $0.5$ in. or more), the main body of the concrete showed no adverse effect. Later testing by Mole (27) confirmed the Bureau results, but it also showed that concrete free of alkali metal could successfully withstand cathodic current densities up to 18 milliamperes (mA) per square foot. Tests by the U.S. Army Corps of Engineers (29) showed measurable loss of bond at 20 mA/sq ft, whereas at 2 and 5 mA no damage occurred for the 54-months' duration of the test.

However, work by the Jersey Production Research Company (31) showed that the bond strength between the high-strength concrete and deformed reinforcing bars did not depend on the applied voltage or current, but on the total applied ampere hours per square foot of embedded steel surface. In this study, different voltages (2 to 48 V) were applied to different specimens for different times. Each specimen was submerged in dilute synthetic sea water with a chloride content of 400 ppm. The test results show that loss of bond strength is roughly proportional to the applied current up to about 3400 amp hr. At this value, loss of about 25 percent in bond strength occurs. The application of an additional 3400 amp hr/sq ft caused no further significant change in the specimen bond strength.

The most recent published information concerning this problem is by Scott (25), who conducted tests on spring-loaded tapered-steel rods cast in concrete. The significant results of Scott’s work are as follows:

<table>
<thead>
<tr>
<th>Applied Voltage, volts</th>
<th>Potential, volts</th>
<th>Specimen</th>
<th>Results of Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>$-0.812$</td>
<td></td>
<td>No loss of bond after 880 days</td>
</tr>
<tr>
<td>1.14</td>
<td>$-1.052$</td>
<td></td>
<td>No loss of bond after 880 days</td>
</tr>
<tr>
<td>1.54</td>
<td>$-1.148$</td>
<td></td>
<td>No loss of bond after 594 days</td>
</tr>
<tr>
<td>2.14</td>
<td>$-1.156$</td>
<td>Rod pulled out in 197 days</td>
<td></td>
</tr>
</tbody>
</table>

*Polars of potential of the steel rod measured to copper sulfate reference.*

Scott’s findings appear to substantiate the field practice.
for the cathodic protection of concrete pipelines. The present practice is to control the polarized potential of the pipeline within the range $-0.90$ and $-1.1$ V to copper sulfate reference. Empirical determinations of the current densities associated with this potential criterion show that the current density required for protection is always less than 1 mA/sq ft (16). Twenty-five years of experience with this criterion indicate that it provides a margin of safety and also permits operational latitude without damage due to over-protection of the protected structure.

**Analog Models**

Cathodic-protection studies have been performed by using analog models of threatened reinforced-concrete structures (14, 16, 31, 32). In general, a model of the steel elements is constructed in a suitable scale, following the essential details of the actual structure. This model is placed in a liquid that simulates concrete in its electrochemical nature. A saturated lime (calcium hydroxide) solution and fresh cement slurry have been determined to be suitable for this purpose, because calcium hydroxide is the principal soluble component of hydrated portland cement (26). The pH of portland cement (about 12.5) and that of saturated lime solution are about the same. In other models, an actual section of the structure, usually a concrete pipe, has been instrumented with corrosion-rate-measurement electrodes (14) and installed in a soil or water electrolyte; in general, the more suitable approach is to immerse the steel elements in a solution simulating the concrete.

Heuze (16) used an analog model to investigate the important electrical parameters, such as electrical continuity of the reinforcing network. He also used the model to analyze the cathodic-protection-current distribution at the surface of complex reinforced-steel structures to be cathodically protected. Such analysis is an important consideration in cases involving electrical-screening effects, in which the current passes through various networks of reinforcement to arrive at a surface requiring protection. In addition to the aforementioned electrical parameters, Heuze investigated the loss of driving potential and associated inequalities in the surface potential on models under various conditions of applied voltage between the cathodic-protection anode and the model.

Although the calcium hydroxide solution permits the flexibility of working in an aqueous solution, both Scott (25) and Heuze (16) recommend a pretreatment of the steel surface before placing the model to be tested in the solution. This treatment consists of applying a high cathodic-current density to the steel surface in a saturated solution of calcium carbonate to deposit a calcium carbonate coating on the steel surface. Because the coated-steel surface more closely simulates the actual cement-coated steel, the current density and potential relationship in any subsequent testing will more closely simulate actual conditions.

Because concrete resistivity will vary widely, depending on many factors, such as the amount and type of contaminants in the environment, Heuze suggested that a suitable low value be selected for the model testing. By selecting a low value for resistivity, the chances for under-estimating the cathodic-current requirements are reduced. Stratfull (1) has found resistivity values as low as 100 ohm-centimeters (ohm-cm) for concrete wet with salt water. The resistivity of the concrete is represented by the resistance of the electrolyte simulating the concrete, divided by the scale. Model scale is often made larger than actual structure scale to enlarge important structural details. In all, four parameters of the model may be varied: (1) the size, (2) the resistivity of the electrolyte, (3) the cathodic potential, and (4) the current or current density used.

In addition to evaluating the aforementioned aspects, Heuze (16) investigated certain other factors concerning extraneous conditions of the cathodic-protection design. These included the placement of the cathodic-protection anodes and the resultant current distribution and potential on the steel reinforcement. His work shows that, except for the factors affected by the somewhat higher than usual current requirements, the exterior portions of the cathodic-protection design for steel reinforcement in concrete are usually very similar to those for protection of purely metallic structures.

**CATHODIC PROTECTION OF BRIDGE DECKS**

Apparently, the only attempt at cathodic protection of an above-grade concrete structure was made by Stratfull in 1958 (4). In this work, a cathodic current was applied to the concrete beams and several deck units of a bridge over San Francisco Bay, on a test basis. The electrical current was introduced into the concrete at various locations by carbon anodes sealed into the structure with a mixture of gypsum, mica, and calcium chloride. The system appeared to work effectively for about one year (no new anodic areas developed during this time). However, because this bridge was severely deteriorated, it was dismembered before conclusive results of the test could be obtained.

Recent work by Stratfull concerns the development of a method to evaluate the electrochemical and electrical state of the steel reinforcement in the concrete deck, as well as the development of a cathodic-protection system for existing bridges. Stratfull's method for evaluating the electrochemical condition and electrical state of the steel reinforcement consists primarily of making a systematic survey of the electrical potential of the steel reinforcement by using a reference electrode and appropriate electrical instrumentation. The measured potential gives a quantitative evaluation of the electrochemical state (active or passive) of the steel and of various electrical parameters essential to the application of cathodic protection, including the electrical continuity of the reinforcing network. His results to date indicate that the steel reinforcement network in bridge decks is electrically continuous.

The essential feature of the new cathodic-protection system for bridge decks under investigation by Stratfull is the development and use of an electrically conductive overlay on the bridge deck. The overlay utilizes coke breeze as the concrete aggregate. The cathodic-protection current is introduced into the overlay at strategic locations from an impressed-current anode. The coke-breeze covering gives
good cathodic current distribution from the anode to the top row of steel rods. (It is Stratfull's intent to protect only the top row.)

The principal application of cathodic protection for steel-reinforced concrete has been for buried pipelines, and cathodic protection has been proved to be effective against the corrosive effects of soil and water, often to save severely damaged pipelines. The use of cathodic protection for bridge decks, however, presents certain problems not encountered with buried structures. Foremost among the problems is the lack of room and suitable environment for the anode. Stratfull has proposed one solution to this problem, but other solutions may be found. Another important consideration concerning the use of cathodic protection for bridge decks relates to the electrical continuity of the deck rebars, which are tied together with steel wire. Again, recent studies by Stratfull indicate that the electrical continuity may prove to be satisfactory.

Investigation of both of these constraints will be possible by using scale models of deck sections. Previous test results with models of various other structures have produced good results and have led to subsequent successful applications of cathodic protection to complex, steel-reinforced-concrete structures.

In summary, it should be pointed out that the principles, techniques, field practices, and other aspects of cathodic protection for steel reinforcement will prove useful in finding a satisfactory solution to the problem of applying cathodic protection to a bridge deck. However, the major questions concerning the implementation of cathodic protection to a bridge superstructure are unanswered. The ultimate success of cathodic protection for bridge decks, therefore, depends on the development of a unique design to permit placement of the anodes and completion of the necessary electrolytic circuit.

APPENDIX B

BIBLIOGRAPHY, CATHODIC PROTECTION FOR STEEL REINFORCEMENT IN CONCRETE

INTRODUCTION

The articles in the following bibliography relate to the cathodic protection of steel reinforcement in concrete. The bibliography is arranged chronologically and, within a particular year, alphabetically according to the authors. Articles without listed authors are placed last in the list of a given year.

In addition to articles providing specific information in the subject area, several are included that describe inadvertent application of cathodic protection of steel reinforcement. These articles serve to illustrate that cathodic protection of steel in concrete is more widespread than is generally recognized. Other articles, although not specifically dealing with application of cathodic protection for steel reinforcement in concrete, relate to the electrochemical reaction of cement-coated steel electrodes and are, therefore, pertinent.

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1913

1948

1949

1952

1954

1955
1956

1957

1959

1960

1961

1962

1963

1964

1965

1966
42. HEUZE, B., "Corrosion and Cathodic Protection of Steel in Prestressed Concrete Structures." Part I, Con-
APPENDIX C

AN INTRODUCTION TO SOME OF THE FIELD PRACTICES
FOR APPLICATION OF CATHODIC PROTECTION

INTRODUCTION

This Appendix will be of interest to the bridge engineer. The general treatment given will provide the individual who may occasionally encounter the subject with a better understanding of the methods, procedures, materials, and equipment used in this work; it will serve, as well, to point out some practices associated with steel in concrete that differ from those normally employed with cathodic-protection systems. It should be noted that the principal use of cathodic protection with steel-reinforced-concrete structures is for structures buried or submerged in soil or water. Accordingly, the external aspects of the cathodic-protection practice for steel reinforcement are largely the same as those for purely metallic structures. Several comprehensive works (17, 18, 19, 33) concerning cathodic-protection practices are available and should be consulted if a critical review of the subject is required.

SACRIFICIAL-ANODE SYSTEMS

Magnesium and zinc sacrificial anodes are the types used with steel reinforcement. When properly installed, these anodes provide a reasonably constant potential without the
Impressed-current cathodic protection is the preferred method for steel-reinforced-concrete structures. The principal difference between impressed-current and sacrificial-anode methods is that the cathodic-protection current can be regulated through selection of the output voltage of the impressed-current power supply. This difference is an advantage in high-resistivity environments in which sacrificial anodes have limited current output.

Anodes

The impressed-current anode, or, as is usually true, a group of anodes, acts as the ground electrode through which protective current is introduced into the soil or water electrolyte. As with the sacrificial anodes, the technology of impressed-current-system anode-material selection and ground-bed design is well known and is usually the same for both steel-reinforced concrete and all steel structures.

Two types of impressed-current anodes are in general use: graphite and a silicon-iron alloy composition. Under some circumstances other materials, such as scrap steel, lead alloy, and platinum-plated titanium, have been used for impressed-current anodes. The use of these materials is not common and, except for steel, their use with reinforced-concrete protective systems has not been reported.

Graphite anodes are inert chemically and have good electrical conductivity. A possible disadvantage is that a carbonaceous backfill is necessary with graphite anodes that are installed underground; however, no backfill is required for graphite anodes in fresh water or in sea water.

Because graphite is insoluble, the anode does not corrode to provide the ions to carry the current through the electrolyte. Instead, the current is carried by ions from the electrolyte. The necessary anodic reaction occurs at the anode surface and, in general, either oxygen or chlorine gas is liberated. When oxygen is the principal product, it may, in turn, react with carbon in the graphite anode to form carbon dioxide. In this way, the anode material may be consumed. Theoretically, graphite anodes have a consumption rate about one-tenth the rate for steel; however, in practice, graphite anodes are spent at a much slower rate. In chloride environments, chlorine is the main anodic-reaction product. Since chlorine does not react with the graphite, graphite anodes may conceivably last indefinitely.

The graphite anode size and shape most widely used is a 3-in.-diameter by 60-in.-long rod. The graphite anodes are often impregnated with a material, such as linseed oil, to make the anode more resistant to spalling in service from deterioration of the binder, which holds the graphite particles together.

The original silicon-iron anode for impressed-current systems contained about 14.5-percent silicon, and was subject to severe pitting attack in chloride environments. Therefore, a more complex alloy (normal composition: 5-% chromium, 14-% silicon, and 1-% manganese) was developed to overcome this problem. Silicon-iron anodes are available in more sizes and shapes than are the graphite type. The most commonly used size is the 2-in.-diameter by 60-in.-long rod, which has essentially the same performance as the 3-in. by 60-in. graphite anode in a similar installation. The silicon-iron anode can be installed in the soil without special backfill; however, under this condition, the maximum current loading per anode must be reduced.

Both graphite and silicon-iron anodes are cathodic to
steel, and their connection in the cathodic-protection circuit results in an inherent back-voltage of about 2 V. This fact must be considered in the selection of the impressed-current operating voltage.

With both types of impressed-current anodes, care must be taken to protect the anode lead wire and its connection from exposure to the environment, because accelerated consumption of the copper wire will occur in exposed areas. Additionally, during anode installation, care is usually taken to prevent excessive current discharge at the anode ends, which may result in separation of the anode from the connecting cable. One way to prevent this problem is to use an insulating end cap on the lead-wire end of the anode. This precautionary measure is very important with anodes installed deep in the electrolytic medium.

Special Backfill

For soil applications, it is common practice to install the impressed-current anodes in special backfill. The backfill used with these anodes is usually a carbonaceous material, such as coke breeze and graphite. Coal coke breeze is most often used; petroleum coke breeze is suitable if it has been calcined to remove oil residue. Graphite, while suitable, is somewhat more expensive than coke breeze.

The carbonaceous backfills function somewhat in the same manner as the special backfill used around sacrificial anodes to provide a uniform environment of low resistivity at the anode surface. They offer the added advantage that they act as an electrical conductor through direct contact with the impressed-current anode surface and between the backfill particles. This transfers much of the anodic reaction to the carbonaceous material and thus lessens anode consumption. Therefore, suitable carbonaceous backfill must have a low electrical resistivity (less than 10 ohm-cm when moist). Another important property of carbonaceous backfill in this application is that it must be uniformly porous to vent gases resulting from the anodic reaction. These gases, if not properly vented, lead to an increase in the anode circuit resistance that could block the current flow from the anode. This so-called "gas blockage" is an important consideration when the anodes are to be installed deep in the electrolyte.

Many carbonaceous backfills include an alkalizer, usually lime, to reduce possible acid buildup, near the anode, which accelerates anode consumption. In addition, this alkalizer in the backfill mixture reduces the electro-osmosis effects that tend to dry out the backfill near the anode.

Ground-Bed Design

Impressed-current anodes are installed in contact with permanent moisture and the soil with the lowest available resistivity. Where low-resistivity soil is not available, various techniques for improving the conductivity of the environment have been employed.

There are two basic arrangements for anodes of an impressed-current ground bed and many variations of each. These basic arrangements consist essentially of: (1) a group of anodes at a location remote to the structure or (2) a distribution of anodes placed relatively near the structure, with each anode protecting some proportional area of the structure. With both designs, the anodes may be installed either horizontally or vertically, depending on the conditions of the environment.

The remote ground bed is located at a point determined to be electrically remote to the structure to provide a uniform earth potential gradient between the ground bed and all areas on the structure. Under this condition the current, except for possible shielding that distorts the pattern of current distribution, will be distributed uniformly over the entire structure surface.

The actual distance from the structure to a remote ground bed varies with the environmental conditions and the shape, size, and current requirements of the structure. For small structures with low-current requirements, the remote ground bed may be only tens of feet away. With large-diameter concrete pipeline (high-current requirements), however, a remote distance would be thousands of feet and unattainable in a practical sense. As has been pointed out, other steps must be taken in such cases to secure uniform current distribution.

A typical remote ground bed consists of a number of anodes installed vertically, in a straight line, connected in parallel to a header cable from the rectifier. The anodes are usually spaced about 15 ft apart to minimize the mutual interference effect between anodes. The ground-bed resistance, the current requirement, and the required anode life determine the number of anodes needed. The deep-well ground bed is a variation of the remote type used with concrete pipelines (35). With this design, the ground bed is buried deep in the earth and, therefore, may be located beneath the pipeline. This type of installation minimizes certain problems concerning ground moisture and anode interference and still provides good current distribution to the pipeline. As has been mentioned, the deep-well installation provides a particularly severe exposure for anodes. Deep-well ground beds are relatively expensive and difficult to repair; therefore, every precaution must be taken against electrolytic attack and gas blockage of the anode to ensure long-term optimum performance.

In the second basic type of anode arrangement (the distributed ground-bed arrangement), the anodes are placed relatively close to the protected structure and distributed so that each anode is geometrically related to a proportionate area of the structure. This design maintains the uniform current distribution, while limiting the spread of current in the electrolyte, and is useful when facilities that are adjacent to the protected structure might be affected by an interference exposure.

The cost of a distributed ground bed will usually be higher than that of a comparable remote ground bed, because more anodes and more extensive wiring are usually needed. With the distributed-anode arrangement, it is necessary to design the system so that each anode discharges about equal amounts of current. Factors associated with anode placement will influence anode current output. Where substantial variations in anode loadings do occur, resistors are inserted in the lead connection of the overloaded anodes to reduce their current output and thereby balance anode current.
Rectifiers

Rectifiers are the most commonly used source of voltage for impressed-current cathodic-protection systems. The function of the rectifier is to convert alternating-current power to direct-current power. The conventional rectifier has two essential elements: (1) a transformer to change the voltage received to the voltage required and (2) a set of rectifier cells to convert the alternating current, now at the required voltage, to direct current.

The rectifier transformer has a number of taps on the secondary winding for regulation of the output voltage. The voltage required will depend on the current requirement and the over-all circuit resistance of the particular application.

The rectifying cells are semiconductors arranged in a circuit that results in a full-wave direct current. Selenium rectifier cells are preferred for cathodic-protection applications, because they are not as susceptible to damage from line-current surges as are other available types.

The standard cathodic-protection rectifier is easily adjusted to compensate for changes in circuit resistance or changes in the current requirements for protection. Nevertheless, a problem of monitoring the system's operation remains. Various environmental changes may occur to alter the current output. These changes could result in either overprotection or underprotection of the structure. Therefore, inspections and adjustments may be necessary at relatively close time intervals, usually at least once a month.

Several methods of minimizing this problem are available. One method is to replace the standard rectifier with one that operates at a constant current. These rectifiers automatically adjust for resistance variations; however, they do not adjust for changes in the current requirements of the structure. A second automatic unit is available that compensates for both of these possible variations. These units are rather expensive and, therefore, are selected for use in applications in which unusual variations in environmental conditions are expected.

Another type of "self-regulating" system used extensively for concrete-pipeline protection is an automatic device (34), which is employed in conjunction with the standard rectifier. With concrete pipelines, it has been observed that once the concrete-coated steel reaches its protective potential range and the protective current is cut off, the drop in potential (depolarization) follows at an extremely slow rate. One observer (15) reported that the depolarization period may be as long as one month. In explaining this aspect, Heuze (34) refers to the action of the steel in concrete, when under cathodic protection, as being somewhat like that of a capacitor, and he points out the possibility of using an intermittent impressed current in applying the cathodic protection.

The Cathostat was developed by Heuze to take advantage of this residual potential. When used in conjunction with the standard rectifier, it is connected in series with the rectifier and consists of a timer switch that operates in an on-off fashion according to voltages. The cathodic-protection rectifier is energized for a predetermined interval, usually 15 min. When the timer turns the rectifier off, a voltmeter compares the voltage of the system with that of a permanent reference electrode. When the voltage reaches —0.9 V referred to a copper sulfate reference, it turns the timer on to begin a new cycle.

A zinc electrode is used for the permanent reference electrode, and the potential difference between it and the structure is monitored to maintain the structure potential in the control range. The location of the permanent reference electrode must be carefully selected to reflect the average voltage of the entire structure. In addition to the economic advantages, one important advantage of the method is that structure potential can be measured during a period when the cathodic current is off, thus minimizing potential gradients caused by the current flow.

FIELD MEASUREMENTS

Electrical Potential

The practical application of a potential criterion requires a field measurement of the polarized potential of the structure by using a reference electrode and appropriate electrical instrumentation. The reference electrode is usually placed in contact with the soil or water electrolyte at some point within the electrical field of the cathodic-protection current. This measured value includes, in addition to the polarized potential of the structure, the earth-potential gradient caused by the flow of protective current through the resistance of the electrolytic path from the reference point to the structure. Therefore, the measured value is often somewhat greater than the actual structure potential. To compensate for this error, the usual practice is to place the reference electrode as close as possible to the structure and, thereby, minimize the earth-potential gradient. In addition, the soil-potential criterion of —0.85 V provides a —0.05-V safety factor. Experience with steel structures has proved this practice to be sufficient. However, for the concrete pipelines, the practice is modified to provide a more accurate value. The concrete-pipeline procedure is to momentarily interrupt the flow of protective current and make the potential measurement the instant the current ceases to flow. With this procedure, it is apparent that the location of the reference electrode is not particularly critical, because the earth-potential gradient no longer exists. Because the "instantaneous off" potential value is always less negative than the "on" potential (by the increment of voltage required to force the current through that portion of the circuit resistance spanned by structure to reference point), the use of a —0.85 minimum potential as a criterion becomes more conservative and the maximum potential criterion less limiting.

Field Current Requirements

The current requirements for cathodic protection of steel reinforcement are difficult to determine and vary with each application. Experience with concrete pipelines shows that the current density needed to attain cathodic protection will vary greatly, depending on the resistivity of the soil and water surrounding the pipeline and, more importantly, on the condition of the concrete cover itself. The following
tabulation presents the typical current requirements for the cathodic protection of concrete pipelines (16):

<table>
<thead>
<tr>
<th>Current Density for Protective Potential, mA/sq ft</th>
<th>Condition of Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04 to 0.1</td>
<td>Good</td>
</tr>
<tr>
<td>0.1 to 0.2</td>
<td>Average</td>
</tr>
<tr>
<td>&gt;0.4</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Thus, from these empirical determinations of the current densities required for successful application of cathodic protection, it appears that the current density required for protection is always less than 1 mA/sq ft.

In addition to the variations in current density for protection, cement-coated steel is very slow to polarize. Consequently, the use of graphical methods, such as the E log I method, of estimating the current requirement for cathodic protection has not been effective. Also, because the potential of cement-coated steel requires long periods of time to stabilize, estimates of current requirements based on short-term testing are often misleading.

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**APPENDIX D**

**ELECTROCHEMICAL STUDIES**

**INTRODUCTION**

One of the most useful aspects of the cathodic-protection method of arresting corrosion is that its effectiveness can be measured by a simple, nondestructive electrical measurement of the potential of the protected structure. A widely used criterion for cathodic protection of steel in soil and water environments is a potential value of —0.85 V measured to a copper/copper sulfate (Cu/CuSO₄) reference contacting the environment reasonably near the steel surface. The criteria for the cathodic protection of steel in concrete are not as clearly established, and potential values ranging from —0.5 to —0.9 V have been indicated (see Appendix A).

A second major difference between the steel-in-soil and steel-in-concrete criteria for cathodic protection is that many investigators recommend that a maximum potential value with cement-coated steel must be limited to about —1.1 V measured to a copper sulfate reference. This is believed necessary to avoid loss of bond between the concrete and the steel as a result of hydrogen evolution at the cathodic steel surface (see Appendix A).

As part of a program to evaluate the feasibility of arresting or preventing corrosion of steel reinforcing bars in concrete bridge decks by cathodic protection, a series of electrochemical studies was conducted on steel exposed to concrete and simulated concrete environments. The specific objectives of these studies were to identify conditions under which reinforcing bars (rebars) would be expected to corrode in concrete, to establish the potential criteria necessary to achieve cathodic protection under these environmental conditions, and to determine the hydrogen-evolution potentials of steel in these environmental conditions.

Investigations into the influence of chloride-ion concentration and pH on the corrosion of steel rebars were conducted in a simulated concrete environment of saturated calcium hydroxide solution (36). In addition, limited number of studies were conducted with rebars embedded in concrete to allow a direct comparison to be made between data obtained in real concrete and that obtained in a simulated environment. This Appendix describes the results of these investigations.

**MATERIALS AND EXPERIMENTAL WORK**

The chemical compositions of the steel rebars and the corrosion probes used in this investigation are given in Table D-1. All corrosive solutions were made from reagent-grade chemicals and demineralized distilled water having a resistance of 10.1 megohm-cm at 25°C.

Hydrogen-bubble-evolution potential measurements were conducted on rebar steel in various solutions by using the

**TABLE D-1**

<table>
<thead>
<tr>
<th>Steel</th>
<th>Composition, weight percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebar stock</td>
<td>C  0.39  Mn  1.46  P  0.006  S  0.021  Si  0.08  Al  0.009</td>
</tr>
<tr>
<td>AISI Grade</td>
<td>C  0.42  Mn  0.35  P  0.009  S  0.026  Si  0.014  Al  0.004</td>
</tr>
<tr>
<td>1036 resistance probes</td>
<td>C  0.42  Mn  0.35  P  0.009  S  0.026  Si  0.014  Al  0.004</td>
</tr>
</tbody>
</table>
apparatus shown in Figure D-1. The hydrogen-bubble-evolution potential \( E_{H_2} \) was evaluated by using the plexiglass cell, shown in the figure, and a low-powered stereomicroscope located directly above the rebar specimen. Increasingly negative potentials were applied to the specimen with a Taccussel potentiostat in 50-mV increments until hydrogen-bubble nucleation was observed. At this point, the potential was made more positive by 100 mV, and the specimen surface was brushed clean of bubbles with a camel-hair brush. Inspection of the specimen for bubbles was made at 12-hr intervals, and, if none were observed, the potential was made more negative by 25 mV for a further 12 hr. Rebar electrodes were tested both in the mill-annealed condition containing scale and in the sandblasted and pickled condition (10-% HCl at 50 C).

Polarization experiments made on descaled, pickled rebar electrodes in the beaker tests were conducted by using the apparatus and mounting techniques described in References (37) through (40). The details of the experimental procedures used on rebars in concrete are given in a later section of this Appendix dealing with conductive-overlay effects.

The corrosivity of various environments was ascertained by the use of 80-mil-diameter AISI Grade 1036 steel electrical-resistance probes (Corrosometer Probe, Model 1036). Two exposure conditions were employed: (1) with the resistance probe exposed to a large, freely convective volume of corrodent; and (2) with the resistance probe immersed in limestone aggregate, which, in turn, was immersed in the corrodent, as shown in Figure D-2. This latter condition was used to stimulate contact corrosion due to the establishment of differential aeration cells (26). The presence or absence of corrosive attack was confirmed by changes in the electrical resistance of the probes as measured by a Magna Corrosometer, Model CK-2. The effectiveness of cathodic protection at a given applied potential was monitored by inspection of the probe-resistance/time plot. With plots of this type, periods of corrosion are indicated by a positive slope, whereas when corrosive attack stops the slope of the plot goes to zero.

All potentials determined in this study were measured against a saturated calomel reference cell (SCE) and converted to the Cu/CuSO reference scale by addition of −72 mV.

RESULTS AND DISCUSSION

In the interests of clarity, the results will be presented in four sections: (1) hydrogen-bubble-evolution potentials, (2) corrosion kinetics, (3) sacrificial galvanic-anode experiments, and (4) conductive-overlay effects.

Hydrogen-Bubble-Evolution Potentials

The purpose of these measurements was to identify the potential and current density at which hydrogen evolution would occur and, thus, to place an upper limit on the cathodic potential which could be applied to stop corrosion without causing a loss of bond, as discussed in the introduction.

Hydrogen-bubble-evolution potential measurements were conducted in various combinations of environments in which the pH and chloride ion (Cl−) concentrations were varied independently. The results of the measurements in terms of the potential \( E_{H_2} \), and the associated cathodic current density, \( i_{H_2} \), are given in Table D-2. The data in this table show the expected trend of shifting to more active potentials (more negative) as the pH of the solution was increased. It should be noted that \( E_{H_2} \) was independent of the Cl− concentration. The values of \( E_{H_2} \) were found
TABLE D-2
SUMMARY OF HYDROGEN-BUBBLE-EVOLUTION POTENTIALS FOR AISI 1036 CARBON STEEL IN VARIOUS SOLUTIONS

<table>
<thead>
<tr>
<th>Solution</th>
<th>pH</th>
<th>$E_b(H_2)$</th>
<th>$i_{g2}^{+}$</th>
<th>$V_{CuSO_4}$</th>
<th>$mA/in.^{2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025M Ca(OH)₂ (satd')</td>
<td>12.5</td>
<td>-1.170</td>
<td>0.129</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ 0.02M Cl⁻</td>
<td>12.3</td>
<td>-1.170</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ 6.1M Cl⁻</td>
<td>12.2</td>
<td>-1.170</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.36M Cl⁻**</td>
<td>9.4</td>
<td>-1.020</td>
<td>0.014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>7.9</td>
<td>-1.035</td>
<td>0.039</td>
<td></td>
<td></td>
</tr>
<tr>
<td>**</td>
<td>4.0</td>
<td>-0.970</td>
<td>0.144</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* $E_b(H_2)$ = hydrogen-bubble-evolution potential determined at 20X magnification.
** $i_{g2}^{+}$ = current density associated with bubble potential.
* [Cl⁻] added as NaCl.
** [Cl⁻] added as CaCl₂, pH adjusted with either HCl or Ca(OH)₂.

also to be independent of whether the rebar electrode contained original mill scale or was acid-pickled prior to the experiment.

Corrosion Kinetics

The objectives of the corrosion kinetic studies were to identify the environmental conditions under which rebars would corrode in simulated concrete environments and, also, to develop potential and current-density criteria by which corrosion attack could be arrested.

Corrosion-rate measurements were conducted on standard AISI Grade 1036 carbon steel electrical-resistance probes in solutions of saturated Ca(OH)₂ to which was added NaCl in amounts of 0.02, 1.0, 3.0, and 5.0 M. The results are shown in Figures D-3 through D-6, and the data are summarized in Table D-3. The data plotted in Figures D-3 through D-6 show that the corrosion potential of the specimens in both the aggregate and the freely washed condition varied considerably during the test period. The potential values given in Table D-3 for the specimens in the freely washed condition were taken at the end of the test period, whereas the values given for the specimens exposed in the aggregate were taken prior to applying the current. In the 0.02 M solution, no evidence of corrosive attack was observed on either the probe immersed in limestone aggregate or the one in the freely washed condition, and, therefore, no current was applied. This observation can be best explained by inspection of the potential/pH diagram, shown in Figure D-7, for the Fe/Fe₂O₃/Fe₃O₄/H₂O system (41).

Figure D-7 indicates that iron exposed to aqueous solutions at pH 11-12 should not corrode, but should maintain a stable passive state.* The specific influence of chlorides on the basic diagram is not known, and it is possible that the regions of passivity and corrosion could be shifted. However, further inspection of Figures D-3 through D-6 and Table D-3 reveals that, in the freely washed condition, even up to chloride levels of 5.0 M, no corrosive attack

* It is recognized that passivated steels do, in fact, corrode, but they do so at a rate that is insignificant in terms of engineering reality.
Figure D-5. Probe resistance/time data for AISI Grade 1036 steel in halide media as a function of applied cathodic potential (3.0 M NaCl solution).

Figure D-6. Probe resistance/time data for AISI Grade 1036 steel in halide media as a function of applied cathodic potential (5.0 M NaCl solution).

Figure D-7. Potential/pH diagram for Fe/Fe₃O₄/Fe₂O₃/H₂O system.

### TABLE D-3

<table>
<thead>
<tr>
<th>Solution</th>
<th>pH</th>
<th>E corr, E protection, ic (mA/in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02 M NaCl</td>
<td>11.86</td>
<td>-0.650*** NC**</td>
</tr>
<tr>
<td>(probe freely washed)</td>
<td>11.83</td>
<td>-0.500*** NC</td>
</tr>
<tr>
<td>1.0 M NaCl</td>
<td>(probe in aggregate)</td>
<td>11.86</td>
</tr>
<tr>
<td>(probe freely washed)</td>
<td>11.86</td>
<td>-0.675*** NC</td>
</tr>
<tr>
<td>1.0 M NaCl</td>
<td>(probe in aggregate)</td>
<td>11.91</td>
</tr>
<tr>
<td>(probe freely washed)</td>
<td>11.91</td>
<td>-0.610*** NC</td>
</tr>
<tr>
<td>5.0 M NaCl</td>
<td>(probe in aggregate)</td>
<td>11.1</td>
</tr>
<tr>
<td>(probe freely washed)</td>
<td>11.1</td>
<td>-0.670*** NC</td>
</tr>
</tbody>
</table>

ic^* = current density for complete cathodic protection.

** NC = No corrosion. Probe self-passivated over duration of test (65 days).

*** = Open circuit potential recorded at end of test period.

+ = Open circuit potential recorded prior to applying current.
was observed (after an initial period 10 to 30 days). From the foregoing, it must be concluded that the basic relationships displayed in Figure D-7 are valid for aqueous solutions of saturated Ca(OH)$_2$ to which NaCl has been added up to the saturation limit. It is of interest to note that no corrosion was observed in the freely washed condition, even though the corrosion potentials, $E_{corr}$, attained quite active values when compared with the $-200$ mV$_{cys}$ values commonly observed in a saturated Ca(OH)$_2$ solution free of chlorides. This result indicates that the relationship between potential and tendency towards corrosion, without any statement regarding the pH of the concrete, is more complex than has been previously recognized.

Sustained corrosive attack was observed, however, when the probes were immersed in aggregate at chloride levels greater than 0.02 M. Once attack was established, the minimum cathodic applied potential necessary to arrest attack was evaluated by progressively increasing the cathodic potential (with a potentiostat) in steps of 30 to 50 mV (see Figs. D-4 through D-6). The protection potentials, $E_{protection}$, and associated current densities, $i_c$, for each environmental condition are given in Table D-3. It is significant to note that $E_{protection}$ in each case was less than the commonly used $-850$ mV$_{cys}$ criterion used in the field (42) to protect buried steel in soil and in water environments. Values within 140 mV negative to the steady-state corrosion potential were sufficient to achieve cathodic protection; specifically, the data obtained under the most severe condition in this study (5.0 M Cl$^-$) reveal that a potential of $-770$ mV$_{cys}$ is an adequate criteria for cathodic protection. It is recognized that the values of $i_c$ in Table D-3 are relatively high, but it should be pointed out that these values were found to decrease with time and represent only the value after 15 to 30 days' exposure. It is very probable, in practice, that $i_c$ would decrease to much smaller values.

In view of the potential/pH relationships shown in Figure D-7, a series of experiments was conducted to evaluate the influence of pH (at constant Cl$^-$ concentration) on the corrosion behavior of rebar steel. This was done by placing resistance probes in the freely washed condition in a saturated calcium chloride solution and adjusting the pH with concentrated HCl and NaOH. The results of the initial tests are shown in Figure D-8.

After a 10-day exposure period, corrosive attack was initiated at each pH condition. The rate of attack, estimated from the slope of the resistance/time plot, was greatest for the pH 4 solution and, as expected, least for the most alkaline condition. After 10 days, the hydrogen-bubble-evolution potential, experimentally determined, was applied potentiostatically for each pH condition to see whether corrosion could be arrested at the maximum cathodic applied potential likely to be used in practice. Figure D-8 indicates that complete cathodic protection was achieved in each case. After 14 days, the protection was terminated, and the probes were allowed to reinitiate corrosion for up to 18 days. At this point, a potential of $-920$ mV$_{cys}$ was applied, and again corrosion was arrested. This latter potential was selected to evaluate whether corrosion could be arrested at low pH, by using potential values previously shown to be successful in the field (43) in arresting corrosion of steel reinforcement in concrete structure, which, in many cases, experienced corrosion without cathodic protection.

It is of interest to note that, according to the diagram in Figure D-7, no corrosion should have occurred in the pH 9.2 environment and also that the pH 7.8 solutions are on the borderline for corrosion and passivity at corrosion potential.
tials between $-0.500$ and $-0.600 \, \text{V}_{\text{CuSO}_4}$. It should be emphasized that Figure D-7 pertains to equilibrium conditions, and it is conceivable that equilibrium conditions were not attained in the pH 7.8 and 9.2 environments in 18 days, and, hence, corrosive attack was observed. To investigate this point, the same tests were repeated, allowing approximately 60 days before the application of cathodic protection. These data are shown in Figure D-9, where it is seen that, in agreement with theory, corrosive attack self-terminated (the steels self-passivated) in the pH 8 and 9 environments.

It is also evident that, in the pH 4 condition, the initial high rate of attack observed over the first 30 days diminished appreciably, but did not cease, as equilibrium conditions were attained. In the pH 4 condition, an applied potential of $-720 \, \text{mV}_{\text{CuSO}_4}$ was adequate to stop corrosion, even in highly acidic media containing a large amount of chloride. It is also of interest to note the low $i_e$ associated with protection in the pH 4 condition. This low $i_e$ value lends credence to the suggestion that the rather high values of $i_e$ reported in Table D-3, would be expected to diminish appreciably with time.

In view of the existence of a stable passive state in chloride-containing solutions, potentiodynamic anodic polarization experiments were conducted to see whether any susceptibility to pitting corrosion was evident, by way of analogy to the localized corrosion behavior of passive stainless steels in halide media (44). Anodic-polarization curves as a function of pH are shown in Figure D-10 for 5.36 M Cl$^-$ solutions. At pH 4, activation-controlled anodic dissolution was observed with no evidence of passivity, in agreement with the data presented in Figure D-9 at pH 4. At pH 8.0, a tendency to passivate was noted, which was quite pronounced at pH 9.0. In the latter case, a poorly defined critical pitting potential (45, 46) was observed ($E_c$), and pitting corrosion was noted on the specimen after test.

The variation in $E_c$ with chloride-ion concentration in saturated Ca(OH)$_2$ solution is shown in Figure D-11. A systematic shift in $E_c$ in the active direction was observed with increasing chloride content, similar to that reported for stainless steels (45). These data suggest that rebars in moist concrete, at pH 12 containing chloride contamination, would be expected to pit if the $E_{corr}$ was more positive than the appropriate $E_c$. It is of interest to note, however, that, even if the chloride contamination level reached 6.0 M in the concrete, application of a cathodic potential of $-770 \, \text{mV}_{\text{CuSO}_4}$ (that found to cathodically protect against general or crevice corrosion, Fig. D-6) would be completely effective in suppressing pitting corrosion of the rebars.

**Sacrificial Galvanic-Anode Experiments**

The purpose of the galvanic-anode experiments was to develop data to assess the feasibility of using sacrificial galvanic anodes to cathodically protect rebars in concrete.

To evaluate the electrochemical capability of zinc and magnesium anodes to cathodically protect rebar steel in simulated concrete environments, a series of experiments was conducted in which various anode/steel surface-area ratios were constructed at a constant anode/steel separation of 0.25 in. The results are shown in Figure D-12 for saturated Ca(OH)$_2$ solution free of chloride contamination and saturated with NaCl.

In the absence of chlorides, zinc and magnesium, short-circuited to steel at an area ratio of 1:100, did not shift the coupled potential to the cathodic-protection region (more negative than $-770 \, \text{mV}_{\text{CuSO}_4}$). At an area ratio of 1:10 and 1:1, magnesium did not polarize the steel; however, the data show that zinc would be effective in protecting the steel. This is undoubtedly due to the ability of zinc to corrode and produce anionic corrosion products (zinc is amphoteric) in the absence of chlorides, whereas magnesium exists in a passive state and does not protect the steel.

In the presence of chlorides, both zinc and magnesium were found to be effective in polarizing the steel into the cathodic-protection range of potentials, regardless of the anode/steel surface-area ratio employed. The corrosion reaction of either the magnesium or the zinc in chloride solutions does not evolve chlorine gas. Therefore, gas blockage and subsequent loss of protective current from the current from the sacrificial anode, from this cause, is eliminated. The zinc anode has an added advantage in that its natural potential is less than that required to produce hydrogen gas on the rebar (cathode) surface in this system. Thus, loss of bond between the rebar and the concrete due to hydrogen evolution is not possible. Under certain conditions, magnesium anodes may cause hydrogen gas to be evolved on the rebar surface in this system. Thus, for service on a bridge deck with a spectrum of chloride contents from zero to saturation, it appears that a zinc sacrificial anode system would be the best, at a surface area ratio greater than 1:25.
Figure D-10. The influence of pH on the anodic dissolution kinetics of rebar steel in 5.36 M Cl⁻ solutions.

Figure D-11. The influence of chloride-ion concentration (as NaCl) on the pitting potential of AISI 1036 carbon steel in saturated Cu(OH)₂ solution at 25°C.
Figure D-12. The influence of anode/steel surface area ratio on the coupled potential in saturated Ca(OH)$_2$ solution with and without Cl$^-$ (electrode spacing 0.25 in.).

Conductive-Overlay Effects

During a series of potential distribution tests conducted on the analog model discussed in Appendix F, it was observed that excessively negative applied potentials were required to stop corrosion on a resistance probe buried in limestone aggregate under a coke-breeze overlay (see Table F-3). The applied potentials in those tests were measured by using a Cu/CuSO$_4$ reference cell placed directly on top of the coke-breeze overlay, which also contained a silicon-iron anode in electrical contact with the overlay.

The purpose of the studies described in this section was to investigate the nature of that effect. To this end a series of tests was conducted, in the laboratory, in glass jars designed to duplicate as closely as possible the conditions prevalent in the analog deck. A schematic of the test assembly is shown in Figure D-13. In addition to a Cu/CuSO$_4$ reference electrode placed on the top of the coke breeze, a Luggin probe was placed through the coke and aggregate in close proximity to the rebar specimen (0.125 in.) to provide a measurement of the true rebar potential.

To evaluate the magnitude of IR effects, a cathode-ray oscilloscope was used to measure instantaneous-off potentials when desired. The electrolyte used during the polarization test consisted of leechings taken from the analog deck on which the original effect was noted.

A typical cathodic-polarization curve for the rebar as a function of the two reference electrodes at differing stations is shown in Figure D-14, for a current-on situation (with IR drop); and in Figure D-15, for the IR-compensated case. A plot of the potential difference developed between the two (originally identical) reference electrodes during polarization, which arises from factors induced across the coke breeze during the test, is also included in Figure D-14.

It is clear from Figure D-15 that the marked discrepancy
Figure D-14. Polarization curve for rebar buried in aggregate and covered with coke-breeze overlay. Note potentials not corrected for IR drop.

Figure D-15. Polarization curve for rebar buried in aggregate and covered with coke-breeze overlay. Note potentials corrected for IR drop, and potential scale expanded over that presented in Figure D-18.

In measured potential is not due to IR effects, because both curves were obtained by the “instantaneous-off” technique. During inspection of the data recorded in Figure D-14, it was noted that, when the potential difference between the two reference electrodes \( E_3 \) was subtracted from the potential of the rebar versus the topside reference electrode \( E_2 \), a complete duplicate of the true polarization curve (obtained from the rebar/Luggin-probe system) was obtained, as shown in Figure D-16. These data indicate that, during the passage of current through the coke-breeze overlay, a separate overlay polarization potential is developed, which is additive to the true rebar potential measurement at any given current density. It is clear from Figures D-14 and D-15 that this overlay polarization effect increases with increasing current density and diminishes to zero at lower applied currents.

Although this effect was reproducible from test to test in the analog deck mock-up, the question of whether it would be prevalent in concrete could not be answered from these tests. To develop data to answer this question, a mini-deck was fabricated. The procedure and materials used were kept as close as possible to those used to fabricate the large-
scale prototype deck described in Appendix H. Figure D-17 shows a schematic of the setup. Five isolated rebars were equally spaced on 5-in. centers for polarization studies. Three reference electrode stations were incorporated: one on top of the coke-breeze overlay, one at the coke/concrete interface, and the third in a Luggin probe placed close to the rebar. A round silicon-iron anode was located in the coke breeze directly above the rebar being tested.

Typical cathodic-polarization data at each reference electrode station are shown in Figures D-18 and D-19 for two different rebars. It is noteworthy to observe the remarkable duplication both in the magnitude of the potentials and current densities and also in the qualitative similarities between the behavior of rebars in concrete and in aggregate. The magnitude of the IR drop through the concrete and at the tip of the Luggin probe was measured with.
the oscilloscope. The value of the IR drop at the Luggin probe at 0.23 mA/in.² was so low as not to be measurable, whereas the value at the concrete/coke interface was 280 mV. This latter value compares well with the difference between the polarization curves for each station at this current density (280 mV, Fig. D-18). The practical significance of these data can be appreciated by considering the point A on the curves in Figure D-18. Using a reference electrode on top of the coke breeze to measure applied potential, a value of ~850 mV_{ClO₄⁻} would correspond to a true value on the rebar of ~280 mV_{ClO₄⁻}, and could possibly mean the difference between protection and no protection.

Similar polarization studies were conducted on an isolated rebar (test rebar A) in the prototype deck with equivalent reference-electrode placements. The results are shown in Figure D-20. From this figure, it is clear that the behavior observed was qualitatively identical with that reported for steel in mortar (47). Oscilloscopic measurements confirmed that no measurable IR drop existed in the curve for the Luggin-probe station.

To explain these phenomena, the following analysis is presented in which the various potentials associated with each interface (rebar/concrete, concrete/coke, coke surface, etc.) are examined.

Simple electrochemical theory dictates that

\[ E_{\text{rebar/concrete}} = E_{\text{rebar}} - IR_{\text{concrete}} \]

that is,

\[ E_{R/C} = E_R - IR_{C/R} \]  

Rearranging Eq. D-2 gives

\[ E_R = E_{R/C} + IR_{C/R} \]

where \( E_R \) represents the true rebar potential at any total applied current, \( I \). If the exposure conditions are at the free corrosion potential (no applied current), \( E_R = E_{R/C} \) because \( IR_{C/R} \) becomes zero.

From the data obtained in the coke overlay on aggregate and also in the mini-deck studies, it was found that

\[ E_{R/C} = E_{\text{surface reference to rebar}} + E_{\text{surface reference to coke}} \]

or

\[ E_{R/C} = E_{R/R} + E_{T/B} \]

Thus, combining Eqs. D-3 and D-5 gives:

\[ E_R = E_{R/R} + E_{T/B} + IR_{C/R} \]  

Equation D-6 relates the true rebar potential, at any given current, to the surface-to-rebar potential, \( E_{R/R} \), and the polarization effect observed across the conductive overlay, \( E_{T/B} \), and also to the resistive component of applied potential from the concrete surface to the rebar. The data shown in Figure D-18 were inserted into Eq. D-6 and the calculated values of \( E_R \) were compared with the actual values of \( E_R \). These results are shown in Figure D-21, where it is seen that excellent agreement was obtained over the entire current-density range investigated.

The exact physical significance of the overlay polarization effect, \( E_{T/R} \), is not known. It is clear, however, that this effect can have considerable influence on the monitoring effectiveness of cathodic protection on bridge decks with conductive overlays, in that the true rebar potential (that involved in cathodic protection) may be significantly more positive than a potential measurement obtained in a deck surface may indicate. Since the various factors involved in Eq. D-6 are not readily obtainable in practice, it appears that the best way to profile a bridge deck with a conductive overlay is to use "instantaneous-off" procedures and place the reference electrode on the concrete surface under the overlay.

CONCLUSIONS

The following conclusions may be drawn from the data presented:

1. Hydrogen-bubble-evolution potentials on rebars in saturated Ca(OH)₂ solution are ~1170 mV_{ClO₄⁻}, regardless of the chloride-ion content of the solution and the surface condition of the rebar (mill scale or pickled). Decreasing the pH of the corrodent containing 5.36 M Cl⁻ from 9.4 to 4.0 will shift the hydrogen-bubble-evolution potential from ~1020 mV_{ClO₄⁻} to ~970 mV_{ClO₄⁻}.

2. No corrosion occurs on AISI Grade 1036 steel exposed in the freely washed condition in saturated Ca(OH)₂ solution containing 0.02, 1.0, 3.0, or 5.0 M NaCl. However, in the presence of crevices (caused by limestone aggregate), corrosion will occur at chloride-ion contents greater than 0.02 M. Under these latter conditions, complete cathodic protection can be achieved by application of a potential of ~770 mV_{ClO₄⁻}. It should be recognized, however, that this protection potential will, in many cases, exceed that required to obtain complete protection, in practice where the environmental factors will not be as severe as those reported herein.

3. Data obtained on specimens exposed in the freely washed condition to 5.36 M Cl⁻ solution at differing pH indicate that the basic potential/pH diagram for Fe/Fe₂O₃/Fe₃O₄/H₂O is correct in predicting the susceptibility of rebars to corrosive attack (that is, no attack in solutions with pH >8; corrosive attack at lower pH such as 4.0).

4. Potentiodynamic anodic-polarization studies indicate that AISI Grade 1036 steel exposed to a solution of 5.36 M Cl⁻ at pH >9 is subject to pitting corrosion, if the corrosion potential is more noble than the critical pitting potential. However, the data show that application of a potential of ~770 mV_{ClO₄⁻} will cathodically protect against pitting corrosion as well as general and crevice corrosion.

5. If the concrete is moist and contains some chloride, both magnesium and zinc anodes are capable of providing cathodic-protection current, on condition that adequate consideration is given to the anode size, spacing, and position and to the relative anode-to-rebar area ratio.

6. Attempts to measure the potential of rebars buried in aggregate or concrete covered with a coke-breeze conductive overlay, by using a reference probe placed on the top
Figure D-18. Cathodic polarization of No. 3 rebar steel in mini-deck as a function of reference electrode placement.

Figure D-20. Cathodic-polarization behavior of rebar in prototype deck as a function of reference electrode placement.
Figure D-19. Cathodic polarization of No. 2 rebar steel in mini-deck as a function of reference electrode placement.

Figure D-21. Comparison between true measured rebar potential in mini-deck and calculated rebar potential, using equation in figure.
of the overlay, give rise to errors, possibly due to a polarization effect in the coke layer. An equation has been developed by which the true rebar potential can be derived from a “topside” reference measurement, but data are required which are not readily available in practice. To avoid this measurement error, it is recommended, in practice, that bridge decks with coke conductive overlays be potential profiled by using the “instantaneous-off” technique with the reference electrode located on the concrete surface under the overlay.

APPENDIX E
CATHODIC-PROTECTION EXPOSURE TESTS

INTRODUCTION

The purpose of the research reported in this Appendix was to determine whether cathodic protection could cause adverse effects on a concrete-to-rebar bond and on the concrete itself. Previous observations by Casad (48) indicated that there is a slight weakening of bond strength of reinforcing bars in concrete with increasing ampere hours of applied cathodic-protection current. He concluded that the decrease in bond strength was the result of deterioration of the concrete and not the result of a decrease in adhesion of the concrete to the steel. Studies by Ewing (30) showed that the loss in bond strength was related to the total applied ampere hours of current. He found that an applied current of 3400 amp/hr/sq ft of reinforcing steel surface caused a 25-percent reduction in bond strength. However, doubling the applied ampere hours did not result in a further decrease in bond strength.

Bureau of Standards tests in 1913 first showed that there was a definite softening of the concrete near the cathode, when reinforcing steel was made cathodic (9). This softening resulted in the loss of the bond between the smooth reinforcing steel and the concrete and was, reportedly, due to the gradual concentration of sodium and potassium ions near the cathode by the passage of the current. Although the area of softening increased with time (as far as 1/4 in. or more), the main body of the concrete showed no adverse effect. Later testing by Mole (27) confirmed the Bureau’s results; this work also revealed that concrete free of alkali metal could successfully withstand cathodic current densities up to 18 mA/sq ft. Tests by the U.S. Army Corps of Engineers (29) showed measurable loss of bond at 20 mA/sq ft, whereas at 2 and 5 mA no damage occurred for the 54-months' duration of the test.

For the study of the effect of cathodic protection and bond strength, a modification of the stub-cantilever-beam specimen described by Kemp et al. (49) has been used. The effect of cathodic protection on the concrete was evaluated by studying the performance of 6- by 12-in. concrete-cylinder samples (containing no reinforcing bars) in the splitting tensile test, after exposure to various levels of applied current.

EFFECT OF CATHODIC PROTECTION ON BOND STRENGTH

Experimental Procedure

The test conditions for the present research were selected to permit a study of the effect of a total applied current of 3400 amp/hr/sq ft (the level at which Ewing observed no further loss in bond strength) as well as at levels substantially above and below 3400 amp/hr/sq ft. To achieve the desired ampere hours in this study, three levels of applied current (2.5, 25.0, and 50.0 mA) and four exposure durations were used. The three levels of applied current are equal to current densities of 48, 480, and 960 mA/sq ft of exposed reinforcing-steel surface. The method of applying current is illustrated in Figure E-1. The polarized (instant off) potentials of each specimen were measured against a copper-copper sulfate half-cell at, on the average, weekly intervals throughout the exposure periods. These readings showed that there was no change in the polarized potentials over the duration of the exposure. The measured potentials ranged from 1.11 to 1.25 V (vs Cu/CuSO₄).

As with the other work in this project, the concrete was prepared and installed in accordance with the Pennsylvania Department of Transportation (PennDOT) specifications for reinforced bridge-deck concrete (50). The concrete used for the test specimens was obtained from the same batch that was used for the analog model of the bridge deck described in Appendix F. The results of concrete compression tests for this batch are given in Table F-1. Two concrete curing times, two months and four months, were used. The test conditions and exposure times are summarized in Table E-1.

The test specimen, Figure E-2, is a modification of the typical beam-end type of pull-out specimen frequently used to evaluate concrete-to-steel-bar bond strength. The modifications, consisting mainly of substituting a reusable steel beam for the bottom portion of the concrete beam, were made to reduce the cost and to facilitate handling (the typical stub-cantilever-beam specimens are up to 3 ft in length). Number 4 (1/4-in.-diameter) reinforcing bars were used in all specimens. As in a conventional steel
The equipment used for the pull-out tests is shown in Figures E-3 and E-4. A horizontal jack, exerting a tensile force recorded by a load cell, was connected to the reinforcing bar by a clamping mechanism. Horizontal, direct-current differential transformers (DCDTs), for measuring longitudinal movements of the bar with respect to the concrete, were supported by clips welded to portions of the bar projecting from each end of the specimen. The DCDT most remote from the jack measured the free-end slip of the bar. The loaded-end slip of the bar was the difference between measurements by the DCDT nearest the jack and the calculated stretch of the bar between that DCDT and the jack.

The specimens were aged in a saturated solution of calcium hydroxide and were then exposed in a 1-percent sodium chloride solution at room temperature. After exposure to the applied current, the specimens were left in the 1-percent sodium chloride solution until the bond-strength tests were conducted. All pull-out tests were conducted at the conclusion of the longest exposure time; thus, any possible effects of aging of the concrete would be the same for all specimens.

The cantilever-beam specimen, the length of the bar embedment was only a portion (5 in. in these tests) of the length of the beam; plastic sleeves prevented bond in other portions of the beam.

The specimens were aged in a saturated solution of calcium hydroxide and then exposed in a 1-percent sodium chloride solution at room temperature. After exposure to the applied current, the specimens were left in the 1-percent sodium chloride solution until the bond-strength tests were conducted. All pull-out tests were conducted at the conclusion of the longest exposure time; thus, any possible effects of aging of the concrete would be the same for all specimens.

The equipment used for the pull-out tests is shown in Figures E-3 and E-4. A horizontal jack, exerting a tensile force recorded by a load cell, was connected to the reinforcing bar by a clamping mechanism. Horizontal, direct-current differential transformers (DCDTs), for measuring longitudinal movements of the bar with respect to the concrete, were supported by clips welded to portions of the bar projecting from each end of the specimen. The DCDT most remote from the jack measured the free-end slip of the bar. The loaded-end slip of the bar was the difference between measurements by the DCDT nearest the jack and the calculated stretch of the bar between that DCDT and the jack.
the beginning of the bar embedment, 8 in. away.

In each bond test, the reinforcing bar was loaded to various pull-out forces, and the readings of the load cell and two DCCT's were recorded by a portable data taker. Computer processing of the punched tape of the data taker subsequently provided the data in a usable form. Generally, the loading was halted and readings were recorded at loadings of zero, 250 lb, 1000 lb, every 1000-lb increment up to 12,000 lb, and every 500-lb increment up to failure.

During each test, the top of the beam was maintained horizontal (as indicated by a carpenter's level) by pumping the vertical jack at the outer end of the specimen. This prevented any tendency for dowel action of the reinforcing bar to split the concrete, and, consequently, resulted in the attainment of levels of bond stress considerably higher than generally observed in bond tests. The bar yielded at a load of about 14,500 lb (above the load at the 0.01-in. loaded-end slip for all but five specimens, but below the ultimate load for all specimens), and the bar continued to load in strain hardening. Failure always consisted of concrete fracture (usually longitudinal splitting, sometimes boring out the concrete), but the reinforcing bar always remained intact with no post-test evidence of necking. The maximum load was indicated by the dial of the loading machine.

The data reduction was concerned with examining the two most significant parameters of the bond tests: the ultimate bond stress and the bond stress at the 0.01-in. loaded-end slip (which would correspond to a maximum tolerable crack of 0.02 in. resulting from bond stress in an actual structure). The latter is generally considered to be the limit of "serviceability" in reinforced-concrete bond research. In each case, the bond stress was computed as an average value equal to the appropriate load divided by the product of the bar average circumference (based on its measured weight) and the 5-in. embedment length. The ultimate load stress was based on the maximum load recorded in the reinforcing bar before unloading. The apparent loaded-end slip was affected by a slight bending of the reinforcing bar as it was gripped by the testing machine at the beginning of loading. Therefore, the origin of the curve for bond stress plotted vs loaded-end slip was assumed to occur where zero stress occurs on a line through the straight-line portion of the experimental curve. The bond stress at the 0.01-in. loaded-end slip was then determined as the stress corresponding to a difference of 0.01 in. between the measured loaded-end movement and the theoretical stretching of the bar between the loaded end of the bond length and the point on the bar where the measurements were made.

Results and Discussion

The results of the bond tests are given in Table E-2. To determine the statistically significant relationships of each dependent variable (ultimate bond stress, bond stress at 0.01-in. loaded-end slip, and ratio of stress at 0.01-in. slip to ultimate stress) to the independent variables (concrete curing time, current density, exposure time, and total amperes), a number of multiple-regression analyses were carried out. These included linear and second-degree effects of these variables. Also, several analyses of variance were performed to study the relative variability of the triplicate specimens.

For ultimate bond stress (30 specimens), all the variables—current density, number of days, and total applied ampere-hours per square foot—have some linear effect. However, because there is a direct relationship among those three variables, and total ampere-hours has the highest simple correlation coefficient (−0.61), it appears reasonable to attribute changes in ultimate bond strength to this variable. There was no indication of an effect related to concrete curing time.

Figure E-5 shows that there was about a 10-percent decrease in ultimate bond strength after the application of 3460 amp hr/sq ft of current. A further application of current to a total of 6920 amp hr/sq ft produced an additional reduction of about 10 percent in bond strength. It should be noted, however, that the 6920 amp hr/sq ft of current that was applied in this study, which was done to observe the effects of excessive amounts of current, is far in excess of any reasonable level of cathodic-protection current that would be applied to a bridge structure. The 6920 amp hr/sq ft is equivalent to about 75 years of pro-
### TABLE E-2

**EFFECT OF CURRENT APPLICATION ON BOND STRENGTH**

<table>
<thead>
<tr>
<th>Total Applied Amp Hr/Sq Ft</th>
<th>Applied As</th>
<th>Bond Stress, psi, at 0.01-Inch Loaded-End Slip</th>
<th>Ultimate Bond Stress, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>346 960 mA/sq ft for 15 days</td>
<td>850</td>
<td>1930</td>
<td></td>
</tr>
<tr>
<td>346 960 mA/sq ft for 15 days</td>
<td>840</td>
<td>2310</td>
<td></td>
</tr>
<tr>
<td>346 960 mA/sq ft for 15 days</td>
<td>880</td>
<td>1910</td>
<td></td>
</tr>
<tr>
<td>346 960 mA/sq ft for 15 days*</td>
<td>1570</td>
<td>2050</td>
<td></td>
</tr>
<tr>
<td>346 960 mA/sq ft for 15 days*</td>
<td>1130</td>
<td>2030</td>
<td></td>
</tr>
<tr>
<td>346 480 mA/sq ft for 30 days</td>
<td>1280</td>
<td>1960</td>
<td></td>
</tr>
<tr>
<td>346 480 mA/sq ft for 30 days</td>
<td>640</td>
<td>2020</td>
<td></td>
</tr>
<tr>
<td>346 480 mA/sq ft for 30 days</td>
<td>1030</td>
<td>2210</td>
<td></td>
</tr>
<tr>
<td>346 480 mA/sq ft for 30 days*</td>
<td>510</td>
<td>2160</td>
<td></td>
</tr>
<tr>
<td>346 480 mA/sq ft for 30 days*</td>
<td>1190</td>
<td>2180</td>
<td></td>
</tr>
<tr>
<td>346 480 mA/sq ft for 30 days*</td>
<td>930</td>
<td>2370</td>
<td></td>
</tr>
<tr>
<td>346 48 mA/sq ft for 300 days</td>
<td>1550**</td>
<td>2250</td>
<td></td>
</tr>
<tr>
<td>346 48 mA/sq ft for 300 days</td>
<td>980</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>346 48 mA/sq ft for 300 days</td>
<td>1390</td>
<td>2180</td>
<td></td>
</tr>
<tr>
<td>3460 960 mA/sq ft for 150 days</td>
<td>690</td>
<td>2050</td>
<td></td>
</tr>
<tr>
<td>3460 960 mA/sq ft for 150 days</td>
<td>1260</td>
<td>1910</td>
<td></td>
</tr>
<tr>
<td>3460 960 mA/sq ft for 150 days</td>
<td>1030</td>
<td>1860</td>
<td></td>
</tr>
<tr>
<td>3460 960 mA/sq ft for 150 days*</td>
<td>1070</td>
<td>1990</td>
<td></td>
</tr>
<tr>
<td>3460 960 mA/sq ft for 150 days*</td>
<td>780</td>
<td>1530</td>
<td></td>
</tr>
<tr>
<td>3460 960 mA/sq ft for 150 days*</td>
<td>890</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>3460 480 mA/sq ft for 300 days</td>
<td>1100</td>
<td>2020</td>
<td></td>
</tr>
<tr>
<td>3460 480 mA/sq ft for 300 days</td>
<td>1620</td>
<td>1840</td>
<td></td>
</tr>
<tr>
<td>3460 480 mA/sq ft for 300 days</td>
<td>1020</td>
<td>1640</td>
<td></td>
</tr>
<tr>
<td>6920 960 mA/sq ft for 300 days</td>
<td>410</td>
<td>1390</td>
<td></td>
</tr>
<tr>
<td>6920 960 mA/sq ft for 300 days</td>
<td>1390</td>
<td>2050</td>
<td></td>
</tr>
<tr>
<td>6920 960 mA/sq ft for 300 days</td>
<td>1410</td>
<td>1730</td>
<td></td>
</tr>
<tr>
<td>Controls No applied current</td>
<td>1320</td>
<td>2180</td>
<td></td>
</tr>
<tr>
<td>Controls No applied current</td>
<td>900</td>
<td>2250</td>
<td></td>
</tr>
<tr>
<td>Controls No applied current</td>
<td>1080</td>
<td>1850</td>
<td></td>
</tr>
</tbody>
</table>

* Four-months cure before application of current; all others two months cure.

** Corresponding to the last valid elongation measured for this particular test, for a net loaded-end slip of 0.009 inch.
tection at a very high level of current density.

The results of this study show a trend similar to that reported by Ewing (30), who observed a 25-percent decrease in bond strength after the application of 3400 amp hr/sq ft of current.

Bond stresses generally are not critical in the design of the reinforced-concrete slabs of bridge decks, because the span-to-depth ratios of the slabs are relatively large. In fact, the AASHTO specification does not require the computation of bond stresses in the design of bridge decks. Therefore, a moderate decrease in ultimate bond stress, such as 10 percent or possibly 20 percent, should not jeopardize the ultimate safety of a deck slab.

Figure E-6 shows that, when the effect of current density on ultimate bond strength is considered, the loss in bond strength is much less with increasing current density than with an increasing total ampere hour per square foot of applied current (Fig. E-5). This result supports the previous indication that changes in ultimate bond strength are attributable to the total applied current (that is, the total number of coulombs passed).

In the case of bond stress to produce a 0.01-in. loaded-end slip (30 specimens), no statistically significant relationships of dependent variables to the independent were found. Analysis of these data (Table E-2) shows that a wide range in the bond stress required to produce a 0.01-in. loaded-end slip occurred in each group of specimens considered.

Inspection of the specimens that split along the reinforcing steel during the pull-out tests disclosed a concentration of light-colored material along the rebar, as shown in Figure E-7. This material was scraped off the surface of the steel and the concrete, and, although not spongy, it appeared to be somewhat softer than the surrounding concrete. It is possible that this reaction was caused by the production of alkali hydroxides in the steel surface as opposed to loss of bond from hydrogen evolution. These hydroxides are believed to attack the calcium and aluminum silicates yielding soluble silicates. In explaining the data in Table E-3, it is noted that there had been a migration of calcium, sodium, and potassium toward the rebar. The deposits scraped from the control specimen, which received no applied current, showed the smallest indication of an enrichment of these elements at the steel surface; the specimen that had received the highest applied current showed the greatest enrichment.

EFFECT OF CATHODIC PROTECTION ON SPLITTING TENSILE STRENGTH OF CONCRETE

Experimental Procedure

For this study, standard 6-in. by 12-in. concrete-cylinder specimens prepared according to ASTM Method C-496 were used. The cylinders were cast from the same batch of concrete as the analog model and the modified stub-cantilever-beam specimens.

A carbon anode 6 in. in diameter and ¼ in. in thickness, drilled and tapped for an electrical lead connection, was placed in contact with one end of each test cylinder. A paste made from powdered carbon and water was placed between the anode and the end of the cylinder to ensure
good electrical contact. The anode end was covered with epoxy to isolate it from the test medium, as illustrated in Figure E-8. A similar 6-in. by ¾-in. carbon-steel cathode was placed in contact with the other end of the cylinder. A paste of cement and water also was used between the cathode and the concrete again to ensure good contact.

The specimens, with the anode on the bottom and the cathode on the top (so that it was above the test solution level), were placed in individual plastic containers, as shown in Figure E-9. The test solution was the same as that used for the stub-cantilever-beam specimens; namely, 1-percent sodium chloride. Applied currents of 0.5, 1.0, and 2.0 mA (2.5, 5.0, and 10.0 mA/sq ft of specimen cross section) were maintained through the specimens, exposed in triplicate, for 300 days.

After the 300-day exposure period, all specimens were tested for splitting tensile strength according to ASTM Method C-496-71. Control specimens that had received no applied current had been tested for splitting tensile strength after 30-days' curing time. To observe any possible effects of aging on the splitting tensile strength, additional control specimens were tested after 300 days.

**Test Results**

After the 300-day exposure period, the anode and cathode plates were removed in preparation for the splitting tensile testing. With the exception of the specimen with the lowest applied current, the carbon-steel cathodes on all specimens were essentially corrosion-free, as illustrated in Figure E-10. Visual inspection revealed no apparent degradation of the concrete at either the anode or the cathode end.

The data in Table E-4 indicate that there was no relationship between applied current and the splitting tensile strength of the specimens. The greatest difference between the average splitting tensile strength of the three controls and that of any set of these test specimens that had been exposed to a current was 85 psi (the 30-day-cure controls vs the 300-day specimens with 2.0 mA applied current). The variations among the triplicate specimens for each
### Effect of Current Application on Alkali Metals in Concrete

<table>
<thead>
<tr>
<th>Specimen Treatment</th>
<th>6 Applied Current</th>
<th>12 Applied Current</th>
<th>24 Applied Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>346 mA/Sq Ft</td>
<td>3460 mA/Sq Ft</td>
<td>6920 mA/Sq Ft</td>
</tr>
<tr>
<td>Adjacent to Rebar</td>
<td>14.56</td>
<td>15.01</td>
<td>15.48</td>
</tr>
<tr>
<td>Increase At Rebar</td>
<td>11.77</td>
<td>11.97</td>
<td>12.61</td>
</tr>
<tr>
<td>Percent Calcium</td>
<td>2.79</td>
<td>3.04</td>
<td>2.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percent Sodium</th>
<th>Percent Potassium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Away From Rebar</td>
<td>Increase At Rebar</td>
</tr>
<tr>
<td>0.23</td>
<td>0.08</td>
</tr>
<tr>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td>0.20</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**Figure E-8. Splitting tensile specimens.**

**Figure E-9. Splitting tensile specimens in plastic containers of 1-percent sodium chloride solution.**
TABLE E-4
EFFECT OF APPLIED CURRENT ON SPLITTING TENSILE STRENGTH

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Splitting Load, Total, ( \text{pounds} )</th>
<th>Tensile Strength, ( \text{psi} )</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control - 30 day cure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>56,500</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>53,500</td>
<td>473</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>46,500</td>
<td>411</td>
<td></td>
</tr>
<tr>
<td>Avg</td>
<td>52,166</td>
<td>461</td>
<td></td>
</tr>
<tr>
<td>300 days exposure to 0.5 mA applied current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>65,000</td>
<td>575</td>
<td>80% shear</td>
</tr>
<tr>
<td>2</td>
<td>60,000</td>
<td>531</td>
<td>75% shear</td>
</tr>
<tr>
<td>3</td>
<td>59,500</td>
<td>527</td>
<td>80% shear</td>
</tr>
<tr>
<td>Avg</td>
<td>61,500</td>
<td>544</td>
<td></td>
</tr>
<tr>
<td>300 days exposure to 1.0 mA applied current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>49,000</td>
<td>434</td>
<td>Sandy pocket</td>
</tr>
<tr>
<td>5</td>
<td>51,000</td>
<td>451</td>
<td>Sandy section through center</td>
</tr>
<tr>
<td>6</td>
<td>65,000</td>
<td>575</td>
<td>100% shear</td>
</tr>
<tr>
<td>Avg</td>
<td>55,000</td>
<td>487</td>
<td></td>
</tr>
<tr>
<td>300 days exposure to 2.0 mA applied current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>64,500</td>
<td>570</td>
<td>80% shear, good matrix</td>
</tr>
<tr>
<td>8</td>
<td>57,500</td>
<td>509</td>
<td>75% shear</td>
</tr>
<tr>
<td>9</td>
<td>63,000</td>
<td>558</td>
<td>90% shear</td>
</tr>
<tr>
<td>Avg</td>
<td>61,660</td>
<td>546</td>
<td></td>
</tr>
<tr>
<td>Control - 300 day cure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>52,000</td>
<td>460</td>
<td>75% shear, erratic break</td>
</tr>
<tr>
<td>B</td>
<td>59,000</td>
<td>523</td>
<td>80% shear</td>
</tr>
<tr>
<td>C</td>
<td>52,000</td>
<td>452</td>
<td>80% shear, sandy matrix</td>
</tr>
<tr>
<td>Avg</td>
<td>54,000</td>
<td>478</td>
<td></td>
</tr>
</tbody>
</table>

Figure E-10. Cathode end of splitting tensile specimen after 300-days' exposure to an applied current.
exposure condition ranged from 48 to 141 psi, with an average range of 82 psi. The major cause of the variations in performance appears to be related to the quality of the test specimen (such as nonuniform distribution of aggregate and the type of subsequent fracture), and not to the effects of the applied currents.

SUMMARY AND CONCLUSIONS

The application of a cathodic-protection current to reinforcing bars in concrete can result in a decrease in bond strength between the steel and the concrete. A total applied current of 3460 amp hr/sq ft, applied at current densities as high as 960 mA/sq ft, produced about a 10-percent reduction in ultimate bond stress in these tests. Doubling the total applied current resulted in a further reduction in bond stress. There was relatively little effect shown between the applied current density and ultimate bond strength. Also, there is no apparent relation between the bond stress required to produce a 0.01-in. loaded-end slip and the application of cathodic protection in this test. It should be noted that the current levels that produced the loss of bond were appreciably higher than would be used in a normal cathodic-protection application. Nevertheless, it is recommended that this negative aspect be minimized in applications of cathodic protection to bridges. In this test, the loss of bond is attributable to total applied current and, to a much lesser extent, applied current density (that is, potential by virtue of the well-known potential/log current density relation). However, the only practical way to lessen the loss of bond is to impose a potential limit corresponding to relatively low applied current density. The net effect of this approach is to extend the time to reach total applied current (ampere hours per square foot) levels corresponding to significant loss of bond. The test results summarized in Table E-5 indicate that the —1.1 V\text{CuSO}_4 limit, discussed in the state of the art (Appendix A), would have lessened the loss of bond in the present test.

As judged by the results of splitting tensile tests on concrete cylinders containing no reinforcing steel, there is no effect on concrete strength from the application of a cathodic-protection current in the ranges covered in this study (2.5 to 10.0 mA/sq ft).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Current Density, mA/sq ft</th>
<th>Average Ultimate Bond Stress psi**</th>
<th>psi***</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>—0.65 (Control)</td>
<td>0</td>
<td>2097</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>—1.07</td>
<td>48</td>
<td>2077</td>
<td>20</td>
<td>0.9</td>
</tr>
<tr>
<td>—1.15</td>
<td>480</td>
<td>1833</td>
<td>264</td>
<td>12.6</td>
</tr>
<tr>
<td>—1.22</td>
<td>960</td>
<td>1720</td>
<td>377</td>
<td>18.0</td>
</tr>
</tbody>
</table>

* Average of three specimens at the indicated current density over the exposure period.
** Average of three specimens.
*** Difference between average for specimens without cathodic protection and specimens at specified protection level.
APPENDIX F

ANALOG MODEL AND RELATED INVESTIGATION

INTRODUCTION

The purpose of this part of the research was to investigate the suitability of various cathodic-protection designs by using an analog model of a reinforced-concrete bridge-deck section. As indicated in Appendix A, cathodic-protection studies have been performed in the past by using analog models of reinforced-concrete structures (14, 16, 31, 32). Heuze (16) used an analog model for investigating important electrical parameters, such as electrical continuity of the reinforcing network, and for analysis of the cathodic-protection current distribution at the surface of complex reinforced steel structures. Such analyses are important considerations in this study, because the reinforced-concrete bridge deck lacks metallurgical bond at the various rebar crossing points and has a reinforcing steel arrangement consisting essentially of two rebar mats: one near the top of the deck, and the other near the bottom.

With this arrangement, it is clear that the introduction of cathodic-protection current from the underside of the bridge deck requires that this current pass through one network of steel reinforcement to arrive at the other requiring protection. In view of these considerations, it was concluded that a preliminary series of cathodic-protection tests should be performed, with the analog model, to determine the essential electrical parameters of a cathodic design for this application. A subsequent investigation would evaluate specific design details, such as type of anodes, anode backfill, and physical and installation requirements of the method selected to satisfy the essential parameters of the cathodic-protection design.

PRELIMINARY CATHODIC-PROTECTION TESTS

Analog Model Design

A 12-ft by 12-ft physical model of a reinforced-concrete bridge-deck section was constructed, as shown in Figure F-1. Although the model scale and most important structural details, such as the size and location of the rebars, are typical of actual bridge decks (51), two important deviations were incorporated in the design. These nonypical aspects and the reason for their inclusion in the deck model are as follows:

1. Electrical Isolation. During construction of the model, provisions were made to electrically isolate each rebar from the others. This was accomplished by inserting a small piece of plastic material between the rebars at their crossing. In lieu of the usual steel-wire tie at each rebar crossing, a plastic strap was used to hold the rebars in position. A copper-wire connection from each end of each rebar to electrical ground was made at a panelboard. This arrangement permitted analysis of electrical effects, such as current distribution, by measurement of voltage and observation of the wave form with an oscilloscope connected across a small-value resistor between the rebar and electrical ground or other rebars.

2. Simulated Concrete Environment. A second important nontypical aspect of the model design is that the top 4 in. of concrete are represented by a saturated calcium hydroxide [Ca(OH)₂] solution. Figure F-1a illustrates this arrangement. Because saturated Ca(OH)₂ is the principal soluble component of hydrated portland cement and has about the same pH (about pH 12.5), it simulates concrete in its electrochemical nature (26). The use of the Ca(OH)₂ solution permits the flexibility of working in an aqueous solution, which is particularly useful in obtaining polarized-potential measurements. The electrical resistivity of the concrete is represented by the resistance of the Ca(OH)₂ solution. Inasmuch as the concrete resistance will vary, the initial plan was to alter (lower) the Ca(OH)₂ resistance with calcium chloride additions. However, this was not done because the initial resistivity of the Ca(OH)₂ solution proved to be relatively low and, thus, represents a low-resistance concrete. Using a low value for resistivity reduces the chances for underestimating the cathodic-protection current requirements.

Figure F-1a shows that the analog has a 4-in. thickness of reinforced concrete at its bottom. The concrete used for this project was formulated and mixed in accordance with the Pennsylvania Department of Transportation (PennDOT) specification for reinforced-concrete bridge decks (50). This concrete composition consists of about 6 bags of cement per cubic yard and a ratio of about 5 gal of water per bag of cement. The results of concrete compression tests, during and after the 28-day cure time, are given in Table F-1. Later in the analog investigation, during work with a top-anode placement, limestone aggregate was used as a filler material in the Ca(OH)₂ solution in the top half of the model. Figure F-1b illustrates this arrangement, which was necessary to support the top anode and its backfill. A cheesecloth membrane was used to separate the limestone and the anode backfill. The conductance (upper half of the deck section), during this latter arrangement, was derived from the Ca(OH)₂ solution, and it was found to be about the same as that obtained during studies without limestone aggregate.

Although the effectiveness of the cathodic-protection application to the analog was generally determined from the resultant polarized potentials of the deck steel, electrical-resistance probes were also used for this purpose. Accordingly, the model was instrumented with six electrical-resistance probes (Corrosometer Model 1036) for measurement of corrosion rate. Four of the probes are embedded in concrete in the underside of the model, equally spaced diagonally across the model. Two probes are placed in the Ca(OH)₂ solution, one in the center and the other near the edge of the deck. Corrosion rates are determined with these probes by measuring the change in the electrical resistance...
a. ANALOG MODEL ARRANGEMENT FOR TESTING SOFFIT ANODE PLACEMENT

b. ANALOG MODEL ARRANGEMENT FOR TESTING TOP ANODE PLACEMENT

NOTE: SEE FIGURE ABOVE FOR DIMENSIONS
of the probe with an appropriate instrument (Corrosometer Model CK-2). The change in resistance is a result of corrosion of the exposed metal element of the probe. An AISI 1010 mild steel element, which except for carbon content has approximately the same composition as the AISI 1030 steel rebars, was used in this project. The probe-test lead is connected to the model's steel reinforcement; and, thus, the exposed metal element of the probe receives about the same cathodic-protection current density as nearby deck steel. The net effect of this test arrangement is that the probes simulate reinforcement. As long as the cathodic-protection system is effective, no change in the probe reading will occur.

Analog Test Procedure

In general, the test procedure was to simulate either a top- or soffit-anode design and to apply cathodic protection with either an impressed-voltage or sacrificial-anode method. The applied voltage was held constant until a steady state of electrical potential of the steel rebar network, top and bottom, was reached. Two locations, one midpoint and the other near the deck corner, were continuously monitored for steady-state potential. Usually, a series of tests consisting of progressively greater impressed voltages was conducted with a given set of design parameters. It was arbitrarily decided that, for safety, the maximum voltage for this application was 40 volts (V). No cathodic protection was applied for several days between design changes to reduce the effects of residual polarization on the test results.

Once steady-state conditions were indicated at the monitored locations during a given test, the polarized potential of the entire top and bottom rebar network was measured by a saturated copper-copper sulfate (Cu/CuSO₄) half-cell placed, as near as possible to the rebars, at the point of interest. Figure F-2 shows the manner in which the half-cell was placed: from the top of the deck (a), and from the bottom (b). It should be noted that, during the work with the soffit-anode design, potential measurements on the bottom steel were made from the top of the model by extending the half-cell through the Ca(OH)₂ solution (see Fig. F-1a). However, with the top-anode studies, this procedure was no longer possible (see Fig. F-1b) and, therefore, the bottom steel potential was measured with the half-cell placed against the underside of the deck, as shown in Figure F-2b.

The potential between the half-cell and the steel was measured by a high-impedance voltmeter, usually a Keithley Electrometer (Model 610C). These measurements were made at locations corresponding to a grid pattern, generally at 2-ft intervals (see Fig. F-2a). The rebar potential values were recorded on a grid sheet, and equipotential lines, usually at 100-millivolt (mV) intervals, were plotted. The resultant equipotential contour maps indicate the area of the rebar network with sufficiently polarized potentials to obtain cathodic protection (the polarized potential for protection was considered to be 850 mV negative to the Cu/CuSO₄ half-cell, pending appraisal of the criteria testing, Appendix E). Also, the maps give an indication of the current distribution obtained as various voltage and design changes were made. As previously mentioned, the effectiveness of the applied cathodic protection was also monitored by six electrical-resistance probes placed in the model.

### TABLE F-1
LABORATORY CORRELATION TESTS FOR ANALOG-MODEL CONCRETE *

<table>
<thead>
<tr>
<th>Age at Test, days</th>
<th>Total Load, pounds</th>
<th>Compression Strength, pounds per sq inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>64,500</td>
<td>2281</td>
</tr>
<tr>
<td>7</td>
<td>62,500</td>
<td>2210</td>
</tr>
<tr>
<td>7</td>
<td>67,500</td>
<td>2287</td>
</tr>
<tr>
<td>14</td>
<td>89,500</td>
<td>3165</td>
</tr>
<tr>
<td>14</td>
<td>87,500</td>
<td>3095</td>
</tr>
<tr>
<td>14</td>
<td>84,000</td>
<td>2971</td>
</tr>
<tr>
<td>28</td>
<td>101,000</td>
<td>3572</td>
</tr>
<tr>
<td>28</td>
<td>105,500</td>
<td>3731</td>
</tr>
<tr>
<td>28</td>
<td>112,000</td>
<td>3961</td>
</tr>
</tbody>
</table>

* Class of Concrete, Pennsylvania Department of Transportation specification AA(50).

W/C Ratio 5.3 gal/bag

Slump 4.0"

% Air 5.2%

The cement used meets the physical and chemical requirements of ASTM specification C-150-71.
Figure F-2. Manner in which the half-cell for potential measurements was positioned: (a) from the top of the analog model and (b) from the bottom. For bottom measurement, the half-cell was modified with a plumber's helper containing a wet sponge to improve surface contact.

Consideration of Rebar Continuity

The successful use of cathodic protection for deck reinforcement requires electrical continuity between the various metallic elements of the reinforcement. Accordingly, the initial work of this investigation related to the electrical continuity of the deck rebars, which, in practice, are tied together with steel wire.

The electrical continuity of any rebar in the deck depends principally on the lowest resistance connection between that rebar and another rebar in the network. Consider, for example, a rebar system in which one row of rebars is connected together by welding a copper wire to each rebar in the row and carrying this wire to ground. In this hypothetical network, any rebar that is not directly grounded will be connected, through a parallel set of resistance contacts (wire ties), directly to a bar that is grounded. In this case, the resistance to ground of any cross rebar is given by

$$\frac{1}{R} = \sum_{i=1}^{N} \frac{1}{R_i}$$

where $R_i$ is the individual contact resistance. Thus, the total resistance to ground for any given rebar will be less than the lowest resistance of any individual wire tie. Experiments conducted in the laboratory show that the wire-tie method results in a contact resistance of $<0.10 \, \text{ohm}$, in more than 50 percent of the cases, and $<0.01 \, \text{ohm}$, in about 10 percent of the cases. Therefore, it is reasonable to assume that the contact resistance of at least one of the cross rebars is a low value and that the entire rebar grid will have a continuous low-resistance contact with ground.

In viewing the bridge as a whole, it is anticipated that the cathodic-protection current will not stray significantly from its intended path (to deck rebars). Current flow through the deck concrete is difficult at best, and flow beyond the rebar network or laterally through the deck slab is unlikely. Where the current is inadvertently applied to structural steel, it would be important that the steel have a continuous low-resistance contact with the rectifier ground. Welded joints are desirable because mechanical (bolted) joints, on occasion, may be of high electrical resistance. A test of these aspects—the possibility of stray currents and adequate electrical continuity of structural steel—must of necessity be performed, however, on an actual bridge (Phase II).

EVALUATION OF DESIGN DETAILS

Soffit-Anode Investigation

The analog model was used to conduct some 28 different tests to determine the effects of an impressed-current method utilizing soffit anodes and conductive backfill placed in a container affixed to the underside of the deck. The impressed-current method of cathodic protection requires an external power supply to drive current from an anode into the structure receiving protection. The basic electrical circuit for this method is shown in Figure F-3. This work included investigation of the effects of different types, sizes, shapes, and locations of the soffit anode under different impressed voltages, both pulsed and continuously applied, on the rebar network potential gradient.

Initial experiments were conducted with a 3-ft by 12-in. by 6-in.-deep anode container; 30-in.-long by 2-in.-diameter, high-silicon iron rod; and graphite flake backfill. Table F-2 contains design information concerning the impressed-current anodes used in this work. Figures F-4 through F-8 show the results obtained with this anode affixed midpoint to the underside of the deck and with various voltages applied. From this work, it was learned that circuit resistance associated with the soffit anode was high (about 15 ohms) and that the protected area achieved with maximum applied voltage (40 V) was limited to about the size of the anode container in contact with the deck.

In an effort to improve current distribution and, there-
Figure F-3. Schematic of full-wave impressed-direct-current cathodic-protection circuit used in analog investigation.

TABLE F-2
ANALOG BRIDGE-DECK-SECTION DESIGN INFORMATION RELATING TO IMPRESSED-CURRENT ANODES

<table>
<thead>
<tr>
<th>Anode Specifications</th>
<th>Silicon-iron</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Name</td>
<td>Duriron 51</td>
<td>None</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Duriron Co</td>
<td>National Carbon Co</td>
</tr>
<tr>
<td>Type (shape)</td>
<td>Disk, rod</td>
<td>Rod</td>
</tr>
<tr>
<td>Size</td>
<td>(Rod) 2 in. diam by 60 in. long</td>
<td>(Disk) 3 in. by 6 in.</td>
</tr>
<tr>
<td>Approximate Wt/anode, lb</td>
<td>Disk 40</td>
<td></td>
</tr>
<tr>
<td>Approximate Consumption Rate, lb/amp-yr</td>
<td>&gt;0.2</td>
<td>&gt;2</td>
</tr>
<tr>
<td>Nominal Composition Inert Anodes, %</td>
<td>Silicon-iron</td>
<td>Graphite</td>
</tr>
<tr>
<td>Si</td>
<td>14.50</td>
<td>-</td>
</tr>
<tr>
<td>Mg</td>
<td>0.75</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>0.95</td>
<td>Total</td>
</tr>
<tr>
<td>Cr</td>
<td>4.50</td>
<td>-</td>
</tr>
<tr>
<td>Fe</td>
<td>Balance</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure F-4. Equipotential contour maps of bridge-deck model before applying cathodic protection, using a soffit-anode design. Contour units are mV negative to Cu/CuSO₄ half-cell. Grid intervals are 2 ft.

Figure F-5. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 9 V and 1 amp. Soffit anode was located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.
Figure F-6. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 15.6 V and 2 amp. Soffit anode was located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.

Figure F-7. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 35 V and 3 amp. Soffit anode was located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.
fore, increase the protected area with a given anode arrangement, a series of tests, in which the impressed voltage was applied intermittently, was conducted with this soffit anode. Other investigators (52, 53) reported improved current distribution with intermittent application of the cathodic protection in marine environments. As a preliminary test, a half-wave impressed-voltage source was used to give 60-cps half-wave rectification. The test circuit arrangement is shown in Figure F-9. Figures F-10 through F-13 show the results obtained with this pulsing voltage source. A comparison of these maps with those obtained earlier under constant voltage shows that a moderate improvement in the protected area of the bottom reinforcement was realized by pulsing.

At this point, several important changes were made in the soffit-anode design to reduce its resistance in the cathodic-protection circuit. As shown on Figure F-14, provisions were made to improve the contact between the anode backfill and the concrete on the underside of the deck; a means of wetting the inside of the anode box was also provided. Additionally, the length of the anode box was increased to 10 ft to accommodate a longer (5-ft) anode and to increase the contact area between the backfill and the underside of the deck.

The results obtained with the modified soffit anode and the half-wave impressed-voltage source are shown in Figures F-15 and F-16. The average operating resistance with this anode method was <10 ohms as compared with about 15 ohms for the previous anode arrangement. An improvement in the amount of deck area with protective potentials was also realized.

Work with pulsed impressed voltage was suspended temporarily, while arrangements for an improved voltage interrupting circuit were completed. This work will be described later in this report.

The next step in the soffit-anode testing was the development of the multi-anode system shown in Figure F-17. Several new materials were used to make up this multi-anode design, including a 5-ft-long by 3-in.-diameter graphite anode with a coke-breeze backfill. One of the anodes was placed near the end of the anode box. Other variations in the design, not shown in Figure F-17, included the use of different materials at the concrete-backfill interface. In one case, a mixture consisting of 50-percent bentonite and 50-percent gypsum was used. In another, the mixture consisted of 75-percent bentonite and 25-percent calcium
chloride. In the third, a bentonite layer was used. The wire hook up to these anodes was designed to permit measurement of the current going to each anode.

Figure F-18 shows two of the soffit anodes in place under the model. The contour maps, Figures F-19 through F-23, are results obtained with the multi-anode system and continuous impressed voltage. These results indicate that no improvement was obtained from the changes in the soffit anode makeup. Comparison of the anode currents shows essentially the same circuit resistance for each anode. Overall, the results of this testing indicated that the protected area obtained with the soffit anode and maximum impressed voltage is less than twice the size of the soffit anode and its backfill in contact with the underside of the deck. This, in effect, points out that the required anode spacing would be too close for a practical cathodic-protection design. Thus, it was clear that, for the soffit-anode design to be economically practical, substantial success would have to be obtained with the additional investigation of intermittent application of current to increase the area protected per anode.

The earlier work with half-wave rectification of an AC voltage showed some improvement in current distribution. To investigate this method more fully, an electromechanical pulsing circuit, illustrated in Figure F-24, was prepared. With this pulsing circuit, changes in the current "on" and "off" periods result from changing the revolutions per minute of a variable speed motor revolving a metal bar through the electrical field of a magnetic switch. This switch, in turn, operates a solenoid switch that opens and closes the
Figure F-12. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 60 V and 2-amp actual current. Soffit anode was located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO$_4$ half-cell. Pulsing rate is constant 60 pulses per second with equal on-off periods.

Figure F-13. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 50 V and 3.5-amp actual current. Soffit anode was located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO$_4$ half-cell. Pulsing rate is constant 60 pulses per second with equal on-off periods.
Figure F-14. Soffit-anode assembly.

Figure F-15. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 36 V and 3.5-amp actual current. Soffit anode was located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulsing rate is constant 60 pulses per second with equal on-off periods.
Figure F-16. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 55 V and 5.85-amp actual current. Soffit anode was located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulsing rate is constant 60 pulses per second with equal on-off periods.

Figure F-17. Equipotential contour maps of bridge deck with no cathodic protection applied and 5 days after completion of previous cathodic-protection testing. Note 3-soffit-anode system. Contour units are mV negative to Cu/CuSO₄ half-cell and plotted on a 2-ft grid.
Figure F-18. View of two of the 10-ft-long soffit anodes (containers) in position under the analog model of a bridge deck.

Figure F-19. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 12 V and 3 amp. Three soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.

Figure F-20. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 12 V and 5.5 amp. Three soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.
Figure F-21. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 21 V and 9 amp. Three soffit anodes were located, as indicated, on the 2-ft grid. Reading units are mV negative to Cu/CuSO₄ half-cell.

Figure F-22. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 40 V and 16.8 amp. Three soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.
A. TOP MEASUREMENTS

Figure F-23. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 44 V and 10 amp. Three soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.

B. BOTTOM MEASUREMENTS

Figure F-24. Schematic of electromechanical interruption circuit used in analog investigation.

cathodic-protection circuit. Although this method was employed for several tests (see Fig. F-25), it was unsatisfactory, because of the lack of accurate pulse control and the narrow range of pulsing times available with this arrangement. Therefore, the electronic pulsing circuit shown in Figure F-26 was prepared. This design permitted virtually unlimited variation of pulse parameters. The pulsed-current conditions investigated were: pulse-wave times from 130 ms to 4.7 seconds (s), cathodic protection “on” periods from 30 ms to 3 s, and “off” periods from 50 ms to 1.75 s. The effect of these pulsing conditions on the cathodic protection was observed with an oscilloscope that was connected across a low-value resistor (0.1 ohm) between a rebar located near a cathodic-protection anode and a rebar located remote from the anodes.

Figure F-27 shows the arrangements for observation of the wave forms during this pulse test. The wave form A in Figure F-27 illustrates the appearance of voltages supplied from the voltage source, whereas B in Figure F-27 is typical of the wave form of the voltage between a rebar near the anode and one remote from the anode. It can be seen from B (Fig. F-27) that, when the cathodic protection is turned off, the voltage between these rebars reverses. In effect, the near rebar receives an electrical charge during the “on” period and supplies current to the remote rebar during the “off” period. Through observation of this effect during the various pulse parameters of this test, an effort was made to determine the conditions that would provide maximum current distribution. As with other studies during the soffit-anode testing, the over-all cathodic protection effectiveness was evaluated from the equipotential profiles. The results, shown in Figures F-28 through F-33, demonstrate that pulsing the impressed voltage reduces the total current required for a given protected area, but it does not significantly improve the current distribution or extend the protected area.

After considering the combined results of all phases of the soffit-anode testing, it was concluded that this approach
Figure F-25. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 46 V and 7.75-amp actual current. Soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulse-wave time is 400 ms with "on" time of 160 ms and "off" time of 240 ms.

Figure F-26. Schematic of electronic interruption circuit used in analog investigation.

Figure F-27. Arrangement for voltage wave-form study—analogue investigation.
Figure F-28. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at peak voltage of 68 V and 13-amp actual current. Soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulse-wave time is 4.7 s with "on" time of 3 s and "off" time of 1.7 s.

Figure F-29. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 70 V and 16-amp actual current. Soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulse-wave time is 2000 ms with "on" time of 300 ms and "off" time 1700 ms.
Figure F-30. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 70 V and 16-amp actual current. Solfit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulse-wave time is 1680 ms with "on" time of 30 ms and "off" time of 1650 ms.

Figure F-31. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at peak voltage of 68 V and 13-amp actual current. Solfit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/SO₄ half-cell. Pulse-wave time is 470 ms with "on" time of 300 ms and "off" time of 170 ms.
Figure F-32. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at a peak voltage of 46 V and 6.9-amp actual current. Soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulse-wave time is 130 ms with “on” time 80 ms and “off” time 50 ms.

Figure F-33. Equipotential contour maps of bridge-deck model with pulsed-voltage cathodic protection applied at peak voltage of 72 V and 15-amp actual current. Soffit anodes were located, as indicated, on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell. Pulse-wave time is 200 ms with “on” time of 100 ms and “off” time of 100 ms.
would not lead to the development of a practical design for a cathodic-protection system for bridge decks.

**Top-Anode Investigation**

During the state-of-the-art review (Appendix A), it was learned that Stratfull of the California Division of Highways was conducting an extensive program to develop a new cathodic-protection method to arrest corrosion of steel reinforcement in concrete bridge decks. The salient feature of his approach is use of an electrically conductive asphaltic overlay on the deck to distribute the protective current over the top rebars. It was also previously determined (Appendix A) that cathodic protection of the top network of steel rebars would be adequate to prevent deterioration of concrete bridge decks. On the basis of the investigations cited and in accord with the scope of the project—namely, to investigate various systems and to establish the optimum design for cathodic protection—the top-anode method, as proposed by Stratfull, was studied.

In all, some 18 experiments were conducted with an impressed-current method and an anode placed in a conductive material over the deck surface. For this test, a 6-in.-diameter, disk-shaped silicon-iron anode was placed in a layer of coke breeze covering the surface of the model (Fig. F-1b). Figures F-34 through F-50 show the results obtained with this design for cathodic protection. These tests indicate that cathodic protection of the top network of steel rebars can be readily accomplished with a very low impressed voltage and total current.

A series of tests was performed to determine the effect of the thickness of the conductive layer on the circuit resistance and the area of the deck surface that can be protected by a single anode. Figure F-51 is a plot of the circuit resistance obtained versus conductive-layer thickness. It is obvious from this figure, that the results of this work are inconclusive, possibly because of the small size (surface area) of the model. However, this information provided a basis for a study of these aspects with the mathematical model. Additional data concerning these parameters are reported in Appendixes G and H.

During the top-anode conductive-overlay tests, it was noted that the electrical-resistance probes monitoring the corrosion of the top network of steel rebars did not stop corroding until an apparent rebar potential value of $>-1260$ mV measured to a Cu/CuSO$_4$ reference half-cell was attained. Table F-3 is a summary of potentials and corresponding corrosion rates for each of the top probes during the top-anode investigation. From the soffit-anode investigation and the studies described in Appendix D, it is known that a much lower value (about $-800$ mV) is sufficient to stop corrosion. This information led to the discovery that placing the half-cell over the conductive overlay (coke breeze) gives an erroneous value for the potential of the steel under investigation. In an effort to determine the cause and extent of this measurement error, an extensive study was conducted. The results of this study are reported in Appendix D.

* Protection of the top mat only is adequate if, at the time cathodic protection is added, there is no evidence of corrosion in the bottom layer of steel and if additional salts do not subsequently reach that steel.
The measurement problem notwithstanding, the top-anode conductive-layer design gave every indication of successfully meeting the electrical requirements of a practical cathodic-protection design for concrete bridge decks. Accordingly, preliminary work was initiated to develop a conductive overlay material suitable for use with an impressed-current system and for bridge-deck service.

Essentially, a material to be used as the conductive component in the overlay for this approach to cathodic protection by the impressed-current method must be chemically inert and a good electrical conductor. Most metals, under the condition of anodic current discharge required for this application, would corrode, with serious consequences to the general condition of the overlay. Those metals that would not corrode in this application, such as platinum, are not candidates for use because of their high cost.

Of the various nonmetals, the carbonaceous materials stand out as best for use in the conductive overlay. These materials, such as coke and graphite, not only meet the aforementioned essential requirements, but they also have a long history of use as cathodic-protection ground-bed material. Graphite particles have been used in electrically conductive asphaltic concrete (54). Electrical current, passed through this conductive pavement, generates heat, which, in turn, prevents the accumulation of snow and ice. Coke, on the other hand, has merit for use in the conductive overlay because it is widely available and is, therefore, relatively inexpensive. For this reason, it was preferred for study over graphite.

Another important asset of coke is that it is nearly insoluble and nonvolatile. It should be noted, however, that a necessary anodic reaction occurs at the coke surface as the cathodic-protection current passes from the coke (electronic conductance) to an adjacent electrolyte (water-ionic conductance). As the result of the reaction, either oxygen or chlorine gas is liberated. With the high concentration of chloride on most bridge decks, chlorine will be discharged at the anode in preference to oxygen. The chlorine does not react with the carbon, and, if only chlorine gas is formed at the coke surface, it should last indefinitely. Even if some oxygen is formed at the anode, the rate of reaction of oxygen with carbon (to form CO,) is sufficiently low that it should not impair the life of the conductive layer. However, as with any cathodic-protection anode bed, the material surrounding the anode must be sufficiently porous to vent gases resulting from the anodic reaction. These gases, if not vented, lead to an increase in circuit resistance of the anode bed and eventually could block the current flow. Also, it should be noted that this system of cathodic protection, as well as other systems proposed, depends on the presence of sufficient moisture near the anode and in the deck concrete to conduct the cathodic-protection current.

In addition to the aforementioned properties, a conductive overlay utilizing coke as the asphaltic concrete aggregate must satisfy traffic durability requirements. Accordingly, the durability of a coke-aggregate asphalt mixture

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* The volatile matter of coal, some of which may be carcinogenic, is removed in the coking process (destructive distillation of coal at temperatures in the range of 1650 to 2000 F).
was investigated. Marshall-type paving specimens were prepared and tested for stability and flow to determine the optimum binder content to use with an aggregate consisting of 95-weight-percent coke breeze and 5-percent pulverized limestone. The addition of alkaline material to carbonaceous backfill has been found advantageous in decreasing the rate of electrochemical attack and increasing the moisture retention (55). Several mix designs were evaluated: (1) an open-graded and a dense-graded mix having a top size of 3/8 in. (100% passing a 3/8-in. sieve), which is the approximate physical analysis of coke breeze used in cathodic-protection application, and (2) a dense-graded mix having a top size of 1 in. As an asphaltic binder, AC 2000* asphalt cement (viscosity at 140°F; 2000 ± 400 poises) was mixed with each aggregate at a temperature of 300°F. AE-90† anionic emulsified asphalt was mixed with the open-graded aggregate, and AE-150† anionic emulsified asphalt was used with the dense-graded aggregates; both of these emulsions were mixed with the aggregates at ambient temperature.

The sizes of the coke-breeze/limestone aggregates used to prepare the mixes are given in Table F-4 along with appropriate ASTM and Pennsylvania Department of Transportation specifications.

Marshall design data for the coke-breeze/asphalt mixes are given in Table F-5. On the basis of these data, the

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Figure F-36. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 7 V and 1 amp. Top anode was located, as indicated, on the 2-ft grid, in a 1-in. layer of coke breeze covering entire deck surface. Contour units are mV negative to Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.

Figure F-37. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 8 V and 1 amp. Top anode was located, as indicated, on the 2-ft grid, in a 2-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.
ASTM 6A and 3A mixes containing AC-2000, although marginal with respect to stability, should perform satisfactorily when overlayed with a conventional asphaltic wearing-course mix. All of the mixes prepared with the emulsions had extremely low stability values. (Specimens were cured at 140 F for 40 hr prior to testing for stability.) This low stability may be inherent with emulsion/coke-breeze mixes; however, it may also be due to the unsuitability of using the Marshall method for testing such mixes. In view of the latter possibility, and especially because the use of an emulsion offers many advantages over the use of an asphalt cement such as AC-2000, emulsion/coke-breeze mixes should not be ruled out.

**Sacrificial-Anode Investigation**

Insofar as it has been shown that cathodic protection of the top steel rebars can be achieved with a low applied voltage and small current, provided that the anode arrangement gives the necessary current distribution, it was concluded that the sacrificial-anode method of cathodic protection may be possible in this application. This method of cathodic protection consists of making the corroding structure the cathode of an electrolytic corrosion cell, with a more active metal as an anode. The structure and the anode operate as a bimetallic corrosion cell, and the anode electrode is corroded, or sacrificed. The driving potential for the cathodic protection is derived from the natural potential difference between the metal of the structure and the anode and, accordingly, is limited to this value. In practice, magnesium (Mg) and zinc (Zn) alloys have been employed for the cathodic protection of steel reinforcement in concrete. The possibility of using a sacrificial-anode design for...
Figure F-40. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 6.8 V and 0.86 amp. Top anode was located, as indicated, on the 2-ft grid, in a 2-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.

Figure F-41. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 7.75 V and 1.35 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.
Figure F-42. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 3.6 V and 1.3 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.

Figure F-43. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 6.1 V and 0.5 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.
Figure F-44. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 4.8 V and 0.3 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.

Figure F-45. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 5 and 0.25 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.
Figure F-46. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 7.5 V and 1.25 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.

Figure F-47. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 6.7 V and 0.8 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.
Figure F-48. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 7 V and 0.8 amp. Top anode was located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.

Figure F-49. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 6 V and 1 amp. Two top anodes were located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.
TABLE F-3
SUMMARY OF CORROSION-RATE READINGS AND INDICATED PROBE POTENTIALS—TOP ANODE SYSTEM

<table>
<thead>
<tr>
<th>Avg Applied Current, amps</th>
<th>Change in Probe Units Per Day</th>
<th>Potential* at Probe, mV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. 6</td>
<td>No. 7</td>
</tr>
<tr>
<td>0.25</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>1.0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.8</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: The four probes embedded in concrete in the underside of the model did not corrode during the exposure period.

Because of changes in various parameters, such as the number of anodes and the anode position, the relation between applied current and probe potential is not meaningful.

* Distorted values measured for the top layer of reinforcing bars near the probe with Cu/CuSO₄ half-cell contacting coke breeze overlay.

Figure F-50. Equipotential contour maps of bridge-deck model with continuous cathodic protection applied at 4.7 V and 0.6 amp. Two top anodes were located, as indicated, on the 2-ft grid, in a 3-in. layer of coke breeze covering the entire deck surface. Contour units are mV negative to a Cu/CuSO₄ half-cell. Potential values measured for top are distorted by coke-breeze overlay.

Figure F-51. Effect of coke-overlay thickness on circuit resistance of the cathodic protection with top anode.
TABLE F-4

SIZE OF COKE-BREEZE/LIMESTONE AGGREGATES
USED TO PREPARE MIXES

<table>
<thead>
<tr>
<th>Pa. Open-Graded Mix</th>
<th>Passing Coke Breeze,</th>
<th>Pa. Dept of Transportation Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve</td>
<td>wt %</td>
<td></td>
</tr>
<tr>
<td>1/2'</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3/8'</td>
<td>90</td>
<td>90-100</td>
</tr>
<tr>
<td>4</td>
<td>30-50</td>
<td>30-50</td>
</tr>
<tr>
<td>8</td>
<td>10-25</td>
<td>10-25</td>
</tr>
<tr>
<td>16</td>
<td>0-18</td>
<td>0-18</td>
</tr>
</tbody>
</table>

ASTM 6A Mix

<table>
<thead>
<tr>
<th>Passing Coke Breeze,</th>
<th>Pa. Dept of Transportation Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve</td>
<td>ASTM ID-2A wearing Course Spec</td>
</tr>
<tr>
<td>1/2'</td>
<td>100</td>
</tr>
<tr>
<td>3/8'</td>
<td>90-100</td>
</tr>
<tr>
<td>4</td>
<td>60-80</td>
</tr>
<tr>
<td>8</td>
<td>35-65</td>
</tr>
<tr>
<td>16</td>
<td>20-45</td>
</tr>
<tr>
<td>30</td>
<td>10-35</td>
</tr>
<tr>
<td>50</td>
<td>5-25</td>
</tr>
<tr>
<td>100</td>
<td>4-14</td>
</tr>
<tr>
<td>200</td>
<td>3-10</td>
</tr>
</tbody>
</table>

ASTM 3A Mix

<table>
<thead>
<tr>
<th>Passing Coke Breeze,</th>
<th>Pa. Dept of Transportation Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve</td>
<td>ASTM ID-2A Binder Course Spec</td>
</tr>
<tr>
<td>1&quot;</td>
<td>100</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>90-100</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>60-80</td>
</tr>
<tr>
<td>4</td>
<td>35-65</td>
</tr>
<tr>
<td>8</td>
<td>20-45</td>
</tr>
<tr>
<td>16</td>
<td>10-35</td>
</tr>
<tr>
<td>30</td>
<td>5-25</td>
</tr>
<tr>
<td>50</td>
<td>4-17</td>
</tr>
<tr>
<td>100</td>
<td>3-18</td>
</tr>
<tr>
<td>200</td>
<td>2-6</td>
</tr>
</tbody>
</table>

Note: All mixes contain 5 wt % of pulverized limestone.

Concurrent with the mock-up test of the anodes, a sacrificial-anode design was evaluated on the analog deck model. For this study, the Mg ribbon was cut into 12-ft lengths and each length was placed across the top of the analog deck. The Mg anodes were in Ca(OH)₂ solution (average resistivity about 3000 ohm-cm) and were supported by limestone aggregate, about 1 in. above the top rebar mat. Different numbers of anodes were placed an equal distance apart. After the anodes were connected to the deck steel, the current output from the anodes and the deck steel potential were monitored until steady-state conditions were indicated. Then, a profile of the deck steel potentials was obtained.

Figures F-54, F-55, and F-56 show the results of this work. Figure F-57 shows that the effect of increasing the number of Mg anodes is to decrease the cathodic-protection circuit resistance and, at the same time, to increase the total anode-current output. From the maps (Figs. F-54, F-55, and F-56), it is clear that the maximum anode spacing for complete protection of the top rebar mat is 6 in. or, essentially, one ribbon anode between each pair of adjacent top rebars. Under the conditions of this test, this anode spacing and size would provide cathodic protection for at least 6 yr. However, additional anode life (cathodic protection) can be obtained by increasing the size of the Mg anodes. Be-
TABLE F-6
ANALOG BRIDGE-DECK DESIGN INFORMATION RELATING TO SACRIFICIAL ANODES

<table>
<thead>
<tr>
<th>A. Anode Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnesium</strong></td>
</tr>
<tr>
<td>Commercial Name</td>
</tr>
<tr>
<td>Manufacture</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Alloy</td>
</tr>
<tr>
<td>Cross-section</td>
</tr>
<tr>
<td>Wt per ft</td>
</tr>
<tr>
<td>Core Wire</td>
</tr>
<tr>
<td>Standard Coil Length, ft</td>
</tr>
<tr>
<td>Estimated Current Rating, amp-hr/ft</td>
</tr>
<tr>
<td>Density, lbs/ft³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Nominal Composition of Sacrificial Anodes—Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Potential, Mg</td>
</tr>
<tr>
<td>Al (min)</td>
</tr>
<tr>
<td>Mn (max)</td>
</tr>
<tr>
<td>Fe (max)</td>
</tr>
<tr>
<td>Ni (max)</td>
</tr>
<tr>
<td>Cu (max)</td>
</tr>
<tr>
<td>Si (max)</td>
</tr>
<tr>
<td>Other (max)</td>
</tr>
</tbody>
</table>

Electrochemical Properties of Galvanic Anode Used*

| Mg | Zn |
|--------------------------|
| Current Capacity-Theoretical, amp-hr/1b | 1000 | 372 |
| Current Efficiency, percent | 50 | 9C |
| Current Capacity-Actual, amp-hr/1b | 500 | 33C |
| Solution Potential, volts | -1.80 | -1.1 |
| Driving Potential to Cathode at -0.90 V, in volts | 0.90 | 0.2 |

* in earth, from Control of Corrosion, by A. W. Peabody.
Figure F-53. Zinc-anode specimens: (a) Zn in asphalt after 56 amp hr and (b) Zn in concrete after 33 amp hr.

Figure F-54. Equipotential contour maps of bridge-deck model with magnesium-ribbon anode system. Anodes were located, as indicated (2-ft centers), on the 2-ft grid. Current output from anodes is 500 mamp. Contour units are mV negative to Cu/CuSO4 half-cell.
Figure F-55. Equipotential contour maps of bridge-deck model with magnesium-ribbon anode system. Anodes were located, as indicated (1-ft centers), on the 2-ft grid. Current output from anodes is 750 mamp. Contour units are mV negative to Cu/CuSO, half-cell.

Figure F-56. Equipotential contour maps of bridge-deck model with magnesium-ribbon-anode system. Anodes were located, as indicated (0.5-ft centers), on the 2-ft grid. Current output from anodes is 920 mamp. Contour units are mV negative to Cu/CuSO, half-cell.
cause the driving voltage of a Zn-anode system is much less than that of the Mg system, it would appear that at least the same anode spacing indicated by the Mg test would be required for a Zn-anode system.

SUMMARY OF THE ANALOG-MODEL INVESTIGATION

The analog-model investigation showed that the essential feature of a design for the application of cathodic protection to a bridge deck is uniform current flow of appropriate value from a well-distributed anode arrangement located over the top rebar mat. A design consisting of a 6-in.-diameter, disk-shaped silicon-iron anode placed in a layer of coke breeze covering the surface of the analog model gave the best results. These results show that the top network of steel rebars can be readily protected by using a low-impressed-voltage cathodic-protection system. Tests performed with a dense-grade asphalt mixture, prepared with a coke-breeze aggregate, show that this material, although marginal with respect to some properties, should have satisfactory resistance to rutting or shoving when provided with a wearing-course overlay.

Results of a test with a Mg-anode design showed that one ribbon anode between each pair of adjacent rebars was needed for complete protection. A mock-up performance test of Mg- and Zn-ribbon anodes, encased in concrete and asphalt, showed that the Mg corrosion results in expansion, which, in turn, causes damage to the encasing material. Little damage was noted with the Zn anodes.

Testing with a soffit-anode location gave poor current distribution from the anode to the top rebar mat. With maximum impressed voltage, an area less than twice the anode-backfill contact area could be protected. Pulsing the impressed voltage lowered the total current needed to maintain the protected area, but it did not improve current distribution or extend the protected area sufficiently to make this design practical.
INTRODUCTION

Efficient design of a cathodic-protection system for bridge decking requires a means for calculating the potential field in the deck for all the various system parameters that might be employed in the design. The ability to make such calculations allows the designer to test a variety of ideas on paper before testing a real system. This, in turn, permits an inexpensive screening of systems to find those that are most promising for further testing. Accordingly, it was the objective of this part of the program to develop a mathematical model for the data generated by the analog-model testing (Appendix F) and to verify the mathematical model with data gathered from tests on the prototype bridge deck (Appendix H).

MATHEMATICAL-MODEL DEVELOPMENT

The cathodic protection of a rebar network in a reinforced bridge deck can be represented by a system of equations for steady-state current flow, in a three-dimensional body, with a wide variety of boundary and internal conditions. The most straightforward model for this system is a nodal approach in which the volume is broken into a mesh of nodes connected by resistances. With this type of model, sources and sinks can be applied directly at the node on which they occur. The application of Ohm's and Kirchoff's laws yields a system of algebraic equations, which uniquely determine the potential distribution and current flow over the network.

Because the number of equations in this system is quite large, a direct approach to their solution is impractical. One method frequently used to solve large systems of equations is the method of relaxation; in this technique, an initial solution is assumed, and the relaxation algorithm is used to improve this solution. Iterations are continued until all of the mathematical criteria for a solution are met to a specified tolerance. The basic criterion for steady state in the system of interest is that, at each node that is not a source or sink, the net current flow must be zero ($\Sigma I = 0$). This gives the basic nodal equation for iterating to a solution.

$$\sum I = \sum \frac{\Delta E}{R} = 0$$

Consider a typical node in a three-dimensional system:

For this system, the current flows can be written

$$\sum I = \sum \frac{\Delta E}{R} = \left[ \frac{E_{i-1,j,k} - E_{i,j,k}}{R_1} \right] + \left[ \frac{E_{i+1,j,k} - E_{i,j,k}}{R_2} \right] + \left[ \frac{E_{i,j+1,k} - E_{i,j,k}}{R_3} \right] + \left[ \frac{E_{i,j,k+1} - E_{i,j,k}}{R_4} \right] = 0$$

For nodes that are not sinks or sources, Eq. G-1 must be satisfied.

Solving for ($E_{i,j,k}$) gives

$$E_{i,j,k} = \frac{E_{i-1,j,k} + E_{i+1,j,k} + E_{i,j+1,k} + E_{i,j,k+1} + E_{i,j,k-1} + E_{i,j,k+1}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} + \frac{1}{R_6}}$$

($G-2$)

$E_{i,j,k}$ is the potential, at node $i,j,k$, that would reduce the net current flow at that node to zero, if all the other potentials in the system remained the same. The basic relaxation algorithm, then, is to assume a potential for each node in the system and use Eq. G-2 to adjust all the assumed potentials. Equation G-1 is checked against a tolerance for each node in the system to see whether the last estimate is close enough to be the required answer. If the error is too great, Eq. G-2 is again used to adjust the potentials; and
the testing process is repeated. Iterations are continued until the tolerance is met; at which point, a practical solution to the problem has been achieved.

Implementation of the aforementioned relaxation procedure requires a computer to carry out the multitude of calculations necessary to get a solution. A computer program has been written for the relaxation algorithm of this system. It accepts as input the size of the concrete slab; the size, spacing, and position of the reinforcing bars; and the resistivity of the concrete along with resistance to ground of the rebar system. The location and size of the cathodic-protection anodes are assigned by selection of nodes which are current sources as opposed to sinks within the three-dimensional model. The applied voltage and any anode contact resistance are assigned to these nodes. The program solves the relaxation algorithm and prints out the potential field in the slab.

One of the problems in the development of the model is to calculate the correct resistance from a node to the rebar in the volume represented by the node. Several approaches to this problem were attempted, and the following was found to be the most consistent with the experimental evidence. Consider the portion of rebar contained in the volume of nodal influence $DX$ by $DY$ by $DZ$. A typical section of rebar in this volume will be $DY$ long and have a diameter $D$. The equation for the resistance, $R$, from the node to a point on the rebar will be

$$ R = \frac{\rho L}{A} \quad (G-3) $$

where $\rho$ is the resistivity of the concrete; $L$ is the distance from the node to the point; and $A$ is the viewing area of the rebar at that point. If $\Delta x$ is the distance along the rebar,

$$ A = D \cdot \Delta x \quad (G-4) $$

Also, if $L_i$ is the point on the rebar nearest to the node and $x$ is the distance from this point to the area of interest,

$$ L = \sqrt{x^2 + L_i^2} \quad (G-5) $$

Now, substituting Eqs. G-4 and G-5 into Eq. G-3 will give the formula for the resistance for any point on the rebar

$$ R = \frac{\rho \sqrt{x^2 + L_i^2}}{D \cdot \Delta x} \quad (G-6) $$

Inasmuch as all of the resistances are in parallel, the total resistance, $R_T$, to this rebar can be written

$$ \frac{1}{R_T} = \sum \frac{1}{R_i} = \sum \frac{D \cdot \Delta x}{\rho \sqrt{x_i^2 + L_i^2}} \quad (G-6) $$

If Eq. G-6 is allowed to pass to the limit,

$$ \frac{1}{R_T} = \sum \frac{1}{R_i} = \frac{D\Delta x}{\rho \sqrt{x^2 + L_i^2}} = \frac{2}{2} \int_0^{\sqrt{\frac{2L_i}{\rho}} \cdot \left(1 + \sqrt{\frac{2L_i}{\rho} + 1}\right)}(G-7) $$

If the integration is performed,

$$ \frac{1}{R_T} = \frac{2D}{\rho} \ln \left[\frac{DY}{2L_i} \cdot \left(1 + \sqrt{\frac{2L_i}{DY} + 1}\right)\right] \quad (G-8) $$

Equation G-8 describes the resistance from the node to one of the rebars in the volume. Similarly, Eq. G-8 can be used to calculate the resistance to each of the other rebars in the volume of interest. Because the resistances are in parallel, the total resistance from the node to all rebars can be calculated by

$$ R_T = \frac{1}{\sum \frac{1}{R_{Ti}}} \quad (G-9) $$

The use of this equation gave good agreement with the analog-model data.

**DETERMINATION OF POLARIZATION POTENTIAL**

Modeling of the bridge-deck system yields the steady-state potential that results when an impressed voltage is applied to the anode. For this result to have meaning in terms of a cathodic-protection evaluation, it is necessary to use this information to predict the "instantaneous off" potentials (polarization potential, as it is measured in the field) at all points on the deck. One method of calculating the instantaneous off potential is through the empirical relationship between current density and polarization potential for steel in a concrete environment. To develop this relationship, potentiostatic cathodic-polarization studies were conducted on an isolated rebar in the prototype deck (Appendix H). Further, it is well known that the current density necessary for cathodic protection of steel in concrete is much lower in the final state than indicated by tests having a short duration (15, 16). Accordingly, the following treatment of the short-term test data was employed to compensate for this factor. The rate of cathodic-current change on the test rebar was measured as the rebar potential was held constant. This procedure was repeated for a number of potentials over a 12-hr period. The data were then plotted on logarithmic scale. The resulting plot of data, a straight line, was extended to determine the current indicated after 100 hr of application. The 100-hr value for the current was used to calculate the current density at each potential. The logarithmic value of this current density was plotted against rebar potential to produce the long-term (100-hr) cathodic-polarization curve for a steel rebar in the prototype deck. The resultant curve is shown in Figure G-1.

For the computer program, these data (Fig. G-1) were represented mathematically by linear functions of the log of current density

$$ E = A \log i + B $$

where $E$ is the rebar potential, millivolt (mV) to copper/copper sulfate (Cu/CuSO₄) half-cell; $i$ is the current density, microampere per square inch ($\mu$A/sq in.); and $A$, $B$ are constants. The values of the constants $A$ and $B$, calculated from the slope for the various regions of current density shown in Figure G-1, are:
These equations have been incorporated in the computer program, and the instantaneous off potential, calculated by using them, is consistent with the observed values.

**INPUT FOR COMPUTER PROGRAM**

A source listing for the computer program is given in Table G-1. The program is written in FORTRAN IV and could run on any computer with a FORTRAN IV compiler; it has been run, without modification, on a CDC 6500 and a DEC 11/45 computer. A description of the input cards for the typical case presented is given in Table G-2.

**COMPUTER OUTPUT**

Typical outputs of the computer program are given in Tables G-3, G-4, and G-5. The output in Table G-3 shows the essential portion of the input parameters; namely, the dimensions of the slab, the resistivity of the concrete in the slab, and the potential applied at the anodes situated on the surface of the slab. In the case presented, the resistivity of the concrete is varied through the thickness of the slab, but it is held constant in the horizontal directions. If the option for total variable resistivity had been selected, the resistivity for each node within the slab would be printed as part of the output. The resistance to ground for the nodes nearest the rebar is also printed in Table G-3. The first 10 lines are for the nodes near the top layer of rebar, and the next 10 lines are for the nodes near the bottom layer. The output in Table G-4 shows the current flow into and out of the slab, along with the potential (with the current flowing) at each point in the slab. The output in Table G-5 shows the polarization potential, or instantaneous off potential, which is calculated from the current density at the rebar surface and by using the cathodic-polarization curve (Fig. G-1).

**VERIFICATION OF THE MATHEMATICAL MODEL**

Verification of the mathematical model is a twofold problem, the first part of which is simply to determine whether the computer program gets the correct solution to the mathematical problem. This is straightforward in that the problem is linear in nature and, thus, can be shown to have a unique solution. Also, if the algorithm used to solve the problem converges, it can be shown that it will converge to the correct solution. The program has been run for a wide variety of conditions and does converge in all cases.
TABLE 3-I
COMPUTER PROGRAM SOURCE LISTING

PROGRAM MAIN(INPUT,OUTPUT,TAPE1=INPUT,TAPE3=OUTPUT)

C PROGRAM TO DETERMINE CURRENT FLOW AND POTENTIAL IN BRIDGE DECKING.
COMMON PI(10,10,10),AR(9,10,10),AP(10,9,10),PD(10,10,9),PG(10,10,2)
COMMON CI(10,10),CR(10,10)
COMMON CUP,CRUP,CPUP,CRUP
COMMON CUP,FCUP,FCRUP,CRUP
CALL INPUT
PIR = 0.0
CIUP = 1.
DO 31 I=1,N
DO 31 J=1,M
DI(J) = 0.0
DO 30 I=1,J
IF(PI(J,J-1) .GT. 31,31,37)
37 PIB = PIB
31 CONTINUE
DO 30 I=1,N
DO 30 J=1,M
PI(J,J) = PI(J,J-1)
DO 70 K=1,L
PI(J,J,K) = PIB
30 CONTINUE
FAC = 1.0
TCOUNT = 0
ZC1 = 0
ACFL = 1.01
9 CONTINUE
IF(FA**.GE.1.97) GO TO 1
FAC = FAC*ACFL
1 CONTINUE
ERR = 0.0
TCOUNT = TCOUNT + 1
DO 90 I=1,N
DO 90 J=1,M
DO 90 K=1,L
IF(I-I)10,10,11
10 RAC = 0.0
PAC = 0.0
GO TO 12
11 RAC = 1./RC(I-I,J,K)
PAC = PI(I-I,J,K)*PAC
12 IF(I-I)14,13,13
13 RAC = 0.0
PAC = 0.0
GO TO 16
14 RAC = 1./RC(I,J,K)
PAC = PI(I,J,K)*RAC
15 IF(J-J)16,15,17
16 RRR = 0.0
PBP = 0.0
GO TO 1A
17 RRR = 1./RR(I,J-1,K)
PBP = PI(I,J-1,K)*RRR
18 IF(J-J)70,19,19
19 RRR = 0.0
PBP = 0.0
TABLE G-1 (continued)

GO TO 21
20 RAP = 1./RP(I,J,K)
PAP = P(I,J+1,K)*RAT
21 IF (K-I) 22, 22, 23
22 PNT = 0.0
PNT = 0.0
IF (P(I,J)) 4, 4, 4
4 RNT = 1./RST
PNT = P(I,J)*PNT
6 CONTINUE
GO TO 24
23 PNT = 1./P(I,J,K-1)
PNT = P(I,J,K-1)*PNT
24 IF (K-L) 26, 25, 25
25 RNB = 0.0
RNB = 0.0
GO TO 27
26 PNB = 1./PN(I,J,K)
PNB = P(I,J,K)*PNB
27 CONTINUE
IF (K=14) 35, 35, 35
35 IF (K=15) 32, 33, 33
32 RLG = 0.0
RLG = 0.0
GO TO 34
36 RLG = 1./RLG(I,J,1)
RNG = CD(I,J)*RLG
GO TO 34
33 RLG = 1./RLG(I,J,2)
RNG = CD(I,J)*RLG
4 CONTINUE
RNG = PAP*PAP+RDR*RDR+PAP*PAP+RDR*RDR
RNG = PAP*PAP+RDR*RDR+PAP*PAP+RDR*RDR
PLOD = P(I,J,K)
PLI(J,K) = P(I,J,K)*(1./-FAI) + FAC*PNUM/DFW
DR = AOS(PLOD-PNUM/DFW)
ERR = ERR+DFW
8 CONTINUE
CALL CURDF
CUR = 0.0
90 DO 50 J=1,N
50 DO 50 I=1,N
CD(I,J) = -CD(I,J)/1000.
CD(I,J) = -CD(I,J)/1000.
IF (P(I,J,K)) 35, 50, 51
51 CUR = CUR + (PI(J,J)-PI(J,J))/RESI
50 CONTINUE
CURDF = AOS(CUR-CURDF)
52 CONTINUE
IF (ICOUNT=50) 42, 43, 43
43 CALL OUTPUT
WRITE (3,100) FRR
100 FORMAT (1H14,8)
ICOUNT = 0
IC1 = IC1 + 1
6 CONTINUE
IF (CURDF.GT.0.0001) GO TO 8
IF (FRR+FRRR.GT.0.001.GT.0.075) GO TO 8
49 CALL OUTPUT
CALL EXIT
END
TABLE G-1 (continued)

**SURROUTINE TO INPUT DATA AND CALCULATE RESISTANCE VALUES**

<table>
<thead>
<tr>
<th>COMMON</th>
<th>P</th>
<th>IFT</th>
<th>DBB</th>
<th>M</th>
<th>L</th>
<th>O</th>
<th>APFT</th>
<th>APFR</th>
<th>REST</th>
</tr>
</thead>
<tbody>
<tr>
<td>D = 1.0/10.0</td>
<td>M</td>
<td>UL</td>
<td>SWT</td>
<td>CM</td>
<td>SWA</td>
<td>CM</td>
<td>SLT</td>
<td>ELT</td>
<td>SLA</td>
</tr>
</tbody>
</table>

**COMMON (10,10,10), CM (10,9,10), PD (10,10,9), PG (10,10,9)**

**C**

**O**

| O = SLAB THICKNESS IN INCHES |
| W = SLAB WIDTH IN FEET |
| UL = SLAB LENGTH IN FEET |
| SWT = SPACING BETWEEN THE TOP ROW OF RFAR ALONG WIDTH |
| OMT = DIAMETER OF TOP ROW OF RFAR |
| SWB = SPACING OF BOTTOM ROW OF RFAR ALONG WIDTH |
| OMT = DIAMETER OF BOTTOM ROW OF RFAR |
| SLT = SPACING OF TOP ROW OF RFAR ALONG LENGTH |
| DLT = DIAMETER OF TOP ROW OF RFAR ALONG LENGTH |
| SLR = SPACING OF BOTTOM ROW OF RFAR ALONG LENGTH |
| DLB = DIAMETER OF BOTTOM ROW OF RFAR ALONG LENGTH |

**NOTE**

ALL SPACING IS FROM THE SURFACE OF ONE BAR TO THE SURFACE OF THE OTHER IN INCHES

**C**

**100 FORMAT(11F5.0)**

**W**

**UL**

**WRITE (3,103)**

**103 FORMAT(14H1,32X,37HCATHODIC PROTECTION OF BRIDGE DECKING///)**

**WRITE(3,104)**

**SWT**

**OMT**

**OMT**

**N**

**H**

**L**

**NUMBER OF NODES ALONG THE WIDTH**

**M**

**NUMBER OF NODES ALONG THE LENGTH**

**T**

**SW**

**1**

**INDICATES CONSTANT RESISTIVITY THROUGHOUT THE SLAB**

**2**

**INDICATES VARIABLE RESISTIVITY AT EACH POINT IN SLAB**

**3**

**INDICATES VARIABLE RESISTIVITY THROUGHOUT THE THICKNESS**

**C**
TABLE C-1 (continued)

\[ WRY = \frac{OY}{SLT+DLT} + 1 \]
\[ WDX = \frac{OX}{SWM+DLT} + 1 \]
\[ N = I = 1,N \]
\[ X = (I-1)*DX \]
\[ M1 = \frac{(X-ETR-DNT/2.)/(DWT+SLT) + 1.}{84} \]
\[ SUMP = 0.0 \]
\[ DR = ETR + M1*(DWT+SLT) + DNT/2. - (NBX/2)*(DWT+SLT) \]
\[ DO 60 II = 1,NBX \]

IF (DR) 67, 61, 61

61 IF (DR) 62, 62, 63

DC = SQRT((NR-X)**2+(IAT-1)*DZ-(SPT+DLT/2.*DNT)**2)

OS = DC - NWT/2.

IF (OS) 66, 67

SUMP = SUMR*1./OMST

GO TO 64

7 SUMR = SUMR + 2.*DWT*ALOG(DY*(1.+SQRT((2.*OS/OX)**2+1.1)/(2.*OS))/

1P(I,1,IAT)

62 CONTINUE

DO = OR + SWT + NWT

60 CONTINUE

SUMR = SUMR

DO 5 J=1,M

Y = (J-1)*DY

N1 = \((Y-ETR-DLT/2.)/(DLT+SLT) + 1.\]

DR = ETR + N1*(DLT+SLT) + DLT/2. - (NBV/2)*(DLT+SLT)

DO 66 JJ = 1,NAY

IF (DR) 64, 65, 65

65 IF (UL-DR) 64, 64, 67

DC = SQRT((NR-Y)**2+(IAT-1)*DZ-(SPT+DLT/2.*DNT)**2)

DS = DC - DLT/2.

IF (DS) 68, 68, 68

8 SUMR = SUMR + 1./OMST

GO TO 66

68 SUMR = SUMR*2.*DLT*ALOG(DX*(1.+SQRT((2.*OS/OX)**2+1.1))/(2.*OS))/

1P(I,J,IAT)

64 CONTINUE

DR = OR + SLT + DLT

66 CONTINUE

IF (SUMR) 69, 69, 79

79 CONTINUE

RG(1,J,1) = 1./SUMR + OMST

GO TO 80

69 CONTINUE

RG(1,J,1) = 10.06

90 CONTINUE

SUMP = SUMR

5 CONTINUE

4 CONTINUE

C CALCULATE RESISTANCE FOR SECOND ROW

TAR = 1*(SPT + DWT + PP + DLT)/DZ + 1.

NAY = \(DY/(SLT+DLT) + 1.\]

NAX = \(OX/(SW9+CW9) + 1.\]

DO 70 I = 1,N

X = (I-1)*OX

N1 = \((X-ETR-DNW/2.)/(CW9+SW9) + 1.\]

SUMP = 0.0

DR = ETR + N1*(CW9+SW9) + DNW/2. - (NAX/2)*(DNW+SW9)

DO 70 II = 1,NAX

IF (DR) 71, 71, 71

71 IF (DR) 72, 72, 72

73 DC = SQRT((DR-X)**2+(IAT-1)*DZ-(SPP+SPT+CW9+DLT+DNW/2.)**2)

DS = DC - DNW/2.

IF (DS) 85, 86, 87
TABLE G-1 (continued)

85 SUMR = SUMR+1./OMSA
GO TO 87
86 SUMR = SUMR + 2.*OMA ALOG(2**1. + SQRT((2.*CS/OM)*2 + 1.))/(2.*OM)
1P(I,J,1,1B)
87 CONTINUE
DR = OR + SWA + OMA
88 CONTINUE
SUMR = SUMR + 1./OMSA
DO 21 J=1,M
I= (J-1)*DY
N1 = (Y-FPR-DL+SLA) + 1.
DR = OR + N1*DL+SLP + DL/2. - (NAY/21)*DL+SLB
DO 76 JJ = 1,NAY
IF (DR)74,75,76
75 IF (UL-DR)76,77,78
76 CONTINUE
77 DC = SQRT((OR-UL)**2+(TB-1)*OZ-(SPT+OLT+SPB+OMT+OMA+DLA)**2)**2)
78 CONTINUE
79 SUMR = SUMR + 1./OMSA
GO TO 76
80 SUMR = SUMR + 2.*DLA ALOG(2**1. + SQRT((2.*OM/OM)**2 + 1.))/(2.*OM)
1P(I,J,1,1B)
81 CONTINUE
DR = OR + SLA + OLA
82 CONTINUE
IF(SUMR)81,91,87
83 CONTINUE
RG(I,J,2) = 1./SUMR + OMA
GO TO 83
84 CONTINUE
RG(I,J,2) = 10.6F6
85 CONTINUE
SUMR = SUMR + 1.
20 CONTINUE
C
COMPUTE THE RESISTANCE BETWEEN NODES
N1 = N-1
DO 10 I=1,N1
DO 10 J=1,M
DO 10 K=1,L
10 RC(I,J,K) = (P(I,J,K) + P(I+1,J,K))/2.*CXX/(CYY*CYY)
M1 = M-1
NO 11 I=1,M
NO 12 J=1,M1
NO 14 K=1,L
11 PR(I,J,K) = (P(I,J,K) + P(I,J+1,K))/2.*CXY/(CXX*CXX)
L1 = L-1
NO 12 I=1,M
NO 13 J=1,M
NO 15 K=1,L1
12 PQ(I,J,K) = (P(I,J,K) + P(I,J,K+1))/2.*OZ/(CXX*CXX)
WRITE (7,100)
100 FORMAT(1HE17HAPPLIED POTENTIAL)
DO 40 J=1,M
WRITE(3,105) (P(I,J),I=1,N)
105 FORMAT(1H 10F10.4)
40 CONTINUE
WRITE (3,107)
NO 50 K=1,2
NO 50 J=1,M
WRITE(3,106) (RC(I,J,K),I=1,N)
90 CONTINUE
106 FORMAT(10F10.4)
107 FORMAT(2240 RESISTANCE TO GROUND )
RTUPK
END
TABLE G-1 (continued)

SUBROUTINE OUTPUT

COMMON P(10,10,10), RC(9,10,10), RP(10,9,10), PD(10,10,9), PG(10,10,2)
COMMON PT(10,10,10), TOT, TRP, N, M, L, OX, OY, AREF, ARER, RFSI
COMMON CP1(10,10), CPD(10,10)
COMMON CUR, CUR0, CTOP, CROT
COMMON CURD, ERR, ERROR
CALL CURDF
WRITE(1,102)
102 FORMAT(1HM)
WRITE(1,103) CUP, CUR0
103 FORMAT(15H CURRENT IN = F10.4/15H CURRENT OUT = F10.4)
WRITE(1,105) CTOP, CROT
105 FORMAT(1HM, 15H TOP OR Bottom CURRENT = F10.6/15H BOTTOM OR Bottom CURRENT = F10.6)
   DO 1 = K=1, L
   WRITE (1,100) K
100 FORMAT(1HM, 15H OFF POTENTIAL FOR PLAN No. , IS)
   DO 2 = J=1, M
   WRITE (1,101)(PIT, J,K), T=1, N
201 FORMAT(1HM, 15H CONTINUE
   1 CONTINUE
 WRITE(1,104)
104 FORMAT(1HM, 15H OFF POTENTIAL ////)
 WRITE(1,105)(CPD(I,J), I=1, N), J=1, M)
105 FORMU(1HM, 10F(10,1)
   DO 3 = I=1, N
   DO 4 = J=1, M
203 FORMAT(1HM, 15H CONTINUE
   RETURN
END

SUBROUTINE CURDF

COMMON P(10,10,10), RC(9,10,10), RP(10,9,10), PD(10,10,9), PG(10,10,2)
COMMON PT(10,10,10), TOT, TRP, N, M, L, OX, OY, AREF, ARER, RESI
COMMON CP1(10,10), CPD(10,10)
COMMON CUR, CUR0, CTOP, CROT
COMMON CURD, ERR, ERROR
FAC = 0.25
ERROR = 0.0
CURD = 0.0
CTOP = 0.0
IF(ERR=CT-2.)FAC = 0.01
CROT = 0.0
IF(CURD-1.1FAC = CURD*5.0
IF(CURD<0.001)FAC = 0.005
ZT = 1000./OX*CY*ARET)
ZB = 1000./OX*OY*AREF)
DO 52 = I=1, N
DO 52 = J=1, M
X = PIT(J,K)-CD(I,J)
IF(X)<1.2
1 CD(I,J) = CD(I,J)*.998
GO TO 33
2 CONTINUE
W = -1000.*CD(I,J)
CD(I,J) = W/PG(I,J,1)
CTOP = CTOP + CD(I,J)
CD(I,J) = CD(I,J)*ZT
II = 1
X = 1000.*CD(I,J)
GO TO 60
TABLE G-1 (continued)

61 CONTINUE
   CD(I,J) = FAC*X + (1.-FAC)*W
   FERROR = FERROR + ABS(W-X)
13 CONTINUE
   X = P(I,J,IM1)-CDR(I,J)
   IF (X)44,.44,55
   CONTINUE
   CD(I,J) = -CDR(I,J)*990.
   GO TO 52
55 CONTINUE
   W = -1000.*CDR(I,J)
   COB(I,J) = X/CG(I,J,2)
   CBOT = CBOT + CDR(I,J)
   COB(I,J) = CDR(I,J)*2
   II = 2
   X = 1000.*COB(I,J)
58 CONTINUE
   IF (X)17,.17,18
17 CONTINUE
   A = 0.0
   B = -200.0
   GO TO 11
19 CONTINUE
   IF (X)3,.3,4
1 CONTINUE
   A = -504.7
   B = -200.0
   GO TO 11
4 CONTINUE
   IF (X)5,.5,6
5 CONTINUE
   A = -267.5
   B = -466.1
   GO TO 11
6 CONTINUE
   IF (X)7,.7,8
7 CONTINUE
   A = -22.18
   B = -918.2
   GO TO 11
8 CONTINUE
   IF (X)15,.15,16
15 CONTINUE
   A = -9.35
   B = -570.4
   GO TO 11
16 CONTINUE
   A = -240.5
   B = 71.76
11 CONTINUE
   X = A*ALOG(X) + B
   GO TO (61,62),11
67 CONTINUE
   CD(I,J) = FAC*X + (1.-FAC)*W
52 CONTINUE
   CURQ = CTOP + CBOT
RETURN
END
# TABLE G-2

## TYPICAL INPUT AND DESCRIPTION OF COMPUTER PROGRAM CARDS

| Col 0 | 5 | Slab thickness in inches |
| Col 6 | 10 | Slab width in feet |
| Col 11 | 15 | Slab length in feet |
| Col 16 | 20 | Spacing between top rebars along width in inches |
| Col 21 | 25 | Diameter of top rebars along width in inches |
| Col 26 | 30 | Spacing between bottom rebars along width in inches |
| Col 31 | 35 | Diameter of bottom rebars along width in inches |
| Col 36 | 40 | Spacing between top rebars along length in inches |
| Col 41 | 45 | Diameter of top rebars along length in inches |
| Col 46 | 50 | Spacing between bottom rebars along length in inches |
| Col 51 | 55 | Diameter of bottom rebars along length in inches |

## Card 2

| Col 0 | 5 | Distance from top of slab to first rebar in inches |
| Col 6 | 10 | Distance from bottom of top rebar to top of bottom rebar in inches |
| Col 11 | 15 | Distance from edge of slab to rebar in inches |
| Col 16 | 20 | Metallic resistance of top rebar in Ohms (Use network resistance) |
| Col 21 | 25 | Metallic resistance of bottom rebar in Ohms (Use network resistance) |
| Col 26 | 30 | Resistance from anode to deck in Ohms |
TABLE G-2 (continued)

Card 3

<table>
<thead>
<tr>
<th>Col</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>Number of nodes along length</td>
</tr>
<tr>
<td>6 - 10</td>
<td>Number of nodes along width</td>
</tr>
<tr>
<td>11 - 15</td>
<td>Number of nodes through thickness</td>
</tr>
<tr>
<td>16 - 20</td>
<td>Switch describing how the concrete resistivity is to be described</td>
</tr>
<tr>
<td></td>
<td>1) Resistivity constant throughout slab</td>
</tr>
</tbody>
</table>

Card 4

<table>
<thead>
<tr>
<th>Col</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 8</td>
<td>Resistivity of slab in Ohm-inches</td>
</tr>
<tr>
<td></td>
<td>2) Resistivity varies at each node</td>
</tr>
</tbody>
</table>

Card 4 to 4 + M XL  
10 Fields of 8 describing resistivity at each node in Ohm-inches

<table>
<thead>
<tr>
<th>Col</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3) Resistivity constant in a plan but varies with thickness</td>
</tr>
</tbody>
</table>

Card 5 on 5 + M XL  
Depending on option to Card 14

<table>
<thead>
<tr>
<th>Col</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 8</td>
<td>Potential applied at this point in volts</td>
</tr>
<tr>
<td>9 - 16</td>
<td>Potential applied at this point in volts</td>
</tr>
<tr>
<td>17 - 24</td>
<td>Potential applied at this point in volts</td>
</tr>
<tr>
<td>25 - 32</td>
<td>Potential applied to this point in volts</td>
</tr>
<tr>
<td>33 - 40</td>
<td>Potential applied to this point in volts</td>
</tr>
<tr>
<td>41 - 43</td>
<td>Potential applied to this point in volts</td>
</tr>
<tr>
<td>44 - 56</td>
<td>Potential applied to this point in volts</td>
</tr>
<tr>
<td>57 - 64</td>
<td>Potential applied to this point in volts</td>
</tr>
<tr>
<td>65 - 72</td>
<td>Potential applied to this point in volts</td>
</tr>
<tr>
<td>73 - 80</td>
<td>Potential applied to this point in volts</td>
</tr>
<tr>
<td>Width</td>
<td>Length</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>8</td>
<td>144</td>
</tr>
</tbody>
</table>

**Distance From Top Of Slab To First Row Of Rebar =** 2
**Distance From Bottom Of The Top Rebar To The Top Of Bottom Rebar =** 1
**Distance From Edge Of Slab To The Rebar =** 4
**Passive Resistance At The Top Row Of Rebar =** 0
**Passive Resistance At The Bottom Row Of Rebar =** 0
**Passive Resistance At Anode =** 0

- **Passivity Varies With Thickness**
  - 50.00 300.00 3000.00 3500.00 3500.00 10000.00 10000.00 10000.00 10000.00

- **PLATE POTENTIAL**

- **Resistance To Ground**
  - 251.14 164.81 207.25 212.24 137.31 125.45 210.05 270.10 177.82 245.23
  - 124.00 100.60 112.46 115.40 109.55 105.40 114.93 114.25 102.75 122.24
  - 124.93 99.86 111.54 114.51 108.77 104.58 113.37 113.29 101.26 171.15
  - 115.19 106.30 119.64 121.06 116.44 111.67 127.33 121.66 106.71 110.77
  - 114.73 104.47 122.40 125.99 119.06 114.07 125.27 124.32 110.95 134.09
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**TABLE G-4**
COMPUTER OUTPUT OF POTENTIAL VALUES WITH CURRENT ON

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some conditions, however, such as when there are areas in
the deck that have very low current flows, the convergence
is quite slow.

The second area of verification is to determine how well
the mathematical formulation of the problem fits the reality
of a bridge deck. This is a much more difficult task be-
cause of the many parameters that must be supplied to the
program. These parameters are available only for repre-
sentative samples of the actual deck material, and they can
vary considerably over an actual deck. This problem, there-
fore, was approached by using the analog model of a deck
section to develop the parameters needed and tune the
model. The prototype deck section was used to prove the
model by predicting the results of actual cathodic-protection
installations on the prototype. The following three cases are
typical of the results obtained during the verification study.

Case 1

A comparison was made between the prototype test re-
sults, shown in Figure H-31, and the computer-model re-
sults. In this cathodic-protection application, the total cur-
rent calculated by the model was 4 amp, as compared with
3.3 amp measured on the prototype test. The "off poten-
tial" contours in this comparison were similar in position;
however, the potentials calculated were 350 mV lower than
those measured. This difference is adequately explained in
Appendices E and H, and it is further evidence of the
potential distortion that occurred whenever the Cu/CuSO₄
half-cell was placed over the conductive layer. Note that
in order to produce polarization potentials as high as are
shown in Figure H-31 consistent with the data in the
polarization curve (Fig. G-1), current densities of several
hundred microamperes per square inch would have to exist
over most of the deck. If this were the case, the total cur-
rent would be much higher than the 3.3 amp measured. It
must, therefore, be assumed that either the measured values
are in error, or the polarization curve (Fig. G-1) is greatly
in error for some situations. Clearly, the measured poten-
tials are in error, because it is unlikely that the polarization
properties could vary that much in the same system. In the
following cases 2 and 3, the true potential for the rebars
was determined by using a modified potential-measurement
technique, as described in Appendix H.

Case 2

Figure G-2 is a computer plot of the off potential under
conditions of the prototype test shown in Figure H-47. The
total current calculated from the Pt/Nb wire-type anode in
a 3-in. conductive overlay was 0.46 amp. A comparison of
this value with the 0.55 amp observed in the prototype test
shows that the difference in total current could be adjusted
to the exact value observed, by lowering the resistance be-
tween the anode and overlay material about 0.8 ohm. The
effect of this adjustment would be to raise the calculated
off potential by about 0.1 mV, without changing the position
of the contour lines. A study of the two contour maps
shows that a reasonable agreement would exist between the
calculated and the measured values.
Figure G-2. Equipotential contour map of top rebar off potential, as determined by mathematical model parameter analysis. The contour map corresponds, with the cathodic-protection application, to the prototype model of the bridge deck presented in Figure H-47. Contour units are mV negative to Cu/CuSO₄ half-cell and are a facsimile of a computer-produced profile on 2-ft intervals.

Figure G-3. Equipotential contour map of top rebar off potential, as determined by mathematical model parameter analysis. The contour map corresponds, with the cathodic-protection application, to the prototype model of the bridge deck presented in Figure H-43. Contour units are mV negative to Cu/CuSO₄ half-cell and are a facsimile of a computer-produced profile on 2-ft intervals.

Case 3

Figure G-3 is a computer plot of the off potential under the conditions of the prototype test shown in Figure H-43. The total current calculated by the model for this test of a disk-shaped anode in a 2-in. conductive overlay was 0.55 amp, as compared with 0.68 amp observed on the prototype system. As in the previous case, this difference in total current could be adjusted to the exact value of the prototype test by lowering the contact resistance between the anode and the conductive-overlay material less than 1 ohm. The effect of this adjustment would be to raise the calculated off potential by about 30 mV, without changing the position of the contour lines. This computed result would then compare favorably with the actual measured values.

MODEL ANALYSIS—CONDUCTIVE-OVERLAY APPROACH

The nomograms in Figures G-4 and G-5 were prepared on the basis of the results of mathematical-model analysis of the conductive-overlay design for an impressed-current

anode system (described in Appendix H). Figure G-4 is used to predict the polarized potentials of a rebar in the top mat, at various distances from a single, disk-shaped silicon-iron anode, for different combinations of conductive-overlay resistivity and layer thickness. Figure G-5 is used to determine the rectifier voltage and current for protection of various surface areas. The conditions used in development of the data for these nomograms are those on the prototype deck during the model-verification study. They consist mainly of a deck resistivity ranging from 3,000 to 10,000 ohm-cm from the slab top to bottom. Other resistivities will give different results.

It is possible that, under certain conditions, the resistivity of concrete could be altered markedly by relatively small changes in moisture and ion concentrations, and it is possible that ions can migrate because of a potential gradient and cause localized changes in resistivity. If and when these anomalies occur, the results of the calculations, which are based on the norm, will be in error. If, however, the resistivity changes can be estimated, they can be entered into the program as new parameters and a correct solution for the problem can be obtained.
Figure G-4. Polarized rebar potential, at a specific distance from the anode, for different conductive-layer parameters (for conditions of prototype deck).

Figure G-5. Cathodic-protection current and voltage for various deck surface areas and conductive-layer parameters (for conditions of prototype deck).
The method used to produce the data for the nomograms was to vary the rectifier voltage until the polarized potential of the rebar near the anode was $-1100$ mV to a Cu/CuSO$_4$ half-cell. This procedure was repeated for various combinations of conductive-layer thickness and specific resistivity. The data obtained were combined to produce the nomograms, which can be employed in several ways. For example, if the resistivity and thickness of the conductive layer are known and it is desired to determine how far from the anode a polarized potential of a certain value will be measured, Figure G-4 can be used, as follows. Start with the resistivity on the left-hand abscissa axis and proceed vertically to the conductive-layer thickness; proceed horizontally to the potential value on the right-hand plot; and continue vertically down to the distance given on the right-hand abscissa axis. The example illustrated in Figure G-4 points out that a 1-in.-thick conductive layer with a 20-ohm-cm specific resistivity will give a rebar potential of 850 mV negative to a Cu/CuSO$_4$ half-cell some 16 ft from the anode. Other variations of the use of the chart are obvious.

To use the nomogram in Figure G-5, the resistivity of the conductive material is first located on the left-hand abscissa axis; a vertical line is followed to the layer thickness; a horizontal line is followed to the size of the square slab surface area with a minimum potential as indicated ($-850$ mV in this case). From this point the current output of the rectifier can be obtained by following a vertical line down to the right-hand abscissa axis, and the voltage of the rectifier can be found by taking the point at which this last vertical line crosses the anode-type line and following a horizontal line to the ordinate axis in the middle of the chart. When the intercept of the horizontal line from conductive-layer thickness and the curve for side of square falls to the right of the anode line, the rectifier voltage is determined by following a vertical line up to the anode line, then left horizontally to the ordinate axis in the middle of the chart. Other variations of this procedure can also be used.

**SUMMARY OF MATHEMATICAL-MODEL DEVELOPMENT**

A mathematical model to determine steady-state current flow in a bridge deck employing cathodic protection has been developed. This model, which uses a digital computer to carry out the calculations, solves the problem of steady-state current flow in a three-dimensional rectangular body with various sources and sinks. The computer program can be used to calculate the area of bridge deck protected with a cathodic-protection system if the various parameters of the system and the deck are known. To use the program, the resistivity of the concrete and the type of anode system, along with the various physical aspects of the deck and cathodic-protection method, must be known. Given these parameters and applied potentials at anodes, the program computes the current flow for each point in the deck and the current density at the rebar surfaces. In turn, an empirical relationship between the current density and the rebar potential is used to calculate the polarized potential of the rebar as measured in practice. This polarized potential corresponds to the potential obtained in the field by using the "instantaneous off" technique and provides a basis for determining the extent of protection achieved with the system.

The mathematical model was developed and verified with data gathered from tests on the analog and prototype models used in this program. On the basis of the results of model analysis of a design consisting of a conductive overlay with a disk-shaped impressed-current anode, nomograms were developed that predict rebar potentials, at various distances from the anode, for various combinations of conductive-layer parameters, and that also predict the required cathodic-protection current and voltage.

**APPENDIX H**

**PROTOTYPE TESTING**

**INTRODUCTION**

The investigation of electrical parameters using the analog model of a bridge-deck section (Appendix F) gave indication of various cathodic-protection designs that have the potential of meeting the requirements for a technically and economically feasible cathodic-protection system for bridge decks.

The subsequent step in the research program was a series of controlled tests of these designs with a full-depth reinforced-concrete specimen that was a realistic prototype of a typical bridge-deck section. The purpose of these tests was to evaluate the effectiveness of the laboratory-developed design parameters and criteria and to develop information concerning applicable materials and procedures for installation, adjustment, and operation of cathodic protection for bridge decks. Further, the measurements made in the prototype deck for the analysis of the effectiveness of the various cathodic-protection designs were used to verify the results of mathematical-model simulation studies (Appendix G).

The essential feature of these designs is uniform current
flow of appropriate value to the top rebar mat from an anode arrangement located over the top rebar mat. A brief description of the cathodic-protection designs that were included in this investigation follows.

1. **Conductive-Overlay Method.** The conductive-overlay method is an impressed-current design featuring an electrically conductive asphaltic-concrete overlay on the bridge deck. The 2-in-thick overlay utilizes coke as the asphaltic-concrete aggregate. The cathodic-protection current is introduced into the overlay at widely spaced points from relatively inert anodes. The current is distributed (electronic conductance) by the coke, which, in turn, serves as a secondary anode.

2. **Modified Conductive-Overlay Method.** This is a system similar to Item 1, except that the conductive-layer thickness is reduced to a more acceptable value (less than 1 in.). Reducing the conductive-layer thickness tends to produce nonuniform current distribution to the top rebar mat. However, by utilizing a distributed-anode arrangement, an acceptable system is obtained. Wire anodes are installed in the conductive layer, so that each anode is geometrically related to a proportionate surface area of the deck.

3. **Distributed-Anode Method.** This design consists of an impressed-current system that depends exclusively on anode distribution to give the necessary cathodic-protection current distribution to the top rebar steel, and it does not involve the use of a conductive overlay. The anode bed is located in the concrete (clear cover) over the top steel mat on the deck. The anodes are a nonconsumable-type wire shape that can be installed in a comprehensive pattern in the deck. Operating voltages with this design will be several times greater than those required with the designs in Items 1 and 2.

4. **Sacrificial-Anode Method.** The salient feature of this design is that it does not require an outside power supply to operate and, when properly applied, provides the needed protection for some predetermined period of time without the need for regulation or adjustment. This design will utilize a continuous-length anode of either zinc or magnesium that will be either embedded in the concrete over the top rebar mat or placed on the concrete and covered with an asphalt overlay. Results of the analog-model studies indicate that, because of the low driving voltage of this system, a well-distributed anode arrangement (less than 1-ft spacing) will be required. Also, pilot performance tests (Appendix F) show that the expansive nature of the resultant anode corrosion produces cracking in normal concrete, and provisions must be made, therefore, to prevent cracking of the grout material when the embedded approach is used. The work with the sacrificial-anode method was initiated with a prototype test of several possible methods of anode installation on the bridge-deck analog model.

**PROTOTYPE DECK DESIGN**

Figure H-1 shows the steel rebar reinforcement and the instrumentation details for the prototype deck section. The scale and other important structural details for this deck, such as the size and location of the rebars, are typical of an actual bridge-deck section (51).

The conventional wire-tie method was employed at each rebar crossing. Chair supports made from rebar stock were used to position the rebar mats. The supports were welded to both the top and bottom rebar mats, thus providing electrical connection between them. Special instrumentation included eight electrical-resistance probes embedded in the deck at the locations shown in Figure H-1. The general test arrangement and purpose for using these probes in this program have been described in Appendix F.

It should be noted, however, that the probe arrangement employed with the prototype test was somewhat different from that previously used with the analog model in that the prototype deck probes were precast in a 3-in.-diameter by 7-in.-long cylinder mold of concrete. The concrete used with these probes was the same mix used for the deck, except that the mixing water was saturated with calcium chloride before mixing to create a corrosive environment for the probe. This was necessary because corrosion of the probes in the prototype deck is required in order to demonstrate the effectiveness of cathodic protection, and experience with the probes installed in the concrete portion of the analog model showed they do not corrode during the brief exposure. To further assure corrosion of the probe in this
concrete environment, each cylinder was wrapped with about 5 ft of No. 14 bare copper wire. Thus, if corrosion of the probe should fail to be initiated in the concrete environment provided, the probe can be coupled with the copper to form a galvanic cell.

Figure H-2 shows the results of a laboratory mock-up test of the prototype deck probe arrangement. The data demonstrate that, although corrosion of the probe did not initiate from exposure to the chloride-containing concrete, it did occur when the copper was coupled with the probe. The eight probe elements on the prototype deck are at an elevation corresponding to the top rebar layer. As can be seen from Figure H-1, four probes will receive cathodic-protection current; and four probes will not receive cathodic-protection current and, therefore, will serve as controls (nonprotected) during the test. Figure H-3 shows two probe cylinders before the concrete deck was poured. In addition to the probes, six rebars in the top layer of the prototype deck were installed in a manner that permits them to be electrically insulated from the deck steel. These rebars (see Fig. H-3) serve as test rebars. The specific location of the test rebars is shown in Figure H-1, and the probe and rebar designations are shown in Figure H-4.

One use of the test rebars was to study the effects of concrete cracking on the cathodic-protection potential and current flow. As a part of this study, saw cuts were made in the finished deck over three of the test rebars to simulate concrete cracks with the following conditions:

1. Test rebar A (rebar designations referred to in Fig. H-4) has a 5-ft-long simulated crack, about 0.063-in. wide, located parallel to and directly over the center of the rebar.
2. Test rebar B has a 5-ft-long simulated crack, about 0.125-in. wide, located parallel to and directly over the center of the rebar.
3. Test rebar C has six equally spaced simulated cracks, about 0.125-in. wide, located in a transverse direction over a 5-ft length of the rebar at its center. The test rebars D, E, and F are controls with no simulated cracks in the concrete cover over them. Each of the simulated cracks extends to the surface of the rebars (about 1 in.).

The specifications for the concrete used for the prototype deck section are the same as those employed by Pennsylvania Department of Transportation (PennDOT) (class AA) for reinforced bridge decks (50). The results of concrete compression tests, during and after the 28-day cure time, are given in Table H-1. These results indicate that a minimum strength requirement of 3750 pounds per square inch (psi) was attained at 28 days.

**GENERAL TESTING PROCEDURE**

The cathodic-protection test procedure followed with the prototype deck section was similar to that employed in the analog-model study (Appendix F). The cathodic-protection anode system was installed for the various cathodic-protection designs tested; the basic rectifier circuit shown in Figure F-3 was used to apply the cathodic-protection voltage. After energizing the rectifier, the applied voltage was adjusted to give a top rebar potential in a range from 770 to 1100 mV negative to a Cu/CuSO₄ half-cell placed at any point on the deck surface. As soon as steady-state conditions of electrical potential on the rebar network were indicated, the potential profile of the top and bottom rebar mats was measured. For the most part, the same instrumentation and techniques described in Appendix F were used to measure the rebar potentials and to develop the equipotential contour maps. In all cases, contact resistance between the deck surface (concrete or asphalt) and the half-cell was minimized by placing a wet sponge between the half-cell and the deck. The effectiveness of each system was judged by results obtained from the electrical-resistance probes, equipotential contour maps, and other electrical measurements. The various electrical-resistance probes were monitored throughout to determine whether corrosion was stopped at the different levels of protection applied. During periods of corrosion, a positive slope of the probe resistance/time plot would be observed; the slope of the plot went to zero when the cathodic protection was effective in stopping corrosion. The equipotential maps, obtained in this investigation, show the area of the deck that attained cathodic protection; the map contour pattern indicates the current distribution from the anodes. Electrical measurements, such as current flow to the test rebars, were also used to judge current distribution.

**TESTING AND DECK TREATMENT PRIOR TO CATHODIC-PROTECTION TESTS**

**Electrical Tests**

The results of electrical measurement of the resistance between the deck steel and the test rebars are given in Table H-2. The data show that the rebars associated with the simulated concrete cracks have much lower resistance to the deck steel than the control rebars. Also included in Table H-2 is information concerning the electrical continuity through the deck rebar network. The electrical resistance measured end to end through the network is about 0.2 ohm and is considered indicative of good electrical continuity between the various rebars in the deck.

**TABLE H-1**

<table>
<thead>
<tr>
<th>Age at Test, days</th>
<th>Total Load, pounds</th>
<th>Compression Strength, pounds per sq in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>102,000</td>
<td>3608</td>
</tr>
<tr>
<td>7</td>
<td>100,000</td>
<td>3537</td>
</tr>
<tr>
<td>7</td>
<td>105,000</td>
<td>3714</td>
</tr>
<tr>
<td>28</td>
<td>140,500</td>
<td>4969</td>
</tr>
<tr>
<td>28</td>
<td>138,000</td>
<td>4981</td>
</tr>
<tr>
<td>28</td>
<td>141,000</td>
<td>4917</td>
</tr>
</tbody>
</table>

*Class of concrete, Pennsylvania Department of Transportation Specification AA(50) W/C Ratio 5.1 Gal/Bag Slump 3.5 inches Air 5.1 percent

The cement used meets the physical and chemical requirements of ASTM Specification C-150-71.
Figure H-2. Electrical-resistance-probe test of prototype deck-probe mock-up.

Figure H-3. Prototype deck reinforcement. Note the electrical-resistance-probe cylinders and three insulated bars for simulated crack testing.

Figure H-4. Plan view showing designation of electrical-resistance probes and electrically isolated rebars on prototype model of concrete bridge deck.
TABLE H-2
ELECTRICAL TEST RESULTS FOR PROTOTYPE BRIDGE-DECK SECTION

a. Electrical isolation of test rebars:

<table>
<thead>
<tr>
<th>Rebar Designation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance, ohms</td>
<td>7.5</td>
<td>70</td>
<td>6.7</td>
<td>28</td>
<td>27</td>
<td>28</td>
</tr>
</tbody>
</table>

b. Electrical continuity of deck reinforcing steel:

![Potential contour maps](image)

![Potential contour maps](image)

1) See Figure F-4 for location of test rebars.

Deck Salt Treatment

Four weeks after pouring the deck concrete, a salt treatment of the deck surface was started. The treatment procedure consisted of ponding a solution of 3-percent sodium chloride over the deck to a depth of 3/8 in. each working day. This treatment was intended to cause salt intrusion into the concrete, and it was continued (about 6 weeks) until the start of the cathodic-protection testing. The equipotential contour maps (measured from the top and bottom of the deck), shown in Figures H-5 and H-6, were obtained during the 28-day curing time prior to the start of salt treatment. The rebar potentials (Figs. H-5 and H-6) are typical of steel in a passive state in concrete. The contour maps in Figures H-7 through H-11 were obtained at various times after starting the salt treatment, and they indicate a changing rebar potential. In general, it can be seen from comparison of these maps with those in Figures H-5 and H-6 that top rebar potentials shifted about 200 mV in the negative direction after the salt treatment. This is an indication that salt has intruded into the concrete near the steel. From these maps, it should be noted that bottom measurements do not differ before and after the salt treatment.

Measurements of the electrical resistivity of the concrete (Fig. H-12) demonstrate that a similar change occurred during this time period. These resistivity values were obtained near the center of the deck surface by using a synchronous vibrator instrument (Vibroground Model 293) and stainless-steel electrodes embedded, during deck construction, 2 in. apart in the concrete at points near the top, middle, and bottom of the slab cross section. The results, shown in Figure H-12, indicate that concrete resistivity near the top and middle increased prior to the initial salt application, and it stabilized at about 3000 ohm-cm after the salt treatment started; the bottom values appear unaffected by the salt and increased to a value above 12,000 ohm-cm. Later in the project, the resistivity values of the top and middle areas again began to increase.

As indicated by the corrosion rates shown in Figures H-13 and H-14, the electrical-resistance probes appear unaffected by the salt applications. From these data, it is noted that essentially no corrosion occurred after the installation of the probes in the deck concrete. However, in accordance with the plan to assure corrosion of the probe by using a copper couple, coupling the probe element with the copper initiated corrosion on the probe element (Figs. H-13 and H-14, test days 36 and 40). It is interesting to note that coupling the probes with the deck steel also initiated corrosion of the probe elements (day 77). At day 80, the initial cathodic-protection test on the deck steel was started; according to the work plan, all probes were connected to their copper couple and the control probes 1, 2, 3, and 4 were disconnected from the deck steel. The results during the cathodic-protection testing will be discussed later. The electrical-resistance probe readings obtained during the entire prototype deck work are given in Table H-3.

On occasion, during the salt-treatment period, the electrical potential of the electrical-resistance probes was measured. Table H-4 contains the potential values obtained. It is interesting to note the relation between potential and the corroding-noncorroding condition occurring near day 77. The probe potentials during the noncorroding period (between 40 and 77 days) are in the range 650 to 840 mV negative to a Cu/CuSO₄ half-cell, whereas these values after day 77 (during the corroding period with the probes connected to deck steel) are in the range 200 to 450 mV negative to a Cu/CuSO₄ half-cell. This result indicates that the relationship between potential and tendency toward corrosion (with more anodic potentials indicating the occurrence of corrosion) is more complex than has previously been recognized.

CATHODIC-PROTECTION TESTING

Distributed-Anode Method

The first cathodic-protection design to be tested on the prototype deck section was the distributed-anode method as proposed in the work plan. This design consists of an impressed-current system that depends exclusively on anode distribution to give the necessary cathodic-protection current spread to the top rebar steel. It does not involve the use of a conductive overlay on the deck. The anodes used in this test are prepared from a continuous platinum-surfaced niobium wire of 0.062-in. diameter. Details concerning the wire anodes are given in Table H-5.

Table H-5 also contains information relative to the anode design used on the prototype deck. Each of the four Pt/Nb anodes is installed about 0.5 in. below the deck surface in a groove 0.25-in.-wide. These grooves are on 4-ft centers,
Figure H-5. Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 2 weeks after pouring the concrete. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.

Figure H-6. Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 4 weeks after pouring the concrete. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.
Figure H-7. Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 5 weeks after pouring concrete and 1 week after start of salt application on deck surface. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.

Figure H-8. Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 2 weeks after initial salt applied to the deck. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.
Figure H-9. Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 4 weeks after initial salt applied to the deck surface. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.

Figure H-10. Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 5 weeks after initial salt applied to the deck surface. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.
Figure H-11. Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 6 weeks after initial salt applied to the deck surface. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.

Figure H-12. Resistivity of prototype deck concrete.
Figure H-13. Prototype deck steel corrosion as indicated by electrical-resistance probe readings, protected condition.

Figure H-14. Prototype deck steel corrosion as indicated by electrical-resistance probe readings, nonprotected condition.
### Table H-3

**DIAL READINGS FOR ELECTRICAL-RESISTANCE PROBES INSTALLED IN PROTOTYPE MODEL OF CONCRETE BRIDGE SECTION CONCRETE**

<table>
<thead>
<tr>
<th>Time After Casting Probe in Concrete, days</th>
<th>Probe Designation</th>
<th>Nonprotected Control</th>
<th>Cathodic Protection Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4</td>
<td>5 6 7 8</td>
</tr>
<tr>
<td>(a)</td>
<td>22</td>
<td>5 6 4 7</td>
<td>8 6 3 0 61</td>
</tr>
<tr>
<td>(b)</td>
<td>30</td>
<td>8 4 5 3 1</td>
<td>4 8 9 3 65</td>
</tr>
<tr>
<td>1</td>
<td>48</td>
<td>28 6 3 5</td>
<td>6 9 8 4 60</td>
</tr>
<tr>
<td>6</td>
<td>61</td>
<td>75 39 61</td>
<td>9 130 80 40</td>
</tr>
<tr>
<td>4</td>
<td>78</td>
<td>66 96 73</td>
<td>95 133 84 109</td>
</tr>
<tr>
<td>13</td>
<td>83</td>
<td>60 100 77</td>
<td>101 138 92 114</td>
</tr>
<tr>
<td>16</td>
<td>81</td>
<td>53 98 77</td>
<td>99 137 90 90</td>
</tr>
<tr>
<td>22</td>
<td>82</td>
<td>55 100 81</td>
<td>101 140 92 114</td>
</tr>
<tr>
<td>29</td>
<td>84</td>
<td>57 100 76</td>
<td>100 138 92 114</td>
</tr>
<tr>
<td>36</td>
<td>81</td>
<td>54 95 75</td>
<td>97 136 88 111</td>
</tr>
<tr>
<td>37</td>
<td>87</td>
<td>60 102 83</td>
<td>104 143 95 119</td>
</tr>
<tr>
<td>38</td>
<td>103</td>
<td>67 130 112</td>
<td>112 154 100 126</td>
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<td>45</td>
<td>128</td>
<td>98 140 120</td>
<td>138 183 123 145</td>
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<tr>
<td>46</td>
<td>130</td>
<td>90 142 123</td>
<td>139 184 123 145</td>
</tr>
<tr>
<td>47</td>
<td>131</td>
<td>92 142 123</td>
<td>139 185 123 145</td>
</tr>
<tr>
<td>48</td>
<td>130</td>
<td>86 132 123</td>
<td>138 183 123 145</td>
</tr>
<tr>
<td>49</td>
<td>138</td>
<td>86 142 120</td>
<td>138 183 124 146</td>
</tr>
<tr>
<td>50</td>
<td>128</td>
<td>81 138 120</td>
<td>135 180 123 144</td>
</tr>
<tr>
<td>51</td>
<td>126</td>
<td>82 141 118</td>
<td>136 183 122 144</td>
</tr>
<tr>
<td>52</td>
<td>131</td>
<td>83 144 125</td>
<td>139 190 126 148</td>
</tr>
<tr>
<td>53</td>
<td>136</td>
<td>94 147 129</td>
<td>145 191 131 154</td>
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<td>135 183 123 145</td>
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<td>55</td>
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<td>82 139 120</td>
<td>136 183 123 145</td>
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<td>56</td>
<td>125</td>
<td>82 140 122</td>
<td>133 184 123 145</td>
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<td>57</td>
<td>128</td>
<td>84 143 118</td>
<td>135 183 123 145</td>
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<td>136 185 123 145</td>
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<td>135 189 125 150</td>
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<td>161</td>
<td>106 209 150</td>
<td>185 201 175 184</td>
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<td>67</td>
<td>170</td>
<td>130 250 175</td>
<td>220 211 190 200</td>
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<td>68</td>
<td>173</td>
<td>132 250 182</td>
<td>231 215 197 201</td>
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<tr>
<td>69</td>
<td>178</td>
<td>139 265 190</td>
<td>237 215 204 198</td>
</tr>
<tr>
<td>70</td>
<td>187</td>
<td>147 298 217</td>
<td>270 215 226 197</td>
</tr>
<tr>
<td>71</td>
<td>204</td>
<td>157 310 232</td>
<td>273 215 226 197</td>
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<td>72</td>
<td>210</td>
<td>163 318 238</td>
<td>280 212 230 200</td>
</tr>
<tr>
<td>73</td>
<td>230</td>
<td>175 333 255</td>
<td>304 210 240 199</td>
</tr>
<tr>
<td>74</td>
<td>237</td>
<td>183 344 263</td>
<td>304 213 248 198</td>
</tr>
</tbody>
</table>

**Note:**
- Probes connected to copper.
- Probes connected to deck steel.
- Probes connected to deck steel.

**Table H-4**

**ELECTRICAL-RESISTANCE-PROBE POTENTIALS IN PROTOTYPE MODEL OF CONCRETE BRIDGE DECK FOR PRECATHERODIC-PROTECTION PERIOD**

<table>
<thead>
<tr>
<th>Time, days</th>
<th>Probe Potential, mV negative to Cu/CuSO₄ reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>575 495 480 565 605 580 525 560</td>
</tr>
<tr>
<td>2</td>
<td>470 435 465 415 405 435 420 450</td>
</tr>
<tr>
<td>3</td>
<td>580 675 690 730 630 690 610 685</td>
</tr>
<tr>
<td>4</td>
<td>765 745 805 675 680 750 650 560</td>
</tr>
<tr>
<td>5</td>
<td>770 790 790 840 745 720 760 760</td>
</tr>
<tr>
<td>6</td>
<td>405 425 280 410 220 450 320 395</td>
</tr>
<tr>
<td>7</td>
<td>390 450 290 410 450 250 260 400</td>
</tr>
</tbody>
</table>

**Note:**
- Probes connected to copper.
- Probes disconnected from copper.
- Probes connected to deck steel.

Starting 2 ft from the 12-ft-long side of the slab, as shown in Figure H-15. After the groove was cut, a small amount of cement mortar was placed in the slot. Next, the Pt/Nb anode was placed in the slot and held by tapping a small wooden wedge over the wire. After every 2 ft, the groove was filled and the surface was smoothed with a polymer cement mix (Top 'N Bond manufactured by Campbell Products). As an experiment, salt was added to the cement mortar used to fill the grooves for anodes 1 and 2 (see Fig. H-15). The data in Table H-5 show that, although the contact resistance of these anodes (with salt) to the deck steel was lower in the beginning, after 2 weeks of operating the system the
TABLE H-5

PROTOTYPE BRIDGE-DECK-SECTION DESIGN INFORMATION RELATING TO DISTRIBUTED-ANODE METHOD

### Anode Specifications

- **99.9% pure annealed niobium wire** platinized on etched surface to an average thickness of 100 microinches.
- **Tensile Strength:** 40,000 psi typical, 33,000 psi minimum
- **Proportional Limit:** 25,000 psi
- **Resistivity:** 79.5 ohm/ft/circular mill at 20°C
- **Specific Gravity:** 8.57 g/cc
- **Approximate Cost:** 30 cent/inch
- **Wire Diameter:** 0.063 inch
- **Coefficient of Resistivity:** 0.4%/°C
- **Wire Weight:** 1.13 pounds/100 ft
- **Resistance:** 2.06 ohms/100 ft
- **Anode Life:** 8 ampere years/ft
- **Breaking Strength:** 75 lb

### Anode Bed Design

4 each 12-foot long Pt/Nb wire anodes installed 0.5 inch below deck surface on 4-foot centers starting 2 feet from the 12-foot-wide ends.

### Anode Bed Resistance After Wetting Deck

<table>
<thead>
<tr>
<th>Anode No.</th>
<th>Initial Resistance, ohms</th>
<th>After 2 Weeks</th>
<th>After 3 Weeks</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.2</td>
<td>6.6</td>
<td>6.4</td>
<td>Anode in Salt - Mortar Grout</td>
</tr>
<tr>
<td>2</td>
<td>7.2</td>
<td>6.0</td>
<td>6.0</td>
<td>Anode in Salt - Mortar Grout</td>
</tr>
<tr>
<td>3</td>
<td>13.0</td>
<td>6.3</td>
<td>6.1</td>
<td>Anode in Mortar Grout</td>
</tr>
<tr>
<td>4</td>
<td>14.0</td>
<td>6.5</td>
<td>6.3</td>
<td>Anode in Mortar Grout</td>
</tr>
<tr>
<td>All Anodes</td>
<td>3.5</td>
<td>1.9</td>
<td>1.8</td>
<td>Normal Operation Arrangement</td>
</tr>
</tbody>
</table>

**Figure H-15.** Plan view showing location and designation of platinized niobium anodes used with distributed-anode system on prototype model of concrete bridge deck.
resistance of all anodes to the deck steel stabilized at about 6 ohms.

The contour maps in Figures H-17, H-18, and H-19 are typical of those obtained at several levels of cathodic protection applied with the Pt/Nb anode system. These maps show that the top deck area near the midpoint between the Pt/Nb anodes does not receive adequate current to achieve a polarized potential of 770 mV negative to a Cu/CuSO₄ half-cell. The bottom measurements give a pattern similar to the top. However, as with the results of analog model testing (Appendix F), these potentials are several hundreds of millivolts lower than the top values. The graphs of probe dial readings, Figures H-20 and H-21, show that probes 5 and 7 are not fully protected during this test (days 80 through 104). Probes 5 and 7 with applied protection, however, show a reduced slope, which indicates that a reduction in corrosion rate has been achieved; probes 6 and 8 show no corrosion during the test period. As indicated from the data in Table H-6, the cathodic-protection current flow is disproportionately much greater to test rebars A and F nearest the anodes. This demonstrates the problem of attaining uniform current flow in this cathodic-protection application. Also, from Table H-6, it can be seen that the cracking associated with test rebars A, B, and C does not appear to have had any influence on the current flow to these rebars. In all, the test with the Pt/Nb anodes on 4-ft spacing indicates that a closer spacing is necessary for total protection.

During the test, an effort was made to keep a stable moisture condition in the concrete. Essentially, the deck was kept damp with the chloride solution used earlier during the test period. This was necessary because current output with this system was very dependent on the moisture condition in the deck. Figure H-22 points out this dependence. It can be seen that, as the deck dried, the rectifier current dropped significantly over a period of several days. Accordingly, it is believed that during dry periods the protection level from a given system would vary. One possible means of minimizing this problem is through the use of a constant-current rectifier. These units may be adjusted to produce the desired current, and they will automatically regulate output voltage to maintain it, thus compensating for the increase in circuit resistance. However, these units are somewhat expensive and will require more upkeep.

The method of installation of the Pt/Nb anodes was not entirely satisfactory in that considerable oxygen and chlorine gas were generated at the anodes. These gases caused some of the polymer cement mortar, and to a lesser extent the cement mortar, to be spalled off. Figure H-23 shows the appearance of the groove after several weeks of applying cathodic protection with the Pt/Nb anodes. Some method of permitting the gases to escape must be provided with future installations.

**Modified Conductive-Overlay Method**

The second cathodic-protection design tested on the prototype deck section was the modified conductive-overlay method. This design is an impressed-current system that utilizes a thin, electrically conductive asphalt-concrete layer placed on the top of the deck. A 2-in.-thick asphalt-concrete wearing course is placed over the top of the conductive layer to protect it from traffic abrasion and to distribute wheel loads. Figure H-24 shows the modified conductive-overlay arrangement. The anodes used to introduce the cathodic current into the conductive layer are the Pt-surfaced Nb wire type described in Table H-5. Also, the spacing of the anodes on the prototype deck is the same (4 ft) as that shown in Figure H-15.

The electrically conductive asphaltic concrete for the test was mixed in the laboratory and formulated in accordance with the information developed during the previous coke aggregate/asphalt durability study (Appendix F). The coke breeze/asphalt mixture, referred to as ASTM 6A mix (described in Tables F-4 and F-5), was selected as the material for the conductive overlay. As can be seen from these tables, this material consists of coke-breeze aggregate of the particle size conforming with the ASTM 6A specification and about 11 percent by weight of the asphaltic binder identified as AC-2000. The mixture was prepared by preheating the coke-breeze aggregate to a temperature above 300°F. The hot aggregate was added to the hot asphalt binder in a mixing drum with lifters in it and mixed on a rolling mill. The coke particles were thoroughly blended in the hot mix, and the temperature of the completed mix, as discharged from the mill, was within the range 275 to 325°F.

The asphaltic-concrete surfaces used during this project were constructed in a manner consistent with usual practice. This consisted generally of spreading the hot mix uniformly over the concrete deck, which previously had been coated with an asphaltic primer coat and compacting. As the conductive layer was spread over the prototype deck surface, the Pt/Nb anodes were placed within this layer of material. The compacting on the small prototype deck was performed with a specially constructed hand-push roller, as shown in Figure H-25. The average contact pressure was estimated to range between 50 and 75 psi, and the compacted thickness of the conductive layer ranged between ¾ and ½ in. The conductive layer was covered with a
Figure H-17. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 20 V and 10 amp. Four platinum-surfaced niobium-wire anodes were located, as indicated (4-ft centers), on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.

Figure H-18. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 40 V and 20 amp. Four platinum-surfaced niobium-wire anodes were located, as indicated (4-ft centers), on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.
Figure H-19. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 40 V and 6.5 amp. Four platinum-surfaced niobium-wire anodes were located, as indicated (4-ft centers), on the 2-ft grid. Contour units are mV negative to Cu/CuSO₄ half-cell.

Figure H-20. Prototype deck steel corrosion as indicated by electrical-resistance probe readings, nonprotected condition.
Figure H-21. Prototype deck steel corrosion as indicated by electrical-resistance probe readings, protected condition.

Figure H-22. Change in cathodic-protection current after wetting deck, Pt/Nb design, 40-V rectifier voltage.
TABLE H-6
PROTOTYPE BRIDGE-DECK-SECTION ELECTRICAL TESTS—DISTRIBUTED-ANODE DESIGN

a. Anode Current, amperes

<table>
<thead>
<tr>
<th>Rectifier Current, amp</th>
<th>Voltage, volts</th>
<th>Anode Designation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>20b)</td>
<td>40</td>
<td>5.3</td>
<td>5.2</td>
<td>5.5</td>
<td>4.9</td>
<td>20.9</td>
<td></td>
</tr>
<tr>
<td>10c)</td>
<td>20</td>
<td>1.8</td>
<td>2.5</td>
<td>2.7</td>
<td>2.3</td>
<td>9.3</td>
<td></td>
</tr>
<tr>
<td>6.5d)</td>
<td>40</td>
<td>1.6</td>
<td>1.7</td>
<td>1.7</td>
<td>1.6</td>
<td>6.6</td>
<td></td>
</tr>
</tbody>
</table>

b. Test Rebar Current Pickup, milliamperes

<table>
<thead>
<tr>
<th>Rectifier Current, amp</th>
<th>Voltage, volts</th>
<th>Test Rebar Designationa)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>20b)</td>
<td>40</td>
<td>1800</td>
<td>138</td>
<td>4.4</td>
<td>1.2</td>
<td>8.4</td>
<td>1340</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10c)</td>
<td>20</td>
<td>460</td>
<td>4</td>
<td>0.2</td>
<td>0.4</td>
<td>5.0</td>
<td>760</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.5d)</td>
<td>40</td>
<td>540</td>
<td>3.4</td>
<td>0.2</td>
<td>0.5</td>
<td>5.0</td>
<td>800</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) See Figure H-4 for location of the test rebars.
b) See Figure H-17 for corresponding equipotential contour maps.
c) See Figure H-16 for corresponding equipotential contour maps.
d) See Figure H-18 for corresponding equipotential contour maps.

Figure H-23. Appearance of wire-shaped-anode grooves after 3 weeks of cathodic protection operation on prototype bridge-deck section. Note the spalled area along the grooves.

Figure H-24. Modified conductive-overlay anode arrangement used on prototype deck.

2-in. (compacted thickness) layer of an asphaltic-concrete wearing course conforming to the PennDOT specification ID-2A. The wearing-course material was purchased from a local supplier, and the installation procedure used for the conductive layer was also used to install the wearing course.

During the analog work with this system, excessively negative applied potentials were required to stop corrosion on the electrical resistance probes (see Table F-3), which were located in the limestone aggregate under the coke-breeze layer. To investigate the influence of the overlay system on the deck, potential measurements were obtained at various stages of the installation of the modified conductive-overlay system. These measurements are shown in Figures H-26, H-27, and H-28. The figures were obtained before installation of the overlay, after installation of the conductive overlay, and after installation of the wearing course on the conductive overlay, respectively. These maps show that placement of the conductive layer greatly altered the pattern and values for the top measurements. After placing the asphaltic wearing course over the conductive layer, a different potential pattern was obtained.
Concurrent laboratory work confirmed the existence of an inherent error in potential measurements made with the reference half-cell on top of the conductive overlay (Appendix D). In these studies, it was observed that the amount of the potential shift was related to current density and was not apparent before current was applied. In view of this, steps were taken to observe whether this potential shift would occur during the modified conductive-overlay investigations. These steps consisted of drilling holes through the overlay system on the deck, at a location midpoint on the deck surface, to give an arrangement similar to that shown in Figure D-13. By placing a half-cell in the various holes, potentials at essentially the same grid location on the deck were obtained with the half-cell contacting (1) the top of the asphaltic-concrete wearing course, (2) the top of the electrically conductive asphaltic-concrete layer, (3) the top of the deck concrete, and (4) the deck concrete very near (¼ in.) the top rebar surface.

The potential readings obtained during this phase of the testing are given in Table H-7. The data show a significant difference in potential values obtained with the half-cell over the conductive overlay and those obtained with the half-cell under the conductive layer. The true potential is considered to be the one obtained with the half-cell near the steel surface. It is important to note from Table H-7 that, in all cases, there is agreement between the true potential and the potentials obtained (rectifier off) with the half-cell on the surface of the concrete (under the conductive overlay). This result is also confirmed by the data presented in Appendix D. As previously noted, potentials obtained with the half-cell above the conductive layer ranged from 100 to 200 mV more negative than the values obtained with the half-cell contacting the deck under the overlay.

This information should be considered when studying the contour maps shown in Figures H-29, H-30, and H-31. These maps are the results obtained with various levels of applied voltage and the four Pt/Nb anode systems shown in Figure H-15. In each case, the potentials shown were obtained with the half-cell over the conductive layer and, therefore, are in error. However, these results give a valid potential-distribution pattern.

From the electrical-resistance probes (Fig. H-21) obtained during this test period, it is concluded that cathodic protection of the prototype deck was achieved at a level of about 4 V applied potential and 1 amp of cathodic current. At this condition, essentially no corrosion was noted on the test probes, and the correct potentials on the deck ranged between 770 and 1100 mV.

To investigate the current-throwing power of the present system, tests were conducted with one and then two end Pt/Nb wire anodes in the thin conductive layer. Figures H-32 and H-33 show the results of this work. Figure H-32 shows that, at a moderate voltage level (8 V), the deck surface with protective potential extended about 2 ft from the anode. When the rectifier voltage was set at a maximum value (42 V), the protection extended to about 4 ft from the anode (Fig. H-33). The high impressed voltage on the anode caused the rebar potentials near the anodes to reach very high values. A comparison of Figures H-32 and H-33 shows that the ratio of protected area is less than the ratio
### TABLE H-7
PROTOTYPE DECK SECTION SPECIAL POTENTIAL MEASUREMENTS
WITH MODIFIED-OVERLAY METHOD

<table>
<thead>
<tr>
<th>Halfcell Elevation</th>
<th>Rebar Potential, millivolts negative to CuSO₄ halfcell</th>
<th>Rectifier Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of asphalt concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>320</td>
<td>3600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1250</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>850</td>
</tr>
<tr>
<td>Top of conductive asphaltic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>concrete layer</td>
<td>285</td>
<td>3600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1350</td>
</tr>
<tr>
<td></td>
<td></td>
<td>890</td>
</tr>
<tr>
<td>Top of deck concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>210</td>
<td>2750</td>
</tr>
<tr>
<td></td>
<td></td>
<td>850</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1650</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>820</td>
</tr>
<tr>
<td>At the surface of rebar (true</td>
<td></td>
<td></td>
</tr>
<tr>
<td>potential)</td>
<td>200</td>
<td>2350</td>
</tr>
<tr>
<td></td>
<td></td>
<td>850</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1050</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1080</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>780</td>
</tr>
</tbody>
</table>

---

**Rectifier Output**

- **None**
- 4.2 Amp & 6 Volts
- 3.3 Amp & 6.5 Volts
- 2 Amp & 5 Volts
- 0.5 Amp & 3.5 Volts

---

### Notes:

- a) See Figure H-28 for corresponding equipotential contour maps.
- b) See Figure H-29 for corresponding equipotential contour maps.
- c) See Figure H-30 for corresponding equipotential contour maps.
- d) See Figure H-31 for corresponding equipotential contour maps.

---

**Figure H-28.** Equipotential contour maps of prototype model of bridge deck with no cathodic protection applied 8 days after completion of last test. This profile was made with the completed, modified conductive overlay installed. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid. Potential values measured for top are distorted by conductive overlay.

**Figure H-29.** Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 3.5 V and 0.5 amp. Four platinum-surfaced niobium-wire anodes were located, as indicated, on the 2-ft grid, in a ½-in. conductive overlay. Contour units are mV negative to Cu/CuSO₄ half-cell. Potential values measured for top are distorted by conductive overlay.

**Figure H-30.** Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 3.5 V and 2 amp. Four platinum-surfaced niobium-wire anodes were located, as indicated, on the 2-ft grid, in a ½-in. conductive overlay. Contour units are mV negative to Cu/CuSO₄ half-cell. Potential values measured for top are distorted by conductive overlay.
Table H-8 gives the conductive-layer resistance measurements made during this work. The data show that the average anode-to-deck resistance changed somewhat, from 4.7 ohms initially to 3.4 ohms at the end of the test. Although laboratory tests of the specific resistivity of the electrically conductive asphaltic concrete performed on Marshall-type specimens gave very low values (<1 ohm), the calculated specific resistivity based on the measured resistance between anodes 3 and 4 was much higher (30.5 ohms). The high resistance may reflect poor compaction obtained with the hand-push roller on the conductive layer.

The overlay resistance was stable through this test. No moisture (except that added by the wet sponges used to improve half-cell contact) was added to the deck surface during the testing; wetting the deck would undoubtedly lower the conductive-layer resistance.

The data from the electrical tests performed during this test period are summarized in Table H-9. The anode current readings indicate that the cathodic-protection current discharged from the anodes evenly into the conductive overlay, whereas the current readings of the test rebars show that the current flow from the conductive layer to the overlay may be caused by ion migration. As ion concentration increases, it causes a localized lowering of concrete resistivity near the anode. Ion concentration increases when the applied voltage is increased. This may be caused by ion migration to the area near the anode. Potential values measured for top are distorted by conductive overlay.
### TABLE H-8
PROTOTYPE BRIDGE-DECK-SECTION RESISTANCE TESTS—MODIFIED CONDUCTIVE-OVERLAY DESIGN

<table>
<thead>
<tr>
<th>Anode No.</th>
<th>Initial Resistance (ohms)</th>
<th>At Time of Energizing</th>
<th>Rectifier</th>
<th>At Completion of Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (NE end)</td>
<td>4.9 refusal</td>
<td>6.5</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>5.5</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>3</td>
<td>4.4</td>
<td>5.0</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>4 (SE end)</td>
<td>5.0</td>
<td>6.0</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>All Anodes</td>
<td>0.8</td>
<td>0.9</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**Before Installation**

| Anodes 3 & 4 | 32 | 8 | 8.5 | 2.9b |

- **a)** This measurement of the resistance between anodes 3 and 4 shows the change in conductive layer resistance during the test.
- **b)** Based upon this value (7.9 ohms) the calculated specific resistivity of the overlay material is 30.5 ohm - cm; whereas the value obtained in the laboratory on a Marshall specimen of this overlay material is <1 ohm - cm.

### TABLE H-9
PROTOTYPE BRIDGE-DECK-SECTION ELECTRICAL TESTS—MODIFIED CONDUCTIVE-OVERLAY DESIGN

#### a. Anode Current, amperes

<table>
<thead>
<tr>
<th>Rectifier Current, amp</th>
<th>Voltage, volts</th>
<th>Anode Designation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>6</td>
<td>0.87</td>
<td>0.93</td>
<td>0.78</td>
<td>0.9</td>
<td>3.3</td>
<td>3.5</td>
</tr>
<tr>
<td>3.5</td>
<td>6.8</td>
<td>0.98</td>
<td>0.73</td>
<td>0.86</td>
<td>0.77</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>3.3b</td>
<td>6.5</td>
<td>0.125</td>
<td>0.084</td>
<td>0.145</td>
<td>0.120</td>
<td>0.474</td>
<td>0.78</td>
</tr>
<tr>
<td>0.5c</td>
<td>3.5</td>
<td>1.77</td>
<td>1.24</td>
<td>1.36</td>
<td>1.20</td>
<td>1.0</td>
<td>3.4</td>
</tr>
<tr>
<td>1</td>
<td>7.7</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8.4d</td>
<td>42</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>4.8</td>
<td>8.8</td>
</tr>
</tbody>
</table>

**Anode disconnected during this test period.**

**Test rebar nearest to anode.**

**Negative value used to indicate current flow from deck steel to test rebar.**

#### b. Test Rebar Current Pickup, milliamperes

<table>
<thead>
<tr>
<th>Rectifier Current, amp</th>
<th>Voltage, volts</th>
<th>Test Rebar Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>6.0</td>
<td>240</td>
</tr>
<tr>
<td>3.5</td>
<td>6.8</td>
<td>172</td>
</tr>
<tr>
<td>3.3b</td>
<td>6.5</td>
<td>154</td>
</tr>
<tr>
<td>0.5c</td>
<td>3.5</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>7.7</td>
<td>-1.2</td>
</tr>
<tr>
<td>8.4d</td>
<td>42</td>
<td>2800</td>
</tr>
</tbody>
</table>

**a)** For position of anodes or test rebars see Figure H-15.

**b)** See Figure H-29 for corresponding equipotential contour maps.

**c)** See Figure H-31 for corresponding equipotential contour maps.

**d)** See Figure H-33 for corresponding equipotential contour maps.
the deck steel was disproportionately much greater to test rebars A and F located nearest the Pt/Nb anodes. The simulated cracks over rebars A, B, and C do not appear to have altered the current flow in any manner.

Over-all, the results of tests with the modified conductive-overlay method are markedly better than those obtained with the distributed-anode design. In general, the required current distribution and polarized potential on the deck were achieved with much lower operating voltages and currents. Further, the system’s effectiveness did not depend on keeping the deck surface damp. As near as could be determined, neither the Pt/Nb wire anodes nor the conductive layer used in this test was adversely affected by the cathodic current or voltage. However, it was apparent from the results of this test that lowering the conductive-layer resistance by making it thicker or, possibly, by improving compaction could improve current distribution over the deck surface and give a more efficient operation.

Conductive-Overlay Method

The third cathodic-protection system tested on the prototype deck is referred to as the conductive-overlay method, which, as has been mentioned, was proposed by Stratfull. This design is an impressed-current system that utilizes a 2-in. electrically conductive asphaltic-concrete layer placed on the top of the deck. As with the previous system, a 2-in.-thick asphaltic-concrete wearing course is placed over the top of the conductive layer to protect it from traffic abrasion and to distribute wheel loads. To investigate different ways of introducing the cathodic-protection current into the conductive layer, two different anode arrangements were installed in this overlay system. These were: (1) two Pt/Nb wire-type anodes positioned in the conductive layer, one 4 ft from each end of the deck (8 ft apart) and (2) a single 12-in.-diameter by 1½-in.-thick, disk-shaped silicon-iron anode located midpoint on the deck top. The various anode locations are shown in Figure H-34.

Figure H-34 also shows that a 2-ft sq surface of deck concrete around the center anode is coated. First, the anode was cemented to the deck surface with an adhesive cement (USS NEXUS S-8005). Then, the area around the anode was coated with an epoxy coating (USS NEXDECK). In addition, a 20-in.-wide strip of the deck surface under the Pt/Nb anode was coated with the epoxy. The coating was used to observe its effects on the current-throwing power from the anodes. Figures H-35 and H-36 show the disk-shaped and wire anodes before they were covered with the conductive layer.

The electrically conductive asphaltic concrete used in this test is the same composition used in the modified conductive system and has been referred to as ASTM 6A mix (Appendix F). However, because of the large quantity required, the mixture was purchased from a local commercial establishment, where it was prepared in accordance with the specification and with coke-breeze aggregate provided by the research contractor. The conductive asphaltic concrete obtained had an average stability of 1037 psi, a flow factor of 12.7, and a specific electrical resistivity of <1 ohm-cm measured on Marshall-type specimens in the laboratory.
The conductive layer was constructed in the manner described earlier in this Appendix, except that the compacted thickness of the layer was increased to 2 in. Figure H-37 shows a cross section of the overlay system and the relative thickness of the two asphaltic layers, as well as the position of the Pt/Nb wire anode in the conductive layer.

During the previous test, excessively negative potentials were obtained with the half-cell contacting the surface above the conductive layer. In this test, the following measurement procedure was adopted to obtain the true rebar potentials. Before energizing the rectifier, 1¾-in.-diameter holes were drilled through the overlay to the concrete surface of the deck, with one hole drilled at each of the 2-ft-grid crossing points. The potential at the grid points for the potential surveys was measured by placing a saturated calomel reference electrode (SCE) in these holes; to obtain a low contact resistance between the half-cell and the deck, the bottom of the hole was dampened with tap water. Figure H-38 illustrates this method. The SCE readings were converted to the Cu/CuSO₄ reference scale (by addition of -72 mV) before preparing the equipotential maps.

The profile map on the left-hand side of Figure H-39 was obtained with the half-cell in the hole; the map on the right was obtained with the half-cell placed on a damp sponge on the asphaltic overlay. These readings are for static conditions before the rectifier was energized, and a comparison of these maps shows little difference in the values obtained. However, the profiles in Figure H-40, obtained in a similar manner after the rectifier was energized, show a major difference between the readings. As was previously noted, those readings with the half-cell contacting the concrete are correct, and a more negative reading was obtained with the half-cell over the conductive layer. Accordingly, in-the-hole readings were used for the balance of this study.

A series of potential-distribution tests was conducted with the silicon-iron anode located midpoint on the deck. The results, shown in Figures H-41 through H-43, indicate that a very uniform potential was achieved and that, based on a criterion of 770 mV to Cu/CuSO₄, a rectifier setting of 7.2 V and 1.25 amp gave complete protection of the deck surface. A second series of tests was conducted, first with the Pt/Nb wire anode over the coated strip on the deck (Fig. H-44) and next with the Pt/Nb wire anode located at the opposite end of the prototype (Fig. H-45). A comparison of these results, shown in Figures H-44 and H-45, reveals that coating the concrete deck surface under the wire electrode did not appear to influence the potential distribution, in view of the fact that the resultant potential profiles for the top measurements are mirror images.

A comparison of the results in Figures H-44 and H-45 with those obtained with a single Pt/Nb wire anode in the ½-in.-thick conductive layer (see Fig. H-32) shows that the 2-in.-thick layer gave protection to an area of the deck at least 4 times larger.

The potential-distribution tests shown in Figures H-46, H-47, and H-48 were conducted by using both Pt/Nb wire anodes. The figures show that very uniform protective potential was attained over the deck surface with an applied voltage at 2.5 V and a current of 0.6 amp. A review of the resistance-probe results obtained during the series of tests with the 2-in.-thick conductive layer (days 143 through 175...
Data relating to other electrical tests made during this work are given in Tables H-10 and H-11. Table H-10 shows that the resistance of the various anodes to the deck steel, although somewhat high initially, was stable through the test. As with the previous test of an overlay system, no water was added to the deck during this test. A comparison of Table H-10 with Table H-8 shows that the Pt/Nb anode resistance to deck steel was much lower with the 2-in. overlay than with the ½-in. layer (average 3.4 ohms as compared with 1.3 ohms for the 2-in. layer). Also, as in the previous overlay tests, laboratory tests of the specific resistivity of the electrically conductive asphaltic concrete gave very low values (<1 ohm-cm), whereas calculated resistivity (based on the measured resistance between anodes a and b) was much higher (23 ohm-cm). The lower value may reflect improved formulation over that of the previous conductive material.

In general, the 2-in. conductive overlay markedly improved on the current distribution as measured by current flow to the test rebars. This can be seen in Table H-11 (part b), where it is apparent that a balance of current flow to the various rebars was attained during this test. The notable lack of current flow to rebars D and F is no doubt caused by the coating over these rebars. As in the earlier work, the cracks over rebars A, B, and C have not had a bearing on the current flow to the test rebars. The results (part a in Table H-11) show that, as in the earlier studies, current is introduced into the conductive layer from the anodes in a uniform manner.

The conductive-overlay method proved to be the most effective of the several impressed-current systems tested. Center-to-center anode distances of more than 20 ft are indicated, and there was no problem associated with gas blockage or deterioration of the anodes or the conductive layer. During the test, the prototype deck was easily protected with about 0.5 amp of applied cathodic current. On the basis of the surface area of the top rebar mat, this is calculated current density of less than 2 mA/sq ft, which is within the range expected and indicative of the excellent current distribution obtained.

Sacrificial-Anode Method

Previous tests with the sacrificial-anode method showed that, because of the low driving voltage of this system (Appendix F), a well-distributed anode arrangement on the surface of the bridge deck will be required to attain cathodic protection of the rebars. Also, pilot performance tests showed that, because of the expansive nature of anode corrosion products, cracking occurs when these anodes are encased in asphaltic or portland cement concrete. To investigate methods of sacrificial-anode installation that overcome these problems, several possible sacrificial-anode installation methods were evaluated in a prototype test.

It is assumed that under certain weather conditions, a limited amount of moisture conceivably could be present on a bridge deck. Furthermore, moisture is necessary for the corrosion process of the sacrificial anodes and for the conductance of the cathodic-protection current from the
Figure H-40. Equipotential contour maps of prototype model of bridge deck top with cathodic protection applied at 11.5 V and 2.4 amp for 1 week. One silicon-iron anode was located midpoint on the deck, as indicated, in a 2-in.-thick conductive layer. Note the potential value distortion caused by position of the half-cell over the conductive overlay. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.

Figure H-41. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 11 V and 2.1 amp. One silicon-iron anode was located midpoint on the deck, as indicated, in a 2-in.-thick conductive layer. Contour units are mV negative to Cu/CuSO₄ half-cell plotted on a 2-ft grid.
anodes to the deck steel, and chloride in the water on
the bridge deck is helpful in both processes. Therefore, the
following test was conducted under two conditions: either
very wet with chloride-bearing water or dry. To acco-
mmodate the test of sacrificial-anode methods in the most
efficient manner, the model used for the analog studies,
described in Appendix F, was adapted for this test.

Figure H-49 illustrates the three installation methods used
for sacrificial anodes. The types of anodes have been pre-
viously described, and detailed information concerning
them is given in Table F-6. From Figure H-49, it can be
seen that two of the methods relate to the use of sacrificial
anodes on an existing bridge deck; the third method relates
to installation on a new or reconstructed bridge deck.

Method I should prove to be the simplest to install in
the field and includes the use of an open-grade asphaltic-
concrete cover over the anodes. The porous nature of this
material permits ready ingress of chloride-bearing water to
the anode and possibly absorbs anode corrosion products
without heaving and cracking. As shown in Figure H-49,
each anode ribbon is placed on a strip of asbestos tape.*
Because asbestos is absorbent, it will become wet and then
aid in holding moisture uniformly along the anode length.

Method II features the use of a gypsum-cement anode
backfill † and a polystyrene pad under the anode to prevent
the expansion of the anode corrosion products from crack-
ing the concrete. In addition to absorbing expansion, the
polystyrene, which will not absorb moisture, will serve to
insulate the anode from the rebar under it and will, thereby,
promote better current distribution. Method II installation
will be tested with and without a 2-in. overlay of the open-
grade asphaltic concrete over the anode. In Method III,
the anode and polystyrene pad are placed on the rebar mat
before pouring the deck concrete and, therefore, the anode
is embedded in the deck concrete. This approach is in-
tended for use during deck construction.

Figure H-50 is a plot plan showing the sacrificial-anode
test arrangement on the basic analog model. The anode
spacing is 6 in.; this provides one anode ribbon between
each pair of rebars (top row). This spacing was indicated
by studies on the analog model (Appendix F). Figure
H-50 shows that the test arrangement is duplicated to ac-
commodate testing of both Zn and Mg anodes and, also,
to investigate conditions of a wet and a cyclic wet and dry
surface on the deck over the anodes. For the wet condi-
tion, a 3-percent NaCl solution was ponded over the deck
(½-in. pond depth) each working day. Generally, this
treatment gave 1 to 3 hr time with some free water laying
on the deck, followed by 12 to 15 hr with a damp deck
surface. For the remaining period the deck surface ap-
peared dry. To simulate the wet and dry conditions, this
NaCl treatment was made once each week. After four
weeks, the surface-treatment procedure was stopped, and
the effects of the deck drying out on the test results were
observed.

A 16-in.-wide open space in the middle of the two test

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* Asbestos may be carcinogenic; therefore, it is recommended that per-
sonnel handling this material wear rubber gloves and face masks.
† The design concept for Method II is based on a suggestion by John
Sainer of the Illinois Department of Transportation.
Figure H-44. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 5.2 V and 1.5 amp. One platinum-surfaced niobium-wire anode was located, as indicated, on the 2-ft grid, in a 2-in.-thick conductive layer. Contour units are mV negative to Cu/CuSO₄ half-cell.

Figure H-45. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 5.2 V and 1.5 amp. One platinum-surfaced niobium-wire anode was located, as indicated, on the 2-ft grid, in a 2-in.-thick conductive layer. Contour units are mV negative to Cu/CuSO₄ half-cell.
Figure H-46. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 3.15 V and 1 amp. Two platinum-surfaced niobium-wire anodes were located, as indicated, on the 2-ft grid, in a 2-in.-thick conductive layer. Contour units are mV negative to Cu/CuSO₄ half-cell.

Figure H-47. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 2.9 V and 0.55 amp. Two platinum-surfaced niobium-wire anodes were located, as indicated, on the 2-ft grid, in a 2-in.-thick conductive layer. Contour units are mV negative to Cu/CuSO₄ half-cell.
Figure H-48. Equipotential contour maps of prototype model of bridge deck with cathodic protection applied at 2.5 V and 0.6 amp. Two platinum-surfaced niobium-wire anodes were located, as indicated, on the 2-ft grid, in a 2-in.-thick conductive layer. Contour units are mV negative to Cu/CuSO₄ half-cell.

Table H-11

Prototype Bridge-Deck-Section Electrical Tests—Conductive-Overlay Design

<table>
<thead>
<tr>
<th>Rectifier Current, amperes</th>
<th>Anode Designation a)</th>
<th>Rectifier Current, Voltage, volts</th>
<th>Silicon-Iron Current, amperes</th>
<th>Platinized Niobium Current, amperes</th>
<th>Total Current, amperes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>11.0</td>
<td>2.1</td>
<td>*</td>
<td>*</td>
<td>2.1</td>
</tr>
<tr>
<td>2.4</td>
<td>10.5</td>
<td>2.4</td>
<td>*</td>
<td>*</td>
<td>2.4</td>
</tr>
<tr>
<td>1.25</td>
<td>7.2</td>
<td>1.25</td>
<td>*</td>
<td>*</td>
<td>1.25</td>
</tr>
<tr>
<td>0.68</td>
<td>3.8</td>
<td>0.68</td>
<td>*</td>
<td>*</td>
<td>0.68</td>
</tr>
<tr>
<td>1.5</td>
<td>5.2</td>
<td>*</td>
<td>*</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1.5</td>
<td>5.2</td>
<td>*</td>
<td>1.5</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>1.0</td>
<td>5.5</td>
<td>*</td>
<td>0.51</td>
<td>0.51</td>
<td>1.02</td>
</tr>
<tr>
<td>0.6</td>
<td>2.5</td>
<td>*</td>
<td>0.31</td>
<td>0.31</td>
<td>0.62</td>
</tr>
</tbody>
</table>

b. Test Rebar Current Pickup, milliamperes

<table>
<thead>
<tr>
<th>Rectifier Current, amperes</th>
<th>Anode Designation a)</th>
<th>Rectifier Voltage, volts</th>
<th>Operation</th>
<th>Test Rebar Designation a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>S/I</td>
<td>11.0</td>
<td>A</td>
<td>18</td>
</tr>
<tr>
<td>2.4</td>
<td>S/I</td>
<td>10.5</td>
<td>B</td>
<td>15</td>
</tr>
<tr>
<td>1.25</td>
<td>S/I</td>
<td>7.2</td>
<td>C</td>
<td>16.4</td>
</tr>
<tr>
<td>0.68</td>
<td>S/I</td>
<td>3.6</td>
<td>B</td>
<td>8.2</td>
</tr>
<tr>
<td>1.5</td>
<td>P/N-b</td>
<td>5.2</td>
<td>A</td>
<td>0.8</td>
</tr>
<tr>
<td>1.5</td>
<td>P/N-a</td>
<td>5.2</td>
<td>B</td>
<td>3.8</td>
</tr>
<tr>
<td>0.6</td>
<td>P/N-a &amp; b</td>
<td>2.5</td>
<td>C</td>
<td>36</td>
</tr>
</tbody>
</table>

* Anode disconnected during this test period.

** Negative value used to indicate current flow from deck steel to test rebar.

Note: S/I indicates silicon-iron anode and P/N indicates platinized niobium.

a) For position of anode or test rebar see Figure H-34.
b) Indicates the anode and test rebars adjacent to coated deck surface.
c) Test conditions same as indicated in Part a above.
### TABLE H-10

**Prototype Bridge-Deck-Section Resistance Tests—Conductive-Overlay Design**

<table>
<thead>
<tr>
<th>Anode Type and No.</th>
<th>Anode Resistance, ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At Time of Energizing</td>
</tr>
<tr>
<td></td>
<td>Initial</td>
</tr>
<tr>
<td></td>
<td>Rectifier</td>
</tr>
<tr>
<td></td>
<td>At Completion of Testing</td>
</tr>
<tr>
<td>S/I a</td>
<td>6.7</td>
</tr>
<tr>
<td>P/N b</td>
<td>3.8</td>
</tr>
<tr>
<td>P/N a &amp; b</td>
<td>1.8</td>
</tr>
<tr>
<td>Between P/N a &amp; b</td>
<td>7.4</td>
</tr>
</tbody>
</table>

^a) This measurement of the circuit resistance between anodes a and b indicates change in conductive layer resistance.

^b) Based on this value (2.9 ohms) the calculated specific resistivity of the overlay material is 30.5 ohm - cm; whereas the value obtained in the laboratory on a Marshall specimen of this overlay material is <1 ohm - cm.

**Note:**
- S/I indicates silicon iron
- P/N indicates platinized-niobium

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![Figure H-49. Sacrificial-anode-test installation methods.](image)

**A. METHOD I**  
(Existing Deck)

**B. METHOD II**  
(Existing Deck)

**C. METHOD III**  
(New Deck)
Figure H-50. Plot plan of sacrificial-anode test arrangement.

Figure H-51. View of the sacrificial-anode-test top rebar mat before pouring the top concrete layer. White bars are the polystyrene pads.
areas (Fig. H-50) served two purposes in this test: (1) the anodes extended through the plexiglass wall (see Fig. H-51) into the open space where the electrical connection between the anodes and the rebars was made, and (2) the ends of each anode in the deck area were visible and could be observed.

To permit a meaningful analysis of the current produced from the anodes in this test, several important steps were taken in the installation phase. The first was to cut the top rebar mat into four equal segments. The segments were then divided with a plexiglass wall (see Fig. H-51). This arrangement gives electrical isolation of the Zn- and Mg-anode test areas from each other. Also, it permits physical and electrical separation (open area) between the wet and the wet and dry cycle test surfaces. During the test, the anodes of a given type (Mg or Zn), with a given installation method and deck surface condition, are connected to the transverse (top) rebars of the top mat in that section. Because each rebar in the analog model is electrically isolated from the others in the model, this arrangement gives electrical isolation of the rebars in a test area from other rebars in the deck. During the test, the rebars in each area are connected together and to those anodes installed in that area through a test panel.

After completion of the necessary advance work, the top 4-in. layer of deck concrete was placed to give the full 8-in. slab thickness. As with the other work described in this Appendix, the concrete was prepared and installed in accordance with the PennDOT specifications for reinforced bridge-deck concrete.

One week after placing the concrete, the balance of the anode installation work (Methods I and II) was performed. This work included placement of the anodes and associated backfill materials (see Fig. H-49). Gypsum-cement concretes from two different manufacturers were used. Table H-12 gives the details concerning the concrete mixtures, which were prepared and installed in accordance with the manufacturers' instructions. Several days after installing these anodes, the 2-in. layer of open-graded asphaltic concrete (see Table F-4 for aggregate fraction) was installed.

Table H-13 summarizes the current output from the anodes and the resultant polarized potentials on the rebars. The values given in this table were obtained four weeks after the test had started. The current value in Table H-13 is the average current output of the 5-ft-long ribbon anode and is obtained by dividing the total measured output of anodes in the group by the number of anodes. It was noted

**TABLE H-12**

<table>
<thead>
<tr>
<th>Backfill Designation</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Name</td>
<td>Duracal</td>
<td>Speedcrete</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>United States Gypsum Co.</td>
<td>Tamms Industries Co.</td>
</tr>
<tr>
<td>Type Used</td>
<td>Aggregated</td>
<td>Aggregated</td>
</tr>
<tr>
<td>Mix Ratio</td>
<td>1 Part Sand</td>
<td>1 Part Sand</td>
</tr>
<tr>
<td></td>
<td>1 Part Pea Gravel</td>
<td>1 Part Pea Gravel</td>
</tr>
<tr>
<td></td>
<td>1 Part Duracal</td>
<td>1 Part Speedcrete</td>
</tr>
<tr>
<td>Water Per</td>
<td>1-3/4 Gal/150 lb</td>
<td>1-3/4 Gal/150 lb</td>
</tr>
<tr>
<td>Gypsum Cement</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure H-52 shows the Zn-ribbon anodes on the deck prior to covering them with the asphaltic concrete. A 2-in. compacted thickness of asphalt was used. This material was purchased from a local supplier, who prepared it in accordance with the previously mentioned specification. The compacting procedure was the same as that described for the prototype deck. Figure H-53 shows the over-all view of the completed sacrificial-anode test arrangement.

Upon completion of the anode installation, the anodes were connected electrically through the panelboard to the appropriate rebars. Current from the ribbon anodes was measured by a voltage drop across a 0.1-ohm shunt installed in series between each group of anodes and the deck steel. Usually, the anode current and rebar potential were measured once each week in the wet surface test area and twice each week in the wet and dry (cycle) surface test area. The latter measurements were obtained the day before wetting the deck and the day after.

At the time of each current determination the potential of the deck steel in the corresponding areas was also measured. The potential measurement was obtained with the equipment and "instantaneous off" procedure similar to that described earlier in this Appendix. Initially, the potential measurement was made at three equally spaced locations along the 5-ft length of rebar with the Cu/CuSO₄ half-cell placed on a sponge on the surface of the deck over the rebar. In addition, a probe measurement, with the SCE electrode in a hole reaching to a point near the rebar surface, was made at the midpoint of the rebar. Later in the investigation, it was learned that the SCE value (converted to Cu/CuSO₄ scale) was representative of rebar potentials across the length, and these measurements were discontinued.
Figure H-52. Zinc-ribbon anodes representing installation Method 1. The concrete deck surface is coated with the asphalt tac-coat prior to placing the asphaltic concrete.

Figure H-53. Over-all view of the sacrificial-anode test deck after completion of the various installations.
### TABLE H-13
SUMMARY OF SACRIFICIAL-ANODE TEST RESULTS

**a. Wet and Dry Surface Condition**

<table>
<thead>
<tr>
<th>Method No.</th>
<th>Mg Ribbon Anode</th>
<th>Zn Ribbon Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td></td>
<td>Avg I, mA</td>
<td>Avg E, mV</td>
</tr>
<tr>
<td>I</td>
<td>21.8</td>
<td>1170</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>32.1</td>
<td>890</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>13.9</td>
<td>580</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>405</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**b. Wet Surface Condition**

<table>
<thead>
<tr>
<th>Method No.</th>
<th>Mg Ribbon Anode</th>
<th>Zn Ribbon Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg I, mA</td>
<td>Avg E, mV</td>
</tr>
<tr>
<td>I</td>
<td>25.1</td>
<td>1230</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>920</td>
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<tr>
<td>II</td>
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<td>1100</td>
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<tr>
<td></td>
<td>11.1</td>
<td>580</td>
</tr>
<tr>
<td>III</td>
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<td>400</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>260</td>
</tr>
</tbody>
</table>

*a) Current per 5-foot anode ribbon.

b) Potential measurement made with electrode at center of the rebar and close to rebar surface. Value is negative to CuSO₄ halfcell.

c) With asphaltic-concrete overlay.

that the 6-in. anode spacing gives about a 10-percent current derating factor because of mutual interference effects. In most cases, current output from a single anode in a given group compared well with current from other anodes in that group. This result reflected a uniform and stable environment of the anodes and the rebar cathode in this test. Further, no particular difference in current output was noted with anodes in the two gypsum-cement types used. Therefore, it is concluded that these materials will perform in a similar manner with respect to anodes.

It can be seen from Table H-13 that the current output from the Mg anodes was higher than that from the Zn anodes. This was expected because of the higher (4 times) driving voltage of Mg as compared with that of Zn (see Table F-6). This result also demonstrates an important advantage of Zn in the present application. Zn has a potential of $-1100$ mV$_{CuSO_4}$, which is above that needed to protect the rebars ($-770$ mV$_{CuSO_4}$) and below the hydrogen-reaction potential of $-1170$ mV$_{CuSO_4}$. This means that no matter how low the circuit resistance between the Zn and the rebar becomes, during periods when copious amounts of water and chloride are present on the deck, the current output from the Zn is controlled by the oxygen reaction (as opposed to hydrogen reaction) and, therefore, by the amount of available oxygen at the rebars. It is of interest to note in Table H-13 that the current outputs (32 to 21 mA) from the Mg are much greater than those from Zn anodes (6 to 3 mA), in each case with rebars that have protective potentials. This self-limiting aspect prevents wasteful current production and gives the anodes a more predictable life.

On the other hand, it can be said that the higher potential ($-1800$ mV$_{CuSO_4}$) of Mg is needed when circuit resistance is high. Table H-13 shows that, with Method II (embedded anodes), the current produced by Mg was adequate for rebar protection, whereas the current from Zn was not. It is reasonable to assume, however, that, as salt penetrates deeper into the concrete, the Zn will produce more current. A comparison of results obtained from Method II, with and without the asphaltic-concrete overlay, supports this opinion. Those anodes in concrete, covered with asphalt, produced more current than those in concrete without the cover. This is a reflection of moisture retention under the overlay, which, in turn, caused increased moisture penetration into the concrete.

Results obtained with Method III also reflect a lack of salt penetration into the concrete. Potential values for the rebars (Method III, Table H-13) in several cases did not change from their original value, and the others changed only slightly. The results relative to the test of Method III are inconclusive.

The data (part a of Table H-13) show that one week of deck drying has little effect on the current input from the anodes and the rebar potentials. At the end of 4-weeks'
testing, the application of NaCl solution was stopped to investigate the effect of an extended drying time. No significant current or potential change occurred during the first two weeks of no deck wetting. Thereafter, both the current and rebar potentials dropped slowly to the 4-week values given in Table H-14. These results suggest that, during a prolonged dry spell, the anode current output can drop below the minimum required to provide cathodic protection; but, if the deck is wet at least once every 2 to 4 weeks, the system should work well.

From the physical damage aspect, all systems performed well except Method I with Mg anodes. It was believed that the porous nature of the asphalt would absorb the corrosion products. However, after about 3 weeks in test, a slight heaving was noticed in the asphalt over the Mg anodes (Method I). Thereafter, this heaving increased until, after 6 weeks of testing, it was apparent that cracks were forming in the asphalt. No signs of physical damage were noted with the Zn anodes installed by using the Method I procedure. This, no doubt, is because the Zn corrosion products are more soluble than the Mg corrosion products and, therefore, were absorbed by the overlay.

Over-all, the results of this test show that a Zn-anode design, consisting of ribbon anodes installed on the deck and covered with an open-graded asphaltic concrete, is promising. Analysis of this design (Method I), using the mathematical model, indicates that one 0.25-lb/ft Zn ribbon placed every 12 in. across the deck will be a suitable design on a full-section deck. Assuming a rebar surface area of 0.5 sq ft/sq ft of deck surface and a cathodic-protection current density of 1.0 mA/sq ft of rebar gives the calculated life of the Zn-anode system as:

\[
\text{Life (yr)} = \frac{\text{Weight (lb)}}{\text{Current Output (A)} \times \text{Anode Capacity (lb/A-yr)}}
\]

\[
\text{Life} = \frac{0.25}{0.0005 \times 25} = 20 \text{ years}
\]

TABLE H-14
SACRIFICIAL-ANODE CURRENT AND REBAR POTENTIALS DURING DRYING PERIOD

<table>
<thead>
<tr>
<th>Method No.</th>
<th>Mg Ribbon Anode</th>
<th>Zn Ribbon Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave</td>
<td>Ave</td>
</tr>
<tr>
<td></td>
<td>I, mA</td>
<td>E, mV</td>
</tr>
<tr>
<td>I</td>
<td>21</td>
<td>1220</td>
</tr>
<tr>
<td>II</td>
<td>27</td>
<td>990</td>
</tr>
<tr>
<td>III</td>
<td>6.6</td>
<td>820</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>605</td>
</tr>
</tbody>
</table>

b. Deck Area with Previous Wet Surface Condition

<table>
<thead>
<tr>
<th>Method No.</th>
<th>Mg Ribbon Anode</th>
<th>Zn Ribbon Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave</td>
<td>Ave</td>
</tr>
<tr>
<td></td>
<td>I, mA</td>
<td>E, mV</td>
</tr>
<tr>
<td>I</td>
<td>16</td>
<td>1220</td>
</tr>
<tr>
<td>II</td>
<td>24.6</td>
<td>1030</td>
</tr>
<tr>
<td>III</td>
<td>22.6</td>
<td>985</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>395</td>
</tr>
</tbody>
</table>

a. Current per 5-foot anode ribbon.

b. Potential measurement made with electrode at center of the rebar and close to rebar surface. Value is negative to Cu/CuSO₄ halfcell.

c. Method II with asphalt cover.
SUMMARY OF PROTOTYPE TESTS

The studies with impressed-current cathodic protection showed that a conductive-layer design is best for distributing the current over the bridge deck. Two different thicknesses of electrically conductive asphaltic concrete in combination with different anode arrangements were tested. In general, all combinations work well and anode spacings of up to 30 ft appear possible with a 2-in. conductive layer and of up to 15 ft with a thin (0.5 in.) layer. Embedment of a wire anode in the concrete (without overlay) did not work well. With this approach, an anode spacing of 2 ft and a high applied voltage and current are necessary.

Measurement of rebar potential over the conductive layer showed that the usual procedure gives excessively negative values. Drilling a hole through the conductive layer, and placing the reference half-cell in contact with the deck concrete (under the conductive layer), gives correct values. When surveying a deck with a conductive overlay, this procedure is necessary at several select locations in the deck to adjust potential readings measured in the normal way.

Over-all results with the impressed-current approach show that this method is practical and that corrosion of rebars in the top mat of the bridge deck will be controlled by applying low voltage and current. Should control of impressed current, during periods when the deck is either very wet or very dry (changing resistance), be difficult, the use of a rectifier that automatically regulates output voltage to compensate for changing resistance would be a solution to this problem. The average current density for corrosion control, expressed in terms of square feet of deck surface, was about 2 mA/sq ft. This value is believed to be somewhat high; however, with continued application of current, the rebars will be polarized and current densities will be reduced to a fraction of this value.

The demonstration of the sacrificial-anode method showed that a Zn-ribbon design is promising. With this method, Zn ribbons are distributed on the deck and are overlayed with asphaltic concrete. Sufficient current for cathodic protection can be generated by using a 1-ft ribbon spacing across the deck. The life of the ribbon is calculated at 20 years. Although prolonged dry periods will result in loss of anode current, the effect is not immediate, and it is believed that under normal weather conditions the production of current will be steady.
THE TRANSPORTATION RESEARCH BOARD is an agency of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 150 committees and task forces composed of more than 1,800 administrators, engineers, social scientists, and educators who serve without compensation. The program is supported by state transportation and highway departments, the U.S. Department of Transportation, and other organizations interested in the development of transportation.

The Transportation Research Board operates within the Commission on Sociotechnical Systems of the National Research Council. The Council was organized in 1916 at the request of President Woodrow Wilson as an agency of the National Academy of Sciences to enable the broad community of scientists and engineers to associate their efforts with those of the Academy membership. Members of the Council are appointed by the president of the Academy and are drawn from academic, industrial, and governmental organizations throughout the United States.

The National Academy of Sciences was established by a congressional act of incorporation signed by President Abraham Lincoln on March 3, 1863, to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance. It is a private, honorary organization of more than 1,000 scientists elected on the basis of outstanding contributions to knowledge and is supported by private and public funds. Under the terms of its congressional charter, the Academy is called upon to act as an official—yet independent—advisor to the federal government in any matter of science and technology, although it is not a government agency and its activities are not limited to those on behalf of the government.

To share in the tasks of furthering science and engineering and of advising the federal government, the National Academy of Engineering was established on December 5, 1964, under the authority of the act of incorporation of the National Academy of Sciences. Its advisory activities are closely coordinated with those of the National Academy of Sciences, but it is independent and autonomous in its organization and election of members.