278

NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **278**

CATHODIC PROTECTION OF CONCRETE BRIDGE SUBSTRUCTURES

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **278**

CATHODIC PROTECTION OF CONCRETE BRIDGE SUBSTRUCTURES

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

STRUCTURES DESIGN AND PERFORMANCE
MAINTENANCE
(HIGHWAY TRANSPORTATION)
(PUBLIC TRANSIT)
(RAIL TRANSPORTATION)
(AIR TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
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WASHINGTON, D.C. OCTOBER 1985

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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.

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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.

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FOREWORD

By Staff
Transportation Research Board

This report will be of interest to bridge maintenance engineers, materials engineers, researchers, and others concerned with arresting chloride-induced corrosion of reinforcing steel in concrete bridge members. The research was directed at developing a suitable cathodic protection system for steel reinforcement, excluding the top reinforcement in bridge decks and reinforcement below soil or water. Laboratory investigations were conducted to choose a material for use as a secondary anode in the cathodic protection system. Based on these tests, a conductive coating was selected, and a cathodic protection system was applied to an actual bridge pier. Three variations of primary anode placements were also incorporated into the eventual cathodic protection system that was evaluated. Early results show promise.

Steel in concrete bridge members corrodes as a result of chlorides in the concrete. Continued corrosion of the steel causes the concrete to crack and spall as evidenced by the well-known bridge deck problem. Cathodic protection has been demonstrated to be an effective means of controlling corrosion in the top mat of reinforcement in bridge decks. However, other concrete components of bridges also suffer from the ingress of chlorides from deicing chemicals or from the presence of a marine environment. Corrosion of reinforcing steel occurs in beams, piers, and abutments exposed to salt (i.e., chloride) from surface run-off, especially from improper bridge drainage and sprays or plowed snow during winter months as well as the more obvious conditions of the marine environment. Awareness of this problem has increased in recent years as indicated in a survey of states performed by a previous NCHRP contractor. Therefore, techniques and materials need to be developed and evaluated for controlling corrosion in other concrete bridge members.

A previous NCHRP study initiated progress toward the development and evaluation of cathodic protection to control corrosion of steel in chloride-contaminated structural members (excluding top steel reinforcement in decks and steel in members below water or soil). However, the findings of the initial effort were not yet suitable for widespread implementation of a cathodic protection system for substructures—suggesting further research.

Under NCHRP Project 12-19B, "Cathodic Protection of Concrete Bridge Structures," the firm of Wiss, Janney, Elstner Associates, Inc. was assigned the objectives of additional laboratory investigations aimed at further development of a cathodic protection system and a field evaluation of an actual installation. Laboratory studies were performed, and a cathodic protection system was installed on a reinforced concrete bridge pier and then monitored. Although monitoring under the NCHRP study lasted only one-year, the researchers report a great deal of promise for substructure cathodic protection.

The methods of affixing the anodes to the bridge pier constituted three variations in the cathodic protection system. However, the secondary anode, i.e., a conductive coating, was the same throughout. The selection of this conductive coating was based on the laboratory testing of two promising materials identified from the previous NCHRP study and a third product that was being evaluated at the time by the Florida Department of Transportation. The laboratory studies indicated that the Florida material optimized the properties of conductivity and durability. However, readers should be aware that since the inception of this project, other materials and methods are appearing and some are being evaluated by state DOT's under FHWA's Demonstration Project No. 923, "Cathodic Protection of Substructures." It is therefore suggested that individuals interested in the application of cathodic protection use this report for guidance and also consult with the FHWA for on-going developments.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 12-19B by Wiss, Janney, Elstner Associates, Inc. (WJE) and Kenneth C. Clear, Inc. WJE was the prime contractor for this study, with Kenneth C. Clear, Inc. acting under a subcontract with WJE.

William F. Perenchio, Senior Consultant, and J. Robert Landgren, Consultant, WJE, were co-principal investigators. The other authors of this report are Kenneth C. Clear, President, Kenneth C. Clear, Inc., and Robert E. West, Senior Consultant, WJE.

The work was done under the general supervision of Messrs. Perenchio, Landgren, and Clear. The laboratory work at WJE was carried out under the supervision of Mr. Landgren. The laboratory/field work on the large FHWA slab was done under the supervision of Mr. Clear. The field work in Rosemont, Illinois, was done under the supervision of Messrs. Perenchio, Landgren, and Clear. Mr. Perenchio was responsible for general administration of the project.

CATHODIC PROTECTION OF CONCRETE BRIDGE SUBSTRUCTURES

SUMMARY

Concrete structures in a corrosive environment undergo accelerated deterioration where deleterious chemical substances, particularly chloride ions, penetrate the concrete and cause corrosion of the embedded reinforcing steel. Accumulation of corrosion products around the reinforcing steel causes cracks to develop in the protective concrete cover, allowing intrusion of additional deleterious material and thereby accelerating corrosion, causing spalling, and diminishing the structural integrity of the member. Considerable attention has been directed to deterioration of bridge decks caused by deicing salts. Deterioration also often is caused by faulty bridge deck drainage that permits chloride contamination of other structural members by deicing salts from the decks. In a marine environment, chloride penetration can affect all bridge members, including piles, caps, girders, and diaphragms, as well as decks.

Cathodic protection has been demonstrated to be a reliable means of controlling corrosion in the top mats of reinforcement in bridge decks. However, application of this protection to vertical surfaces has been hampered by the lack of a suitable means for spreading the protective electrical current over the surface. NCHRP Project 12-19 identified several brands of conductive coatings or paints which showed promise. The present study first evaluated the durability of three of these materials by laboratory testing. One of these appeared to possess the required resistance to wetting and drying, freezing and thawing, ultraviolet radiation, etc., and was therefore used in a prototype installation on an existing distressed highway bridge pier in Illinois.

After initial results of the laboratory work indicated that one of the three conductive coatings would be superior to the other two in performance, a simulated field application of cathodic protection (CP) was made on a large slab cast earlier in the FHWA laboratory. Its performance was then monitored to develop information of general interest as well as to generate findings with respect to use in the design of the CP system for the field installation.

After one full year of operation the prototype system appears to be functioning well. Initial concern over possible loss of the coating due to rapid escape of chlorine gas from the concrete or acid generation beneath the coating appears to be unfounded. Although some loss of coating was observed, it amounted to less than 1 percent of the surface area of the pier.

Although no practical direct evaluation of the effectiveness of a cathodic protection system is available, the indirect measurements of cathodic polarization of the steel and current received by discrete sections of reinforcing bars used as probes indicate that the prototype system is functioning well. The research team believes that the system should be installed in additional full scale trials because it offers a relatively low cost solution to a serious problem in concrete bridge maintenance.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

A large number of concrete bridge structures in many areas of the United States are suffering distress caused by corrosion of the embedded reinforcing steel. The first awareness of this problem was raised by the development of delaminations and spalls in the wearing surfaces of decks. However, soon afterward, the same type of distress was noted in piers, abutments, beams, diaphragms, and the bottom surfaces of decks. Similarly, cathodic protection (CP) systems were developed first for applications to bridge decks (*1*), but interest in developing systems suitable for the other members of concrete bridges soon followed.

In 1976, both the California and Oregon highway departments submitted problem statements on the subject to the NCHRP, which resulted in the convening of Project Panel C12-19. Project 12-19 was awarded to Corrosion Engineering and Research Company late in 1977. The results of that study produced a state-of-the-art report on cathodic protection and identified a number of conductive coatings which appeared to have promise in spreading protective electrical current over the surface of concrete.

While NCHRP Project 12-19 was still in progress, Project 12-19A was awarded to Wiss, Janney, Elstner Associates. This project consisted of evaluating various sealers for their ability to restrict the ingress of salt water but allow the passage of water vapor out of concrete.

NCHRP Project 12-19B, initiated in late 1982, was designed to develop the use of conductive coatings as secondary anodes for the cathodic protection of concrete bridge substructures. Laboratory and field studies were carried out to demonstrate the efficacy and durability of a complete impressed current cathodic protection system using a conductive coating.

BACKGROUND AND CURRENT KNOWLEDGE

A questionnaire sent out to state departments of transportation in a previous study (*2*) was returned by 41 of the 50 states, all of whom reported having problems brought on by corrosion. Of these, 28 had used concrete surface sealers in an attempt to stop or at least minimize the corrosion. Although this study of concrete sealers identified several materials that were capable of greatly reducing the ingress of salt water while still allowing some passage of water vapor out of the concrete, later work at the Federal Highway Administration (FHWA) (*3, 4*) suggested that such surface treatments were only marginally effective in reducing the corrosion rate of embedded steel. Additional work, funded by the FHWA and private industry, but being carried out at the laboratories of Wiss, Janney, Elstner Associates, Inc. (WJE), has indicated a much greter degree of effectiveness. Leaders in the field of corrosion control of embedded reinforcing steel currently believe strongly, however, that the only certain method for arresting corrosion is cathodic protection. Indeed, a report (*5*) prepared in February 1984 by the FHWA entitled, "A Manual for the Corrosion Control of Bridge Decks," discusses cathodic protection in detail. Although sacrificial anode systems have been studied (*6*), and are currently in use on concrete structures partially immersed in sea water, the manual and current practice for bridges are essentially limited to impressed current systems.

The major differences between various impressed current cathodic protection systems are the means by which the current is distributed over the outside surfaces of the concrete. One widely used system for bridge decks covers the whole wearing surface with a layer of conductive asphaltic concrete. Other systems for bridge decks conduct the protection currents with a grid of closely spaced conductors located in slots cut in the deck or fastened to the surface of the bridge deck and then covered with a thin bonded concrete overlay.

Developments of cathodic protection systems for vertical surfaces on bridge structural elements seem to be paralleling those of bridge decks. This study was made using a paint-like conductive coating material covering virtually all outside surfaces of a bridge pier. Other conductive surface coating materials applied directly over all surfaces of bridge substructures are also being investigated. For example, the California Department of Transportation (*7*) is studying the use of flame-coated metal films deposited on the outer surfaces of structures. Another system for applying cathodic protection currents to bridge subtructures uses a grid of conductive polymer wire-like primary anodes fixed to the concrete surface and covered by an overlay of shotcrete (*8*).

RESEARCH APPROACH

The overall objective of this study was to continue along the general lines of development pursued in NCHRP Project 12-19, which was to establish a viable cathodic protection system for concrete bridge structural elements other than the top surface of decks. The study consisted of two major phases and a secondary phase.

The first phase was the laboratory study. That study evaluated the resistance of three conductive paints to damage when exposed to freezing and thawing, alkalies, wetting and drying, ultraviolet light and thermal cycles. Also evaluated was the change in resistivity of the surface concrete in the first 1½ in. below the coating with drying time, the effect of film cracking on conductivity and the bonding of the coatings to concrete and a decorative cover coat to the conductive paints.

The secondary phase of work consisted of tests performed on a large slab produced earlier in the FHWA laboratory and exposed to the weather. The slab was made of concrete which contained either no chloride or large amounts of chloride driven in by impressed current. It also contained a great deal of instrumentation in the form of thermocouples, corrosometers, current pickup bars, and ground wires. Top and bottom mats of steel were not connected electrically within the slab, but could be connected externally by means of existing lead wires. A conductive coating cathodic protection system was designed for the slab, based on tests which established its current condition, which was then monitored with time and changing conditions, both natural and artificial. Information gained in the study of this slab was used in designing the cathodic protection system for the prototype pier.

The second (major) phase of the study was the design, installation, and monitoring of a cathodic protection system, based on the conductive paint identified in the laboratory phase as most durable, for an existing concrete bridge structural element in distress due to corrosion of embedded steel. Several states indicated willingness to cooperate; however, Illinois was chosen for convenience. (The bridge is located adjacent to O'Hare Airport and approximately 15 miles from the WJE offices). The east pier of the bridge, which carries the eastbound John F. Kennedy expressway over River Road in suburban Rosemont, Illinois, was selected also because of its advanced state of distress as shown in Figure 1.

Once the pier had been selected, an initial condition survey was conducted. This included a visual survey with photographic documentation, a delamination survey, and a copper-copper sulfate half-cell potentials survey. Also determined at selected locations were depth of concrete cover over the reinforcement, chloride content of the concrete at various depths down to the depth of the reinforcement, and electrical continuity of the reinforcing steel.

A cathodic protection system then was designed, based on the laboratory and FHWA slab findings, the results of the initial condition survey, and previous experience. The design was then submitted to the NCHRP review panel for comments and suggestions, which were included where appropriate.

After structural repairs were made, along with embedment of necessary instrumentation such as the macrocell probe, the current pickup bar probes, and ground connections to the reinforcing steel, the cathodic protection system was installed. This consisted of applying the conductive and decorative coatings (following light sandblasting to prepare the concrete surface) and installing the primary anodes, the junction boxes, transformers, and rectifiers.

Before the conductive coating was applied, areas were masked with duct tape to separate the pier into eight separate electrical zones, to prevent shorting of the coating to the beam bearing pads and to provide bare spots surrounding each of the points used for copper-copper sulfate half-cell determinations. The necessary electrical connections were then made and static electrical potentials, current to current pickup bars, CP system AC resistance, etc. were measured.

Following installation of the system components and determination of static electrical values, E log I tests were done. Separate tests were made for each of the eight electrical zones of the pier. These zones consisted of the three columns, three sections of the cap, and two halves of the base. After these test data were analyzed, the zones were activated to the current levels indicated, and their performance was monitored, on an approximately bi-monthly basis. The system was deactivated and depolarization measurements were made on two occasions.

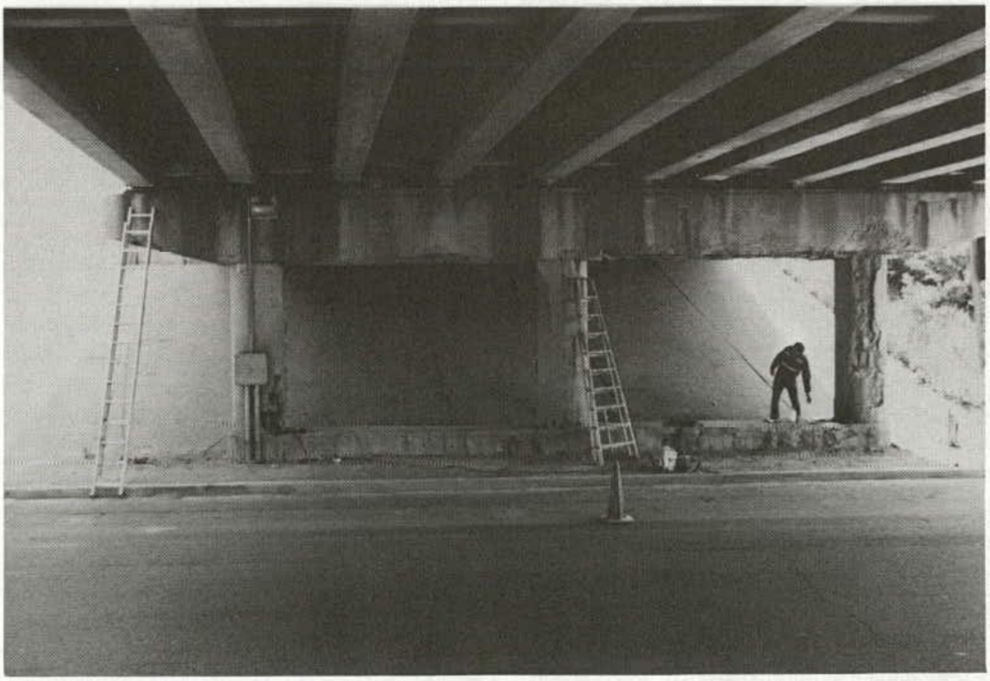

Figure 1. Condition of Rosemont Pier before repair.

CHAPTER TWO

FINDINGS

LABORATORY EVALUATION OF COATINGS—PHASE I

A durable, weather-resistant conductive coating is required to serve as a secondary anode to spread current uniformly over the surface of a concrete structure which is being cathodically protected. Before field work was undertaken, a laboratory evaluation was made of the performance of three candidate conductive coatings. Candidate coating A, a solvent-based acrylic "mastic" filled with graphite, was suggested by work done by the Florida Department of Transportation. Two other coatings which were evaluated had been identified during NCHRP Project 12-19. Conductive coating B is a water-based acrylic coating filled with graphite. Coating C is a latex-based coating filled with carbon.

The three conductive coatings were applied to small concrete slabs and tested for resistance to freezing and thawing, to cycles in a tank of cool water alternating with periods in a 140 F drying oven, and to ultraviolet exposure. Changes in the electrical resistance of surface concrete directly beneath the conductive coatings were determined as coated concrete specimens were continuously air-dried and subjected to rewetting. The effects of cracking of the coatings upon coating electrical conductivity were also evaluated. The results of these tests are described briefly in this chapter.

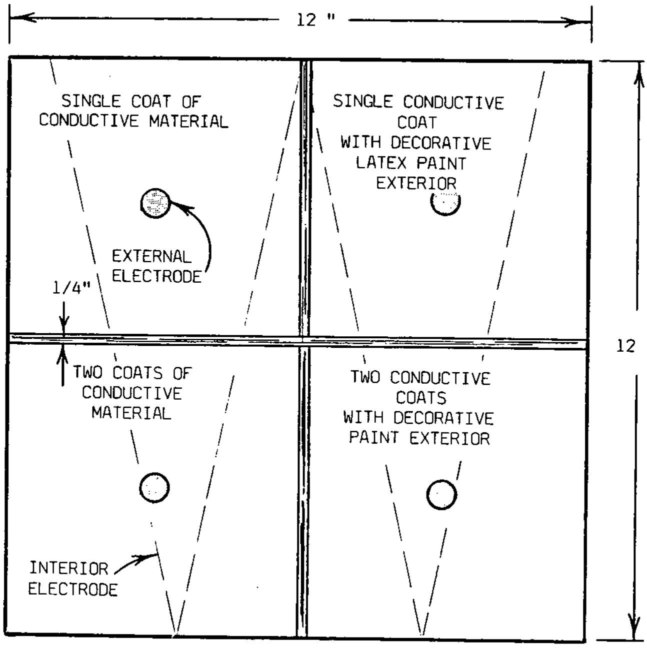

Figure 2. Coating configuration for concrete test slabs.

Laboratory Slab Coatings

Small air-entrained concrete slabs with a nominal 28-day concrete compressive strength of 4,000 psi were prepared for the laboratory tests. One face of each slab was coated as follows. Half of each 1-ft square slab face was coated with one layer of the conductive material applied in the thickness recommended by the manufacturer. The remaining half of the coated slab face was coated with an additional equal thickness of the conductive coating material. After drying, a light-colored decorative paint was applied to half of each coated area in the thickness recommended by the paint manufacturer. Typical slab coatings are shown in Figure 2.

Freeze/Thaw Tests

As a means of determining the durability of the conductive coatings when applied to concrete, slabs of concrete 1 ft × 1 ft × 2 in. were coated on the 1-ft square face and then exposed to 100 cycles of freezing and thawing.

The freeze/thaw specimens were frozen and thawed, with water ponded on the coated surfaces, once a day. The specimens were rated visually and photographs were taken periodically throughout the testing. At the end of 100 freeze/thaw cycles, test results indicated the following:

1. Coating A performed very well. No significant loss of bond occurred between that coating and the surface of the concrete slab, between the two layers of conductive coating material, or between the conductive coating and the decorative latex paint.

   The freeze/thaw durability of slabs coated with material A was clearly superior to the durability of slabs coated with the other two conductive coatings.

2. Coating B deteriorated rapidly during freeze/thaw testing. Early loss of bond occurred between the two layers of the conductive coating material and between the conductive coating and the decorative paint overcoat. After 100 cycles of freeze/thaw very little conductive coating B remained bonded to the concrete, except for the material which had penetrated into the concrete pores.

3. From 5 to 30 percent of the slab areas coated with conductive coating C had spalled away from the concrete surface after 100 cycles of freeze/thaw testing. The freeze/thaw durability of this material was significantly improved when it was covered with 1 coat of decorative latex paint, although such covered areas still experienced limited bond loss, particularly at the edges of the painted sections.

Wetting and Drying, Heating and Cooling Tests

Laboratory tests were made to determine if alternating exposure to a wet and cool environment followed by drying at an elevated temperature would affect the bond of the coatings to concrete and to each other.

Coated slabs were soaked in saturated limewater for 3 days and then dried in an oven at 140 F for 4 days. After 50 cycles of this alternate wetting and cooling-heating and drying testing, no visible distress was apparent on any of the test specimens. Tensile bond tests also indicated that the bond strength between all coatings and the substrate concrete remained high at the conclusion of this testing.

After cycling, one set of specimens was left in the limewater bath for a month. Specimens coated with conductive materials A and C were not affected by the prolonged soaking. Specimens coated with material B developed a significant number of large water-filled blisters between the decorative paint and the conductive coating.

Exposure to Ultraviolet Light

Ultraviolet light is known to deteriorate organic materials, such as the conductive coatings and decorative paints contemplated for use in this project. Coated slabs were stored beneath a concentrated source of ultraviolet light (UV) for approximately 3 months to determine if this exposure deteriorated the bond between the conductive coating and the surface of the concrete slab. It is believed that this exposure is equivalent to exposure to natural sunlight for over one year.

Bond strengths of UV-irradiated slab areas coated only with the conductive coatings were similar to those obtained on control samples earlier in the laboratory work. Bond strengths of UV-irradiated slab areas coated with both the conductive coating and the light-colored decorative paint were from 1¼ to 1½ times as high as those of the control samples. Additional curing of both the concrete and the coatings probably was responsible for this increase in bond strength. The data indicate that a light-colored outer layer of decorative paint does protect the underlying conductive coating from the moderate deterioration due to ultraviolet light exposure which would otherwise occur.

Electrical Resistance of Surface Concrete

The electrical resistance of concrete immediately beneath conductive coatings has an important bearing on the amount of current and/or voltage required for the cathodic protection system. For example, concrete with a high electrical resistance interposed between the conductive coating at the surface and the reinforcement may require high CP system driving voltages. Furthermore, variations of concrete electrical resistance as a function of concrete moisture content or humidity may cause significant variations in the voltage-and-current parameters of the CP system. To explore these factors, a limited test series was initiated to determine the effects of drying and resaturating coated specimens upon the electrical resistance of concrete between the conductive coating and grid of platinum-niobium coated wire in the plane 1½ in. beneath the conductive coating. A typical test specimen is illustrated in Figure 2.

Except for the slab face coated with the conductive materials, all surfaces of these 6 in. deep slabs were coated with a penetrating epoxy sealer to prevent drying through any but the coated surface. Concretes for these surface-resistance slabs contained 1.5 and 15 percent admixtured chloride by total weight of concrete. During a prolonged drying period of approximately 18 months, it was found that:

1. Specimens made with the high content of chloride had an electrical resistance approximately one-tenth that of similar specimens made with concrete having a low chloride content.
2. Air-drying at 73 F and 50 percent RH increased the electrical resistance of the concrete beneath the conductive coatings. The resistance increase was approximately linear with time.
3. Additional coats of either conductive coating material or of decorative latex paint decreased the rate at which air-drying increased the electrical resistance of the concrete beneath the coatings.

After prolonged drying the test specimens were exposed to high humidities and then to remoistening. A short period of storage at 75 percent RH of the specimens dried at 50 percent RH for over a year reduced the resistance of the concrete beneath the coatings by approximately one-half. Resoaking the coated faces for periods as short as 15 min tended to drastically reduce the electrical resistance of the surface concrete.

The resistance tests indicated that prolonged drying significantly increased the electrical resistance of the surface concrete beneath conductive coatings, with and without a decorative paint overcoat. Increasing the relative humidity of the environment of the coated concrete or wetting the coated concrete surface decreased the electrical resistance of the surface concrete.

In summary, the data indicate that the resistance of concrete between conductive coatings on the surface and at a depth 1½ in. below the surface will vary inversely with the moisture of the environment. As a consequence, in a wet environment lower voltage drops will occur between a conductive coating and embedded reinforcement in a constant-current cathodic protection system or more cathodic protection current will flow in a constant-voltage cathodic protection system. Conversely, a drying environment will increase the coating-to-reinforcement voltage in a constant-current CP system, while the current will decrease in a constant-voltage CP system.

Effect of Cracks on Coating Conductivity

Laboratory experiments were conducted to determine the effects that cracks or other types of breaks in the conductive coating have upon the coating electrical conductivity through or around the crack. Cracks in the conductive coating layer were simulated by scribing full-depth channels with widths of from 0.01 to 0.07 in. through single-thickness layers of the conductive coatings.

The tests indicated that openings in the conductive coating as narrow as 0.01 in. increased the electrical resistance across the opening by as much as a factor of 100. This increase in resistance was caused when currents were forced to bypass the channels through high resistance concrete. If the break in the coating were caused by reflection of an open crack in the substrate concrete, the path length through concrete would be considerably longer than that caused in the tests. The increase in electrical resistance across a break in both the conductive coating and the crack in the concrete would be much larger than those encountered in the laboratory tests. These data emphasize that long, open cracks in the conductive coating will cause localized high electrical resistances, excessive voltage drops in the coating and possible loss of cathodic protection for the structure on the side of the crack away from the current source.

Selection of the Cathodic Coating for Field Tests

Coating A was selected for use in the field tests. This selection was made mainly because this coating was much more durable than the other two tested.

TESTS ON LARGE FHWA TEST SLAB—PHASE IA

The Federal Highway Administration generously made a large, heavily instrumented concrete slab available for the use of the research team for this project. The slab was located in their outdoor exposure site in McLean, Virginia. It had been used for a laboratory study in 1981. Most of the slab was relatively free of chlorides, while a small portion had been infused with chloride ion by impressed current.

Although partially demolished, repairs to the slab were readily made. It was convenient for use in an intensive study of an impressed cathodic protection system based on platinum and niobium clad primary anode wire and the conductive coating secondary anode identified as feasible in the laboratory study, Phase I (coating A).

Certain unique features of the slab promised to yield useful information. One area of the slab was slightly delaminated at the time of the test. Corrosion probes were already emedded in the slab and could be measured while the CP system was in place. Finally, the slab was reinforced with two unconnected layers of reinforcement which afforded a means of measuring the amounts of CP current applied to one face of the structure which would be pre-empted by the reinforcement layer nearest to, and furthest from, the conductive coating anode.

Following repairs, the CP system was installed and current requirements were determined through E log I testing. After the polarized (instant-off) potentials were measured, the rectifier was set at the appropriate current. Subsequently, the system performance was monitored throughout a 1.2 year period to determine changes in voltage and current with respect to changing climatic conditions. The durability of the coatings was also determined against natural weathering and the effects of current flow.

The E log I test procedures generally followed the methods proposed by Stratfull (*10*). Computer iteration (*10, 11*) was used to confirm which of several apparently linear portions of the E log I curve was appropriate and to determine the protective current to be applied to the slab. The CP rectifier was set to deliver the required protective current.

During the 1.2-year period of operation, average protective current delivered by the current-regulated rectifier to the top layer of reinforcing steel was reasonably constant, varying from 72 to 81 mA. During that period, current received by the top layer of reinforcement varied from 37 to 51 mA, while currents to the bottom layer of reinforcement varied from 29 to 37 mA. During this time, system voltages ranged from 4.6 to 2.4 volts. These data indicate that while the rectifier currents were reasonably constant, the variations in current received by the two layers of reinforcement were significantly more variable. Variations in voltage were greater still, which was expected because Ohm's law requires that changes in concrete resistance in a constant-current system will be compensated for by commensurate changes in voltage.

On the average, the top mat of reinforcement received 2.76 mA of protective current, while the bottom mat received an average of 1.59 mA of current per sq ft of steel surface.

The fact that the lower layer of reinforcement received approximately three-fourths of the current received by the upper layer of reinforcement is significant. The upper layer of reinforcement was located between the conductive coating anode and the bottom reinforcing layer, but was not capable of preempting all the current delivered by the CP system.

Rebar probes were located in chloride-free areas of the slab and in areas containing concrete with high chloride contents. On an average, probes in the chloride-free concrete areas received approximately one-fifth of the current delivered to probes in concrete areas with high chloride contents.

At various times, the CP system was shut down for an extended period to allow the structure to "depolarize" from operating potentials to "free corrosion" potentials. The first time this was done, the depolarization difference between instant-off and static potentials was 0.491 volts. When the system was finally shut down, depolarization potentials for the top reinforcing mat averaged 0.368 volts, while the lower reinforcing averaged 0.211 decreased volts. Further evidence that cathodic protection had decreased the tendency of the slab reinforcement to corrode were general observations that static half-cell potentials at the end of the testing period were less negative than at the beginning of the test period. Also, measured corrosion currents between the bottom and top reinforcing mats were significantly lower following the test period.

After a prolonged summer dry period, electrical properties of the slab were measured. Then the slab was wetted and the electrical properties were again determined. The partial wetting caused some decrease in system voltage, but had little effect on total operating current or the currents received by each of the two mats.

At the conclusion of the testing period, the condition of the conductive coating was evaluated. It was found that significant areas of conductive coating disbonded over areas of concrete with high chloride contents. None occurred in areas with low chloride contents. Although no formal tests were made, it did not appear that the bond failures were due to consumption of the coating by the CP system.

FIELD EVALUATION OF CATHODIC PROTECTION SYSTEM—PHASE II

In August of 1983, a cathodic protection system, using conductive coating A to spread current over the concrete surface, was designed and installed on a bridge pier in Rosemont, Illinois, after an initial evaluation of the condition of the pier. As shown in Figure 1, the pier was in an advanced state of deterioration because of waterborne chlorides penetrating a construction joint from the roadway above and spraying upwards from traffic below the bridge structure. Widespread spalling had exposed large areas of reinforcement on the pier while an area approximately equal to that of the spalls had delaminated concrete.

Before the structure was repaired, a survey was made of spalled and delaminated areas, the general condition of the exposed reinforcing steel, chloride contents of concrete in selected areas of the structure, and half-cell potentials over the surface of the pier.

The structure was repaired by employees of the Illinois Department of Transportation using, for the most part, ordinary repair procedures. Repairs involved removal of unsound concrete, chipping completely around the circumference of exposed reinforcing bar, sandblasting the surfaces of corroded reinforcing bars to bright metal and installing "helper bars" when loss of reinforcing bar cross section was excessive, reforming excavated areas to conform to original contours of the structure, and recasting the structure with an air-entrained 6½ bag per cubic yard concrete mixture containing a high range water-reducer.

During the repairs, instrumentation was embedded in cavities in the concrete. These were a "macrocell" and four "rebar probes," which were embedded in special concrete containing 15 lb of chloride ion per cubic yard of concrete. Two half-cell electrodes also were embedded in repair concrete. No. 14 solid copper ground wires were brazed to reinforcement before repair concrete was cast. The location of the various grounds and instrumentation was determined by the initial plan for cathodic protection—at least two grounds and either a macrocell or rebar probe were assigned to each of the four major pier "zones." The location of the four zones, each of which had a separate CP rectifier and instrumentation, is shown in Figure 3.

In an important departure from ordinary repair procedures, the repair crews were instructed to remove metal chairs and bolsters from intact concrete on the soffit of the pier beam. If left in place, these pieces of steel would constitute a short-circuit from the bottom reinforcement to the concrete surface coated with the conductive film. Such short-circuits waste power and, of more importance, cause steel in the area of the short-circuit to become anodic and undergo accelerated corrosion. An attempt was made to utilize magnetic detectors to locate possible steel short-circuits near the concrete circuit. However, it was found that surface steel which was detectable by the available instruments was also evident because of rust stains on the outside surface of the concrete. Care was taken to avoid repair practices which might result in introducing short circuits during the repair (i.e., use of chairs, form-ties that terminated at the surface, etc.). A vigorous search for, and elimination of, potential short-circuits between the face of the concrete structure to be coated with the conductive material and the structural reinforcement is essential for the success of the cathodic protection installation.

Following the casting and curing of the repair concrete, 117 volt AC power was brought to the pier and distributed to 4 fiberglass boxes which housed the CP instrumentation. These boxes contained terminals for all instrumentation wiring, the rectifiers to provide DC current for the CP system, and the rectifier control circuitry. When the control boxes were in place, the primary anodes were applied to the structure and terminated in the control boxes. Three different primary anode configurations were used in the structure. Configuration A consisted of a platinum-niobium plated, 0.03-in. diameter anode wire embedded in a conductive polymer placed in a saw kerf cut in the surfaces of the pier columns. Type B primary anodes consisted of anode wire embedded in a windrow of conductive polymer extruded on the surface of the concrete. Precast conductive polymer anodes (Type C) were cemented to the surface of the pier cap.

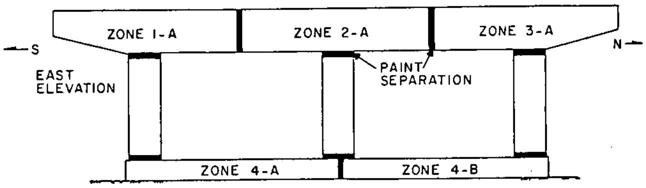

Figure 3. Conductive paint separations divide pier into cathodic protection zones.

Before conductive coating A was applied to the pier, critical areas of the pier surface were masked-off. Areas in which paint was not to be applied to the concrete surface were:

1. Small rust spots which indicated potential or actual short circuiting metal.
2. Two-inch square openings in the conductive coating to be used as locations for periodic half-cell potential determinations.
3. Strips around control boxes, metal lighting fixtures, and metal conduit leading to them.
4. Thin strips of bare concrete to isolate one cathodic protection "zone" from another.

The conductive coating was applied to the freshly sandblasted, clean and dry concrete surfaces with a conventional paint roller. It was no more difficult to apply than an ordinary paint. Application rate was 90 sq ft/gal of coating material.

An off-white exterior latex house paint was applied over the dried conductive coating film at a rate of 400 sq ft/gal.

The rectifiers utilized for the pier produced a half-sine wave pulsing DC current. This waveform was utilized to make "instant-off" measurements of polarized potentials during the "off" portion of the 60-hz waveform. E log I measurements were made at various high potential sites on the pier face in order to set rectifier current output at optimum values using procedures developed by Stratfull (*10*). After the rectifiers were initially set to deliver the appropriate current, it was not necessary to make further adjustments during the term of active testing of the pier cathodic protection installation.

Periodic measurements were made of the CP system to determine its performance over the span of 1 year. Measurements routinely performed were determinations of:

1. Voltage drop from the primary anode to reinforcing steel ground. This measurement was made using the AC scale of a high-quality digital voltmeter capable of measuring root-mean-square (RMS) electrical quantities.
2. Current delivered to each primary anode. This was calculated by Ohm's law from the measured IR voltage drop (AC RMS) across a precision resistor in series with the anode.
3. "Peak" and "back" voltages from the primary anode to the reinforcing steel ground. These voltages represent the maximum and minimum (or instant-off) voltages of the pulsing direct current waveform delivered to the CP system. An oscilloscope or a peak-reading voltmeter is necessary to obtain these data.
4. Copper-copper sulfate half-cell potentials were obtained at approximately 80 fixed locations on the structure. These deter-

minations were made before the CP system was activated and twice while the CP system was shut down and depolarized after approximately 6 and 11 months of system operation. Half-cell measurements also were made while the CP system was operating. These latter measurements had to be made using either an oscilloscope or a peak-reading voltmeter.

5. The DC potentials between both the macrocells and the rebar probes relative to the rebar network, as ground, were determined while the CP system was operating.

General observations about the performance of the bridge pier cathodic protection system after 1 year of service are as follows:

1. The primary anodes which were recessed in saw kerfs or windrowed above the concrete surface performed well.
2. The ends of the large precast primary anodes separated from the concrete of the cap to which they were cemented. Thermal incompatibilities between the concrete and the conductive polymer of the precast anodes probably caused the end separations.
3. No significant new concrete delaminations were detected after 1 year of the CP system operation.
4. The bond of the decorative latex paint to conductive coating A was excellent. No failures between them were observed on the pier.
5. Minor failures of bond between conductive coating A and the original structural concrete occurred during the first year of operation. The cause of these failures is uncertain.
6. Repair of the minor failures in the conductive coatings was a simple, fast operation.
7. Most electrical measurements confirmed that the CP system rectifiers delivered reasonably constant CP current.
8. As expected, while the CP system was operating, the half-cell potentials at the surface of the structure were driven to a more negative potential. Half-cell readings were ordinarily depressed by from 200 to 300 millivolts.
9. Mean half-cell potentials varied seasonally. Potentials measured in the winter and spring were generally higher than those measured at other times.
10. The embedded macrocell and rebar probes were always positive with respect to rebar ground, indicating that these instruments were receiving CP current and remaining in a noncorroding condition.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

GENERAL

The results of this project have demonstrated that cathodic protection systems based on conductive coatings are feasible for vertical and horizontal concrete members. Used in combination with platinum-coated copper primary anode wires spaced at relatively large distances (as much as 6 ft), such a system promises to be the least expensive method yet evaluated for spreading protective current over concrete surfaces.

The precursor to this study, NCHRP Project 12-19A, identified several surface coatings that are capable of largely preventing the ingress of salt water while still allowing vapor transmission. This is one approach to providing corrosion protection to repaired concrete structural units. Tests carried out at the FHWA laboratories in McLean, Virginia, have indicated that such surface sealer treatments are only marginally effective in reducing corrosion currents; however, very recent work in progress at the laboratories of Wiss, Janney, Elstner and sponsored by the FHWA and private industry indicate them to be extremely effective in this regard. In any case, most experts in the field of corrosion of steel in concrete agree that only cathodic protection can totally halt corrosion once it has started. Therefore, the development of an effective and inexpensive cathodic protection system is mandatory if concrete bridge structures are to be properly and economically maintained.

FHWA TEST SLAB

Work done with the CP system installed on the large FHWA slab produced considerable data of interest. The slab had a surface area of 37 sq ft, with two mats of reinforcing steel and current-induced chloride contamination in selected areas. The CP system was energized to a current level of 2.13 mA TRMS (true root mean square), as indicated by the E/log I test, per sq ft of concrete or 2.09 mA TRMS per sq ft of total reinforcing bar. Testing indicated that 43 percent of the total current was received by the bottom mat rebars. The average current densities were 2.76 mA/sq ft for the top mat and 1.59 mA for the bottom mat. However, current received by the top mat in chloride-contaminated concrete averaged several times higher than that in chloride-free concrete.

The CP system on the FHWA slab functioned very well throughout the test period with significant polarization of the reinforcing steel measured in all cases. The voltage required to maintain the constant current varied from 2.4 to 4.6 volts during the 1.2-year test period. Such a variation is not unusual for above-ground reinforced concrete CP systems subject to large temperature and moisture variations. Partial wetting tests in the summer months indicated that the CP system was not greatly affected when only a portion of the surface was wetted.

Some conductive coating loss did occur during the test program. It appeared that the deterioration occurred at the concrete/coating interface, and the conductive and overcoat paints became disbonded and eventually flaked off. Also, the deterioration appears to be directly related to the current density at the coating/concrete interface. One area operating at an estimated curent density of 13.5 mA TRMS per sq ft showed minor deterioration in 4 months and more widespread deterioration at 9 months. In other areas operating at current densities of 2.4 to 4.1 mA TRMS per sq ft, minor visual deterioration, but no significant paint disbonding, occurred at 1.2 years. The majority of the paint anode, however, which operated at estimated paint current densities of 1 mA per sq ft or less showed no deterioration throughout the test program. It is notable that the conductive coating deterioration did not have a significant effect on functioning of the CP system. Repair would be relatively easy and involve only wire brushing, light cleaning, and repainting of less than 10 percent of the slab surface. At the end of the test program, the cathodic protection system was turned off. When the static half-cell potential and macrocell corrosion current measurements, one month after deactivation, are compared to the "before CP" measurements, all indications are that the natural (i.e. no cathodic protection) corrosion rate of the rebar was greatly reduced because the CP system had been operated for 1.2 years.

ROSEMONT BRIDGE PIER INSTALLATION

Operation of the full-scale cathodic protection system on the Rosemont bridge pier for approximately 1 year also has produced very useful information.

The constant current rectifiers performed well during the monitoring period. Potential changes due to application of GP currents were generally more negative, as expected. All measurements of the macrocell and rebar probes indicated that these instruments were receiving CP current and were in a noncorroding condition.

The three different methods used for attaching primary anodes to the structure resulted in the very definite conclusion that these anodes should be restricted to small cross sections. They also should be cast-in-place to assure proper adhesion to the concrete. Because the bond failure of the large precast anodes strongly indicates that coefficient of thermal expansion mismatch between the polymer mortar and the concrete is a potential problem, serious considration should be given to imbedding the anodes in saw kerfs. This provides mechanical restraint to the anode material by the surrounding concrete.

Rust stains appeared soon after the CP system was installed. These proved to be due to the presence of tramp steel left in the bottom of the forms before repair concrete was placed. This is a detail which should be included in any pre-concreting inspection.

Bonding of the conductive coating to the base concrete was generally good; however, a small amount of scaling did occur. The scaling always occurred from original concrete, never repair concrete. The most likely causes for this scaling are acid production or chlorine gas generation by the CP system. However, the action of freezing and thawing is a possibility. Repairs were made and, if the cause of the scaling was either acid or chlorine gas, it is not expected to repeat itself. Such repairs are readily and easily made and may be expected after the first year of operation of such a system. However, recurrences are considered unlikely.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The overall conclusion that can be drawn from this study is that cathodic protection systems based on conductive coatings appear to be feasible. Except for minor surface scaling in both the FHWA slab and the full-scale bridge pier installation, no major difficulties were identified. The primary wire anodes need to be anchored by the conductive polymer mortar used as cast-in-place material, preferably contained within shallow saw kerfs.

The distance between primary anodes can be at least 6 ft without losing effectiveness of the CP system.

Although direct or nearly direct electrical shorts have been a problem on similar installations, it was not encountered in this case. A contributing factor to this good fortune may be the relatively deep concrete cover over most of the reinforcing steel. Also, this structure was old enough that rust stains appeared over steel near the surface of the structure.

The resistivity of the concrete between the steel and the conductive coating remained relatively constant throughout the year, thereby removing one of the major initial concerns for possible problems with the system. However, water came through the expansion joint in the deck very readily. This served to prevent the concrete between the conductive coating and the reinforcing steel from drying out. A more sheltered installation may have produced different results; however, because the average humidities throughout the United States range from 50 to 80 percent (with the exception of the desert areas of the southwest), extremely high resistivities should not be a serious problem. The laboratory tests on resistivity described in Appendix A showed that relatively dry surface concrete beneath the conductive coating dropped significantly in resistivity after exposure to 75 percent RH.

The decorative paint bonded very well to the conductive coating and maintained its adhesion throughout the monitoring period.

SUGGESTED RESEARCH

The research team feels that the feasibility of the CP system described herein has been established. However, long-term durability has not yet been proven. Therefore, the first recommendation for additional research is to continue the monitoring of the present CP system on the Rosemont bridge pier for an additional 5 years. Of particular interest during this period would be to monitor coating bond and to determine whether the repaired areas of conductive coating scale off again. Also, periodic E log I testing should be done to establish whether operation of the system is reducing the need for protection.

Improved procedures for analyzing and interpreting E log I curves obtained on reinforced concrete structures are needed. Multiple breaks in such curves, assumed to be caused by concentration polarization, and the process of using tedious graphical analyses and manually directed computer programs are very time consuming. An overall effort to simplify this process is needed.

Alternatives to E log I testing are needed as criteria to establish the amount of current which would provide adequate cathodic protection. Possible alternatives are:

1. Determining negative shift criteria for potential which occurs from the "freely corroding" potential to the instant-off potential determined while the CP system operates.
2. Controlling the system with embedded half-cell electrodes or using currents obtained from embedded rebar probes as references determining the CP system current settings.

Other manufacturers of conductive paints or coatings should be encouraged to develop and improve their products. It is significant that 2 out of the 3 materials tested failed under freeze-thaw testing. Suggested laboratory testing procedures are: freezing and thawing, thermal cycling (cool and wet, hot and dry), and ultraviolet exposure.

Other materials may also prove to be of practical use as conductive coatings. Thin deposits of metal, for instance, have been used in California.

The manufacturer of coating A has devised a system for embedding platinum-niobium clad anode wire directly inside the conductive coating. This system is faster to apply and almost certainly less expensive than the procedures used to fabricate primary anodes on the Rosemont pier. This system and other possible recent alternatives for the rapid fabrication of primary anodes should be explored.

Whatever materials are proposed for use, changes in bond to the substrate with time under the test conditions above are considered crucial to their evaluation.

Electrical shorting problems (i.e., direct or almost direct contact between the CP anode and the structure rebar) were not encountered in this effort. However, such problems have been encountered in other projects at an alarming rate. Such shorts are difficult to locate when the entire surface is covered with conductive paint. It would appear that a proper tack may be to build into the CP system a means of preventing these shorts. For the conductive paint systems, a sprayable, cementitious coating which could be applied at a thickness of 1/4 to 1/2 in., prior to anode placement, appears to be a viable approach. The coating would need to exhibit good bond and environmental durability characteristics as well as compatibility with the conductive paints. Such an approach may also have the added advantage of providing a lime rich, highly alkaline surface in contact with the conductive paint. This might increase anode life at a given discharge current density by slowing acid attack at the concrete/paint interface. Commercially available, sprayable, cementitious coatings such as the latex modified portland cement coatings reportedly used successfully to coat concrete silos appear to be the best starting point.

Alternatively, it may be possible to find and isolate short circuits from coatings to reinforcement by heat sensing or electrical resistance methods. Short circuits will cause electrical and heat concentrations at the location of the short, particularly if the current applied is momentarily increased to high power levels. By searching the conductive surface, using infrared sensing methods, it may be possible to locate shorts or near shorts. Once located, the coating surrounding the short can be removed by chipping or shallow core drilling to isolate the conductive coating from the offending short.

Finally, additional trial CP installations should be made under a variety of exposure conditions, including a warm marine environment, to further demonstrate the effectiveness of the conductive coating system and to identify any possible problems.

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APPENDIX A

PHASE I—LABORATORY INVESTIGATION

INTRODUCTION

The purpose of this laboratory study was to investigate the suitability of three commercially available conductive coatings for use in a cathodic protection system applied to an existing bridge structure. The laboratory procedures served as screening tests to select one conductive coating for use in the field study described in Phase II of this report. These laboratory tests consisted of the following:

1. Freeze/thaw tests performed on concrete panels coated with the three conductive coatings and a decorative paint cover coat. These tests were conducted to determine the comparative durability of various coating combinations in a northern environment.
2. Alternate wetting and drying, heating and cooling tests of concrete panels with various coating combinations. This test cycle was used to determine the ability of the coatings to withstand cycles of heating and drying at 140 F and cooling underwater at 73 F.
3. Resistivity of surface concrete determinations on coated concrete specimens which were continuously air-dried at 73 F and 50 percent RH. This test was employed to determine if long-term drying causes the concrete beneath the coatings to dry enough to develop excessive electrical resistance to the flow of cathodic protection currents through the concrete to the reinforcing bars beneath.
4. Effect of film cracking on conductivity determined by tests in which the coatings applied to concrete slabs were cut through to make film discontinuities of various widths. This test simulated the effects of cracks through the conductive coatings and evaluated the effects of such cracks in the coatings on the electrical conductivity across the cracks as the concrete specimens were wetted and dried.
5. Bonding capabilities of coatings to concrete determinations using tensile bond tests and ASTM Method D3359. Some bond tests were made immediately after coatings were applied and cured in the normal laboratory environment. Companion specimens were exposed to intensive ultraviolet light radiation before the bond of the coatings to concrete was determined.
6. Miscellaneous bond tests conducted to evaluate bond of the coatings to concrete and to each other after durability tests of the coated panels were completed. Bond tests were made of panels coated with conductive coating A after freezing and thawing tests had been performed on the panels. Other tests were conducted on panels that had been exposed to 50 cycles of heating and drying, cooling and wetting.

MATERIALS

Three commercially available conductive coatings were selected for screening tests. Coating A reportedly has been used with success by the Florida Department of Transportation. This material (Acrylic Conductive Coating XP 90895™ manufactured by Porter Chemical Co.) is a solvent-based acrylic "mastic," containing graphite.

Another conductive paint (Electrodag 37™) had interesting properties, as described in the final report of NCHRP Project 12-19, but is not presently available. A currently available conductive coating made by the same manufacturer (Acheson Colloids Company) was used instead, as Coating B, in the laboratory test series. This product (Electrodag 188™) was considered by FHWA to be the most similar currently-manufactured product and was used in this work. It is a water-based acrylic material filled with graphite.

Coating C (Chromerics 4130™ manufactured by Chromerics, Inc.) was partially evaluated in the final report of NCHRP Project 12-19, also. It is a latex-based coating filled with carbon.

All three conductive coatings were black, an inappropriate color in the dark environment of an overpass. Consequently, the use of a light-colored cover paint over the black conductive coatings was necessary. A buff Sherwin-Williams "Super

Paint™" exterior acrylic latex was used as a decorative cover coating in the laboratory studies.

For measurements of the electrical resistance of surface concrete beneath the conductive coatings, small "anode" wires, manufactured with a copper core and corrosion resistant exterior plating of platinum and niobium, were embedded in certain concrete panels.

Electrical contact was made with the coatings by embedding short lengths of anode wire in small 5/8-in. diameter plugs of "conductive polymer" cemented to the faces of concrete test panels. The conductive coating was applied over these plugs and the remainder of the concrete surface to be coated. The conductive polymer was formulated by combining 1 part by weight of vinyl resin, 0.0375 parts of catalyst, and 2.3 parts of electrically conductive carbon filler.

One-foot square concrete test panels with depths ranging from 2 in. to 6 in. were cast as substrates for the application of the conductive coatings. The concrete aggregates used were Eau Claire granitic sand and gravel with a 3/4 in. maximum size. These materials have a low chloride content and a demonstrated good resistance to freezing and thawing deterioration.

Nominal concrete properties were: 4,000 psi compressive strength at 28 days, entrained-air content of 5 percent, water-cement ratio of 0.5, and cement content of 4¾ bags per cubic yard of concrete. Some slabs were cast with calcium chloride admixtures for use in tests involving the electrical resistance of concrete. All slabs were cast in unoiled plastic coated plywood molds.

FREEZE/THAW TESTS

Test Procedures

Concrete specimens used to evaluate the resistance of the conductive coatings to freezing and thawing measured 12 × 12 × 2 in. These slabs were moist-cured under wet burlap and polyethylene covers for 21 days, then air-cured for a period of 7 days at 73 F and 50 percent RH. During this air-cure period, the slabs were sandblasted lightly on the bottom surfaces, as cast, to remove surface laitance.

After curing, the bottom surfaces of the slabs were coated. One-half of each surface received one coat of the conductive material, the other half received two coats. A decorative cover coat of latex paint was applied to one-half of each of these areas, thereby providing four test conditions per slab. Each coated slab quadrant was separated from the others by a 1/4-in. strip of uncoated concrete. The coatings were cured for a period of 7 days in laboratory air before freezing and thawing tests started. During this period, foamed styrene water-retention dikes were glued around the upper edge of each slab surface and waterproofed by the application of silicone caulk.

The slabs, with water ponded on the coated surfaces, were frozen overnight for approximately 18 hours at a temperature of 0 F. Each morning the slabs were removed from the freezer and thawed in laboratory air at approximately 70 F for 6 hours, thereby completing one cycle of freezing and thawing each day. Testing continued until 100 cycles of freezing and thawing were performed.

After each 10 cycles of freezing and thawing, the specimens were rated visually to estimate the percentage of coating failure. Periodically, photographs were taken of the test surfaces.

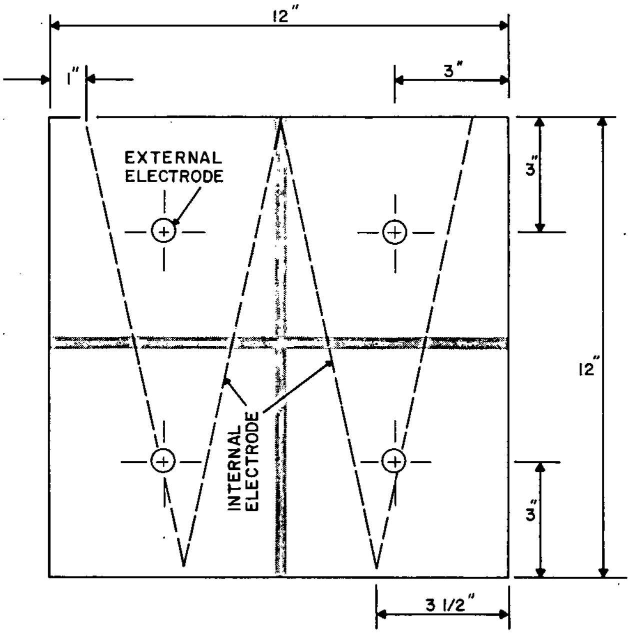


Figure A-1. Plan view of slabs and electrodes for measurement of electrical resistance of surface concrete beneath coatings.

The alternating current electrical resistance between the surface coatings and electrodes buried at half-depth in the concrete was also determined before and after freezing and thawing testing as a means of evaluating the deterioration of bond between the conductive coating and the concrete substrate panel. Figure A-1 is a plan view of the slabs, showing the general layout of the coated sections, the location of the top electrode made of conductive polymer mortar and a buried strip of wire, and a grid of "anode wires" buried at half-depth in the concrete panels.

Test Results

Figure A-2 shows three slabs, each coated with a single conductive coating, after 100 cycles of freeze/thaw testing. Coating A resisted deterioration by freezing and thawing better than coatings B or C. The visual examination indicated that:

1. Both slabs with coating A performed very well in the freeze/thaw test. Except for a small surface void which had lost the coating on its edges, no deterioration was apparent on either slab. The decorative paint still adhered to all surfaces to which it had been applied. All surface electrodes remained coated at the end of freeze/thaw testing.

2. Coating B deteriorated significantly during freeze/thaw testing. After 16 test cycles, water-filled blisters between the conductive coating and the decorative paint covered more than 50 percent of the area painted with the decorative material. After 40 cycles, virtually all of the decorative paint was detached from the underlying conductive coating. After 55 cycles, the conductive coating was being seriously eroded. After 80 cycles, virtually all decorative paint was lost, as were exterior layers of the conductive coating over an estimated 80 percent of the

coated area. After 100 cycles, a thin layer of coating B material which had bonded directly to the slab surface remained. However, the coating had lost most of its thickness, and aggregate articles and small areas of mortar were revealed on the surface of the slab. All coatings were detached from the conductive polymer surface electrodes, which were still securely bonded to the surface of the concrete slab.

3. The performance of coating C during freezing and thawing may have been affected by its tendency to develop short cracks or "checks" as it dried on the concrete surface. Some of the cracks penetrated through the coating and provided channels for the ingress of water to the substrate concrete. As freezing and thawing proceeded, the bond of this conductive coating to the decorative paint remained strong, although the decorative paint layer started to deteriorate at approximately 40 freeze/thaw cycles, and deteriorated greatly by 80 cycles. After 55 cycles of freeze/thaw the conductive coating started to lose bond with the substrate concrete, exposing small patches of mortar. After 100 cycles, significant areas of conductive coating C had lost bond with the concrete. The decorative paint improved the performance of areas of this coating significantly, although some loss of coating did occur along the edges of the coated areas. Bond of the coatings to the conductive polymer was good, and all conductive polymer electrodes remained firmly attached to the surface of the concrete slab.

Tensile bond tests were performed on the freeze/thaw slabs coated with conductive coating A after the slabs had completed 100 cycles of freezing and thawing. Tensile bond test procedures are described later in this report. Bond test results were:

1. 2 coats A + decorative paint = 260 psi
2. 2 coats A only = 260 psi
3. 1 coat A + decorative paint = 197 psi
4. 1 coat A only = 254 psi

Approximately 50 percent of the bond failure areas in these tests occurred in surface mortar, while the remainder occurred at the mortar-to-coating interface. These bond strengths were approximately 65 percent of the bond strengths obtained originally on the slabs for the same coating combinations.

Electrical resistance was determined using an AC bridge. Resistances were measured before freezing and thawing testing (after slab surfaces were inundated with water for 1 day), after 55 freeze/thaw cycles, and when testing was completed. The highest measured electrical resistance was usually that obtained after the short period of presoaking the slab. The electrical resistance after 55 cycles of freeze/thaw was generally the lowest value measured. This decrease in resistance was probably caused by an increased level of water saturation during the concrete testing. After 100 freeze/thaw cycles, the electrical resistance through the external electrode, coatings and concrete had increased slightly over that of the 55 cycle values, usually by about 15 percent. This slight increase in electrical resistance may have been caused by a slight loss of bond, continued hydration of cement, or a combination of these two factors.

WETTING AND DRYING, HEATING AND COOLING TESTS

Test Procedures

Two-inch thick concrete slabs, coated identically to the

Figure A-2. Freeze-thaw slabs after 100 cycles of freezing and thawing.

freeze/thaw slabs just described, were subjected to wetting and drying thermal cycles. The weekly test cycle for these slabs was:

1. Soak for 3 days in saturated lime water at laboratory room temperature.
2. Dry in a chamber maintained at 140 F for 4 days.

The specimens were examined and rated visually after the end of every fifth weekly cycle. Testing of the specimens continued for a total of 50 weekly cycles. At the end of the testing period, representative coated slabs that withstood 50 cycles of the wet/dry heat cycling were tested for bond of the coatings to each other and to the substrate concrete.

Test Results

Except for minor scratches in the coatings caused by handling, no distress was observed in the coatings of these slabs during the 50 cycles of drying at 140 F and wetting at 73 F.

When test cycling was completed, tensile bond tests were performed on one slab coated with each of the materials. Bond strengths were significantly higher than those obtained during the initial bond tests, which were performed when the coatings were fresh and the concrete was approximately 6 weeks old. Therefore, bond was not decreased by the heating and drying, wetting and cooling cycling.

After cycling, one set of test specimens was left in lime-saturated water for a month. Specimens coated with conductive materials A and C were not affected by the prolonged soaking. The slab coated with material B developed a number of water-filled blisters approximately 1/2 in. in diameter between the decorative paint and the conductive coating.

ELECTRICAL RESISTANCE OF SURFACE CONCRETE

Introduction

The efficiency of a cathodic protection system is dependent on the electrical properties of the current path from the conductive coating anode through the concrete to the underlying reinforcement. If the electrical resistance of the concrete between the anode and the reinforcement varies, changes will occur in the other electrical parameters. For example, in a constant current CP system, increasing concrete resistance increases voltage drop from the anode to the reinforcement.

A laboratory study was made to determine the effects of long-term drying, and remoistening, upon the electrical resistance of concrete between conductive coatings and conductor 1½ in. below the coated concrete surface.

Test Procedures

Concrete specimens measuring 12 × 12 × 6 in. deep were cast for these tests. Electrical resistance determinations were made between portions of the slab which were coated and a parallel plane within the slab 1½ in. from this face. The internal electrode in this plane was a network of "anode wire" arranged as shown in Figure A-1. The electrodes at the surface of the concrete were lengths of anode wire embedded in 5/8-in. diameter plugs of conductive polymer cemented to the surface of the slab and overcoated with the conductive coating material.

The concrete specimens fabricated for these tests contained variable quantities of admixtured chlorides. The specimens with "low chloride contents" contained 1.5 lb of chloride ion per cubic yard of concrete. The slabs with "high chloride contents" contained 15 lb of chloride ion per cubic yard of concrete. Conductive coatings and decorative paint coats as described for the previous tests were applied to the lightly sandblasted concrete surface and cured for the indicated time. Then all other exposed concrete surfaces were painted twice with a relatively impervious epoxy "sealer" to impede the loss of moisture through concrete not coated with the conductive materials.

The specimens were stored in a laboratory maintained at 73 F and 50 percent RH. Resistance measurements were made with an AC bridge weekly during the first month, then monthly for over 1 year. At the end of this drying period, resistances were measured, and the specimens were temporarily stored at a humidity slightly above 75 percent RH. Specimen resistances were measured again after 2 weeks of high humidity storage. Then the slabs were turned over and their tops immersed in a 1/4-in. deep pool of water for 15 min. When this brief period of wetting was completed, specimen resistances were again measured. After wetting, the specimens were again placed in the room controlled at 73 F, 50 percent RH. Resistance values were determined at 1-week intervals for a total of 3 weeks.

Test Results

Graphs of surface concrete resistance changes for specimens coated with conductive Coating A are shown in Figures A-3 and A-4. They show resistance data for the low-chloride content slabs (1.5 lb of chloride per cubic yard of concrete) and high-chloride content slabs (15 lb of chloride per cubic yard of concrete), respectively. Test results for Coating A were similar to those obtained for coatings B and C.

The resistance data indicate the following:

1. The specimens made of concrete with a high chloride content had an electrical resistance approximately one-tenth that of similar specimens made with concrete having a low chloride content.
2. The electrical resistance of the concrete specimens always increased during storage under air-dry conditions and decreased dramatically when the coated surfaces of the concrete specimens were moistened for only 15 min.
3. The long-term air-drying of the concrete specimens was characterized by a gradual increase in electrical resistance of the concrete surface. Although remoistening the specimens lowered the resistance of the concrete to about the same values as when testing was started, resistances of the concrete increased rapidly thereafter when the specimens were subsequently redried. After a 3-week period of redrying, concrete surface resistances increased to approximately the peak resistance values.
4. Concrete surface electrical resistance is apparently very sensitive to ambient relative humidities. A short period of 75 percent RH storage of the specimens previously dried at 50 percent RH reduced the resistance of the concrete surfaces by about one-half. This observation is consistent with known "water-vapor absorption" weight increases which occur in portland cement pastes and concrete subjected to increases in relative humidity.

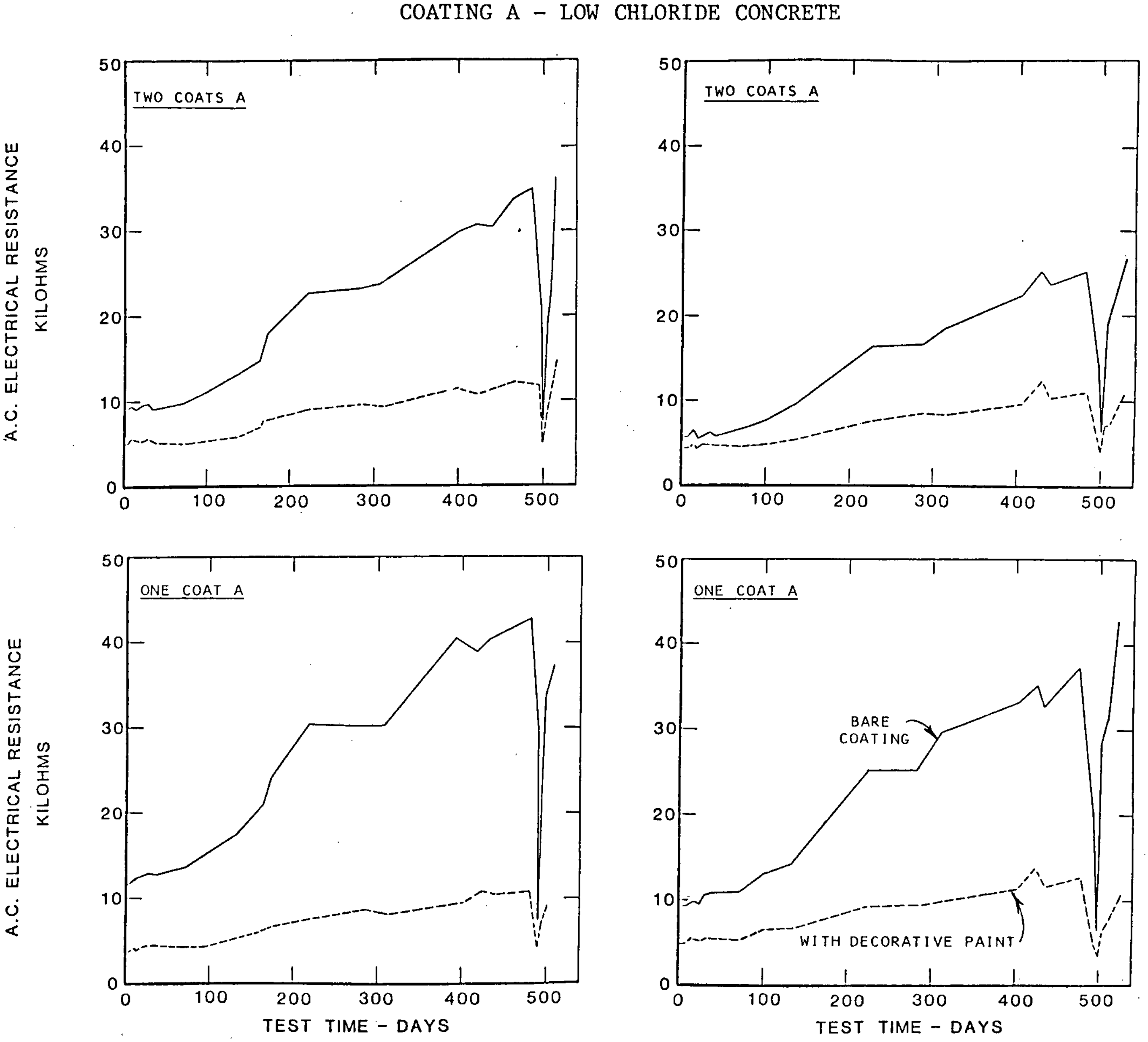


Figure A-3. Resistance change in surface concrete during air drying—Coating A—low chloride concrete.

5. A second coat of conductive paint decreased the rate at which electrical resistance increased during air-drying. A cover coat of latex paint over the conductive coating did the same. The retardation of changes in the resistance of surface concrete by extra coatings was particularly apparent in concrete slabs that did not contain high chloride contents and consequently had high electrical resistance.

6. The increase in electrical resistance with time during air-drying appeared to be nearly linear.

EFFECT OF FILM CRACKING ON CONDUCTIVITY

In a structural CP system, conductive coatings must provide a path for current from the primary anodes to points several feet away on the surface of the structure. Concrete ordinarily has a much higher electrical resistivity than conductive coatings. If conductive coatings crack, the current must travel from a cracked edge of the coating to the other edge through a path in high resistivity concrete. Long, wide cracks in the conductive coating will certainly decrease the preventive current available to portions of the CP system on the side of the crack away from the primary anode. This study was done to estimate the effects such cracks in conductive coatings have on electrical resistance.

Test Procedures

Twelve-inch square specimens which were 2 in. deep were cast and cured as described earlier. Several lengths of bare 24-gage copper "jumper" wire were stretched across a sandblasted face of the concrete slab and cemented at the ends with epoxy

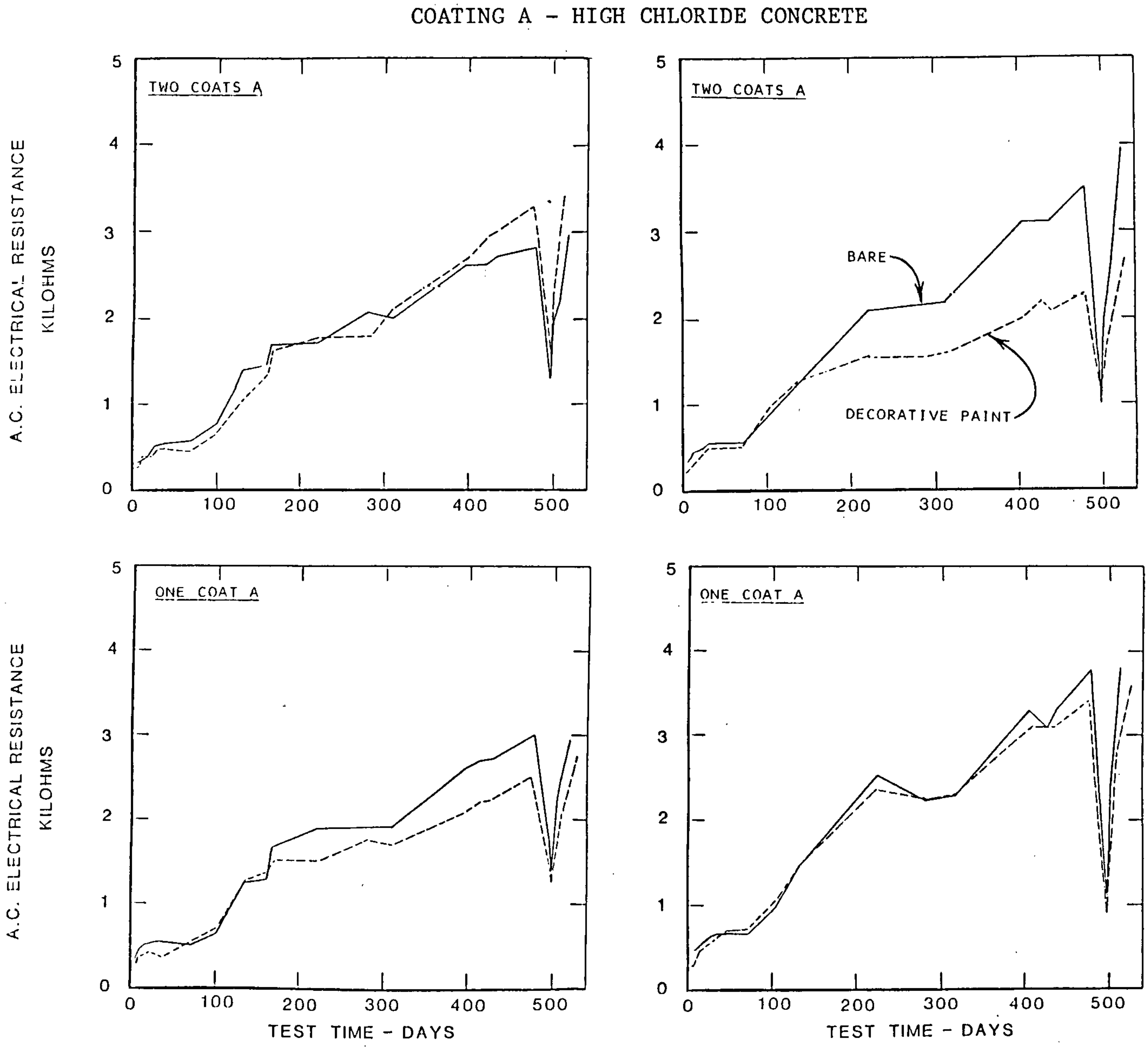


Figure A-4. Resistance change in surface concrete during air drying—Coating A—high chloride concrete.

cement. The wires were parallel and approximately 1½ in. apart. A single thickness of conductive coating material was painted over the copper wires and the face of the concrete slab.

Alternating current resistance readings were made between adjacent sets of coated wires. The coatings were then cut through so the distances between intact faces of coating material were of variable width. A "razor blade saw" was used to cut the grooves in the coatings. With this tool it was possible to cut grooves in the coatings as thin as 0.010 in. Several grooves, most ranging in width from 0.01 in. to approximately 0.04 in., were cut through the conductive coatings on each slab. The widths of the grooves were determined by averaging five widths measured at various points along the groove with an optical comparator. The electrical resistance between the wires on either side of the opening in the coating was then measured. Afterwards, the coated slabs were immersed in water for 7 days. Resistances were determined when the slabs were towel dried, and at intervals for a period of approximately 2 weeks of storage at 73 F and 50 percent RH.

Test Results

Test results indicated:

1. Any small cracks that interrupt the conductive coating will cause a large increase in the electrical resistance of the coating. Interruptions in the coating with a width of approximately 0.01 in. increase the resistance of coatings on water-saturated low-chloride substrate concrete by a factor of approximately 100. The increase in resistance caused by such cracks in coatings applied to high-chloride concrete substrates

would certainly be less, but still would represent an increase in resistance by a factor of 10 over that found for a continuous coating.

2. The electrical resistance through the grooved section of coating increases greatly as the substrate concrete dries. In thoroughly dried, low-chloride concrete the resistances across interruptions in the conductive coating are so great that they virtually amount to an open circuit between sections of coating on either side of the groove or crack.

3. Increased widths of groove are associated with increased electrical resistance across that groove.

Figure A-5 shows the resistance data corrected for variable groove widths for coating A. The ordinate of the figure is the logarithm of the ratios of the measured electrical resistances (in ohms) divided by the width of the grooves (in inches). Data in the figure indicate that the resistance across the "cracked sections" of varying thickness appears to be a direct function of the width of the opening in the conductive coating.

Actual cracks through conductive coatings may often be reflections of surface cracks in the underlying concrete structure. If a crack in the concrete is deep and air-filled, the passage of CP current from one edge of the crack to the other requires current flow in concrete down one side of the crack, across solid concrete and up the other side to the conductive coating isolated by the crack. An actual crack in a concrete structure may require current passage through greater lengths of high-resistance concrete than those considered in these tests and therefore may offer greater resistance to current flow than the data in this section indicate.

Short cracks through conductive coatings may not be a significant barrier to current flow, since current can easily pass through the conductive coating around the ends of short cracks with little voltage loss. However, longer continuous cracks which parallel the primary anode current source have the capability of significantly reducing the voltage of the conductive coating on the side of the crack away from the primary anode. The presence, orientation, and length of cracks will affect the efficiency of the CP system and will require periodic maintenance. Narrow cracks that might degrade CP current flow should be overcoated with conductive coating material. Large cracks in the coating could be filled with conductive polymer to promote current flow across the cracked area.

BONDING CAPABILITIES OF COATINGS TO CONCRETE

The tensile bond strengths of various combinations of conductive coatings and decorative paint were determined on both smooth and lightly sandblasted concrete surfaces. The bond test procedure was a method which has been used extensively to evaluate the bond strength of overlays to base concrete in the WJE laboratories. Adhesion tests were also performed in accordance with ASTM D3359, Method B, in which pressure-sensitive tape is applied to patterns scribed through coatings and slowly pulled free. The amount of coating that is pulled free by the tape is compared to a standard, and the adhesion of the coating to the substrate is subjectively rated.

Bond tests were run on dry coated concrete panels and on panels soaked in water for 2 days prior to test. Separate tests were also run on panels that were exposed to ultraviolet light for over 3 months.

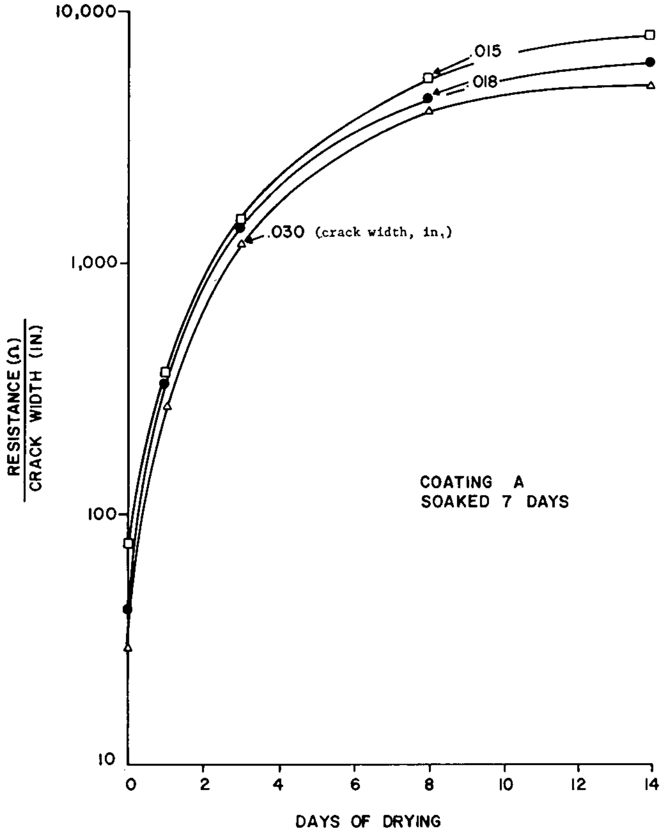


Figure A-5. Ratio of electrical resistance to crack width for air drying slabs coated with Coating A.

Test Procedures

Two-inch thick by 1-ft square concrete panels were coated with single and double thicknesses of conductive coating materials on both smooth formed and sandblasted surfaces. Portions of the coatings were also painted with the light-colored decorative paint.

Tensile bond tests were performed by:

1. Gluing 2-in. diameter steel plugs to the coating with an epoxy cement.
2. Scribing a circle through the coating around the perimeter of the plug.
3. Placing a heavy steel support over the steel plug. This support is a reaction frame that suspends a hydraulic ram above the surface of the slab so the ram can pull the plug away from the face of the slab. Figure A-6 is a schematic view of the bond test apparatus.
4. Screwing a length of 1/2-in. threaded rod into the threaded hole in the top of the steel plug. This rod is used to pull the plug away from the slab with the center-hole hydraulic ram.
5. Placing a center-hole flat load cell over the threaded rod, resting on a spherical nut and washer combination and the piston of the ram.
6. After failure, calculating the applied force from initial and final strain bridge readings. Ultimate tensile bond stress was then calculated as the ratio of ultimate force (in pounds) to the effective area of the 2-in. diameter steel cylinder (3.14 sq in.).

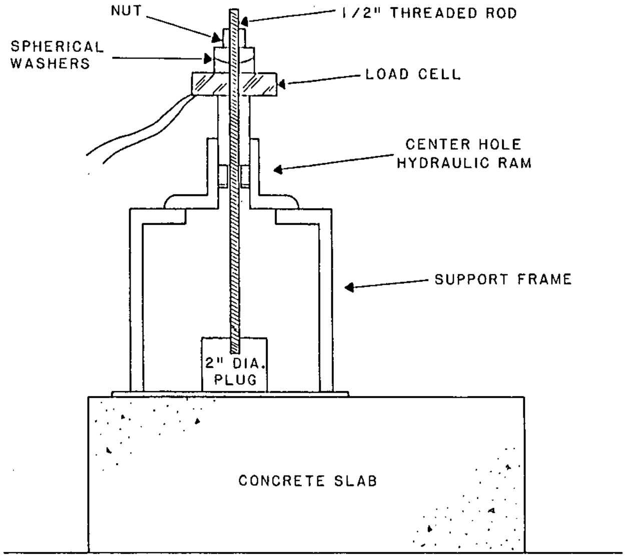


Figure A-6. Schematic of bond testing apparatus.

Separate coating adhesion tests (peel tests) were also made using the procedures of ASTM D-3359, Method B. In this procedure, a lattice of cuts 2 mm apart was made through the coating with a razor blade. A standard 1 in. wide pressure sensitive transparent tape was applied to the lattice of cuts and pulled off the coating. The area of coating removed by the cutting operation and pulling off the tape was estimated and given a visual rating according to instructions in the test method.

Test Results

Table A-1 shows the tensile bond strengths determined for the initial bond tests performed after the coatings had been applied and cured approximately 1 week. Bond (or tensile) strength for the dry specimens ranged from 280 psi to 560 psi. The highest strengths were obtained for double coats of conductive coating material without a covering of decorative paint. The lowest strengths were obtained when a sandblasted base concrete was coated with two thicknesses of conductive coating material and one coat of decorative paint.

Most of the failures during this phase of testing occurred in the substrate concrete. The exceptions to this type of failure occurred when sandblasted concrete surfaces were coated with conductive Coating B. This coating-substrate combination almost always failed in bond at the interface between the sandblasted concrete and Coating B. The tensile bond test data indicate that the bond of the coatings to concrete and to each other was reasonably good for dried specimens.

Limited tests were performed on companion specimens that were soaked in water for a period of 2 days before bond testing. The soaked bond strengths of the panels coated with conductive materials A and C were similar to their bond strengths when dry. The soaked bond strength of the sample of conductive Coating B without any cover was slightly lower than that of the same coating when dry. The significantly lower bond strength of this material, when covered with a decorative paint, was probably due to the apparent failure in bond which occurred between the cover coat and the decorative paint.

"Peel" tests made with the procedures of ASTM D-3359 indicated that good adhesion was obtained between the decorative paint and conductive coatings A and C. Both had an adhesion classification of 5. Peel tests indicated poor adhesion between a substrate of conductive Coating B and the decorative paint. In this instance, considerable coating was lost while cutting the lattice and approximately two-thirds of the paint was peeled away after the test.

It was extremely difficult to conduct realistic peel tests on the bond between concrete and the conductive coatings, because the coatings were absorbed slightly into the substrate concrete and penetrated into the surface voids. However, the peel tests were performed after cross-cuts were made into the substrate concrete and the surfaces were carefully dusted. In all cases, the adhesion classification was 5 or between 4 and 5.

In summary, all tests indicated a good adhesion between the conductive coatings and substrate concrete. Adhesion and bond were good between the decorative paint and conductive coatings A and C. Adhesion between the decorative paint and Coating B was poor. The tensile bond test indicated a fair bond between these same coatings when dry, but only a marginal bond after the concrete panel was moistened for 2 days.

These tests correlated well with experience in other test procedures. Bond of all coatings to concrete was reasonably good in the freeze/thaw test. Adhesion between the decorative paint and coatings A and C was also good in the freeze/thaw test. Loss of adhesion between B and the decorative paint in the freeze/thaw test, and after long-term soaking of the wetting and drying, heating and cooling test, confirms the questionable nature of bond of this paint to Coating B.

BOND TESTS OF COATINGS EXPOSED TO ULTRAVIOLET RADIATION

Conductive coatings applied to the outside surfaces of structures are usually exposed to deterioration by ultraviolet radiation from the sun. To evaluate the deterioration of the conductive coatings and the decorative paint caused by continued exposure to ultraviolet radiation, coated concrete panels were exposed to ultraviolet radiation in the laboratory. Bond tests were made on the irradiated coatings to determine the effects of ultraviolet radiation on the bond of the coatings to concrete and to each other.

Test Procedures

Three concrete test panels with dimensions of 1 ft × 1 ft × 2 in. were cast and coated using procedures that were previously described.

An ultraviolet light exposure system, similar to that described in *NCHRP Report 244* (*2*) was used to irradiate the panels continuously for a 3-month period. At that time, little coating deterioration was apparent, so ultraviolet exposure was continued until the panels had been irradiated for a total of 2,650 hours. On the basis of the ultraviolet exposure relationships described in *NCHRP Report 244,* this exposure to ultraviolet light was equivalent to about 350 days of sunlight in southern latitudes or 440 days of exposure in the northern regions of this country.

Table A-1. Initial bond tests.

	Direct tension bond strengths, psi							
	Formed face				Sandblasted face			
Conductive coating	One conductive coat		Two conductive coats		One conductive coat		Two conductive coats	
	Plain	Decorative	Plain	Decorative	Plain	Decorative	Plain	Decorative
			DRY SPECIMENS					
COATING A	370	360 370	480 560	310 430	380	360 410	510 500	400 400
Mean	370	370	520	370	380	390	510	400
COATING B	410	400 390	460 460	350 550	340	410 370	510 460	280 280
Mean	410	400	460	450	340	390	490	280
COATING C	380	350 424	560 370	350 510	410	420 380	540 550	350 550
Mean	380	390	470	430	410	400	550	450
			WATER SOAKED SPECIMENS					
COATING A	390	410						
COATING B	320	190						
COATING C	320	450						

Test Results

Tensile bond tests were made on the coated faces of the irradiated panels. All bond stresses were generally quite high. However, the tensile bond strengths of the portions of the slabs that were coated with decorative paint were from 1¼ to 1½ times the bond strengths of portions of the same slabs that were not coated with the decorative paints. This is significant evidence that the conductive coatings tested were adversely affected by the ultraviolet exposure and were protected by an overcoat of the light-colored decorative latex paint.

Despite these differences, it was apparent that all coating materials maintained a powerful bond to the substrate concrete. Figure A-7 shows that bond failures almost always occurred in the substrate concrete coated with Coating C. With Coating B, similar bond failures occurred when bonded to as-cast surfaces. However, as described with previous bond tests, failures with this conductive coating generally occurred at the bond line of the sandblasted surfaces. This mode of failure apparently did not result in bond strengths that were significantly different from those obtained in tests where failure occurred in the concrete. Failures of Coating A in the bond tests were similar to those of Coating C.

CONCLUSIONS

The laboratory test data lead to the following conclusions regarding the three conductive coatings that were tested:

- *Freeze/Thaw Testing*

1. Coating A had much better freeze/thaw resistance than the other two coatings. Reasonably good bond was found between Coating A and the substrate concrete after 100 cycles of freezing and thawing were completed. Decorative paint also adhered to the outside surface of Coating A after freeze/thaw cycling.

2. Freeze/thaw cycling quickly destroyed the bond between conductive Coating B and the decorative paint applied to it. The conductive coating itself rapidly deteriorated because of freezing and thawing, although vestiges of the coating remained on the substrate concrete after 100 cycles of freezing and thawing were completed.

3. The decorative paint remained bonded to conductive Coating C throughout the freeze/thaw test cycling. The conductive coating itself remained intact during this testing. However, when freeze/thaw testing was completed, large areas of Coating C had scaled from the face of the concrete panels beneath it.

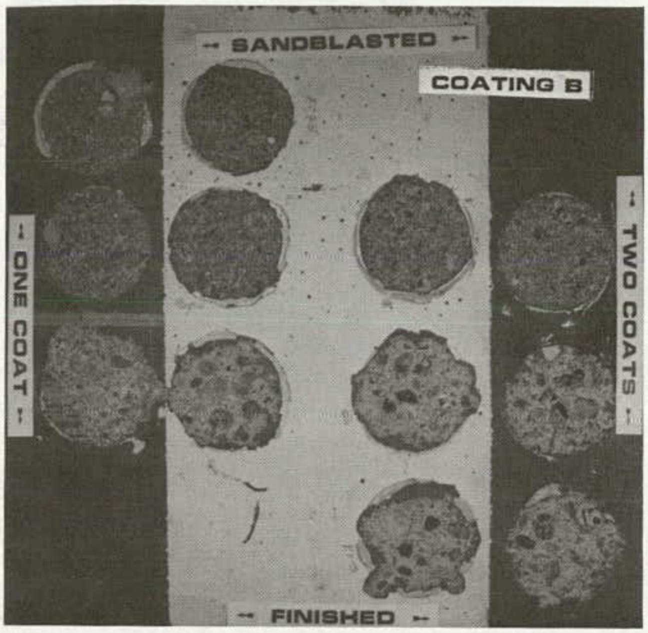
4. No bond failures occurred between the conductive polymer and the concrete substrate to which it was bonded during 100 cycles of freeze/thaw testing.

- *Heat, Cool, Wet, Dry Testing*

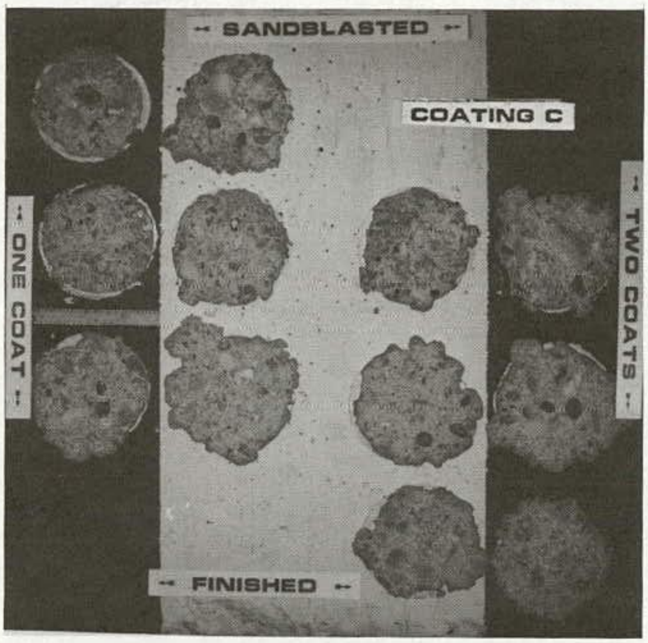
1. Weekly cycling of coated concrete panels between an oven maintained at 140 F and a limewater-saturated tank at 73 F for a total of 50 weeks did not produce visible deterioration of the conductive coatings or decorative paints applied to the concrete panels.

2. Selective tensile bond tests of the coated panels after this cycling indicated that the bond of the coatings to the concrete had not deteriorated.

3. Long-term storage of the panels in saturated limewater after this cyclic testing was completed caused a failure in adhesion between the latex decorative paint and conductive Coating B.



(a) Coating B



(b) Coating C

Figure A-7. Ultraviolet slabs after bond testing.

Long-Term Changes in Concrete Electrical Resistance

1. During the studies of the electrical resistance of surface concrete beneath the conductive coatings, continuous exposure to air-dry conditions eventually produced high concrete resistance which would require the application of high cathodic protection voltages to obtain adequate protective currents.

2. During continuous air-drying at controlled temperatures and humidities, the increase in the resistivity of surface concrete with time was nearly linear.

3. The electrical resistance of concrete with 1.5 lb of chloride ion per cubic yard of concrete was approximately 10 times that of concrete with 15 lb of chloride per cubic yard.

4. After air-drying at 50 percent RH, the resistance of surface concrete beneath the conductive coatings dropped significantly when the test specimens were exposed to comparatively high relative humdities (approximately 75 percent RH).

5. When the surfaces of coated panels were wetted for 15 min, resistance of surface concrete beneath the coatings immediately dropped to comparatively low values. However, resistance increased rapidly during air-drying after such brief periods of surface-wetting.

6. Outercoats of ordinary latex paint, used to lighten the dark surfaces of the conductive coatings, decreased the rate at which the electrical resistance of surface concrete increased during air-drying.

- *Effect of Cracks on Conductivity*

1. Cracks in conductive coatings, which were simulated by cutting grooves in the coatings, introduced high-resistivity concrete into the electrical path between the coating at either edge of the groove. The electrical resistance measured across such grooves was much greater than the resistance of the coating before grooving, even when the concrete beneath the coating was saturated with water.

2. The electrical resistance across the grooves tested, and presumably of the cracks the grooves simulate, increases as the concrete substrate air-dries.

3. Drying causes such high electrical resistance that cracks through conductive coatings over thoroughly dried concrete may approximate an open circuit.

4. The electrical resistance across the grooves increases almost linearly with the width of groove.

5. Air-filled cracks in the conductive coatings in real structures may be more effective in impeding current flow than the simulated cracks of these tests. Long cracks in conductive coatings which parallel primary anodes should affect CP current flow significantly. Such cracks should be filled periodically either with a conductive coating or conductive polymer.

- *Tensile Bond Strengths*

1. Tensile bond tests of coated panels indicated that a good initial bond was obtained between the three conductive coating materials and the substrate concrete.

2. After freeze/thaw testing for 100 cycles, the tensile bond of Coating A to the concrete beneath was approximately two-thirds of the initial bond strength.

3. After 50 cycles of heating and drying, wetting and cooling, tensile bonds of the coatings to concrete had increased over the initial bond values.

4. Exposure to intense ultraviolet radiation, which was equivalent to about 1 year of outside exposure, decreased the tensile bond strength of conductive coatings directly exposed to ultraviolet radiation by about one-third.

5. A covering of decorative paint protected conductive coatings beneath the paint from the deteriorating effects of ultraviolet radiation.

6. Adhesion tests (ASTM D-3359) indicated that the adhesion between the decorative paint and conductive Coating B was poor. The adhesion of the decorative paint to coatings A and C and of the three conductive coatings to substrate concrete was good.

APPENDIX B

PHASE 1A—FHWA SLAB TESTS

BACKGROUND

Phase IA involved cathodic protection application and monitoring on a large test slab at the Federal Highway Administration Outdoor Exposure Site in McLean, Virginia.

The test slab was constructed on May 20, 1981 (see Fig. B-1) and used in a study of corrosion of steel in concrete. Accelerated corrosion was first induced in June 1981 by driving sufficient chloride to the top mat rebar using an impressed DC current applied between the rebar and copper wires in a sodium chloride solution on the surface (see Fig. B-2). Using this and natural ponding procedures, corrosion of the top mat steel was induced as well as some rust staining, very fine cracking and delamination in six select areas. Thus, both anodic and cathodic areas exist on the top mat reinforcement and, when coupled, the top mat is anodic to the bottom mat reinforcement.

The slab concrete met Virginia Department of Transportation specifications for air-entrained bridge deck concrete. Slab and reinforcement dimensions are shown in Figure B-3. All reinforcing bars within each mat are electrically continuous. However, the reinforcing steel mats are not electrically connected to each other within the concrete, but can be connected by means of external lead wires.

In addition to the main reinforcement, 6 in. lengths of rebar are positioned at various locations—parallel to, but not in electrical contact with, the slab reinforcement. The "current pickup rebars" each has a leadwire attached which exits the slab and can be coupled to the slab rebar externally via that leadwire and the companion main reinforcement leadwire positioned near each probe location. Also located adjacent to the top mat reinforcement are two 10 in. long, 50 mil rate of corrosion probes. One is located in a chloride-free area and one in a chloride intrusion area.

Upon completion of the work in the previous study, in the fall of 1981, a 2-ft 4-in. section of one side of the slab was cut off and demolished. The remaining portion, 7 ft 4 in. by 5 ft 0 in., was transported to the FHWA Outdoor Exposure Yard. It remained exposed to natural weathering until use in this study was initiated in December 1982.

TEST PLAN

After minor slab repairs were made, the following test program was initiated:

1. Establish present corrosion conditions by half-cell potential grid surveys, AC resistance and current flow measurements between top and bottom mats, and corrosion probes. Define chloride content at various locations and depths.
2. Tilt one side of the slab upward to simulate a bridge substructure more closely and repeat the corrosion condition measurements.
3. Define and install a conductive coating cathodic protection system, using the results of tests performed during Phase I laboratory testing.
4. Activate the system, determine E log I relationships, and measure polarized potentials (instant-off using an oscilloscope in the nulling mode). Set the rectifier at the appropriate constant current.
5. Monitor system performance with time throughout the contract period up to start of final report preparation. Record changes in voltage and current with respect to changing climate conditions.

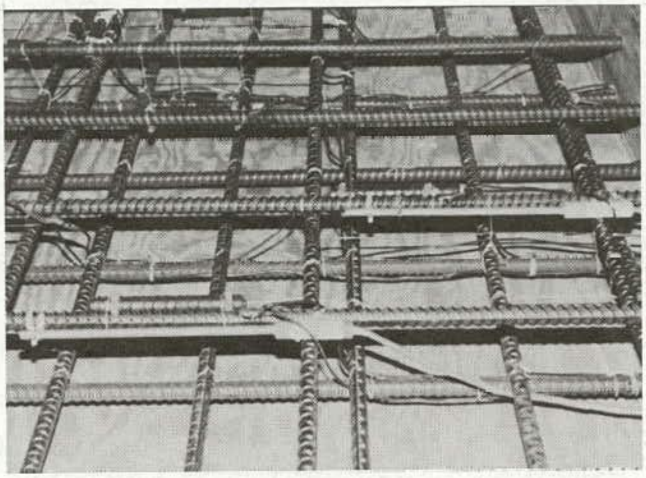


Figure B-1. Closeup of rate of corrosion and rebar probe instrumentation.

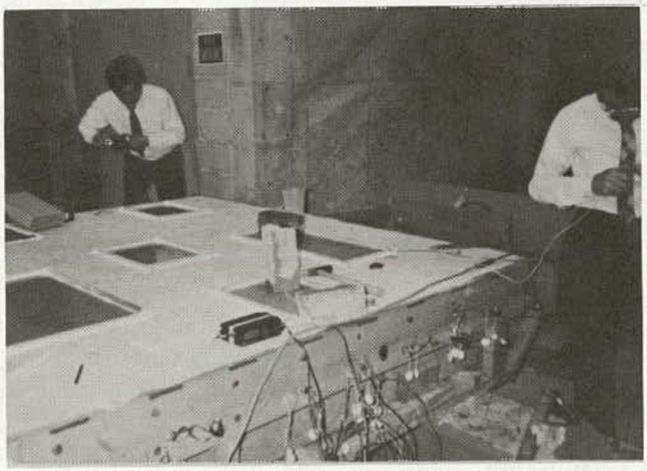
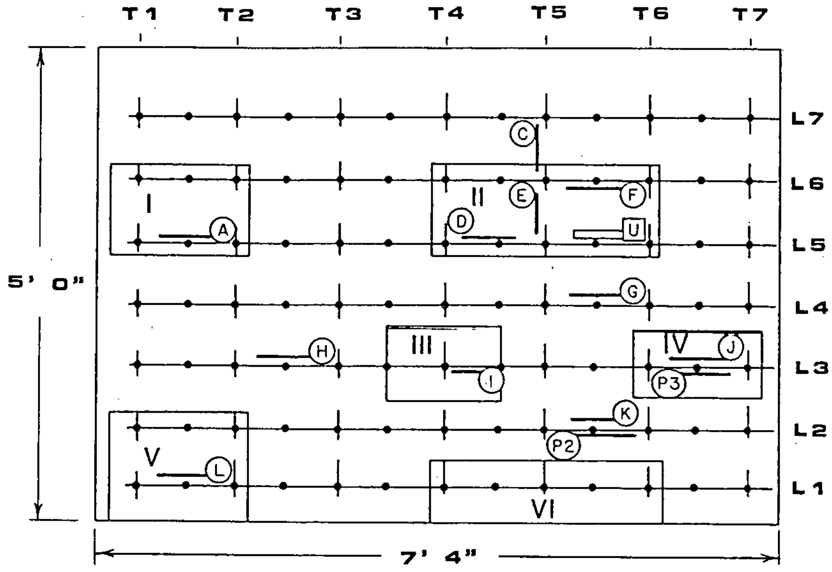


Figure B-2. Chloride intrusion procedure.



Slab: 7 in. thick
Concrete cover: Top mat = 1.5 in.
Concrete cover: Bottom mat = 1.0 in.

TOP MAT
L bars are #6, 7 ft 4 in. long, spaced @ 9 in. (7 bars)

T bars are #5, 5 ft 0 in. long, spaced @ 13 in. (7 bars)

BOTTOM MAT
L bars are same as top

T bars are #5, 5 ft 0 in. long, spaced @ $6^1/_4$ in. (14 bars)

Ⓐ = Top mat rebar and rate probe (circled)

U = Bottom mat rebar probe

Surface areas:
Concrete = 36.65 ft^2
Top mat rebar = 15.80 ft^2
Bottom mat rebar = 21.525 ft^2
1 rebar probe = 91 cm^2 = 0.0980 ft^2
1 rate of corrosion probe = 77 cm^2

Figure B-3. Locations for instrumentation and chloride intrusion.

During dry periods, wet portions of slab and determine effect on current distribution. Visually evaluate durability of conductive coating against natural weathering and effects of current flow.

6. Deactivate the CP system, determine depolarization characteristics.

BEFORE CP TEST FINDINGS

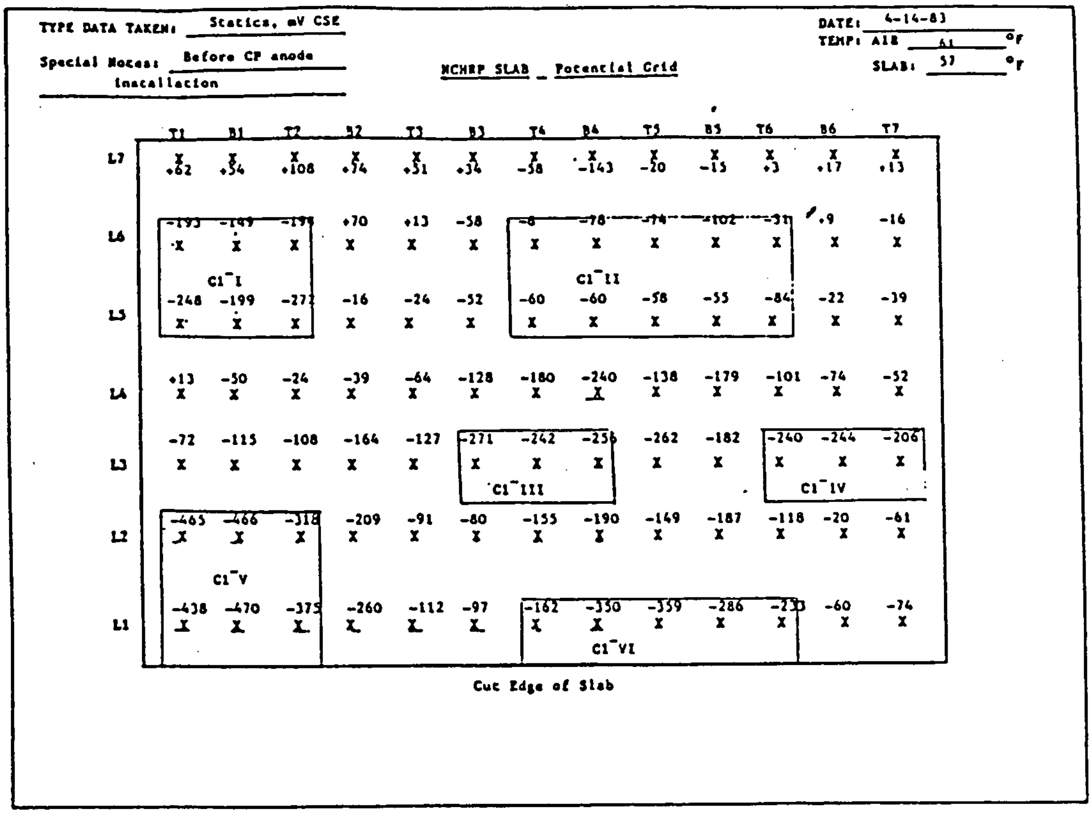
Figure B-4 presents the findings of the half-cell potential surveys performed in April 1983 before installation of the cathodic protection system. The data indicate that corrosion of the reinforcement is active at select locations on the top mat rebar and that these locations generally correspond to the chloride intrusion areas of the previous study, except that intrusion area II shows little corrosion activity. In the April 1983 survey, performed at 57 F, potential differences of more than 200 mV between measurements in close proximity were common. Summarizing:

More negative than −0.35V CSE = 9 percent
−0.20V to −0.35V CSE = 15 percent
Less negative than −0.20V CSE = 76 percent

Similar results were obtained in the May 1983 survey.

The mat-to-mat corrosion current flow data also indicated active corrosion of the top mat rebar (bottom mat rebar cathodic). The measurement was made by coupling the rebar mats externally via a 0.21-ohm resistor and defining the voltage drop across the resistor (negative lead of voltmeter to the bottom mat rebar). The uncoupled mat-to-mat AC resistance was defined in December 1982 as 3.6 ohms at a concrete temperature of 48 F. It was 2.15 ohms in May 1983 at an average concrete temperature of 66 F. In December, −1,238 μA of corrosion current was measured. In April 1983, at a slab temperature of 57 F, the mat-to-mat corrosion current was −2,095 μA. It is notable that similar measurements in the previous study prior to chloride intrusion showed no corrosion current flow between the rebar mats.

The chloride analyses data confirmed that high rebar level



TYPE DATA TAKEN: Statics, mV CSE

Special Notes: Before CP anode installation

NCHRP SLAB _ Potential Grid

DATE: 4-14-83

TEMP: AIR 61 °F

SLAB: 57 °F

	T1	B1	T2	B2	T3	B3	T4	B4	T5	B5	T6	B6	T7
L7	+62	+54	+108	+74	+51	+34	-58	-143	-20	-15	+3	+17	+13
L6	-193	-149	-19	+70	+13	-58	-8	-78	-74	-102	-31	+9	-16
L5	-248	-199	-27	-16	-24	-52	-60	-60	-58	-55	-84	-22	-39
L4	+13	-50	-24	-39	-64	-128	-180	-240	-138	-179	-101	-74	-52
L3	-72	-115	-108	-164	-127	-271	-242	-25	-262	-182	-240	-244	-206
L2	-465	-466	-318	-209	-91	-80	-155	-190	-149	-187	-118	-20	-61
L1	-438	-470	-375	-260	-112	-97	-162	-350	-359	-286	-233	-60	-74

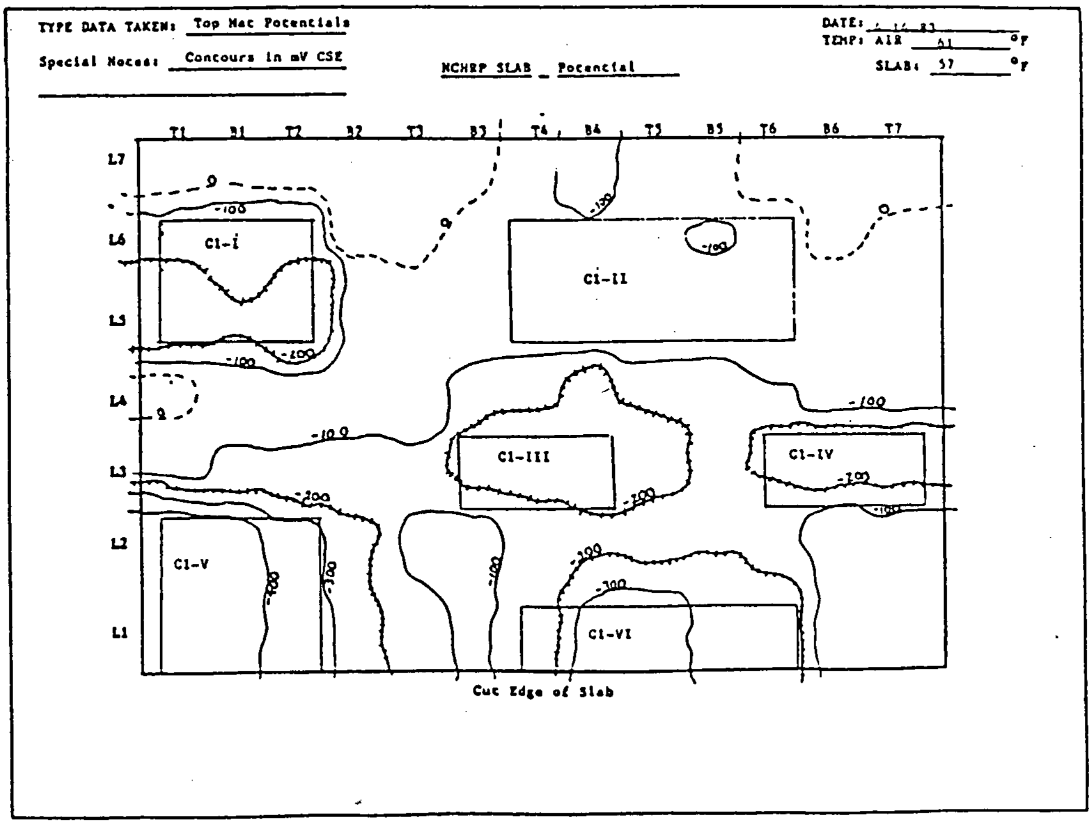


Figure B-4. Half-cell potentials of top mat reinforcing before CP—April 1983.

chloride contents exist at the actively corroding sites and that low levels of chloride are present in the slab areas not subject to salt intrusion. Based on the chloride intrusion areas, about 17 percent of the concrete surrounding the top mat rebar exhibits total chloride ion contents in excess of 1.3 lb chloride per cubic yard.

A delamination survey was also performed. Sounding indicated a probable delamination located in chloride intrusion area V. A crack along the cut edge of the slab at that location and the point that cores were taken during the previous study (in the adjacent portion of intrusion area V which was later cut off and demolished) supported the belief that a tight delamination was probably present.

THE CP SYSTEM

In May 1983 the test slab was tilted about 30 deg from the horizontal, was thoroughly sandblasted, and small plastic pipe half-cell "wells" were cemented to the surface to allow potential measurements to be taken without contacting the conductive coating.

The CP system was then installed, first by placing two primary anodes as windrows on the slab surface. Distance between the two primary anodes installed near the 5-ft long edges was 6 ft 8 in. The conductive polymer concrete exhibited a compressive strength of about 12,000 psi and an electrical resistivity of about 3 ohm-cm.

After this material had cured, conductive Coating A was applied by roller and brush at a rate of 90 sq ft per gallon. After a brief test on May 26, 1983 which showed the system was viable, the light color decorative acrylic latex paint ovecoat was applied. The photographs of Figures B-5 and B-6 show the installation process and the completed slab.

The CP system is powered using a small half wave, unfiltered constant current rectifier which is variac controlled with wiring and shunts to allow measurements of the current to each primary anode and that being received by the top rebar separately from that received by the bottom rebar.

SYSTEM ACTIVATION TESTING

Upon completion of the CP system installation, but prior to connection of the anode to the slab reinforcement, static half-cell potentials were again measured. Results were similar to previous measurements. Readings on the rate of corrosion probes were as follows. The probe in salt-free concrete, coded P2, read 77 units, while the probe in salt-bearing concrete, coded P3, read 209 units. Natural corrosion current measurements between the probes and surrounding rebar indicated that probe P3 (in salty concrete) was anodic to the rebar and thus would be expected to corrode rapidly without cathodic protection.

E log I testing of the Phase IA slab to define power requirements was performed on May 31, 1983 using the CP system rectifier under double variac (in series) control. Two different half-cells were monitored. Cell 1 was located near chloride intrusion area III at grid point L4, T4 while Cell 2 was in salt intrusion area V at grid point L1, T1. Test procedures generally followed those defined in "A Manual for the Corrosion Control of Bridge Decks," edited by Richard F. Stratfull (*10*), and all instant-off potential measurements were defined using an oscilloscope operated in the nulling mode. System currents and voltages were recorded as average DC values but later converted to true RMS values using the following experimentally defined equations:

$$\text{Current: True RMS} = 1.652\ (\text{Ave. DC}) + 1.83$$
$$\text{Voltage: True RMS} = 1.261\ (\text{Ave. DC}) - 0.21$$

The true RMS values are DC (resistance) coupled measurements defined using a Tektronics 213 oscilloscope with built-in digital multimeter. The above equations are the best fit straight lines through experimentally defined Ave. DC and true RMS data. In the case of the current conversion, the estimated variance of the slope was only 0.0000082, that of the intercept = 0.0063, and the sample correlation coefficient was 0.999949. For the voltage conversion, the values were 0.000074, 0.0003, and 0.99905 respectively.

Field plots were made during E log I testing and graphically interpreted on site. The power level was set at the I_{PROT} current plus 10 percent as a safety factor, and the CP system was operated at that level, 46 mA Ave. DC = 78 mA TRMS, throughout the test problem. In terms of current density, the above total current equals:

ITEM	CURRENT DENSITY, MA/SQ FT AVE DC	 TRUE RMS
Concrete Surface	1.26	2.13
Total Rebar Surface	1.23	2.09

Analyses of the E log I curves were later completed to confirm that the initial settings were correct. The resulting plots are given in Figures B-7 and B-8 and all data are listed in Table B-1.

In summary:

CELL NUMBER	I_{CORR} MA RMS	I_{PROT} MA RMS	E_{STATIC} MV CSE	E_{PROT} MV CSE	DELTA E MV	BC MV/DECADE
1	21	70	−262	−337	75	126
2	42	72	−416	−495	79	347

Linear polarization values for I_{CORR} were also defined using calculated (and graphically defined) Ba values, and were as follows: Cell 1 = 22 mA, Cell 2 = 43 mA. The linear polarization plots are also shown in Figures B-7 and B-8. The linear polarization data are in reasonable agreement with the I_{CORR} values obtained from the E log I plots. Interestingly, the plots of the two Tafel slopes do not meet at the measured static potential as is required by theory, and the linear polarization plots do not pass through the point of zero current and zero potential shift. (Our experiences indicate that such is a fairly common occurrence in cases when several current increments result in no change or a slightly positive change in potential near the start of the E log I test.) It is not known whether the I_{CORR} value defined from the E log I plot should be defined as the point at which the cathodic Tafel slope intersects the measured static potential, or as the point of intersection of the anodic

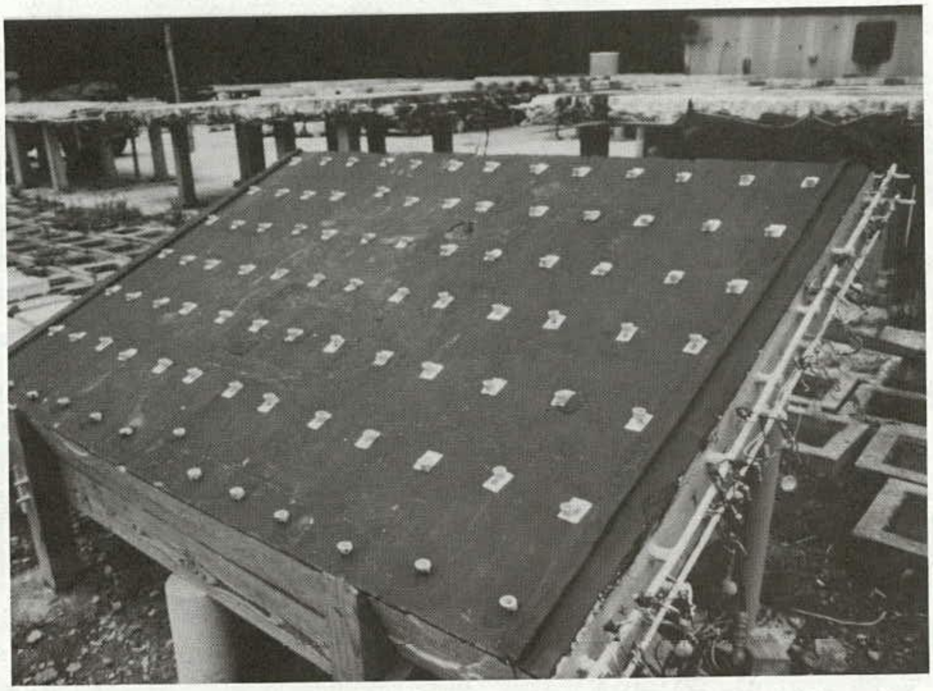


Figure B-5. Slab with black conductive paint.

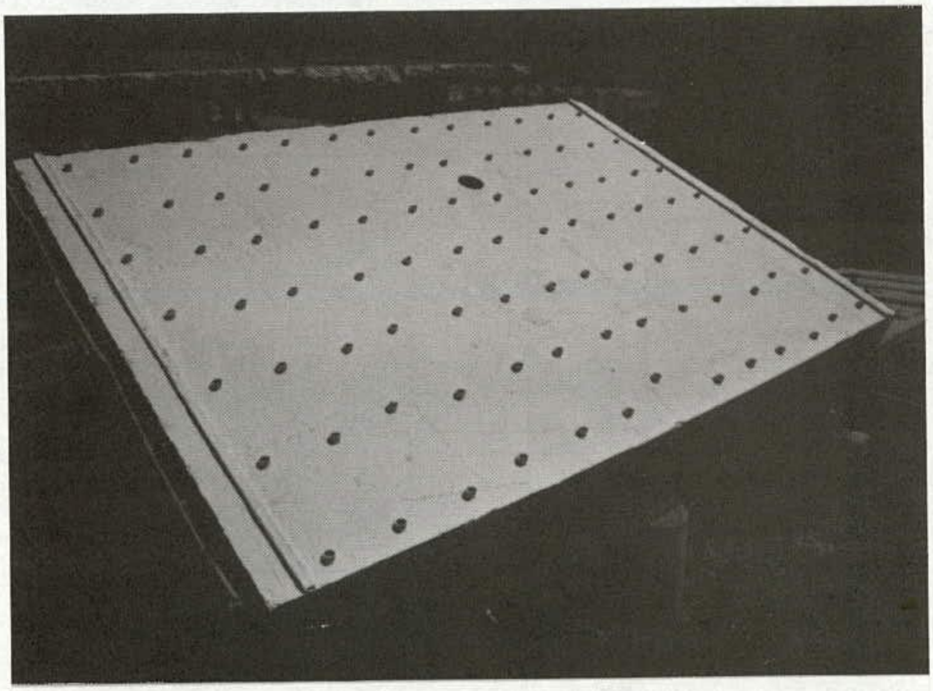


Figure B-6. Completed slab-front.

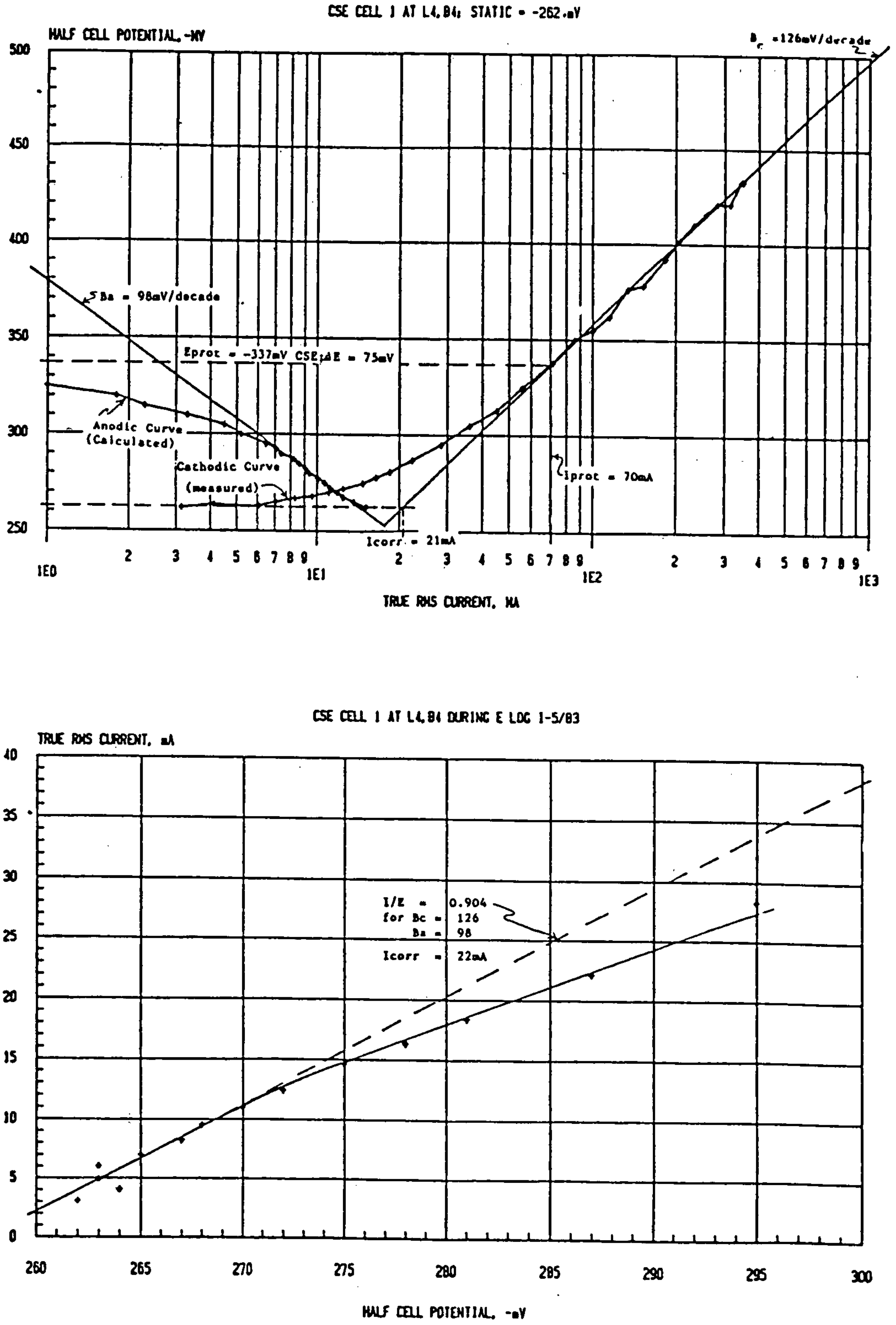


Figure B-7. E log I and linear polarization plots, Cell 1.

and cathodic Tafel lines. The former approach was taken to define the data given in the above table. If the latter approach was used, the I_{CORR} value for Cell 1 would be 18 mA and that for Cell 2 = 39.5 mA. Although the differences are not great, this offset has an effect on computer analyses which is discussed below.

As additional confirmation that the proper cathodic Tafel slope was chosen, the E Log I data were evaluated using a recently published and copyrighted computer program (*11*) modified to allow multiple runs on various portions of the data and to modify the print format. The program calculates the corrosion current and the anodic and cathodic Tafel slopes from

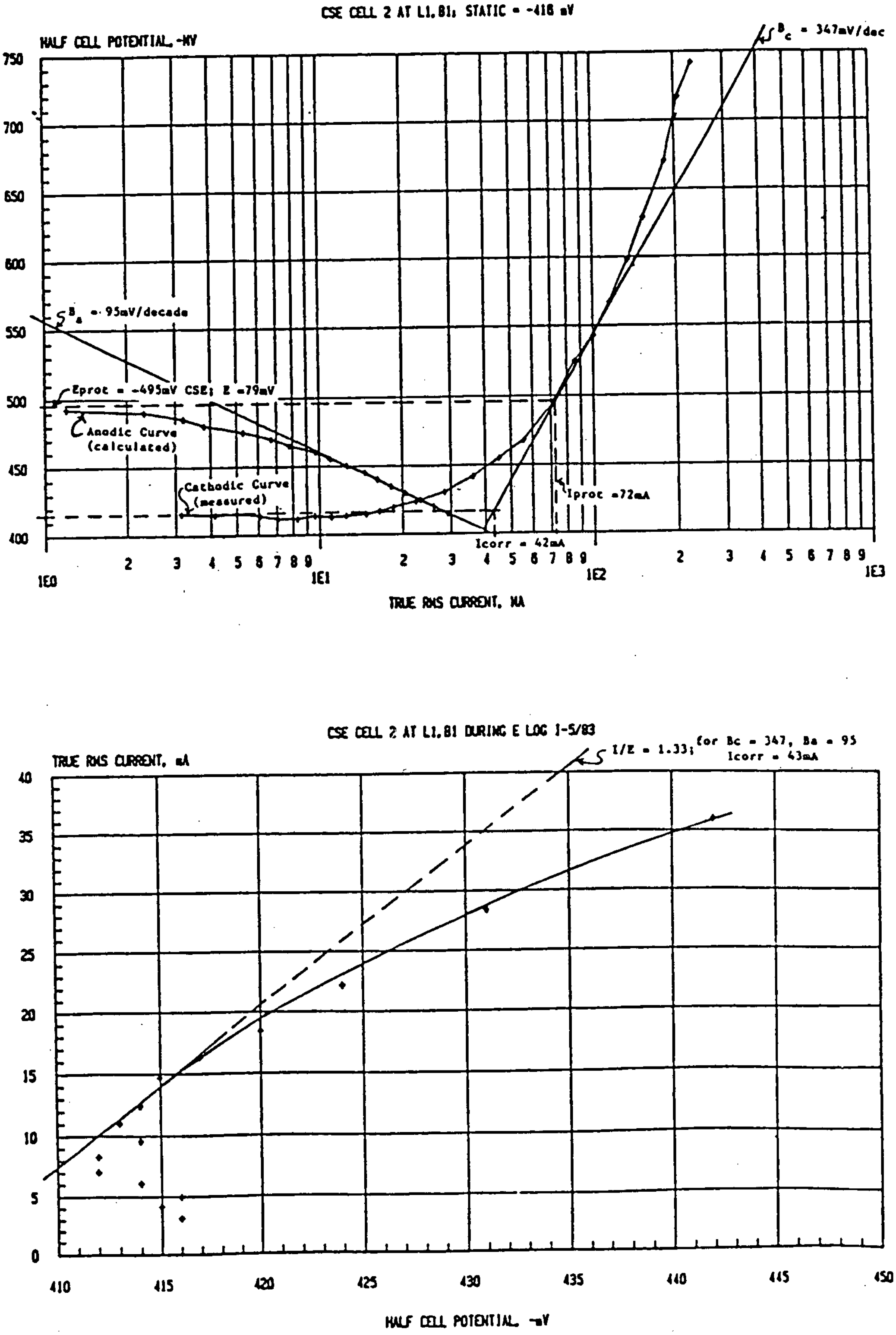


Figure B-8. E log I and linear polarization plots, Cell 2.

experimentally measured polarization data. The program is helpful in assuring that the cathodic Tafel slope was properly located during a graphical solution of E log I data. The need for such confirmation is great because several straight-line portions and breaks commonly occur in E log I data obtained on reinforced concrete and, thus, one is often unsure of which straight-line portion represents the cathodic Tafel line. It is generally believed that the multiple breaks are the result of concentration polarization (oxygen demand by the cathodic steel is greater than that available).

Unfortunately, one cannot simply input all data and have the computer calculate, because the equation given above does not

Table B-1. E log I testing—May 31, 1983.

Average Current Left Anode, mA	Average Current Right Anode, mA	Average Current Top Rebar, mA	Average Current Bottom Rebar, mA	System Volts Avg DC	Instant off Potential, mV CSE Cell 1	Instant off Potential, mV CSE Cell 2	Total Current mA Average	Sum of Rebar Currents Average	Estimated Total Current mA True RMS	Calculated TRMS Voltage
0.00	0.00	-2.22	2.22	--	-262	-416	0.00	0.00	0.00	--
0.34	0.46	-1.81	2.62	0.69	-262	-416	0.80	0.81	3.13	0.66
0.60	0.81	-1.46	2.86	0.87	-264	-415	1.41	1.40	4.12	0.89
0.81	1.12	-1.14	3.08	1.01	-263	-416	1.93	1.94	4.96	1.06
1.09	1.52	-0.72	3.34	1.11	-263	-414	2.61	2.62	6.07	1.19
1.32	1.89	-0.36	3.57	1.20	-265	-412	3.21	3.21	7.04	1.30
1.61	2.36	0.10	3.86	1.27	-267	-412	3.97	3.96	8.28	1.39
1.90	2.87	0.61	4.16	1.35	-268	-414	4.77	4.77	9.58	1.49
2.23	3.42	1.17	4.48	1.42	-270	-413	5.65	5.65	11.01	1.58
2.55	3.98	1.75	4.81	1.49	-272	-414	6.53	6.56	12.44	1.67
3.06	4.85	2.61	5.31	1.57	-275	-415	7.91	7.92	14.68	1.77
3.45	5.49	3.25	5.69	1.63	-278	-417	8.94	8.94	16.36	1.85
3.92	6.28	4.05	6.16	1.70	-281	-420	10.20	10.21	18.41	1.93
4.78	7.76	5.54	7.05	1.81	-287	-424	12.54	12.59	22.21	2.07
6.15	10.17	7.94	8.45	1.96	-295	-431	16.32	16.39	28.35	2.26
7.83	13.17	10.90	10.17	2.13	-305	-442	21.00	21.07	35.96	2.48
9.74	16.76	14.45	12.15	2.32	-313	-455	26.50	26.60	44.90	2.72
12.04	21.00	18.74	14.47	2.52	-325	-468	33.04	33.21	55.52	2.97
15.38	27.35	25.15	17.83	2.81	-338	-495	42.73	42.98	71.27	3.33
18.14	33.25	31.00	20.66	3.16	-350	-525	51.39	51.66	85.35	3.77
21.33	39.18	36.96	23.87	3.42	-355	-543	60.51	60.83	100.17	4.10
24.47	45.07	42.99	26.98	3.65	-362	-567	69.54	69.97	114.84	4.39
28.53	52.74	50.77	30.91	3.99	-376	-598	81.27	81.68	133.91	4.82
32.47	60.20	58.52	34.82	4.32	-378	-629	92.67	93.34	152.44	5.24
39.01	72.55	71.10	41.23	4.82	-392	-671	111.56	112.33	183.14	5.87
43.80	81.82	80.52	46.01	5.19	-402	-717	125.62	126.53	205.99	6.33
49.15	91.90	90.70	51.27	5.61	-410	-742	141.05	141.97	231.06	6.86
54.25	102.23	101.08	56.39	6.19	-416	-814	156.48	157.47	256.14	7.60
59.42	112.05	111.16	61.55	6.63	-421	-855	171.71	172.71	280.50	8.15
66.20	125.30	124.44	66.38	7.23	-421	-933	191.50	190.82	313.05	8.91
72.57	137.60	136.94	74.88	7.71	-433	-971	210.17	211.82	343.40	9.51
73.41	140.29	139.24	75.95	7.82	-433	-1007	213.70	215.19	349.13	9.65

consider concentration polarization. The program authors state, "If data deviate because of concentration polarization . . . , the program aborts. . . ."

Thus, attempts were made to develop an analysis scheme in which the data are sequentially analyzed in such a way that the portion influenced by concentration polarization can be identified and discarded. The procedure followed is:

1. Plot all data as one would normally do for graphical analysis.
2. By "eye" draw as many straight lines as appear valid through appropriate portions of the data.
3. Make computer runs first using all data, and then subsequently less and less of the data (i.e., eliminate first those data enveloped by the most negative straight-line portion, then those data representing the two most negative straight-line portions, etc.) in an attempt to drop off that influenced by concentration polarization and find the first valid straight line (i.e., the cathodic Tafel slope).

Also investigated has been the process of inputting only those data which represent each straight-line portion, although by inputting only a portion of the data, one must realize that the average deviation becomes less important and the question being asked is only whether or not the data conform to the Stern-Geary equation. And, in some instances, E_{STATIC} was altered slightly (most often in cases when the graphical B_a and B_c slopes do not intersect exactly at the measured E_{STATIC}) and the runs were repeated. The above approach has been used in many projects and generally has been successful. Judgment remains important however. With respect to the Phase IA slab data, the following are typical computer findings.

E STATIC	DATA POINTS	B_c MV/DEC	B_a MV/DEC	I_{CORR} MA	AVE DEV %
Cell 1:					
−262	1 to 30	130	20	17.7	16.1
−262	3 to 29	131	25	18.0	12.4
−262	3 to 26	124	19	16.3	13.5
−262	1 to 18	82	5	9.8	20.4
−254	3 to 29	142	123	19.2	3.7
−254	3 to 18	Program would not calculate			
−258	3 to 29	135	57	18.1	4.4
Cell 2:					
−416	1 to 31	580	32	51	35.8
−416	11 to 31	828	94	78	18.4
−416	11 to 22	297	15	35	15.0
−416	1 to 21	Program would not calculate			
−412	11 to 31	857	132	81	13.1
−412	11 to 22	308	32	36	7.9

Thus, although a wide range of computer analyses results can be obtained, those with the least average deviation in general agree with the graphical analysis. In the case of Cell 1, in which only one major straight-line portion occurs and encompasses data points 18 through 30, the computer generated B_c of 124 to 131 mV per decade and I_{CORR} of 16.3 to 18.0 for the measured E_{STATIC} of −262 mV CSE is in close agreement with the graphical results (B_c = 126 mV per decade and I_{CORR} = 21 mA).

Cell 2 is more difficult to analyze in that multiple breaks occur, and the data at the start of the test are nontypical. However, if the early data are eliminated, the computer-defined values for all data (through point 31) show higher deviations than those for only data through the graphical break (through data point 21) chosen. This tends to confirm the chosen B_c. Several other points concerning the computer analysis are also demonstrated by the above data. In the case of Cell 1, B_a is very sensitive to the E_{STATIC} value, whereas B_c and I_{CORR} are affected to a lesser extent. Also, the average deviation value is greatly affected by the data at the start of the E log I test. By eliminating the early points of no or slight potential change from the analysis, much lower average deviations result.

POST ACTIVATION TESTING

After system activation, system performance was monitored for more than 1 year. Data obtained include system voltages and current, polarized potentials and current received information on the rebar probes and the top and bottom slab reinforcement.

System Operation

Table B-2 shows anode current output and CP system voltages. The cathodic protection system has functioned well during the 1.2 years of testing. The average and range of output currents and voltages were as follows:

ITEM	AVERAGE	RANGE
Total Current, mA TRMS	77	72 to 81
Anode 1 Current, mA TRMS	43	37 to 51
Anode 2 Current, mA TRMS	34	29 to 37
System Volts, TRMS-DC coupled	3.2	2.4 to 4.6

The polarization voltage or back EMF was measured periodically during the last 6 months of the test program. The measurements averaged 1.5 volts and ranged from 1.1 to 1.9 volts.

Current Received by Reinforcement

In addition to monitoring the current output from the anodes, the current received by each rebar mat was defined. Table B-3 summarizes these data. On the average, 43 percent of the total current was received by the bottom mat reinforcing steel. The slab contains 15.8 sq ft of top mat rebar surface and 21.5 sq ft of bottom rebar. In terms of current density, top mat rebar received on the averages 2.76 mA per sq ft (TRMS) of steel during the test program, while the bottom mat steel current pickup averages 1.59 mA per sq ft (TRMS). Current received by the rebar mats was relatively stable with time. However, in February 1984, after about 230 days of CP, a change did occur. Current received by the top mat rebar increased about 0.5 mA TRMS per sq ft, while that received by the bottom mat decreased proportionately. During the last 7 months of the test program, the top mat density averaged 2.99 mA TRMS per sq ft and the bottom mat density averaged 1.28 mA TRMS per sq ft. Interestingly, February 1984 was also the date in which conductive paint deterioration in chloride intrusion area V became widespread.

The currents received by the rebar probes positioned at the level of, and parallel to, the slab reinforcement were also monitored. Current received by the probes in salt-free concrete was significantly less than that received by probes in high chloride concrete. Summarizing the averages throughout the program in mA average DC per sq ft of steel:

Salt-free Concrete: 0.18, 0.91, 0.98, 1.48;
Avg = 0.89
High Chloride Concrete: 2.19, 8.49, 4.53, 1.81;
Avg = 4.26

Some changes with time did occur, but no general pattern exists except for Probe L in chloride intrusion area V which exhibited the high average current pickup of 8.49 mA per sq ft. Current received by this probe was quite high and relatively stable in the range of 9 to 14 mA per sq ft throughout 1983. Significant and consistent decreases occurred throughout 1984, and at the end of the test program, current pickup of only 1.85 mA per sq ft was recorded. During this same period, anode deterioration in intrusion area V became significant and static potentials became more positive, suggesting less corrosion. Both these factors may have influenced probe current pickup.

A single bottom mat probe (U) was monitored throughout the test program. Current pickup was consistent throughout the testing and averaged 0.35 mA average DC per sq ft.

Half-Cell Potentials

Polarized potentials (instant-off using an oscilloscope) were defined at 12 random locations 2 weeks after system activation. The potentials averaged −379 mV CSE with a range of −262 to −556 mV CSE. Comparing each measurement to the before CP static potential at that location indicated that the average polarization was 193 mV with a range of 127 to 306 mV.

Table B-2. CP system operating data—expressed as both avg. DC and true RMS currents and voltages.

Date	Days Under CP	Avg DC Current Anode 2 mA	Avg DC Current Anode 1 mA	Avg DC Total Current mA	Avg DC System Volts	Concrete Temp F	True RMS Current Anode 2 mA	True RMS Current Anode 1 mA	True RMS Current Total mA	True RMS Volts
5-31-83	0	17.72	27.47	45.19	2.66	99	31.10	47.21	78.31	3.14
6-08-83	8	20.49	25.75	46.24	2.11	72	35.68	44.37	80.04	2.45
6-15-83	15	18.67	27.61	46.28	2.19	77	32.67	47.44	80.11	2.55
7-05-83	35	18.82	27.25	46.07	2.11	77	32.92	46.85	79.76	2.45
7-28-83	58	16.30	29.60	45.90	2.54	77	28.76	50.73	79.48	2.99
8-17-83	78	16.91	28.91	45.82	2.40	79	29.76	49.59	79.35	2.82
8-24-83	85	18.81	28.29	47.10	2.08	88	32.90	48.56	81.47	2.41
9-12-83	104	16.60	29.06	45.66	2.56	84	29.25	49.84	79.09	3.02
9-22-83	114	18.62	26.83	45.45	2.59	65	32.59	46.15	78.74	3.06
9-28-83	120	17.72	27.76	45.48	2.49	76	31.10	47.69	78.79	2.93
10-05-83	127	18.86	27.22	46.08	2.20	81	32.98	46.80	79.78	2.56
11-17-83	139	19.12	25.68	44.80	3.01	48	33.41	44.25	77.67	3.59
11-22-83	153	19.44	25.92	45.36	2.37	63	33.94	44.65	78.59	2.78
12-07-83	168	19.65	24.70	44.35	3.05	43	34.29	42.63	76.92	3.64
01-04-84	196	18.78	24.70	43.48	3.80	31	32.85	42.63	75.48	4.58
01-24-84	216	23.06	22.25	45.31	2.79	33	39.92	38.59	78.51	3.31
02-16-84	239	20.63	22.17	42.81	2.30	49	36.50	39.00	75.50	2.64
03-07-84	251	20.57	22.36	42.93	2.19	50	36.40	39.30	75.70	2.50
03-23-84	267	19.83	22.30	42.13	2.80	50	35.20	39.20	74.40	3.26
04-11-84	286	20.14	21.31	41.45	3.07	50	35.70	37.60	73.30	3.61
04-23-84	302	21.06	22.30	43.36	2.39	70	37.20	39.20	76.40	2.75
05-23-84	328	19.77	22.54	42.31	3.11	65	35.10	39.60	74.70	3.66
07-06-84	372	20.76	21.25	42.01	2.95	63	36.70	37.50	74.20	3.45
08-31-84	428	19.83	20.83	40.65	3.62	77	35.20	36.80	72.00	4.30
09-11-84	439	20.33	21.25	41.57	3.89		36.00	37.50	73.50	4.64
AVERAGES		19.30	25.01	44.31	2.69	65	33.93	43.35	77.27	3.16

NOTE: Data through January 1984 taken as average DC. All subsequent data measured as True RMS.

A complete top mat instant-off potential survey was performed on August 17, 1983 after 78 days of cathodic protection. The average polarization, defined as the difference between the static potentials determined on May 26, 1983 for each grid point and the instant-off potential, was 162 mV for all grid points and 228 mV for the grid points located in salt intrusion areas 1 and 3 through 6.

Instant-off potentials were again defined at all top mat grid points on February 16, 1984, after 239 days of cathodic protection. The CP system was then turned off for 1 week, and the static potentials were redefined. Depolarization, defined as the difference between the February 24th static potentials and the February 16th instant-off potentials, averaged 491 mV for all grid points as well as in the case of only those points located in salt intrusion areas 1 and 3 through 6. Interestingly, a comparison of the May 1983 static half-cell potentials and contours with those defined in February 1984 indicates that potential differences between grid points in close proximity in salt-free and salt bearing areas were much less in February 1984 than in the "before CP" survey. In addition to the static potential survey, the rate of corrosion probes was read during the system-off period in February 1984. The resulting data (77 units for probe P2 and 198 units for probe P3) indicate that no corrosion had occurred on either probe during the previous nine months of CP system operation. The data for probe P3 are particularly significant in that this probe was in salt-contaminated concrete and was determined to be highly anodic to the surrounding rebar prior to activation of the CP system.

Polarization was again defined at each grid point from a complete instant-off potential survey on March 7, 1984 (the CP system had been reactivated after the February 24th static potentials were obtained). Average polarization at all top mat grid points was 29 mV.

The CP system continued to operate through September 11, 1984. Instant-off potentials were defined on August 31, 1984 at all top mat grid points and at 10 random locations on the slab underside. After 1 month without cathodic protection, static potentials were defined at each location. Figure B-9 presents the instant-off potential data and depolarization values calculated by subtracting the instant-off potentials from the static half-cell potentials. Average depolarization for all top mat grid points was 368 mV while the underside (bottom rebar) depolarization averaged 211 mV. The static potentials at corroding rebar locations in October 1984 are significantly more positive than those measured 1.2 years earlier, before cathodic protection was applied and the potential differences between salt-free and salt-bearing areas are significantly less than in the earlier surveys. Comparing the top mat potential data:

Table B-3. Current received by rebar mats—expressed as both avg. DC and true RMS values.

Date	Days Under CP	Avg DC Current Top Mat mA	Avg DC Current Bot Mat mA	Avg DC Current Total mA	Percent to Bottom Mat	Concrete Temp F	True RMS Current Top Mat mA	True RMS Current Bot Mat mA	True RMS Current Total mA
05-31-83	0	25.52	19.96	45.48	44	99	43.99	34.80	78.79
06-08-83	8	25.44	20.90	46.34	45	72	43.85	36.35	80.21
06-15-83	15	25.96	20.29	46.25	44	77	44.71	35.35	80.06
07-05-83	35	25.75	20.51	46.26	44	77	44.37	35.71	80.08
07-28-83	58	28.00	18.00	46.00	39	77	48.08	31.56	79.65
08-17-83	78	23.62	22.53	46.15	49	79	40.85	39.05	79.90
08-24-83	85	23.79	22.98	46.77	49	88	41.13	39.79	80.92
09-12-83	104	23.59	22.37	45.96	49	84	40.80	38.78	79.58
09-22-83	114	23.39	22.30	45.69	49	65	40.47	38.67	79.14
09-28-83	120	23.53	22.36	45.89	49	76	40.70	38.77	79.47
10-05-83	127	23.65	22.72	46.37	49	81	40.90	39.36	80.26
11-17-83	139	23.08	22.05	45.13	49	48	39.96	38.25	78.21
11-22-83	153	23.28	22.49	45.77	49	63	40.29	38.98	79.27
12-07-83	168	22.71	21.75	44.46	49	43	39.34	37.76	77.10
01-04-84	196	22.56	21.36	43.92	49	31	39.10	37.11	76.21
01-24-84	216	23.06	22.25	45.31	49	33	39.92	38.59	78.51
02-16-84	239	28.14	15.16	43.30	35	49	48.70	27.60	76.30
03-07-84	251	28.70	15.03	43.73	34	50	49.60	27.40	77.00
03-23-84	267	28.33	14.91	43.24	34	50	49.00	27.20	76.20
04-11-84	286	27.83	14.73	42.56	35	50	48.20	26.90	75.10
04-27-84	302	27.53	16.51	44.04	37	70	47.70	29.80	77.50
05-23-84	328	26.79	16.45	43.24	38	65	46.50	29.70	76.20
07-06-84	372	26.91	16.14	43.05	37	63	46.70	29.20	75.90
08-31-84	428	25.86	15.77	41.64	38	77	45.00	28.60	73.60

ITEM	APRIL 1983	OCTOBER 1984
Most negative, mV CSE	−466	−270
Percent more negative than −350 mV CSE	9	0
Percent between −200 and −350 mV CSE	15	12
Range of Potentials, mV	578	294
Average Potential, mV CSE: Salt Intrusion Area V only	−422	−134

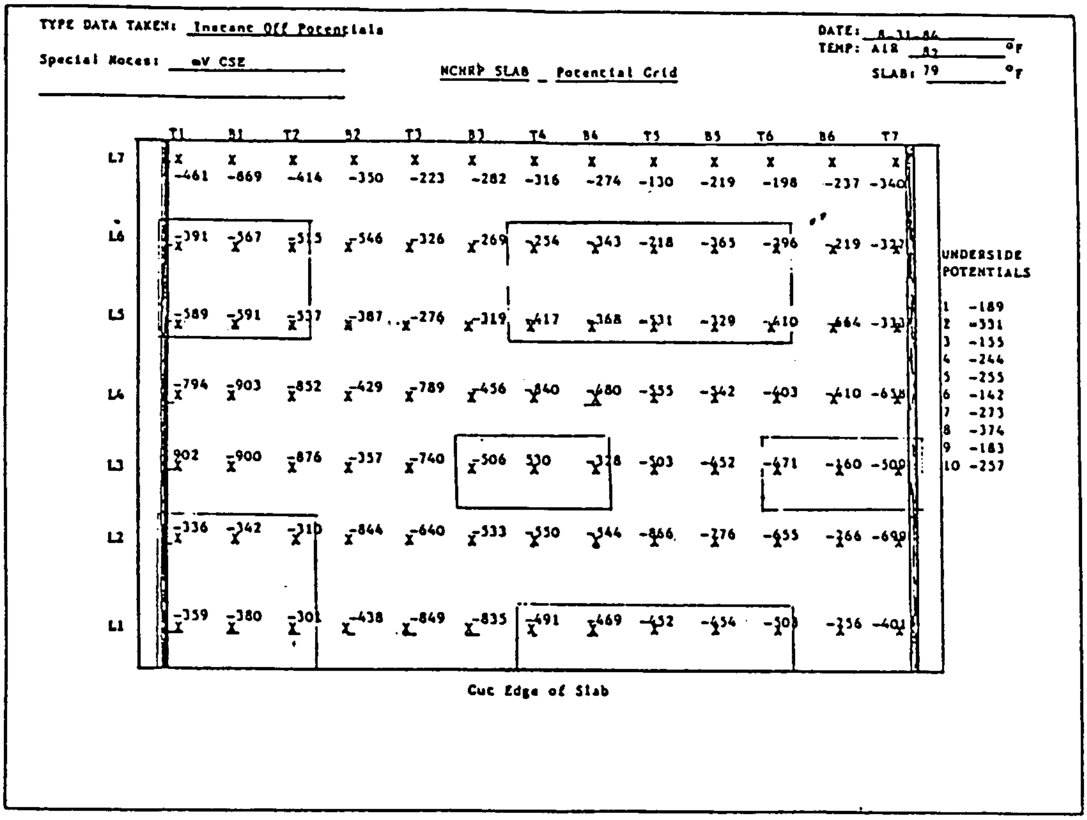
Chloride intrusion area V provides the greatest contrast. Before cathodic protection, half-cell potentials were highly negative and indicative of widespread rebar corrosion; whereas after 1.2 years of CP, the most negative potential was −193 mV CSE. Area V contained a delamination and received a very high current density during all except the last few months of the test program.

Although the foregoing data suggest reduced corrosion as a result of 1.2 years of cathodic protection, confirmation would be valuable since many factors can affect half-cell potentials. The static mat-to-mat corrosion current, which had been measured prior to application of cathodic protection, was remeasured in October 1984 after the CP system was off and disconnected for 1 month. The natural mat-to-mat corrosion current of −570 microamps (top mat rebar anodic) defined in October 1984 at an average concrete temperature of 58 F was significantly less than the "before CP" corrosion currents (only about one-fourth) defined in April 1983 (−2,095 microamps at 57 F). Thus, both the static half-cell potential and the mat-to-mat corrosion current data indicate that the 1.2 years of cathodic protection have resulted in reduced natural corrosion rates of the top mat rebar, even when the system is turned off.

Partial Wetting Tests

No unexpectedly, large changes in operating voltage to maintain the constant current were noted during the 1.2-year test period. The system voltage range of 2.4 to 4.6 volts TRMS (DC coupled) is typical for exposed reinforced concrete subject to various temperature and moisture conditions. This is quite encouraging since the test period involved hot, dry summer weather. Previous tests on paint systems without overcoats indicated great sensitivity to weather condition (i.e., wetting or drying of the thin surface concrete layer beneath the paint caused large changes in circuit resistance).

To study further the susceptibility of the system to such effects, partial wetting tests were performed in August of 1983 and 1984. On the average, the weather in the Washington, DC, area had been quite dry during the summer in each instance and no rain had occurred for about a week prior to each test. The 1983 test first involved the measurement of the operating characteristics of the CP system and the current being received by the instrumentation probes in the concrete. One-half of the slab (the left half when facing the slab from the cut edge, which includes intrusion areas I and V) was then thoroughly wetted by running water across the surface for 10 minutes. The CP operating characteristics were then remeasured.



TYPE DATA TAKEN: Instant Off Potentials

Special Notes: mV CSE

NCHRP SLAB _ Potential Grid

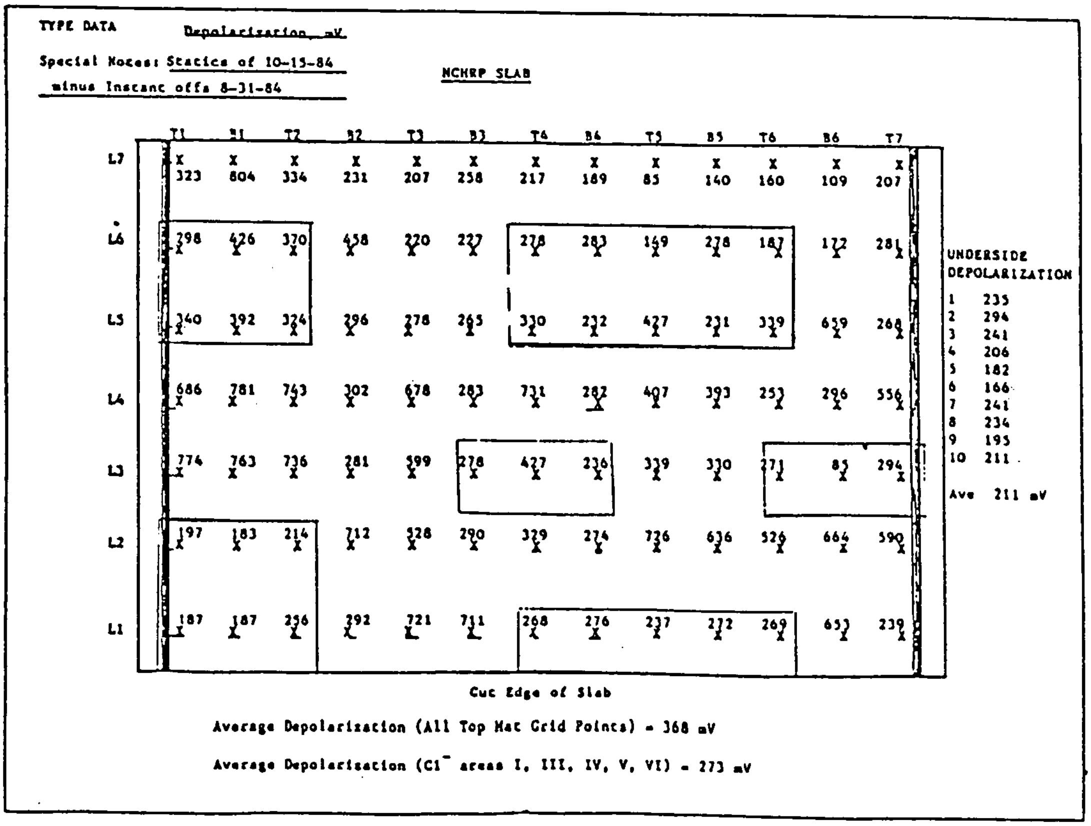
DATE: 8-31-84
TEMP: AIR 82 °F
SLAB: 79 °F

	T1	B1	T2	B2	T3	B3	T4	B4	T5	B5	T6	B6	T7
L7	-461	-869	-414	-350	-223	-282	-316	-274	-130	-219	-198	-237	-340
L6	-391	-367	-515	-546	-326	-269	-234	-343	-218	-365	-296	-219	-332
L5	-589	-591	-537	-387	-276	-319	-417	-368	-531	-329	-410	-664	-333
L4	-794	-903	-852	-429	-789	-456	-840	-480	-555	-542	-403	-410	-658
L3	902	-900	-876	-357	-740	-506	530	-328	-503	-452	-471	-160	-500
L2	-336	-342	-310	-844	-640	-533	-550	-544	-866	-276	-655	-366	-690
L1	-359	-380	-301	-438	-849	-835	-491	-469	-452	-454	-503	-356	-403

Cut Edge of Slab

UNDERSIDE POTENTIALS

1	-189
2	-331
3	-155
4	-244
5	-255
6	-142
7	-273
8	-374
9	-183
10	-257



TYPE DATA Depolarization, mV

Special Notes: Statics of 10-15-84 minus Instant offs 8-31-84

NCHRP SLAB

	T1	B1	T2	B2	T3	B3	T4	B4	T5	B5	T6	B6	T7
L7	323	804	334	231	207	258	217	189	85	140	160	109	207
L6	298	426	370	458	220	227	278	283	149	278	187	172	281
L5	340	392	324	296	278	265	330	232	427	231	339	659	268
L4	686	781	743	302	678	283	731	282	407	393	253	296	556
L3	774	763	736	281	599	278	427	236	339	330	271	85	294
L2	197	183	214	712	528	290	329	274	736	636	526	664	590
L1	187	187	256	292	721	711	268	276	237	272	269	653	239

Cut Edge of Slab

UNDERSIDE DEPOLARIZATION

1	235
2	294
3	241
4	206
5	182
6	166
7	241
8	234
9	195
10	211

Ave 211 mV

Average Depolarization (All Top Mat Grid Points) = 368 mV

Average Depolarization (Cl^- areas I, III, IV, V, VI) = 273 mV

Figure B-9. Instant-off potentials and depolarization—August 1984.

Comparison of the before and after wetting showed virtually no change in CP system voltage (2.83 volts TRMS dry vs. 2.69 volts TRMS wet), or current output from each of the two primary anodes even though one was wet (dry current = 29.8 and 49.6 mA TRMS, wet current = 29.9 and 49.6 mA TRMS). Similarly, current received by the reinforcing mats and the probes changed very little. No anode deterioration was visible during these tests.

The data from the August 1984 partial wetting test indicated that partial wetting caused some decrease in system volts (4.18 volts before wetting to 3.69 volts TRMS after wetting), but had little effect on the system operating current or current received by the reinforcing mats. The voltage change is not considered great in that a similar change will occur due to relatively small variations in temperature.

Visual Examination of Anode Condition and Comparison to Current Density and Polarization Data

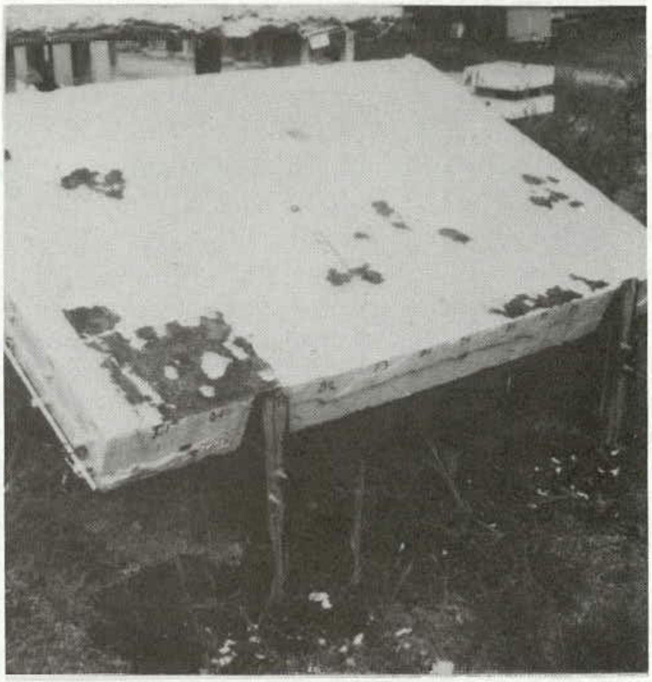
The conductive coating secondary anode was visually examined for deterioration during each site visit. No deterioration was found during the first 4 months of system operation. In September 1983, several 1/4-in. diameter blisters were detected in chloride intrusion area V. These remained relatively unchanged for several months, until late winter when in February 1984 somewhat larger areas of coating in intrusion area V became disbonded.

To define areas of disbondment completely, the entire slab surface was wire brushed after 1.2 years of operation. Photo A of Figure B-10 shows the slab surface after wire brushing. Paint loss occurred in all the chloride intrusion areas except area II, which was not as greatly salt-contaminated and did not exhibit corrosive half-cell potentials prior to test. Examination of the disbonded paint and the concrete surface in these areas indicated that the deterioration appeared to occur at the slab concrete/paint interface with the result that the conductive and overcoat paints became disbonded and eventually would "flake off." No consumption of the conductive paint was noted (although no actual measurements were made). No paint loss was found in areas exhibiting passive potentials prior to test (i.e., the salt-free areas of the slab).

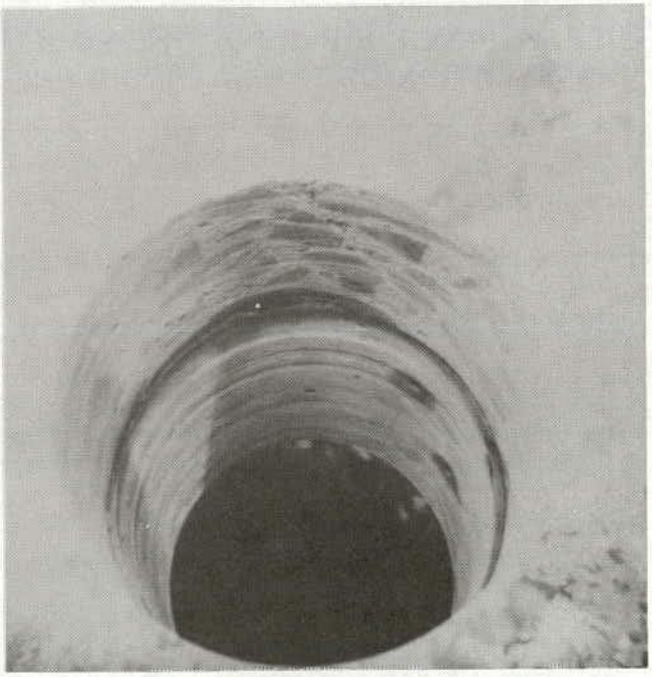
In addition, two cores were taken from intrusion area V to confirm that a delamination was present. A delamination was confirmed at the top mat rebar level. See photo B of Figure B-10. Several points concerning this situation are notable.

1. The coating loss was visually annoying, but, as evidenced by the potential survey results, had no large adverse effect on the cathodic protection system's ability to stop corrosion.

2. The coating loss areas are located at points of high current density (as evidenced by the rebar probes). Intrusion area V, containing probe L and a delamination at the top mat rebar level, exhibited paint loss first. During the first 6 months of test, the current received by probe L averaged 10.8 mA DC per sq ft of steel. If one assumes that all rebar in intrusion area V received similar current, the conductive paint anode in this area would have dissipated 8.1 mA average DC and 13.5 mA TRMS per sq ft of paint surface. If a similar calculation is performed for all chloride-bearing areas with probes and the salt-free concrete with probes, to estimate conductive paint discharge current densities, the following results are obtained:



A. Anode condition after wiring brushing paint surface—September 1984



B. Core hole—area V. Note delamination at top rebar level in intrusion area V.

Figure B-10. Paint anode and slab condition in February and September 1984.

LOCATION AND PROBES	PAINT CURRENT DENSITY, MA/SQ FT	
	AVE DC	TRMS
Chloride I —Probe A	2.08	3.49
Chloride II —Probes D, E, F	0.60	0.98
Chloride III—Probe I	2.45	4.11
Chloride IV—Probe P3	1.43	2.41
Chloride V —Probe L	8.13	13.48
Salt-free —Probes C, H, G, K	0.35	0.63

Only the data through December 1983 were used in the above calculations for probe L in chloride area V, whereas data for the entire test program were used in all other instances. The probe average current densities appear to be a valid indicator of average top mat rebar current density in that a cross-check achieved by multiplying each current density in the foregoing table by the concrete surface area (area 6 with no probes was assumed to have a density equal to the average of areas 1, 3, and 4) and then summing the results, yielded an average calculated top mat rebar current density of 46 mA TRMS per sq ft of top mat rebar, a value within 5 percent of the average of the actual measured values (44 mA TRMS per sq ft of rebar).

Thus, these data indicate that in a delaminated area of very high current density (13.5 mA TRMS per sq ft of paint surface), paint loss was first visible, but minor, in 4 months. At 9 months, it became visibly significant, although by that time the highly corrosive potentials in that area had been eliminated by the CP system (see static potentials of February 1984). In 1.2 years, visible paint loss of a minor nature, but significant paint disbonding occurred in areas in which the average current density was in the range of 2.4 to 4.1 mA TRMS per sq ft of paint surface. This disbondment and paint loss had no adverse effect on functioning of the CP system. No paint loss or disbonding occurred in the areas in which the average current density was 0.6 and 1.0 mA TRMS per sq ft of paint (concrete) surface during the 1.2 year test program. This "no paint deterioration" area covered more than 85 percent of the slab surface.

APPENDIX C

REPAIR PROCEDURES FOR THE ROSEMONT PIER AND INSTALLATION OF THE CATHODIC PROTECTION SYSTEM ANODES

INTRODUCTION

This appendix describes the structural repair of, and installation of a cathodic protection system for, the east pier carrying the eastbound lane of the Kennedy Expressway overpass above the northbound lane of River Road in Rosemont, Illinois. This pier had been damaged significantly by reinforcement corrosion caused by road salts containing chloride. The structural repairs were completed by the State of Illinois Department of Transportation during the summer of 1983. An experimental cathodic protection (CP) system, utilizing a conductive paint coating, was then installed on the pier and activated that autumn.

CONDITION OF PIER

During the summer of 1983, repairs were made to the piers beneath the eastbound lane of the Kennedy Expressway overpass at River Road in Rosemont, Illinois. At that time, the structure was 25 years old. The pier has been exposed to considerable amounts of chloride each winter. By 1983 the piers were in poor condition (see Figs. C-1, C-2 and C-3), with considerable areas of delaminated and spalled concrete caused by significant steel corrosion. Repairs to the pier were indicated.

A request was made of the Illinois Department of Transportation that they allow the east pier of the structure to be used for this cathodic protection study, to which they agreed.

Before repairs were started, a study was made of corrosion damage to the structure. This included determining CSE half-cell potentials (ASTM C-876). Half-cell potentials ranged from −0.22 to −0.65 volts, with a mean value of −0.44 volts. A survey was made of chloride contents in the concrete at various depths beneath the concrete surfaces. Concrete chloride contents at the surface of the pier averaged 18.4 lb of chloride ion per cu yd of concrete. At a depth of from $\frac{1}{2}$ to $1\frac{1}{4}$ in. below the concrete surface, chloride contents averaged 17.3 lb/cu yd concrete. At depths of from $1\frac{1}{4}$ to 2 in. and 2 to 3 in., chloride contents averaged 9.1 and 5.4 lb/cu yd of concrete, respectively. Concrete delaminations were also located and marked. Figure C-4 shows the extent of the delaminaation removal on the pier face next to River Road traffic lanes.

After the condition survey on the structure was completed, Illinois DOT forces repaired the pier. They were requested, insofar as possible, to follow routine repair proceduers for chloride damaged piers of this type. Repair methods consisted of:

1. Installing shores to support the pier cap during the repairs.
2. Removing all delaminated and unsound concrete with light chipping hammers. Where steel reinforcement was exposed, concrete behind each bar was chipped away to a minimum depth of 3/4 in. around the bar.
3. Sandblasting the reinforcement and adding extra reinforcement where needed.

4. Setting forms to replace concrete removed during the chipping operation. When possible, forms were fixed to the original structure with steel bands to minimize shoring and the need for form ties (see Figs. C-5 and C-6).

5. Premoistening original concrete surfaces before placing new concrete.

6. Placing air-entrained repair concrete obtained from a local ready mix concrete supplier. The concrete mix was made using Type I cement, a nominal cement content of 6½ bags/cu yd, high-range water-reducing admixture (superplasticizer), and 3/8-in. maximum size aggregate. Slump of the repair concrete was approximately 4 in. Concrete was placed through pockets in the forms and vibrated internally and externally with a spud vibrator.

Forms were removed approximately 3 days after casting. Additional moist curing was applied the following 4 days.

Because a cathodic protection system was to be installed after repairs were completed, certain features of the repair were unique. The most important extra work performed by the repair crew to facilitate installation of the CP system was as follows.

The engineers and repair crew tried to detect and eliminate all small pieces of steel, such as chairs, bolsters, tie wires, form ties, etc., which ran between the outside concrete surface and the internal steel reinforcement. These steel items ultimately would cause short-circuits between the conductive coating painted on the concrete surface and the steel reinforcement if not removed. This wastes power. Furthermore, the short-circuit would reduce the voltage of the conductive coating in the area surrounding the short-circuit. Reinforcement near these low-voltage areas would not receive sufficient CP current to obtain full protection against further corrosion. Meanwhile the actual steel causing the short-circuit would become anodic and corrode very quickly. Major efforts to eliminate shorts were:

1. Chipping out concrete around the feet of reinforcing steel chairs exposed on the soffit of the cap and clipping off the chair

Figure C-1. General deterioration of pier base, column and cap (south end).

Figure C-2. Spalled base of pier cap.

Figure C-3. Deteriorated base of north column.

Figure C-4. Bridge pier after removal of majority of delaminated and unsound concrete.

feet at a level approximately 3/4 in. beneath the finished concrete surfaces.

2. Chipping out and removing exposed bar-support bolsters from sound concrete on the bottom of the cap.

3. Investigating any exposed rust areas on the surface of sound concrete. If the source of the rust was a tie wire or snap tie end too close to the concrete surface, the metal was cut back away from the concrete surface and the void was repaired with dry-pack concrete.

4. Using cone-type snap ties to support the form for the beam soffit during the concrete repair. With these ties it was possible to examine each broken snap tie and confirm that tie ends were at least 3/4 in. beneath the finished concrete surface, which was later painted with the conductive coating material.

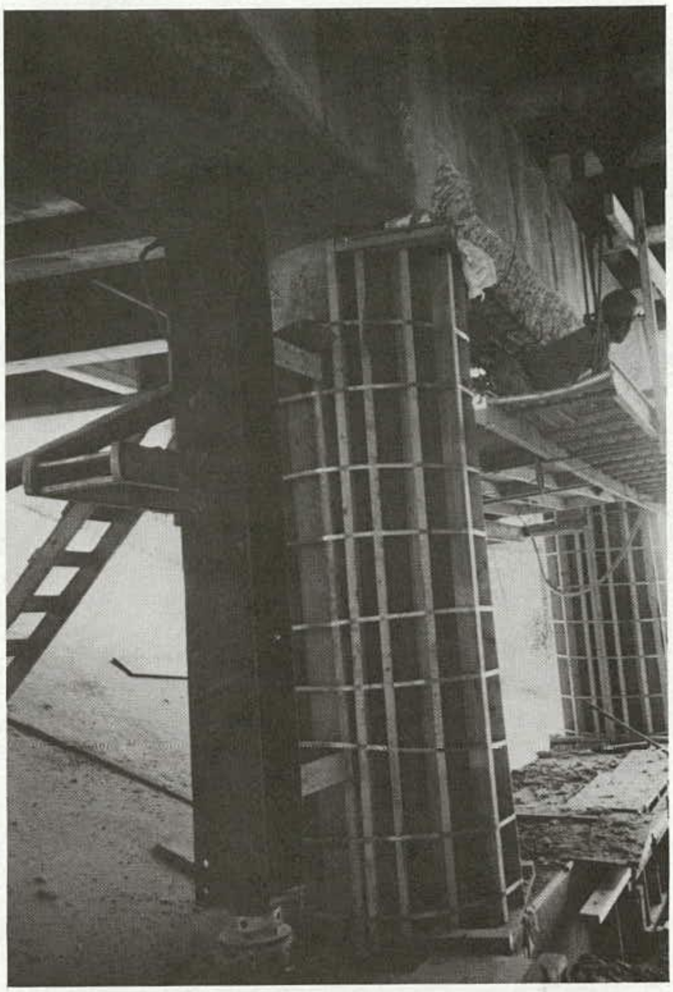


Figure C-5. Wood form details for column repair.

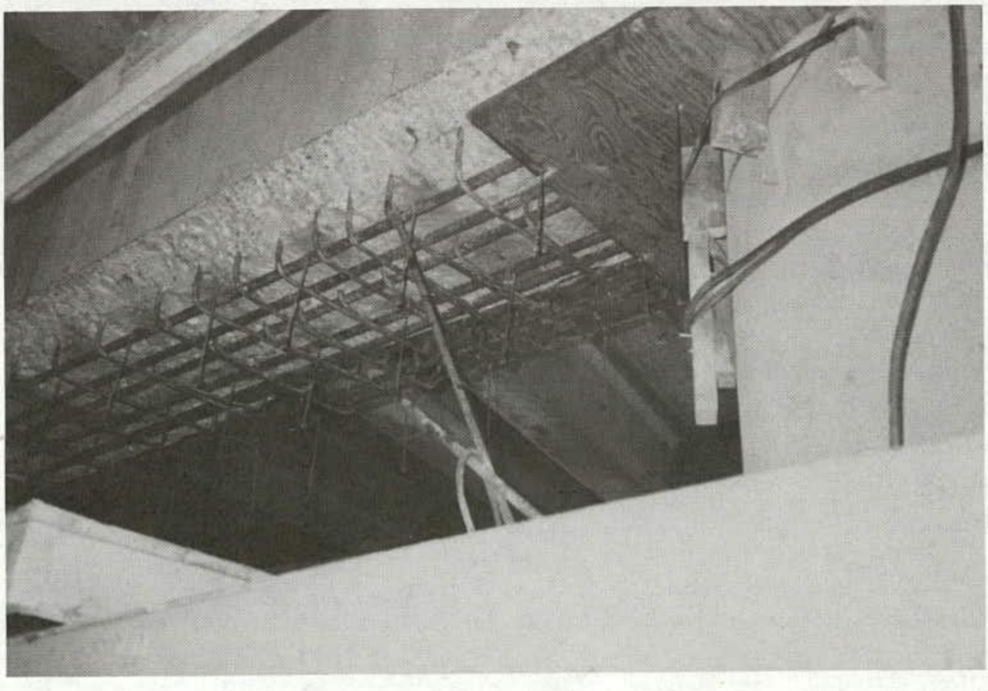


Figure C-6. Use of snap form ties to support wooden forms for pier cap soffit.

Electrical ground wires (see Fig. C-7) were brazed to reinforcing bars. The ground wires installed in the pier were insulated, single conductor, No. 10, solid copper wires which were not easily burned-through by brazing. After brazing, each ground connection was carefully cleaned and potted with a flexible epoxy to protect it from subsequent localized corrosion.

A 2½ x 2½ x 8½ in. "macrocell" was embedded in the south column, or zone 1. It was necessary to cut away some of the column reinforcement and place "helper bars" at the edges of the large void required for the macrocell, which is shown in Figure C-8.

"Rebar probes" (see Fig. C-9) were embedded at various locations in the structure. These probes are short pieces of No. 5 reinforcing bars with a copper wire lead attached. The connections are potted in epoxy. The probes were placed in voids chipped in the original concrete and embedded in repair concrete having chloride content of 15 lb/cu yd to simulate the chloride content of the surrounding structural concrete.

Two reference cells were embedded in the center column. The molybdenum-molybdenum oxide cell and the silver-silver chloride cell were placed in areas of original concrete at the level of the reinforcement. Small cavities were chipped out between reinforcing bars to accommodate these cells. The cells were embedded in repair concrete containing 15 lb of chloride per cu yd, also to simulate surrounding concrete.

Whenever possible ground wires and leads from the various electrical devices just mentioned were embedded in repair concrete to prevent them from being vandalized. When it was not possible to install leads inside repair concrete, saw kerfs approximately 1/2 in. wide and 3/8 in. deep were cut in existing concrete surfaces. Two such parallel, vertical saw kerfs are shown in the column in Figure C-7. One was cut to hold the ground wire, the other a primary anode. Loose ground wires were cemented in the saw kerfs with a vinyl ester-sand mortar.

A separate AC electrical circuit to power the cathodic protection system was brought to the pier and stubbed off at a circuit breaker in a weatherproof box. Conduit was run from this box to other boxes which contained CP system controls, such as rectifiers, variable autotransformers, shunts, and connections for grounds, the macrocell, rebar probes, the two reference cells and a thermocouple.

PRIMARY ANODES

The primary anodes used for the CP installation consisted of two different materials; a special wire conductor inside a thick outside coating of a conductive polymer mixture of vinyl ester and carbon filler.

The anode wire is specially made for cathodic protection. It has a total diameter of 0.031 in., and consists of a core of copper wire and outside platings of niobium and platinum metals. These coatings prevent the rapid corrosion of the anode wire.

All anode wires terminate at one of the four control boxes. Long runs of this wire, to the individual areas where they actually serve as anodes, were insulated with shrink-fit tubing. At locations where the wires served in primary anodes, they were always embedded in a layer of conductive polymer. The shell of conductive polymer surrounding the anode wires had three purposes:

1. It surrounded the wire with a conductive material that was comparatively impermeable to the ingress of corrosive solutions from the concrete—this prolongs the life of the wire.
2. It solidly anchored the conducting wire to the structure—

Figure C-7. Ground wire attached to exposed reinforcing bar of column.

Figure C-8. Precast marcocell assembly suspended between reinforcing bars with plastic ties prior to casting repair concrete.

Figure C-9. Rebar current pickup probe in place.

this minimizes the possibility of vandals or ordinary weathering tearing the wire away from contact with the conductive coating.

3. It provided a large contact area between the primary anode and the conductive coating—the larger contact area is more durable and has a longer life than a smaller contact area obtained only between anode wire and the conductive coating.

Figure C-10 shows the arrangement and numerical designations of the primary anodes installed on the pier.

Figure C-11 shows the three primary anode configurations used for the Rosemont pier. Figure C-11(a) is a cross section of primary anodes 1-3, 2-3, and 3-3 installed on the columns. A saw kerf was cut with a carborundum blade the full length of the columns. Bare anode wire was run through the saw kerf, centered in the void, stretched tight, and held with a putty-like compound at intervals throughout the length of the kerf. Then the conductive polymer was gradually trowelled into the saw kerf around the wire until the full length of the saw kerf was filled with the polymer. The plastic polymer was struck off level with the face of the concrete. This procedure produced a neat, extremely rugged primary anode.

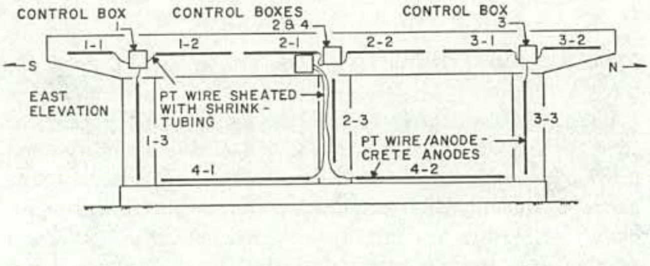
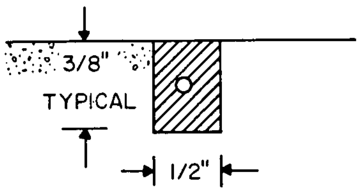
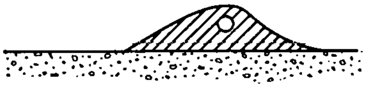


Figure C-10. Primary anode locations.

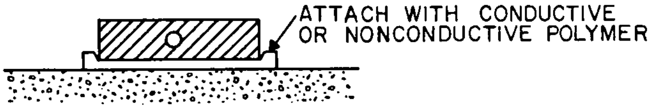
Figure C-11(b) shows the configuration of primary anodes 4-1 and 4-2 used on the base of the pier. The anode wire was weighted at either end of the pier base so it was at the proper location but suspended approximately 1/8 in. away from the concrete. A bead or windrow of conductive polymer was placed around the wire, compacted, and finished with a small trowel.



(a) PRIMARY ANODE IN SAW KERF



(b) WINDROW PRIMARY ANODE



(c) PRECAST PRIMARY ANODE

Figure C-11. Primary anodes.

The bead was formed by extruding the polymer from a hole in a heavy-gage plastic food bag.

Figure C-11(c) shows a cross section of the "precast anodes" 1-1, 1-2, 2-1, 2-2, 3-1, and 3-2, which were attached to the pier cap. These anodes were precast by a commercial supplier and cemented to one side of the pier cap. Half of the precast anodes were cemented to the concrete with conductive polymer. The other half were cemented with a nonconductive mixture of vinyl ester resin and silica sand.

All the primary anodes used on the structure were cast or attached to the concrete before the conductive coating was applied. The conductive coating was simply painted over all primary anodes and then rolled outward over other concrete surfaces.

APPLYING THE CONDUCTIVE COATING

Before the conductive coating was applied to the pier, the concrete was sandblasted to clean the concrete surfaces and provide a rough base to which the coating could adhere. Loose particles remaining after sandblasting were removed with an air-blast. Coating the structure was deferred until it had sufficient time to dry after repeated rainstorms, which occurred after cleaning had been done.

Conductive coating A was applied to virtually all surfaces of the pier. Areas of the pier which were not coated were:

1. Support hardware for the bridge beams which rested on the pier cap.
2. Small steel articles, such as anchor bolts for electrical conduit and fixtures on the pier, which were embedded at the concrete surface and might cause shorts between the conductive coating and the reinforcement.
3. Electrical conduit, fixtures, and control boxes.

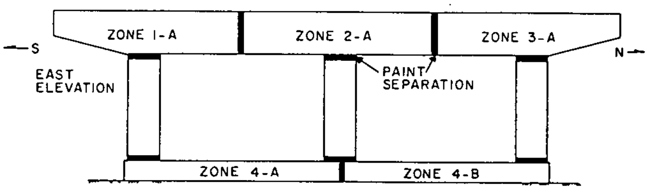


Figure C-12. Conductive paint separations divide pier into cathodic protection zones.

To prevent short-circuits to soil, the conductive coating was discontinued on portions of the base within 2 in. of the ground.

Various "zones" of the structure, which had different controls and primary anodes, were isolated by 2-in. wide bands of bare concrete. These uncoated bands were masked-off with tape before the conductive coating was applied to the structure. Figure C-12 shows the individual zones isolated by the paint separations.

According to the manufacturer of conductive Coating A used for the CP installation, the coating may be applied either with a brush, roller, or pressure-spray. The pier was coated using a roller, with minor touching-up using a brush. It was found that roller application of the conductive coating was simple and effective.

The conductive coating was applied in 2 coats, with a combined coverage of approximately 90 sq ft/gal.

SUMMARY

The east pier of the eastbound Kennedy Expressway over River Road in Rosemont, Illinois, was repaired in the summer of 1983. Then an experimental cathodic protection system was installed and utilized a skin of conductive paint at the media for distributing CP current across the faces of the structure.

Repair procedures ordinarily employed by the Illinois DOT for piers were used to restore the corrosion-damaged pier. Particular care was necessary during the repairs to eliminate all short-circuits between the conductive coating at the concrete surface and the steel reinforcement. Such conductors as steel ties, chairs, and bolsters would short-circuit CP currents from the conductive coating directly to the reinforcement, and therefore were removed during repair. Miscellaneous items of instrumentation and CP circuit grounds were installed during the structural repairs. The cathodic protection system was then installed. It was constructed as follows:

1. Primary anodes, made of platinum-coated wire surrounded by an electrically conductive polymer, were attached to the concrete surfaces after the repair.
2. An overall coating of conductive paint was applied with a roller. The structure was cleaned by sandblasting and dried sufficiently to provide good bond before the conductive coating was applied.
3. A separate AC line was installed to provide power for the CP system.
4. Control boxes were installed to house equipment rectifying CP currents. Among this equipment were variable autotransformers and rectifiers to deliver low-voltage DC pulses.

APPENDIX D

PHASE II—INSTRUMENTATION OF THE CATHODIC PROTECTION SYSTEM

INTRODUCTION

Planning the layout of a cathodic protection system for a structure requires that assumptions be made as to the number and location of zones to be protected, and also the power rating and number of regulators required. Generally, the initial assumptions are based on the designer's estimate of the CP current required per square foot of surface area. This estimate can be confirmed or disproved only after the system has been installed and E log I tests indicate what the CP current requirements for the structure will be. This appendix discusses some of the factors considered in planning the layout of the CP system for the Rosemont pier.

The location and use of the various instruments in the structure are discussed in this appendix, as are the routine tests performed while monitoring the CP system.

PLANNING OF CATHODIC PROTECTION ZONES

The Rosemont pier might have been cathodically protected with fewer zones and half of the rectifiers actually used. However, this was primarily a research project with a number of variables, such as the configurations of primary anodes, which would not be present in an ordinary CP installation. This, and the need to collect and compare data from a number of different sites on the structure, governed the decision to increase the number of zones and rectifiers beyond minimum requirements. The number of the test locations and the variety of test instruments were also greater for this research installation than those which would be installed in the ordinary CP installation.

Considerations in this selection of the number of control units and the areas of the structure to be controlled were:

1. Control boxes were placed away from access by vandals. The best position was on the side of the cap away from the traffic lanes (see Fig. D-1).

2. To minimize wiring runs, areas near a control unit should be controlled by that unit, if possible. This requirement was met by having units 1, 2, and 3 control portions of the cap on which they were located and the pier column immediately beneath. Thus only unit 4, which controlled the base, was located at some distance from the zone which it controlled.

3. If possible, each of the 4 units should control approximately one-quarter of the structure. Table D-1 gives the areas of concrete and of reinforcement protected in each of the zones. The units for zones 1, 2, and 3 have similar areas of reinforcement and concrete to protect. The base area (zone 4) was somewhat smaller than the areas protected by the other units. However, there was a possibility that some shorting of CP current to ground might occur when the structure was wet. This factor warranted extra capacity in that unit.

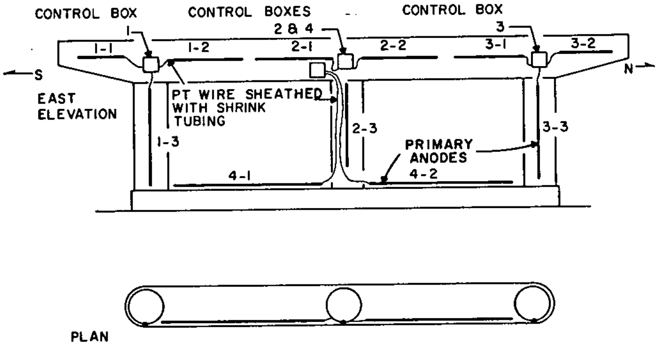


Figure D-1. Anode locations.

Table D-1. Illinois substructure—Pier 3, surface areas.

Item	Concrete Surface, ft^2	Rebar Surface, ft^2	Ratio Rebar/Concrete
A. Pier Cap			
1. Top	186.2	89.6	0.48
2. Side	180.3	89.8	0.50
3. Bottom	159.1	115.5	0.73
Entire Cap (Top, 2 Sides and Bottom)	705.9	384.7	0.54
B. Column	78.5	52.9	0.76
C. Footing			
1. Top	99.4	52.0	0.52
2. Side (above-ground)	52.3	16.9	0.32
Entire Footing (Top and 2 Sides)	204	85.8	0.42
Entire Project (Cap, 3 Columns and Footing)	1145	650.2	0.57
By ZONE			
CP Zone 1 - 1/3 cap and 1 column	314	188	0.60
CP Zone 2 - 1/3 cap and 1 column	314	188	0.60
CP Zone 3 - 1/3 cap and 1 column	314	188	0.60
CP Zone 4 - Footing	204	85.8	0.42

4. As indicated previously, the potential output of the rectifiers was greater than the actual power demand of the CP system. This became evident during planning. However, the advantages of obtaining data from a greater number of areas and the ease of starting up the system and maintaining it in operation when only small segments of the structure were involved were considerable. Furthermore, elimination of overcapacity is simpler than last-minute addition of extra regulators.

THE CONTROL UNITS

Figure D-2 is a schematic of the CP electrical system, with the electrical gear required to control and measure current applied to the CP system shown as a "control unit" in the figure. The control unit produces a pulsating direct current waveform which is applied to the anodes of the CP system. The present output of each control unit in the system is approximately 2 watts, at 3 volts RMS.

The figure shows that the positive lead from the control unit is attached to the primary anode, which is in direct contact with the conductive coating covering most of the structure. The negative lead from the control unit is grounded to the reinforcement in the pier. The location of the various grounds to which the rectifier negative leads are attached is shown in Figure D-3.

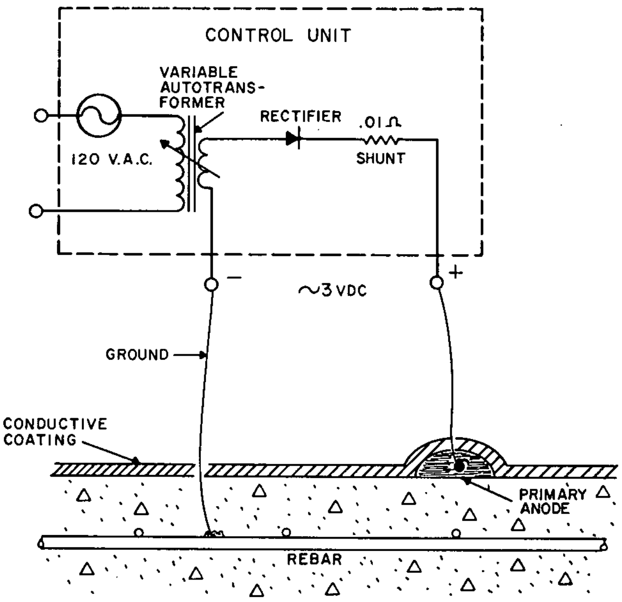


Figure D-2. Schematic of cathodic protection system.

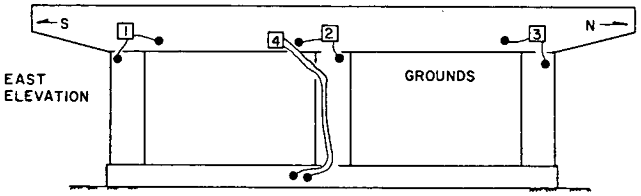


Figure D-3. Location of rebar grounds.

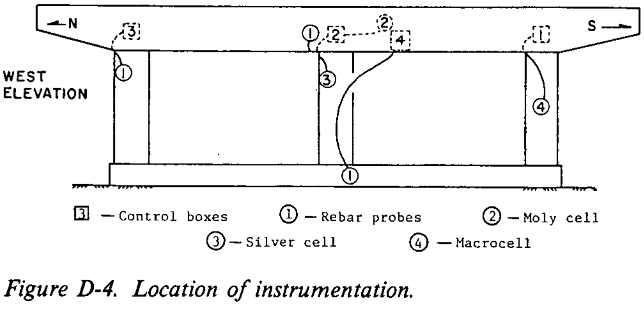


Figure D-4. Location of instrumentation.

Although not shown in the figure, one extra ground wire was run to each control unit in addition to the ground wire conducting the CP current. This additional "instrument ground" was used only during system measurements, when noise on a common ground could interfere with measurement accuracy.

Each control unit is housed in a separate fiberglass control box. These boxes are rugged and corrosion resistant, a practical requirement in the very corrosive environment of the pier.

The schematic shows the important equipment in the control unit. Whenever possible, commercially available apparatus was used to instrument and operate the system. The devices in the control unit are:

1. A fuse or circuit breaker.
2. A variable autotransformer (1-amp capacity), which delivers a continuously adjustable AC voltage at its output. The adjustable low voltage is used to set the desired output of the rectifier.
3. The rectifier units, which were purchased from a vendor of CP electrical apparatus. The constant-current rectifiers are low power (1-amp maximum, rated at 24 volts), low-cost units providing half-wave rectified DC output. The pulsing DC waveform of the rectifiers was left "unfiltered" to facilitate the use of an oscilloscope or peak meter to measure instant-off potentials without artificial interruption of the protective current. One rectifier was connected to each of the primary anodes shown in Figure D-1. A total of 11 rectifiers were used for the entire CP system.
4. A low-resistance shunt, provided for the measurement of current and voltage output of the control unit.
5. Leads to various instruments, which terminated in the control boxes so that several measurements could be made at one location. Leads to the molybdenum and silver chloride cells, a thermocouple for temperature measurement, three rebar probes, and one macrocell were connected to control box terminal strips. The location of these instruments in the pier is shown in Figure D-4.

Figure D-5 shows the interior of a control box. The variable autotransformer is located in the upper right corner of the box. The three clustered white horizontal cylinders are the rectifiers, encapsulated in a waterproof housing. With only one variable autotransformer in each unit, the output of all three regulators in the unit was controlled by the setting of that transformer. Immediately below the rectifiers are three vertical wires bolted to the back of the box. These are 0.01-ohm precision resistors, used as measurement shunts. The main terminal strip for input power and ground leads is at the bottom left corner of the box. The small terminal strip to the bottom right contains the leads from instruments such as rebar probes, reference cells, etc.

As shown in Figure D-1, two or three primary anodes were controlled from each control box. For example, zone 1 consisted of the southern portions of the upper part of the pier. Individual areas of this zone, each driven by a single rectifier, were: (1) the south column of the pier, (2) the portion of the cap south of the column, and (3) half of the cap between the south and middle column. Each anode was driven by one rectifier, but all rectifiers in a particular control box were controlled by the variable autotransformer in that box. The autotransformer was set so the rectifier delivered the current required to protect the area in the zone having the largest negative potential found during the initial half-cell survey of the structure. The current required was determined by an E log I test of that area.

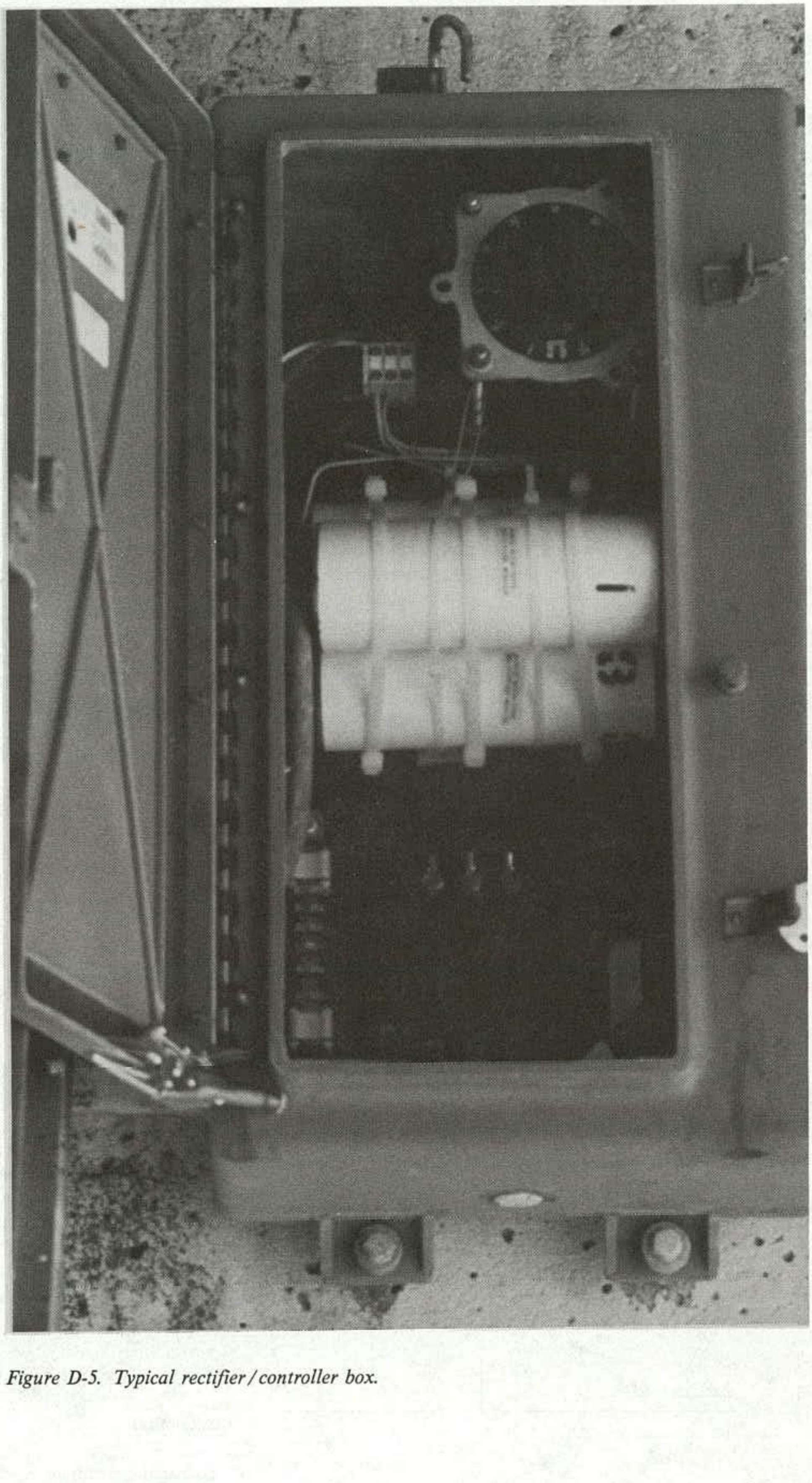


Figure D-5. Typical rectifier/controller box.

DETERMINING CP CURRENT WITH THE E LOG I TEST

The "E Log I Test" is a laboratory technique, which has been adapted by R. F. Stratfull as a means of determining the minimum corrosion protection current necessary to protect concrete reinforcement against corrosion. This section is a summary of the procedures used to determine the E log I test properties of the pier. With minor variations, the tests were performed in accordance with Stratfull's method (Refs. *10, 11*).

In the E log I test procedure, a copper/copper sulfate half-cell location is selected which has a corrosion potential as great as, or greater than, 95 percent of the half-cell potentials measured in a particular cathodic protection zone. The potential at this location is continuously monitored with a half-cell as small increments of current area slowly applied to the cathodic protection anodes. The reaction of the half-cell potentials to the increased current in the CP system provides a means to determine:

1. The corrosion current (I_{corr}) occurring in the cathodic protection zone.
2. The minimum required cathodic protection current (I_{prot}) to protect the reinforcement against further corrosion.
3. The "system voltage" which must be applied to the CP zone to obtain particular cathodic protection currents.

Figure D-6 shows an E log I plot obtained during initial calibration of the pier. Note that this is a semilogarithmic plot, relating the half-cell voltage, E, to the logarithm of current I which is applied to the anode of the CP system. Before testing starts, the initial or static half-cell potential, E_{stat}, is determined and recorded. Then small increments of current are applied to the CP anodes to raise the half-cell voltages in steps of 2 mV, initially, and afterwards in steps of 5 mV. The required settling time for the system is approximately 3 min between steps. Ultimately, the data plotted in semilog format will attain a straight-line relationship sloping upwards and to the right. This is the "Tafel slope."

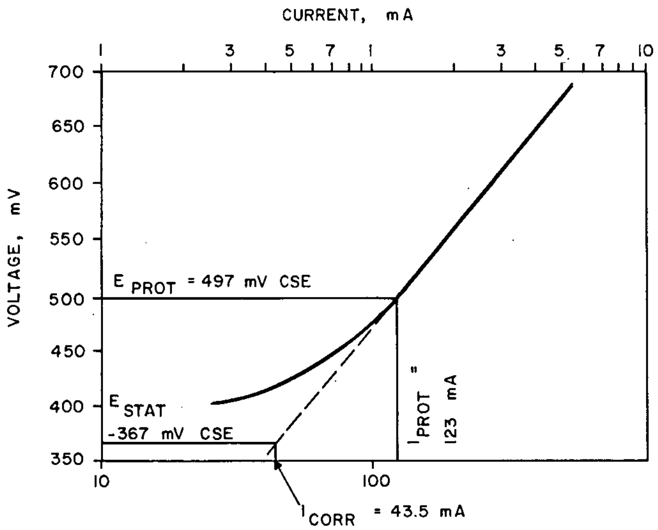


Figure D-6. Typical E log I curve.

The straight-line Tafel slope portion of the E log I curve is extended downward and to the left to intersect the original static half-cell potential line. That intersection gives the original corrosion current, I_{corr}, in the system. The point where the E log I curve joins the straight-line Tafel slope determines the minimum current, I_{prot}, that can be applied to the anodes to prevent corrosion of the reinforcement.

After E log I data had been obtained and the minimum currents required for each anode were calculated, the autotransformers were set to deliver slightly more than the minimum required protective current to the various primary anodes.

PERIODIC MEASUREMENT OF SYSTEM PERFORMANCE

After the regulators were set, the following measurements were taken at least once every 2 months:

1. Currents delivered by each rectifier were measured. This measurement was obtained by determining the voltage drop across the fixed, 0.01-ohm resistor previously mentioned. That voltage drop was converted to current using Ohm's law. Voltage drops were measured as RMS equivalent values using a voltmeter capable of measuring equivalent combined AC and DC components of these values. When, on occasion, a reading was determined with an RMS meter that had a coupling capacitor at its input so that only the AC component value was determined, the equivalent RMS value was calculated as the square root of the sum of the squares of the DC and AC (RMS) values.
2. RMS (AC + DC) voltage above rebar ground was measured at the output of the rectifier and recorded.
3. The waveform delivered by the rectifier was characterized by measuring the peak voltage and the back voltage (the minimum voltage of the waveform). These values were measured with a peak detector and confirmed with an oscilloscope.
4. The AC and DC components of voltage to instrument ground of the macrocell and rebar probes were determined and recorded. The significant measurement here was the DC component. If this voltage was positive, the device was in a noncorroding state.
5. Concrete temperature was determined by reading the embedded thermocouple.
6. The Moly and silver-silver chloride reference cells were read only after the CP system was shut down for a short period of time.
7. The many half-cell locations were tested while the system was operating and, occasionally, after the system had been shut down for approximately a week. In the first instance, "instant-off" measurements were made while the CP system was operating. A negative peak device (see Fig. D-13) was used to bias an oscilloscope output during these readings until it became apparent that the scope was redundant.

HALF-CELL MEASUREMENT PROCEDURES

Introduction

Potential measurement with a copper-copper sulfate half-cell is an extremely important technique in cathodic protection technology. This section describes procedures that can be used to determine half-cell potentials on a structure to which cathodic protection is being, or has been, applied.

Initial half-cell determinations in the structure provide a means to determine if corrosion activity is great enough to warrant cathodic protection. Mapping potentials across the face of the structure before cathodic protection is applied provides base data to which potentials taken at a later time, when cathodic currents to the structure have been temporarily shut off, can be usefully compared. The procedures for determining "static" half-cell potentials on a structure, which is not subjected to cathodic protection currents at the time potential measurements are being made, are described in ASTM C-876.

Half-cell measurements can also be made while the cathodic system on the structure is operating. Such half-cell measurements are essential for development of the E log I curve for individual areas of the structure. Measurements while the CP system is operating are also important when determining the negative potential shift that the structure experiences due to the cathodic protection system.

Preparation of Half-Cell Measurement Locations

When making half-cell measurements on a structure which has a conductive coating for cathodic protection, it is essential that the measurement be made on a bare concrete surface and not on the conductive coating. Short-circuits between the half-cell and the conductive coating will cause spurious half-cell readings that do not represent the true potentials.

Approximately 80 half-cell locations were selected for the Rosemont pier before the conductive coating was applied. Each half-cell location was masked with 1½ in. sq of masking tape to provide a patch of bare concrete free of the conductive coating after the coating had been applied.

On horizontal concrete surfaces, a bead of silicone caulk was placed around the exposed concrete half-cell location so the concrete inside could be wetted to provide electrical contact while avoiding short circuits between the half-cell and the conductive coating material outside the bead (see Fig. D-7).

On vertical concrete surfaces, a 1/2-in. diameter hole was drilled at a slight downward angle in the center of the bare concrete square (see Fig. D-7b). A small sponge was placed in this hole. The opening of the hole was ordinarily sealed with a nonsetting puttylike material to prevent water loss from, and salt-water ingress into, the hole. Just before determining half-cell potentials, the material sealing the hole was removed and the sponge dampened with a jet of water from a wash bottle to improve electrical contact. Any excess water remained in the sloping hole and did not spill down the face of the exposed concrete, causing an inadvertent electrical short to the surrounding conductive coating.

After the conductive coating had been applied to the structure and the half-cell location masks had been removed, bare concrete in these areas was painted with a coat of decorative house paint to inhibit drying of concrete near the half-cell location. The decorative paint was not an electrical insulator and, in the case of the horizontal half-cell locations, potential measurements were made through the paint coating.

A small half-cell with the thickness of a pencil, which allowed it to fit down inside the 1/2-in. holes on vertical surfaces, was used to determine all the half-cell potentials of the structure.

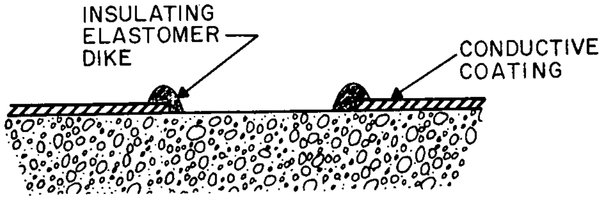


Figure D-7a. Insulating dike elastomer bead placed around horizontal half-cell location.

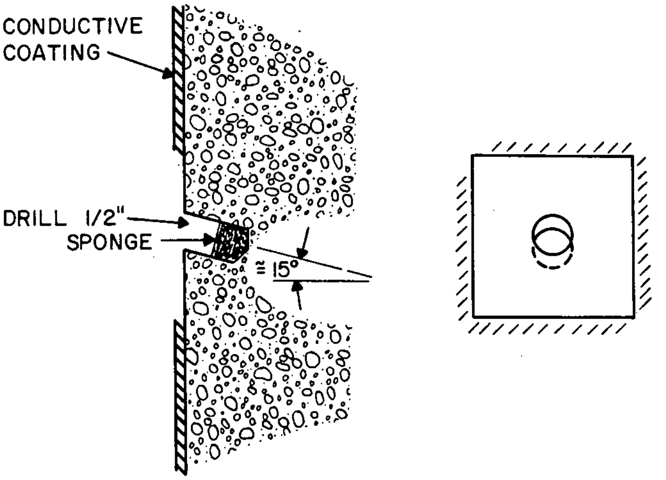


Figure D-7b. One inch deep hole drilled for vertical half-cell location.

CP System Half-Cell Potential Measurement

One measure of the level of cathodic protection which is obtained in a structure is the provision of a minimum negative polarization above the "free-corrosion potential." This is determined by measuring with a half-cell the amount of depolarization that occurs after the protective current is interrupted. For example, the half-cell, digital voltmeter (DVM) measuring circuit is set up while the cathodic protection system is on and current is being delivered to the conductive coating anode. Then, the protective current is interrupted, and the potential is read **immediately,** say within a second or two of shutoff. This measurement approximates the "instant-off" potential (see Fig. D-8). The structure is permitted to "depolarize" toward its "free-corrosion" condition. When the potential stabilizes at the "free-corrosion" condition it is again measured. The time required to attain rough potential stability after depolarization might be as short as an hour, but some authorities believe that complete depolarization might take as long as a week. The potential difference between the two readings is the negative potential shift imparted by the cathodic protection system. Although there is no consensus as to the negative potential shift which is indicative of adequate cathodic protection of concrete reinforcement, other disciplines do recognize such criteria. For example, a criterion for adequate cathodic protection of buried steel pipelines is a minimum negative corrosion potential shift of 100 mV.

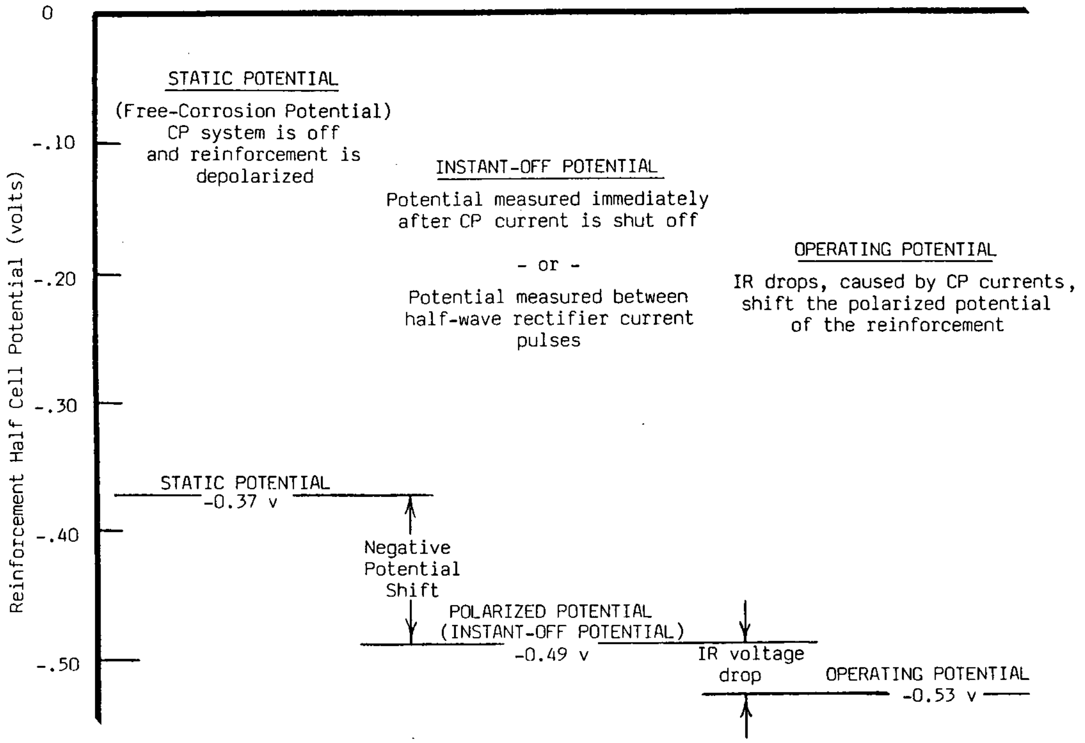
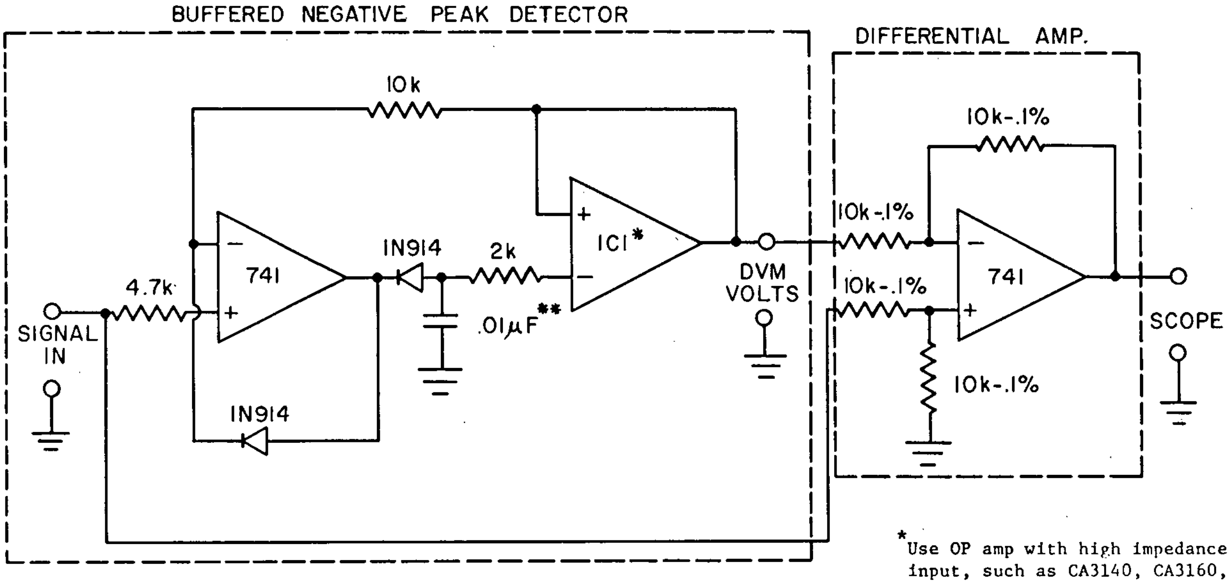


Figure D-8. Relationships of measured half-cell potentials.



*Use OP amp with high impedance input, such as CA3140, CA3160, TL081, or ICL7611

**Use low leakage capacitor. Adjust for appropriate droop and settling time

Figure D-9. Negative peak detector.

Figure D-9 is a schematic of the "negative peak detector" ultimately used to determine "instant-off" half-cell potentials as the CP system rectifiers were operating. With this instrument, one operator can take the potentials at approximately the same speed as one might take "static" half-cell potentials. An oscilloscope was not used, or needed, for routine half-cell measurements. The circuit shown in Figure D-9 is a variation on the classic buffered peak detector shown in many texts on linear integrated circuit (I.C.) applications.

If potential measurements are made while the CP system is delivering current, the IR voltage drop potential developed by the applied current flowing through resistive concrete from anode to reinforcement is added to the polarized half-cell potential of the structure.

SUMMARY

General assumptions must be made during the planning of a CP system as to the general area to be included in each cathodic protection zone and the size and type of regulator to power each zone. General rules of thumb regarding the ordinary cathodic protection power requirements, as a function of surface area, serve as a guide in this type of planning. However, a precise determination of power requirements for the CP system cannot be made until the system is installed and the system is adjusted to capacity through the use of E log I tests. Also, the half-cell potentials at critical points on the surface of the structure must meet the criteria for minimum negative polarization above the "free corrosion potential" obtained before the CP system was activated.

Decisions must also be made regarding the number and types of instruments to be used in the various CP zones because these instruments are ordinarily embedded in the structural concrete. Instrument embedment is most economical if it is done at the same time general repairs are made to the structure. The instruments embedded in the Rosemont pier were:

1. A "macrocell," which is a short length of reinforcement embedded in a prism made with concrete containing a high chloride concentration. This probe is used to measure the amount of current picked up by, and the voltage shift of, a piece of steel of known surface area activated by the CP system.
2. Several "rebar probes," or short lengths of reinforcement cast into concrete voids which were repaired with high chloride content concrete. As with the macrocell, the current pickup and voltage change of such probes reflect the reaction of reinforcement to the CP system.
3. Silver chloride and molybdenum half-cells were embedded in the concrete and their potentials measured when the CP system was shut down.
4. An embedded thermocouple was used to measure internal concrete temperature.

Constant current rectifiers delivering a rectified half-wave pulsing waveform were used for the Rosemont pier. This waveform permitted measurement of "instant-off" potentials while the CP system was operating. E log I tests were made on high-potential areas of the structure. These test values were used to set rectifier voltages.

While the CP system was operating, the following electrical measurements were performed:

1. Voltage and current flow were determined from the primary anodes to the reinforcing ground of the structure.
2. Peak voltages and back EMF (or the polarized potential of the reinforcement) were measured.
3. Copper-copper sulfate half-cell potentials of selected areas on the face of the structure were measured.

The latter measurements were made using "instant-off" procedures, using an oscilloscope and/or peak meter.

APPENDIX E

PERFORMANCE OF THE ROSEMONT PIER CATHODIC PROTECTION SYSTEM

INTRODUCTION

At the time the last data in this report were recorded, the cathodic protection system on the Rosemont pier was approximately 1 years old. The installation had not been operating long enough to make definite conclusions concerning the suitability of the various CP components, the estimated maintenance costs of the system, and its probable service life. However, the early performance of the system has provided interesting preliminary data, which are summarized here.

During August of 1984 the Rosement pier was given a thorough evaluation. At that time, the electrical properties of the system were retested. A small amount of required maintenance of the CP system was also done.

DURABILITY OF THE CP SYSTEM COMPONENTS

The Primary Anodes

The primary anodes that were embedded in saw kerfs on the columns performed very well. No distress was apparent in the conductive polymer, the conductive coating, or the decorative paint applied over the embedded primary anodes.

The windrowed primary anodes cemented to the base were also intact, except for a short length (about 2 in.) which had lost its coats of conductive material and decorative paint. The windrowed primary anodes appeared to remain well bonded to the substrate concrete.

The precast anodes cemented to the pier cap did not perform as well as the other types of primary anodes. The ends of several of the precast anodes were detached from the concrete for a distance of approximately 1 ft (see Fig. E-1). This condition was apparent when the first winter inspection was made in February 1984. The bond of these anodes to the concrete beneath had deteriorated slightly more by the time of the summer inspection.

Both the epoxy mortar repairs and the precast anodes are long, comparatively thick sections of material with significantly greater thermal expansion coefficients than the substrate concrete to which they are cemented. A plausible explanation for the end failures is that during cold weather the polymer materials shrink more than the substrate concrete and tear away from the concrete at the critically stressed end sections.

SURFACE DISCOLORATION

Considerable dirt and rust stains washed down on the pier from the expansion joint immediately above. This quickly gave the renovated pier an "aged" appearance. It also interfered with the search for rust spots, which could indicate continued corrosion activity. However, isolated and distinct rust stains became evident on the light-painted surfaces of the pier by midwinter of 1983–84. Most of these were located on the soffit of the pier cap, in repair concrete.

When these rust spots were chipped out, random pieces of steel (nails, bits of wire, etc.) were found to be the sources of the surface rust. These were apparently left on the bottom of the form before the repair concrete was placed.

Such random pieces of steel which were not grounded to the main mat of reinforcement were not protected against corrosion by the CP system. Consequently, the early rust staining was only cosmetic.

BOND OF THE DECORATIVE PAINT

The decorative paint had very good adhesion to the underlying conductive Coating A. There were virtually no failures between the two coatings. Limited bond failures did occur between concrete and the decorative paint in areas where concrete was exposed to isolate the different cathodic protection zones, but the overall bond was generally good.

BOND OF "CONDUCTIVE COATING A" TO CONCRETE

Some areas of conductive coating scaled from the concrete. This scaling always occurred between the conductive coating and the original structural concrete. Bond to the repair concrete was excellent. Figure E-2 shows typical small-scaled areas of coating next to the north column of the pier. Figure E-3 shows scraped areas of scaled coating before the coatings were reapplied to the area.

Figure E-4 shows the largest areas of scaled coating on the pier. The scaled portion of the base shown in Figure E-4a probably has the most severe exposure in the entire structure. This area is exposed to direct sunlight and significant ultraviolet radiation. In the winter, it is exposed to severe chloride spray. Figure E-4b shows an area of the cap being recoated. The bottom of the scaled area is the joint between the original concrete above and repair concrete below. This area, like all others, with significant conductive coating scaling, was located on the side of the pier next to traffic, where exposure to salt spray from the River Road was the greatest.

Several factors may be responsible for the scaling of the conductive coating over the original concrete of the structure. Some possible reasons are the following:

Figure E-1. Loss of bond between the concrete and the precast anode.

Figure E-2. Small scaled areas on top of the base.

Figure E-3. Scaled coating on the side of the base.

1. High chloride areas have comparatively low electrical resistivity. Higher current flow is to be expected in such areas, with a consequent migration of large amounts of acid toward the interface between the concrete and the conductive coating. This effect will eventually impair bond between concrete and the coating. It is a major factor affecting the life of a cathodic protection system and was identified in Phase IA of this project.

2. The chloride content of the original concrete may accelerate the loss of bond due to the effects of freezing and thawing.

3. Concrete containing chloride is more difficult to oven-dry than concrete without chloride. It may also be more difficult to air-dry. If this is true, surface pores in the high chloride concrete may not be as well prepared for the penetration by the coating and development of good bond as the repair concrete, with its low chloride content.

A. Scraping coating off a scaled area of the base.

B. Reapplying the conductive coating.

Figure E-4. The largest areas of scaled conductive coating.

4. The air content of the surface concrete might be sufficient to resist freeze/thaw action when exposed to air but not when covered with an impermeable coating. For example, some concrete surfaces with good durability if exposed can fail when asphalt is applied to the surface.

The comparatively small, isolated areas of scaled coating shown in Figures E-2 and E-3 probably have little effect on the operation of the cathodic protection system. Several cathodic protection systems mentioned previously use grids of conductive elements, with spacings between filaments of the grid that are larger than the isolated scaled areas of the coatings shown in Figures E-2 and E-3.

The size and location of the large-scaled area of the base shown in Figure E-4a made it important to apply new conductive coating to this area. Similarly, the long-scaled area in Figure E-4b might interfere with current flow past the bare concrete surface. Consequently, these areas were recoated during the summer of 1984. Approximately 2 man-hours were spent scraping and preparing these and other areas for recoating. A similar amount of time was required to coat the areas with conductive Coating A and an overcoat of light-colored decorative latex paint. The ease of reapplying the conductive coating to scaled areas is a definite advantage to the use of this material in a cathodic protection system.

MISCELLANEOUS

The structure was sounded, particularly in the original concrete adjacent to repairs, during the summer inspection to determine if delaminations had occurred after the CP system was put in operation. No delaminations were detected.

Figure E-4a shows the concrete slab protecting the slope between the pier base and the bridge abutment. During the winter, this area quickly fills with wet trash and snow, which have the potential to short-circuit protective current from the pier base. Removing this refuse in back of the pier may be a continuing maintenance job.

A vexing minor problem is keeping padlocks for control boxes operable in the corrosive environment of the Rosemont pier.

DURABILITY SUMMARY

The primary anodes that were recessed in saw kerfs or applied to the surface in shallow windrows performed well during the first winter the CP system operated. The ends of the precast anodes applied to the pier cap were detached from the concrete beneath, probably because of thermal incompatibilities between the conductive polymer mortar and the concrete.

Minor surface rust stains were found to be caused by isolated bits of tramp steel embedded in repair concrete.

No significant new concrete delaminations were found when the pier was sounded during the summer of 1984.

Bond between the decorative paint and conductive Coating A and bare concrete of the pier was good.

Some small areas of conductive coating scaled off the original concrete of the pier during the winter. The exact cause of this scaling is not known. It was comparatively easy to scrape and recoat those scaled surfaces for which recoating was considered necessary. The simple maintenance required for deteriorated paint-type conductive coatings is a comparative advantage with these materials in cathodic protection systems.

ROUTINE ELECTRICAL MEASUREMENTS

While the CP system was in operation, periodic electrical measurements were made to determine the following parameters for each subzone of the pier:

1. Input current (DC + AC) RMS (measurement of the total RMS current, both DC and AC, of the signal; sometimes termed a DC coupled measurement of AC current; properly defined as "effective current").
2. Voltage drop across the anodes, concrete and reinforcement grounds (DC + AC)RMS.
3. Half-wave rectifier peak voltage (DC).
4. Half-wave back EMF (BEMF) or minimum voltage (DC).
5. Thermocouple temperature of pier cap, at depth of reinforcement (°F).
6. Potential of macrocell and rebar probes to instrument gound (DC).

During the application of CP currents, instant-off half-cell potentials were determined for the various half-cell locations shown in Figure E-5. These were the same locations where static half-cell potentials were measured before the CP system was activated and during the spring and late summer of 1984 when the system was shut down and permitted to depolarize. While the CP system was shut down, the direct current potentials were measured for the two reference cells embedded in the repair concrete of the structure.

Half-Cell Potential Measurements

Static and dynamic half-cell potentials for two CP zones (1 and 2) of the pier are summarized in Tables E-1 and E-2. Static half-cell potentials are recorded in the tables in columns 1, 5, and 10. The remaining potentials recorded in columns 1 through 11 were taken using instant-off procedures while the cathodic protection system was operating. The half-cell potentials recorded in the figures generally indicate the following:

1. Instant-off half-cell potentials determined as the CP system was operating were invariably more negative then static potentials determined at the same locations.
2. Average differences between instant-off and stable static half-cells potentials varied from 0.17 to 0.25 volts for pier zones 1 and 2, from 0.20 to 0.25 volts for zone 4, and from 0.17 to 0.2 volts for zone 3.
3. The differences between instant-off and static half-cell potentials were slightly greater during the spring 1984 shutdown period than they were when the system was shut down in the fall of 1984.
4. There is a seasonal variation in the half-cell potentials measured for the Rosemont pier. Potentials measured during the winter and spring were slightly more negative than those measured during the summer.

Figure E-6 is a plot of time versus mean half-cell potential for the four different zones. It shows that zone 4, the base, has significantly more negative half-cell potentials than the other zones. This indicates that the changes in potential with time are cyclic and shared by the different zones.

A concern with cathodic protection is the possibility that portions of the structure next to the primary anodes might be preventing current from reaching areas that are further from the anodes. The same potential data given in Tables E-1 and E-2 were rearranged to group half-cell locations close to the primary anodes and locations further away from the anodes. It is assumed that current diversion by areas close to the primary anodes would be accompanied by higher mean half-cell potentials and greater differences between instant-off and static half-cell potentials. Such data for zone 1 are given in Table E-3. The "long-term-shut-off differences" represent differences between

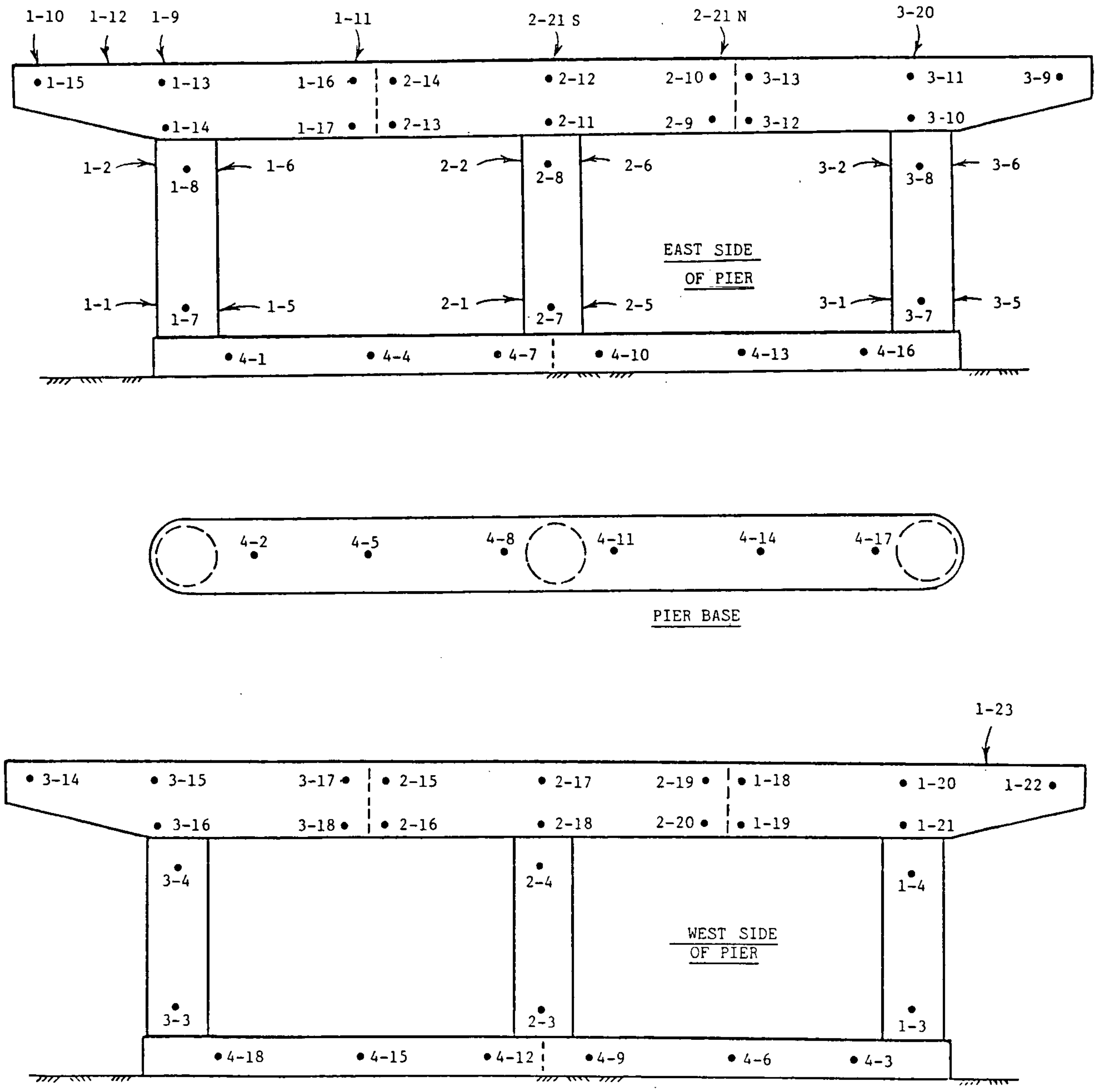


Figure E-5. CSE half-cell locations.

instant-off operating potentials and static potentials after the structure depolarized. Apparent differences for this zone and zones 2 and 3 did not decrease greatly with distance from the primary anode. The data for base zone 4 suggest that half-cell locations further away from the primary anode did have somewhat lower offsets of instant-off versus static potentials than the locations closer to the primary anode. However, zone 4 data are clouded somewhat by the fact that the locations furthest from the primary anode were also closest to traffic and probably more contaminated with chloride than other locations on the base.

Voltage and Current Measurements

As indicated previously, the current applied to each primary anode was determined by measuring the voltage drop across a small-value resistor and calculating the current using Ohm's law. The voltage applied was measured between the terminal to the primary anode and the instrument ground attached to the reinforcement. The current and voltage measurements are given in Table E-4. The data indicate that:

1. Current measurements over the span of time that the CP system was operating were reasonably constant for each sub-

Table E-1. Comparisons of half-cell potentials—Zone 1.

(All Values Negative Voltages)

POINT	1 OFF STAT. Oct.31	2 ON I.O. Feb.23	3 ON I.O. Apr.9	4 OFF ONE HOUR STAT. APR.9	5 OFF FOUR DAYS STAT. Apr.13	6 ON TWO HOUR I.O. Apr.13	7 ON I.O. May 30	8 ON I.O. July 6	9 ON I.O. Aug. 22	10 OFF SIX DAYS STAT. Aug.28	11 ON I.O. Sep.3	12 INITIAL SHUTOFF-TURN ON DIFFERENCES	13	14 LONG-TERM SHUTOFF DIFFERENCES	15	16 LONG-TERM TURN ON DIFFERENCES	17	18 INITIAL STATIC TO FIRST SHUTOFF	19 INITIAL STATIC TO SECOND SHUTOFF
												(3-4)	(6-5)	(3-5)	(9-10)	(7-5)	(11-10)	(1-5)	(1-10)
					REPAIR CONCRETE														
1	0.303	0.456	0.580	0.455	0.346	0.530	0.636	0.458	0.445	0.298	0.475	0.125	0.184	0.234	0.147	0.290	0.177	-0.043	0.005
3	0.198	0.535	0.663	0.595	0.437	0.537	0.616	0.455	0.444	0.267	0.461	0.068	0.100	0.226	0.177	0.179	0.194	-0.239	-0.069
4	0.198	0.568	0.790	0.743	0.529	0.590	0.765	0.565	0.468	0.342	0.432	0.047	0.061	0.261	0.126	0.236	0.090	-0.331	-0.144
5	0.268	0.328	0.398	0.338	0.257	0.340	0.489	0.380	0.358	0.237	0.375	0.060	0.083	0.141	0.121	0.232	0.138	0.011	0.031
17	0.299	0.366	0.458	0.401	0.299	0.361	0.366	0.335	0.317	0.244	0.343	0.057	0.062	0.159	0.073	0.067	0.099	0.000	0.055
19	0.331	0.527	0.592	0.489	0.389	0.493	0.561		0.488	0.370	0.497	0.103	0.104	0.203	0.118	0.172	0.127	-0.058	-0.039
21	0.226	0.546	0.675	0.517	0.413	0.576	0.608	0.443	0.478	0.323	0.466	0.158	0.163	0.262	0.155	0.195	0.143	-0.187	-0.097
MEAN	0.260	0.475	0.594	0.505	0.381	0.490	0.577	0.439	0.428	0.297	0.436	0.088	0.108	0.212	0.131	0.196	0.138	-0.121	-0.037
MAX.	0.331	0.568	0.790	0.743	0.529	0.590	0.765	0.565	0.488	0.370	0.497	0.158	0.184	0.262	0.177	0.290	0.194	0.011	0.055
MIN.	0.198	0.328	0.398	0.338	0.257	0.340	0.366	0.335	0.317	0.237	0.343	0.047	0.061	0.141	0.073	0.067	0.090	-0.331	-0.144
					ORIGINAL CONCRETE														
2	0.253	0.527	0.691	0.455	0.297	0.463	0.636	0.528	0.521	0.283	0.520	0.236	0.166	0.394	0.238	0.339	0.245	-0.044	-0.030
6	0.340	0.470	0.553	0.388	0.270	0.388	0.545	0.492	0.470	0.264	0.491	0.165	0.118	0.283	0.206	0.275	0.227	0.070	0.076
7	0.291	0.447	0.548	0.366	0.264	0.383	0.589	0.477	0.478	0.280	0.480	0.182	0.119	0.284	0.198	0.325	0.200	0.027	0.011
8	0.259	0.436	0.480	0.319	0.193	0.315	0.454	0.426	0.438	0.254	0.420	0.161	0.122	0.287	0.184	0.261	0.166	0.066	0.005
9	0.494	0.566	0.699	0.613	0.546		0.681	0.562	0.617	0.490	0.581	0.086		0.153	0.127	0.135	0.091	-0.052	0.004
10	0.329	0.558	0.718	0.523	0.376									0.342					
11	0.286	0.501	0.591	0.420	0.293	0.491	0.593	0.460	0.493	0.324	0.499	0.171	0.198	0.298	0.169	0.300	0.175	-0.007	-0.038
12	0.585	0.682	0.784	0.674	0.411		0.653		0.598	0.525	0.585	0.110		0.373	0.073	0.242	0.060	0.174	0.060
13	0.451	0.577	0.704	0.648	0.591	0.608	0.706	0.635	0.616	0.489	0.620	0.056	0.017	0.113	0.127	0.115	0.131	-0.140	-0.038
14	0.327	0.538	0.675	0.488	0.366	0.521	0.640	0.443	0.416	0.316	0.433	0.187	0.155	0.309	0.100	0.274	0.117	-0.039	0.011
15	0.448	0.470	0.567	0.484	0.438	0.494	0.576	0.551	0.547	0.375	0.551	0.083	0.056	0.129	0.172	0.138	0.176	0.010	0.073
16	0.350	0.497	0.603	0.427	0.284	0.473	0.618	0.544	0.540	0.282	0.545	0.176	0.189	0.319	0.258	0.334	0.263	0.066	0.068
18	0.236	0.457	0.556	0.375	0.250	0.426	0.520	0.439	0.439	0.254	0.459	0.181	0.176	0.306	0.185	0.270	0.205	-0.014	-0.018
20	0.501	0.541	0.650	0.558	0.491	0.574	0.592	0.573	0.583	0.479	0.568	0.092	0.083	0.159	0.104	0.101	0.089	0.010	0.022
22	0.246	0.427	0.454	0.385	0.326	0.467	0.500	0.338	0.344	0.282	0.344	0.069	0.141	0.128	0.062	0.174	0.062	-0.080	-0.036
MEAN	0.360	0.513	0.618	0.475	0.360	0.467	0.593	0.498	0.507	0.350	0.507	0.140	0.128	0.258	0.157	0.234	0.158	0.003	0.012
MAX.	0.585	0.692	0.784	0.674	0.591	0.608	0.706	0.635	0.617	0.525	0.620	0.236	0.198	0.394	0.258	0.339	0.263	0.174	0.076
MIN.	0.236	0.427	0.454	0.319	0.193	0.315	0.454	0.338	0.344	0.254	0.344	0.056	0.017	0.113	0.062	0.101	0.060	-0.140	-0.038

Table E-2. Comparisons of half-cell potentials—Zone 2.

(All Values Negative Voltages)

POINT	1 OFF STAT. Oct.31	2 ON I.O. Feb.23	3 ON I.O. Apr.9	4 OFF ONE HOUR STAT. APR.9	5 OFF FOUR DAYS STAT. Apr.13	6 ON TWO HOUR I.O. Apr.13	7 ON I.O. May 30	8 ON I.O. July 6	9 ON I.O. Aug. 22	10 OFF SIX DAYS STAT. Aug.28	11 ON I.O. Sep.3	12 INITIAL SHUTOFF-TURN ON DIFFERENCES	13	14 LONG-TERM SHUTOFF DIFFERENCES	15	16 LONG-TERM TURN ON DIFFERENCES	17	18 INITIAL STATIC TO FIRST SHUTOFF	19 INITIAL STATIC TO SECOND SHUTOFF
												(3-4)	(6-5)	(3-5)	(9-10)	(7-5)	(11-10)	(1-5)	(1-10)
					REPAIR CONCRETE														
1	0.245	0.564	0.639	0.378	0.233	0.508	0.571	0.451	0.444	0.216	0.475	0.261	0.275	0.406	0.228	0.338	0.259	0.012	0.029
4	0.238	0.381	0.411	0.336	0.202	0.359	0.396	0.353	0.354	0.180	0.355	0.075	0.157	0.209	0.174	0.194	0.175	0.036	0.058
9	0.243	0.427	0.538	0.379	0.229	0.416	0.563	0.487	0.471	0.209	0.490	0.159	0.187	0.309	0.262	0.334	0.281	0.014	0.034
13	0.289	0.355	0.413	0.355	0.269	0.328	0.366	0.332	0.213	0.252	0.263	0.058	0.059	0.144	-0.039	0.097	0.011	0.020	0.037
20	0.294	0.528	0.587	0.496	0.418	0.558	0.538	0.456	0.438	0.342	0.447	0.091	0.140	0.169	0.096	0.120	0.105	-0.124	-0.048
MEAN	0.262	0.451	0.518	0.389	0.270	0.434	0.487	0.416	0.384	0.240	0.406	0.129	0.164	0.247	0.144	0.217	0.166	-0.008	0.022
MAX.	0.238	0.564	0.639	0.496	0.418	0.558	0.571	0.487	0.471	0.342	0.490	0.261	0.275	0.406	0.262	0.338	0.281	0.036	0.058
MIN.	0.238	0.355	0.411	0.336	0.202	0.328	0.366	0.332	0.213	0.180	0.263	0.058	0.059	0.144	-0.039	0.097	0.011	-0.124	-0.048
					ORIGINAL CONCRETE														
2	0.238	0.522	0.722	0.288	0.143	0.415	0.615	0.503	0.501	0.169	0.505	0.434	0.272	0.579	0.332	0.472	0.336	0.095	0.069
3	0.201	0.388	0.456	0.353	0.254	0.453	0.452	0.377	0.388	0.214	0.391	0.103	0.199	0.202	0.174	0.198	0.177	-0.053	-0.013
5	0.195	0.412	0.444	0.250	0.126	0.387	0.450	0.330	0.338	0.150	0.345	0.194	0.261	0.318	0.188	0.324	0.195	0.069	0.045
6	0.195	0.405	0.492	0.254	0.126	0.362	0.459	0.415	0.384	0.142	0.378	0.238	0.236	0.366	0.242	0.333	0.236	0.069	0.053
7	0.165	0.442	0.598	0.281	0.148	0.401	0.536	0.510	0.502	0.202	0.522	0.317	0.253	0.450	0.300	0.388	0.320	0.017	-0.037
8	0.169	0.371	0.520	0.218	0.081	0.344	0.488	0.465	0.471	0.133	0.477	0.302	0.263	0.439	0.338	0.407	0.344	0.088	0.036
10	0.260	0.417	0.494	0.345	0.246	0.422	0.519	0.459	0.447	0.225	0.458	0.149	0.176	0.248	0.222	0.273	0.233	0.014	0.035
11	0.228	0.398	0.450	0.306	0.219	0.350	0.443	0.395	0.312	0.235	0.388	0.144	0.131	0.231	0.077	0.224	0.153	0.009	-0.007
12	0.391	0.440	0.512	0.424	0.399	0.463	0.548	0.520	0.516	0.369	0.520	0.088	0.064	0.113	0.147	0.149	0.151	-0.008	0.022
14	0.387	0.439	0.536	0.410	0.314	0.452	0.537	0.493	0.466	0.327	0.499	0.126	0.138	0.222	0.139	0.223	0.172	0.073	0.060
15	0.220	0.398	0.455	0.286	0.189	0.366	0.480	0.453	0.508	0.197	0.502	0.169	0.177	0.266	0.311	0.291	0.305	0.031	0.023
16	0.292	0.429	0.506	0.370	0.249	0.410	0.484	0.399	0.472	0.220	0.467	0.136	0.161	0.257	0.252	0.235	0.247	0.043	0.072
17	0.318	0.441	0.550	0.379	0.310	0.466	0.518	0.487	0.502	0.290	0.507	0.171	0.156	0.240	0.212	0.208	0.217	0.008	0.028
18	0.204	0.401	0.471	0.365	0.259	0.434	0.464	0.370	0.408	0.222	0.456	0.106	0.175	0.212	0.186	0.205	0.234	-0.055	-0.018
19	0.271	0.466	0.539	0.279	0.291	0.453	0.543	0.467	0.469	0.260	0.470	0.260	0.162	0.248	0.209	0.252	0.210	-0.020	0.011
N21	0.278	0.402	0.497	0.346	0.264	0.484	0.547	0.478	0.452	0.292	0.444	0.151	0.220	0.233	0.160	0.283	0.152	0.014	-0.014
S21	0.278	0.402	0.497	0.346	0.264	0.484	0.512	0.420	0.419	0.351	0.435	0.151	0.220	0.233	0.068	0.248	0.084	0.014	-0.073
MEAN	0.252	0.422	0.514	0.324	0.228	0.420	0.506	0.444	0.444	0.235	0.457	0.191	0.192	0.286	0.209	0.277	0.222	0.024	0.017
MAX	0.391	0.522	0.722	0.424	0.399	0.484	0.615	0.520	0.516	0.369	0.522	0.434	0.272	0.579	0.338	0.472	0.344	0.095	0.072
MIN.	0.165	0.371	0.444	0.218	0.081	0.344	0.443	0.330	0.312	0.133	0.345	0.088	0.064	0.113	0.068	0.149	0.084	0.084	0.084

zone, except in the case of zone 1, which was measured on January 29, 1984. It is believed that the excessive current measured at that time was due to the weather, which was cold and wet. The zone 1 portion of the pier, which is closer than the other zones to traffic moving into the underpass area, received more splashed chloride-bearing water than the other zones. Because of this inconsistent set of readings, further monitoring of the pier during wet weather was avoided. The results obtained then became more consistent.

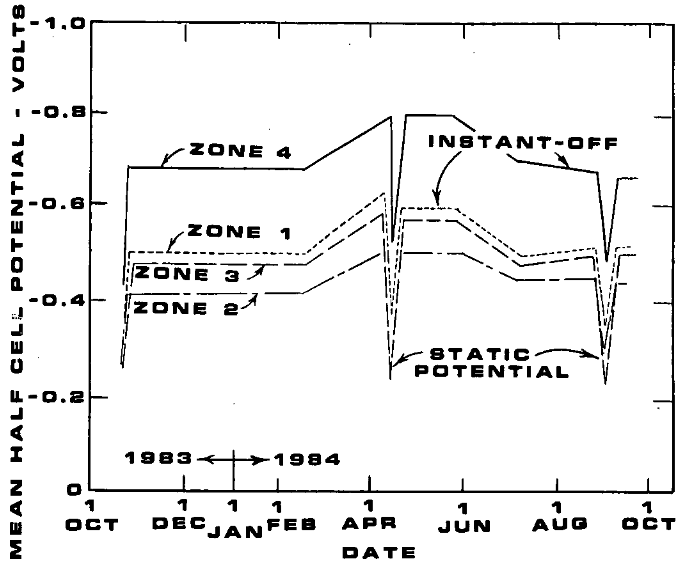


Figure E-6. Variations in static and instant-off half-cell potentials with time.

Table E-3. Half-cell differences arranged according to distance from primary anode—Zone 1.

11	12	13	14	15	16	17	18	19
Point	Initial Shutoff-Turn on Differences		Long-Term Shutoff Differences		Long-Term Turn on Differences		Initial Static to First Shutoff	Initial Static to Second Shutoff
7	0.182	0.119	0.284	0.198	0.325	0.200	0.027	0.011
8	0.161	0.122	0.287	0.184	0.261	0.166	0.066	0.005
13	0.056	0.017	0.113	0.127	0.115	0.131	-0.140	-0.038
15	0.083	0.056	0.129	0.172	0.138	0.176	0.010	0.073
16	0.176	0.189	0.319	0.258	0.334	0.263	0.066	0.068
Mean	0.132	0.101	0.226	0.188	0.235	0.187	0.006	0.024
Max	0.182	0.189	0.319	0.258	0.334	0.263	0.066	0.073
Min	0.056	0.017	0.113	0.127	0.115	0.131	-0.140	-0.038
NEAR PRIMARY ANODE								
1	0.125	0.184	0.234	0.147	0.290	0.177	-0.043	0.005
2	0.236	0.166	0.394	0.238	0.339	0.245	-0.044	-0.030
5	0.060	0.083	0.141	0.121	0.232	0.138	0.011	0.031
6	0.165	0.118	0.283	0.206	0.275	0.227	0.070	0.076
9	0.086		0.153	0.127	0.135	0.091	-0.052	0.004
11	0.171	0.198	0.298	0.169	0.300	0.175	-0.007	-0.038
12	0.110		0.373	0.073	0.242	0.060	0.174	0.060
13	0.056	0.017	0.113	0.127	0.115	0.131	-0.140	-0.038
14	0.187	0.155	0.309	0.100	0.274	0.117	-0.039	0.011
17	0.057	0.062	0.159	0.073	0.067	0.099	-0-	0.550
Mean	0.125	0.123	0.245	0.138	0.227	0.146	-0.007	0.063
Max	0.236	0.198	0.394	0.238	0.339	0.245	0.174	0.550
Min	0.056	0.017	0.113	0.073	0.067	0.060	-0.140	-0.038
DISTANT FROM PRIMARY ANODE								
3	0.068	0.100	0.226	0.177	0.179	0.194	-0.239	-0.069
4	0.047	0.061	0.261	0.126	0.236	0.090	-0.331	-0.144
18	0.181	0.176	0.306	0.185	0.270	0.205	-0.014	-0.018
19	0.103	0.104	0.203	0.118	0.172	0.127	-0.058	-0.039
20	0.092	0.083	0.159	0.104	0.101	0.089	0.010	0.022
21	0.158	0.163	0.262	0.155	0.195	0.143	-0.187	-0.097
22	0.069	0.141	0.128	0.062	0.174	0.062	-0.080	-0.036
Mean	0.103	0.118	0.221	0.132	0.190	0.130	-0.128	-0.054
Max	0.181	0.176	0.306	0.185	0.270	0.205	0.010	0.022
Min	0.047	0.061	0.128	0.062	0.101	0.062	-0.331	-0.144

2. Voltages measured on November 4, 1983 and September 3, 1984 were lower than other voltages measured. In both instances, these measurements were taken shortly after current was applied to the CP system. Presumably, the system had not stabilized when these readings were taken.

Peak and Back EMF Voltages

Measurement of the peak voltage of the half-wave and the "back voltage," or minimum voltage in the half-wave, were routinely determined for the various subzones of the CP systems. These values are given in Table E-5. Both tended to have higher values in the winter than in the summer.

Average peak voltages over the 1-year period of operation for zones 1, 2, 3, and 4 were 3.9, 3.5, 3.7, and 3.5 volts, respectively. Average back EMF values (or the polarized potential of the CP systems) for comparable zones were 1.7, 1.8, 1.8, and 1.9 volts, respectively. Standard deviations for both peak and back EMF potentials for each zone were approximately 0.5 volts.

Resistance Measurements

The electrical resistance (in ohms) of the current path through the primary anodes, conductive coatings, surface concrete, and reinforcement was measured with a Nilsson 400 AC resistance bridge when the CP system was not operating. No corrections were made for capacitive reactance.

The resistance data obtained were rather inconsistent. The resistance data probably reflect such variables as changes in moisture content, chloride content, temperature, etc. No drastic increases in electrical resistance were noted which might reflect loss of bond between the conductive coating and the substrate concrete.

Resistances were calculated from measurements of current and voltages (both RMS, AC component only) with an accurate voltmeter. These attempts were not reproducible because the resistances of the current measuring "shunts," which were furnished as original equipment, were too low. Replacement of these shunts with ones of higher resistance would facilitate this type of resistance measurement, and should be done in continuing work with the pier.

Macrocell and Rebar Probes

Routine measurements of the macrocell and the three rebar probes installed in chloride-rich pier concrete always indicated that these devices had a slightly positive potential with respect to instrument ground. Consequently, these steel accessories were routinely found to be in a noncorroding condition.

Electrical Summary

The routine electrical measurements tended to fluctuate somewhat with the seasons. During the winter and spring, half-cell potentials were higher than they were in summer and fall.

Half-cell potentials taken during operation of the CP system were consistently more negative than the static potentials taken when the CP system was shut down. This "depression" of half-cell potential varied from 150 to 350 mV.

Table E-4. Voltage and current measurements.

APPLIED CURRENT (RMS milliamp)

DATE

ZONE	POSITION	Nov. 4 1983	Nov. 18 1983	Jan. 29 1984	Feb. 23 1984	Mar. 28 1984	Apr. 9 1984	May 30 1984	July 6 1984	Aug. 22 1984	Sep. 3 1984	Sep.10 1984
1	1/3 cap-south	75.0	115.0	312.0	117.0	101.0	110.0	109.0	115.0	115.0	116.0	119.0
	1/3 cap—north	70.0	120.0	301.0	118.0	100.0	109.0	110.0	114.0	114.0	115.0	119.0
	South column	90.0	120.0	301.0	128.0	109.0	119.0	122.0	123.0	123.0	128.0	129.0
	MEAN	78.3	118.3	304.7	121.0	103.3	112.7	113.7	117.3	117.3	119.7	122.3
2	1/3 cap-south	85.0	108.0	91.0	102.0	88.0	93.0	83.0	102.0	102.0	103.0	---
	1/3 cap north	80.0	106.0	84.0	94.0	131.0	87.0	89.0	95.0	95.0	96.0	---
	Center Column	80.0	120.0	88.0	93.0	310.0	85.0	89.0	95.0	93.0	101.0	---
	MEAN	81.7	111.3	87.7	96.3	176.3	88.3	87.0	97.3	96.7	100.0	
3	1/3 cap-south	70.0	100.0	107.0	113.0	105.0	102.0	108.0	113.0	114.0	114.0	---
	1/3 cap-north	70.0	93.0	109.0	115.0	108.0	105.0	111.0	116.0	116.0	113.0	---
	North column	90.0	91.0	118.0	127.0	125.0	116.0	123.0	128.0	127.0	126.0	---
	MEAN	76.7	94.7	111.3	118.3	112.7	107.7	114.0	119.0	119.0	117.7	
4	1/2 base-south	150.0	169.0	167.0	173.0	161.0	159.0	167.0	170.0	188.0	180.0	179.0
	1/2 base-north	150.0	172.0	172.0	177.0	158.0	164.0	171.0	172.0	188.0	180.0	179.0
	MEAN	150.0	170.5	169.5	175.0	159.5	161.5	169.0	171.0	188.0	180.0	179.0

VOLTAGE APPLIED (RMS Volts)

ZONE	POSITION	Nov. 4 1983	Nov. 18 1983	Jan. 29 1984	Feb. 23 1984	Mar. 28 1984	Apr. 9 1984	May 30 1984	July 6 1984	Aug. 22 1984	Sep. 3 1984	Sep.10 1984
1	1/3 cap-south	2.39	2.89	2.49	2.46	2.49	2.57	2.58	2.49	2.55	2.19	2.48
	1/3 cap-north	2.43	2.87	2.47	2.41	2.42	2.51	2.47	2.44	2.54	2.21	2.48
	South column	2.01	2.79	2.30	2.15	2.14	2.28	2.13	2.12	2.23	1.72	2.16
	MEAN	2.28	2.85	2.42	2.34	2.35	2.45	2.39	2.35	2.44	2.04	2.37
2	1/3 cap-south	1.68	2.99	2.12	2.04	2.02	2.16	2.08	1.99	2.02	1.68	---
	1/3 cap-north	1.84	2.93	3.00	2.13	2.11	2.19	2.14	2.04	2.06	1.74	---
	Center Column	2.00	2.61	2.44	2.33	2.32	2.49	2.34	2.24	2.31	1.73	---
	MEAN	1.84	2.84	2.52	2.17	2.15	2.28	2.19	2.09	2.13	1.72	
3	1/3 cap-south	2.60	2.21	2.69	2.62	2.67	3.06	2.68	2.56	2.62	1.99	---
	1/3 cap-north	2.54	2.31	2.55	2.44	2.47	2.56	2.45	2.36	2.37	1.85	---
	North Column	2.08	2.62	2.35	2.21	2.18	2.32	2.15	2.05	2.10	1.48	---
	MEAN	2.31	2.38	2.53	2.42	2.44	2.65	2.43	2.32	2.36	1.77	
4	1/2 base-south	2.17	2.67	2.42	2.38	2.30	2.41	2.31	2.27	2.31	1.88	2.26
	1/2 base-north	2.09	2.73	2.28	2.23	2.15	2.29	2.26	2.24	2.23	1.90	2.22
	MEAN	2.13	2.70	2.35	2.31	2.23	2.35	2.29	2.26	2.27	1.89	2.24

Continued operation of the CP system appeared to cause a steady decline in the static potentials in zone 3 during the measurements of static potential while the system was shut down.

Currents and voltages applied to the CP system were relatively constant except when weather and moisture conditions of the pier were exceptional.

Limited determinations of electrical resistance between the primary anodes and instrument ground indicated that there were slight variations in resistance, possibly because of changes in moisture content, temperature, and other variables.

Measurements of the embedded macrocell and rebar probes always indicated that these devices were positive with respect to instrument ground and, consequently, in a noncorroding state.

E LOG I TESTING OF THE PIER

E log I tests were made on the structure to obtain data on the cathodic protection currents required to protect the pier reinforcement against further corrosion. The procedures for making the E log I tests and calculating the required protective currents, I_{corr}, are discussed in Appendix D of this report. The initial test data obtained in early November 1983 are given in Table E-6.

The E log I tests were repeated in late August 1984 on three selected subzones of the structure. These data are also given in Table E-6. The pier cap, column, and pier base subzones which had previously shown the highest corrosion rate and cathodic protection current requirements were purposely chosen (south

Table E-5. Rectifier half-wave properties.

BACK EMF (volts)

DATE

ZONE	POSITION	Nov. 4 1983	Nov. 18 1983	Jan. 29 1984	Feb. 23 1984	Mar. 28 1984	Apr. 9 1984	May 30 1984	July 6 1984	Aug. 22 1984	Sep. 3 1984	Sep.10 1984
	1/3 cap-south	1.5	2.7	1.6	1.8	1.1	1.8	1.8	1.7	1.7	1.5	1.6
1	1/3 cap—north	1.5	2.7	1.7	1.8	1.0	1.7	1.7	1.7	1.7	1.4	1.6
	South column	1.4	2.7	1.8	1.8	1.1	1.8	1.7	1.7	1.7	1.4	1.6
	MEAN	1.5	2.7	1.7	1.8	1.1	1.8	1.7	1.7	1.7	1.4	1.6
	1/3 cap-south	1.2	2.8	1.6	2.6	2.0	1.6	1.6	1.6	1.5	1.2	---
2	1/3 cap north	1.3	2.8	1.6	1.7	2.1	1.6	1.6	1.6	1.5	1.2	---
	Center Column	1.4	2.6	1.6	1.8	2.8	1.8	1.8	1.8	1.8	1.3	---
	MEAN	1.3	2.7	1.6	2.0	2.3	1.7	1.7	1.6	1.6	1.3	
	1/3 cap-south	1.4	2.2	1.6	1.8	2.6	1.8	1.7	1.7	1.7	1.3	---
3	1/3 cap-north	1.3	2.2	1.6	1.7	2.4	1.8	1.7	1.7	1.7	1.2	---
	North column	1.3	2.6	1.8	1.6	2.2	1.8	1.7	1.7	1.7	1.2	---
	MEAN	1.3	2.3	1.7	1.7	2.4	1.8	1.7	1.7	1.7	1.2	
4	1/2 base-south	1.6	2.6	1.9	2.0	2.2	1.9	1.9	1.8	1.8	1.5	1.7
	1/2 base-north	1.5	2.7	1.9	1.9	2.1	1.9	1.9	1.9	1.8	1.5	1.7
	MEAN	1.6	2.7	1.9	2.0	2.2	1.9	1.9	1.8	1.8	1.5	1.7
	PEAK EMF (volts)											
	1/3 cap-south	4.2	5.3	3.9	4.2	4.1	4.1	4.1	3.9	4.1	3.5	3.9
1	1/3 cap-north	4.2	5.3	4.0	4.2	4.0	4.2	4.0	3.9	4.1	3.5	4.1
	South column	3.4	5.7	3.6	3.2	3.2	3.3	3.2	3.0	3.2	2.5	3.2
	MEAN	3.9	5.4	3.8	3.9	3.8	3.9	3.7	3.6	3.8	3.2	3.7
	1/3 cap-south	3.1	5.5	5.2	3.3	2.9	3.3	3.2	2.8	3.0	2.5	---
2	1/3 cap-north	3.3	5.4	4.5	3.7	3.1	3.5	3.3	3.0	3.1	2.6	---
	Center Column	3.4	4.4	4.3	3.7	3.3	3.7	3.5	3.1	3.3	2.5	---
	MEAN	3.3	5.1	4.7	3.6	3.1	3.5	3.3	3.0	3.1	2.5	
	1/3 cap-south	4.5	3.9	3.4	4.6	4.2	4.5	4.3	4.0	4.1	3.2	---
3	1/3 cap-north	4.3	4.1	3.8	4.0	3.8	4.1	3.9	3.6	3.7	2.8	---
	North Column	3.4	5.4	4.0	3.4	3.0	3.5	3.1	2.8	3.0	2.1	---
	MEAN	3.9	4.5	3.7	4.0	3.7	4.0	3.8	3.4	3.6	2.7	
4	1/2 base-south	3.7	4.7	3.8	3.8	3.5	3.6	3.5	3.2	3.3	2.8	3.4
	1/2 base-north	3.4	4.6	3.3	3.6	3.1	3.3	3.3	3.0	3.1	2.8	3.4
	MEAN	3.5	4.7	3.6	3.7	3.3	3.5	3.4	3.1	3.2	2.8	3.4

1/3 of pier cap, south column, and south 1/2 of pier base). Two half-cell locations were monitored within each subzone, one at the same location used in the previous testing and the other at the most negative half-cell potential monitoring location in each subzone.

Table E-6 summarizes the authors' interpretation of the findings of the E log I testing of each zone and also presents the results in terms of current density (by square feet of concrete and square feet of rebar). The indicated current densities vary from 1.55 to 2 mA per sq ft of concrete (2.1 to 3.7 mA per sq ft of rebar), which for 2 of 3 areas tested are higher values than those defined in November 1983. In general, graphical analysis procedures were used to define the straight-line portion indicative of the Tafel slope and the cathodic protection current requirements. However, a review of the data shows that multiple breaks in the E log I curves were common. Thus, it was difficult to select the "proper" straight line indicative of the Tafel slope. For this reason, the computer program "Betacrunch" (*10*) was used extensively, following the procedures defined in the appendix on the Phase 1A slab, as an aid in ensuring that the proper cathodic Tafel slope was defined. Further, a conservative tact was taken, in that the graphical solution was deemed adequate if the computer program-defined cathodic Tafel slopes and I_{corr} values were less than or equal to the graphical values. Each of the E log I findings is discussed individually in the following sections.

Table E-7 presents the data obtained on the south one-half of the pier base (zone 4). The data for the CSE cell located at monitoring point 4-2 are plotted in Figure E-7, while those for the cell at 4-6 are presented in Figure E-8. I_{prot} values of 175 and 140 mA were defined for the two cells (average = 1.55 mA per sq ft of concrete and 3.68 mA per sq ft of rebar. Aboveground portions only were considered.) This is similar to the 150-mA value defined by the testing performed in November 1983. The linear polarization cross check for the present data is not in good agreement. However, "Betacrunch" computer

Table E-6. E log I test results for the Rosemont Pier.

Zone	Portion	Measured E_{Static} mV, CSE	E_{prot} mV, CSE	Delta E mV	I_{prot} mA	I_{corr} mA	B_c mV/Decade
1	Cap-cell 1-12	-574	-750	176	175	66	419
1	Cap-cell 1-19	-308	-462	154	175	77	435
1	Column	-291	-463	172	88	43	695
2	Cap	-367	-497	130	123	44	289
2	Column	-330	-488	158	76	26	330
3	Cap	-283	-483	200	85	25	370
3	Column	-247	-416	169	74	42	671
4	Base South 1/2	-476	-675	199	150	47	396
4	Base South 1/2 Cell 4-15	-487	-568	81	56	28	262
4	Base North 1/2 Cell 4-17	-474	-595	121	36	16	349
AUGUST 1984 TESTS							
1	Column Cell 1-4	-345	-392	47	125	50	127
1	Column Cell 1-6	-270	-401	131	125	50	324
1	Cap Cell 1-12	-540	-621	81	460	160	181
1	Cap Cell 1-19	-372	-463	91	470	255	315
4	Base South 1/2 Cell 4-2	-633	-756	123	175	68	297
4	Base South 1/2 Cell 4-6	-486	-528	42	140	68	124

COMPARISONS

	I_{prot}, mA		I_{prot} mA/ft^2 Aug. 1984	
	Nov. 1983	Avg. Aug. 1984	of Rebar	of Concrete
South 1/2 Pier Base	150	158	3.68	1.55
South Column	88	125	2.09	1.59
South 1/3 of Pier Cap	175	465	3.63	1.98

analyses generally confirm the chosen cathodic Tafel slopes for both curves.

During E log I testing of the south column, CSE cells were positioned at locatins 1-4 and 1-6 and monitored throughout the testing. Additionally, the macrocell rebar probe installed during repair was monitored throughout the E log I test. As expected, in the static state the probe was highly anodic to the surrounding rebar in patch concrete (calculated corrosion current density on probe equalled 1.79 mA per sq ft of rebar). This corrosion current decreased with each increment of CP current. Galvanic current flow between the probe in salty concrete and the surrounding rebar in salt-free concrete was reduced to zero when the CP current to the column equalled 155-mA TRMS. At CP currents above that value, the probe rebar received ever-increasing amounts of current. Both CSE cells 1-4 and 1-6 indicate that 125-mA TRMS of protective current are required. This translates to 1.6 mA per sq ft of concrete and 2.1 mA per sq ft of rebar, values that are about 45 percent higher than those defined in November 1983. The computer analyses of the E log I data confirm that the I_{prot} values are no higher than those defined and also suggest that perhaps lower straight-line portions may be indicative of the cathodic Tafel lines. The indication that such a line exists at an I_{corr} value of about 33 mA and a B_c of about 90 mV per decade is strong for cell 1-4, and suggested for cell 1-6 at I_{corr} = 33mA and B of about 220 mV per decade. If such were the case, the I_{prot} values would be 50 mA for cell 1-4 and 50 mA for cell 1-6, values that translate to 0.64 mA per sq ft of concrete and 0.83 mA per sq ft of rebar.

E log I data for the south one-third of the pier cap, at CSE cells positions 1-12 and 1-19, were monitored throughout the testing. The data indicate that about 465 mA of CP current are required for protection. This translates to 2.0 mA per sq ft of concrete and 3.6 mA per sq ft of reinforcing steel, which is more than twice that indicated by the November 1983 testing. The computer analyses are not strong, but tend to confirm the graphically defined I_{corr} and cathodic Tafel slope values. Such a difference between the November 1983 and August 1984 E log I findings was unexpected. Possible explanations for the differences include: improper test results or interpretation of the results in one of the instances or a change in corrosion state with time. Repeat testing is the best means to establish the present situation. Because of the susceptibility of paint anode systems to rapid deterioration at high current densities, one is reluctant to increase the system output until it is certain that such is necessary. The excellent polarization achieved on the south one-third of the pier cap at about 175-mA TRMS total current is documented elsewhere in this report.

CONCLUSIONS

Examination of the cathodically protected pier after 1 year of service indicated the following:

1. The primary anodes recessed in saw kerfs or windrowed performed well.
2. The ends of the large precast primary anodes separated from the concrete of the cap to which they were cemented. Thermal incompatibilities between the concrete and the conductive polymer of the precast anodes probably caused the separation.
3. No significant new concrete delaminations were detected.
4. The bond of conductive Coating A to the repair concrete was excellent. No failures between them were observed on the pier.
5. Minor failures of bond between conductive Coating A and the original structural concrete occurred during the first year of operation. The cause of these failures is uncertain.
6. Repair of failures in the conductive coatings was a simple, fast operation.

Most electrical measurements confirmed that the cathodic protection system rectifiers delivered reasonably constant CP current. Measurements indicated that the CP system caused all

Table E-7. E log I testing.

PROJECT: NCHRP 12-19B CHICAGO SUBSTRUCTURE - CONDUCTIVE PAINT CP SYSTEM

DATE: Aug 29,1984;LOCATION (zone etc.): ZONE 1, PIER CAP (both primary anodes)

TIME, minutes	STEP #	INSTANT OFF POTENTIALS CELL 1 @1-12 CSE	CELL2 @1-19 CSE	mV DROP TRMS,DC Coupled	TRMS CURRENT mA	TRMS CURRENT mA per sq ft of rebar	SYSTEM VOLTS TRMS, DC coupled
0	0	-540	-372	0	0.00	0.00	-
3	1	-540	-372	2.8	2.7	0.02	
6	2	-540	-372	4.4	4.2	0.03	
9	3	-541	-373	7.3	7	0.05	
12	4	-542	-372	9.7	9.3	0.07	
15	5	-542	-373	13.1	12.5	0.10	
18	6	-545	-373	18.7	17.9	0.14	1.055
21	7	-546	-374	24.2	23.1	0.18	
24	8	-549	-375	32.1	30.7	0.24	1.089
27	9	-551	-375	36.9	35.3	0.28	1.173
30	10	-554	-376	47.5	45.4	0.35	1.268
33	11	-557	-378	67.9	64.9	0.51	1.385
36	12	-562	-380	90.3	86.3	0.67	1.47
39	13	-566	-382	102.6	98.1	0.77	1.568
42	14	-570	-385	116.9	111.8	0.87	1.652
45	15	-574	-387	131.1	125.3	0.98	1.77
48	16	-578	-391	151.6	144.9	1.13	1.918
51	17	-583	-396	179.9	172	1.34	2.16
54	18	-585	-400	215	206	1.60	2.31
57	19	-589	-406	242	231	1.80	2.51
60	20	-593	-412	279	267	2.08	2.79
63	21	-600	-423	334	319	2.49	3.01
66	22	-605	-431	366	350	2.73	3.21
69	23	-611	-440	407	389	3.04	3.35
72	24	-615	-447	436	417	3.25	3.63
75	25	-621	-459	490	468	3.65	3.89
78	26	-627	-467	528	505	3.94	4.06
81	27	-631	-476	554	530	4.13	4.34
84	28	-637	-487	604	577	4.50	4.6
87	29	-643	-499	654	625	4.88	4.87
90	30	-648	-507	700	669	5.22	
93	31	-653	-517	749	716	5.59	5.51
96	32	-661	-529	823	787	6.14	
99	33	-668	-541	889	850	6.63	
102	34	-673	-550	942	901	7.02	
105	35	-680	-559	994	950	7.41	6.44
108	36	-686	-569	1040	994	7.76	6.73
111	37	-693	-578	1106	1057	8.25	7.11
114	38	-699	-588	1158	1107	8.64	7.42
117	39	-708	-599	1219	1165	9.09	7.71
120	40	-714	-606	1278	1222	9.53	8
123	41	-720	-613	1322	1264	9.86	8.69
126	42	-728	-622	1398	1337	10.43	9.1
129	43	-739	-632	1470	1405	10.96	9.55
132	44	-749	-642	1557	1489	11.61	10.02
135	45	-758	-652	1609	1538	12.00	10.48
138	46	-772	-664	1741	1664	12.98	11.28
141	47	-785	-676	1860	1778	13.87	11.97
144	48	-801	-689	1996	1908	14.88	12.3
147	49	-809	-697	2065	1974	15.40	13.2
150	50	-825	-710	2210	2113	16.48	14
153	51	-841	-723	2390	2285	17.82	

NOTES: CURRENT SHUNT IS 1.046 OHMS

ESTIMATED CONCRETE TEMP IS= 85 degrees F

E LOG I TEST EQUIP: HALF WAVE, UNFILTERED
ELOGI TESTER & TEKTRONICS 213 SCOPE/ TRMS DMM;
ISOLATION TRANSFORMER & TRMS DMMs'

1/3 PIER CAP = 235.3 SQ FT CONCRETE & 128.2 SQ FT OF REBAR SURFACE

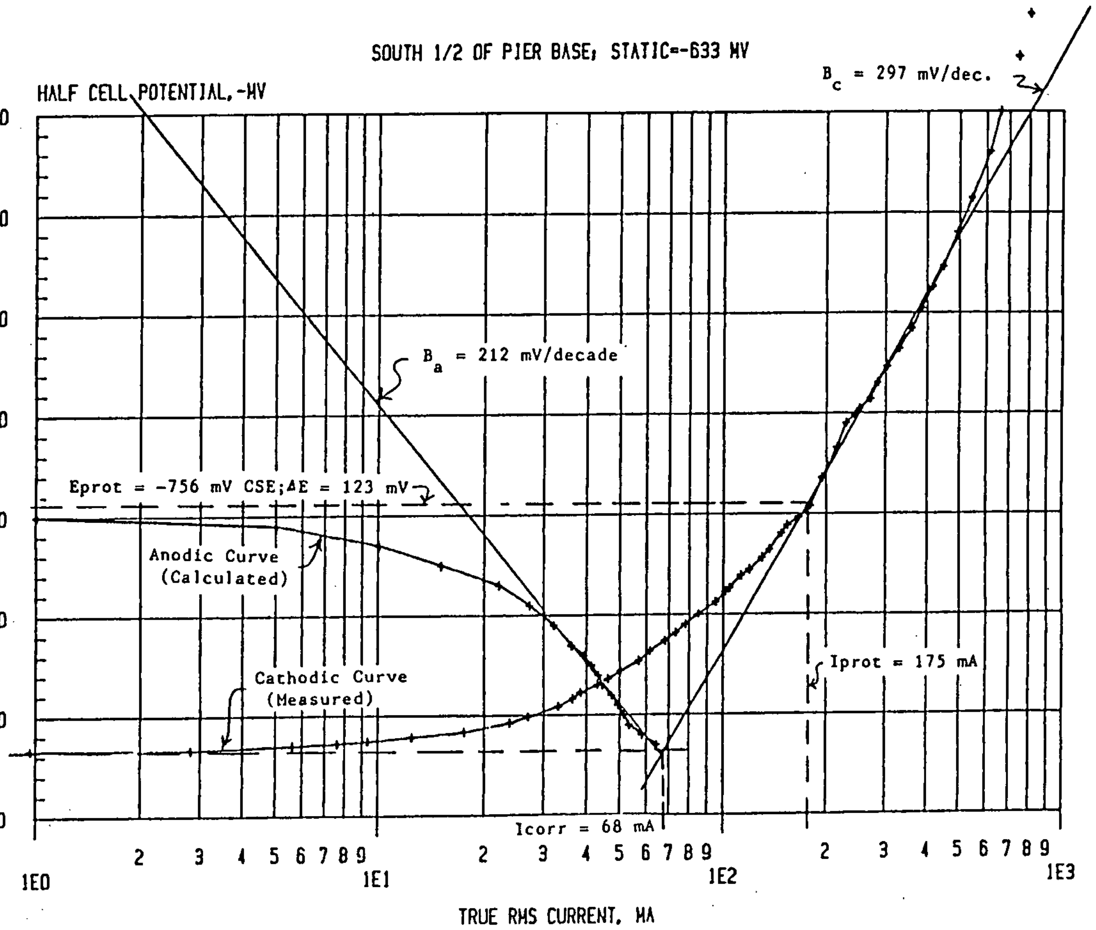


Figure E-7. E log I data for pier—Aug. 29, 1984.

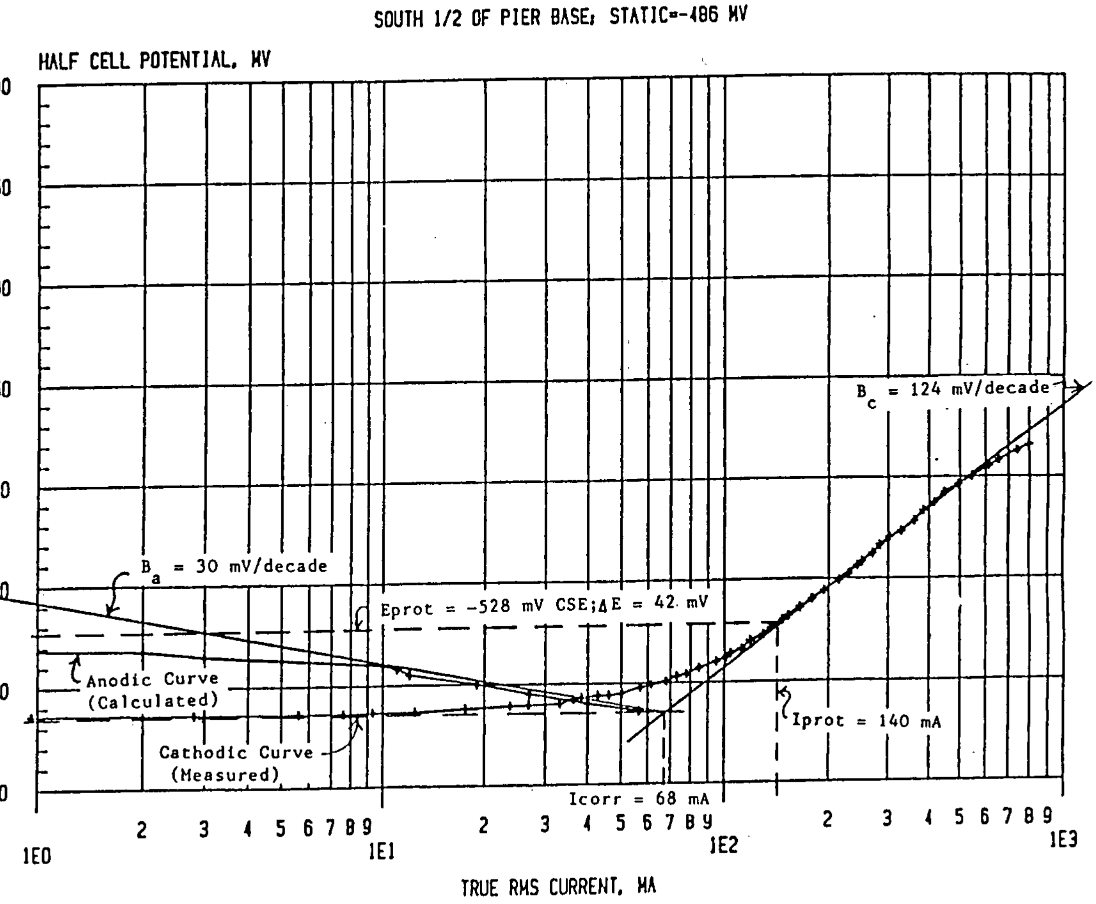


Figure E-8. E log I data for pier—Aug. 29, 1984.

half-cell potentials to become more negative. Depending on location and CP zone, mean half-cell potentials in a zone were depressed by from 1/6 to 1/3 volts.

Mean half-cell potentials varied seasonally. Potentials measured in the winter and spring were generally higher than those measured at other times.

The embedded macrocell and rebar probes were always positive with respect to instrument ground, indicating that these instruments were in a noncorroding state.

E log I measurements were initially used to determine the CP current settings for the various zones. Retesting of the system during September 1984 tended to confirm the initial tests of half-cell locations 4-2 and 4-6 and probably confirm test values for locations 1-4 and 1-6. E log I retesting of positions 1-12 and 1-19 indicated that protective currents are required that are significantly higher than those indicated by the initial measurements. Retesting these two locations at a later date is recommended.

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