# EXPERIMENTAL CATHODIC PROTECTION OF A BRIDGE DECK

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An electrically conductive asphalt concrete was made by substituting coke breeze for the natural aggregate. Paving a bridge deck with the electrically conductive asphalt concrete indicated that cathodic protection could be applied to the reinforcing steel. The cathodic protection was measured to be effective when the corrosion of steel strips embedded in concrete containing 10 percent calcium chloride by weight of the cement was stopped. It is estimated that, for the approximately 3,300 ft<sup>2</sup> (307.6 m<sup>2</sup>) of bridge deck under cathodic protection, the top mat of reinforcing steel has an applied current density of  $0.7 \text{ mA/ft}^2$  (7.5 mA/m<sup>2</sup>) of steel surface. The total current used is about 1.0 A with a driving voltage of 1.65 V for a total power requirement of 1.65 W. As an experimental method of repair, 2 polymers and an epoxy were injected to bond the undersurface fractures. The epoxy could be injected in all cases where the concrete emitted a hollow sound when struck with a hammer. However, the epoxy could not be injected when the concrete emitted a hollow sound from only the use of the chain drag but not from the use of the hammer. The cost of the cathodic protection installation is estimated to be about  $3/ft^2$  of deck  $($33/m^2)$ .

• A NUMBER of reports in the literature have related to the problem of bridge deck deterioration from the use of de-icing salts (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12). In general, the reports have been concerned with detection and determination of causes of reinforcing steel corrosion and techniques and methods for structural repair and prevention of corrosion by use of waterproof membranes. Even though the techniques may not be applicable to bridge decks, one report (12) describes cathodic protection used experimentally to control corrosion of reinforcing steel in beams of a bridge superstructure. However, use of cathodic protection to inhibit ongoing corrosion of concrete-embedded steel has been well established for concrete pipelines (14, 15, 16, 17). This report presents results of experimental cathodic protection installation on a deteriorated bridge deck scheduled for repair and also describes the use of experimental monomer-polymers and epoxy injection to bond delaminated concrete.

That corrosion of steel in concrete is electrochemical in nature has been well established (18, 19, 20, 21). The theory of cathodic protection (22, 23, 24) is to apply sufficient current in a proper direction so that corroding anodes on steel are prevented for discharging current (ions) into the electrolyte or, in this case, concrete. Thus, if the anodes on the steel receive current, they are no longer current-discharging anodes but are noncorroding current-receiving cathodes.

In the corrosion cell, the tendency is for the half-cell potential of the steel to come into equilibrium (23, 24). For example, if the open-circuit potential of a noncorroding cathode is, say, -0.10 V (relative to the saturated copper-copper sulfate half cell, CSE), and the corroding anode is, say, -0.50 V CSE, and if then they are electrically connected together, the combined or equilibrium potential of both electrodes may be -0.40 V CSE. The cathode always becomes more negative as it receives current from the more negative anode. As a result, even though the cathode will shift to a potential of -0.40 V, it still is a cathode and may not be corroding.

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From the theory of cathodic protection, the existing anodes on the steel, to be protected, must be caused to receive electrical current. For this, the half-cell potential of all of the steel must be made more negative than the most negative potential of the anodes. For steel pipelines, the empirical criterion for cathodic protection is that the steel must be made more negative than -0.85 V CSE (25). Although this potential value of -0.85 V CSE has been successfully used on concrete pipelines (16), it has also been reported (26, 27) that cathodic protection should be effective for steel in calcium hydroxide solutions containing chloride at potentials of about -0.71 V CSE. In addition, other work has shown that the most anodic half-cell potential of corroded steel in corrosion-caused cracked concrete was -0.67 V CSE (28). Excessive voltage, however, must not be used because of possible impairment of the concrete to steel bond.

It would appear that the potential of concrete-embedded steel probably should be no less than -0.85 V CSE (where reported past experience on concrete pipelines has been successful) and no more than -1.10 V CSE (18, 26, 27) to avoid the possibility of loss of bond strength. However, the possibility for controlling the corrosion of concrete-embedded steel at a potential of -0.71 V CSE should receive further investigation.

## CATHODIC PROTECTION SYSTEM

There are 2 basic means  $(\underline{22})$  for applying cathodic protection: (a) galvanic anodes and (b) impressed current.

In the galvanic anode system, a sacrificial metal higher in the electromotive or galvanic series is chosen because its electrical potential is more negative than the metal to be protected. Therefore, when the 2 different metals are electrically connected, a current will flow causing the metal under protection to receive current or become a cathode. For a bridge deck, the galvanic system appears to have 2 important drawbacks: (a) voltage between the metals is limited to the maximum electrical potential difference and (b) current output of the galvanic anode will vary with moisture content or electrical resistance of the electrolyte.

For bridge decks, the impressed current system has a number of distinct advantages: (a) voltage output of the anodes can be varied from less than 1 V to more than 100 V, (b) current output can be automatically controlled irrespective of moisture content or electrical resistance of the electrolyte, and (c) half-cell potential of the steel can be automatically maintained independently of the electrical resistance of the environment.

Although various methods for applying cathodic protection to other types of structures are well known, a different system for applying cathodic protection would be required for a bridge deck. From this, it is apparent that the basic electrical circuit of steel in the deck concrete and a theory for applying cathodic protection must be developed and evaluated.

Figure 1 shows some assumed electrical values for the circuit. With the anode in the concrete, an adjacent reinforcing steel bar theoretically can be cathodically protected. However, as shown in the lower part of the figure, bars beyond the most immediate one (rebar 2) are actually in a series parallel circuit with an essentially 0 resistance between bars and power source. Theoretically, to cathodically protect all the reinforcing steel equally, anodes would have to be placed in concrete longitudinally and transversely at the location of every second bar.

To get an effective current to rebar 2 requires that the anode be removed from the concrete and placed in an electrically conductive overlay on the concrete surface to provide essentially equal resistance from all bars to the power source as shown in Figure 2.

One material that can be used as a conductive overlay is carbon in the form of coke, which has had a long record of use as an anode backfill material (29). In a dry state, coke is reported to have a specific electrical resistance of 52  $\vec{\Omega} \cdot \vec{cm}$  (29), which is about twice the electrical resistance of seawater (23). Coke is a highly conductive material as compared to the about 10 000- $\vec{\Omega} \cdot \vec{cm}$  resistance of water-saturated concrete (30), and when wet coke has about one-half the specific electrical resistance of seawater.

The feasibility of using a highly conductive overlay is shown in Figure 2. For purposes of illustration, it is assumed that the electrical resistance of the coke for the

distance between the reinforcing steel is 1  $\Omega$  and the electrical resistance of the concrete between the interface of the coke and concrete to the surface of the steel is 100  $\Omega$ . From these assumptions and laws of electrical current flow, horizontal travel of electricity through coke would only be reduced by the ratio of 1- $\Omega$  resistance in the coke to the 100- $\Omega$  concrete resistance to the reinforcing steel as the current spread out through the deck. Therefore, this general method was chosen as the most promising method of applying cathodic protection to a deck.

## BRIDGE CONSTRUCTION

The bridge selected for the experimental cathodic protection scheme was built in 1964 and is located on US-50 at Sly Park, California, at an elevation of 4,000 ft (1219 m). The average annual precipitation is 42 in. (107 cm), which includes about 18 in. (46 cm) of snowfall. The annual air temperature range is from 15 to 105 F (-9.4 to 40.6 C).

The bridge is a continuous 3-span T-beam that is 48 ft (14.6 m) wide and 110 ft (33.5 m) long; it carries 2 lanes of westbound traffic.

The specifications for the concrete in the bridge deck called for 7 sacks/yd<sup>3</sup> (9.2 sacks/m<sup>3</sup>) of type 2 low-alkali cement, 4 to  $4\frac{1}{2}$  percent entrained air. Mixing water, including that in the aggregate, was not to exceed 45 lb/sack (20.4 kg/sack) of cement, and the concrete curing was specified to have 7 days of curing by water. A pigmented curing compound was to be applied following the wet cure.

In a review of the construction records, only 1 of the many concrete cylinders could be positively identified as being from the deck concrete. The identification ticket with the sample indicated that the concrete contained 7 sacks/yd<sup>3</sup> (9.2 sacks/m<sup>3</sup>) of cement (ASTM type 2 modified, low alkali) and had a  $4\frac{1}{2}$ -in. (11.4-cm) slump. The mixing water content was 44 lb/sack (20 kg/sack) of cement. The 28-day compressive strength of this cylinder was 3,730 lb/in.<sup>2</sup> (25.7 MPa). The other samples from this bridge showed entrained air contents of 4.4 percent and 28-day compressive strengths ranging from 3,860 to 4,460 lb/in.<sup>2</sup> (26.6 to 30.8 MPa).

The specified concrete cover over the reinforcing steel was  $1\frac{1}{2}$  in. (3.8 cm).

#### BRIDGE CONDITION

Because of corrosion-caused concrete spalling, the bridge deck had been scheduled for initial repairs and overlay during the 1973 construction season. All evidence of deterioration on this bridge is the result of reinforcing steel corrosion. There is no visual evidence of distress as a result of reactive aggregate or freeze-thaw damage.

In April 1972, this bridge was surveyed for concrete delamination, electrical potentials, depth of cover over the steel, and chloride content in preparation for the repair contract. The surveying technique has been previously reported (12). In addition, as part of the cathodic protection installation, the deck was again surveyed for concrete delamination and electrical potentials in June 1973.

Results of chloride analysis from cores, shown below, indicate the high level of chloride-ion at the level of the steel.

Depth (in.)	$Lb/Yd^3$	
0 to 1	7.24	
1 to 2	3.52	
2 to 3	0.96	
3 to 4	0.44	

From a total of 426 measurements with a pachometer, the average depth of concrete cover over the reinforcing steel was 1.68 in. (4.3 cm), the standard deviation was 0.22 in. (0.56 cm), and the range was between 1.10 and 2.70 in. (2.79 and 6.86 cm), which indicates reasonable compliance with specifications.

Comparison of results of 1972 and 1973 electrical potential and concrete delamination survey are given below and indicate a change in physical and electrical conditions of the bridge in 1 year (14 months) of service. The percentage of concrete delamination is the percentage of the total deck surface that is spalled. The percentage of corrosion potential is that percentage of all measured potentials that are corrosive (and are potentials more negative than -0.35 CSE).

	Concrete	Corrosive
	Delamination	Potentials
Year	(percent)	(percent)
1972	2	53
1973	12	71

### DECK PREPARATION

Figure 3 shows the equipotential contours for the bridge deck survey made in June 1973. Also shown are the locations of the undersurface fractures. As indicated by the extent of the fractures, some deck repairs had to be made prior to the application of cathodic protection. Otherwise, there was a possibility that the existing concrete spalls eventually may be loosened by traffic and thus cause structural failure of the cathodic protection overlay.

In an attempt to keep costs as low as possible, it was decided not to repair the deterioration by the process of concrete removal and replacement. Previous repairs of this kind had cost up to  $16/ft^2$  ( $172/m^2$ ) of repaired area. Instead, it was reasoned that if the concrete could be bonded together by injection of a suitable ''glue,'' then structural loosening by traffic would be minimized. Also, if the cathodic protection system were successful, then continued corrosion-caused spalling would be stopped. Two materials were selected to use to bond the loose concrete to the underlying deck: a monomer, used recently in experimental concrete impregnation studies and an epoxy resin (32). The locations where each material was used are shown in Figure 3. At each spall, at least one  $\frac{1}{2}$ -in. (1.3-cm) diameter hole was drilled into a central area. The debris from the hole was then removed by the use of an industrial vacuum cleaner. All injections of monomer and epoxy resin were made via these holes as shown in Figure 4.

By use of a grease gun, methyl methacrylate and styrene monomers were injected into the spalls. Later, 4-in. (10.2-cm) diameter cores were obtained to determine whether the concrete was truly bonded. Except for 1 core sample from the styreneinjected area, none of the monomer-injected concrete spalls was bonded. It was surmised that the methyl methacrylate was too thin and was absorbed by the concrete instead of filling the crack void. From visual observations, the styrene monomer appeared to have great curing shrinkage, which may have adversely affected bonding. However, the experimental monomer injection was performed with hand equipment. Better equipment and the selection of other monomers could have produced different results.

As shown in Figure 3, when a maximum pumping pressure of 160 lb/in.<sup>2</sup> (1.1 MPa) was used, the epoxy injection was both successful and unsuccessful. The successful cases, where the cores showed the concrete was well bonded together, were found where the concrete emitted a hollow sound when the surface was struck with a hammer. The unsuccessful locations were found where the chain drag indicated a hollow sound but the hammer did not. In these latter locations, the epoxy could not be injected into the spalls at the pressures normally used. Previous but unreported work (as evidenced by concrete cores) by the author has shown that the chain drag will indicate delaminated concrete in locations where the hammer method will not.

Prior to and after the injection of the monomers and the epoxy, half-cell potentials were made at the specific locations of the concrete spalls. The apparent maximum reduction in the half-cell potential of the steel after injection was in the order of 0.05 V. Therefore, it was concluded that the injection of bonding materials would not significantly affect the penetration of cathodic protection currents to the surface of the reinforcing steel. It is surmised that, for the tested areas of this bridge, the concrete



Figure 3. Original half-cell potentials and concrete spalls.

Figure 2. Schematic of anode in coke.







Figure 4. Injecting epoxy into undersurface structure.



Figure 5. Panel for controlling current to anodes.



Figure 1. Schematic of anode in concrete.

within the undersurface fractures still has numerous points of contact. Therefore, filling of the void with dielectric epoxy or monomer does not create a continuous electrical shield between the reinforcing steel and the surface of the concrete. The ca-thodic protection currents to the steel should be effective in these areas of repair.

## ELECTRICAL CONTINUITY

The use of cathodic protection depends on the electrical continuity of the structure being protected. If there are portions of the structure under cathodic protection that are not electrically connected to the system, they can be caused to corrode by stray currents at an accelerated rate (22, 29). Therefore, care must be exercised in determining whether the reinforcing steel in a bridge deck is electrically continuous.

Even with a detailed amount of testing, there is always the chance that one reinforcing bar out of the hundreds in a bridge deck may not be electrically continuous. In that case, damage will occur. If stray current damage occurs to 1 or 2 bars, the resultant concrete spalling and corrosion of the steel are expected to be no different from the condition that exists before cathodic protection is applied. However, when such a condition arises, repair can be made and the ''loose'' piece of steel welded to adjacent reinforcing steel. It then becomes a part of the protected grid. As a result, the corrosion can be stopped, which is not the case when conventional methods are used for repairing the damage.

In practice, it has been required that, at least at every third crossing of the reinforcing steel, a tie wire be used to mechanically interconnect the steel. Therefore, there is a strong likelihood that all reinforcing steel will be interconnected simply by normal construction procedures.

A previous report (28) showed that, if the half cell were left in the same location on a deck surface, the measured half-cell potentials would be different if an electrical contact were made to various electrically disconnected pieces of steel embedded in the concrete. Conversely, if the steel were interconnected, the half-cell potential relative to a stationary half cell would be the same, irrespective of the location of the connection to embedded steel. This assumes that the electrical resistance of the steel is minor compared to the electrical resistance of the concrete.

On the Sly Park Bridge, at 4 equidistant locations along the curb line and also on the concrete section of the railing, the electrical measurements showed that all reinforcing steel was interconnected. However, the bolted-on aluminum guardrail was not electrically connected to the reinforcing steel.

For the 'ground' of the cathodic protection system, at all 4 deck locations at which the steel was used for continuity testing, No. 8 direct burial stranded copper wires were welded to the bars and brought out to the control panel.

## CONTROL CABINET

As shown in Figure 5, a standard traffic controller cabinet was modified to house the electrical circuitry and the standard automotive type 6 and 12-V battery power sources.

Also installed on a panel inside the cabinet are 36 each of  $3-\Omega$ , 5-W wire-wound resistors. The purpose of these resistors is to control the amount of direct current to each of the anodes. This current control capability is necessary because of the expected variations in the electrical resistance of the portland cement concrete and coke-breeze asphalt concrete.

Included within the control panel are selector switches that allow the measurement of current flow by means of an  $0.01-\Omega$  shunt in series with each anode connection.

An ammeter is also installed on the panel to measure gross current flow. There are provisions for external equipment, such as a timer, that will automatically turn the current on and off so that polarization measurements can be obtained. The control panel without modification is to be used with an automatic potential control cathodic protection rectifier.

## COKE-BREEZE ASPHALT CONCRETE

Insofar as coke breeze has been used as a backfill material for impressed current cathodic protection anodes, its feasibility as an asphalt concrete aggregate was evaluated. As received, coke breeze No. 90 was graded and found to meet January 1973 standard specifications of the California Division of Highways for aggregate grading of  $\frac{3}{6}$ -in. (0.95-cm) maximum aggregate for asphalt concrete.

Some of the physical properties determined were as follows: The specific gravity was 1.64 for the aggregate and 1.25 for the mix with 15 percent of 85 to 100 penetration asphalt (California test method 38); the K value was 3.0 for the coarse coke breeze and 1.7 for the fine aggregate (California test method 303); the surface area of the mix was  $37.4 \text{ ft}^2/\text{lb}$  (7.66 m<sup>2</sup>/kg) (California test method 303); and the stabilometer value for a mixture of coke breeze and 15 percent of 85 to 100 penetration asphalt was approximately 28 (California test method 304).

Based on preliminary work, it was determined that, for optimum electrical properties, coke breeze should be 3 in. (7.6 cm) thick. However, the lower asphalt content mixtures tested were not sufficiently cohesive to be exposed directly to wheel loads. Therefore, it was decided to overlay the coke-asphalt concrete layer with about 2 in. (5 cm) of a dense-graded  $\frac{3}{8}$ -in. (0.95-cm) maximum natural aggregate asphalt concrete for a total overlay thickness of 5 in. (12.7 cm).

To determine the durability of composite pavement, a 50-ft-long by 12-ft-wide (15.2- by 3.66-m) test section was placed on a new but unused portland cement concrete pavement. After it was mixed at a plant, the coke-breeze asphalt concrete was spread by using a Layden box spreader. Initial rolling was done with a 4-ton (3628-kg) roller, and final rolling was done with a 10-ton (9071-kg) roller. The coke breeze was mixed with 15 percent of 85 to 100 penetration asphalt, and the  $\frac{3}{6}$ -in. (0.95-cm) maximum natural aggregate wearing course was mixed with 5.4 percent of the same asphalt.

At one end, a 12-ft (3.66-m) length of 5-in. (12.7-cm) thick all-natural-aggregate asphalt concrete was used as a control section. In the test section, the coke-breeze layer was covered with Petromat. However, after the natural aggregate concrete was placed, it was observed that the Petromat tended to wrinkle and its further use was questioned at that time. It was not used on the bridge overlay. A Dynaflect was used to measure deflections, and cross sections were taken at various stations.

To quickly test the load-carrying capacity of the composite pavement, a 10-wheel truck weighing about 44,000 lb (20 000 kg) complying with the legal load limit of 18,000 lb (8165 kg) per axle was used to apply loads to the test section. The results were that, at the end of 3,802 passes of the truck, no distress was observed or measured.

On the basis of this test series, it was decided that the composite asphalt concrete pavement would be reasonably durable when used on a bridge deck.

# INSTALLATION OF ANODES AND OVERLAY

The iron-alloy anodes were disc shaped, 10 in. (25.4 cm) in diameter and  $1\frac{1}{4}$  in. (3.2 cm) thick, and had an average weight of approximately 29 lb (13.2 kg). Based on test data (31) for similar anodes, they had a consumption rate of about  $\frac{1}{4}$  lb (0.1 kg) per ampere year of current flow. In other words, if 1 A was caused to be continuously discharged by the anode, it would be entirely consumed by corrosion in about 116 years.

Initially 3 rows of anodes were laid out on the bridge deck 12 ft (3.66 m) center-tocenter. The anodes in effect were placed on 12-ft (3.66-m) centers directly beneath the 3 traffic strips that delineate the 2 lanes across the bridge. After locations of the anodes were marked out on the pavement, a fast setting epoxy adhesive (California standard specification 721-80-42) was placed on the concrete surface and the anode was then placed on the epoxy. Epoxy was used to hold the anodes in place during the paving operation and to prevent current discharge from the bottom surface of the anode. Limiting the current discharge from the bottom of the anode would inhibit the lifting of the anode, which could cause pavement distress due to the formation of a layer of rust between the anode and the concrete pavement. Also, the epoxy layer would reduce the current discharge directly beneath the anode, which could cause a high current density flow to the reinforcing steel directly under it and, thus, result in a "hot spot." At the conclusion of the paving operation, 1 out of 36 anode connections was damaged. The damage was likely caused by the roller passing close to the point where the lead wire leaves the anode, thereby pulling it loose.

Before the bridge deck was paved, an SS-1 asphalt emulsion tack coat was applied at a rate of  $0.05 \text{ gal/yd}^2$  (0.23 liter/m<sup>2</sup>). Previous electrical testing on the pavement test section showed that use of the tack coat at this rate of coverage would not adversely affect the electrical performance of the cathodic protection system.

The coke breeze was initially dried at the batch plant to a temperature of about 230 F (110 C) to which the 85 to 100 penetration grade asphalt at 310 F (154 C) was added. Final temperature of 21 tons (19 050 kg) of coke-breeze asphalt concrete at the batch plant ranged between 240 and 270 F (116 and 132 C). The haul distance from the batch plant to the bridge was approximately 55 miles (89 km). A Blaw-Knox rubber-tired paving machine was used to lay all coke-breeze asphalt concrete in about 10-ft (3-m) widths. An area approximately 1,500 ft<sup>2</sup> (139.4 m<sup>2</sup>) was paved with an all-natural-aggregate asphalt concrete. The 5 anodes in this area cannot operate as intended and are, therefore, not included in the protection system. As will be discussed later, only 7 of the remaining anodes were needed to provide the desired protection.

The coke-breeze asphalt concrete layer was consolidated initially with a 4-ton (3628-kg) roller and finally with a 12-ton (10 886-kg) roller. Initially, there was some "shoving" of this mixture because of its lack of cohesion. Further studies are being made to improve the cohesion of the coke-breeze asphalt concrete by using a heavier grade of asphalt or a higher asphalt content or both.

The natural-aggregate asphalt mix for the surface or wearing course arrived at the job site at a temperature of 270 F (132 C), and its placement in 1-in. (2.54-cm) lifts and rolling to final grade were performed without incident.

Thus far (2 months of service) there is no evidence of distress on the pavement due to traffic, which includes up to maximum legal load limits of commercial and logging truck traffic. However, the pavement has not yet been subjected to inclement weather, such as rain or snow, or to chain traffic.

Figure 6 shows the anodes in place, and the paving operation in progress. Figures 7 and 8 show the actual depths of the loose or uncompacted coke-breeze asphalt concrete as well as the area that contains full-depth (5-in., 12-cm) natural-aggregate asphalt concrete. As shown in Figure 8, the thickness of various areas of the uncompacted depth of coke breeze is  $3\frac{1}{2}$ , 3, and  $2\frac{1}{2}$  in. (8.9, 7.6, and 6.4 cm). The varying depth of coke-breeze asphalt concrete was used to explore the feasibility of reducing the total depth of the composite asphalt concrete.

The Sly Park Bridge does not have expansion joints; therefore, no consideration was given to the use of expansion dams.

## CIRCUIT RESISTANCE

After the installation was completed, but before any current was applied, electrical measurements were made on the deck at various intervals of time. It was observed that for about 1 week after construction the half-cell potentials of the steel would not reasonably duplicate those values that were originally measured on the concrete surface.

It was speculated that, when the hot (270 F, 132 C) asphalt concrete was placed on the deck surface, free water was driven out of the portland cement concrete. In the dry and hot climate typical at the time of construction (air temperatures about 95 F, 35 C), a few more than 7 days were required for the moisture level to increase enough to make the upper surface of the concrete electrically conductive.

By use of a commutated direct current ohm meter, the average electrical resistance was measured between the anodes and the reinforcing steel. The average values of electrical resistance for the various uncompacted thicknesses of coke-breeze asphalt concrete are given below. Compacted thickness is probably about  $\frac{1}{2}$  in. (1.3 cm) less than that given. Also given are the average electrical resistance values when cathodic protection was being applied at a current of 1.01 A and a driving voltage of 1.65.

Uncompacted Depth (in.)	Commutated dc Resistance $(\Omega)$	After Polarization $(\Omega)$	
$2^{1/2}$	1.43	14.7	
3	1.16	12.1	
$3^{1/2}$	1.09	9.3	

There is a significant difference in electrical resistance for the different uncompacted depths of the coke-breeze asphalt concrete. The effect of polarization during the flow of cathodic protection currents is also shown as an electrical resistance for the different depths of coke asphalt concrete. The measurements were made on the compacted composite pavement, and the term ''uncompacted depth'' applies to the depth of the asphalt concrete before compaction or consolidation.

During the process of cathodic protection, the polarization of the anode and cathode results in a back electromotive force, EMF (22, 29). In the case of the Sly Park Bridge, when the anodes were disconnected, the polarization (or back EMF) that was measured between the anodes and reinforcing steel was an average of 1.44 V.

The locations of the 7 operating anodes outside the traveled lanes are shown on Figures 7 and 8. The only reason that not all of the anodes are being used is that during the preliminary testing it was possible to sustain the cathodic protection system without using all of the installed anodes. The locations of the anodes being used have a mechanical and economical advantage over the use of anodes that were installed in the traveled lanes. These anodes would be subject to greater traffic loading as compared to those in the shoulder and median areas of the bridge.

## DISTRIBUTION OF CATHODIC PROTECTION CURRENTS

It was initially planned that for equal current distribution throughout the bridge deck surface all of the originally installed anodes might be used. However, initially, 4 adjacent anodes that were located at the shoulder side of the west end of the bridge were turned on with a total current flow of 3.6 A. The cathodic protection currents could polarize the reinforcing steel to a protective potential for a longitudinal distance of 65 ft (19.8 m) from the nearest anode. Also, the steel began to polarize quite rapidly so that after 2 hours the output current from the 4 anodes was reduced to 2.0 A. Three days later, the current flow to the 4 anodes was further reduced to 1.6 A. Seven days later, the 4 anodes at one end of the bridge were deactivated and the 7 anodes (as shown in Figs. 7 and 8) were activated with a total current output of 1.08 A.

The performance of the 7 anodes after 19 days of operation is given below. The anodes that are numbered 1-1 through 1-9 are near the shoulder area; 1-1 is at the most westerly end of the bridge. The anodes numbered 3-1 and 3-4 are nearest the centerline or median area of the twin-bridge installation.

Anode	Ampere	Driving Voltage	Back EMF
1-1	0.12	1.65	1.48
1-3	0.12	1.65	1.52
1-5	0.21	1.65	1.42
1-7	0.20	1.60	1.38
1-9	0.15	1.60	1.38
3-1	0.10	1.72	1.42
3-4	0.15	1.82	1.48

Figure 7 shows the voltage gradients relative to the CSE when the cathodic protection currents are on. Even though the current is on, the measurements of the half-cell potential of the reinforcing steel beneath the 5-in. (12.7-cm) thick nonconductive natural-aggregate asphalt concrete are unaffected and near the same values as originally measured and shown in Figure 3. This shows that the steel in this area is not



Figure 7. Cathode protection current on.



Figure 8. Current off polarized potentials.



Figure 9. Distribution of half-cell potential.



Figure 10. Effect of cathodic protection.



affected by the other parts of the system, and the basic theory of deck protection is confirmed (i.e., no current will flow through the nonconductive layer).

Figure 8 shows the current in the off condition, or the distribution of the polarized half-cell potentials of the steel. The maximum range of the difference of polarized potentials of the steel is 0.35 V. Also, as indicated by the potentials being more negative than -0.85 V, the cathodic protection currents should be effectively controlling the corrosion of the steel.

Even though the activated anodes shown in Figures 7 and 8 are at a 24-ft (7.3-m) center-to-center spacing, the inactive anodes could be energized and result in a more even distribution of potentials. However, as previously pointed out, it is desirable to have the cathodic protection system operate with anodes not placed in the traveled lanes of the pavement. The inactive anodes will be placed under cathodic protection so that, when or if the operating ones are consumed or become inoperative, the inactive ones will be available and no new anodes will have to be installed.

The ''storage'' of in-place inactive anodes by cathodic protection that are installed at the same time as the active anodes may be of considerable value on structures of high vehicular density where maintenance operations are of critical concern.

Measurements were made to determine whether the cathodic protection currents were affecting the bottom mat of reinforcing steel. The half-cell potential of this steel changes only a few millivolts when the cathodic protection current is turned on and off. The bottom mat is not significantly affected by the cathodic protection currents, so any corrosion of this steel will not be controlled by the system.

Because the 2 mats of steel are interconnected by the "crank" or truss bars, a calculation of the cathodic protection current density to the surface of the steel can only be an estimate. Therefore, for this particular structure, the existing current density used to obtain cathodic protection is estimated to be about  $0.7 \text{ mA/ft}^2$  (7.5 mA/m<sup>2</sup>) for the top mat of steel.

As an indication of the distribution of the half-cell potentials of the reinforcing steel, Figure 9 shows the original current on and the current off polarized potentials.

Figure 9 shows that 98 percent of all of the polarized potentials are greater than -0.85 V; therefore, about 2 percent of the area of the steel within the conductive asphalt concrete may not have adequate cathodic protection. The potentials at those locations of less than -0.85 V CSE can be easily changed so that the current output of the anodes is increased.

Although the conditions reported were observed during battery operation, a rectifier has been installed that will automatically control the cathodic protection current according to the half-cell potential of the steel. As a result, a permanent half-cell is being placed on the deck that will provide the means for the rectifier to ''sense'' the half-cell potential of the steel and make automatic adjustments of the current. Automatic operation will supply the proper level of cathodic protection regardless of other varying conditions.

#### EFFECTIVENESS OF CATHODIC PROTECTION

Literature references are cited wherein effectiveness of a cathodic protection system can be related to the polarized half-cell potential of the steel. However, since this might be the first demonstration of cathodic protection on a bridge deck and involves some unique features as compared to, say, pipelines or tanks, effectiveness of the system should be demonstrated, preferably by a short-time test. A test of sorts was devised to measure the effect of the system on corrosion of steel strips embedded in 3- by 3- by 12-in. concrete blocks containing 10 percent calcium chloride by weight of cement. By external means, the steel strips were measured to determine their electrical resistance. Any corrosion of the steel strips will result in a change in their cross section, and thus there will be an associated change in electrical resistance of the steel. This technique has been widely reported (33) and used.

The concrete blocks and embedded steel strips described above were placed in the conductive coke asphalt concrete as shown in Figure 10. Steel strip 1 was allowed to corrode for  $6\frac{1}{2}$  days before it was connected to the cathodic protection system. Cor-

rosion was essentially stopped after the application of cathodic protection current. The polarized potential of the strip was measured and found to be -1.31 V CSE. Steel strip 2, which also was embedded in the same kind of concrete, was placed in the electrically conductive coke asphalt concrete and immediately connected to the cathodic protection system. Essentially no corrosion occurred. After 6 days, the strip was disconnected from the cathodic protection system and corrosion began. However, as shown by the performance of steel strip 2, the loss of cathodic protection does not result in an immediate and catastrophic corrosion rate because of the apparently longterm ''decay'' of polarization. The half-cell potential of steel strip 2 was -0.67 V CSE on the twentieth day of test.

As indicated by the corrosion measurements of the steel strips with and without cathodic protection applied, the system is feasible and does control corrosion of embedded steel. However, the long-time durability and performance of the paving system and the anodes themselves have not yet been confirmed for this type of application.

There is still the possibility that there will be pavement failure as the result of untouched and loose concrete spalls in the deck. However, such failures would be considered not a failure of the cathodic protection system but an indicator of necessary deck preparation prior to the placement of the overlay.

# COST OF CATHODIC PROTECTION

Although an experimental installation provides a poor criterion of costs, it is at this time the only available indicator. Therefore, the cost of the cathodic protection installation is to be regarded as an estimate and could vary considerably from that given below:

Item	Estimate	
Paving (including cost of coke breeze)	\$ 8,867.57	
Epoxy injection (repairs of deck)	1,507.50	
Anodes	1,500.00	
Installation of anodes	75.00	
Wiring (ac power)	1,600.00	
Rectifier	900.00	
Control panel	1,500.00	
	\$15,950.07	

Based on the total square feet of deck area, the cost for the cathodic protection system was about  $3/ft^2$  ( $33/m^2$ ) of deck area. This figure does not include the cost of the original bridge survey or the testing that was performed subsequent to the installation of the cathodic protection system.

# SUMMARY AND CONCLUSIONS

Cathodic protection has had a long history of successful use in protecting concreteembedded steel in pipelines. The results of these experimental installations demonstrate that, if certain conditions are met, cathodic protection can be applied to a bridge deck. One condition necessary for successful uniform application of electrical current to embedded steel is a conductive layer of relatively low electrical resistance that can be spread over the area to be protected. Although there are other materials that can be used as an electrically conductive overlay, coke breeze was found to provide the necessary properties. When mixed with a relatively low amount of asphalt binder, the coke-breeze asphalt mixture was stable enough to function also as a base for a regular asphaltic concrete wearing course.

Prior to the installation of the cathodic protection system, the bridge deck was surveyed for half-cell potentials and concrete delaminations by means of the chain drag. For the 1-year period between 1972 and 1973 prior to this work, the undersurface concrete fractures increased from 2 to 12 percent of the total deck area and the percentage of corrosive potentials increased from 53 to 71 percent of the total measurements. The average chloride-ion content of the concrete 1 year before the installation of the cathodic protection system was  $3.52 \text{ lb/yd}^3 (2.08 \text{ kg/m}^3)$  at the level of the reinforcing steel.

Because past experience has indicated that concrete removal and replacement at delaminations have cost as much as  $16/ft^2 (172/m^2)$  of repaired area, an experiment for bonding rather than removing the concrete was performed. A methyl methacrylate, a styrene monomer, and also an epoxy were injected into the undersurface fractures. From cores, the results indicated the epoxy injection was by far the best bonding agent. However, since this was the first test with monomer injection of this kind, the results of the use of these materials are not considered conclusive.

The effectiveness of the cathodic protection was demonstrated by arresting corrosion of steel strips that were embedded in concrete bars containing 10 percent calcium chloride by weight of the cement. The bars were placed within the coke-breeze asphalt layer on the bridge deck. Corrosion losses of the steel were measurable as increases in electrical resistance.

From the test results, a current density of about  $0.7 \text{ mA/ft}^2$  ( $6.5 \text{ mA/m}^2$ ) of reinforcing steel surface (upper bar mat) may control corrosion in a salt-laden concrete bridge deck. Measurements recorded on the experimental deck cathodic protection system show that the corrosion is apparently controlled on about 3,311 ft<sup>2</sup> ( $307.6 \text{ m}^2$ ) with a driving voltage of about 1.65 and about 1 A of current for a total power consumption of about 1.65 W. As a result, power, per se, is not considered to be a limiting factor in the cathodic protection system.

Although the optimum spacing of the impressed current anodes was not clearly determined by this experiment, their effectiveness can exceed a 12-ft (3.7-m) radius. However, the maximum polarization potential of the steel should be limited to a maximum of about -1.10 V CSE to prevent any possible loss of bond of the steel to the concrete.

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