

# Cathodic Protection of Bridge Decks: A Study of Three Ontario Bridges

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Many concrete bridge decks are being damaged by surface spalling or internal delaminations caused by corrosion of the reinforcing steel. Cathodic protection can be applied to bridge decks to stop this type of damage. Cathodic protection was applied to three bridge decks in Ontario: two slab decks on AASHTO beams and a voided, posttensioned structure. Each deck was equipped with resistance probes, which showed that the corrosion of the reinforcing steel was stopped when cathodic protection was applied. The bridges were studied to determine the minimum potential required and the most advantageous electrode configuration and spacing for adequate protection. The technique for measuring the polarized potential on the steel was studied, and probes buried in the conductive layer were found to be more effective than half-cell measurements. Data for all three bridges are presented. The protection on the first two of these bridges has been operated successfully for 1 year, and that on the third bridge has been operated successfully for 9 months.

Some exposed concrete bridge decks in Ontario have begun to show signs of deterioration in the form of spalling of the concrete over or under some of the reinforcing bars. Closer examination of these decks showed that delaminations were also present within the deck. These problems were caused by corrosion of the reinforcing steel and the resultant buildup on the bar of corrosion products, which exert pressure on the concrete and cause it to rupture.

This corrosion is caused by deicing salt solutions entering the concrete and eventually reaching the steel bars. This may occur even with high-quality, high-strength concretes. A review of the literature on this subject is given by Stratfull (1). Another study concerning the corrosion of steel in bridges has been reported by Moore (2).

Reinforcing steel in concrete is normally in a non-corroding, passive condition. The pH of normal concrete ranges from 12.5 to 12.8 (3, 4). In this pH range, steel is essentially passive (4, 5, 6). When salt solutions, either sodium chloride or calcium chloride, enter the concrete and reach the level of steel, however, corro-

sion of the reinforcing steel usually results. Gouda (6) has shown that alkaline solutions in which steel is normally passive become corrosive when sodium chloride is present in certain concentrations. Salt solutions reduce the pH of the concrete to about 11.5 (4), at which level the steel is no longer passive. Distressed bridge decks that have been investigated by the ministry have always been found to contain considerable quantities of chloride at the level of the steel reinforcing bars (7). This effect has been found by others (8, 9). To stop the corrosion requires that either the chloride ion be removed or that the corrosion reaction be inhibited by some other means.

One method that has been available for years to prevent corrosion when a corrosive medium is present is cathodic protection (1, 10, 11, 12). This method was first used by Stratfull (13) when he applied it to the reinforced concrete beams of the San Mateo Bridge over San Francisco Bay. Stratfull has since applied this technique to part of the deck of the Sly Park Bridge near Sacramento (1). The apparent success of this first application warranted further investigation, so it was experimented with on some Ontario bridge decks.

## CATHODIC PROTECTION

The corrosion of steel is an electrochemical reaction (14). When steel is in the state of active corrosion there are many small electrochemical cells on its surface. At the anodic areas an oxidation reaction takes place and the iron goes into solution as ions. At the cathodic areas a reduction reaction takes place and electrons are consumed. Of the several possible cathodic reactions, the one that occurs depends on the conditions existing at the cathode in question. The anodic reaction and one common cathodic reaction are symbolized below.

1. Anodic reaction:  $\text{Fe} \rightarrow \text{Fe}^{++} + 2e$
2. Cathodic reaction:  $\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2e \rightarrow 2(\text{OH})^-$

The corrosion reaction can be stopped (or retarded) by preventing the access of oxygen or moisture to the cathodic areas. Another method of stopping the reaction is to lower the potential of the entire steel bar.

Galvanic corrosion is halted when all points on the bar have been polarized to a potential equal to or more than the open circuit potential of the most anodic point on the structure (15). This method is known as cathodic protection and has been used for years to inhibit the corrosion of buried pipelines, concrete water tanks, and ships' hulls. In cases such as these, the application is straightforward. In the case of bridge decks, however, there is no surrounding conducting medium. The deck is suspended in air. Therefore, a conducting medium has to be supplied. Stratfull (1) solved this problem by using a conductive layer consisting of a coke breeze and asphalt mixture on the deck. The coke mix was laid and energized by anodes at several points so that an even distribution of power was accomplished over the deck. The flow of current then was from the rectifier through the coke then down through the concrete bridge deck to the reinforcing steel and back to the rectifier. The coke breeze mix was covered with a wearing course of asphalt concrete to complete the system.

In this type of installation it is important that the coke mixture be insulated from any bare reinforcing steel, deck scuppers, expansion joints, and the like to prevent a direct short circuit to the bridge steel. The circuit diagram for such an installation is shown in Figure 1.

#### EXPERIMENTAL DESIGN

Initially two bridge decks were tested: a posttensioned, voided deck and a slab deck on AASHTO beams. Each of the decks showed signs of active corrosion. One part of each deck was protected, and the other part was left unprotected for comparison.

Sufficient electrodes were placed on each deck so that different electrode configurations could be studied. Both a regular high silicon-cast iron electrode (16) and a regular graphite electrode were used. These were compared for efficiency at distributing the current over the bridge and for cost.

The circuit was designed so that varying amounts of current could be fed to each individual electrode and an even distribution of power could be obtained across the bridge deck.

The rectifier used was a constant current type to avoid the use of a standard cell buried in the deck. It was feared that the severe winters in Canada could damage a standard cell.

To determine whether corrosion had been halted, resistance probes were buried at several locations in each deck.

After cathodic protection had been installed on two bridges and operated for some time, improvements in construction and protective equipment were indicated. A third bridge, which was also showing active corrosion, was then selected and the improved methods of protection were applied to it.

#### BRIDGE DATA

The first bridge chosen was a posttensioned voided structure. It was one of the ramp bridges at a major interchange in the Toronto area. This 8-year-old bridge is 113 m (370 ft) long and 7.8 m (25.5 ft) wide and is a curved superelevated structure. The bridge was showing active corrosion in only one area near its western end. It was, however, the only bridge of its type available in which there was some active corrosion and for which it was possible to obtain a reasonable traffic control without causing a major traffic disruption. This bridge will be referred to as bridge 9.

The second bridge chosen has a concrete slab deck, 20 cm (8 in) thick on AASHTO beams. It was 7 years

old, 28 m (92 ft) long, and 11 m (36 ft) wide with 0.9-m (3-ft) sidewalks. This bridge was showing very active corrosion in several areas and has many spalled areas on its surface. It is the Duffins Creek bridge.

The surface of each bridge deck was surveyed to determine the extent of corrosion. This was determined by means of a Cu/CuSO half-cell (CSE) by using the technique described by Stratfull (17, 18). The data were plotted to show lines of equal voltage on a diagram of the bridge deck. The data for Duffins Creek bridge (Figure 2) show that there were many areas of active corrosion where the voltage detected was greater than -0.35 V with reference to the CSE (1).

All reinforcing steel, cable ducts, and guardrails were found to be continuous electrically on both bridges. There was, therefore, very little danger of any part of the steel being electrically isolated and thus in danger of stray current corrosion.

Each bridge deck was cored in several locations, and the cores were analyzed to determine the chloride content. The results of three cores selected from each bridge are shown in Table 1.

The other cores showed similar salt contents. These data show that there was sufficient chloride present at the level of the reinforcing steel to cause corrosion. It has been reported that the threshold level to cause the onset of corrosion is 0.59 kg of sodium chloride/m<sup>3</sup> of concrete (1 lb/yd<sup>3</sup>) (1). The upper level of the steel in both of these bridges was within 2.5 to 3.5 cm (1 to 1½ in) of the surface.

#### CONDUCTIVE LAYER TESTS

A coke breeze-asphalt cement mix similar to that used by Stratfull (1) was used for the conductive layer. Samples of coke breeze were obtained from a local steel company. This material had the following gradation:

Sieve Size	Percentage Passing	Sieve Size	Percentage Passing
No. 4	100	No. 50	18
No. 8	68	No. 100	12
No. 16	47	No. 200	7
No. 30	32		

The coke breeze was blended with 85 to 100 penetration grade asphalt cement to make a series of blends with increasing asphalt cement concrete. The mixes were made into beams by using a steel mold and were compacted with a kneading compactor followed by a leveling load applied by a compression testing machine. The density and resistivity of each beam were determined (Table 2).

From the data the blend containing 20 percent by weight of asphalt cement was chosen for this project. The resistivity of all blends was quite low. It was thought that the extra asphalt cement would give the blend chosen greater resistance to water action (stripping) since some water was almost certain to collect in this porous coke layer.

The work done by Stratfull (1) showed that the coke breeze-asphalt mixture appeared to have sufficient strength to stand up under traffic; hence, no further testing was done in this direction.

#### ELECTRICAL CIRCUIT

The electrical circuit used is shown in Figure 3. This circuitry was installed in a panel box mounted beside the current rectifier on an abutment under the bridge. A switching arrangement made it possible to switch the panel ammeter into the circuit so that the current flow

Figure 1. Cathodic protection circuit.

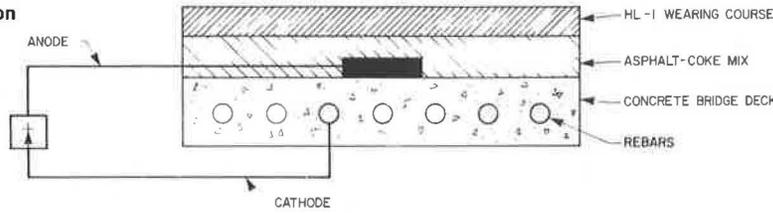


Figure 2. CSE potentials on Duffins Creek bridge.

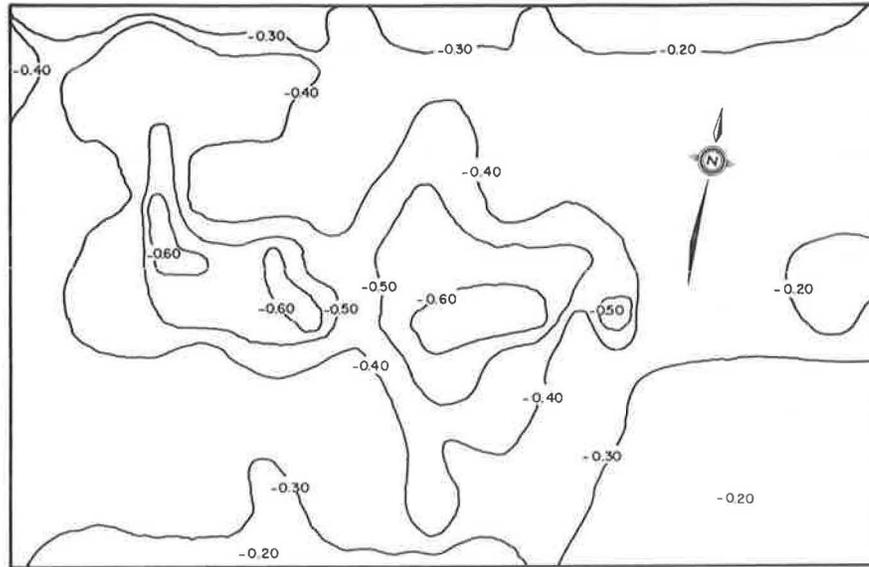


Table 1. Chloride content of bridge deck cores.

Bridge	Core	Depth (mm)	NaCl (kg/m <sup>3</sup> )	Bridge	Core	Depth (mm)	NaCl (kg/m <sup>3</sup> )	
9	1	6.35	9.3	Duffins Creek	1	12.7	11.4	
		12.7	3.3			25.4	6.5	
		25.4	2.2			38.1	3.4	
		50.8	2.2			50.8	2.2	
	2	12.7	12.0		2	6.35	17.8	
		25.4	6.5			12.7	9.1	
		38.1	3.1			25.4	1.1	
		50.8	2.6			50.8	0.5	
	3	76.2	2.4		3	6.35	9.9	
			6.35			9.9	12.7	5.4
			12.7			5.5	25.4	0.8
			25.4			2.9	50.8	0.4
		50.8	2.8					

Note: 1 mm = 0.039 in; 1 kg/m<sup>3</sup> = 1.7 lb/yd<sup>3</sup>.

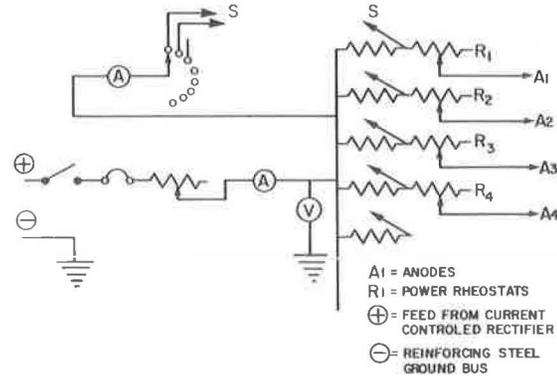
Table 2. Conductive mix properties.

Asphalt Grade	Percentage of Asphalt by Weight	Mix Density (g/cm <sup>3</sup> )	Resistivity (Ω·m)
85/100	10	0.99	0.0125
85/100	13	1.02	0.0125
85/100	15	1.06	0.0124
150/200	15	1.08	0.0133
85/100	17	1.14	0.0128
85/100	20	1.17	0.0143

Note: 1 g/cm<sup>3</sup> = 62.4 lb/ft<sup>3</sup>.

to each individual anode could be measured. The power rheostats in each anode circuit made it possible to vary the anode resistance if necessary so that equal current flowed to each anode.

Figure 3. Cathodic protection circuit.



The majority of anodes used were made from high silicon-iron alloy (Duriron). This alloy is very resistant to corrosion, and its weight loss in such service is stated to be about 0.18 kg (0.4 lb) per ampere-year (16). Some experimental graphite anodes were also used on each deck. All of these anodes were approximately 30.5 cm (12 in) in diameter and 3.8 cm (1.5 in) thick. To keep the circuit resistance low despite the long runs of wire, No. 6 gauge wire was used. Wire with Canadian Standards Association specification TWU insulation was used. This is a heavy insulation for underground use and was used as the best available to resist the high temperatures (149° C or 300° F) of the coke-asphalt mixture.

The resistance probes used to determine whether and when corrosion was stopped were designed for underground service.

## INSTALLATION ON BRIDGE DECK

Before the circuitry was installed on the deck, all delaminations were repaired by an epoxy cement injection technique developed by Crumpton (19). All spalls were repaired with concrete, and any exposed iron on the deck was covered with epoxy cement to insulate it from the coke mix.

The anodes were placed on each deck in three rows, each anode within a row separated from its adjoining anode by 3.6 m (12 ft). The plan of the two first decks is shown in Figures 4 and 5. Each anode was cemented to the deck with epoxy cement to prevent it from moving when the coke mixture was compacted.

Ground connections to the reinforcing steel were made at five randomly chosen locations on each deck. A resistance probe was placed in the hole and grounded to the bar. The hole was then refilled with concrete containing sodium chloride to initiate corrosion on the probe. The grounding cable was run to the curb to join the common grounding bus. Then all cables were run along the curb to a hole in the deck and down through the hole to the control boxes under the bridge.

After all the electrical equipment was installed on the surface, the coke layer was placed. This was spread by hand and compacted to a thickness of 5 cm (2 in). The coke was hand spread to prevent any injury to the cables and anodes. The following day a 3.8-cm (1.5-in) layer of wearing course was spread by a regular paver, and the compaction was done in the normal manner.

On bridge 9 only the western 33.5 m (110 ft) of the bridge was protected. On the Duffins Creek bridge the eastbound lane of the bridge was protected cathodically while the westbound lane was left unprotected.

## EXPERIMENTAL DATA FROM BRIDGES

After all the electrical equipment had been installed on the bridge decks and they had been paved, they were left in that condition without any power being applied for 4 weeks. The purpose was to permit the probes to begin to corrode to such an extent that the trend was clearly indicated. Then the effectiveness of cathodic protection could be determined by the behavior of the probes.

### Anode Resistance

The resistance of each anode circuit in both bridge decks was measured. Inasmuch as a potential difference of about 0.2 V normally exists between the concrete and the reinforcing steel, a normal ohmmeter could not be readily used. A meter for measuring soil or ground bed resistance was used. This was a battery-operated instrument that applied a high ac voltage, used a dc blocking capacitor, and could be read accurately to 0.05  $\Omega$ . Resistance was measured at the control panel between the wire leading to each anode and the common ground connection.

These values ranged from 0.9 to 2.8  $\Omega$  at bridge 9 and from 1.2 to 3.7  $\Omega$  at the Duffins Creek bridge. The resistance of the graphite anodes was generally lower than that of the silicon-iron anodes.

### Voltage Measurement in Coke Bed

When the power was first applied to bridge 9, anodes 1, 2, 6, 7, 11, 12, 16, 17, 21, and 22 were connected, and at the Duffins Creek bridge anodes 101, 105, 106, 110, 111, 115, 116, and 120 were connected. Figures 4 and 5 show the location of these anodes on the bridge decks.

Initially the rectifiers (current controlled) were set to deliver 1 A to each bridge deck. Voltage readings were taken on the anode connections at the control panel and these varied from 1.6 to 1.8 V.

As soon as the power was applied to these bridges, the readings of one of the two active probes at Duffins Creek stopped rising. The other probes had still not become active. This cessation of corrosion is shown in Figure 6 for the probes at the Duffins Creek bridge. The curve in this figure for probe D showed an immediate halt in corrosion on the twenty-seventh day when the power was applied. Probe E, however, continued to rise. Some further testing showed that the connection between probe E and the reinforcing steel had been broken. On the fifty-sixth day this probe was reconnected to the steel. Immediately the probe values stopped rising. Since these probes were connected directly to the bridge steel it was a reasonable assumption that the bridge steel had also stopped corroding due to the application of the protective cathodic polarizing voltage.

Stratfull (1) measured the voltage drops in the coke by means of a CSE placed on a wet sponge on the asphalt surface by using a high-impedance solid-state voltmeter and grounded to the rebars. The charts for the Sly Park deck (1) showed considerable voltage variation across the deck. It was felt here that this variation could possibly be due to varying resistance in the asphalt concrete surfacing through which the readings had to be made. The coke mix itself has low resistivity and should not lead to such relatively large voltage drops. When this technique was tried on the decks of bridge 9 and the Duffins Creek bridge, even wider potential variations were measured. In some areas of the deck virtually no readings could be obtained. Inasmuch as 10 electrodes were in use on bridge 9, and 8 on the Duffins Creek bridge, a very even voltage distribution should have been present. The surfacing mixes used in Ontario are denser and have fewer voids than those used in California, so it appeared to be a problem of conductivity.

A series of holes was then drilled through the asphalt concrete surfacing to reach the coke layer, and No. 6 gauge insulated wires were driven into the holes to contact the coke mix. When the CSE was placed on these wires, the expected readings of 1.6 to 1.8 V were obtained. When the voltmeter probe was placed directly on the wire the same readings were obtained. It was obvious that the CSE was not needed in this instance to read the voltages. It was acting only as a liquid voltmeter probe and not as a half-cell. (The CSE or other half-cell is necessary, however, when a deck is surveyed to detect the presence of corrosion.) Because fewer than half of the anodes on each of these decks were being used to distribute the power, the remaining anodes were available for use as voltage probes by connecting the voltmeter to the anode wires at the control panel. In this way the entire bridge surface could be surveyed for potential drops by working from the control panel.

It was found that the voltage distribution across both decks was very even, within  $\pm 0.1$  V. This suggested that a considerable reduction could be made in the number of electrodes used.

### Polarization of Bridge Decks

When power was first applied to the bridge decks the voltage of the supply was relatively low because the method being used was a current control system and there was little or no back EMF in the bridge deck. After a short time the steel began to polarize and the back EMF began to build up in the decks. Thus, the effective resistance of the decks increased and the applied voltage rose and maintained the set current strength. This polarized (or

Figure 4. Bridge 9.

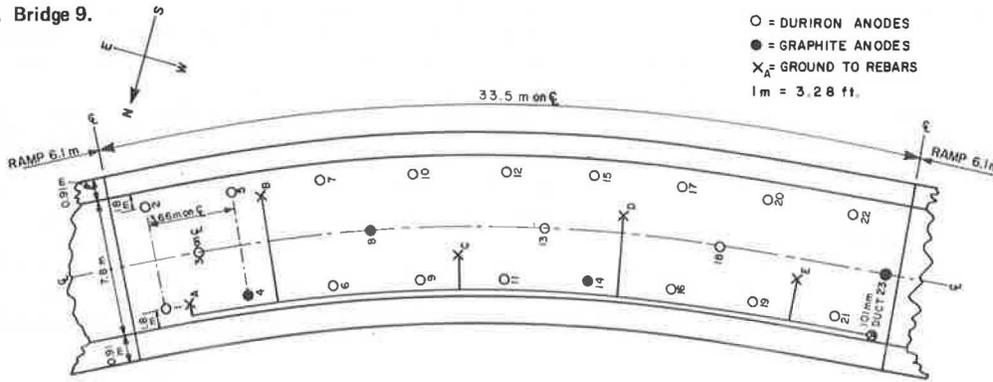


Figure 5. Duffins Creek bridge.

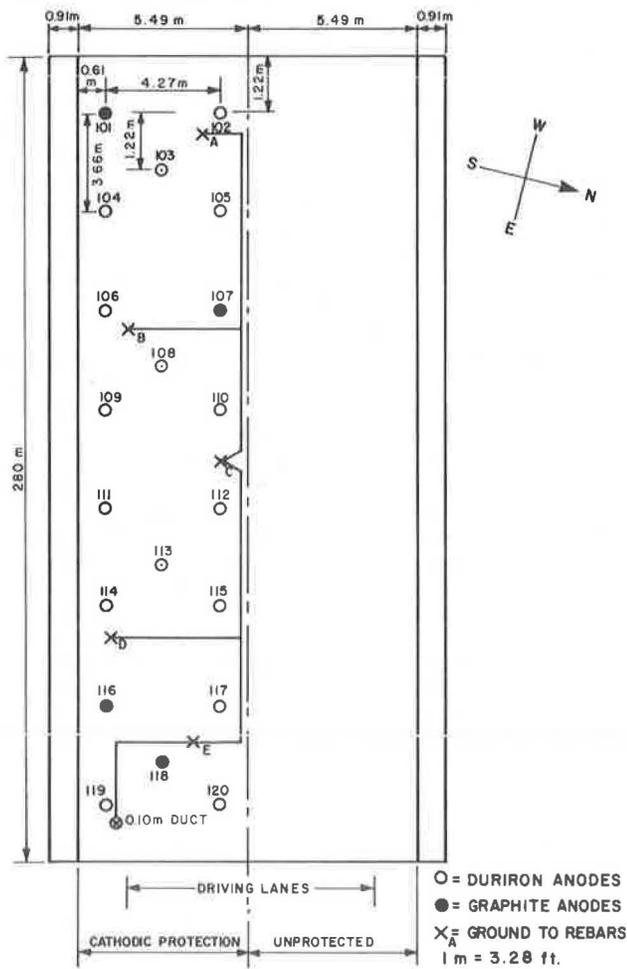


Figure 6. Probe values on Duffins Creek bridge.

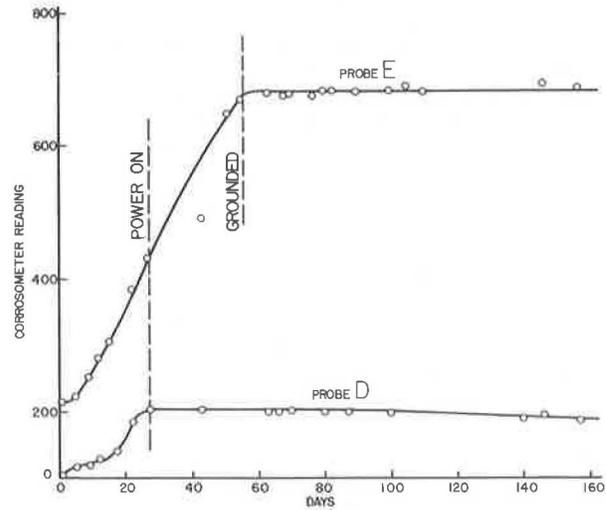
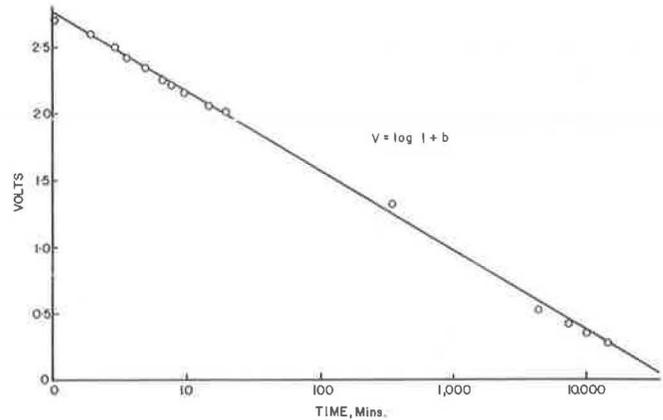


Figure 7. Residual voltage decline with time.



residual) voltage was measured between the anodes and the ground after the rectifier was switched off. After the bridges had attained electrical equilibrium the voltages were measured:

Item	Bridge 9	Duffins Creek
Current, A	1.0	1.0
Average applied voltage	1.85	1.6
Average residual voltage	1.40	1.0

It is common practice to polarize structures such as pipelines or water tanks in the range of -0.85 to -1.1 V

with respect to the CSE in order to obtain protection (12, 20, 21, 22). The upper limit should be set at -1.1 V to prevent weakening of the bond between the reinforcing steel and the concrete (12, 22). A somewhat lower minimum potential for protection had been suggested by both Scott and Hausman. This value was -0.71 V (12, 22).

Electrode Configuration Trials

To determine the best configuration of electrodes for the

distribution of power throughout the bridge decks several different electrode combinations were tested. These tests were all run on bridge 9. After each test, the power was turned off so that the residual voltage on the deck could drop to a potential of  $-0.5$  V or less. Before this study on the bridges a series of experiments was run on reinforced concrete slabs in the laboratory. The rate of decline of voltage with time for one of these slabs is shown in Figure 7. It was found that this curve matched very closely the rate of decline for both bridges. These bridges, however, were never polarized to such a high residual voltage as shown in the curve for the experimental slab.

Several different anode configurations were studied. When electrodes 3, 8, 13, 18, and 23 down the center of the bridge were used, a very even distribution of voltage again was obtained.

When electrodes 3, 13, and 23 were used at a current strength of 0.8 A, a good power distribution was obtained over the bridge surface once equilibrium had been established. This effect is shown in Figure 8. Curve A shows the drops in the applied voltage down the length of the deck when the power was first applied. Before this application of power the bridge had been left without power until the residual voltage on the reinforcing steel had subsided to  $-0.2$  V. After 3 days the bridge had attained electrical equilibrium and the voltage drop across the surface was as shown by curve B in Figure 8. It can be seen that these three electrodes separated by 15.2 m (50 ft) from each other produced a very regular power distribution across the deck surface.

The next trial was run by using just two anodes, 5 and 19, again at a current strength of 0.8 A. The data obtained are shown in Figure 9. From the coincidence of curves D and E it can be concluded that equilibrium was obtained in approximately 48 h. The voltage drops here, however, were greater than when three anodes were used. Here a maximum difference between the applied voltage and the lowest point on the deck was 0.42 V.

Two tests were made by using one anode. The first was made by using anode 13, which was situated near the center of the bridge deck. In this test also the current strength was 0.8 A. The voltage drops along the deck are shown in Figure 10 for the applied voltage. Even after 48 h, the voltage drops between the applied voltage and the lowest points on the deck were 0.8 V, which were much too wide for satisfactory operation. The second test applied power to anode 23 at the extreme end of the deck. For this test the current strength was reduced. To force 0.8 A through the deck from one anode, as shown in the previous test, much too high a voltage (2.5 V) was required. For this test the rectifier was set to deliver 0.2 A. The voltage drops in the deck are shown in Figure 11. Curve A shows the applied voltage at the start of the test and curve A<sub>1</sub> the resulting residual or polarized voltage. Curves B and B<sub>1</sub> showed the situation after 24 h. The deck voltages were again measured after 5 days, and the curve obtained was slightly higher but virtually identical with curve B. The bridge under these conditions was used for comparing voltage measurement techniques and this is described in the next section.

The above tests suggested that the best anode configuration was the one in which three anodes were used and were spaced down the center of the deck. Anodes 3, 13, and 23 were again connected, and the current was set to deliver 0.4 A. When the bridge had attained equilibrium after 48 h, the voltage drops in the bridge deck were as shown in Figure 12. The voltage applied was 1.05 V, and the voltage at the lowest point in the deck was 0.85 V. This resulted in a residual or polarized voltage varying from  $-0.88$  to  $-0.82$  V, which was satisfactory for the

protection of the reinforcing steel.

At the Duffins Creek bridge when power was first applied, eight electrodes were used. This gave a very uniform power distribution. The anodes were then reduced to four situated in the center of the protected lane. A current strength of 0.5 A was used, and the resulting voltages in the coke varied between 0.96 and 1.14 and the polarized voltage varied between  $-0.93$  and  $-0.99$ . Thus the steel in this deck was satisfactorily protected.

Thus to protect bridge 9 only 0.5 W of power was required (1.13 V, 0.4 A on three anodes) and to protect the Duffins Creek bridge only 0.6 W of power (1.2 V, 0.5 A on four electrodes) was required.

#### Comparison of Voltage Measurements

Some doubt was expressed regarding the accuracy of the measurements of the applied and polarized voltages using probes in the coke bed to determine the actual voltage in the concrete slab. It was felt that the highly conductive coke mix could possibly even out local potential differences that might exist. Because the anodes being used as voltage probes were also quite large and were insulated from the deck directly below them, these would also tend to average out small differences in potential. To determine whether such was the situation a series of tests was conducted on both bridge 9 and the Duffins Creek bridge.

Bridge 9 for this test was powered only by anode 23 at one end of the deck. The current strength was 0.2 A. The voltage drop and the polarized voltages along the deck are shown in Figure 11.

Holes 5.4 cm ( $2\frac{1}{2}$  in) in diameter were drilled through the asphaltic concrete surfacing and the coke mix to expose the concrete. The holes were drilled 1.2 m (4 ft) from the curb and close to anodes 4, 6, 9, 11, 14, 16, 19, and 21.

At each hole the CSE was placed in contact with the exposed concrete surface, and on and off voltage readings were obtained. A regular steel voltmeter probe was then thrust into the coke at the side of the hole, and on and off voltage readings were obtained on the probe and on each anode connection. These results are given in Table 3.

The data show that there is little difference between the readings taken in the hole with either the CSE or the voltmeter probe. The slight difference of  $+0.05$  V higher for those taken with the probe could be due to higher resistance in the CSE or higher contact resistance. There is, however, a consistent difference of  $+0.16$  V on the average higher for off readings taken on the anodes and for those taken by the CSE when used as a probe. This might be explained by the lower surface resistance between the anodes and the coke; there was a much greater contact surface in this case than there was when the CSE or voltmeter probe was used.

A somewhat similar test was run at the Duffins Creek bridge. Here eight holes were bored through the surfacing and the coke mixes in the protected side of the bridge to expose the concrete. The anodes were not so close to these holes as they were on bridge 9, so a close comparison between anode and CSE probe voltages could not be obtained. The anode readings did seem to be 0.1 to 0.2 V higher than the CSE probe readings similar to those obtained on bridge 9. When the voltage readings obtained with the CSE on the concrete surface in the hole were compared with the voltmeter probe readings in the coke at the sides of the hole, the same relationship held as at bridge 9: The probe in the coke readings was a little higher than the CSE on the concrete readings. In addition to the above tests, voltage readings were taken in each hole by simply placing the voltmeter steel probe

Figure 8. Voltage drop along deck of bridge 9 (0.8 A to anodes 3, 13, and 23).

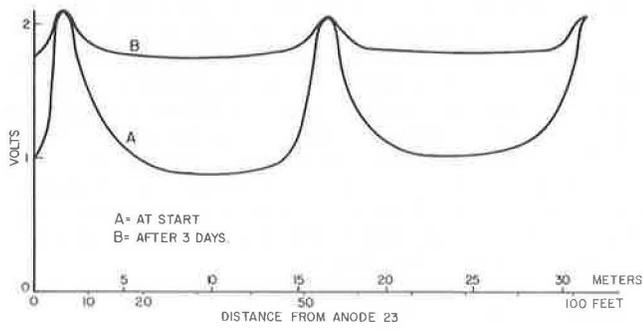


Figure 9. Voltage drop along deck of bridge 9 (0.8 A to anodes 4 and 19).

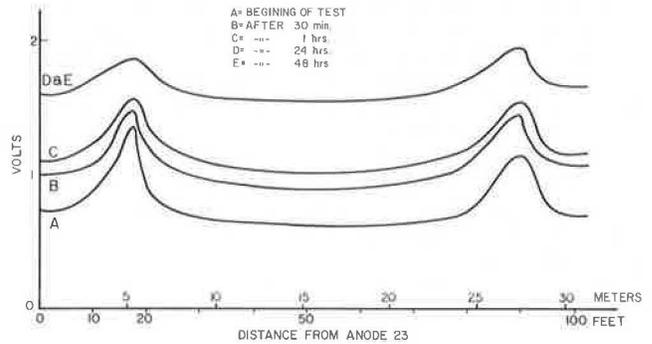


Figure 10. Voltage drop along deck of bridge 9 (0.8 A to anode 13).

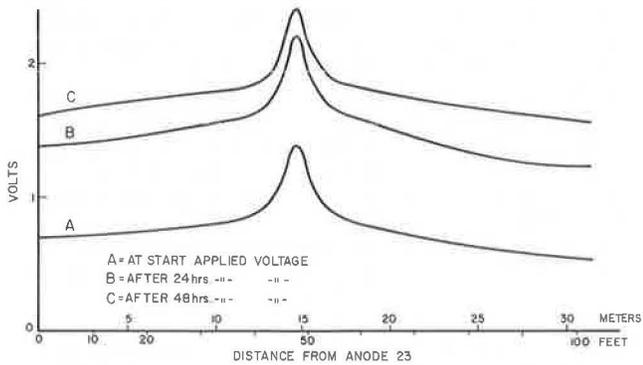


Figure 11. Voltage drop along deck of bridge 9 (0.2 A to anode 23).

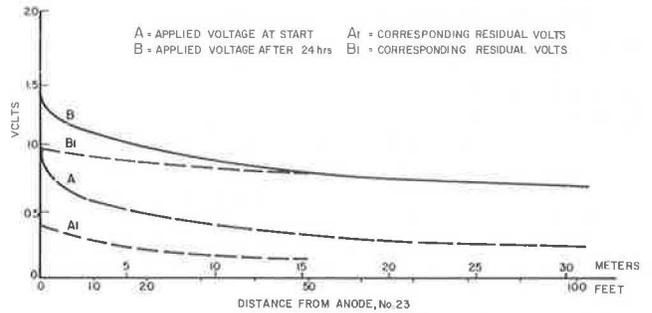


Figure 12. Voltage drop along deck of bridge 9 at equilibrium (0.4 A to anodes 3, 13, and 23).

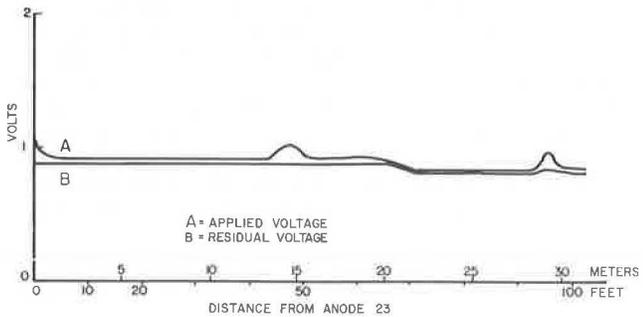
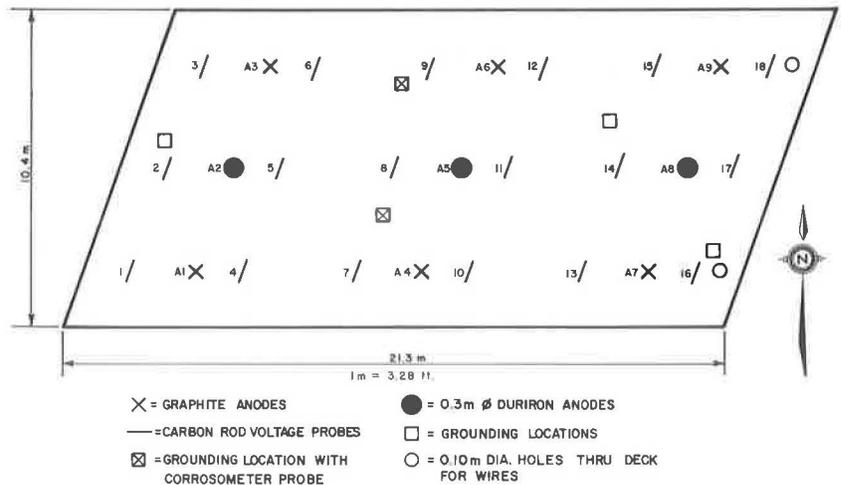


Table 3. Comparison of voltage measurement methods on bridge 9.

Anode	Anode On	Voltage Off	CSE on Concrete Surface		Voltmeter On	Probe in Coke Off
			On	Off		
1	0.68	0.67	0.56	0.56	0.58	0.57
4	0.70	0.70	0.52	0.52	0.55	0.55
6	0.72	0.71	0.57	0.56	0.60	0.59
9	0.76	0.75	0.60	0.59	0.62	0.62
11	0.78	0.77	0.58	0.58	0.62	0.62
14	0.80	0.79	0.64	0.63	0.67	0.66
16	0.83	0.82	0.67	0.65	0.70	0.68
19	0.87	0.85	0.72	0.69	0.83	0.80
21	0.93	0.86	0.82	0.73	0.86	0.76

Figure 13. Anode and probe placement on Medway Creek bridge.



directly on the concrete surface. A series of good readings was obtained; these were a little higher than the CSE readings but a little lower than the probe in the coke readings.

These tests showed that it was perfectly feasible and accurate to monitor the polarized voltages on the reinforcing steel by means of probes buried in the coke layer.

#### MEDWAY CREEK BRIDGE

The data obtained from bridge 9 and the Duffins Creek bridge showed that the circuit could be simplified, the number of anodes could be reduced, and voltage probes properly spaced in the deck could be used to monitor the bridge. To try these ideas out it was decided to apply protection to another medium-sized bridge and to protect the entire bridge deck and not just a portion of it.

The bridge chosen was the 8-year-old Medway Creek bridge, and its deck was in a state of active corrosion. The surface of this deck was spalling, and some delaminations were present within the deck. A CSE half-cell survey was made of the deck. This survey showed that there were several areas in a state of active corrosion with CSE potentials greater than  $-0.35$  V.

Graphite anodes were used for this bridge. Graphite rods 3.2 cm (1.3 in) in diameter were obtained, and the anodes were fabricated locally from this material. The rod was cut into pieces 41 cm (16 in) long, and four lengths were connected together so that the anode could be laid out on the deck in the form of a four-pointed star with a central connection. Some silicon-iron anodes were also used in case problems arose with the use of the graphite anodes. The data obtained from bridge 9 indicated that two anodes should be sufficient to provide protection for this bridge. Because this was still an experimental installation, extra anodes were used on the deck so that different anode configurations could be used if this became necessary.

Voltage probes were placed on the deck and buried in the coke mix so that it would not be necessary to use the anodes as voltage probes. These probes consisted of small carbon rods, 2.5 cm (1 in) in diameter and 15.2 cm (6 in) long, to which a No. 10 wire would be attached with a mechanical seal.

The layout of the deck is shown in Figure 13. The six graphite anodes were evenly spaced, three on each side of the deck. The three silicon-iron anodes were placed down the centerline. The voltage probes were laid out on 3.6-m (12-ft) centers, and five ground connections were made to the reinforcing steel.

The control panel was made smaller and simpler. Each of the nine anodes had a power rheostat in the circuit in case adjustments had to be made. The connection to each voltage probe was through a banana plug jack on the panel. There were three meters, one for the applied volts, one for the total current, and one for the current to each individual anode, which was selected through a switching system.

#### Construction Method

The experience gained at the two test bridges suggested that the electrical equipment and both the coke and surfacing mixes could be laid and compacted in 1 day for each half of the deck with a minimum of inconvenience to traffic. This involved closing half of the bridge each day for construction and using the remaining half for two-way traffic, which was controlled by flagmen.

After the electrical equipment and wire had been placed on the deck it was covered by 6 cm (2 in) of coke mix similar to that used previously. This was then

protected by a 3.8-cm ( $1\frac{1}{2}$ -in) wearing course of asphaltic concrete.

#### Experimental Data

After the electrical installation was completed the anode resistances were measured. These values, measured between the anode connection at the control panel and the connection to the reinforcing steel, were as follows:

Anode	Resistance ( $\Omega$ )	Anode	Resistance ( $\Omega$ )
1G	1.5	6G	2.1
2	2.3	7G	1.8
3G	1.9	8	2.6
4G	1.8	9G	2.6
5	2.6		

Again, the silicon-iron anodes had generally higher resistance than the graphite anodes.

The bridge was allowed to remain without power being applied for 4 weeks. During this period the probes began to corrode because salt had been added to the concrete covering them. After the trend was clearly established power was applied to the circuit. Immediately the reading of each probe ceased rising, showing that corrosion had been effectively halted. This is shown in Figure 14.

Current was applied to the bridge at a strength of 0.9 A, and anodes 3 and 7 were used to distribute the current. After the bridge had achieved electrical equilibrium the voltage drops within the deck were as shown in Figure 15. The residual or polarized voltage in the deck with the current off was measured at an average value of 1.03 V.

The electrical characteristics of the installation of this bridge were studied during the winter and spring of 1974 and 1975. Unlike the other two bridges, this bridge was more sensitive to the weather, particularly to the amount of precipitation and to the use of deicing chemicals. After heavy rains and during the winter, the resistance of the deck decreased with a resulting drop in potential since this deck was also under current control. This required that the rectifier be reset to deliver a larger amount of current to maintain the required residual potential on the steel.

After one heavy rainstorm the polarized potential dropped to a range of 0.6 to 0.7 V, i.e., the probes remained steady and did not show the onset of corrosion. It seemed that rainwater had seeped into the porous coke layer and from it was entering into the concrete, thus lowering its resistance and thereby requiring a larger amount of current to keep the voltage in the coke at a sufficiently high level (about 1.2 V) to induce a polarized potential on the steel of 0.9 to 1.0 V. To compensate for this the current strength was raised to 1.2 A.

When the current strength at the bridge was 1.0 A, the bridge required 1.4 W for protection; the rise in current to 1.2 A raised the power required to 1.7 W for complete protection.

Resistance measurements had been made at the start on each voltage probe. The resistance was measured between each probe and the reinforcing steel, and it was also measured between probe 1 and each of the other probes to obtain the interprobe resistance. These values were checked again after the deck potential began dropping because of what was assumed to be increasing moisture and salt in the concrete. Some of these data are given below.

Probe	November 8, 1974	June 24, 1975
1-4	3.0	2.5
1-7	3.6	2.3
1-10	4.0	2.2
1-13	4.2	16.0
1-16	4.2	2.1

The high resistance between probes 1 and 13 on June 24 was caused by development of a poor contact between probe and wire.

An examination of the data brought out two points. The probes are all 3.6 m (12 ft) apart; the resistance does not decrease linearly with distance. There is little increase in resistance after probe 10, 11 m (36 ft) from probe 1. This suggests that from this point on most of the current had passed down to the concrete and was flowing along the reinforcing steel then back up to the probe connected to probe 1. The data for June follow the same pattern only to a greater extent. Here the resistance was the same all down the deck. This suggested that the concrete had absorbed a lot of brine during the winter and the rain which had recently fallen decreased the resistivity of the concrete to a level where a much larger current was required to achieve the polarizing voltage sufficient to protect the steel.

DISCUSSION OF RESULTS

During the anode configuration experiments the polarized voltage on the bridge steel was allowed to subside on several occasions in a series of steps. During these tests it was found that the probes did not show the onset of corrosion until the polarized voltage had dropped below -0.55 (CSE) V. The same effect was seen at the Duffins Creek and Medway Creek bridges when power

Figure 14. Probe values on Medway Creek bridge.

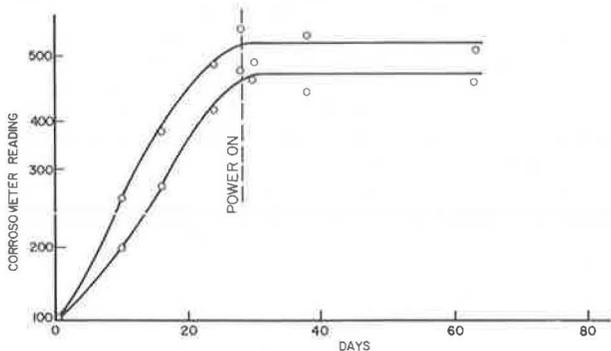
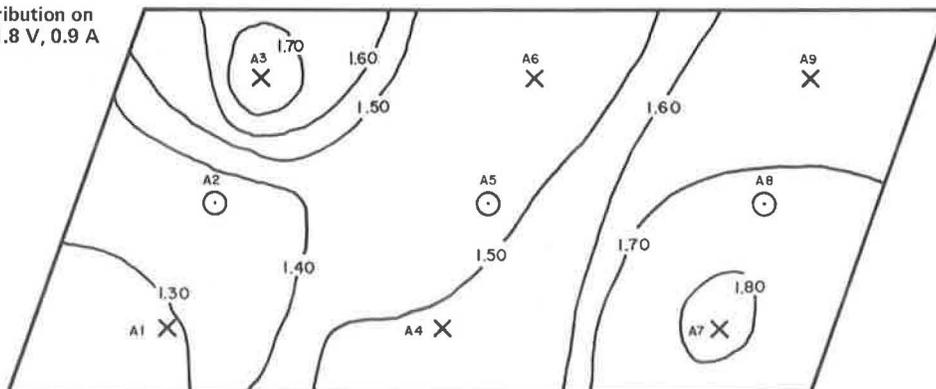


Figure 15. Voltage distribution on Medway Creek bridge (1.8 V, 0.9 A on anodes 3 and 7).



failures occurred. There may have been a lag between the voltage falling to a certain point and the onset of corrosion. The results do point out, however, that several days' protection is built into the deck in case of a power failure if the polarized voltage on the steel has been kept at a level of -0.85 V or higher.

The experiments showed that an anode separation of 15.2 m (50 ft) was suitable on all bridges to keep the voltage drop in the coke layer at a reasonable level. At Medway the anode separation was less than 15.2 m (50 ft).

The amount of power required to provide adequate protection to the three bridge decks is given in Table 4. The table shows the amount of power in watts required for the entire bridge deck. Also shown is the current flow per square meter of deck. These figures show that the amount of power required is negligible and could quite conceivably be supplied in remote locations by solar cells in conjunction with storage batteries.

The principal of using voltage probes in the coke layer to determine the voltage and the polarized voltage has been proved to work at the Medway bridge. The experiments on all these bridges have shown that either graphite or silicon-iron anodes are suitable for supplying power and protection. Because graphite anodes are not sacrificial, the anode reaction must be some chemical reaction other than the oxidation of the metal to form ions. It could be the oxidation of chloride ions to either the gaseous state or to some higher valence state.

The use of a constant current type of rectifier has advantages and disadvantages. This type of rectifier did not require a standard cell in the bridge deck, which could have been damaged by the low temperatures in this country. At bridge 9 and at Duffins Creek this type of rectifier worked very well. There were voltage swings at these bridges caused by weather conditions. Weather conditions caused changes in the resistivity of the deck, and this change in resistance caused the voltage to fluctuate to maintain a constant current. The applied voltage remained, however, within the limits required to provide adequate protection, the protection being judged by the polarized voltage. There were wider voltage

Table 4. Power requirements for bridge decks.

Bridge	Current (A)	Deck Area (m <sup>2</sup> )	Power (W)	Current Density (mA/m <sup>2</sup> )
Bridge 9	0.4	277.12	0.5	1.44
Duffins Creek	0.5	153.84	0.6	3.2
Medway	1.0	221.1	1.4	4.5
Creek	1.2	221.1	1.7	5.4

Note: 1 m<sup>2</sup> = 10.76 ft<sup>2</sup>; 1 mA/m<sup>2</sup> = 10.76 mA/ft<sup>2</sup>.

swings at Medway Creek bridge. This deck appeared to be more open, and in dry weather the supply voltage would swing high and then drop to lower levels in wet weather. This type of bridge could have benefited from potential control.

When the coke mix was being laid, it was very absorbent and could contain considerable quantities of water. This was disadvantageous because it could hold water in contact with the bridge surface, which could result in increased freeze-thaw damage to the decks. It was feared that this water might cause stripping of the asphalt from the coke surface and then cause the mix to lose strength. Samples of the coke mix were removed from the Medway Creek deck after 6 months' service and were examined. The mix seemed to have retained all its strength, and no sign of stripping was detected. It could be an advantage to have a more impervious mix that would keep the water away from the bridge deck and yet have sufficient voids to permit any gas formed at the interface to escape. Such a mix is being developed in these laboratories.

The area to which the cathodic protection extends in a deck is being studied. It was mentioned in discussion with other researchers that perhaps the upper layer of steel intercepted most of the current and there was little remaining current to provide protection to the lower layers. Investigations in progress in these laboratories indicate that the protection goes much deeper, especially in the case of slab decks. Heuze (24) suggested that the deck may behave like a capacitor. These bridge decks have the property of storing large quantities of current, and to do this they must act either as a capacitor or as a battery. The experiments currently in progress tend to confirm the capacitor action.

#### CONCLUSIONS

1. Cathodic protection of bridge decks is feasible and has been demonstrated on three bridge decks.
2. A conductive coke-asphalt mix with anodes spaced 15.2 m (50 ft) apart in the mix is suitable for providing power to the bridge deck.
3. Voltage probes buried in the coke mix have proved acceptable for monitoring the applied voltage and the polarized voltage.
4. Both slab and posttensioned voided decks can be protected by this method.
5. The power required for protection is very small and varies from 0.014 to 0.04 mA/m<sup>2</sup> of deck surface.
6. The cost of epoxy injection concrete repairs and of applying the cathodic protection is small compared to the cost of replacing the deck.

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