

midway between the rebars. After a few days, the readings between the two sets became similar. It was concluded that a half-cell close to a rebar would give a better, more sensitive type of control than one placed farther away.

A new potential control rectifier has now been obtained, and the bridge is now being controlled by the zinc half-cell close to a rebar.

Cathodic protection is now accepted as a suitable system for bridge-deck repair by MTC. Other accepted methods in Ontario are the use of low-slump concrete and the use of latex-modified concrete overlays.

#### CONCLUSIONS

1. Cathodic protection is successful in preventing or retarding the corrosion of bridge-deck steel. This was shown on the Duffins Creek bridge through the corrosometer probes and by the fact that there was a much lower degree of damage on the protected side of the bridge deck.

2. Examination of the deck after three years of cathodic protection showed that epoxy injection was not a good method of bridge-deck repair.

3. A conductive mix that has a low void content should be used to prevent water absorption.

4. Cathodic protection is now accepted in Ontario as a method for protecting bridge decks after repair.

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## New Approach to Cathodic Protection of Bridge Decks and Concrete Structures

J. P. NICHOLSON

**Until now, cathodic protection of bridge decks has been accomplished by installing anodes on the concrete surface or by recessing them into the concrete and covering them with a conductive paving layer to spread the current over the entire surface of the structure to be protected. Tests are reported in which wire anode consisting of platinized niobium was installed in a bridge deck in sawed slots with conductive backfill. Tests to date indicate that if the wire anode is carefully spaced a bridge structure can be protected without using a conductive paving layer. This eliminates to a great extent the cost of conductive paving and of other wearing courses required to protect the conductive paving layer.**

The deterioration of concrete bridge decks and support structures occurs worldwide, but the deterioration can be accelerated by the use of deicing salts or by salt spray in coastal areas. Since the pH of concrete is generally in the range of 12.5-12.8, one would normally anticipate that steel would not corrode in concrete. In this pH range, steel is usually passive; in the presence of chlorides, however, corrosion of the reinforcing steel can occur quite rapidly. In the United States, the U.S. Environmental Protection Agency estimates that the annual cost of bridge damage caused by deicing salts is about \$0.5 billion/year. No doubt the damage to bridge structures in Canada is high, since deicing salts are used extensively during the winter months, but I have not been able to locate any estimates in the literature of the cost of this damage.

Slater and others (1) have suggested that chloride levels of 0.02 percent or less be considered the threshold value for corrosion of reinforcing steel. In their investigations, the

steel remained passive at levels below this figure and, at chloride concentrations above the 0.02 percent level, corrosion occurred. Slater and others did some investigation on chloride concentration at various depths in concrete bridge structures. As data given in Table 1 show, chloride concentration decreases with the depth of concrete cover. This is no doubt attributable to the permeability of the concrete and the ability for ionic transfer.

Before a bridge deck can be protected, the criteria for protection of steel in concrete must be determined. Many papers suggest that National Association of Corrosion Engineers (NACE) standard RP-01-69 should apply to concrete structures that contain reinforcing. This standard offers three criteria for establishing whether or not a structure is cathodically protected.

To intelligently use these criteria, it is necessary to understand how they were established. Schwertdferger and McDorman (2) did some analytic work on the current and potentials required for the protection of steel in soils. Their investigation indicated that "cathodic protection is the maintenance of a critical potential at the surface of the cathode." This potential, which Schwertdferger and McDorman define by the point of intersection of the potential-pH curve for steel in air-free soils and the potential-pH curve for the hydrogen electrode at atmospheric pressure, was found to be approximately -770 mV referred to the saturated calomel electrode, or -530 mV referred to the standard hydrogen electrode. This converts to -850 mV re-

Table 1. Average chloride content of cores taken from bridge deck before electrochemical treatment.

Depth of Sample from Deck Surface (cm)	Chloride Content					
	Cores Taken in November 1973		Cores Taken in August 1974		Cores Taken in April 1975	
	Amount (kg/m <sup>3</sup> )	Percent	Amount (kg/m <sup>3</sup> )	Percent	Amount (kg/m <sup>3</sup> )	Percent
0.25	6.94	0.31	8.95	0.40	9.2	0.41
3	3.5	0.16	5.16	0.23	4.5	0.20
5.8	1.12	0.05	1.36	0.06	1.36	0.08
8.6	0.23	0.01	0.23	0.01	0.23	0.01
11.4	0.23	0.01	0.23	0.01	-	-

Note: Chloride content based on dry concrete weight of 2242 kg/m<sup>3</sup>. Data are average values obtained on two cores.

Figure 1. Potential of steel in air-free soils versus soil pH.

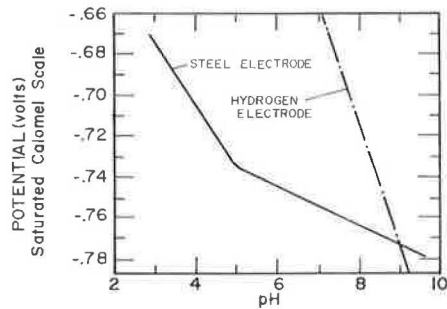


Figure 2. Critical polarization potential for cathodic protection of steel in saturated lime solutions containing sodium chloride.

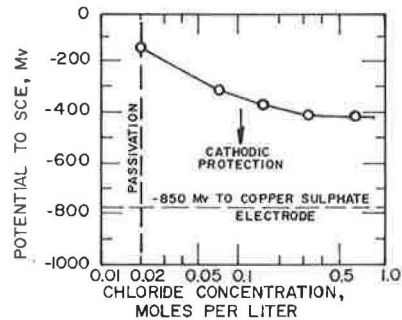
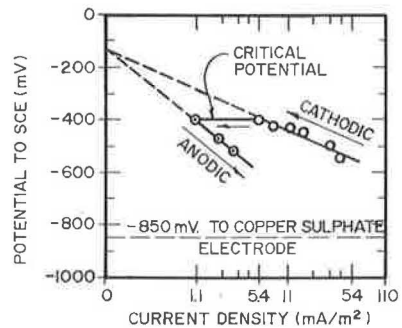


Figure 3. Characteristic change in current during cathodic depolarization of steel in saturated lime solution containing 4.4 percent sodium chloride.



ferred to the copper/copper sulfate (Cu/CuSO<sub>4</sub>) electrode (see Figure 1). This does not necessarily mean that the criteria in the NACE standard can be used as an indication of satisfactory protection of steel embedded in concrete in the presence of chloride ions.

In his work, Hausmann (3) determined from analytical procedures that the critical protective po-

tential is a function of chloride concentration for steel in concrete. The critical potential was plotted as a function of chloride ion concentration (see Figure 2). This curve is discontinuous at a chloride concentration of 0.02 molar, the threshold concentration previously determined for passivation of mild steel in saturated lime solutions. At a chloride concentration of 0.64 molar (4.4 percent sodium chloride), the critical polarization potential is -435 mV to a saturated calomel electrode, or approximately -515 mV to a Cu/CuSO<sub>4</sub> electrode. Hausmann found from the current-potential relationship during depolarization that the cathode potential became less negative as a logarithmic function of the current density. This relationship, shown in Figure 3, is consistent with observations made by Tomashov (4).

This relationship held until the cathode was depolarized to its critical polarization potential and corrosion occurred. At initiation of corrosion, the current reversed direction and subsequently increased in magnitude. The potential also appeared to be a logarithmic function of current density. The cathodic and anodic potential curves intersect at the base potential of bare steel and saturated lime solution. The current at the projected intersection is shown as zero in Figure 3 (the current scale is discontinued at about 1.1 mA/m<sup>2</sup>). At lower current densities, the cathodic depolarization curve is to be considered linear, as suggested by Tomashov (4). In his conclusions, Tomashov states that corrosion of steel can be prevented in concrete exposed in high-chloride-content environments if sufficient current is applied to shift the steel polarization potential to a minimum value of -515 mV to a Cu/CuSO<sub>4</sub> electrode and that corrosion of steel can be arrested in chloride-contaminated concrete if sufficient current is applied to shift the polarization potential to a minimum value of -710 mV to a Cu/CuSO<sub>4</sub> reference electrode.

In some polarization scans, I have found that, in freely corroding reinforcing steel in chloride-contaminated concrete, the minimum potential for cathodic protection was -700 mV to a Cu/CuSO<sub>4</sub> reference electrode, which agrees very well with the values given by Hausmann (3) and Tomashov (4).

The conclusion of many authors is that cathodic protection for reinforcing steel in concrete is practical and can preserve the structure from the degradation resulting from corrosion of the reinforcing steel induced by chlorides. The present state of the art is to use graphite or high-silicon cast-iron anodes on the surface or slightly recessed into the surface of the concrete structure and then to use a conductive paving layer to offer a low-resistance, electronically conductive path for the cathodic protection current to reach remote parts of the structure. This method is both cumbersome and expensive. The conductive paving

Figure 4. Model reinforced-concrete deck.

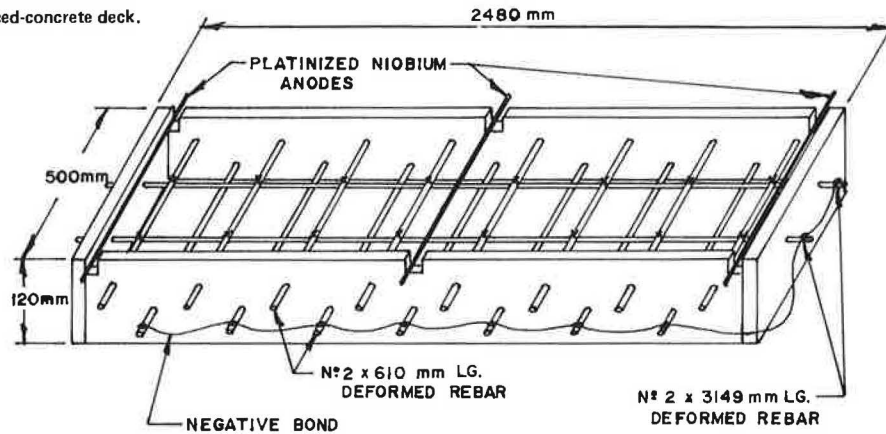


Figure 5. Reference potential locations in experimental deck.

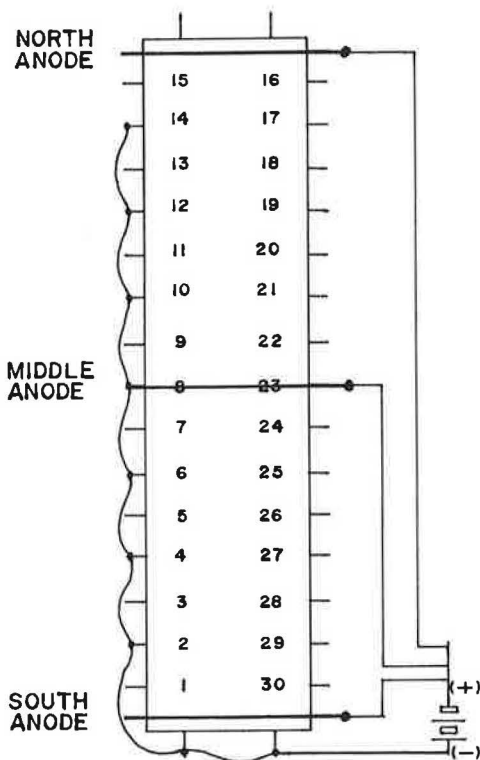
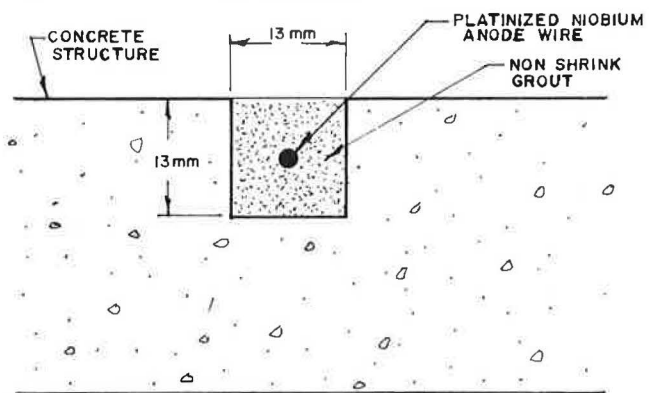


Figure 6. Installation of anode wires in saw slots.



layer is difficult to mix and apply and adds greatly to the weight of the structure.

It has been theorized that, with the new advances in anode materials, cathodic protection of reinforced concrete structures could be simplified and the cost reduced greatly.

It is difficult for a consultant who does not own a bridge structure to experiment with cathodic protection to determine the design parameters needed to protect reinforcing steel in chloride-contaminated concrete. Nevertheless, a small-scale experiment was set up to try to duplicate the conditions that would be experienced on a large, reinforced-concrete structure. Figure 4 shows the model reinforced-concrete deck that was fabricated. The model deck was deliberately fabricated with a thin (120-mm) cross section to accentuate any shielding effects that the upper course of reinforcing bars might have on the lower course. In addition, the use of a thin cross section reduced the effective current path,

thus creating a worst case for current distribution. The deck also had a concrete surface area (1.115 m<sup>2</sup>) equivalent to the total area of embedded steel, which corresponds to the situation found in actual bridge decks.

The plan view in Figure 5 shows reference potential locations that were used throughout the experiment. Various anode configurations were tried. One platvanized niobium anode was embedded in the concrete when the model bridge deck was poured. Three additional anode wires were installed in 13x13-mm saw slots and grouted in (see Figure 6). A variety of grouting materials that were both electronically and electrolytically conductive were used.

The bottom layer of reinforcing steel in the experimental model was not connected internally to the longitudinal bars but was bonded together with an external copper conductor so that current flow to the individual bars could be monitored during the experiment. This proved impractical, however, because of the low current densities required to achieve satisfactory potentials in the actual experiment.

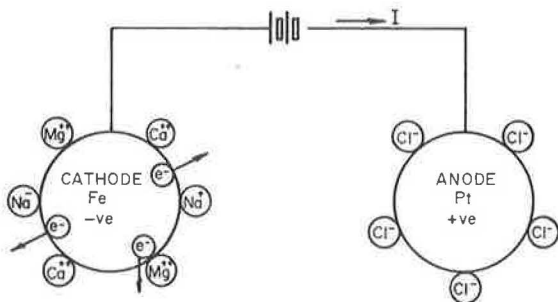
Table 2 gives the potential of the reinforcing steel recorded over a seven-month interval. The first potential measurements were taken on March 10, 1978, approximately 48 h after the concrete was poured. The range of the potential of the reinforcing steel at that time was approximately -400 to -500 mV measured to a Cu/CuSO<sub>4</sub> reference electrode. The potential of the steel varied daily for more than 30 days as the concrete cured. Cathodic protection was then applied to the structure. Potentials recorded in May and June of

Table 2. Experimental results of bridge-deck cathodic protection.

Half-Cell Location	Potential (-mV to Cu/CuSO <sub>4</sub> half-cell)										
	Current On				Current On			Current Off			
	March 10 <sup>a</sup>	May 23, 27 mA/m <sup>2</sup>	June 8, 36 mA/m <sup>2</sup>	July 8 <sup>b</sup>	Aug. 18, 20 mA/m <sup>2</sup>	Sept. 5, 16.2 mA/m <sup>2</sup>	Sept. 12, 24.3 mA/m <sup>2</sup> (salt)	Sept. 19, 27 mA/m <sup>2</sup> (salt)	Sept. 25, 11 mA/m <sup>2</sup> (salt)	Oct. 3, 22 mA/m <sup>2</sup>	Oct. 17, 27 mA/m <sup>2</sup>
1	445	980	1080	290	1050	1350	1250	1460	650	840	1000
2	440	600	650	300	625	700	820	1310	600	740	830
3	430	520	580	320	525	570	690	1240	570	640	770
4	430	530	570	330	480	515	640	1200	550	650	720
5	435	530	600	360	470	500	650	1190	540	650	710
6	520	550	650	345	470	530	735	1230	570	700	760
7	425	700	850	360	640	650	960	1350	640	840	940
8	420	3750	4200	340	7800	9800	880	1380	580	840	920
9	435	790	880	355	740	790	1040	1400	620	810	940
10	425	570	620	350	490	500	720	1250	570	690	750
11	415	520	540	360	440	450	600	1180	540	630	700
12	480	495	530	350	420	400	610	1180	530	625	690
13	410	510	550	325	470	410	660	1220	540	665	720
14	440	610	680	340	690	550	900	1320	580	750	810
15	415	900	1140	340	1700	1180	1410	1420	620	830	900
16	415	860	980	340	1100	1160	1520	1370	630	780	1010
17	445	585	680	340	660	530	915	1300	620	725	860
18	400	505	530	340	500	410	690	1270	575	675	780
19	460	490	500	345	410	400	620	1210	570	650	760
20	410	510	530	360	430	440	615	1210	575	660	760
21	470	570	620	365	520	530	730	1280	600	725	830
22	440	750	860	355	960	870	1150	1400	630	820	930
23	415	3750	4300	325	7700	9900	880	1420	620	820	1000
24	430	660	780	350	715	670	1060	2330	670	780	990
25	510	540	600	345	480	520	750	1270	600	715	820
26	425	510	550	340	440	460	640	1220	560	670	740
27	440	510	550	340	470	495	630	1210	550	660	720
28	430	520	570	330	515	540	690	1250	560	665	750
29	455	600	640	300	600	640	870	1300	580	700	790
30	450	980	1040	310	1220	1920	1420	1440	580	785	860

<sup>a</sup>Two days after pour.<sup>b</sup>Static readings after current was off for 30 days.

Figure 7. Cathodic protection system operating in presence of chloride ions.



1978 at current densities of 27 and 36 mA/m<sup>2</sup>, respectively, show the potential of the structure when the rectifier was operating. No allowance was made in these readings for drops in voltage caused by electrolyte resistance. Since very little current spread could be obtained, it was decided to turn the rectifier off for a time to reestablish the static potentials. Static readings were taken on July 8, 1978, after the current was off for approximately 30 days. The static potentials were in the range of -300 to -400 mV. Current was then reapplied to the deck. The controller was set to hold the current density at 27 mA/m<sup>2</sup>. Readings taken in August and September, during a period of extremely dry weather, show very little spread of current away from the anodes, and the controller was unable to maintain the current density required because of voltage limitations.

By mid-September, the model bridge deck was six months old and had fully cured in a weathering

exposure, although July and August had been unusually dry. It was then decided to continue the experiment and apply rock salt to the surface of the deck on a weekly basis at an application rate of 0.047 kg/m<sup>2</sup> and to allow natural rainfall to wash this salt into the concrete matrix. After the results for the first six months were examined, it was theorized that the addition of chlorides would increase the conductivity of the concrete matrix and thus assist the spread of cathodic protection currents. This proved to be the case after the application of the salt. Measurements taken on September 12, 19, and 26 show the change in current spread in the structure and the potential of the reinforcing steel after the application of salt. On September 19, the lowest potential recorded when the cathodic protection current was interrupted was -1210 mV.

All of the measurements given in this paper are the result of a constant-current cathodic protection system, since the initial data desired were minimum current density and maximum anode spacing. In practice, a potential-controlled rectifier would be used and the potential of the reinforcing steel would be maintained at -1000 mV to Cu/CuSO<sub>4</sub>. As the literature suggests, a potential of -700 mV or more will afford protection of reinforcing steel in chloride-contaminated concrete.

After the September 19 measurements were taken, current density was reduced to establish the density required to maintain the structure at approximately -700 mV to a Cu/CuSO<sub>4</sub> reference electrode with the current momentarily off; this produced the lower potentials recorded after September 19.

The initial results obtained in this experiment and the literature review on the protection of reinforcing steel in concrete indicate that a reinforced-concrete structure can be protected by

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**Transportation Research Record 762**

page 17, column 2, reference 4  
Change "1976" to "1966"

**Transportation Research Record 778**

page 36, column 2, line 20  
Change "\$6000" to "\$660 000"

**Transportation Research Record 790**

page 74, column 1, Equation 1  
Change to " $Y = b_0X_0 + b_1X_1 + b_2X_2 + b_3X_1^2 + b_4X_2^2 + b_5X_1X_2$ "

page 75, column 1, Table 1  
Change "Variable" column to  
"Variable

$X_0$   
 $X_1$   
 $X_2$   
 $X_1^2$   
 $X_2^2$   
 $R^2$ "

**Transportation Research Record 792**

page 2, column 2

Insert the following before the last paragraph:

"The speakers present papers that indicate how they have taken steps to reduce such adversary relationships in contractual work, and provide various evaluations of the resulting work. The various papers are placed in proper perspective to provide an overall introductory picture of the subjects to follow this introduction. Three teams of three authors each present viewpoints on three projects, and two authors add their thinking to the seminar."

"This seminar examines three other projects, each of which is addressed by three speakers with three different points of view, namely the owner's, the contractor's, and the engineer's or the Federal Highway Administration's representative. The projects are

1. West Virginia Department of Highways Quality Assurance Program;
2. Eisenhower Memorial Tunnel, Second Bore, in Colorado under Loveland Pass; and
3. Pittsburgh's South Busway.

"In addition we have

1. A paper by two researchers from Virginia.
2. Some thoughts by a service engineer of a large corporation who is constantly out in the field looking at all these problems and thus is in a position to observe what is going on."

**Transportation Research Record 797**

page ii, price should be \$7.20

**Transportation Research Record 816**

page 34, Table 6, line 9, column "Realistic Saving"  
Footnote b-Change to "0 to 3.8"  
Change "Annual liters of fuel saved . . ." to "1000's of liters of fuel saved annually . . ."

page 29, column 1, line 21  
Change "millileters" to "milliliters"

**Transportation Research Record 834**

page ii  
Change subject areas to 13, 15, 25  
Change mode to 01 only

**Preprint Volume for the National Seminar on Portland Cement Concrete Pavement Recycling and Rehabilitation**

page 94, column 2, last line  
Change "a 0.241-cm (3/4-in.)" to "0.241-cm (0.095-in.) diamond sawblades at 1.9 cm (3/4 in.)"

page 96, column 2, paragraph 2, line 3  
Change "(3/15-in.)" to "(3/16-in.)"

page 98, Figure 33, line 3  
Change "apepar" to "appear"

page 98, column 2, line 5 below Figure 35  
Change "(51,000 sq. yds.)" to "(57,000 sq. yds.)"

**NCHRP Report 238**

title page, author's name  
Change "Shebr" to "Shelar"

**NCHRP Synthesis of Highway Practice 66**

page 5, caption for Figure 3  
Change to "... as a type II ..."

**NCHRP Synthesis of Highway Practice 69**

Foreword, page iv  
Delete paragraph 3

page 13, Table 2, item 2.6  
Change formula to  $T_t = \sum P_i(t_i + \sqrt{h})$

page 41, column 2  
Change formula to  $T_t = \sum P_i(t_i + \sqrt{h})$

page 45, Table 15, title  
Change to "GUIDELINES FOR SERVICE CHANGES: (Port Authority of Allegheny County)"

page 86, box under Toronto, item 2-6  
Change formula to  $T_t = \sum P_i(t_i + \sqrt{h})$

***NCHRP Synthesis of Highway Practice 76***

page 2, line 5  
Change "\$50" to "\$25"

page 7, column 2  
Change "i = 1" to "l = 1"

*i = l to i = 1*

page 13, Table 9, under Pennsylvania  
Change "10%" to "100%"

page 16, column 1, line 18  
Change "\$50" to "\$25"

page 23, column 1, line 29  
Change "\$50" to "\$25"

using platinized niobium anode wire without installing a conductive layer on the surface of the structure. The experiment with the model deck will be continued to optimize design criteria for the anode spacing and current densities required to protect reinforcing steel in chloride-contaminated concrete.

A cathodic protection system operating in the presence of chloride ions performs two beneficial functions:

1. It prevents the corrosion of the reinforcing steel by maintaining a surplus of electrons on the steel surface, thus preventing the migration of the iron ions into solution.

2. The chloride ion is attracted to the anode, and this reduces the chloride concentration in the vicinity of the reinforcing steel (cathode) (see Figure 7), thus increasing the pH of the cathode.

The cost of protecting a reinforced-concrete structure by using a conductive paving layer is about \$30/m<sup>2</sup>, whereas platinized niobium wire anodes installed in saw slots would cost about \$12/m<sup>2</sup>. It is anticipated that this cost will decrease further as design parameters are refined and installation methods perfected.

This new concept of cathodic protection was applied to a new 803-m<sup>2</sup> deck in the fall of 1979. In that application, 600 m of 0.8-mm platinized niobium anode wire was installed in 10x13-mm saw slots cut in the deck at 1-m intervals. The wire anode was grouted in the slot and cathodic protection applied. After approximately 350 h at a current density of 18.5 mA/m<sup>2</sup>, a potential of -770 mV to Cu/CuSO<sub>4</sub> was achieved midway between the anodes, and the

potential-controlled rectifier output was automatically reduced to approximately 9.0 mA/m<sup>2</sup>, the current required to maintain -770 mV after polarization was achieved. During January 1980, the circuit resistance varied between 0.9 and 1.2 Ω between the unfrozen and the frozen condition.

The deck has been given numerous applications of deicing salt and has undergone many freeze-thaw cycles without loss of protection or damage to the anode grout material.

The system is a viable method of cathodically protecting reinforcing steel in concrete in both the vertical and horizontal position without conductive overlays. It lends itself to the protection of lightweight decks, parking garages, and support structures for bridges and docks.

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3. D. A. Hausmann. Criteria for Cathodic Protection of Steel in Concrete Structures. *Materials Protection*, Oct. 1969, pp. 23-25.
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*Publication of this paper sponsored by Committee on Corrosion.*

## Cathodic Protection for Continuously Reinforced Concrete Pavement in Minnesota

R. G. TRACY

The corrosion of steel in concrete can be suppressed by the use of cathodic protection, which involves applying a low-voltage direct current to the steel from a remote anode so that corrosion is transferred to the remote anode and the steel becomes a protected cathode. The results of the application of cathodic protection to continuously reinforced concrete pavement (CRCP) in Minnesota are presented and discussed. Several segments of CRCP are undergoing rapid, premature deterioration that is directly related to corrosion of the embedded mesh reinforcement. Pavement testing revealed that salt concentration at the reinforcement is high, and copper/copper sulfate half-cell potentials indicated widespread corrosion activity. Essential elements from pipeline and bridge-deck applications of cathodic protection were integrated, and a prototype system was installed along a 1000-ft section of CRCP. Two methods of power (current) application were examined: (a) burying anodes in a trench filled with a conductive aggregate and (b) burying anodes in individual postholes along the pavement shoulder. Both installations were connected to a central rectifier controller, which was interfaced with an automatic device for monitoring and recording the data. An initial data evaluation, expected by late summer of 1980, will provide information on the performance and effectiveness of the system.

During the past three years, an increasing number of continuously reinforced concrete pavements in Minnesota have been exhibiting a spalling type of

deterioration. The frequency and extent of this deterioration have progressed from isolated and random in 1975 to widespread and concentrated on certain pavement designs in 1978. The pavements that show severe and moderate delamination and spalling are of the two-course construction type designed with a steel-to-concrete ratio of 0.6 percent. The reinforcement used was deformed wire mesh with specified clear cover of 2-4 in. In most cases, steel was at the minimum cover of 2 in.

#### BACKGROUND

Construction of continuously reinforced concrete pavement (CRCP) in Minnesota began in 1963 with the placement of a rather extensive test section on I-35W near Faribault. It was hoped that this trial would provide some specifics on construction techniques, design adequacy, and short-term performance. Variable ratios of steel to concrete—0.5, 0.6, and 0.7 percent—were used, and different combinations of base-course thicknesses