

document and as convenient identification labels. (It is not practical to refer to paints by their formulations throughout the text.)

It should be noted that the products mentioned in this study have not been used in the manner intended by their manufacturers, but in a novel man-

ner. Success or failure in this project should not reflect on their performance when used in normal service.

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Cathodic Protection of Bridge Substructures: Burlington Bay Skyway Test Site, Design and Construction Phases

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ABSTRACT

The design and construction phases of a research program to develop an effective cathodic protection system for use on bridge substructures are described. Construction of four experimental systems on columns of the Burlington Bay Skyway Bridge was completed in 1982. One sacrificial anode system and three impressed-current systems were installed, each covering approximately 38 m² of column surface. The sacrificial anode system used zinc ribbon anodes with a shotcrete overcoat. A conductive polymer concrete was used as the primary anode in all the impressed-current systems. In System 1 the anodes were used with a shotcrete overcoat. System 2 consisted of the primary anodes with an exposed secondary anode of conductive paint. System 3 employed a secondary anode network of multifilament carbon strand, also with a shotcrete overcoat. A range of instrumentation was designed and installed to determine the effectiveness and efficiency of the four systems.

Considerable efforts have been expended in recent years to develop methods for the rehabilitation of highway bridges that have deteriorated as a result of the corrosion of embedded reinforcement. Most of this work has concentrated on bridge decks (1,2), but similar deterioration is present in substructure elements where it is more difficult and expensive to repair.

Of all the methods available for the repair of structures, only cathodic protection positively arrests the corrosion process. A system of cathodic protection has been used for the rehabilitation of bridge decks in Ontario since 1974 (3,4). Although the principles of this treatment are applicable, the

materials and methods of construction used for bridge decks cannot be used on substructures.

OBJECTIVES OF RESEARCH PROGRAM

The overall objective of the research program initiated by the Ontario Ministry of Transportation and Communications in 1981 was to develop a method for the permanent repair of bridge substructures.

Cathodic protection was selected as the most promising method of achieving this goal. A number of projects were begun in support of the program objective. These included laboratory and exposure-plot studies of the various components of cathodic protection systems. The major project in the program involved the design, installation, and evaluation of four experimental systems. Each system consisted of a small-scale section applied to a real structure such that data could be collected to be used in the design of a full-scale demonstration of cathodic protection on a bridge substructure. The specific objectives of this project were to

1. Determine the effectiveness and efficiency of each system in stopping corrosion,
2. Make a technical and economic comparison of the systems, and
3. Identify potential long-term deficiencies.

The design and construction phases of this project are described in this paper.

GENERAL REQUIREMENTS OF A CATHODIC PROTECTION SYSTEM

Cathodic protection is a process that prevents the anodic corrosion reaction by creating an electric field at the surface of the metal so that current flows into the metal (5). This sets up a potential gradient at the metal surface that prevents the release of metal ions as the product of corrosion.

The source of the electric field that opposes the

corrosion reaction may be a direct current power supply (usually a transformer rectifier) connected to a network of anodes; this technique is called impressed-current cathodic protection. Alternatively, the current may be supplied from the preferential corrosion of a metal anode that has a stronger anodic reaction than does the structure. This technique is known as sacrificial anode or galvanic cathodic protection.

The requirements for a cathodic protection system for bridge substructures are given in the following list. They are based on requirements for coating systems identified by Apostolos (6):

1. Effectiveness: A low resistance between the anode system and the reinforcement throughout the area to be protected is needed to ensure an even distribution of current and low power consumption;
2. Durability: System materials must be resistant to electrical and structural breakdown within the service environment of salt-contaminated concrete; they must also remain bonded to the protected surface and be resistant to degradation from factors in the external environment, including weathering;
3. Availability, simplicity, and ease of installation: System components must be readily available, must be able to be installed with a minimum of special training, and must be tolerant of a variable quality of workmanship;
4. Minimum maintenance: Systems should be stable with respect to changes in the environment (temperature and humidity) and not require periodic manual adjustment of the power settings;
5. Low cost;
6. Acceptable appearance;
7. Versatility: The system should be capable of application to a variety of substructure sizes and geometries; and
8. Lightweight: The system should add a minimum of dead load to the structure.

SITE SELECTION

The Burlington Bay Skyway Bridge, which is a multiple-span, high-level structure over the entrance to Hamilton Harbour in southern Ontario, was selected for the installation of the test systems. The rectangular columns of the structure are exposed to surface run-off from leaking expansion joints and roadway drains. Salt-staining is frequently visible in the winter months, as shown in Figure 1. The condition of the columns is a function of the exposure



FIGURE 1 Salt straining on pier bents, Burlington Bay Skyway.

to salt and therefore varies from column to column and from area to area on the same column.

The site was selected for the following reasons.

1. Columns could be chosen that were exhibiting active corrosion while showing a minimum of physical distress. This means the test conditions were realistic, both in terms of the condition of the structure and the exposure, but repair work was kept to a minimum.
2. The structure is scheduled for major rehabilitation in the near future, and the data collected will be used in designing the rehabilitation scheme.
3. The substructure was readily accessible for construction and monitoring activities without the need for traffic control measures.
4. Electrical power was available.

As can be seen in Figure 1, the height of the columns varies, reaching a maximum of 24 m. A characteristic feature of all the columns is the presence of rustication strips at 1.22-m centers. Where reference is made to a panel elsewhere in this paper, this is the area of one face between adjacent rustication strips. The section of the columns at the location of the test sites was approximately 2.1 x 4.0 m.

All the systems were installed in the same configuration: three panels high on the south face and two panels high on the remaining faces. This was done to determine if the third panel on the south face influenced the corrosion activity over the adjacent unprotected faces. The total concrete surface area in each system was approximately 38 m².

DESIGN OF CATHODIC PROTECTION SYSTEMS

System 1

The design was an impressed-current system that consisted of primary anodes of a conductive polymer composite spaced vertically at 450-mm centers with a shotcrete overcoat. The design drawing is shown in Figure 2.

The conductive polymer composite was developed by the FHWA laboratories and consisted of a vinyl ester binder with the addition of spherical carbon particles that provided a specified resistivity of less than 10 ohm·cm. The polymer was supplied as a two-component material, and anodes 25 x 12 mm in section were cast before system construction. Two strands of 30,000 filament carbon fiber were embedded the full length of each anode to increase anode conductivity. The fiber used had an extremely low resistivity (18 x 10⁻⁴ ohm·cm), high tensile strength (2.7 GPa), and is made from a polyacrylonitrile (PAN) base. One hundred-millimeter lengths of platinized niobium copper core wire, 0.79 mm in diameter, were embedded a length of 50 mm in the ends of the anodes to facilitate connection of electrical supply lines. The anodes were 2.4 m long on the faces that had two panels. Two anodes were used on the south face, each 1.8 m long, for ease of handling.

A separate feeder line was extended from the terminal box to the anodes on each face so that the faces could be activated independently if desired. Switch boxes were provided for the connections from the feeder line to the anodes on the east face so that individual anodes could be disconnected to optimize anode spacing.

A separate constant current rectifier was used to power each of the three impressed-current systems. They were connected to system anodes and ground at the individual system terminal boxes.

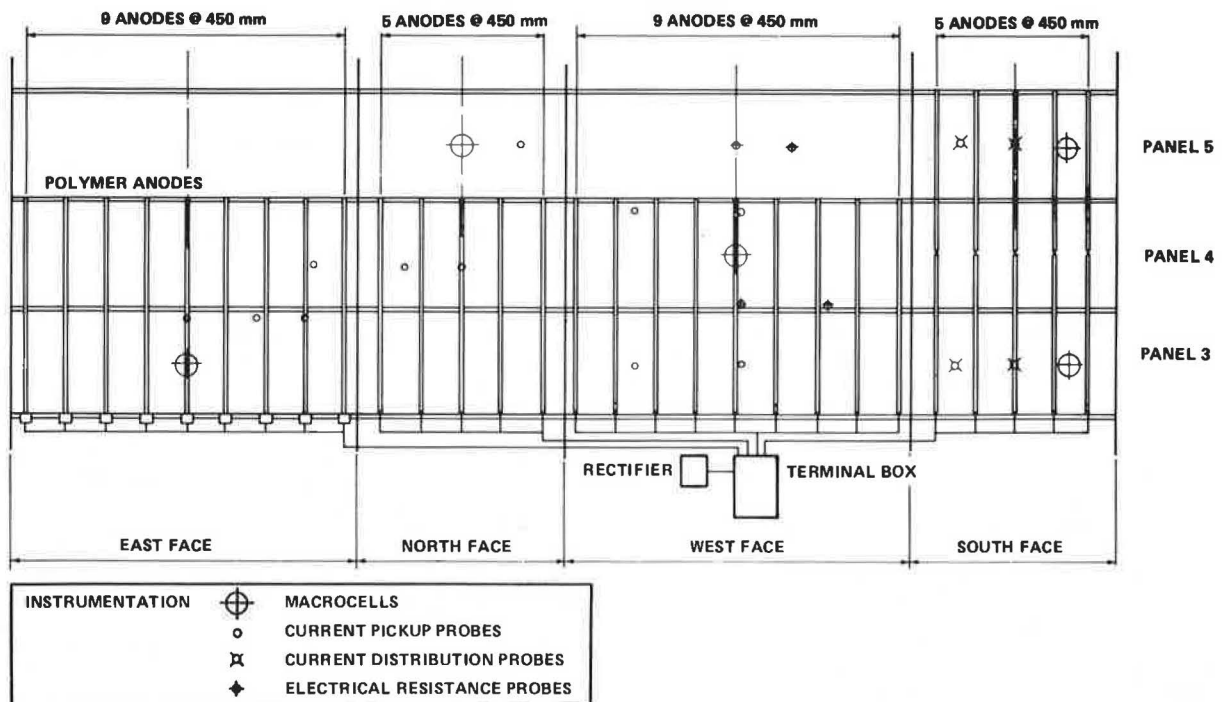


FIGURE 2 System 1: anode and instrumentation placement.

A 40-mm-thick layer of conventional portland cement shotcrete was applied over the entire system.

System 2

The primary anodes were the same as in System 1, except that a single strand of platinized wire was embedded the full length of the anode, rather than carbon strand, to reduce the resistivity of the anodes.

The system was designed with the anodes placed horizontally on the column and connected at the corners to form three rings around the column at the

level of the rustication strips, as shown in Figure 3. Power was supplied to the open southwest corner of each ring. Switch boxes were placed in each anode line at the northeast corner so that half of each anode could be disconnected to investigate current distribution in the system. A single anode was placed at the top of the third panel on the south face and provided with its own power supply line. The four supply lines were connected to a rectifier through a terminal box with switches in each line so that the anodes could be powered individually or in groups.

A secondary anode of graphite-pigmented conductive paint was placed on the surface of the panels

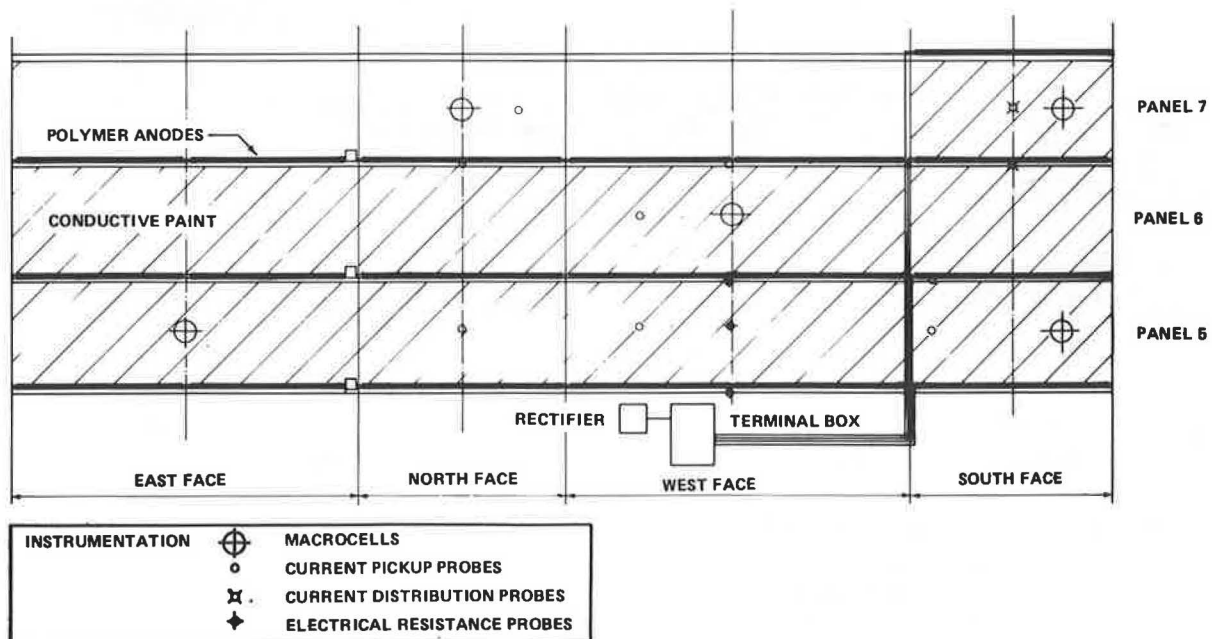


FIGURE 3 System 2: anode and instrumentation placement.

bordered by the anodes to lower resistance between the anodes and the reinforcement. The product used was selected because of its low resistance and promising durability characteristics determined in an earlier investigation (7).

System 3

This design was also an impressed-current system that used the same anodes used in System 2. The anodes were placed vertically, with two anodes at the third points of the long faces and one anode at the center of the short faces, as shown in Figure 4. Each anode was connected to a separate supply line from the terminal box, with a switch in each line to permit individual control. A secondary anode of carbon fiber was applied to form a network on the concrete surfaces. Anchors were placed 100 mm from the edge of each face at points spaced 100 mm apart vertically. The fiber was connected by zig-zagging between the anchor points using a single length of fiber. In this way the fiber on each face was continuous, but there was no connection between adjacent faces. Two types of fiber were used. The south and west faces used a double strand of the 30,000 filament PAN fiber described in System 1. A 20,000 filament pitch-based fiber overbraided with dacron was used on the north and east faces. The resistance per unit length of the 20,000 filament pitch fiber was approximately equivalent to 60,000 filaments of the PAN fiber. The carbon content of the pitch fiber exceeds 99 percent compared with 93 percent for the PAN fiber.

The entire system was covered with 40 mm of conventional portland cement shotcrete.

System 4

This was the only sacrificial anode or galvanic system. Work elsewhere (8,9) had shown that various configurations of zinc anodes could provide adequate

protection to steel reinforcement in concrete. The anodes used were in the form of a continuous diamond-shaped (9 x 12 mm) zinc ribbon with a 2.5-mm steel core by which connections to the anode could be made. The anodes were placed vertically on 150-mm centers, as shown in Figure 5. All the anodes on each face were connected to a single feeder cable. The four feeder cables were extended to the terminal box where each was connected through a switch to leads attached to the reinforcement on the corresponding faces.

Because the driving voltage of the system is limited to the potential difference between the zinc anode and the steel reinforcement, it is essential that the circuit resistance be kept to a minimum. Salt was therefore added to the shotcrete to reduce its resistance and also to ensure that the potential of the zinc was active. In long-term installations it would be desirable to use an overcoat material with a high air content so that corrosion products formed on the surface of the anodes are dissipated without cracking the overcoat. However, the overcoat cannot be too porous because it would then be vulnerable to drying, which would greatly increase circuit resistance. Because System 4 was designed only as a short-term experimental installation, no provision for a high air content shotcrete was made. The specified salt content was 0.5 percent Cl^- by mass of shotcrete.

Instrumentation

Instrumentation was needed to determine the effectiveness and permit a comparison of the four cathodic protection systems. Information was required specifically on the current distribution and density within each system over time. There was a lack of commercially available instrumentation to satisfy these needs and, after reviewing the experience of others (10,11), the following instrumentation was developed and fabricated. The specific locations of the various probes are shown in Figures 2-5.

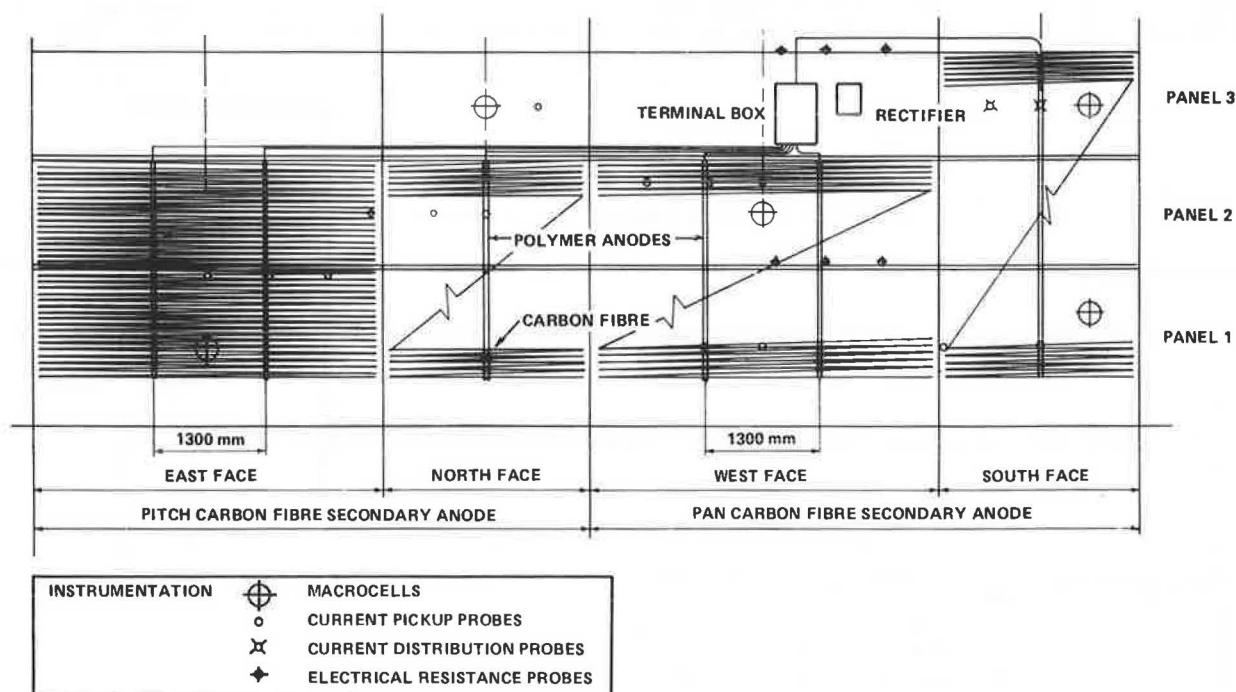


FIGURE 4 System 3: anode and instrumentation placement.

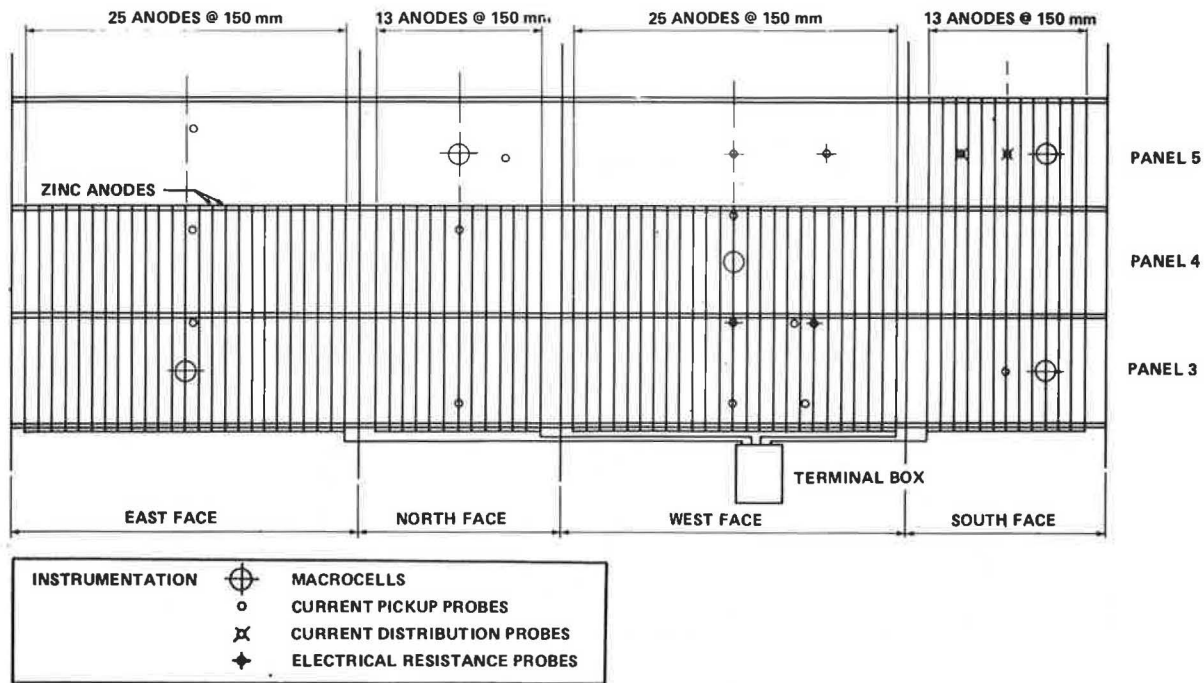


FIGURE 5 System 4: anode and instrumentation placement.

Macrocells

The principle of the macrocell is to create a strong natural corrosion cell. This is done by forcing a portion of the reinforcement to act as a cathode with respect to an anode implanted adjacent to the reinforcement. (It is important to distinguish between this anode, which is a natural half cell, and the anodes that are applied to the surface of the concrete and act as a current distribution system.) The macrocell anode consisted of a short length of reinforcing steel encased in mortar of a high chloride content. Leads extending from the anode and cathode can be connected externally at the terminal box to measure the magnitude and direction of current flow in the cell. It was intended that the current flow in the macrocell would be at least equal to corrosion currents elsewhere in the structure. Consequently, if the application of cathodic protection reverses the direction of current flow in the macrocell, this is an indication that all other corrosion cell activity has been arrested. The applied current necessary to reverse the macrocell is also a measure of the effectiveness of the system.

A thermocouple and a zinc-zinc sulfate reference cell, used for potential measurements at the level of the reinforcement, were also embedded in the macrocell, as shown schematically in Figure 6.

Macrocells were located directly under anode lines, midway between them, and in unprotected areas of the structure. The cells in the unprotected areas were designed to act as controls as well as to measure the effect of any stray currents.

Current Pick-Up Probes

Current pick-up probes provide another means of examining current distribution in the structure. Each probe consists of a short piece of rebar embedded at the level of main reinforcement and connected by a lead wire to the instrumentation panel in the terminal box. By measuring current flow be-

tween the probes and ground, the current density at various points in the structure can be calculated. Unlike the macrocells, the probes are free to act as either cathodes or anodes, depending on whether the current flow is to or from the probe.

The current pick-up probes are inexpensive to fabricate and relatively easy to install, as they require little concrete removal. Several probes were installed in each system at locations both beneath and remote from the anode lines.

Current Distribution Probes

The current distribution probes consist of three current pick-up probes installed in a line at different depths from the concrete surface, as shown in Figure 7. The probes are used to measure the variation of current density with depth at different locations in the structure.

Electrical Resistance Probes

The probes were fabricated from thin steel sections that comprise two arms of a bridge circuit. The probes are embedded at the level of the steel, and as one arm corrodes (the other being protected) the resistance increases. By monitoring the probe with a suitably calibrated meter, the rate of corrosion can be expressed in terms of metal loss per year. Similar commercial probes have been used successfully to monitor cathodic protection circuits in bridge decks (4).

Construction

Systems 2 and 3 were placed on the same column, separated by an unprotected area one panel high. System 1 was placed on the second column of the same bent. This was done so that the rectifiers for the three impressed-current systems could be serviced by

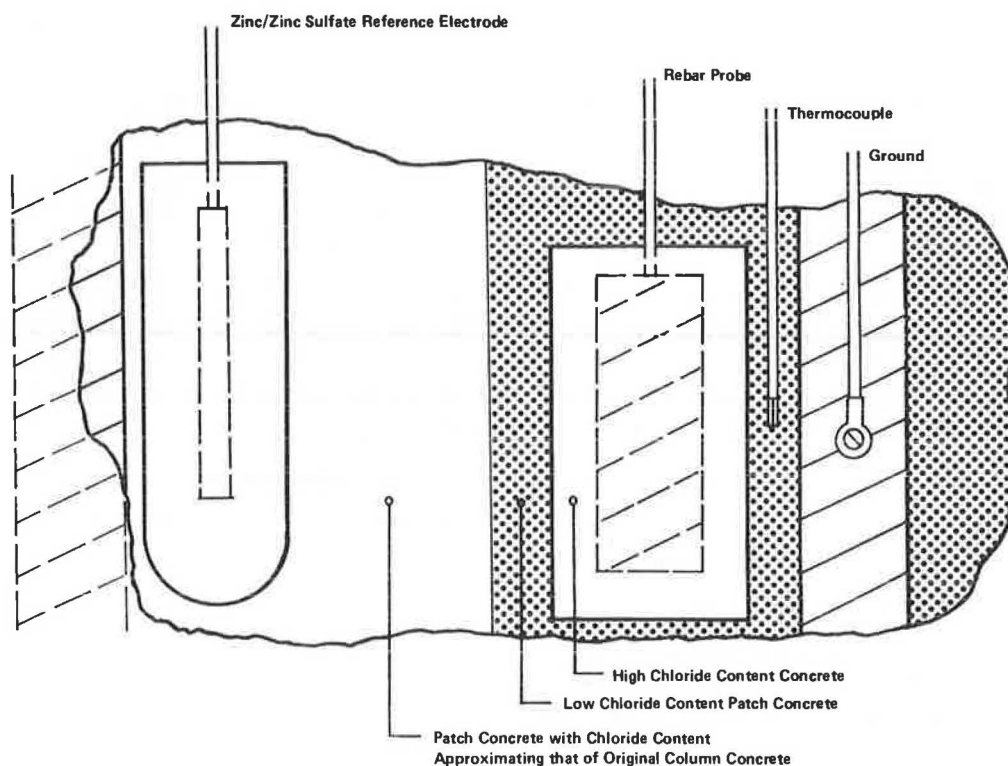


FIGURE 6 Schematic drawing of a macrocell.

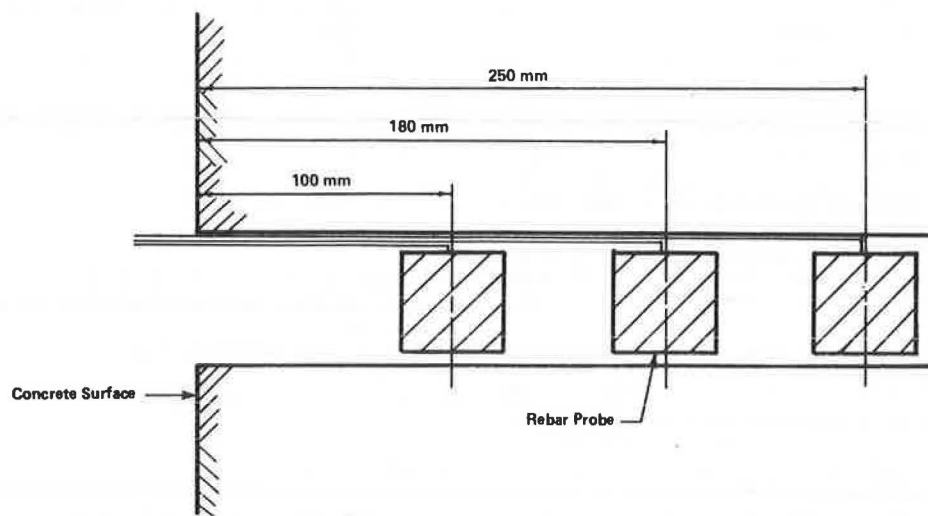


FIGURE 7 Current distribution probes.

a single power supply line. System 4 was placed on the adjacent bent.

The construction of the four systems was completed by Ministry personnel, with the exception of the shotcreting. The reasons for this were threefold:

1. The materials and installation techniques were unproven, so that specifications could not be prepared to enable the work to be done by contract;
2. Design modifications could be readily made as practical difficulties were identified; and
3. A more thorough assessment of technical feasibility could be made by obtaining hands-on experience.

Condition Survey

Before installation of the cathodic protection systems, the condition of each column was documented by a visual survey, measurement of corrosion potentials, detection of delaminated areas by sounding, and determination of chloride content by using cores.

The corrosion potential data (measured in accordance with ASTM C876-77) are given in Table 1, and the total chloride contents (measured in accordance with AASHTO T260) are given in Table 2. The chloride measurements indicate that, after allowing for background chloride levels, the chloride content at the depth of the steel (75 to 100 mm) is greater than

TABLE 1 Half-Cell Potentials

System	Column Face	Half-Cell Potentials		
		> -0.20 V (%)	< -0.20 V > -0.35 V (%)	< -0.35 V (%)
1	North	0	88	12
	South	0	87	13
	East	0	84	16
	West	0	73	27
	Total	0	82	18
2	North	0	96	4
	South	0	88	12
	East	0	84	16
	West	16	73	11
	Total	5	84	11
3	North	0	100	0
	South	0	100	0
	East	0	96	4
	West	2	87	11
	Total	1	94	5
4	North	0	80	20
	South	0	75	25
	East	1	91	8
	West	0	78	22
	Total	1	81	18

the normally accepted threshold value for corrosion at some, but not all, locations. The background chloride levels in the concrete are unusually high because of the high chloride content of the limestone aggregate (12). The half-cell potentials also varied from panel to panel, but active corrosion potentials were included within each system.

Sequence of Construction Activities

The sequence of construction and details of the procedures on each of the four systems are as follows.

1. Repair of delaminated areas with concrete patches.

2. Concrete removal for placement of instrumentation: The instrumentation took much longer to install than anticipated. This was because all the drilling and coring had to be done from a bucket truck, the concrete was of a high quality, and the depth of cover was in the range of 75 to 100 mm. Locating the probes precisely with respect to the reinforcement and the position of the surface anodes also proved to be time consuming.

3. Sandblasting: All the concrete surfaces to be cathodically protected were sandblasted.

4. Installation of instrumentation: After placement of the probes the lead wires were bundled, wrapped, and anchored in place to prevent damage during shotcreting.

5. Epoxy coating of exposed metal: All of the

exposed form ties were covered with two coats of epoxy resin to prevent a system short circuit.

6. Installation of primary and secondary anodes: The primary anodes of conductive polymer were pre-cast. All the anodes were attached to the concrete surface by using plastic straps. Completed anode systems are shown in Figures 8 and 9. A close contact between the anode and the concrete was particularly important in System 3, where the carbon fiber was sandwiched between the primary anode and the column surface. This mechanical contact was the only connection between the primary and secondary anodes in this system. The design of the connections of the feeder lines to the anodes in Systems 1 and 4 was modified to ensure that all the connections would be accessible after shotcreting to allow individual anodes to be disconnected. Two coats of conductive paint were applied by hand in System 2. (The finished system is shown in Figure 10.) Because of susceptibility of the carbon fiber network in System 3 to vandalism, it was installed just before shotcreting.

7. Shotcreting (except System 2): The shotcreting was uneventful except for a slight sagging of the PAN carbon fiber on System 3, as shown in Figure 8. The measured chloride content of the shotcrete in System 4 was 0.47 percent Cl by mass as compared with 0.048 percent Cl by mass of the shotcrete in Systems 1 and 3.

8. Connection of instrumentation and control panels: A terminal box was provided for each system that contained a panel on which all instrumentation and anode leads were terminated.

9. Hook-up of rectifiers (Systems 1, 2, and 3): Unfiltered, full-wave rectifiers with a maximum output of 16 V, 12 A were installed adjacent to the terminal boxes. The size of the rectifiers was based on polarization tests conducted after the anodes were installed. Rectifiers that had less capacity would have been adequate but were not available locally. Constant-current rectifiers were used rather than potential control because the latter require the use of a reference cell. The long-term stability of reference cells embedded in concrete is unproven. The use of constant-current rectifiers also offers the advantage of allowing the current passed by the anodes over a given time period to be calculated.

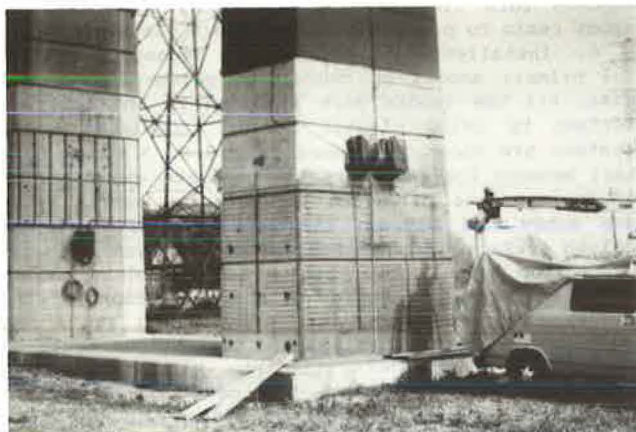
Costs

An estimate of the costs of the four trial systems is given in Table 3. These costs are approximate, calculated only to give an indication of the relative costs of the four systems, and of the costs of substructure repair in general.

Although it was not possible to divide accurately the total time spent among the individual systems, it is believed that the figures reliably reflect the relative costs of the systems. It should be noted that more than half the time spent on this project

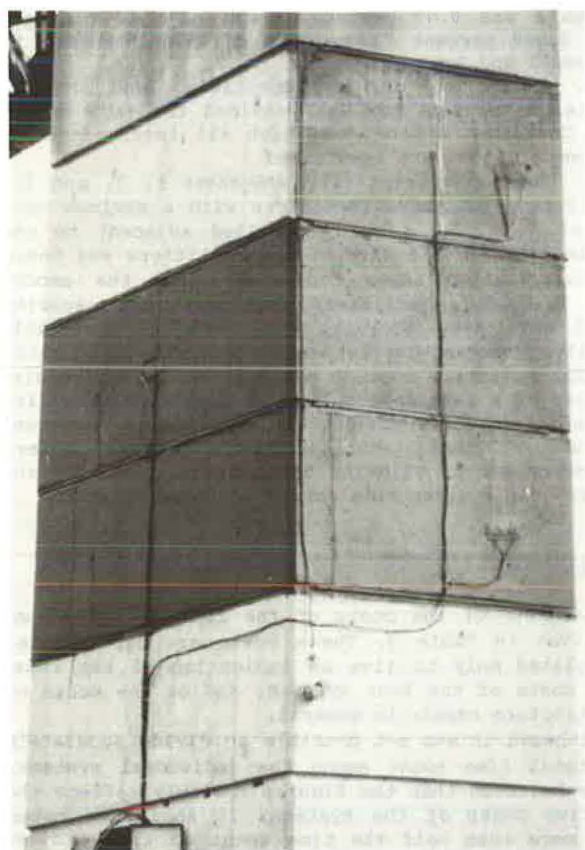
TABLE 2 Chloride Content Determinations, Burlington Skyway Cores

Cathodic Protection Installation	Percentage of Total Chlorides (by mass of concrete) by Depth Below Surface (mm)							
	0-12	12-25	25-50	50-75	75-100	100-125	125-150	150-175
System 1: east face	0.3318	0.2691	0.1368	0.0826	0.0794	0.0755	0.0806	0.0785
System 3								
East face	0.2962	0.3216	0.2172	0.0657	0.0746	0.0781	0.0689	0.0789
West face	0.2416	0.3027	0.1703	0.1051	0.0870	0.0747	0.0823	0.0795
System 4								
East face	0.2223	0.4263	0.3663	0.2201	0.1536	0.1104	0.0936	0.0781
North face	0.1755	0.3895	0.2460	0.1565	0.1195	0.0930	0.0890	0.0754



Note: The relative positions of the three impressed-current systems are seen here; System 1 on the far column, and Systems 2 (upper) and 3 (lower) on the near column. Note the system terminal boxes and the extension of anode and instrumentation lines to them. Rectifiers were later placed adjacent to each box. Note the sagging of the PAN carbon fiber during shotcrete application.

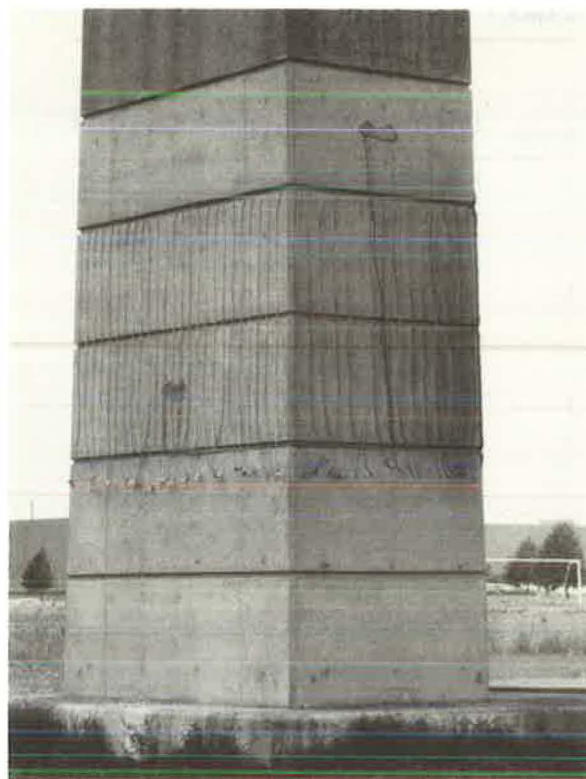
FIGURE 8 Systems 1, 2, and 3.



Note: Polymer concrete anodes can be seen at the level of the rustication strips, with black conductive paint covering the protected surface. Macrocell leads (from two cells on the south face and one on the west face) are anchored to the concrete and extended to the system terminal box.

FIGURE 9 System 2, south and west faces.

was devoted to fabrication and installation of instrumentation. This level of instrumentation would not be employed in a full-scale system. The high construction costs also reflect the fact that many materials and procedures were being used for the first time. The small scale of the project also led



Note: The system is shown before shotcreting, with instrumentation and anode lines in place. Connection cables extend from each anode, ready for connection to feeder cables.

FIGURE 10 System 4, north and east faces.

TABLE 3 Cost of Experimental Cathodic Protection Systems

Item	Cost (\$)			
	System 1	System 2	System 3	System 4
Anode materials				
Conductive polymer (including fabrication)	1,830	1,040	570	
Conductive paint		150		
Carbon fiber			70	
Zinc ribbon				890
Shotcrete	2,660		2,660	2,660
Instrumentation (materials only)	1,800	1,800	1,800	1,800
Rectifiers (including connection)	1,380	1,380	1,380	
Other ^a	15,500	16,500	16,500	18,200
Total	23,170	20,870	22,980	23,550
Cost per m ²	610	549	605	620

^aIncludes labor, vehicle and equipment rental, travel expenses, and consulting fees.

to high unit costs for shotcreting, power hook-ups, and purchase of rectifiers.

Nevertheless, even with greater experience and economies of scale, substructure rehabilitation will be expensive. The figures reported in Table 3 are approximately 5 times greater than typical costs for deck rehabilitation (13).

Discussion of Results

Although all four systems were activated in November 1982 and the initial indications are that they are functioning satisfactorily, a number of practical

difficulties must be overcome before full-scale applications of similar systems can be made routinely.

The casting and the handling of the polymer concrete anodes was especially difficult. Problems were encountered in maintaining a uniform mixture throughout the casting sequence and in adjusting to the variations in working time, which resulted from changes in ambient temperature. It was also difficult to release the anodes from the molds, and several breakages occurred. The hardened anodes were brittle and required careful handling. The purchase of anodes, commercially made under controlled conditions, is a much more attractive proposition to the user, and such anodes are expected to become available in the marketplace.

The electrical connections to the anodes were the weak link in all of the systems. The platinum wire tails on the polymer concrete anodes were particularly vulnerable to damage and breakage. Most of the connections to the anodes were in fact made outside the concrete because of concern for the performance of connections embedded in concrete. The point-to-point connection between the carbon fiber and polymer anodes in System 3 may be vulnerable to degradation and might be expected to exhibit durability problems.

The PAN-type carbon fiber was difficult to handle to prevent fraying and breakage. It could not be installed under windy conditions, as it tended to snag on the structure. The overbraided fiber was easier to handle, but care was required to avoid sharp bends to prevent breakage. The large number of anchorage points required for the zig-zag network was a disadvantage of the system. A woven fabric or mesh may overcome most of these objections.

The main disadvantage of System 4 was also the large number of anchors required to prevent the zinc ribbon from twisting, as can be seen in Figure 10. An alternative would be to apply the zinc in sheet or strip form. The use of flame-applied zinc is also being investigated (6).

The field of cathodic protection of reinforced and prestressed-concrete structures is developing rapidly, and alternative anode materials are being identified. A project has been initiated recently at the Ministry to develop screening tests for anodes to evaluate the performance of candidate materials under both laboratory and exposure plot conditions.

The time required for the installation of the instrumentation was grossly underestimated. The macrocells were especially time consuming to install because of the amount of concrete removal required. Although a large amount of instrumentation was required to provide a rapid assessment of the effectiveness of each system, there is a need to define the type of instrumentation and the minimum amount that must be installed in full-scale systems to ensure that their operation is satisfactory.

Initial polarization studies raised questions regarding the long-term stability of the zinc-zinc sulfate reference cells. This has led to the development of a laboratory program to investigate alternative reference cells with the goal of identifying a cell that can be permanently embedded in concrete.

FUTURE WORK

The four systems are being monitored regularly for power consumption, current distribution, and half-cell potentials. Resistivity and temperature measurements are made at the same time. In addition, the systems are carefully inspected for evidence of degradation of the materials. Changes will be made in the configuration of the systems by disconnecting

anodes, and measurements will be made to determine optimum anode spacing.

Future work will concentrate on monitoring the existing systems; solving some of the problems that have been identified, including connection details; and developing second-generation experimental systems that will lead to a system suitable for full-scale application.

REFERENCES

1. D.G. Manning and J. Ryell. Durable Bridge Decks. Report RR203. Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, 1976, 67 pp.
2. Durability of Concrete Bridge Decks. NCHRP Synthesis of Highway Practice 57. TRB, National Research Council, Washington, D.C., 1979, 61 pp.
3. H.J. Fromm and G.P. Wilson. Cathodic Protection of Bridge Decks: A Study of Three Ontario Bridges. In Transportation Research Record 604, TRB, National Research Council, Washington, D.C., 1976, pp. 38-47.
4. H.J. Fromm. Cathodic Protection of Rebar in Concrete Bridge Decks. Materials Performance, National Association of Corrosion Engineers, Vol. 16, No. 11, 1977, pp. 21-29.
5. Cathodic Protection--Thumbnail Sketch. Materials Performance, National Association of Corrosion Engineers, Vol. 21, No. 1, 1982, p. 50.
6. J.A. Apostolos. Cathodic Protection of Reinforced Concrete Using Flame-Sprayed Zinc. Paper 180. Presented at National Association of Corrosion Engineers Conference Corrosion 83, Anaheim, Calif., April 1983.
7. W.J. Ellis and R.E. Colson. Cathodic Protection of Concrete Bridge Structures, Final Report. NCHRP Project 12-19. TRB, National Research Council, Washington, D.C., 1980.
8. J.B. Vrable. Cathodic Protection for Reinforced Concrete Bridge Decks: Laboratory Phase. NCHRP Report 180. TRB, National Research Council, Washington, D.C., 1977, 135 pp.
9. D. Whiting and D. Stark. Galvanic Cathodic Protection for Reinforced Concrete Bridge Decks: Field Evaluation. NCHRP Report 234. TRB, National Research Council, Washington, D.C., 1981, 63 pp.
10. K.C. Clear. FCP Annual Progress Report--Year Ending September 30, 1980, on Project 4K, "Cost Effective Rigid Concrete Construction and Rehabilitation in Adverse Environments." FHWA, U.S. Department of Transportation, 1980.
11. C.E. Locke and C. Dehghanian. Embeddable Reference Electrodes and Chloride-Contaminated Concrete. Materials Performance, National Association of Corrosion Engineers, Vol. 18, No. 2, 1979, pp. 70-73.
12. C. Rogers and G. Woda. The Chloride Ion Content of Concrete Aggregates from Southern Ontario. Report EM-17. Ontario Ministry of Transportation and Communications, Downsview, Ontario, Canada, 1977.
13. D.G. Manning and R.P. Northwood. The Rehabilitation of Structures on an Urban Freeway: A Case Study. In Proc., Bridge Maintenance and Rehabilitation Conference, West Virginia University, Morgantown, Aug. 1980, pp. 644-668.

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