FINAL REPORT

CATHODIC PROTECTION OF CONCRETE BRIDGE DECKS USING TITANIUM-MESH ANODES

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ABSTRACT

Anodes are a critical component of cathodic protection systems. A continuous research effort in Virginia is being aimed at searching for the most suitable anode for use in cathodic protection of the various types of concrete bridge components that are exposed to intrusion by chloride ions. As part of this effort, three different catalyzed titanium mesh anodes were tested, side by side, in a cathodic protection system that was designed and constructed (in conjunction with the rehabilitation of several concrete deck spans) to prevent further reinforcement corrosion-related damage to these structures. The purpose of this study was to determine whether this type of new anode is suitable for application in bridge decks, and if any of the three mesh anodes tested in this study excels over the other.

It was observed during construction that the installation of these mesh anodes is compatible with the normal construction procedures used in the rehabilitation of bridge decks. Observations made during the first four years of operation indicated that, among all the different types of anodes tested to date for bridge decks, the three mesh anodes tested in this study were the most effective. These newly tested anodes probably have a considerably longer service life than other anodes that have been tested to date. Furthermore, there was no significant difference in the operational characteristics of the three mesh anodes tested in this study.

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INTRODUCTION

After a concrete bridge has been exposed to winter deicing salts and the subsequent intrusion of chloride ions from these salts, some areas on the surface of the reinforcing steel eventually become more corrosion-active than other areas. The active steel areas (the anodes) start to corrode by releasing electrons to the passive areas (the cathodes). As in many other corrosion problems, cathodic protection (CP) is an effective way of reducing or eliminating on-going reinforcing steel corrosion in concrete bridges. As stated by Uhlig and Revie in their widely used book *Corrosion and Corrosion Control*: "Cathodic Protection is perhaps the most important of all approaches to corrosion control. By means of an externally applied electric current, corrosion is reduced virtually to zero, and a metal surface can be maintained in a corrosive environment without deterioration for an indefinite time."[1] The feasibility of applying CP to an existing concrete bridge deck has long been demonstrated. In 1972, CP was applied on a northern California bridge deck. This bridge deck is still in good condition, which demonstrates the effectiveness of the CP method in not only stopping corrosion from occurring on the reinforcing steel, but also in preventing the likely premature deterioration of the structure.[2]

To apply impressed-current CP to a concrete structure, a supplemental anode, which is capable of sustaining oxidation reactions without suffering any significant physical damage, is introduced into or installed on the concrete. When this anode is connected to the positive terminal of a power supply (while the entire network of reinforcing steel is connected to the negative terminal), all of the steel in the structure is forced to become cathodic. As long as the power remains on, the steel remains cathodic and corrosion of the steel can only occur at a very low rate, if at all. Therefore, the essential components of an impressed-current CP system for a concrete structure are:

1. An external direct current source
2. An electrode (anode)
3. Wiring
4. Concrete-embeddable evaluation/control devices (reference electrodes, corrosion probes, etc.)

The anode is perhaps the most critical component of a CP system, because it serves to distribute the protective current across the structure and provides the locations for anodic reactions to take place in lieu of the reinforcing steel. Therefore, while the system is in service, the anode, instead of the reinforcing steel, will degrade. Consequently, for a CP system to be effective and durable, it is very important that the anode is sufficiently chemically inert and dimensionally stable for use in concrete bridge decks, which are subjected to traffic load and surface wear. The anode must also be embeddable in the concrete and compatible with the normal construction practices involved in deck rehabilitation. These practices or procedures may include milling of the old deck surface, followed by excavation of damaged concrete down to a depth slightly below the top mat of steel bars, as well as patching and placement of the overlay. An ideal anode is, therefore, one that possesses all of the above desirable attributes and can also be placed on the deck after all of the necessary concrete patching has been completed and before the overlay is placed.

Using funds from the Demonstration Project 84 of the Federal Highway Administration, Virginia constructed its first impressed-current CP system for a bridge deck in 1982.[3] To distribute the protection current across the deck, a system of 0.75-in deep slots was cut into the deck surface. A combination of platinum-niobium-copper wires and bundled carbon filaments were then placed in these slots, which were subsequently filled with a conductive polymer (vinyl-ester resin) grout. While this anode system was found to be effective in distributing the protection current across the concrete deck, it had a serious weakness. The conductive polymer grout was susceptible to slow degradation by the chlorine and acid generated at its interface with the concrete substrate.[3] This degradation eventually affected the ability of this anode system to stay in place in the slots and to function properly. Even if this degradation process did not occur, the labor-intensive nature of its installation was enough of a disadvantage that could prevent the acceptance of this anode system.

It became clear that the conductive polymer grout did not have the stability necessary to last sufficiently long enough to be a useful anode. Consequently, additional efforts were undertaken in Virginia to search for alternative anodes. One such effort was initiated before 1988 to develop a conductive Portland cement concrete that could also be used as a deck overlay.[4] The study found that a concrete with 100 times higher electrical conductivity and better mechanical properties than conventional concrete could be obtained by incorporating 6-mm (0.25-in) long, high-modulus carbon fibers into the concrete mixture. It was concluded that with some improvement in the freeze-thaw resistance of this material, it should be possible to test it as both an anode and an overlay for a concrete deck.

At approximately the same time, a new commercial anode consisting of an expanded titanium mesh catalyzed by a proprietary mixed metal-oxide coating became available. It was claimed that the presence of the metal oxide coating helps to prevent the evolution of undesirable chlorine around this anode. This coating would therefore eliminate the problem faced by the conductive polymer grout, and thus would allow this anode as well as the concrete to last a long time. The honeycomb-like pattern of this mesh anode would allow for maximized bonding to the concrete. This mesh would also provide for a uniform distribution of protective current across the structure as well as providing low circuit resistance. Another possible advantage of this mesh is that its installation appears to be compatible with the typical bridge deck rehabilitation procedures used in Virginia and many other states. With these advantages, this mesh anode seemed to hold promise as a potentially good anode for CP for concrete bridge decks. Consequently, it was decided that this new titanium mesh anode would be tried on concrete decks and monitored. This report describes this effort.

PURPOSE AND SCOPE

The purpose of this study was to observe how effectively and efficiently the titanium mesh performs as an anode and how the required installation procedures are compatible with the normal rehabilitation construction processes for bridge decks. This study was accomplished by incorporating three different catalyzed titanium mesh anodes in a CP system for two concrete bridge decks that needed rehabilitation.

This investigation did not attempt to prove the effectiveness of CP in stopping steel corrosion in existing concrete bridge decks, since this phenomenon has already been demonstrated over a long period of time by previous research.

Also, because it was expected that these mesh anodes would be extremely difficult to secure properly over vertical concrete surfaces found on concrete piers, it was envisioned that these mesh anodes would be impractical to apply on concrete piers. Therefore, no concrete piers were included in this effort.

METHODOLOGY

The methodology involved the design and installation of a CP system for two adjacent bridge decks that utilized activated titanium mesh anodes. Then, following the activation of the system, its operation was monitored regularly–in terms of the cathodic protection current flowing through the anode to each span, the rectifier driving voltage required to supply this current, and the response of the reinforcing steel in each span to the protection current.

Since there were three different competing activated titanium-mesh anodes that potential users (such as the Virginia Department of Transportation and other transportation agencies) can eventually choose from, the evaluation plans included installation of these three similar anodes separately in adjacent deck spans. The characteristics of these three anodes, Elgard 150, Lida CN25, and Tectrode S6, are provided in Table 1. At the inception of the project, it was decided that this CP system would require either a single bridge deck with a sufficient number of spans to allow installation of all three anodes in separate deck spans or in two separate decks (preferably twin decks)–with the total number of spans equal to or larger than a multiple of three.

Fortunately, there were two twin bridge decks, each with three spans, that were scheduled for repair at the time. As indicated in Table 2 and illustrated in Figure 1, it was decided that each of the three anodes would be installed on a separate span in each of these two decks, and each span would be a separate CP zone with a protection current to be provided by a separate independent circuit in a rectifier.

Table 1. Materials Specifications for the Mesh Anodes

	Elgard 150	**Lida CN25**	**Tectrode S6**
Max. Current Density in Concrete	65 mA/m^2	25 mA/m^2	34 mA/m^2
Composition--Mesh	Titanium (Gr.1)	Titanium (Gr.1)	Titanium (Gr.1)
Catalyst	Mixed metal oxide	Mixed metal oxide	Mixed metal oxide
Mesh: Diamond Dimension	76 mm x 35 mm	62 mm x 23 mm	87 mm x 39 mm
Thickness	1 mm	2 mm	1 mm
Width	1.1 m	1.2 m	n.a.
Length	81 m	50 m	n.a.
Weight	0.13 Kg/m^2	0.2 Kg/m^2	0.16 Kg/m^2
Anode Surface Area / Mesh Area	n.a.	n.a.	0.16 m^2 / m^2
Resistance (Lengthwise)	0.085 ohm/m	0.1 ohm/m	< 0.1 ohm/m

Table 2. Designation of Anodes and Test Spans

Span	**Area, m^2 (ft^2)**	**Anode / Manufacturer**
1	187 (2,016)	Lida / Dow Chemical
2	183 (1,974)	Elgard 150 / Elgard
3	156 (1,680)	Tectrode S6 / ICI
4	187 (2,016)	Lida / Dow Chemical
5	172 (1,848)	Elgard 150 / Elgard
6	156 (1,680)	Tectrode S6 / ICI

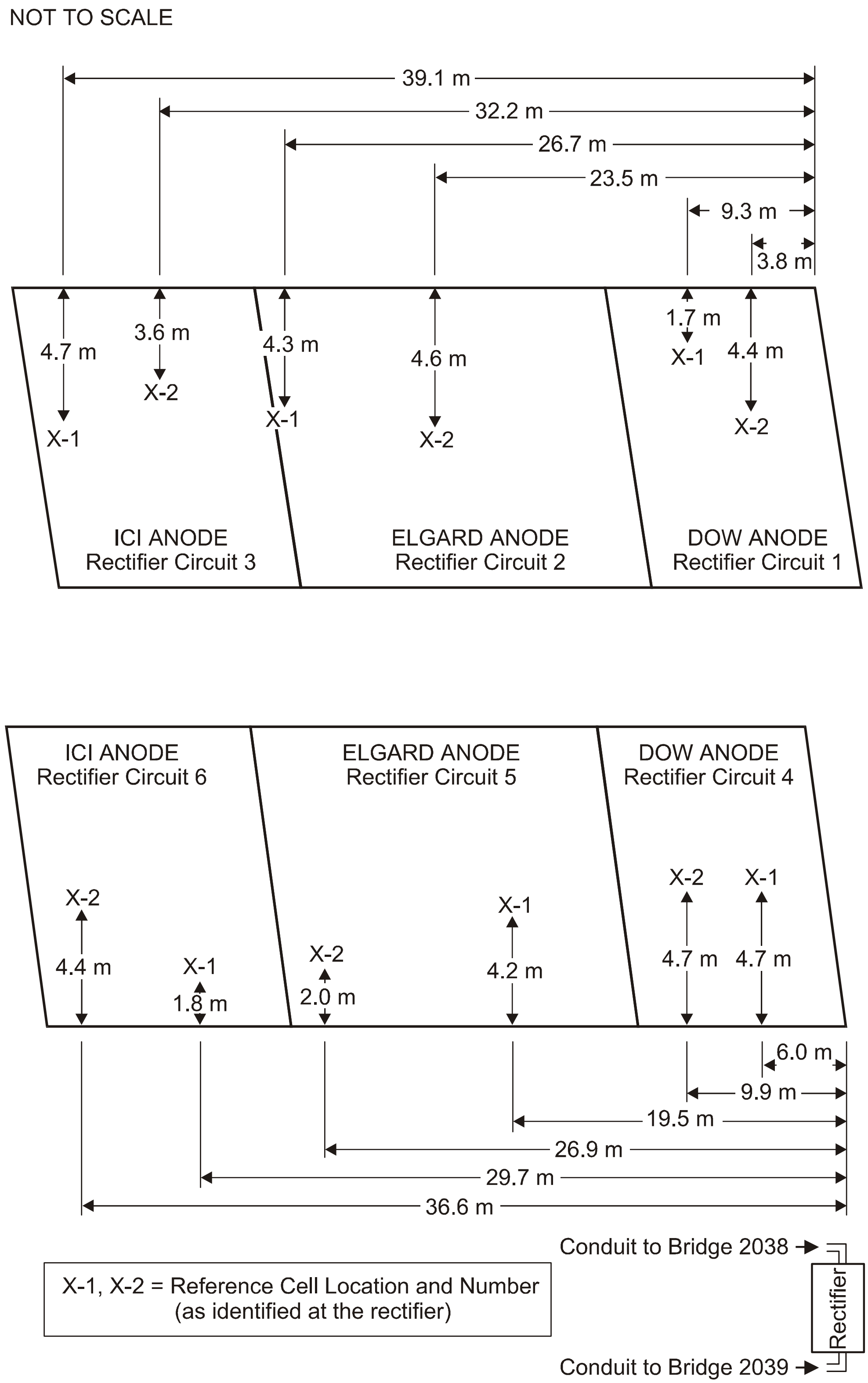

Figure 1. Layout of the CP system, utilizing three different activated titanium meshes as anode.

Construction and Start-Up of the CP System

The procedures that were required for installing the activated titanium mesh on these two decks integrated well with the typical procedures used in repairing concrete decks; therefore, no significant adjustments on the latter procedures were found to be necessary. Since the construction of the CP system is still relatively new to many potential users of CP from transportation agencies who could benefit from such knowledge, a brief description of the general procedures involved in such a construction project is worthwhile here. In general, the repair of the decks and the construction and start-up of the CP system proceeded in the following sequence:

1. **Repair of the damaged concrete in the deck**. This included milling of the top 10 mm (0.5-in) of the deck surface, removal of the damaged concrete down to a depth of at least 25 mm below the top mat of reinforcing steel, and cleaning of the rusted steel bars with sandblasting. All of these standard procedures were performed in accordance with VDOT's specifications for repairing existing concrete decks.

2. **Verification of the existence of electrical continuity in the steel-bar network in each span**. The purpose of this procedure was to ensure, as much as possible, that all of the steel in each span was electrically continuous; if a steel bar was left isolated, it would not be protected by the CP system. The most convenient time to conduct this test is typically immediately after the completion of the above procedures, when many steel bars are conveniently exposed and have already been cleaned. To test for electrical continuity between any one of the steel bars in each excavated location and any one of the designated system ground bars in each span, the DC resistance between these two steel bars was measured with a high-impedance ($\geq$ 10 MΩ) multimeter. Then, the leads were reversed and the measurements were repeated. If the two measurements were stable and differed by less than 3 ohms, the steel in that location was considered electrically continuous with the rest of the steel in that span. This procedure was repeated on the other exposed steel and designated ground bars. During this installation process, the metals tested in each span were found to be electrically continuous. After the tests, the excavations were then patched with Portland cement concrete per VDOT's specifications.

   If any steel bar was found not to be electrically continuous with the rest of the steel bars, that non-electrically continuous steel bar would then have to be electrically bonded by thermite-welding a piece of No. 10 AWG copper wire (with HMWPE insulation) to that steel bar as well as to a nearby exposed continuous steel bar. Next, the two welded spots had to be sealed and waterproofed by a nonconductive, two-part epoxy paste.

3. **Installation of reference cells in each span**. Although reference cells are not absolutely necessary as a component of a CP system, they are useful for measuring the response of the steel (immediately next to where these cells are installed) to the CP current. When reference cells are installed in bridge decks, such measurement can be conducted without the need to interrupt the traffic on the decks. Therefore, for redundancy, two graphite reference cells were installed in each span at two different locations, where the steel potentials (as measured with a portable $Cu/CuSO_4$ cell) were the most negative and the concrete had not yet been disturbed. These criteria ensured that the reference cells would be located where the ongoing steel corrosion in each span was at its worst. To install each reference cell at a designated "worst-case" location, an area of approximately 100 mm by 170 mm (4 in by 7 in) was excavated to the depth of the surrounding steel bars without exposing any of the steel bars or disturbing their surrounding concrete. Each reference cell was then placed flat at the bottom of the excavated area, with its lead wire routed through a hole drilled through the concrete and along the underside of the deck. Each reference cell was then connected to a junction panel in the rectifier. To install the corresponding negative lead wire of the reference cell, a slightly smaller area (at approximately 0.5 m [2 ft] away) was excavated to expose the steel bar. The lead wire was then bonded to the exposed bar by thermite welding, followed by waterproofing the bond with a vinyl-ester resin sealant and routing the rest of the wire through the deck and onto the rectifier junction panel. Then, both areas were patched with Portland cement concrete.

4. **Following the completion of all necessary patching, areas with shallow steel bars were identified and electrically insulated. A survey of each span was conducted in order to locate areas with shallow steel bars for applying the insulation**. Using a covermeter, the spans were scanned to locate areas where the steel bars had a concrete cover of less than 10 mm (0.5 in). When these areas were detected, they then had to be covered with an electrically insulating vinyl-ester resin to prevent the occurrence of a "near short-circuit" between the steel and the anode. This short-circuiting problem had the potential to interfere with the uniform distribution of the protection current across a span. The survey indicated that the concrete covers in several areas were inadequate; as a result, these areas were insulated with the vinyl-ester resin.

5. **Installation of a predesignated, activated titanium mesh in each span**. In general, the installation was started from one corner of each span, where the end of a roll of 1.2-m (4-ft) wide mesh was secured to the concrete surface with plastic fasteners (Figure 2). This was followed by unrolling the rest of the mesh longitudinally over the remaining area of the span. While applying a slight tension to the mesh, the mesh was then pressed against the deck and fastened onto the deck with plastic fasteners at approximately every 3 m (10 ft) and at the end of the span. Then, additional plastic fasteners were used to ensure that the mesh was secured flat to the concrete, especially at the edges, and without any warping of the mesh. The placement of the mesh was repeated transversely across each span until the entire width of the span was covered with the mesh.

Figure 2. Securing an activated titanium mesh on the concrete decks with plastic fasteners.

Because the mesh came in rolls and has a tendency to rolled up again, it was often difficult to keep the mesh completely flat during placement. Another problem encountered was that the secured mesh could be accidentally pulled from the deck when construction workers walked over the mesh. This problem was alleviated by laying sheets of plywood end-to-end along the length of the deck for walkways and instructing the workers that, if it was necessary to walk directly over a section of newly installed mesh, to do so carefully.

6. **Bonding of all sections of the mesh**. This was accomplished by resistance-welding several strips of 12–mm (0.5-in) wide titanium ribbons transversely over the mesh (Figure 3). These titanium ribbons would function as distributors of current to the mesh. For redundancy, additional titanium ribbons were welded to the mesh at every 5 m (15 ft) along the length of each span, as shown in Figure 4. The titanium ribbons were then bonded to insulated titanium connectors, which, in turn, were bonded to lead wires. Next, these lead wires were routed through access holes drilled through the deck to the underside of the deck and then to a positive output terminal in the rectifier. The output terminals were designated for each span. The portion of each lead wire that traversed through the deck was then insulated with a heat-shrunk tubing to prevent possible electrical contact with the reinforcing steel.

Figure 3. Electrical bonding of all anode mesh by resistance welding to several strips of titanium ribbons, which were subsequently connected through lead wires to the positive terminal of the rectifier.

Figure 4. For redundancy, additional titanium ribbons were welded transversely across the deck to all sections of mesh. Notice that the mesh sections were hardly distinguishable from the concrete deck surface underneath.

7. **Placement of the concrete overlay**. To allow concrete delivery trucks to reach the span that was being overlaid and not accidentally pull up the mesh with their tires, full-width plywood boards were laid, end-to-end, on the deck for the trucks to slowly drive over. Figure 5 shows the placement of the titanium mesh overlay. To further ensure that there would not be any short-circuits between the mesh anodes and the reinforcing steel, the anodes and reinforcing steel (in each span being overlaid) were connected to a portable battery charger. Then, as placement of the overlay progressed, the system was carefully monitored for any abrupt increase in current and drop in voltage between each anode and the steel. These increases in current were indications of a direct contact between these two components. At any sign of these contacts, the overlaid placement needed to be stopped so that the contact point could be pinpointed and insulated before the overlay placement could resume.

Figure 5. Placement of a latex-modified concrete overlay over the deck, after the installation of the titanium mesh anode.

8. **Completion of the system's electrical wiring**. All of the lead wires–for the anode, the reinforcing steel (the system ground), the reference cells, and the ground for the cells–were carefully labeled and inspected. Then, these wires were routed through a system of PVC conduits and junction boxes to the rectifier/controller unit. All critical electrical connections between the wires and the rectifier terminals were tested to ensure that these connections were properly made.

To allow each of the six spans to be powered independently, the rectifier was specified to have six independent circuits, each rated at a maximum DC output of 24 volts and 12 amps. It was expected that this current output capacity would be more than sufficient to cathodically polarize the steel in these six spans, since the required initial current density is, at a maximum, approximately 15 mA/m^2, and the largest of the 6 spans was 187 m^2 (Table 2). The rectifier (MP-89151) used, which was of a switch-mode design, required an AC input of 115 volts, 60 Hz, single phase.

9. **Start-up of the CP system**. Before the system was activated, the electrical resistance in each span between the anode and the steel and between the embedded reference cells and their grounds were measured to ascertain that all components were in proper order. As Table 3 shows, the resistances between the anode and the reinforcing steel network in the spans ranged from 0.28 to 0.45 ohm. These resistances were lower than those resistances observed in the previously reported slotted conductive grout system,[2] which ranged from 1.8 to 2.7 ohms. These mesh anode resistances indicated that, as expected, the activated titanium meshes were providing better contact with the concrete and, therefore, were resulting in lower, smaller circuit resistances. The observed resistances between the embedded reference cells and their grounds in this installation ranged from 130 to 380 ohms (Table 3). These resistances were well below the acceptable maximum of 10,000 ohms suggested in a recent guide.[5]

Table 3. Electrical Resistance Between Components

Span	Rectifier Circuit	Anode Wires No.	Resistance (ohm)		
			Anode-to-Steel	Ref. Cell 1-to-Cell Ground	Ref. Cell 2-to-Cell Ground
1	1	1,2,3	0.32	170	190
2	2	4	0.28	190	380
3	3	5,6	0.36	260	130
4	4	4,5,6	0.28	160	150
5	5	3	0.33	190	170
6	6	1,2	0.45	150	170

Following these initial checkups, the rectifier was switched on and each circuit was adjusted to provide, as close as possible, a constant current output of approximately 15 mA/m^2 to each span.

RESULTS AND DISCUSSION

Initial Settings for the CP System

Table 4 shows the actual initial operational settings on the rectifier and the responses of the embedded reference cells (as measured with a portable high-impedance multimeter instead of a built-in meter in the rectifier). It was possible to estimate the effective resistivity of each CP zone or bridge span from the driving voltage that was required for the initial current setting for each circuit. This resistivity can be viewed as an indicator of the efficiency of a specific mesh anode's ability to distribute the protection current. As indicated in Table 4, the estimated effective resistivities differed between spans and varied from 0.119 to 0.162 ohm-m^2. Grouping these resistivities by the makers of the anode, the mean resistivity was 0.140 ohm-m^2 for the Lida mesh, 0.130 ohm-m^2 for the Elgard mesh, and 0.137 ohm-m^2 for the Tectrode mesh. The differences in resistivities between the three meshes were small, and it is doubtful that these differences are significant. However, the differences in the resulting effective resistivities appeared to mirror the differences in the dimensions of the diamond patterns in these meshes (see Table 1), especially if one ignores the resistivity in span 1. It is worthwhile to note that the power requirements for each of the six circuits varied from 5.0 to 7.8 watts only. The total power requirement of these circuits was 37.7 watts, which is approximately the same wattage of a small light bulb.

In response to these initial levels of protection currents, the embedded graphite reference cells indicated that the steel bars were polarized from a range of -702 to -420 mV.

Table 4. Initial Operational Data

Span / Circuit	Anode	Current		Voltage (V)	Wattage (W)	Resistivity (ohm-m^2)	Potential (mV)	
		(A)	(mA/m^2)				RC-1	RC-2
1	Lida	3.0	16.0	2.6	7.8	0.162	-674	-669
2	Elgard	3.0	16.4	2.0	6.0	0.122	-431	-420
3	Tetrode	2.5	16.0	2.0	5.0	0.125	-452	-444
4	Lida	3.0	16.0	1.9	5.7	0.119	-517	-522
5	Elgard	3.0	17.5	2.4	7.2	0.137	-702	-648
6	Tetrode	2.5	16.0	2.4	6.0	0.150	-556	-580

Operation of the System

After approximately four months of operation, a depolarization test was performed on all circuits to determine if the reinforcing steel in all six spans was getting adequate protection. According to a 1990 National Association of Corrosion Engineers criterion, which is now widely used, if the reinforcing steel depolarizes by at least 100 mV (after adjustment for the IR drop), the steel is considered to be adequately protected.[6] This test is conducted by turning off the current flowing into each circuit and monitoring the change in the potential of the steel–typically for four hours. As shown in Table 5, the reference cells in all of the spans exhibited depolarization of more than 100 mV. The mean depolarizations ranged from 171 to 454 mV, with circuits 2 and 3 exhibiting the least depolarizations. This indicated that the steel in all spans was most likely to be adequately protected; however, perhaps for extra assurance, the current levels for circuits 2 and 3 could have been increased slightly, while the levels for the rest of the circuits could have been decreased.

While the circuits were still turned off, the resistances between each anode and the steel and between the reference cells and their grounds were measured again (Table 5). Comparing the latest observed resistances between the anode and the steel and the resistances observed before the startup of the system (Table 3), this latest resistance had increased for all spans except span 4. The increases were 3%, 4%, 9%, 11%, and 14% for spans 1, 6, 5, 2, and 3, respectively. This raised a question regarding whether there is any relationship between the comparatively high increases in this resistance for spans 2 and 3 and the relatively low depolarizations for these same spans. Further, the potentials for the steel in these spans were the most positive at the startup (Table 4).

Regarding the resistance between each embedded reference cell and its ground, Table 5 shows that after 4 months, this resistance increased by an average of approximately 22%, except for reference cell 2 of span 2.

Table 5. Depolarization and Resistances Observed 4 Months After Startup

Span / Circuit	4-hr Depolarization (mV)*			Resistance (ohm)			
	RC-1	RC-2	Mean	Anode/Steel	RC-1 /Ground	RC-2 /Ground	Mean
1	464	445	454	0.33	120	150	135
2	199	146	172	0.31	150	430	290
3	154	189	171	0.41	240	92	166
4	398	365	381	0.28	120	110	115
5	376	400	388	0.36	145	130	137
6	424	482	453	0.47	110	130	120

Following these measurements, the current flowing into spans 2 and 3 were adjusted upward, while the current for the remaining spans were decreased. Table 6 shows the adjusted settings and the corresponding potential of the steel.

Table 6. Second Settings on the Rectifier

Span / Circuit	Current		Voltage (V)	Potential (mV)	
	(A)	(A/m^2)		RC-1	RC-2
1	1.5	8.0	1.3	-423	-412
2	3.2	17.4	2.0	-345	-389
3	2.9	18.6	2.2	-364	-412
4	1.5	8.0	1.2	-312	-309
5	1.5	8.7	1.4	-324	-345
6	1.1	6.4	1.4	-299	-370

After these adjustments were made, the system was monitored regularly. Figures 6 to 14 illustrate the manner in which the current flowing into each span, the corresponding driving voltage, and the estimated circuit resistance for each span varied with time. Since each of the three mesh anodes was installed on two spans, each figure was arranged to show how a certain electrical parameter for one of the anodes behaved over a period of time in the two different spans. This process of monitoring the system allowed for some determination of whether the behavior of an anode would differ from span to span. As Figures 6, 9, and 12 show, the rectifier maintained reasonably constant the protection current that flowed into each span at the level set for that span. The exception was an unexplained spike in the current for span 3 between 1,220 and 1,235 days. Overall, the least fluctuation in current was observed in span 2, with a standard deviation of 0.8%. The highest fluctuation was in span 1, with a standard deviation of 7.0%. This relatively high fluctuation in span 1 should be disregarded, because the current level to that span was relatively low.

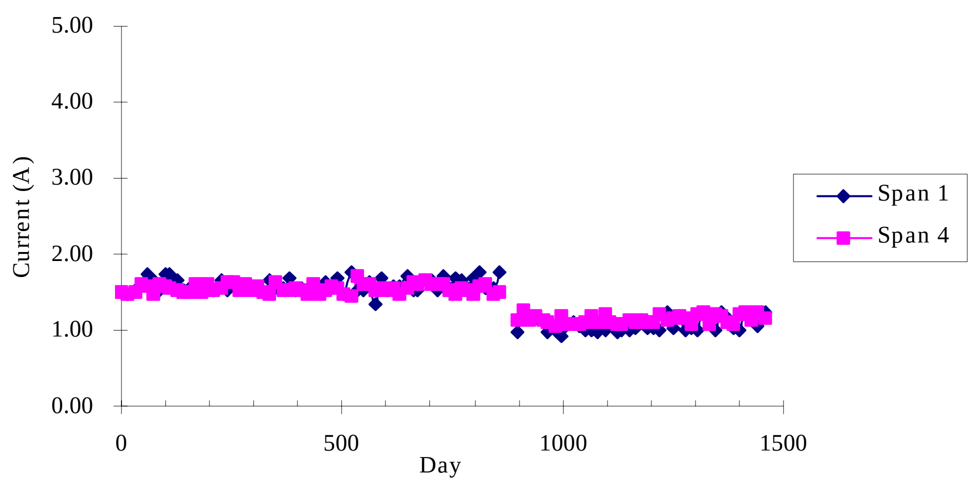

Figure 6. Cathodic protection current flowing into spans 1 and 4.

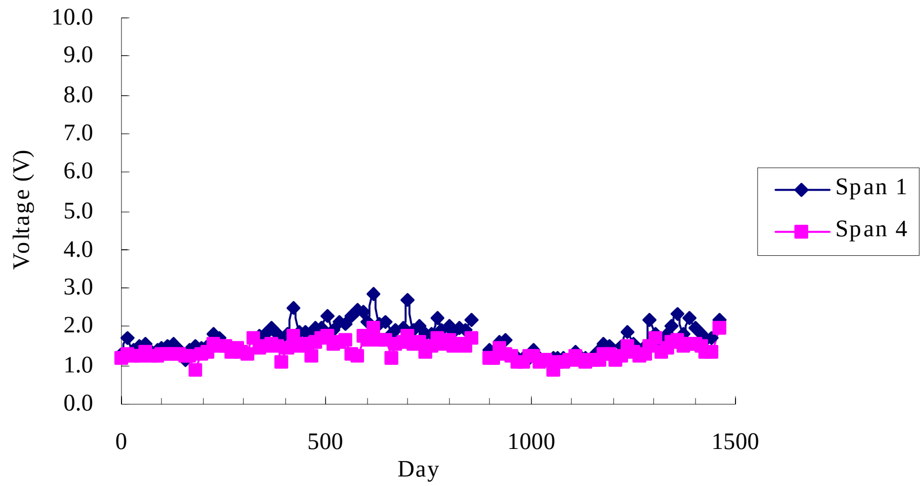

Figure 7. Voltage necessary to supply the current to spans 1 and 4.

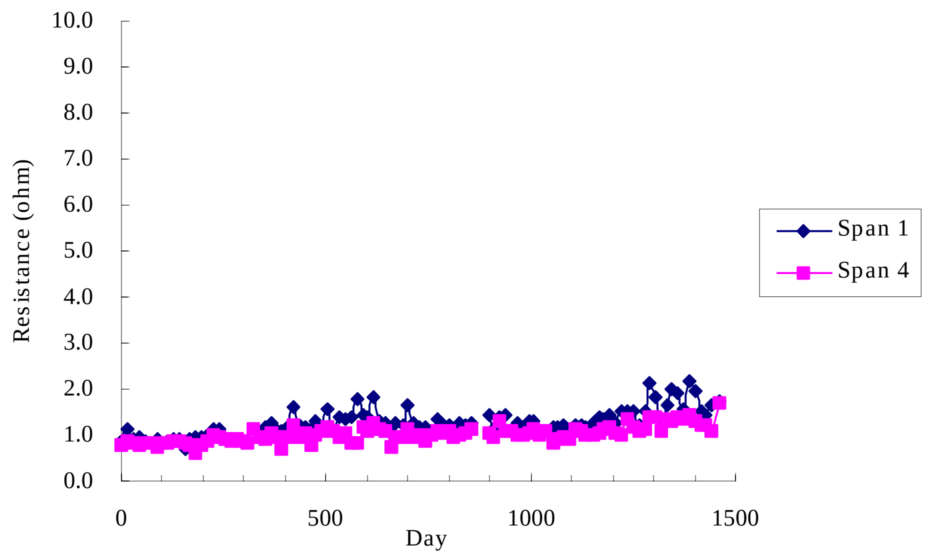

Figure 8. Effective circuit resistance in spans 1 and 4.

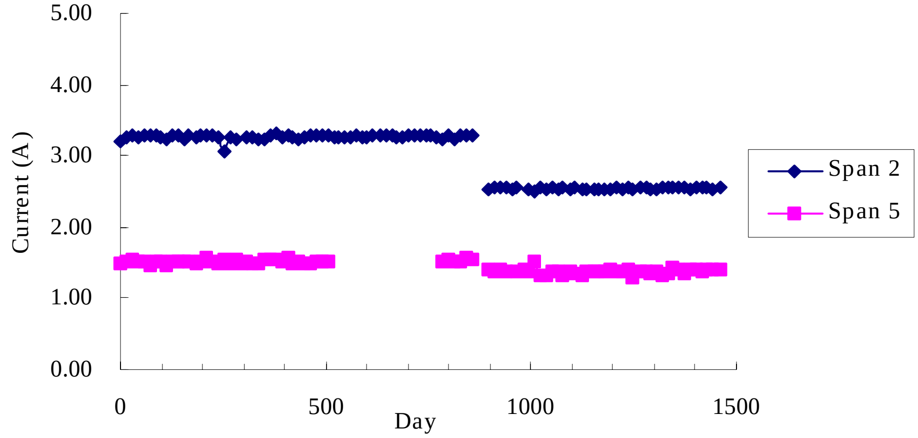

Figure 9. Cathodic protection current flowing into spans 2 and 5.

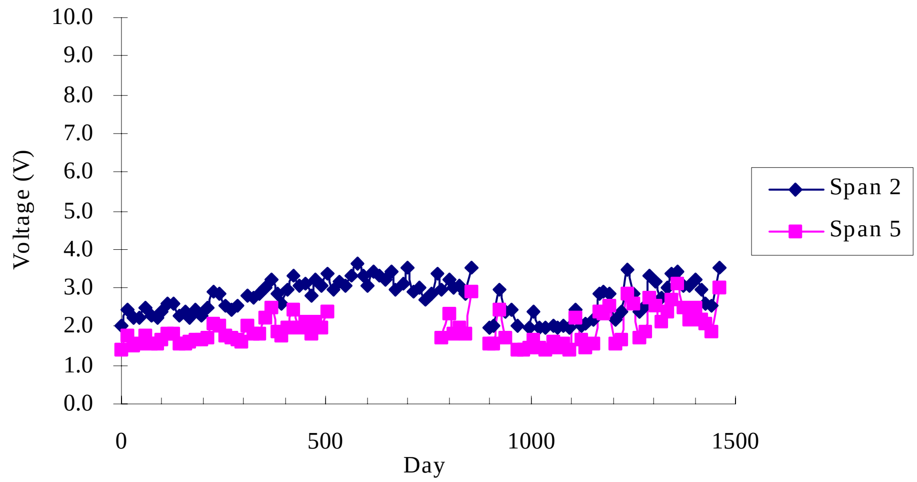

Figure 10. Voltage necessary to supply current to spans 2 and 5.

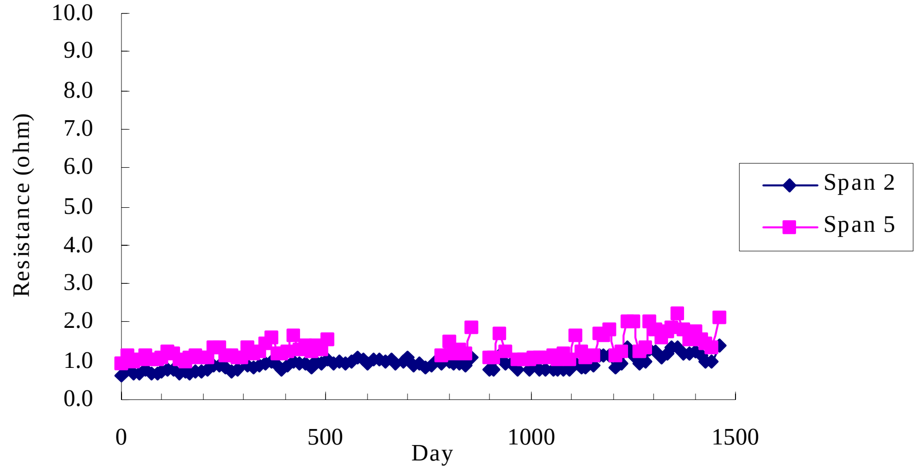

Figure 11. Effective circuit resistance in spans 2 and 5.

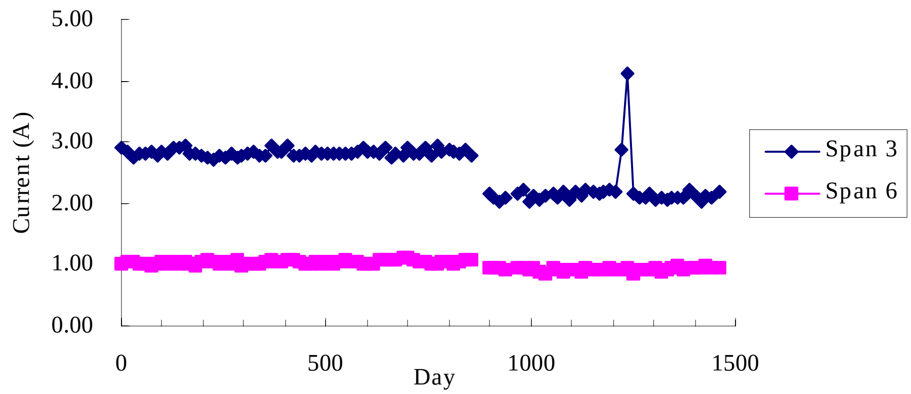

Figure 12. Cathodic protection current flowing into spans 3 and 6.

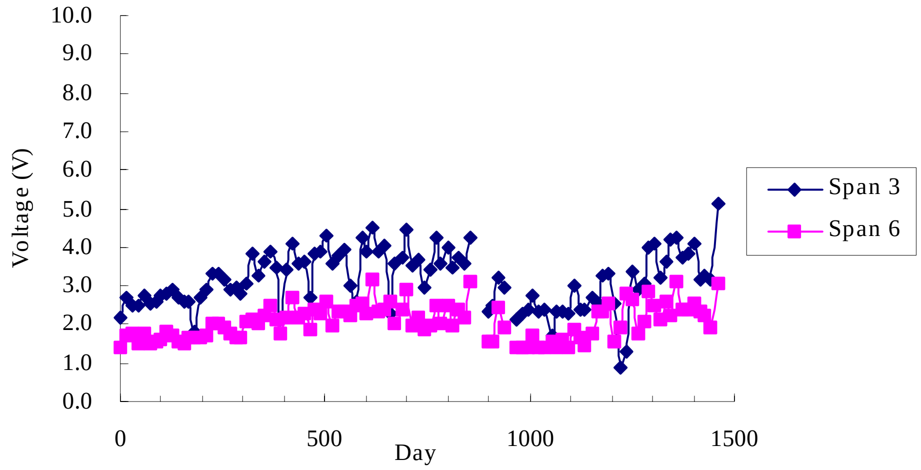

Figure 13. Voltage necessary to supply current to spans 3 and 6.

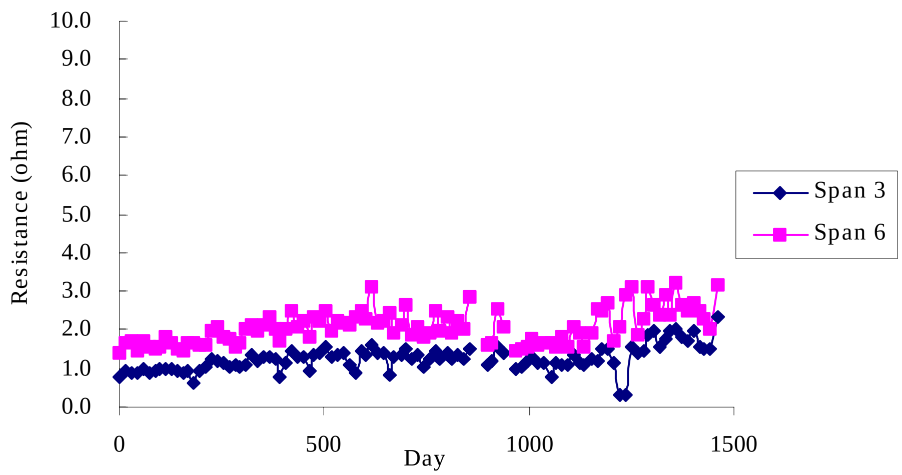

Figure 14. Effective circuit resistance in spans 3 and 6.

Notice in Figures 6, 9, and 12 that on day 897 the levels of current in all spans decreased further to various extents. This followed another set of depolarization tests conducted shortly before this decrease, which indicated that the steel in all of the spans was still receiving more than sufficient polarization, as indicated in Table 7. These new current settings averaged 1.5 A, or approximately 8.7 mA/m^2 (0.81 mA/ft^2), which is slightly above 50% of the settings at the start-up of the CP system.

Figure 7 shows how the driving voltages for the two circuits that supplied the current to spans 1 and 4 behaved during that period. (Both of these spans used the Lida mesh anode.) The manner in which the voltages for the two spans fluctuated was similar. The fluctuations were normal responses to the day-to-day change in resistance of the concrete and the relatively slow long-term change in the overall resistance of the system in these spans. It can be concluded, therefore, that the driving voltage behavior of this Lida mesh anode, as a function of age, was similar from one span to another. It is clear that the same conclusion regarding voltage behavior is also valid for the other two mesh anodes (Elgard and Tectrode), when the same voltage-versus-time plots for the spans with these two anodes are examined (Figures 10 and 13).

Table 7. Third Current Settings

Span / Circuit	Depolarization (mV)	Current (A)	Current Density (mA/m^2)	Change (%)
1	397	1.0	5.3	-33
2	250	2.5	13.6	-22
3	444	2.1	13.5	-28
4	345	1.1	5.9	-27
5	286	1.4	8.1	-7
6	360	1.1	6.4	-9

In comparison to the driving voltage behaviors of the two circuits indicated in Figure 7, the trends shown in Figures 10 and 13 may be an indication that these two anodes, especially Tectrode, may have degraded slightly faster than the first anode (Lida). This small difference in degradation becomes more apparent when the circuit resistance for all of the spans, as illustrated in Figures 8, 11, and 14, are examined. A trend analysis would indicate that the circuit resistance increased by 0.12 ohm/year for the Lida anode, 0.14 ohm/year for the Elgard anode, and 0.24 ohm/year for the Tectrode anode. However, these rates of resistance increases were still 5 to 6 times lower than those increases observed on conductive paint anodes tested on some concrete piers in Virginia, which were projected to have a service life of approximately 12 to 15 years.[6] In comparison, then, these titanium-mesh anodes should last from 60 to 90 years.

On approximately day 1,240, another set of depolarization tests was conducted to ascertain that the current flowing into the spans was still providing adequate polarization to the reinforcing steel. As the results of these tests show in Table 8, the observed depolarization of the steel was considerably more than the suggested minimum of 100 mV. This meant that even at the low current densities of 5.3 to 13.6 mA/m^2, the 6 spans were being more than adequately protected and that the current levels could be reduced slightly further. More importantly, these data indicate that the longer a reinforced concrete span has been under cathodic polarization, the smaller the amount of current is necessary to maintain protection of the steel in that span.

Visual inspection of the concrete decks after almost four years of operation revealed no signs of any adverse effects of the use of the mesh anodes on the concrete. However, during this comparative assessment of the three mesh anodes, an unrelated and unexpected problem was encountered that was not related to the anodes. As Figures 6, 9, and 19 show, there were various periods during which either some or all of the circuits were out of order. In almost all cases, the cause was extensive damages to electronic circuit boards in the rectifier, requiring replacement of those circuit boards. The nature of these damages pointed toward light surges at the DC ends of the rectifier as the cause. It was suspected that this, in turn, arose from lightning strikes on the metal railings above the deck parapets. As stated earlier, this problem was not expected, since such railing features are normally required by VDOT standard specifications to be grounded during construction. An examination of the current VDOT specifications indicated that there is room for improvement in grounding measures, since these specifications do not specify any limit on the maximum allowable resistance between such appurtenances and the ground.[7] This particular experience pointed to the need to include such a provision when designing CP systems for bridge decks with these features. In addition, the construction procedures should include making sure that this type of elevated metal appurtenance, if present, needs to be properly isolated from the reinforcing steel network.

The lack of adequate durability of the rectifiers used in this investigation was unexpected. Through years of experimentation with various anodes, problems with rectifiers were common.[3,7] The reason for this unexpected problem perhaps could have been the tendency to use too sophisticated and invariably problem-prone rectifiers, instead of using more basic and durable rectifiers. In the design of future CP systems, this pitfall should be avoided.

Table 8. Depolarization Tests on Day 1,240

Span/ Circuit	Potential (mV)			Depolarization (mV)
	Circuit On	Instant-Off	After 4 Hours	
1	-402	-344	-54	290
2	-534	-483	-196	287
3	-576	-462	-130	332
4	-427	-387	-154	233
5	-507	-412	-194	218
6	-390	-338	-88	250

CONCLUSIONS

1. Although some caution needs to be observed in their installation, *mesh anodes are compatible with the normal construction procedures used in the rehabilitation of concrete bridge decks suffering from steel corrosion-related concrete damages.*

2. *The three meshes tested appeared to be effective and efficient anodes for use in CP of concrete bridge decks and are also most likely to have a long service life (from 60 to 90 years).*

3. *There were no significant differences in the operational characteristics of the three different mesh anodes tested, although one of these anodes may have a slightly shorter service life than the others*. Nevertheless, all three of these mesh anodes should provide service for a significantly longer life than other types of anodes that are in use at this time for concrete bridge decks.

RECOMMENDATIONS

1. *VDOT should incorporate titanium-mesh anodes in the designs for catholic protection systems for concrete bridge decks*.

2. *To facilitate implementation, special provisions that incorporate the important characteristics of titanium-mesh anodes should be prepared*.

3. In designing CP systems for concrete bridge decks, *design provisions for sufficient grounding and isolation of metal appurtenances that are elevated higher than the decks, if such appurtenances are present, should be developed*.

4. *Regulated rectifiers that are more rugged and reliable than the ones currently in use should be installed in future CP systems*.

5. The use of solar panels as an alternative source of DC protection current should be investigated.

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