

INTERIM REPORT

**PILOT APPLICATIONS  
OF ELECTROCHEMICAL  
CHLORIDE EXTRACTION  
ON CONCRETE BRIDGE DECKS  
IN VIRGINIA**

GERARDO G. CLEMEÑA, Ph.D.  
Principal Research Scientist

DONALD R. JACKSON  
Senior Program Manager  
Office of Technology Applications  
Federal Highway Administration



**Interim Report**

**PILOT APPLICATIONS OF ELECTROCHEMICAL CHLORIDE EXTRACTION  
ON CONCRETE BRIDGE DECKS IN VIRGINIA**

**Gerardo G. Clemeña, Ph.D.  
Principal Research Scientist  
Virginia Transportation Research Council**

**Donald R. Jackson  
Senior Program Manager  
Office of Technology Applications  
Federal Highway Administration**

**(The opinions, findings, and conclusions expressed in this  
report are those of the authors and not necessarily  
those of the sponsoring agencies.)**

**Virginia Transportation Research Council  
(A Cooperative Organization Sponsored Jointly by the  
Virginia Department of Transportation and  
the University of Virginia)**

**In Cooperation with the U.S. Department of Transportation  
Federal Highway Administration**

**Charlottesville, Virginia  
May 1996**

**VTRC 96-IR3**

**Copyright 1996, Commonwealth of Virginia**

## ABSTRACT

A recent SHRP study confirmed that applying an electrical field between the surface of a concrete structure and the rebars (like cathodic protection, except with 50 to 500 times more current) can expel the chloride ions from salt-contaminated reinforced concrete and mitigate rebar corrosion. This new rehabilitation method was tried on two whole deck spans, as part of pilot trials in Virginia to demonstrate the practicality of this electrochemical chloride extraction (ECE) process on full-sized bridge elements and to help refine the technique.

The total concrete area treated was approximately 720 m<sup>2</sup> (7,750 ft<sup>2</sup>). To avoid traffic interruption, half of the deck was treated at a time (for 8 weeks, though a shorter time would likely suffice). The treatment used a very simple installation and procedure, involving placement of a temporary electrolyte-soaked anode system (of inert catalyzed titanium mesh sandwiched between two layers of felt) on the surface of the deck, and the application of total charges that varied between 741 to 1,077 A-hr/m<sup>2</sup> (68.8 to 100.1 A-hr/ft<sup>2</sup>) in 57 to 58 days between the anode and the rebars. Approximately 72.2 to 82.1% of the initial chloride ions were removed from the concrete in various depths. These magnitudes surpassed the removal rate of 40 to 50% that was suggested for very heavy treatment by one SHRP report. A minor rectifiable difficulty was encountered in neutralizing the acidity generated in the electrolyte, especially during the first several days of each treatment phase. Lithium was used in the electrolyte for two portions of the deck and was observed to migrate readily into the concrete. However, a similar attempt to simultaneously inject a cationic corrosion inhibitor (tetraphenylphosphonium) into the concrete, which represented a first attempt ever on a concrete deck, yielded uncertain results. It is uncertain whether the corrosion inhibitor had migrated into the concrete; if it had, it was in quantities less than the minimum detection level of 25 ppm, by the capillary electrophoresis method used. Overall, the pilot treatment of the deck was judged to be very simple to perform and more than reasonably successful.

## **Interim Report**

# **PILOT APPLICATIONS OF ELECTROCHEMICAL CHLORIDE EXTRACTION ON CONCRETE BRIDGE DECKS IN VIRGINIA**

Gerardo G. Clemeña, Ph.D.  
Principal Research Scientist  
Virginia Transportation Research Council

Donald R. Jackson  
Senior Program Manager  
Office of Technology Application  
Federal Highway Administration

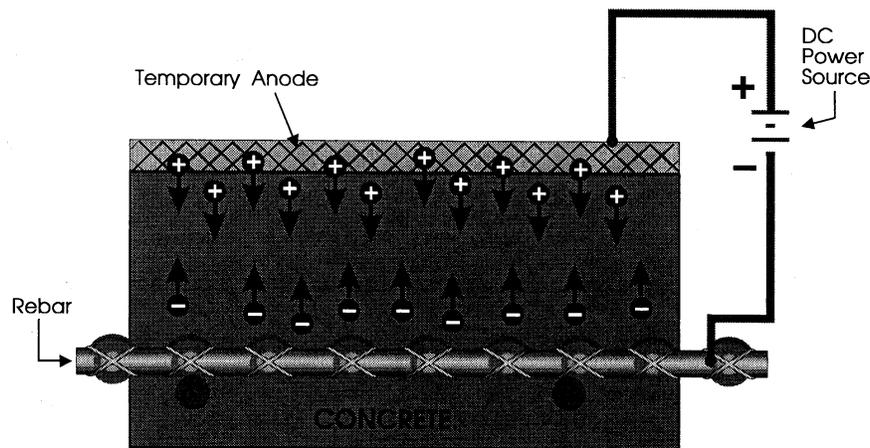
## **INTRODUCTION**

Once chloride ions from deicing salts intrude into a concrete structure, it is only a matter of time before rebar corrosion damages the concrete. Because corrosion is electrochemical, effective permanent rehabilitation of a salt-contaminated concrete structure requires the repair of all damaged concrete and then application of an electrochemical measure such as cathodic protection. Otherwise, all the concrete contaminated with sufficient chloride to initiate rebar corrosion, whether it is already damaged or still structurally sound, should be excavated and replaced. This latter option is wasteful and can often be expensive -- especially with concrete piers, where load-bearing concrete is often involved.

Cathodic protection, which stops corrosion by cathodic polarization of the rebars, is a truly effective way to permanently halt rebar corrosion in salt-contaminated structures and prevent untimely and costly bridge replacements. However, in practice, the effectiveness of a cathodic protection system on a bridge lasts only as long as the system is inspected and maintained regularly. This type of electrical maintenance, which is relatively new to bridge engineers, is often very simple and inexpensive. However, bridge engineers are already preoccupied by more traditional types of maintenance, and this may have dampened some of the

interest in cathodic protection -- especially with many transportation agencies downsizing their work forces.

The electrochemical removal of chloride from intact, contaminated concrete by electrochemical means, without excavating any concrete, has been studied since the mid-1970's. The Kansas Department of Transportation used a sacrificial copper anode to show that chloride ions can be expelled from concrete by passing a direct current between the rebars and the anode, as in cathodic protection except at considerably higher level of current.<sup>1,2</sup> In another study, Battelle Columbus Laboratories treated a total of 200 ft<sup>2</sup> of concrete on a bridge deck in Ohio with an average current density roughly between 23-28 A/m<sup>2</sup> (2.3-2.8 A/ft<sup>2</sup>), under a constant voltage of 100 V, for 12-24 hours, confirming the feasibility of electrochemical removal of chloride from concrete.<sup>3</sup> When a direct current is conducted through concrete, the relatively mobile ions (such as Cl<sup>-</sup>, OH<sup>-</sup>, Na<sup>+</sup>, K<sup>+</sup>, and Ca<sup>+</sup>) in the concrete would migrate, with each ion moving toward the electrode with the opposite charge (Figure 1). The same electromigration of ions occurs in cathodically protected concrete structures and is manifested noticeably during the first several months of operation of a new cathodic protection system by an increase in its circuit resistance.



*Figure 1. Electromigration of cations and anions when an electrical field is applied between the rebars and a temporary anode on the surface of the concrete.*

However, the unnecessarily high levels of direct current used in these early studies had some adverse effects, like increasing concrete permeability, decreasing the concrete-to-steel bond, and cracking in the concrete. The adverse effects delayed the use of electrochemical chloride extraction (ECE) as a remedial method for the permanent rehabilitation of concrete bridges for several years. Consequently, it is still common for bridge engineers to require the excavation and replacement of all salt-contaminated concrete (as located by high chloride content and/or half-cell potentials less than -350 mV), regardless of its structural soundness, during permanent rehabilitation.

To address those concerns, laboratory slabs were studied and ECE field trials were conducted on portions of some bridge elements as part of the recent Strategic Highway Research Program.<sup>4,5,6</sup> These studies concluded that, if the level of applied current is kept below 5A/m<sup>2</sup> (0.5A/ft<sup>2</sup>), ECE treatment is unlikely to have any adverse effect on the concrete. The ECE treatments removed 20 to 50% of the chloride ions from the concrete and redistributed the remaining chloride well away from the rebars. The investigators also claimed that, as expected from the known chemical reaction of water molecules at a cathode, the treatment increased the concentration of hydroxide ions [OH<sup>-</sup>] at the steel surface. This also helps arrest rebar corrosion in the concrete, which is dependent more on the ratio of the concentration of chloride to the concentration of hydroxide, [Cl<sup>-</sup>]/[OH<sup>-</sup>], than on chloride concentration [Cl<sup>-</sup>] alone.

An independent study in Canada treated portions of a concrete pier column and confirmed the removal of some of the chloride in the concrete and the passivation of the rebars.<sup>7</sup>

The remaining uncertainty about ECE is the length of the protection period that the treatment provides a concrete structure. This can only be determined by long-term monitoring of the concrete treated in these studies. The latest half-cell potential and corrosion rate data from the Canadian experiment, which was conducted six years ago, indicated that the rebars under the treated sections are still passive.<sup>8</sup> Unpublished results from followup investigation of the concrete slabs and portions of different structures treated in the SHRP studies show the same long-term passivation of the rebars.

These latest studies showed that ECE requires considerably less electrical current than the earlier studies used, avoiding any adverse effect on the concrete. The elimination of the side-

effects has rekindled interest in the method, which has a very important advantage over cathodic protection in that there are no electrical components or anode materials to be maintained after the treatment is completed. Since these studies involved only concrete specimens and very small sections of several bridges, the next step was to demonstrate the practicality of the treatment on full-sized concrete bridge elements, and further refining the technique. Pilot ECE treatments were therefore conducted on some full-sized concrete bridge decks and piers in Virginia.

Also, a new concept, the electrochemical injection of synergistic corrosion inhibitor into concrete decks simultaneously with ECE treatment, was attempted. Developed recently by SRI International of Menlo Park, California, this process involved the injection of positively-charged corrosion inhibitive ions into concrete during the electrochemical removal of the negatively-charged chloride ions. Because the process potentially offers long-term synergistic benefits that ECE alone cannot offer, it was investigated with concrete slabs in a separate SHRP study,<sup>9</sup> which demonstrated beyond doubt that corrosion inhibiting cations such as quaternary phosphoniums and ammoniums can be electrochemically injected into concrete, at different rates.

These efforts will help bring these new technologies to Virginia and other parts of the U.S. where the costly problem of rebar corrosion exists. This report describes the treatment of a bridge deck in Virginia. A similar treatment of concrete piers is described in a companion report.<sup>10</sup>

## **ECE TREATMENT OF A CONCRETE BRIDGE DECK**

### **Installation**

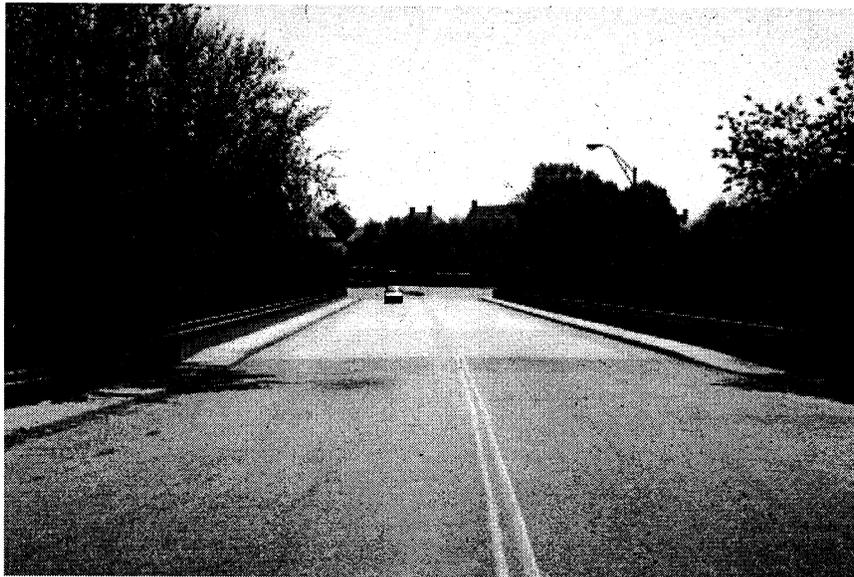
The bridge deck, approximately 28 years old, is on the 34th Street bridge over Interstate Route 395 in Arlington, Virginia (Figure 2). The reinforced concrete deck is 109 m (362 ft) long and 17 m (58 ft) wide, with a curb-to-curb width of 14 m (48 ft). The deck consists of five simple spans, supported by steel beams. Recent inspection of the deck spans indicated that 2 to 29% of the concrete in each span was delaminated due to rebar corrosion.<sup>11</sup> Although wide enough for four traffic lanes, the bridge carries only two lanes of traffic (eastbound and westbound). Traffic was maintained on half of the deck while the rest was subjected to conventional delamination repair and ECE treatment. Because available funds were limited and

some full-sized concrete piers were to be included in these pilot trials, only two spans were treated. The other three spans were used as controls for long-term monitoring. Spans 4 and 5 were selected for treatment, since they had the least concrete delamination (2 to 5%), compared to 7 to 29% on the other spans. To maintain traffic flow, the treatment was conducted first on the north portions of the spans, and then on the south portions.

ECE treatment is similar in many ways to cathodic protection. One major difference is the use of a temporary anode as a key component of ECE treatment. The simplest anode system or design, similar in many respects to one used in a trial on a small section of a bridge deck in Ohio in the SHRP study,<sup>5</sup> was installed on each span by Vector Construction Limited of Winnipeg, Canada, sequentially as follows:

#### *Preparing the Concrete Surface*

1. Removal and patching of any damaged concrete in the deck.
2. Application of cement grout to cover all cracks on the surface of the concrete, to avoid electrical shorts. *Failure to do this may jeopardize treatment of all or part of an area.*



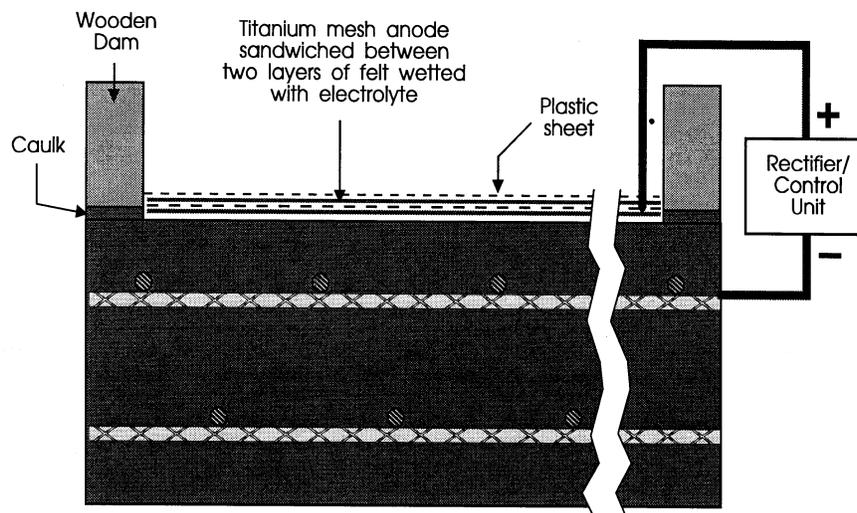
*Figure 2. The 34th Street Bridge in Arlington, Virginia.*

3. Testing to ensure electrical continuity between rebars in the span, followed by establishing four ground connections to the rebars on each span. The connections were located near the centerline so the same connections could be used during the treatment of the other half of the span.

### *Installing an Anode System Over the Concrete*

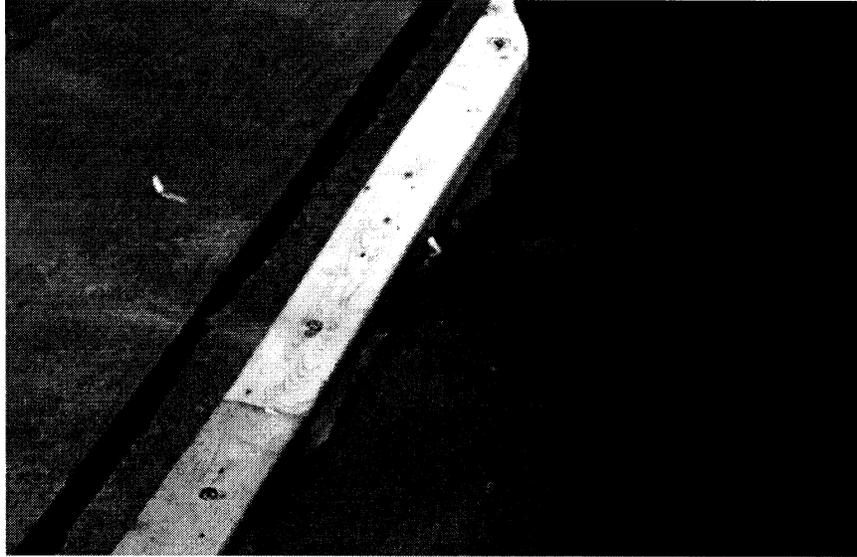
The temporary anode system used was a layer of inert catalyzed titanium anode mesh sandwiched between two layers of synthetic felt, surrounded by a dam and kept wet by an electrolyte (Figure 3).

1. Construction of a wooden dam around the area to be treated, stopping within 7 cm (3 in) of the joints. This was accomplished by securing 5 cm x 10 cm x 365 cm (2 in x 4 in x 12 ft) wood strips around the perimeter of the area with anchor bolts and applying enough silicone caulk underneath and all around the base of the wood strips to seal the edges (Figure 4).
2. Placement of a layer of 6 mm (0.25 in) thick felt over the entire area within the dam (Figure 5). The felt, which comes in width of 1.8 m (6 ft), was cut to the length of the area for longitudinal placement, from end to end of the area, with adjacent pieces overlapping by 2.5 to 5.0 cm (1 to 2 in).



*Figure 3.*  
*treatment of*

*Setup for ECE*  
*bridge deck.*

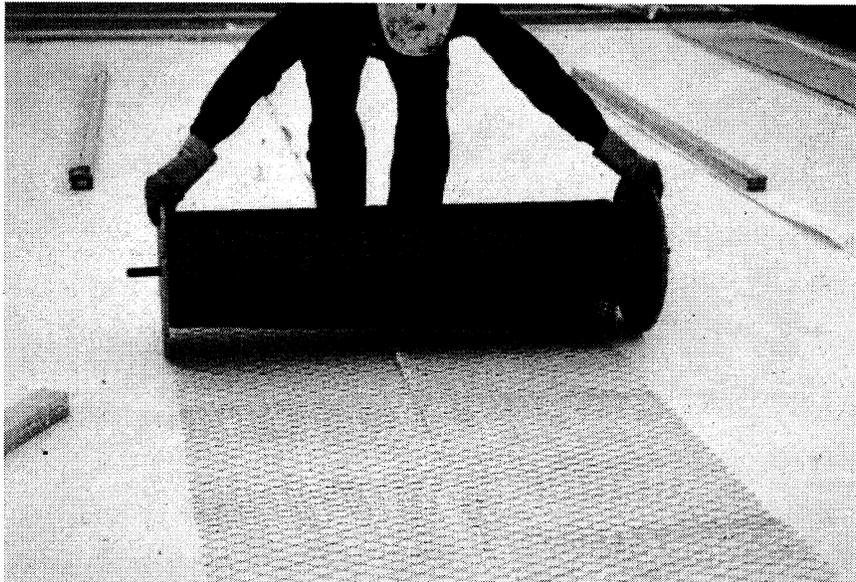


*Figure 4. Installation of ponding dam around a treatment area with wood strips and silicone caulk.*

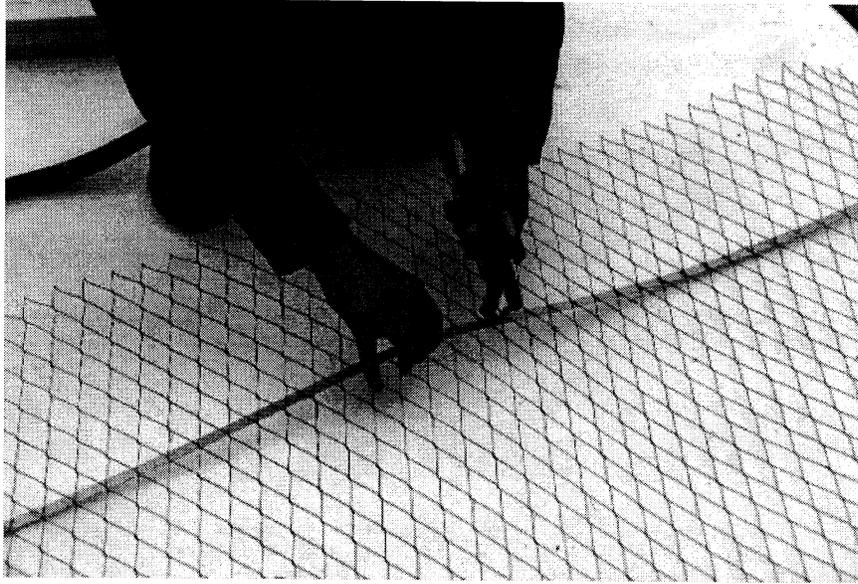


*Figure 5. Placement of the first layer of synthetic felt on the concrete within the treatment area.*

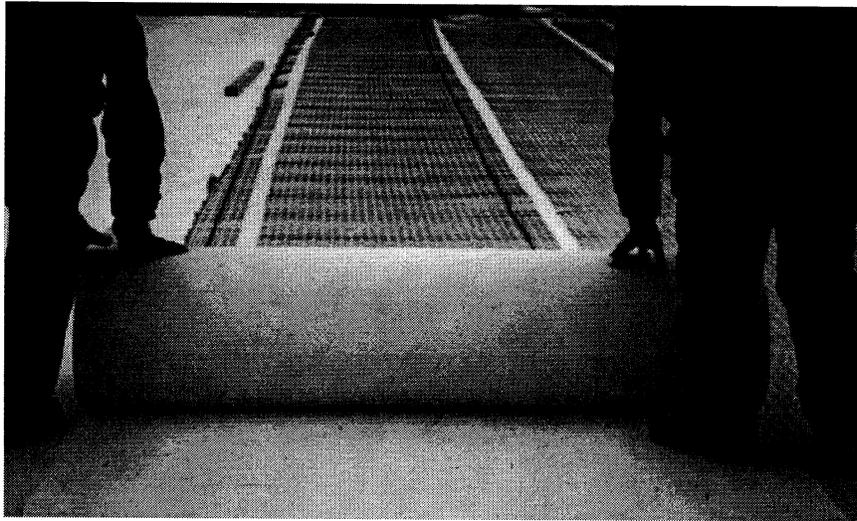
3. Placement of a layer of titanium anode mesh (Elgard 210) over this layer of felt (Figure 6). (Any equivalent titanium anode mesh will suffice.) The anode mesh, 1.2 m (4 ft) wide, was cut to the length of the area to run continuously from end to end. Covering the entire 7.3 m (24 ft) width of the area required five full-width strips and one half-width strip of the mesh. The gap between adjacent strips was kept less than 8 to 11 cm (3 to 4 in).
4. Electric resistance welding a continuous piece of 12 mm (0.5 in) wide titanium ribbon every 0.6 to 0.9 m (2 to 3 ft), to each strip of anode mesh (Figure 7). Each ribbon was then cut to extend approximately 0.3 m (1 ft) beyond each end of the anode mesh it was connected to. (As described below, both ends of each ribbon would be connected to a rectifier.)
5. Placement of a second layer of felt over the anode mesh (Figure 8).



*Figure 6. A layer of 1.2 m wide titanium anode mesh being placed above the first layer of synthetic felt.*



*Figure 7. A continuous piece of 12 mm wide titanium ribbon is connected by electric resistance welding to each strip of titanium anode mesh.*



*Figure 8. Placement of a second layer of synthetic felt over the titanium mesh and the first layer of felt.*

6. Routing a soaker water hose, from the lowest corner of the treatment area, along three sides of the area. A small water pump was connected to the hose at the lowest corner to allow recirculation of the electrolyte to the entire area.
7. Wetting the entire felt/mesh/felt anode system with an electrolyte. Table 1 shows the various electrolytes used in the treated areas. As a source of  $\text{LiBO}_3$ , approximately 950 liters (250 gal) of the electrolyte Renew™, from FMC Corporation, was used in the north half of each span.
8. Covering the entire area with a thick black plastic sheet (Figure 9).

Table 1  
ECE Treatment of 34th St. Bridge, Arlington, Virginia

Phase	Span	Half Treated	Area (m <sup>2</sup> )	Electrolyte
1	4	North	174	$\text{LiBO}_3, \text{H}_2\text{O}$
	5	North	183	$\text{LiBO}_3, \text{TPPCL}, \text{H}_2\text{O}$
2	4	South	180	$\text{Ca}(\text{OH})_2, \text{H}_2\text{O}$
	5	South	183	$\text{Ca}(\text{OH})_2, \text{H}_2\text{O}$



*Figure 9. Entire treatment area covered with plastic sheets, after wetting with electrolyte.*

### Startup of Treatment

1. Designating each half of each span into two zones, each with three of the six strips of titanium anode mesh (Figure 10).
2. Connection of all three strips of anode mesh in one of the zones to the positive terminal of a rectifier. This was achieved by connecting each end of the three welded titanium ribbons to the rectifier through a separate insulated copper lead wire of adequate gauge. The rectifiers required a single phase 220 V AC line. Each had a maximum output rating of 150 A at 40 V.
3. Similar connection of the second zone to a second rectifier.
4. Connection of the four ground connections in each span to the negative terminals of these rectifiers, using the same type of wires as the positive leads.

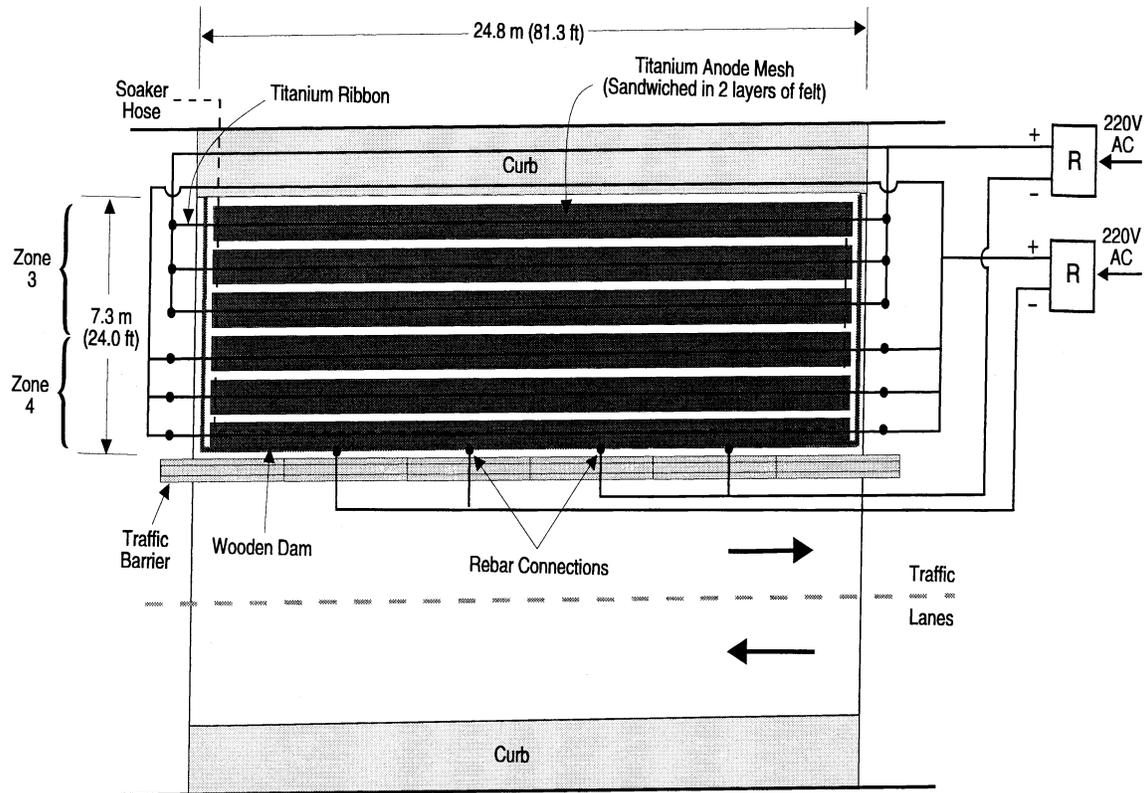


Figure 10. Plan of ECE setup for north half of span 5 (identical to other 3 areas).

5. Switching on the rectifiers. Each rectifier was operated in the constant-voltage mode, with the DC output set at as high as possible but not to exceed 40 V and 1 A/m<sup>2</sup> (or 100 mA/ft<sup>2</sup>) of concrete.

### *Monitoring the Treatment*

The treatment was initially planned to last 6 to 8 weeks. During the duration of the treatment, the dams were often checked for possible leakage of the electrolyte. The output voltage and current of each rectifier, the current passing through each of all the positive and negative (ground) lead wires, and the pH of the electrolytes were measured once every week. During the first few weeks of the treatment, when the formation of acid around the titanium anodes appeared to be most pronounced, it was necessary to adjust the electrolyte pH by spreading lime over the anode system.

### **Pre-Treatment and Post-Treatment Tests**

To assess the effect of ECE treatment on the concentration of the chloride ions in the concrete, pulverized concrete samples were collected from each span, before and after treatment. The sampling points in each span were determined on a grid (Figure 11). At each point, separate concrete samples were taken at two depths from the surface: between 0.6 to 1.9 cm (0.25 to 0.75 in), and 1.9 to 3.2 cm (0.75 to 1.25 in). No samples were taken at depths below 3.2 cm (1.25 in), because the depths of the transverse rebars ranged from only 1.9 to 4.4 cm (0.90 to 1.75 in). To minimize the possible effect of the natural variability in the composition of concrete on the results, the pre- and post-treatment samples from each sampling point were collected within 1 cm (0.5 in) of each other. A potentiometric titration procedure, described elsewhere,<sup>12</sup> was used to determine the total chloride contents of all concrete samples.

In addition, capillary electrophoresis (CEP) analyses were also conducted on 75% of the concrete samples, selected randomly, to determine the amount of lithium and inhibitor tetraphenylphosphonium (TTPP) that may have migrated from the electrolytes into the concrete.

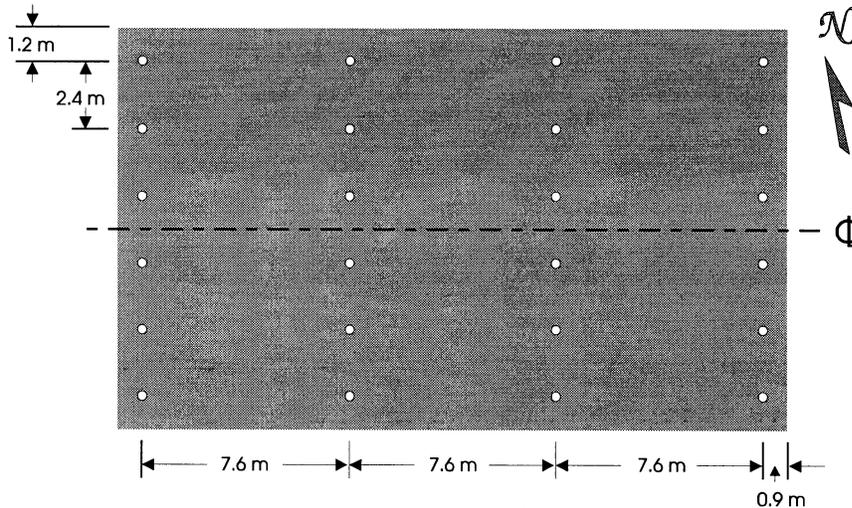


Figure 11. Grid layout of the sampling points used to conduct various pre- and post-treatment tests on the concrete of both halves (or treatment areas) of span 5. The sampling grid used for span 4 was similar.

A Digischmidt rebound hammer was used to measure the surface hardness of the concrete in each span, before and after the treatment, to determine if there is any adverse effect on the concrete surface.

## RESULTS AND DISCUSSION

Because the bridge deck was wide enough to carry four lanes of traffic and was only used for two lanes, the treatment caused very little inconvenience to motorists. However, on bridges that are used to their full capacity, diverting traffic to allow several weeks of treatment would interrupt traffic.

At the beginning of each phase of the ECE treatment of this deck, the output voltage of the rectifier for each zone was adjusted so that the total current passing through a span was less than  $1 \text{ A/m}^2$  ( $100 \text{ mA/ft}^2$ ). The voltages were in most cases kept constant throughout the entire treatment. Figures 12 and 13 show the change in the density of direct current passing through the north and south halves of both spans during treatment, which lasted for 57 or 58 days. As these illustrations show, the current passing through each area generally decreased as the treatment progressed. For example, in the north half of span 4, the current started at  $925 \text{ mA/m}^2$  ( $86.0$

mA/ft<sup>2</sup>) and ended at 662 mA/m<sub>2</sub> (61.5 mA/ft<sup>2</sup>). This decreasing trend is typical and is the net result of the electromigration of different ions of different charges into and out of the concrete. Table 2 shows a summary of various electrical parameters recorded for all areas during their treatment.

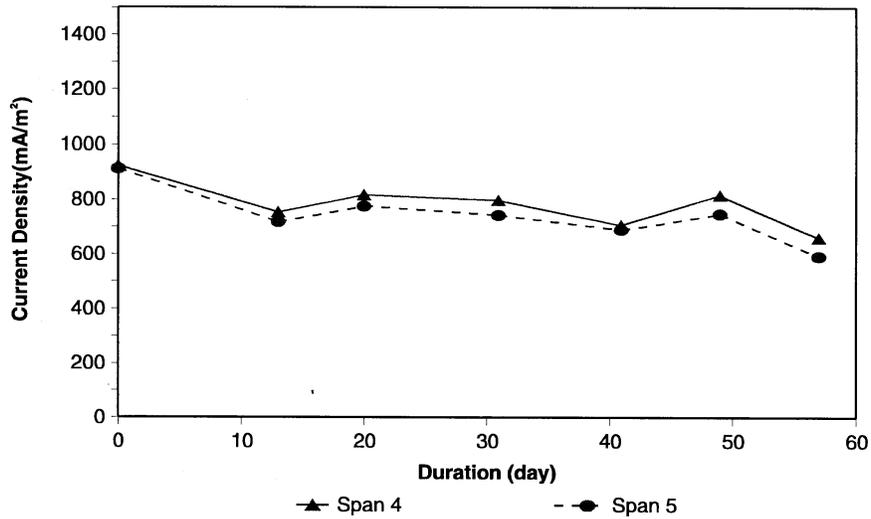


Figure 12. Density of treatment current passing through the north half of spans 4 and 5.

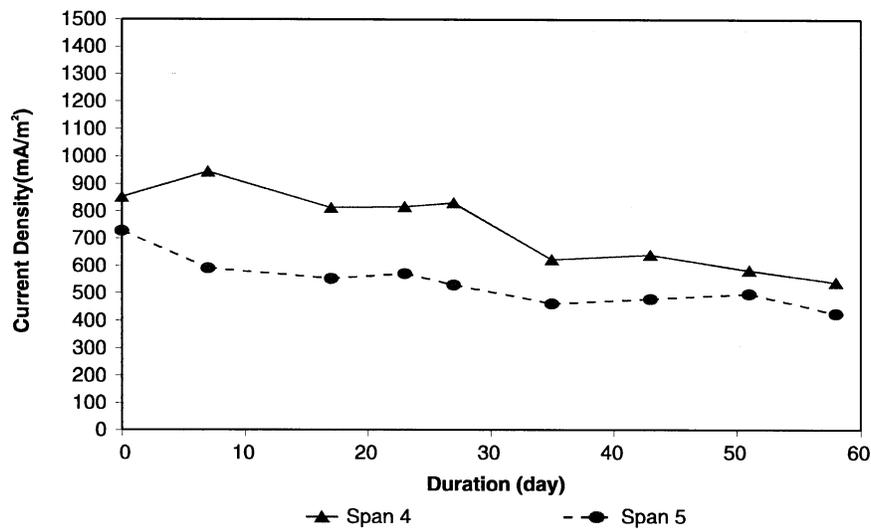


Figure 13. Density of treatment current passing through the south half of spans 4 and 5.

Table 2  
Various Electrical Parameters Recorded During the  
ECE Treatment of the Deck

Span (Half)	Duration (day)	Average Voltage (volt)	Current Density (mA/m <sup>2</sup> )		Total Charge (A-hr/m <sup>2</sup> )
			Initial	Final	
4N	57	30.2	925	662	1,077
5N	57	32.5	914	593	1,033
4S	58	29.3	854	541	1,019
5S	58	36.6	730	427	741

Figures 14 and 15 show the estimated amount of total electrical charge that passed through each area, at different stages of the treatment, as a result of the current applied. At the end of treatment, the accumulated charge varied from a low of 741 A-hr/m<sup>2</sup> (68.8 A-hr/ft<sup>2</sup>) for the south half of span 5, to a high of 1,077 A-hr/m<sup>2</sup> (100.1 A-hr/ft<sup>2</sup>) for the north half of span 4 (Table 2).

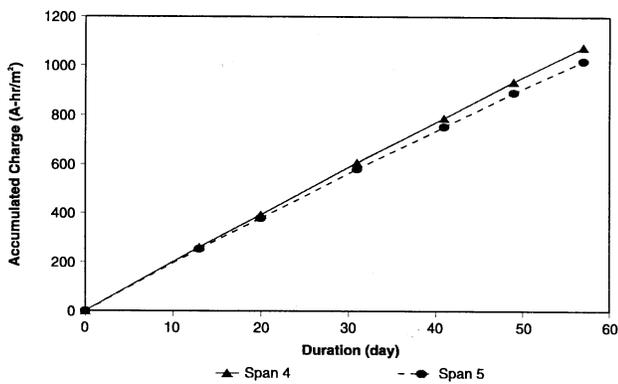


Figure 14. Estimated total electrical charges applied to the north half of span 4 and 5 at different stages of the treatment.

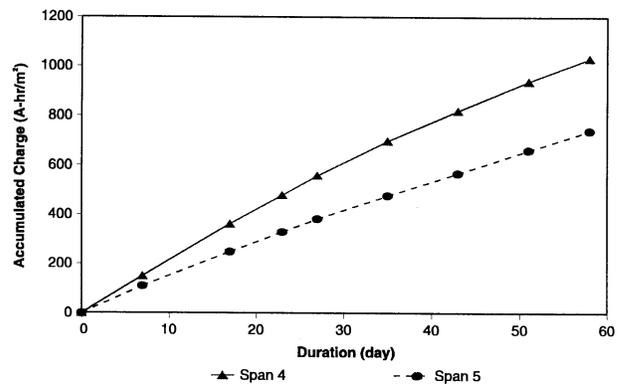


Figure 15. Estimated total electrical charges applied to the south half of span 4 and 5 at different stages of the treatment.

During the treatment, the accumulation of  $H^+$  (produced by the electrolysis of water molecules at the anode) and chlorine (from the oxidation of the chloride that migrated out from the concrete) sometimes made the electrolyte too acidic. This problem was most pronounced in the first few weeks of the treatment of the north half of both spans, despite the presence of buffer  $LiBO_3$  in the electrolytes. It was necessary to flush some of the electrolytes and add lime. The presence of inhibitor TPPCl in the electrolyte for the north half of span 5 appeared to decrease the buffering capacity of  $LiBO_3$ .

To avoid this problem, a modified setup was used to treat the south half of both spans. Instead of containing and recirculating the electrolyte within the dams, fresh water was allowed to flow continuously from the highest corner and drain out at the lowest corner in each span. To eliminate the possible environmental impact of the lithium salts and TPPCl draining out of the deck, calcium hydroxide was used instead, if necessary. This considerably lessened the need to neutralize the electrolytes during the second treatment phase of these spans.

If the electrolyte is too acidic for too long, there may be etching and softening of the concrete surface. The average surface hardnesses of the concrete in each area were measured before and after treatment by a Digischmidt rebound hammer. With the exception of the south half of span 4, there appeared to be slight decreases of hardness due to the treatment (Table 3). However, from the corresponding standard deviations in the measured surface hardnesses for each area, the change in the hardness was statistically significant (at the 99% confidence level) only for the north half of span 5, where acidification of the electrolyte was most pronounced.

Table 3  
Relative Surface Hardness of the Concrete Before and After ECE Treatment

Span (Half)	Relative Surface Hardness (N/mm <sup>2</sup> )				
	Before ECE		After ECE		Change (%)
	Mean	SD (%)	Mean	SD (%)	
4N	60	7.8	56	4.5	-6.7
5N	56	5.5	51	4.1	-8.9
4S	56	2.9	57	2.6	1.8
5S	57	4.7	55	4.7	-3.5

The electrolyte must be prevented from becoming acidic for too long. In states like Virginia, where scarifying the old surface of a concrete deck before applying a new concrete overlay is a standard practice, a slight etching of the surface concrete would be of no concern. However, to avoid this situation, the setup for the ponding dam and the anode system would have to be modified somehow to make it easier to add lime directly over the entire treatment area and to effectively circulate the buffered electrolyte through the entire area. Covering the area with plastic minimized evaporation of the electrolyte and prevented vandalism, but made it difficult to spread lime across the whole area when necessary. A converted mixing tank was used in the treatment of the concrete piers in the companion study, and possibly can also be used with this deck treatment system.<sup>10</sup>

Another problem in the treatment of the south half of the deck was the failure of the contractor to provide a large enough drain pipe for the water flowing through the system (which probably contained chloride removed from the concrete). This led to some leakage of the water onto the concrete piers below. Except for this problem, the dams were very effective in keeping the deck areas wet during treatment.

Comparison of the chloride contents in the concrete of all treated areas, before and after the ECE treatment, indicates that the amount of chloride removed from the concrete closest to the surface of the deck was consistently slightly higher than the amount removed from deeper concrete (Table 4). This correlation reflects the combined effect of the strength of the electrical field and the distance of travel on the rate of outward migration of the chloride ions. The results in Table 4 also show that the treatment led to significant decreases in the concentration of chloride in the concrete samples from both depths, in all four treatment areas (Figures 16 to 19). The amount of chloride removed varied between the areas, ranging from 75.8 to 82.1% at a depth of 0.6 to 1.9 cm (0.25 to 0.75 in) and slightly lower (72.2 to 81.7%) at a depth of 1.9 to 3.2 cm (0.75 to 1.25 in). The amounts of chloride that were removed from the treated spans surpassed the maximum of 40 to 55% for very heavy treatments suggested by one of the SHRP reports.<sup>4</sup>

Comparing the amounts of electrical charge or ampere-hours used to the amounts of chloride removed, current efficiencies varied from 11.2 to 15.0%, with an average of 13.0% (Table 5). These efficiencies were lower than the 20% that one of the SHRP reports claimed could be expected on a field structure.<sup>4</sup> It must be emphasized that, by definition, current

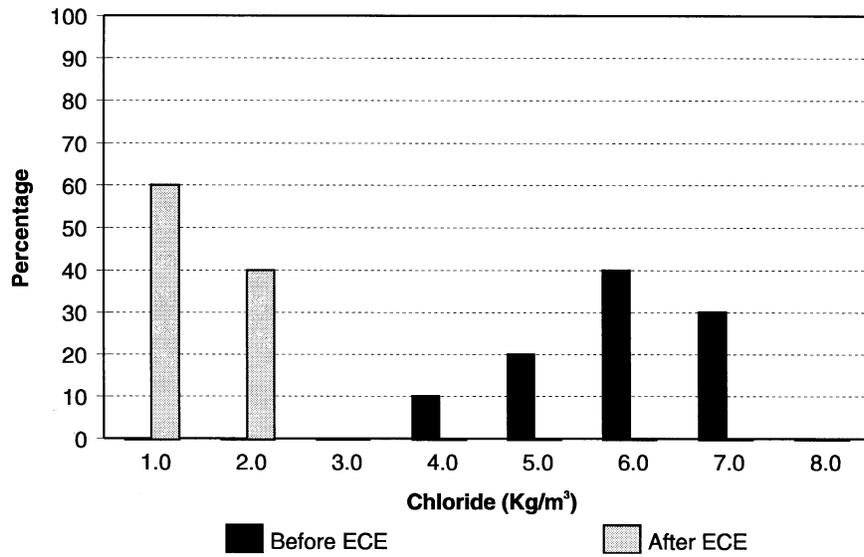
efficiency is the fraction of total current (in ampere-hours) carried by the amount of chloride ions removed in a particular treatment. This would vary from treatment to treatment depending on what other mobile ions are present in the concrete and the electrolyte to carry the rest of the current. Current efficiencies would have appeared more impressive if the treatments had been terminated earlier, at 40 days instead of 57 to 58 days. Figures 12 and 13 show that current densities across the different treated areas started to stabilize around 40 days. This trend toward stability in the current density is typical. It signifies the establishment of overall equilibrium between the outward movement of the anions and the inward movements of the cations, and means that longer treatment would not remove significantly more chloride.

Table 4  
Average Concentrations of Chloride Ions (At Various Depths)  
in the Concrete Decks -- Before and After ECE Treatment

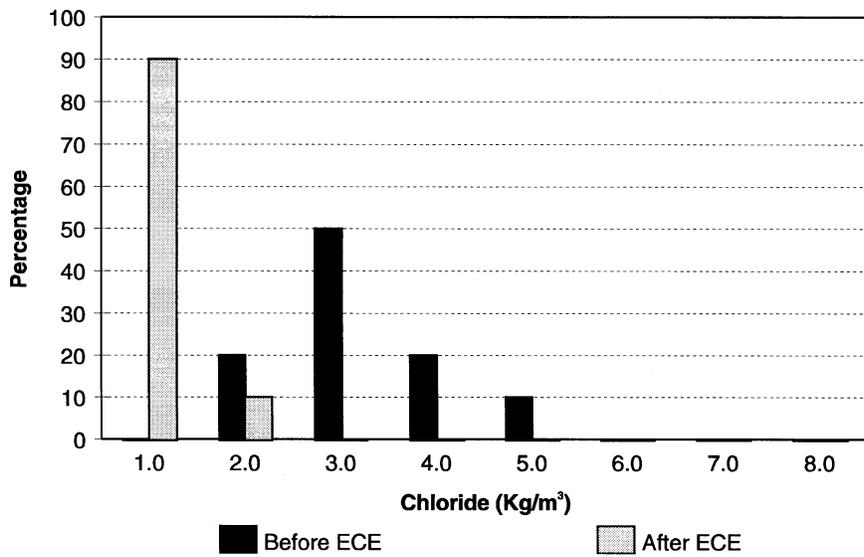
Span (Half)	At 0.6 - 1.9 cm			At 1.9 - 3.2 cm		
	[Cl <sup>-</sup> ] (kg/m <sup>3</sup> )		Change (%)	[Cl <sup>-</sup> ] (Kg/m <sup>3</sup> )		Change (%)
	Before	After		Before	After	
4N	5.20	1.04	-80.0	2.68	0.59	-78.0
5N	5.92	1.06	-82.1	3.78	0.69	-81.7
4S	5.03	1.07	-78.7	3.05	0.71	-76.7
5S	4.97	1.20	-75.8	2.34	0.65	-72.2

Table 5  
Estimated Current Efficiency of the ECE Treatment of  
the Concrete Decks

Span (Half)	4N	5N	4S	5S
Current Efficiency	11.2%	15.0%	11.7%	14.2%



Span 4 (North Half): 0.6 - 1.9 cm



Span 4 (North Half): 1.9 - 3.2 cm

Figure 16. Change in the population distribution of chloride concentrations in the concrete of the north half of Span 4 at two different depths after ECE treatment.

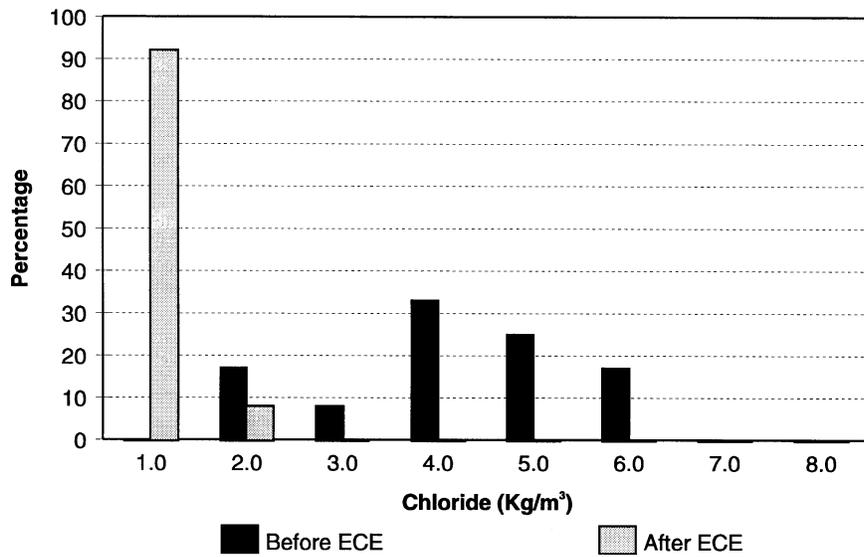
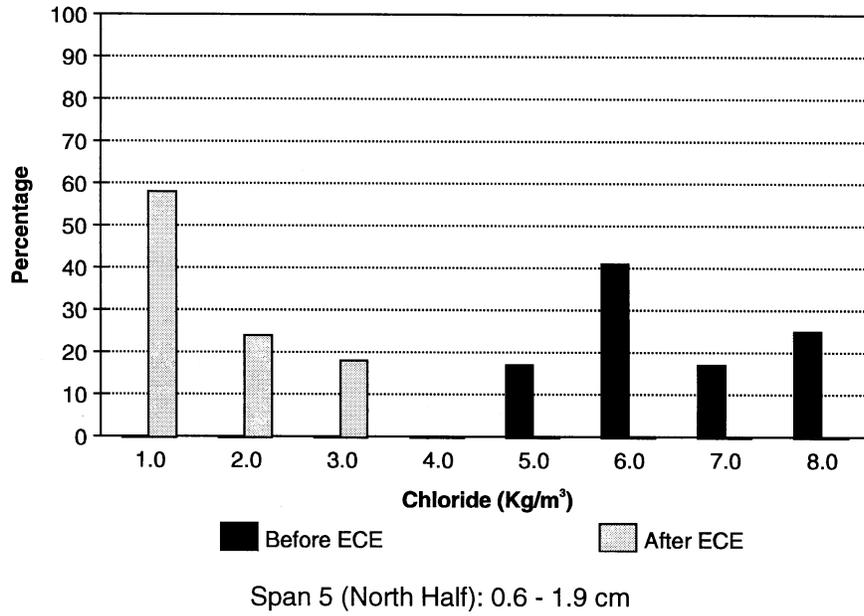
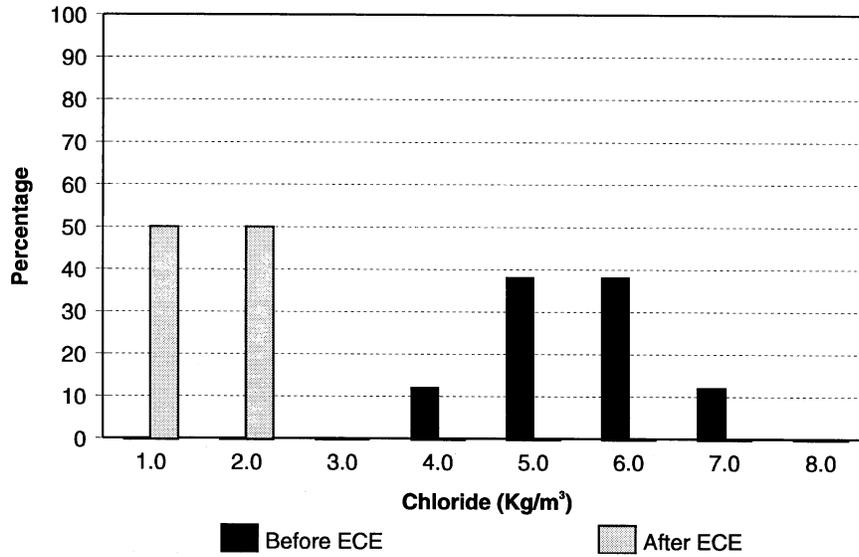
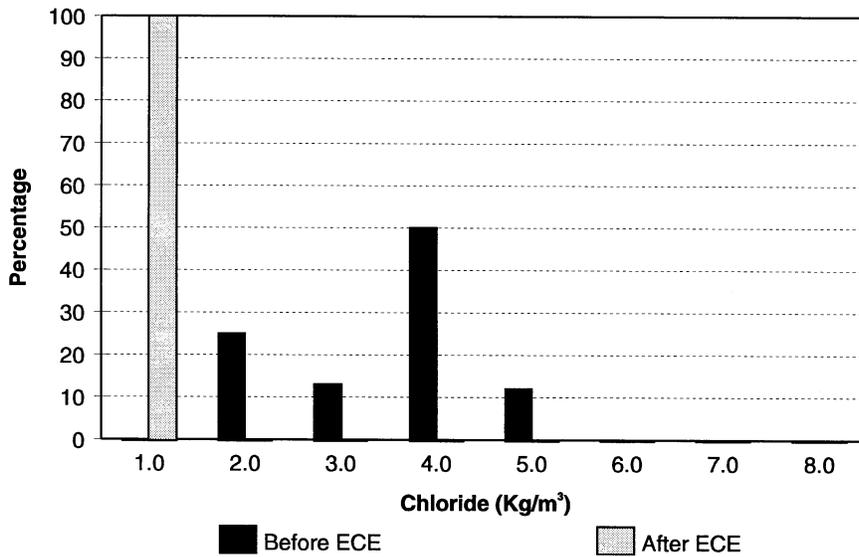


Figure 17. Change in the population distribution of chloride concentrations in the concrete of the north half of Span 5 at two different depths after ECE treatment.

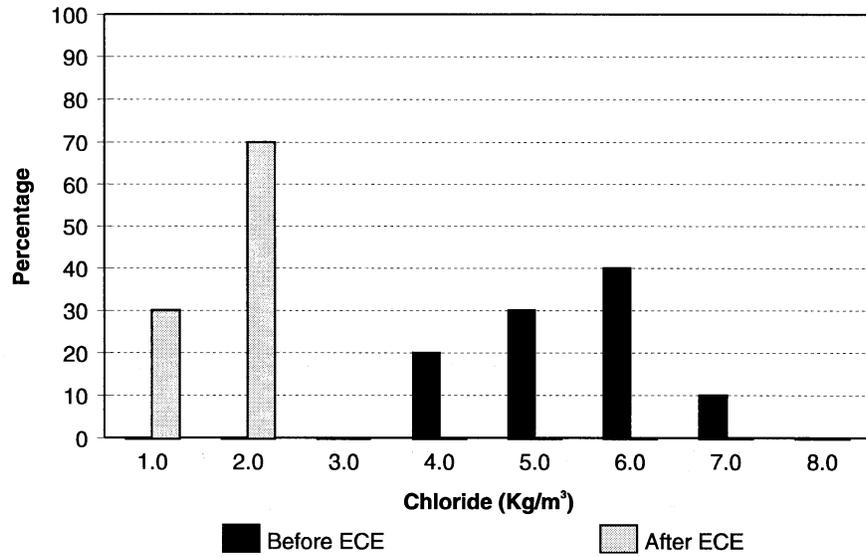


Span 4 (South Half): 0.6 - 1.9 cm

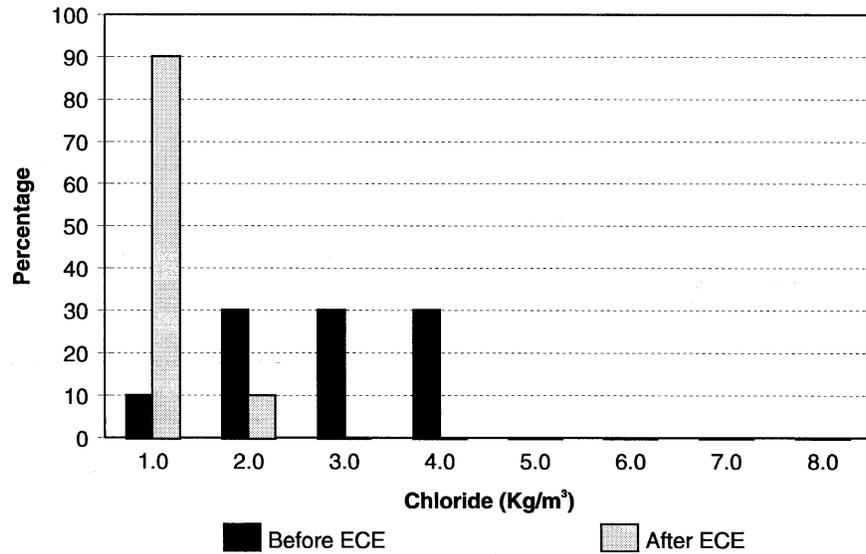


Span 4 (South Half): 1.9 - 3.2 cm

Figure 18. Change in the population distribution of chloride concentrations in the concrete of the south half of Span 4 at two different depths after ECE treatment.



Span 5 (South Half): 0.6 - 1.9 cm



Span 5 (South Half): 1.9 - 3.2 cm

Figure 19. Change in the population distribution of chloride concentrations in the concrete of the south half of Span 5 at two different depths after ECE treatment.

Comparison between the four areas indicates that the current efficiencies appeared to be reasonably uniform between halves for a given span, and that the efficiencies were consistently higher for span 5 than for span 4. Perhaps some unknown difference in the concrete between the spans had a more discernible influence on the removal efficiency than did any differences in the electrolytes (Table 1).

Within the practical duration for an ECE treatment (10 to 50 days), the treatment cannot be expected to remove all the chloride ions, especially when the average initial chloride level is very high. Unsurprisingly, some of the concrete samples collected from the decks after the treatment still contained some chloride, albeit at considerably lower levels than before treatment. As Table 6 shows, in each area the treatment considerably decreased the number of concrete samples or locations with enough chloride to exceed the generally accepted corrosion threshold level of 0.77 kg/m<sup>3</sup> (1.3 lb/yd<sup>3</sup>). Before the treatment, all the concrete samples from each area exceeded the corrosion threshold; after the treatment, only 20 to 33% of the samples still exceeded the threshold. Rebars in these remaining locations would not necessarily corrode soon. By simultaneously reducing the chloride concentration considerably and producing some hydroxide at the rebars, ECE beneficially reduces the [Cl<sup>-</sup>]/[OH<sup>-</sup>] ratio, which influences the potential for corrosion more than chloride concentration alone does. In addition, the applied charge cathodically polarized and passivated all the rebars.

Table 6  
Percentage of Concrete Samples with Chloride Levels  
Exceeding Corrosion Threshold (at Depth of 1.9-3.2 cm)

Span (Half)	Before Treatment	After Treatment
4N	100	20
5N	100	33
4S	100	25
5S	100	20

As noted in Table 1, the electrolytes used for the treatment of the north half of both spans contained  $\text{LiBO}_3$ , which is recommended for mitigation of possible ASR in concrete. Since data on the amount of  $\text{Li}^+$  that can be electrochemically injected into a concrete, in conjunction to ECE treatment, have never been reported, concrete samples from these areas were chemically analyzed by the CEP method. The results (Table 7) indicate that a considerable amount of  $\text{Li}^+$  electromigrated from the electrolyte on the surface into the concrete in both areas; as high as 265 ppm at the depth of 1.9 to 3.2 cm on the north half of span 4. As expected, the  $\text{Li}^+$  concentration in the concrete was consistently higher near the surface than near the rebars or in deeper concrete.

As mentioned earlier, the electrochemical injection of a corrosion inhibitive cation into a concrete simultaneously with removal of chloride was conducted on the north half of span 5. This represents the first field trial of this new concept. The inhibitor suggested for this trial and supplied free by SRI International was tetraphenyl phosphonium chloride (TTPCl). Application involved dissolving 2.5 Kg (5.5 lb) of this inhibitor in sufficient amount of water, then brushing or brooming a copious amount of this aqueous solution on the surface of the deck, before the placement of the first layer of felt.

Table 7  
Average Concentrations of Lithium Ions (At Various Depths)  
in the Concrete Decks -- Before and After ECE Treatment

Span (Half)	[Li <sup>+</sup> ] (ppm)			
	At 0.6-1.9 cm		At 1.9-3.2 cm	
	Before	After	Before	After
4N	89	315	25	265
5N	24	343	62	203

Analysis of the after-treatment concrete samples by the CEP method indicated no detectable amount of TTP<sup>+</sup> in any of the samples. This implies that, if any amount of this inhibitor managed to migrate into the concrete, it was less than 25 ppm, or 25 microgram inhibitor per gram of concrete, which was the estimated minimum detection limit of this inhibitor by the powerful analytical method used. A major difference between the experiments conducted by SRI International on concrete slabs and this pilot trial on a concrete deck was that Li<sup>+</sup> was not present in the electrolyte used in the concrete slab experiments. We postulate that when both Li<sup>+</sup> and TTP<sup>+</sup> are present simultaneously in the electrolyte, the size of the TTP<sup>+</sup> allows the considerably smaller and more mobile Li<sup>+</sup> to dominate the inward migration of cations into the concrete deck. The detection of a considerable amount of Li<sup>+</sup> in the treated areas (Table 7) is certainly consistent with this view. In future trials, it may be advisable to modify the procedure slightly to allow TTP<sup>+</sup> or any similarly large inhibitive ions to be alone in the electrolyte for the first few days of a treatment before adding Li<sup>+</sup> into the electrolyte, if the latter is necessary.

Vertical sections of six different 57 mm (2.25 in) cores taken from the treated areas were examined petrographically to evaluate the quality and condition of the concrete, with particular attention to any signs of abnormality. Two cores each came from the north half of both spans, and one from the south halves. The concrete in all six cores was crack-free, and of good quality and condition. The coarse and fine aggregates were tightly bonded in a low water/cement ratio (0.45-0.50) cement paste with an excellent entrained-air void system. The wearing surface of the two cores taken from the south half of both spans showed a very slight loss of paste around the fine aggregate particles, which is likely the effect of chemical erosion or etching that occurs when the electrolyte becomes acidic during some stages of the treatment.

A very limited amount of alkali-silica reactivity (ASR) was observed around a few chert particles in three cores -- one each from the two north halves, and one from the south half of span 4. There was no evidence, in any core, of extensive ASR activity. It is possible that the minimal ASR activity in the three core samples occurred before ECE treatment. It is probably still too early to determine whether the use of LiBO<sub>3</sub> in the electrolyte for the north halves helps mitigate possible ECE-induced ASR activity, or is even necessary. One SHRP study reported that treatment of a section of a pier column that contained ASR-susceptible fine aggregates without using LiBO<sub>3</sub> did not aggravate ASR activity.<sup>5</sup>

The total cost of the treatment was \$92,412.50 or \$128.35/m<sup>2</sup> (\$11.93/ft<sup>2</sup>) of concrete. Table 8 contains a breakdown of this total. This is lower than the cost of \$226/m<sup>2</sup> (\$21/ft<sup>2</sup>) for the previous SHRP experimental ECE treatment of a small section of an Ohio bridge deck, which involved only a fifth as much concrete area as the present trial. However, to many potential users, a unit cost of no more than \$86/m<sup>2</sup> (\$8/ft<sup>2</sup>) would be desirable. The absence of competitive experienced applicators of this treatment is probably a major reason for the high cost. When arrangements were being made for the treatment, Vector Construction, because of its involvement in the Canadian trial, was the only contractor in North America known to have experience with the process. Since the contractor is based in Winnipeg, Canada, VDOT Research Council personnel became involved in correcting each problem that came to light during the treatment process. Even though the problems were minor, this was a challenge for the agency, and would also challenge other transportation agencies that are already shorthanded.

Table 8  
Costs Associated with the ECE Treatment of the  
Concrete Decks in Arlington, Virginia

Item	Cost
Mobilization	\$ 6,442.50
ECE Treatment	69,220.00
Electrical Service	14,250.00
Lithium Borate	2,500.00
<b>Total</b>	<b>\$92,412.50</b>

Obviously, more contractors need to train for this new technology, to reduce the logistical problems and bring costs down. This is an extremely good opportunity for corrosion engineering firms already involved in the cathodic protection of concrete structures to expand their market.

## CONCLUSIONS

1. In general, ECE treatment of full-sized salt-contaminated reinforced concrete decks is reasonably simple to install, and highly practical. The only real hindrance may be traffic control.
2. The treatment process and the installation require monitoring and inspection, especially during the first weeks.
3. The ponding dam used in this trial should be improved to allow the reasonably easy spreading of lime over an entire treatment area when necessary, and the proper draining and collection of spent electrolyte.
4. A typical (up to 50 day) treatment removes a considerable amount of chloride; however, it cannot be expected to remove all the chloride. However, the treatment also offers other beneficial effects that help arrest rebar corrosion: redistributing the remaining chloride away from the rebars, decreasing the  $[Cl^-]/[OH^-]$  ratio, and cathodically passivating the rebars.
5. Lithium ions can easily be injected electrochemically into the concrete. However, the benefit of doing it to prevent ECE-induced ASR activity is not clear yet.
6. It is uncertain whether the attempt to inject the corrosion inhibitor  $TTP^+$  into the concrete deck was successful, in the presence of  $Li^+$  in the electrolyte. If it was, the quantities were less than the minimum detection level of 25 ppm (by the CEP method).

## RECOMMENDATIONS

ECE treatment is a reasonably practical method for removing significant amounts of chloride from salt-contaminated concrete in full-sized bridge decks, thereby mitigating rebar corrosion. VDOT should include this treatment among its methods for permanently rehabilitating concrete bridge decks. ECE treatment also provides the same beneficial effects to the rebars as cathodic protection, without involving permanent system components that require long-term inspection and maintenance. Since the treatment can take 10 to 50 days, depending on the

electrical resistance of the concrete and the amount of chloride, it may not always be economically or politically suitable for bridge decks that carry heavy traffic.

ECE treatment would be a useful tool in many other states, and a showcase should be developed by the Office of Technology Applications of the Federal Highway Administration to help transfer this new technology to other DOTs. The showcase would be a good forum for sharing ideas and experiences with other states.

Additional research efforts should be devoted to identifying a few suitable corrosion inhibitors, with criteria such as injection rate (with and without the presence of other cations such as  $\text{Li}^+$ ), toxicity, corrosion passivating capacity, etc., to use for the synergistic electrochemical removal of chloride and injection of inhibitor into concrete structures.

#### **ACKNOWLEDGEMENTS**

Appreciation is extended to the Office of Technology Applications of the Federal Highway Administration (FHWA) for providing the necessary funds to conduct and evaluate these field trials, and to Claude Napier, Virginia Division of FHWA, Malcolm Kerley of the VDOT Structure and Bridge Division, and Bud Cook (retired), Jim Lillard, and Fawaz Alsaraf, of the Bridge Section of VDOT Northern Virginia District, for their support and cooperation. Appreciation is also extended to FMC Corporation, especially David Stoke, for their assistance, including arranging for petrographic examination of some of the concrete core samples.

The authors are indebted to many coworkers at the Virginia Transportation Research Council, especially Cesar Apusen, Alan French, Roger Howe, and Mike Sprinkel, and to Robert Kelly and Maria Inam of the Center for Electrochemical Science and Engineering at the University of Virginia, for their assistance.

## REFERENCES

1. Morrison, G.L., Virmani, Y. P., Stratton, F. W., and Gilliland, W. J. 1976. *Chloride Removal and Monomer Impregnation of Bridge Deck Concrete by Electro-Osmosis*. Report No. FHWA-KS-RD 74-1. Topeka: Kansas Department of Transportation.
2. Jayaprakash, G. P., Bukovatz, J. E., Ramamurti, K., and Gilliland, W. J. 1982. *Electro-Osmotic Techniques for Removal of Chloride from Concrete and for Emplacement of Concrete Sealants*. Report No. FHWA-KS-82-2, Topeka: Kansas Department of Transportation.
3. Slater, J. E., Lankard, D. R., and Moreland, P. J. 1976. Electrochemical Removal of Chlorides from Concrete Bridge Decks. *Transportation Research Record*, 604, 6.
4. Bennett, J. E., Thomas, T. J., Clear, K. C., Lankard, D. L., Hartt, W. H., and Swiat, W. J. 1993. *Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Laboratory Studies*. Report No. SHRP-S-657. Washington, D.C.: National Research Council.
5. Bennett, J. E., Fong, K. F., and Schue, T. J. 1993. *Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Field Trials*. Report No. SHRP-S-669. Washington, D.C.: National Research Council.
6. Bennett, J. E., and Schue, T. J. 1993. *Evaluation of NORCURE Process for Electrochemical Chloride Removal from Steel-Reinforced Concrete Bridge Components*. Report No. SHRP-C-620. Washington, D.C.: National Research Council.
7. Manning, D .G., and Pianca, F. 1990. *Electrochemical Removal of Chloride Ions from Reinforced Concrete: Initial Evaluation of the Pier S19 Field Trial*. Report No. MAT-90-14. Ontario, Canada: Ontario Ministry of Transportation.
8. Ip, A., and Pianca, F. October, 1995. Private Communication with D. Whitmore, Re: Burlington Skyway.

9. Asaro, M. F., Gaynor, A. T., and Hettiarachchi, S. 1990. *Electrochemical Chloride Removal and Protection of Concrete Bridge Components (Injection of Synergistic Corrosion Inhibitors)*. Report No. SHRP-S/FR-90-002. Menlo Park, California: SRI International.
10. Clemeña, G. G., and Jackson, D. R. 1996. *Pilot Application of Electrochemical Chloride Extraction on Concrete Piers in Virginia*. Report No. VTRC 96-IR4. Charlottesville: Virginia Transportation Research Council.
11. Jackson, D. R., and Scannell, W. 1993. *Evaluation of Bridge on 34th Street over I-395 in Arlington, Virginia as a Candidate for Electrochemical Chloride Removal*. Washington, D.C.: Federal Highway Administration, Office of Technology Applications.
12. Clemeña, G. G., Reynolds, J. W., and McCormick, R. 1977. Gran Method of Endpoint Determination in Chloride Analysis by Potentiometric Titration. *Transportation Research Record* 651, 1.