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Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Field Trials

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Contents

List of Figures

List of Tables

Abstract

Electrochemical chloride removal procedures developed in the laboratory for rehabilitation of concrete bridge structures were executed in field validation trials. Field trials were completed on an Ohio bridge deck, a Florida marine column substructure, a New York land column substructure, and an Ontario bridge abutment. All four field trials were successful. This report discusses the results of these trials.

Executive Summary

Corrosion of reinforcing steel is recognized today as one of the major contributors to the deterioration of reinforced concrete structures. This corrosion is induced primarily by chlorides from deicing salts, seawater, and components of the concrete. One technique for dealing with this problem is chloride removal. The electrochemical removal of chloride from concrete structures is accomplished by applying an anode and electrolyte to the concrete surface, and passing direct current between the anode and the reinforcing steel, which acts as a cathode. Since anions (negatively charged ions) migrate toward the anode, it is possible to migrate chloride ions toward the anode and away from the steel.

Under this contract, the feasibility of chloride removal from reinforced concrete bridge components was examined, first in Volume I, Laboratory and Test Yard Studies, and in this, Volume II, Field Validation Studies. A package was also provided to assist the State Highway Engineer in the implementation of chloride removal technology.

Four field validation trials were conducted between the fall of 1991 and fall of 1992. Chloride removal was conducted on an Ohio bridge deck, and bridge substructures in Florida, New York and Ontario. Based on the laboratory and test yard studies, a current less than 500 A/ft^2 (5 A/m^2) and a voltage less than 50 V was used. The treatment was applied until a total charge of 60 to 135 A-hr/ft^2 (600 to 1,350 A-hr/m^2) of concrete was accumulated. The pH of the electrolyte was maintained neutral or basic to prevent etching of the concrete surface and the evolution of chlorine gas.

Each field site was selected based on criteria established by the laboratory studies and the SHRP Expert Task Group. Active corrosion was occurring on a substantial portion of each selected structure, and chloride contamination was well above threshold levels.

The absence of alkali reactive aggregate was a factor, until the final trial when a structure with alkali reactive aggregate was selected as a test case.

The first field trial was conducted on an Ohio bridge deck in the fall of 1991. No physical deterioration of the deck was evident. The treatment was conducted by constructing a pond on the deck, and placing an inert catalyzed titanium anode in the pond together with a sodium borate buffer electrolyte. Current density for this trial was low because of cold temperatures and very resistive concrete, hence the treatment time was 61 days. Chloride analyses of the ponded electrolyte indicate that about 11 grams of chloride was removed per square foot (110 gm/m^2) of concrete during the treatment at a current efficiency of about 20 percent. Problems encountered include vandalism and overflow of the pond due to excessive rainfall.

The second field trial was conducted in the spring of 1992 on pilings underneath the B. B. McCormick bridge near Jacksonville, Florida. Prefabricated anode/blanket composites were strapped on each pile, and seawater was used as the electrolyte. The system operated for 18 days at an average current density of 0.33 A/ft^2 (3.3 A/m^2), accumulating a total charge of 135 A-hr/ft^2 (1,350 A-hr/m^2). The success of this trial is difficult to judge since the electrolyte could not be analyzed for an increase in chloride concentration. Although steel in the treatment area was strongly polarized and chloride was certainly removed, the efficiency and amount of chloride removed could not be determined.

The third field trial was conducted on the substructure of a bridge in Albany, New York in June 1992. Prefabricated anode/blanket composites were strapped on the columns and a sodium borate electrolyte was continuously circulated through a closed system. Localized high current densities were reported. This was probably a result of the inhomogeneous nature of the structure due to the patching. Current densities ranged from 0.1 to 0.3 A/ft^2 (1 to 3 A/m^2), and two zones accumulated 80 and 93 A-hr/ft^2 (800 and 930 A-hr/m^2) in 17 and 24 days, respectively. Based on concrete analyses, chloride removed was 9 to 15 grams per square foot (90 to 150 gm/m^2) at a current efficiency of 7 to 13 percent. Problems at this site included difficulty in preventing electrolyte leakage through small vertical cracks that extended below the removal zone on two columns, and electrolyte dilutions due to rainwater runoff.

The last chloride removal field trial was conducted on abutments of a bridge over the Montreal River in Latchford, Ontario, in August, 1992. This trial was especially important since the structure contained alkali reactive aggregate, and was suffering from a combination of ASR and corrosion-induced damage. The laboratory studies found that unless lithium was in the electrolyte, ASR damage would be aggravated by the chloride removal process. Consequently, a lithium borate buffered solution was used. An anode/blanket composite was installed on each abutment corner and electrolyte was continuously circulated through the system. The system operated 23 days at an average current density of 0.16 A/ft^2 (1.6 A/m^2), accumulating 84 and 89 A-hr/ft^2 (840 and 890 A-hr/m^2) of charge on two zones. Post treatment analyses showed that 21 and 14 grams of chloride per square foot (210 and 140 gm/m^2) had been removed from the two zones at current efficiencies of 19 and 12 percent, respectively. Petrographic analysis of the concrete showed that the treatment did not aggravate the alkali-silica reaction occurring in the structure. The main problem encountered was again electrolyte dilutions due to excessive rainwater runoff.

The calculated costs for the four field trials were: Ohio, \$21/ft^2; Florida, \$32/ft^2; New York, \$13/ft^2; and Ontario, \$78/ft^2. These costs are considered high, and should not be regarded as expected costs for chloride removal as a routine, commercial business. Costs were inflated by ineffective use of major equipment items (at Ontario and Ohio), high labor costs (at Florida and Ontario), and high electrolyte and electrolyte disposal costs (at Ohio, New York, and Ontario).

In summary, all four field validation trials were successful. The long-term success of the treatment cannot be judged from data taken during or immediately after the process. That can only be determined from long-term monitoring. Careful post-SHRP monitoring has been recommended.

1

Introduction

Chlorides are the primary cause of reinforcing steel corrosion in concrete bridge structures. Although steel in concrete is normally "passive," or covered with a protective oxide film,[1] chloride ions interact with this film to break it down and allow corrosion to occur. For bridge structures, it has generally been found that a concrete chloride content in the range of 1.0 to 1.4 pounds chloride per cubic yard (0.6 to 0.8 kg per cubic meter) is critical because at values above this threshold, corrosion of reinforcing steel in concrete can occur.[2,3,4] Chlorides may be introduced in the form of deicing salts or seawater, or in concrete materials and admixtures.

The resultant corrosion products occupy more volume than the steel and this exerts tensile stresses on the surrounding concrete. When these stresses exceed the tensile strength of the concrete, cracking develops. This cracking often interconnects between reinforcing bars and the common under-surface fracture, or delamination, develops. As corrosion continues, the concrete cover breaks up and a pothole or spall is formed. This is frequently accelerated by additional stress from freezing and thawing and traffic pounding. Today the nation's bridges continue to deteriorate at an alarming rate, largely due to corrosion of the reinforcing steel.

One way to deal with this corrosion problem is electrochemical removal of chloride from the concrete. Chloride removal is accomplished by applying an anode and electrolyte to the structure surface, and passing direct current between this anode and the reinforcing steel which acts as a cathode. Since anions (negatively charged ions) migrate toward the anode, it is possible to migrate chloride ions away from the reinforcing steel and out of the concrete structure. The speed at which this process is accomplished is largely dependent on the magnitude of the applied current. An additional benefit of charge passed is the buildup of hydroxide ions at the surface of the reinforcing steel. This further prevents the corrosion of reinforcing steel since corrosion is more dependent on chloride/hydroxide ratio than on chloride concentration itself.

Only a portion of the total applied current will be carried by chloride ions moving toward the anode. The balance of the current will be carried by any other ions which are present. These include primarily hydroxide, calcium, sodium and potassium ions. The relative concentration of these ions is a major factor in determining the percentage of current carried by chloride, and therefore the efficiency for chloride removal. If the removal efficiency was 100 percent, then one Faraday of charge (28.8 A-hr) would remove one mole of chloride (35.5 g). But since many other ions are carrying charge as well, practical current efficiencies for chloride removal are typically only 10 to 30 percent. In other words, the passage of each amp-hr of charge will remove about 0.25 grams of chloride.

Research studies under Strategic Highway Research Program Contract SHRP-87-C102-A, "Electrochemical Chloride Removal and Protection of Concrete Bridge Components," began in early 1987. The results of work conducted under this contract are divided into two parts: Volume I which contains the results of laboratory and test yard work, and Volume II (this report) which contains the results of field validation trials.

A separate study is also described in "Evaluation of NORCURE™ Process for Electrochemical Chloride Removal from Steel-Reinforced Concrete Bridge Components," SHRP Report No SHRP-C-620, 1992, by Jack Bennett and Thomas J. Schue, ELTECH Research Corporation. A "Chloride Removal Implementation Guide" suitable for use by operating agencies has also been prepared. It contains a description of equipment and procedures used to implement the chloride removal process. This information is available in SHRP Report No. SHRP-S-347.

The work reported in Volume I of this study confirmed that electrochemical chloride removal is a technically feasible technique for rehabilitation of concrete bridge components. Results reported in Volume I include removal efficiency, distribution and remigration of chloride in, corrosion rate and steel potential measurements, rebar bond strength, concrete compression strength, concrete cracking, acid attach, chlorine gas evolution, alkali-aggregate reaction, hydrogen embrittlement, concrete sealing, and appropriate treatment current and time.

The actual amount of chloride removed in laboratory and test-yard studies was rather disappointing, and early technical targets were not met. Even very heavy treatments removed only 40 to 55 percent of the total chloride present. But further test results indicate that more complete removal may not be necessary. The chloride left in the concrete was positioned between and behind the reinforcing bars, and remained well away from the steel. Chloride contents around the top reinforcing steel were greatly reduced by the treatment and show no significant change after 40 months. It is also clear that in addition to removing chloride away from the bars, the treatment results in a build-up of hydroxide ions at the steel surface. This undoubtedly plays an important role in arresting corrosion, since corrosion is more dependent on chloride/hydroxide ratio rather than chloride concentration alone. Examination of rebars removed from treated slabs show only very slight rusting, whereas bars from the untreated control were heavily corroded.

The effectiveness of the treatment was also demonstrated by several other measurements. The macrocell current (current flowing between top and bottom mats of steel) was reduced from an average of 0.42 mA to very near zero by the treatment. Macrocell currents remain near zero 3-1/2 years after chloride removal. Half-cell potentials of the steel on the control slab were very corrosive, whereas steel potentials on treated slabs were very non-corrosive.

Work under this contract also addressed several concerns which arise as a result of the passage of large amounts of current through concrete. Reinforcing steel-concrete bond strength was measured over the full range of current and charge experienced for chloride removal. The application for a very high current density, 5,000 mA/ft^2 (50 A/m^2), and/or high amount of total charge, 200 A-hr/ft^2 (2,000 A-hr/m^2), did result in a reduction of bond strength when compared to controls containing salt. The use of either lower current density or lower charge, however, had no adverse effect.

Concrete compressive strength was not reduced at lower current densities, but concrete treated at high current, 2.0 A/ft^2 (20 A/m^2), for long periods of time, 500 A-hr/ft^2 (5,000 A-hr/m^2), did experience a softening of the cement paste around the reinforcing steel. This softening is probably also responsible for the loss of bond strength of severely treated specimens. This strong treatment also caused one slab to crack and delaminate. For these reasons, the current regime used in previous studies, up to 2,000 mA/ft^2 (20 A/m^2), was judged to be excessive, and more modest treatment conditions were used for field trials.

The possible hydrogen embrittlement of conventional reinforcing steel was also studied. Although a slight, temporary loss of ductility was noted on smooth specimens, this loss was determined to be not structurally significant. The possible hydrogen embrittlement of high-strength steel contained in prestressed concrete structures was not studied under this contract. The risk of hydrogen embrittlement of prestressed steel is considered high, however, and such structures were not considered for chloride removal field trials.

The generation of chlorine gas from the anode, which could present a safety hazard, was also studied and is reported in Volume I. It was decided that the electrolyte should be maintained at a basic pH to prevent generation of chlorine gas. Several buffers were studied for this purpose, and a sodium borate buffer was found to be the most effective and practical. Control of the electrolyte pH in this way also prevented any etching or acid attack of the concrete surface.

Other studies have shown that electrochemical treatment of concrete causes an increase in the alkali cation concentration in the vicinity of the reinforcing steel. The studies reported in Volume I confirmed these results, and demonstrated that serious damage could result if the chloride removal process was used on concrete containing alkali-reactive aggregate. But it was also found that the presence of lithium ion in the electrolyte could be used to mitigate this problem. Where alkali-sensitive aggregate is present, the use of lithium borate buffer is recommended. The field trial in Ontario was conducted on a structure which contained alkali-sensitive aggregate.

Based on the laboratory and test yard results, a chloride removal treatment process was defined which results in effective removal of chloride without any damage to the concrete or reinforcing steel. All treatment areas, current densities, and total charges are based on concrete surface area unless otherwise noted. Treatment current density is limited to less than 500 mA/ft^2 (5 A/m^2) of concrete. System voltage is also limited by OSHA to less than 50 volts for safety reasons. Under these conditions, treatment time for chloride removal can be expected to be 2 to 4 weeks. Typical applied charge will be 80 to 120 A-hr/ft^2 (800 to 1200 A-hr/m^2). Treatment times and charges greater than these will probably yield little additional benefit in terms of chloride removed or corrosion prevented. This treatment is probably more suitable for a bridge substructure rather than a deck, which would require closure to traffic for a relatively long period of time. For this reason, the original plans to treat two bridge substructures and two decks were modified, and field validation trials were finally conducted on three bridge substructures and only one deck.

The chloride removal system proposed for field validation trials consists of an inert catalyzed titanium anode, which is applied to the surface of the concrete together with a blanket material which serves to contain electrolyte. The blanket is a composite of a reusable geotextile outer blanket and an inner water-absorbent layer. The anode/blanket composite is fixed to the outer surface of the structure, and may be prefabricated for standard bridge members. An electrolyte of approximately 0.2 molar sodium (or lithium) borate buffer is then continuously circulated to the top of the chloride removal system. From there the electrolyte flows by gravity down the blanket and back to a sump compartment.

Several states were contacted, and many volunteered their willingness to participate in the chloride removal field trials. Each of these states supplied information on candidate structures. Based on this information, a limited number of structures were visited for further evaluation. Finally, the structures described in this report were selected for field validation of electrochemical chloride removal.

2

Ohio Bridge Deck Field Trial

Summary and Conclusions

The first chloride removal field trial was conducted on Bridge 295-0412 near the Neopolis/Waterville Road intersection in Lucas County, Ohio. This bridge deck had a total surface area of 3024 square feet (300 m^2), of which half was treated and half was left as a control area. Testing showed the bridge to be actively corroding, although the concrete was not yet showing distress. Chloride concentration ranged from 23 lb/yd^3 (14 kg/m^3) near the top of the deck surface to 3.4 lb/yd^3 (2 kg/m^3) at the reinforcing steel. All the chloride analyses prior to treatment showed chloride concentrations well above the accepted threshold for corrosion. Linear polarization corrosion rate readings[1] ranged from 1.1 to 1.8 mA/ft^2 (1.1 to 1.8 $\mu A/cm^2$), which indicates deterioration due to corrosion will occur in the range of 2 to 10 years.[2] Only 5 percent of the potential readings taken during the potential survey were greater than -200 mV versus copper/copper sulfate electrode (CSE or $Cu/CuSO_4$), the range characterized by ASTM C 876-91 as being non-corrosive.

Since the treated area was a horizontal slab, electrolyte confinement was obtained by building a pond on the bridge deck. A catalyzed titanium mesh anode was placed in the pond together with a 0.08 M sodium borate electrolyte. Current density at the maximum applied voltage (50 V) was low, starting at 0.07 A/ft^2 (0.7 A/m^2) and gradually declined to 0.03 A/ft^2 (0.3 A/m^2). This low current was partly due to the cold temperatures experienced in October and November of 1991, and partly due to the high resistivity of the concrete cover. Because of the low current level, treatment time was long. A total of 61 and 64 $A\text{-}hr/ft^2$ (610 and 640 $A\text{-}hr/m^2$) was attained for the south and north zones, respectively, in about 61 days of operation.

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[1]Measurements were made with the KCC INC 3LP Device.

[2]Clear, K.C. "Measuring Rate of Corrosion of Steel in Field Concrete Structures," January, 1989.

Post-treatment analysis of the concrete showed that chloride content within 1 in. (2.5 cm) of the steel had been reduced from an average of 4.5 to 1.8 lb/yd^3 (2.7 to 1.1 kg/m^3). Chloride analyses of the electrolyte pond indicate that about 11 gm of chloride per square foot (110 gm/m^2) was removed during the treatment. The efficiency was about 20 percent. Current efficiency is herein defined as follows:

$$\%CE = \frac{(grams\ chloride\ removed)}{1.32 \times (ampere\text{-}hours)} \times 100$$

Problems encountered, other than the low current level and long treatment time, include overflow of the pond due to excessive rainfall, and vandalism.

This chloride removal trial was considered a success, and the site was scheduled for post-SHRP monitoring.

This deck has recently received a protective epoxy overlay, which must be breached for future testing.

Installation

Background

The bridge deck had no overlay, no significant cracks, no apparent signs of corrosion-caused damage or other deterioration, and carried minimum traffic volume. Chloride concentrations exceeded the corrosion threshold at the top reinforcing steel making this bridge deck an ideal candidate for the electrochemical chloride removal treatment.

Surface Preparation

Approximately 25 percent of the surface on the designated treatment area was partially covered by asphalt from a recent road resurfacing project adjacent to the bridge. A company specializing in high pressure washing was contracted to perform surface cleaning.

A biodegradable emulsified solution, Caustic Butyl Booster #116, manufactured by Algoma Product Incorporated, was used to break down the asphalt before high pressure washing. Within 30 minutes after the solution was applied, the asphalt began to dissolve. The water temperature for cleaning was about 200°F (93°C) with a nozzle pressure of 1000 psi. After washing, tiny patches of asphalt, less than the size of a dime, were left scattered on the bridge deck surface.

Electrolyte Containment Ponds

Cement blocks, 4 in. x 4 in. x 16 in. (10 cm x 10 cm x 40 cm), were used to construct the ponds over the treatment area to contain the electrolyte. The area to be treated was divided into two equal zones. Each zone comprised two equal reservoirs separated by a weir. This was to retain the electrolyte so that the anode was permanently immersed despite the fall of the deck from the median to the curb. The ponds were named according to their locations on the deck. Two ponds on the south end of the bridge were a single zone and identified as south curb (SC) and south middle (SM). Similarly, the two ponds on the north side of the bridge were a single zone and identified as north curb (NC) and north middle (NM) (Figure 2-1).

Cement blocks were used for the dams to form the ponds. A scrub coat of mortar was applied onto the base of the dam to maximize the bond between the deck and the blocks. The blocks were set on a 1/2-inch (1-cm) thick latex modified mortar base. The 1/4-inch (0.8-cm) gaps between the cement blocks were also filled with the same mortar. Within an hour, the mortar cured and the cement blocks were firmly secured in place.

The latex modified mortar was a mixture of styrene-butadiene rubber (SBR) latex solution, water, and dry mortar mix. The latex and water were pre-mixed at a 1:1 ratio. Approximately 1-1/2 gal (6 l) of the latex-water solution was mixed per 90-pound (43-kg) sack of dry mortar mix.

Sikaguard 61, an underwater epoxy with 30-minute pot life, was used to coat the interior surfaces of the blocks.

A thick layer of the epoxy was applied to the dam and approximately 1 in. (2.5 cm) of the deck to keep the electrolyte from penetrating the cement blocks and leaking out (Figure 2-2).

Prior to start-up, a leak test was conducted on the reservoirs. Several leaks in the dam were identified along the east side of the bridge. After several unsuccessful attempts to stop leaks, a latex mortar barrier was cast behind the dam along the east edge of the bridge. A form was constructed by wedging wooden 2-by-4s between the guardrail supports and wooden 1-by-8s which were placed vertically against the edge of the deck. A bead of silicone caulk was placed on the 1-by-8s where the board came in contact to the edge of the concrete deck to form an additional seal.

The latex mortar was prepared and poured into the forms. The end product was a dense, 1-in. (2.5-cm) thick latex mortar barrier behind the dam. The form work was left in place and was removed after the treatment (Figure 2-2).

Figure 2-1. Zone Dimensions and Configuration

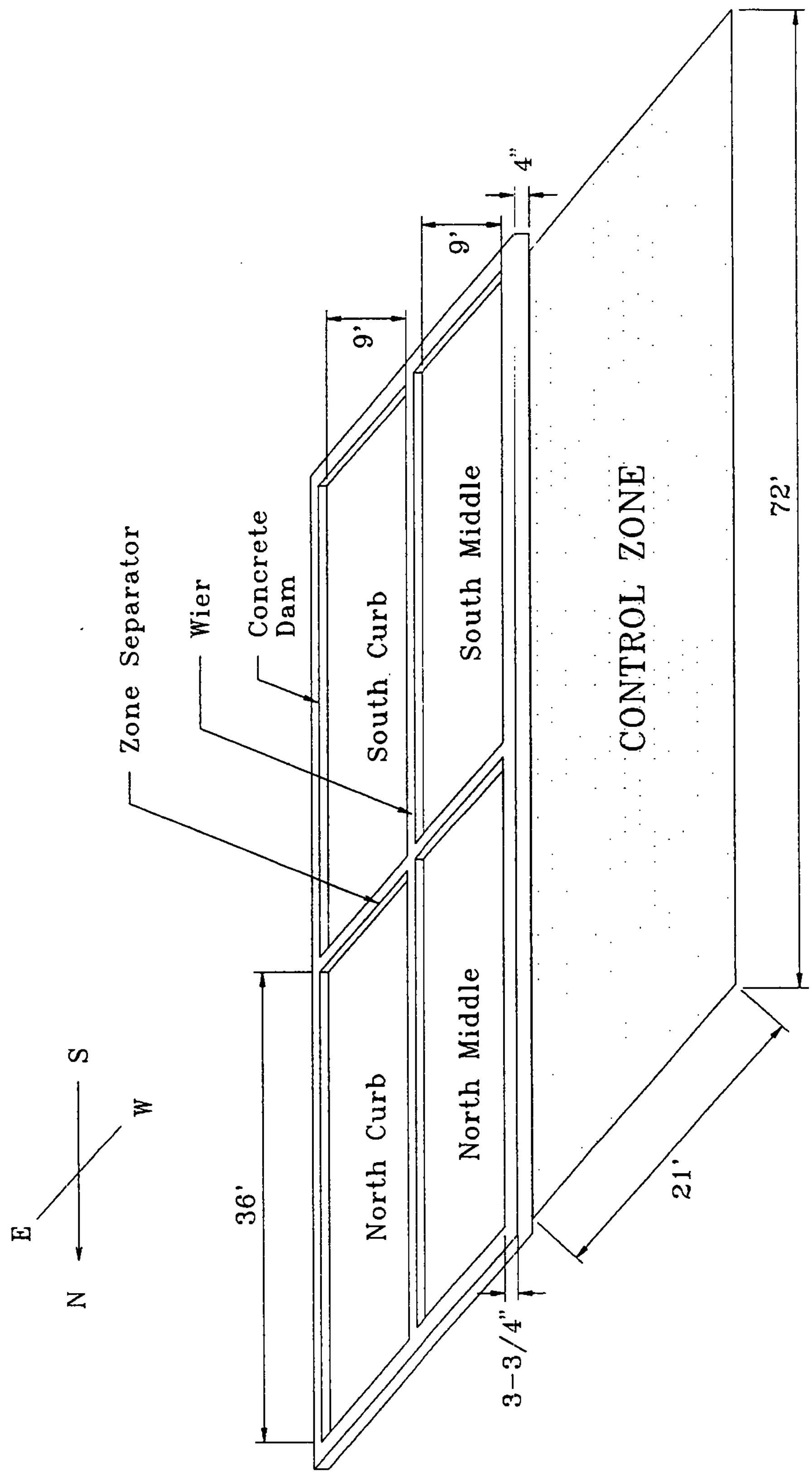
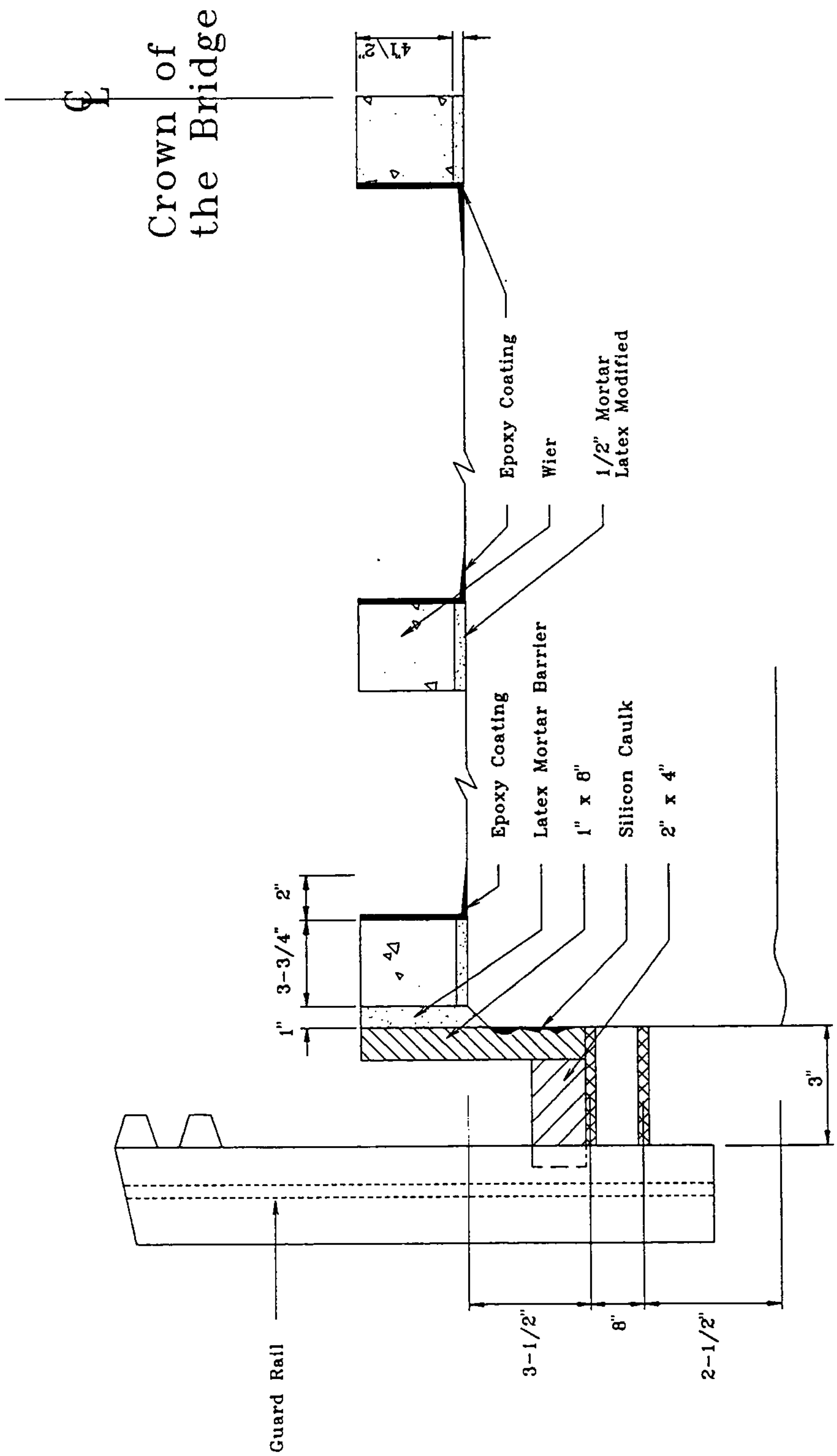


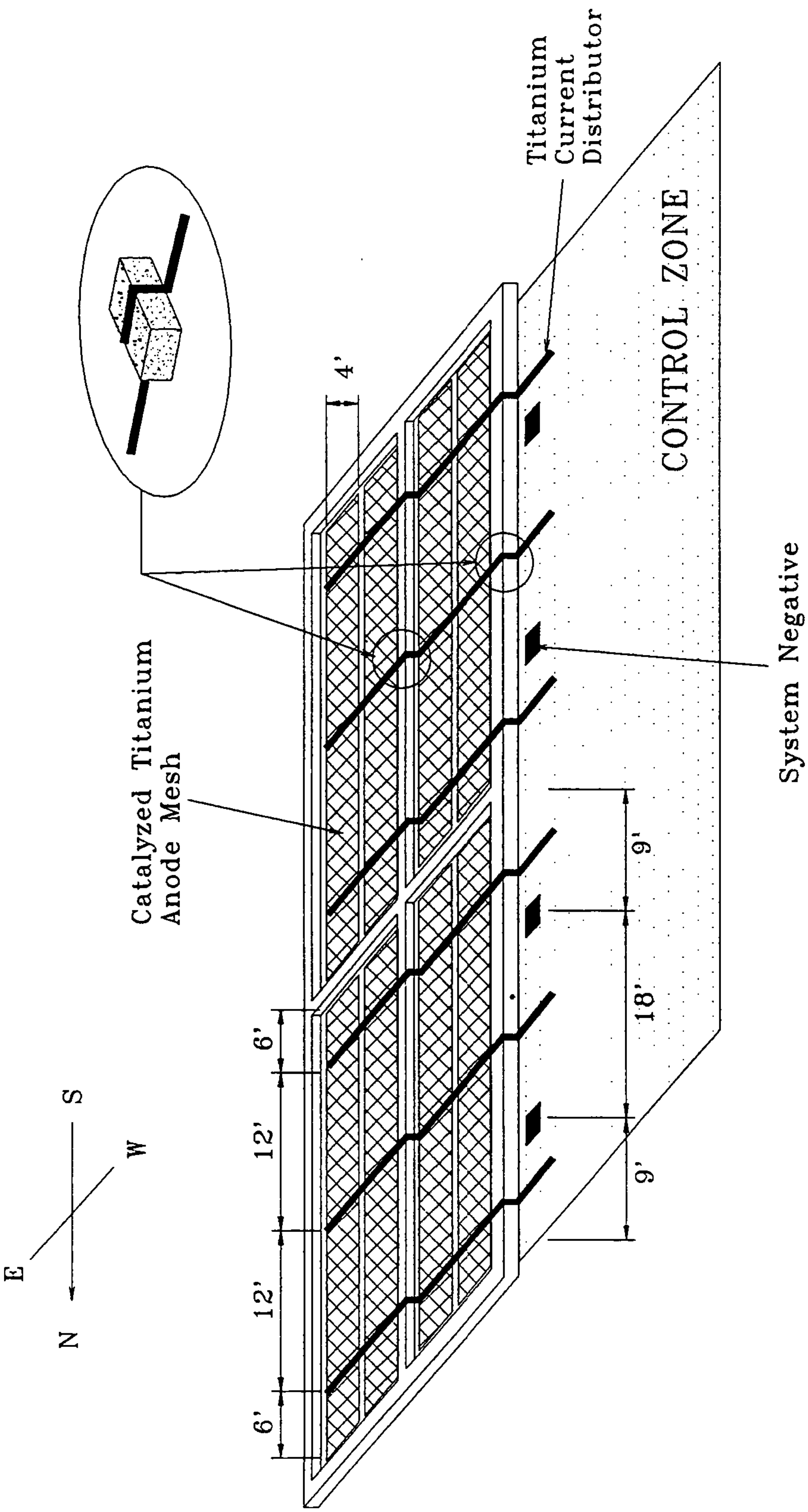
Figure 2-2. Dam Epoxy Coating Schematic



Current Distributor Strips and Anode Mesh

Six 21-inch-long (53-cm) anode current distributor strips, 0.5 in. wide x 0.035 in. thick (1 cm x 0.09 cm), were positioned parallel to the expansion joint in the bridge deck. The current distributors were ASTM 265, Grade 1 titanium. To minimize voltage drop and maintain uniform current distribution, three current distributor strips were used per zone. Figure 2-3 shows the dimensions and locations of the current distributor network. The strips were designed to run over the weir as shown in the detailed view of Figure 2-3. An inert anode mesh coated with precious metallic oxides was installed over the current distributor strips. Elgard 300 mesh, which provides 0.30 ft^2 of anode area per ft^2 of concrete (0.3 m^2/m^2), was selected to maximize the anode area available. The mesh was placed in 4-foot widths (1.2-m) to cover the treatment area and held in place with non-conductive plastic fasteners hammered into pre-drilled holes. Generally, the fasteners were only required at the ends of the quadrants but occasionally sor ·ere requ.red at locations where the mesh bowed upward. The anode mesh was then resi: .e welded to the current distribution strip at approximately four spots per lin. ft (30-cm) of strip. The current distributor net· rk was designed for 200 A per zone, equating to approximately 300 mA/ft^2 (3 A/m^2) of conc .te.

Figure 2-3. Anode Mesh and Anode Current Distributor Schematic



Equipment

Rectifiers Two rectifiers, custom built by Darrah Electric Company Incorporated, provided SCR controlled DC power to the chloride removal system. Both rectifiers required 220 VAC-3ϕ power, and were air cooled and had DC volt, amp, and ampere-hour meters. The rectifiers were capable of being operated at constant current or constant voltage. The outdoor enclosure had provisions for locking. The operational ratings of the rectifier are listed in Table 2-1.

Table 2-1. Rectifier Description

Specification	Rating
Output DC Voltage	0 - 50 V
Output DC Amperes	0 - 200 A
DC Kilowatt	10 KW
Input AC Voltage	230 V
Input AC Amperes	32 A
Phase	3 ϕ
Frequency	60 Hz

Electric Power Generator Since local 3ϕ AC power lines were not available, a diesel fueled electric generator manufactured by Isuzu, Japan, was rented from Williams Detroit Diesel-Allison to provide the AC power for the system. The specifications for the generator are shown below in Table 2-2 and 2-3.

Table 2-2. AC Electric Power Generator Operation Data

Phase	3
Frequency	60 Hz
Rated Output	60 KVA
Rated Voltage	240 V or 480 V
Rated Current	144 A or 72.2 A
Power Factor	0.8

Model: DB-0661 I Serial Number: 3619828

Table 2-3. Engine Operation Data

Model: Isuzu Qd-145 (68D1)	
Rated Output	18 HP @ 1800 RPM
Displacement	5785 cc
Fuel Tank Cap	89 gallons

A 200-gallon (750-liter) diesel fuel tank was rented and kept filled by a local diesel fuel company. During operation, the generator was checked and refueled every two days.

System Connections

Generator Wiring to Rectifier Four-conductor, Nº 8 AWG cables were used to connect the rectifier to a 220 V-3ϕ generator. One-half-in. (1.25-cm) copper lugs were crimped to the cables and connected to the generator. The other end was connected to the rectifier.

System Positive Connections Each current distribution strip was connected to a Nº 4 AWG welding cable. The other end of the cable was connected to a single Nº 1 AWG cable which terminated at the positive lug terminal of the rectifier. The exposed system positive wire connections were wrapped with electrical tape. A typical system positive connection is shown in Figure 2-4.

System Negative Connections Two system negatives were installed per zone, and were located approximately 6 in. (15 cm) away from the dam. A pachometer was used to locate reinforced steel. Then a 6 in. x 4 in. (15 cm x 10 cm) rectangular hole was excavated, exposing the rebar for the system negative connection.

The exposed steel was cleaned, drilled and tapped. One end of a Nº 4 AWG cable, with a 1/4-in. (0.64-cm) copper attachment lug was connected to the steel. The two cables were connected to a single Nº 1 AWG cable. This cable terminated at the negative terminal in the rectifier. The connection at the steel was coated with a thick layer of Sikaguard 61 epoxy to prevent moisture intrusion and corrosion. The other exposed connections were wrapped with electrical tape. A typical system negative connection is shown in Figure 2-5.

Figure 2-4. System Positive Connection

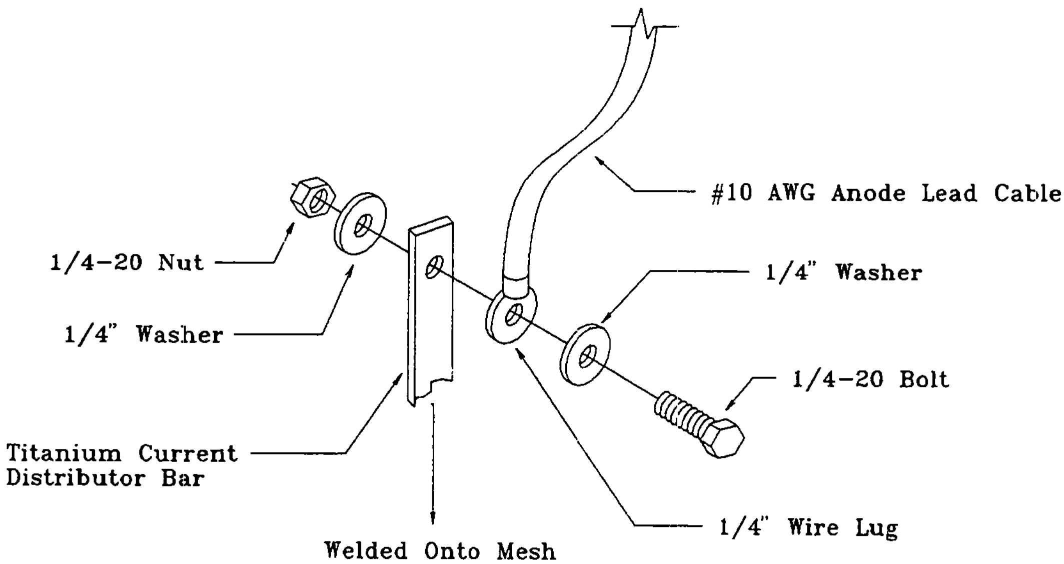
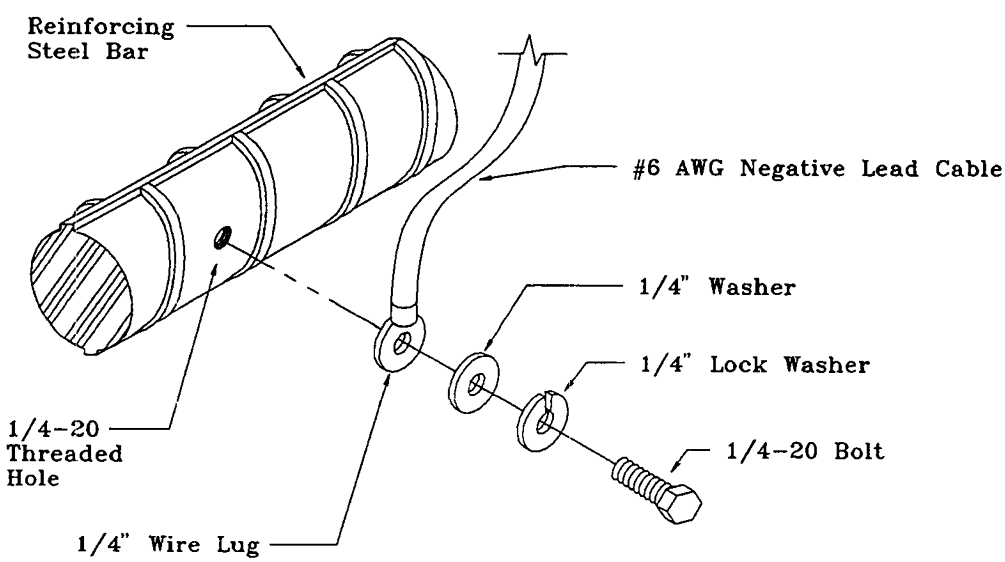


Figure 2-5. System Negative Connection



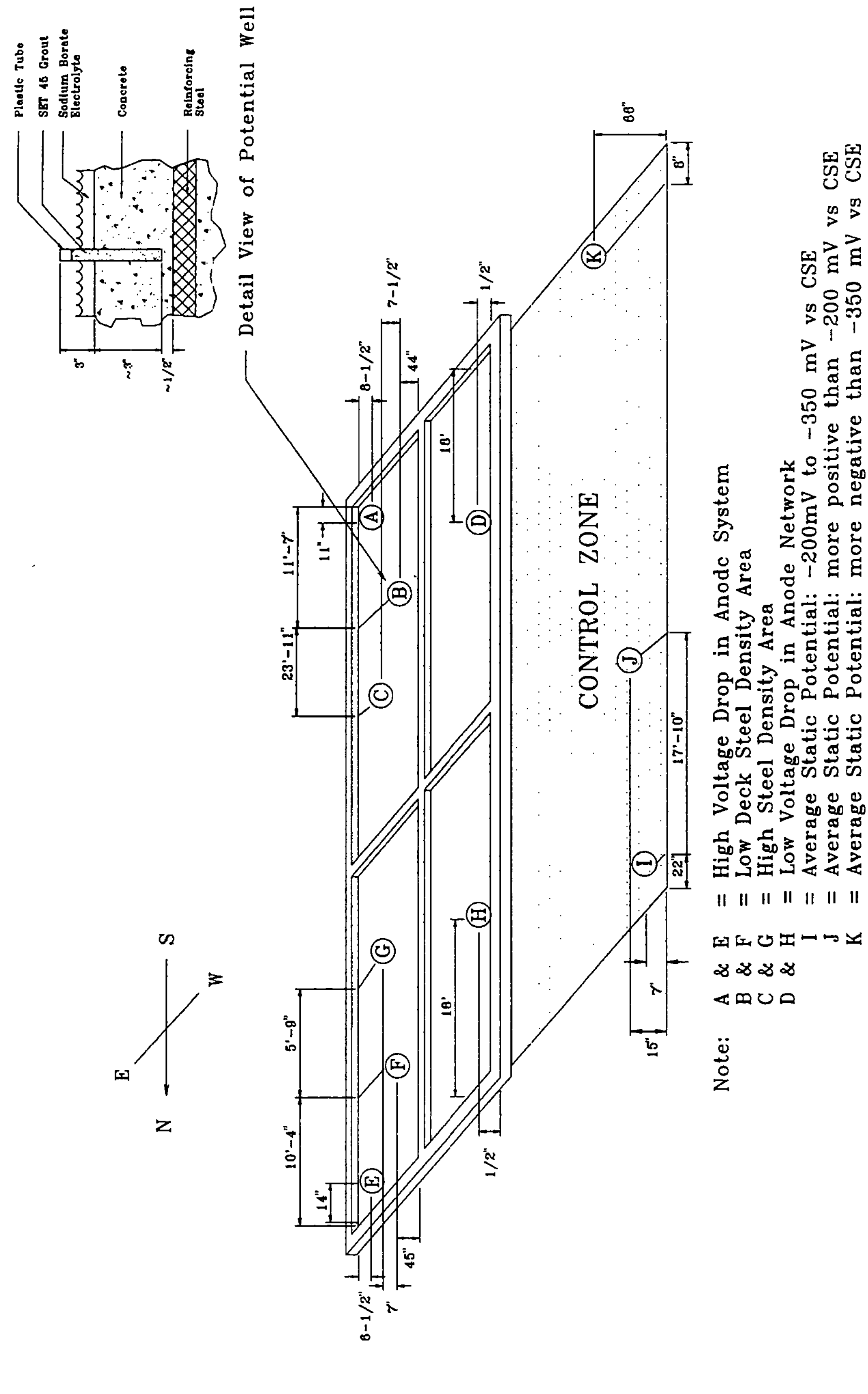
Potential Well Installations

Four potential wells were installed per zone. The potential wells were located where the voltage drop through the anode network would be the highest and the lowest, and at the highest and lowest steel density areas.

The potential well was constructed by first determining the location and depth of the reinforcing steel. A 1/2-in. (1-cm) diameter, approximately 3-in. (8-cm) deep hole was drilled into the concrete within 1/2 in. (1 cm) of the steel. The residual concrete powder was cleaned from the hole and a 1/2-in. (1-cm) diameter plastic tube was inserted and trimmed to above the anticipated electrolyte level. This was done to isolate the potential well from the sodium borate electrolyte. The tube was backfilled with Set 45 quick setting mortar. The locations of the potential wells are shown in Figure 2-6.

Three locations per zone were marked in the untreated control area for potential monitoring. The control area sites were chosen to monitor steel with corrosion potentials in the more positive than -200 mV, between -200 mV and -350 mV, and more negative than -350 mV range with respect to a $Cu/CuSO_4$ reference cell. The locations of the three sites are also shown in Figure 2-6.

Figure 2-6. Potential Well Location Schematic



Electrolyte

The sodium borate (Na_3BO_3) electrolyte was prepared by dissolving 15.5 lb (7.02 kg) of anhydrous boric acid (H_3BO_3) and 27.5 lb (12.5 kg) of anhydrous sodium hydroxide (NaOH) in a 55-gal (210-l) chemical resistant drum containing potable water. Two drums of electrolyte were prepared for each reservoir, added added to the reservoir, and then diluted with an additional 5 drums of potable water. The resulting solution in each reservoir was 375 gal (1,420 l) of 0.08 M sodium borate electrolyte. Prior laboratory results showed that, due to the anticipated low current density, this solution would maintain a basic pH for a significant length of time.

The initial pH level was 12.2, 12.2, 12.5, and 12.7 for quadrants SC, SM, NC, and NM, respectively. The pH and sodium borate concentration decrease proportional to the amount of charge passed during the treatment.

After filling each reservoir with 375 gal (1,420 l) of electrolyte, the electrolyte level for each quadrant was measured and recorded. The depth was permanently marked so that the monitoring crew could always refill the reservoir with potable water to the pre-marked level. The electrolyte depth was 1-13/16 in. (4.6 cm), 2 in. (5.1 cm), 1-1/16 in. (2.7 cm), and 1-3/8 in. (3.5 cm) for quadrant SC, SM, NC, and NM, respectively.

Operation

Pre-Treatment Evaluations

Static Half-Cell Potential Survey

A static potential survey was done that included 590 readings. A contour map of these static potential readings is shown in Figure A-1 in Appendix A, and the readings summarized in Table 2-4. The northbound and southbound lanes of the deck were similar, but the northbound lane was slightly more corrosive.

Table 2-4. Pre-Treatment Static Potential Survey of Ohio Bridge Deck Field Site

Static Potentials (mV vs. $Cu/CuSO_4$)					
Southbound (298 Readings)			Northbound (292 Readings)		
<-350	-350 to -200	>-200	<-350	-350 to -200	>-200
50	191	57	52	225	15
17%	64%	19%	18%	77%	5%

3LP Corrosion Rate

The three electrode linear polarization (3LP) rate of corrosion technique was used for identifying relative corrosion rates of reinforcing steel in field structures. This procedure is based on the Stern-Geary characterization of the typical polarization curve for corroding metals, in which a linear relationship is described mathematically for a region on the polarization curve in which slight changes in current applied to corroding metal in an ionic solution cause corresponding changes in the potential of the metal. If a large current is required to change the potential a given amount, the corrosion rate is high.

Linear polarization corrosion rate readings were taken at four high static potential locations on the deck and ranged from 1.1 to 1.8 mA/ft^2 (1.1 to 1.8 $\mu A/cm^2$) as shown in Table 2-5. This correlated to a corrosion rate (derived from Faraday's Law) of 0.5 to 0.9 mil per year, and represented high rate of corrosion despite relatively low deck temperatures at the time of testing. Readings in this range would lead one to expect significant deterioration due to corrosion in the range of 2 to 10 years.[3]

[3]KCC 3LP Device Manual, Kenneth C. Clear, Inc., Virginia

Table 2-5. Pre-Treatment 3LP Corrosion Rate on Ohio Bridge Deck Field Site

4 Locations on Northbound Lane with KCC 3LP Device

1: 1.8 mA/ft^2; -297 mV vs. $Cu/CuSO_4$
2: 1.1 mA/ft^2; -292 mV vs. $Cu/CuSO_4$
3: 1.1 mA/ft^2; -255 mV vs. $Cu/CuSO_4$
4: 1.4 mA/ft^2; -387 mV vs. $Cu/CuSO_4$

mils/year = mA/ft^2 x 0.4915

Concrete Chloride Content

Three 4-inch (10-cm) diameter cores were taken at locations corresponding to 3LP readings No. 1, No. 2, and No. 3 in Table 2-6. The core taken at location 3 was over crossing bars and was analyzed for chloride content (Table 2-6). The analyses showed chloride concentrations well above the 1.1 $^{\#}Cl^-/yd^3$ of concrete (0.7 kg/m^3) threshold for corrosion.

Table 2-6. Pre-Treatment Concrete Chloride Analyses of Ohio Bridge Deck Site

Distance from Surface, inches	%Cl^- by wt concrete	$^{\#}Cl^-/yd^3$
7/16 to 11/16	0.582	22.77
31/32 to 1-7/32	0.266	10.43
1-7/16 to 1-11/16	0.245	9.59
1-15/16 to 2-3/16	0.161	6.29
2-7/16 to 2-11/16	0.086	3.35

Top of #6 bar is at 2-11/16 inches

Core Petrographic Analyses

A concrete core without steel in it was characterized as an air-entrained portland cement concrete containing a 1-1/2 in. nominal (4-cm) maximum size limestone coarse aggregate and a natural sand. The limestone coarse aggregate was a cryptocrystalline to microcrystalline rock that was hard and dense. The limestone aggregate varied from pale yellowish-brown to dusky yellowish-brown in color. The fine aggregate was composed principally of quartz, carbonate rock types, and shale. The proportions of fine and coarse aggregate in the concrete were judged to fall within a normally accepted range. The concrete represented by the core was well consolidated and showed no gross porosity or honeycomb.

The total air void content of the concrete was estimated at 6 to 8 percent and the quality of the entrained air system was judged to be excellent.

The cement paste was well matured with a water-cement ratio estimated at less than 0.40. This relatively low water-cement ratio and the maturity of the cement paste may in part be responsible for the relatively high resistivity in this concrete. In general, there was a tight bond between the aggregate particles and the cement paste.

Overall, the concrete comprising this core was judged to be of excellent quality from the point of view of quality of the concreting materials, consolidation, quality of the entrained air system, water-cement ratio, and cement maturity. The concrete has shown excellent durability over its service life.

Laboratory Chloride Removal Testing

Two of the three 4-in. (10-cm) diameter cores taken from the Ohio bridge deck were set up for trial chloride removal. This was done to get an estimate of field trial parameters and to identify any possible problems prior to actual field trial. Results indicated that a current density of 0.1 to 0.2 A/ft^2 (1 to 2 A/m^2) at 50 V would be realized. This relatively low current density was unexpected even though there was 2-1/2 to 3-1/2 in. (6 to 9 cm) of concrete cover thickness. The low current density was apparently due to the high concrete cover and high resistivity.

Site Monitoring

Maintenance of the system required fuel additions to the generator, water additions for the electrolyte, and routine checks of power supply operations.

Site visits were made twice a week to obtain detailed operating data and collect electrolyte samples. The electrolyte samples were analyzed for pH and chloride ion concentration. A copy of the check list is in Appendix A, Figure A-2.

System Current

Each zone (north and south) of 684 ft^2 (68 m^2) was operated at constant voltage, 48 to 50 V. Start-up currents for both zones were 48 A, or 0.07 A/ft^2 (0.7 A/m^2), at 70°F (21°C) temperature. This is only slightly lower than expected according to laboratory testing of the pre-treatment core. The temperature was frequently 50 to 60°F (10 to 15°C), and the resulting currents dropped to approximately 30 A. November temperatures were very cold, as low as 30°F (0°C), and the currents dropped off even further to approximately 20 A, or 0.03 A/ft^2 (0.3 A/m^2). Lowering temperature was the major reason for current drop-off, and this was confirmed when the current later increased when the temperature increased.

On October 10, 1991, a black, reinforced polypropylene plastic cover was installed over the north zone in an attempt to maintain a higher electrolyte temperature and increase operating currents. The electrolyte temperature was increased by less than 2°F (1°C); indicating that the concrete deck temperature was the major influence.

It was a goal for this trial to obtain 100 A-hr/ft^2 (1000 A-hr/m^2) of total charge passed, approximately 8 weeks at 0.07 A/ft^2 (0.7 A/m^2). This was the total charge that the chloride removal efficiency in all of the laboratory slabs began to considerably decrease. By October 19, 1991, after 4-1/2 weeks of operation, only 32 A-hr/ft^2 (320 A-hr/m^2) of total charge had been accumulated and currents were decreasing due to low temperatures. It was felt that 100 A-hr/ft^2 (1000 A-hr/m^2) was not attainable at this site. Therefore, it was decided that at least 60 A-hr/ft^2 (600 A-hr/m^2) of total charge needed to be attained. This was comparable with two laboratory slabs that operated to that level. An additional 4-1/2 weeks of operation were required to reach this goal. A total of 61 and 64 A-hr/ft^2 (610 and 640 A-hr/m^2) was attained for the south and north zones, respectively, after nine weeks of treatment.

The south zone rectifier was found not operating several times. AC fuses had blown, but these were replaced and the rectifier was restarted.

Electrolyte Management

There was significant rainfall in the first week of October and the electrolyte overflowed. This pond flooding was another reason why the plastic cover was installed. Obtaining monitoring data became very difficult, and very windy conditions made the cover extremely difficult to manage. The cover was removed after about two weeks.

The pH was also monitored. It was 6 weeks into the treatment before an addition of sodium hydroxide was needed to raise the pH. This was the only time during the treatment that pH adjustment was needed. If heavy rains had not displaced some of the buffer solution, it is likely that pH adjustment would not have been needed at all.

Half-Cell Potential Monitoring

Half-cell potential measurements were taken at eight locations in the treated area. These readings indicated whether the location was receiving current. Initial pre-treatment values at these locations were approximately -0.300 V versus Cu/$CuSO_4$. Off potentials, taken when steady approximately 15 sec after current was turned off, during the treatment ranged from -1.4 to -1.8 V versus Cu/$CuSO_4$. Static potentials taken at three locations in the untreated control zone remained relatively steady. Typical data are shown in Appendix A, Figure A-2.

Vandalism

Several items totaling $500.00 were stolen, but the operation of the system was unaffected.

Post-Treatment Evaluations

Swiss Hammer Survey

A Swiss Hammer survey using ASTM C 805, the Standard Test Method for Rebound Number of Hardened Concrete, was made on the deck following the treatment. Eight traverses were made from east to west on the deck across both the treated and untreated lanes with hammer readings taken.

The average rebound number on both the untreated and treated sections of the deck was 34. This indicates that the treatment did not have an adverse effect on the integrity of the wearing surface.

Post-Treatment Cores

Four 4-in. (10-cm) diameter concrete cores, 4 to 5 in. long (10 to 13 cm), were taken for petrographic analyses to determine the effect of the electrochemical chloride removal process. One core was taken immediately adjacent to the core taken for pre-treatment chloride analysis for comparitive purposes. A ph showing the concrete core drilling process is shown in Figure A-3 in Appendix A.

The core from quadrant NC co...ned a #7 rebar 3-1/4 in. (8.3 cm) below the wearing surface of the deck. The core from quadrant SM contained a #8 bar located 3-1/4 in. (8.3 cm) below the wearing surface. Both cores contained two hairline ss than 0.001 in. wide (0.003 cm), vertically-oriented crazing cracks which penetrated the ring surface to a depth of 1 to 1-1/2 in. (2.5 to 5 cm). Cracks such as these are norma on bridge decks and were present in the deck prior to treatment. The treatment caused no new cracks.

microscopic examination of the wearing surface confirmed that the deck surface was virtually unaffected by the electrochemical treatment.

The mortar phase surrounding the steel showed a color change relative to the remaining bulk of the concrete. The change in color was from the normal light grey to a light brownish grey and had a "wet" appearance.

In the laboratory studies, this color change had been associated with an accumulation of alkali cations in the paste surrounding the bar. In either case, neither the continuity of the reinforcing steel/concrete bond nor the hardness of the cement paste surrounding the steel was adversely affected by the treatment.

In summary, petrographic results indicated that the treatment had no adverse effect on the quality or integrity of the deck.

Concrete and Electrolyte Chloride Analyses

Chloride analyses were performed on concrete powder samples taken from the four cores according to the Standard Method AASHTO T 260. Initial and final results are plotted on the graph in Figure 2-7. All these results are from cores containing steel, and laboratory testing indicated that much more chloride is removed from the concrete above steel than from concrete between steel. Since the major goal of the chloride removal process was to move chlorides away from the steel and reduce corrosion of chloride on steel, the results can be considered successful. The data show that, with only 60 A-hr/ft^2 (600 A-hr/m^2) of total charge passed, chlorides within 1 in. (2.5 cm) of the steel were reduced from 3 to 6 lb/yd^3 (1.8 to 3.6 kg/m^3) to 1-1/2 to 2 lb/yd^3 (0.9 to 1.2 kg/m^3). Similar results were obtained with the laboratory slabs.

The graph of Figure 2-8 contains plots showing the chloride ion concentration increase in the north and south zones. The initial portions of the curves, 0 to 17 A-hr/ft^2 (0 to 170 A-hr/m^2), represent a 20 to 24 percent removal efficiency. This was in line with the laboratory slab results. Heavy rains that caused electrolyte pond overflows and freezing temperatures that iced over the ponds prohibited the use of this method of chloride removal monitoring during the remainder of the trial.

Figure 2-7. Initial Versus Final Cl⁻ Profiles for Ohio Bridge Deck Field Trial

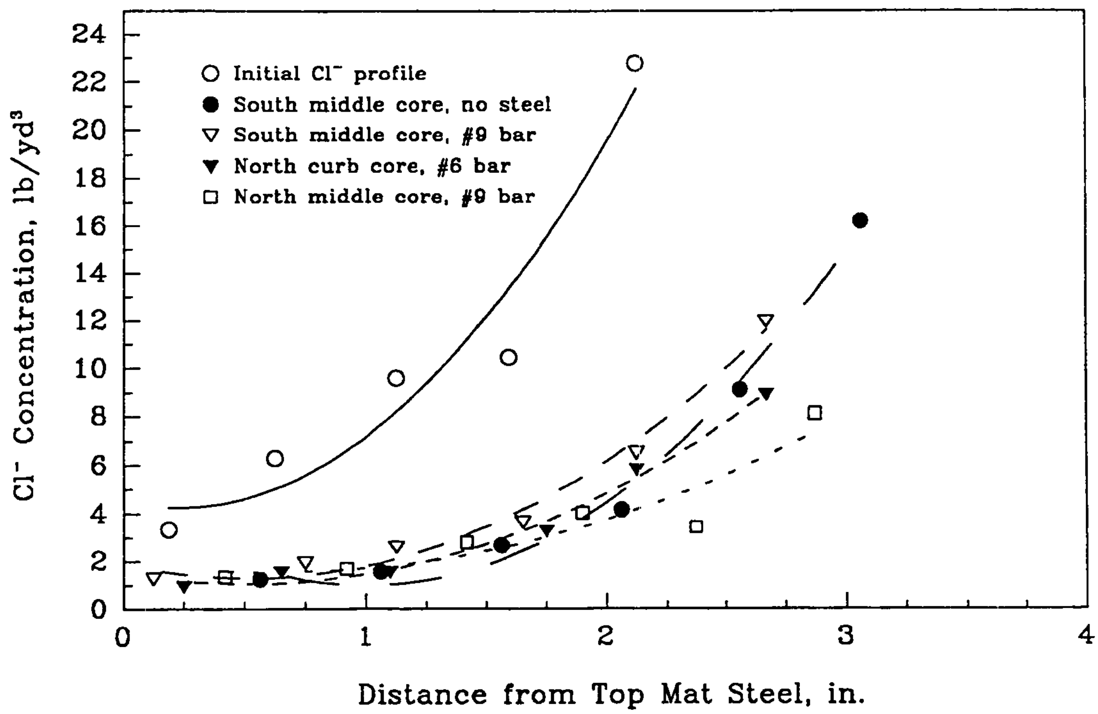
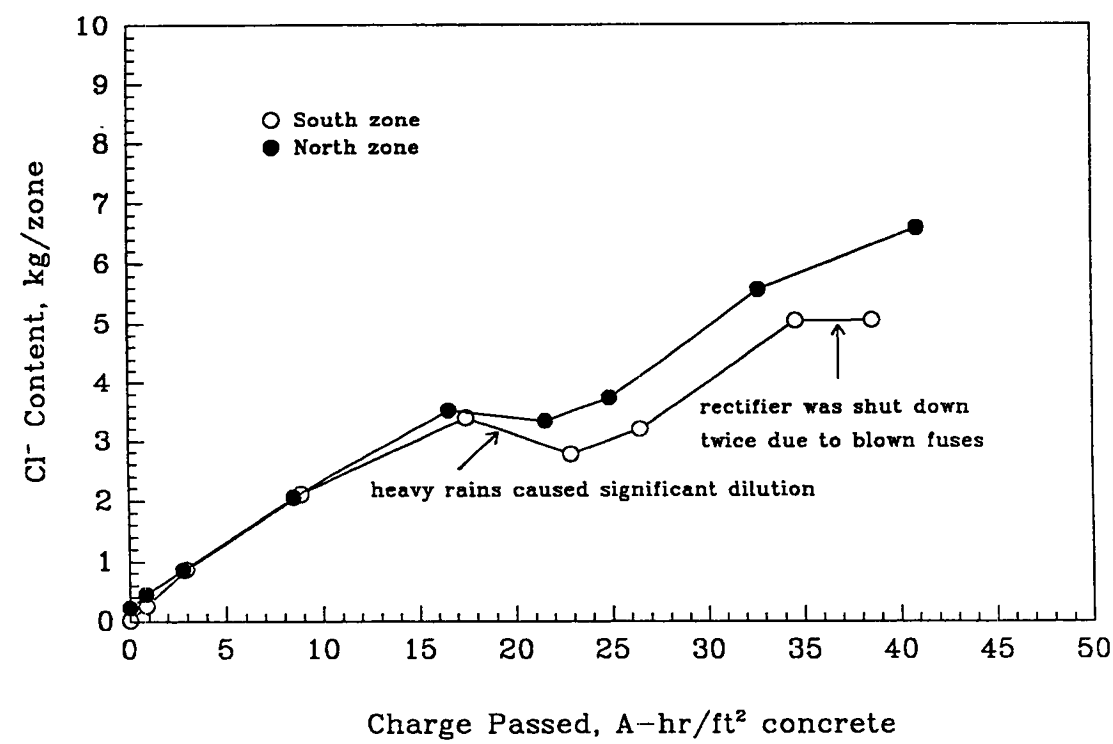


Figure 2-8. Electrolyte Chloride Content



System Removal

After the last set of field data were recorded, the power supply of the electrochemical chloride removal system was turned off and the system was dismantled.

Electrolyte

The spent electrolyte was pumped from the reservoir into chemical resistant drums. The drums were sealed and taken to the laboratory for disposal. The activities are shown in the photos in Appendix A, Figures A-3 and A-4.

Anode Material

After disconnecting the cables from the power sources, the anode current distributor strips were cut from the anode mesh. The plastic anode mesh fasteners were removed, the anode mesh was rolled up and stored away. See Figure A-5 in Appendix A.

Reservoir Dam

The cement blocks were easily removed with no apparent damage to the bridge deck. A rotary hammer drill with a chisel was used to remove the remaining mortar. See Figures A-6 and A-7 in Appendix A.

Form Work

The mortar barrier was removed with minor difficulties. There were two areas along the edge of the bridge where part of the concrete came off along with the barrier. This is shown in Figures A-8 and A-9 in Appendix A. The damaged areas were patched.

Costs

Materials

A list of disposable and single-use items is tabulated in Table 2-7. The cost per square foot of treatment area for these items was \$12 (\$120/m^2).

Table 2-7. Single-Use Item Costs

Material/Equipment	Description	Quantity	Price, \$
Cement blocks	4" x 4" x 16"	246 units	248.50
Mortar	Redi-Mix 80-lb bag	8 bags	36.00
SBR latex	Mortar additive	10 gallons	60.00
WaterPlug	Leak sealer	20 lbs	23.20
Epoxy	Sikagard 61 (A & B)	2 gallons	100.00
Concrete	Mix-Quik 90-lb bag	5 bags	20.50
Wood	2" x 4" - 8' long	13 units	28.50
Wood	1" x 8" - 8' long	10 units	57.60
Drums	55 gal water storage	8 units	625.00
Water	Electrolyte additive	Est. 3000 gal	90.00
NaOH	Na_3BO_3	160 kg	360.00
H_3BO_3	Na_3BO_3	70 kg	440.00
Current distributor	.035" x 1/2" x 21'	6 units	53.00
Generator rental	60 kW (9 weeks)	1 unit	6500.00
Fuel	For generator	1765 gal	1500.00
Ground rod	1/2" x 8' Copper	1 unit	9.20
Ground lug	Copper	1 unit	2.40
AC buss fuse	250 VA	24 units	20.40
Trailer rental	Transport supplies	1 day	58.90
Truck rental	Transport supplies	1 day	183.00
Miscellaneous tools	Brushes, brooms, etc.		100.00
Electrolyte disposal	Drums of Na_3BO_3	28 units	5600.00
		Total:	\$16,115.70
		Treatment area:	1368. ft^2
		Cost/unit area:	\$11.78/ft^2

Table 2-8 lists tools and equipment used for this trial that could be amortized over the course of several treatments. The single-use cost per square foot of treatment area for these items was $10/ft^2 ($100/m^2). An amortized cost for these items, assuming 10 such treatments, was $1/ft^2 ($10/m^2).

Table 2-8. Amortizable Item Costs

Material/Equipment	Description	Quantity	Price, $
Chain	Security	100 ft	110.00
Padlocks	Security	13 units	130.00
DC lead cable	#4 AWG - 20 ft	8 units	134.00
DC lead cable	#1 AWG - 6 ft	4 units	41.30
DC lead cable	#4 AWG - 10 ft	2 units	16.80
DC lead cable	#8 AWG/4 cond.-30 ft	2 units	81.70
Anode mesh	ELGARD 300	1368 ft^2	4100.00
Rectifier	Darrah 50VDC-200ADC	2 units	8400.00
Misc. cable connector	#4, #1, and #8	34 units	36.60
Strain relief	#8 - 4 conductor cable	2 units	22.00
Strain relief	#1 welding cable	10 units	4.00
Bolts	1/4"-20 x 3/4"	10 units	0.30
Bolts	3/8"-16 x 1"	4 units	0.30
Nuts	1/4"-20	6 units	0.10
Nuts	3/8"-16	4 units	0.20
Washers	1/4"	16 units	0.15
Washers	3/8"	8 units	0.90
Plastic cover	25' x 100'	1 roll	229.20
Caution tape	Safety	1 roll	30.00
SCE electrode	Test equipment	1 unit	30.00
pH meter	Test equipment	1 unit	100.00
Multimeter	Test equipment	1 unit	300.00
		Total:	$13,767.55
		Treatment area:	1368. ft^2
		Cost/unit area:	$10.06/ft^2
		Amortized cost:	$1.01/ft^2

Total material costs, single-use and amortized, were $13/ft^2 ($130/m^2).

Labor

Table 2-9 summarizes the man-hour requirements for this chloride removal trial. The total labor cost for installation, maintenance, and removal was $8/ft^2 ($80/m^2).

Table 2-9. Man-Hour Requirements

Installation

Crew	Hours	Rate, $/hr	Cost, $
Supervisor/laborer	42	55.00	2310.00
Operator/laborer	42	40.00	1680.00
Laborer	42	25.00	1050.00
Total man-hours:	126	Labor cost:	$5040.00

Operation

Crew	Hours	Rate, $/hr	Cost, $
Supervisor/laborer	36	55.00	1980.00
Operator/laborer	36	40.00	1440.00
Laborer	54	25.00	1350.00
Total man-hours:	126	Labor cost:	$4770.00

Removal

Crew	Hours	Rate, $/hr	Cost, $
Supervisor/laborer	6	55.00	330.00
Operator/laborer	6	40.00	240.00
Laborer	8	25.00	200.00
Laborer	8	25.00	200.00
Total man-hours:	28	Labor cost:	$970.00

Total labor costs:	$10780.00
Treatment area:	1368. ft^2
Cost/unit area:	$7.88/ft^2

Man-hour estimates include only the time spent at the site. Installation and removal tasks were discussed earlier in this chapter. Operation tasks include data collection four times a week, electrolyte maintenance, electrical equipment maintenance, and generator refueling.

The hourly labor rates were estimated, based on salary and overhead in the year 1991.

Total Costs

The cost of this trial, including single-use materials, amortized materials, and labor, was $21/ft^2 of treated area ($210/m^2). This does not include travel expenses or standard tools, such as drills and hammers. The cost of chloride removal could be reduced by fully developing the process and procedures and treating larger areas at one time. A business could accomplish this by buying materials in bulk, owning and amortizing major equipment (generator), and finding economical electrolyte disposal means.

3

Florida Marine Substructure Field Trial

Summary and Conclusions

The second chloride removal field trial, and the first on a bridge substructure, was conducted on pilings beneath the B. B. McCormick Bridge, located on State Road 212 south of Jacksonville, Florida. Corrosion cracking had been reported on pilings, a result of high chloride content in the splash zone. Chloride content averaged 9.4 lb/yd^3 (5.6 kg/m^3) in the top 4 in. (10 cm) of concrete within 1 ft (30 cm) of mean high tide. A potential survey indicated a high probability of corrosion at and below mean high tide level, and no corrosion above mean high tide level.

Chloride removal anode/blanket composites were installed on each pile from 3 ft (1 m) above high tide to 5 ft (1.5 m) below high tide. The bottom of the composites was about 1 ft (30 cm) under water at low tide. Seawater was continuously circulated from the top and then drained down. The electrolyte was not captive and could not be used to assess system performance. The blankets were wrapped with plastic film to inhibit leakage of current to seawater.

The system operated for about 18 days at an average current density of 0.33 A/ft^2 (3.3 A/m^2), accumulating 135 A-hr/ft^2 (1,350 A-hr/m^2) of total charge. System voltage was only about 20 V, indicating a very low resistivity.

During operation, the lower 4 ft (1.2 m) of anode received about 85 percent of the total current, while the upper 4 ft (1.2 m) received the remainder. Although the lower portion of the piling might be expected to be more conductive, and therefore draw more current, this imbalance indicates that considerable current was leaking to the seawater despite the outer plastic wrap. This was current which did not take part in the removal process. Because of this, the amount of charge applied to the piling is unknown.

A potential survey taken after system removal indicated strong cathodic polarization of the steel, particularly on the lower portion of the test area. Only limited chloride analyses were conducted after treatment, and the amount of chloride removed could not accurately be assessed.

Although the steel was strongly polarized, and some chloride was removed during treatment, the success of this trial is difficult to judge.

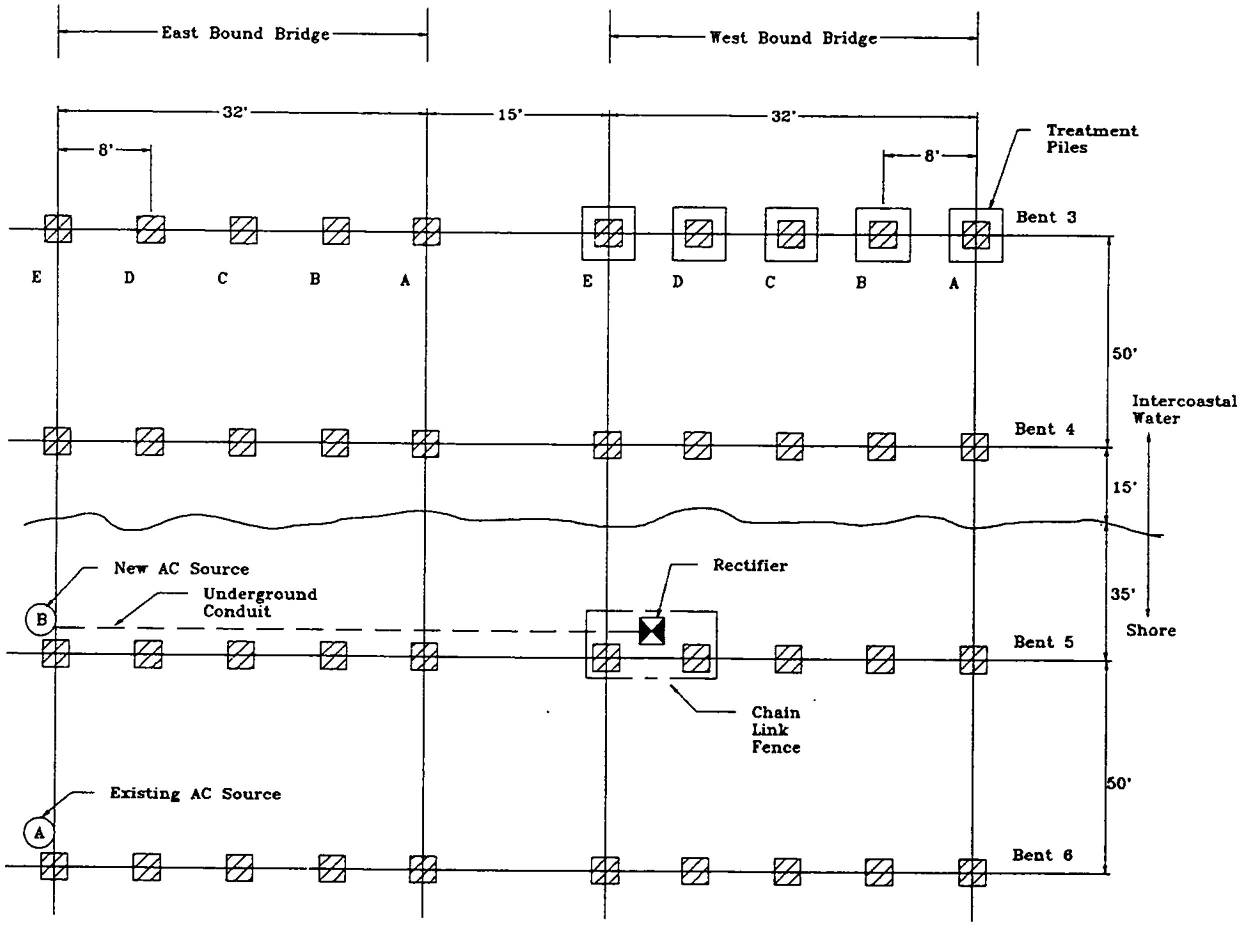
Installation

Background

The construction of the B. B. McCormick Bridge was completed in 1948. The bridge was built using quartzite river rock coarse aggregate for the concrete, and consisted of two parallel and identical eastbound and westbound bridge structures, coded as Nos. 720068 and 720069. The overall length of each bridge is 515 ft (157 m), and is located on State Road 212 (US 90) spanning across the Atlantic Intracoastal Waterway south of Jacksonville, Florida.

The deck elevation is approximately 30 ft (9 m) above the average high tide. Six bents are used to help support the deck. Each bent consists of a bent-cap on five 18-in. x 18-in. (45-cm x 45-cm) square piles reinforced with conventional Grade 60 reiforcing steel. The bents of the westbound and eastbound bridges were numbered from 1 through 6 beginning from the east. The piles were identified as A through E beginning from the north and running southward. Some of the supporting piles were partially submerged in seawater and subjected to tidal actions (Figure 3-1). The tidal change has been measured as high as 8 ft (2.5 m). The chloride content, electrical resistivity, and pH of the seawater are 9,000 to 10,280 ppm, 40 ohm-cm, and 7.3, respectively. The splash zone is a highly corrosive environment.

Figure 3-1. General Plot Plan: B. B. McCormick Bridge, Florida

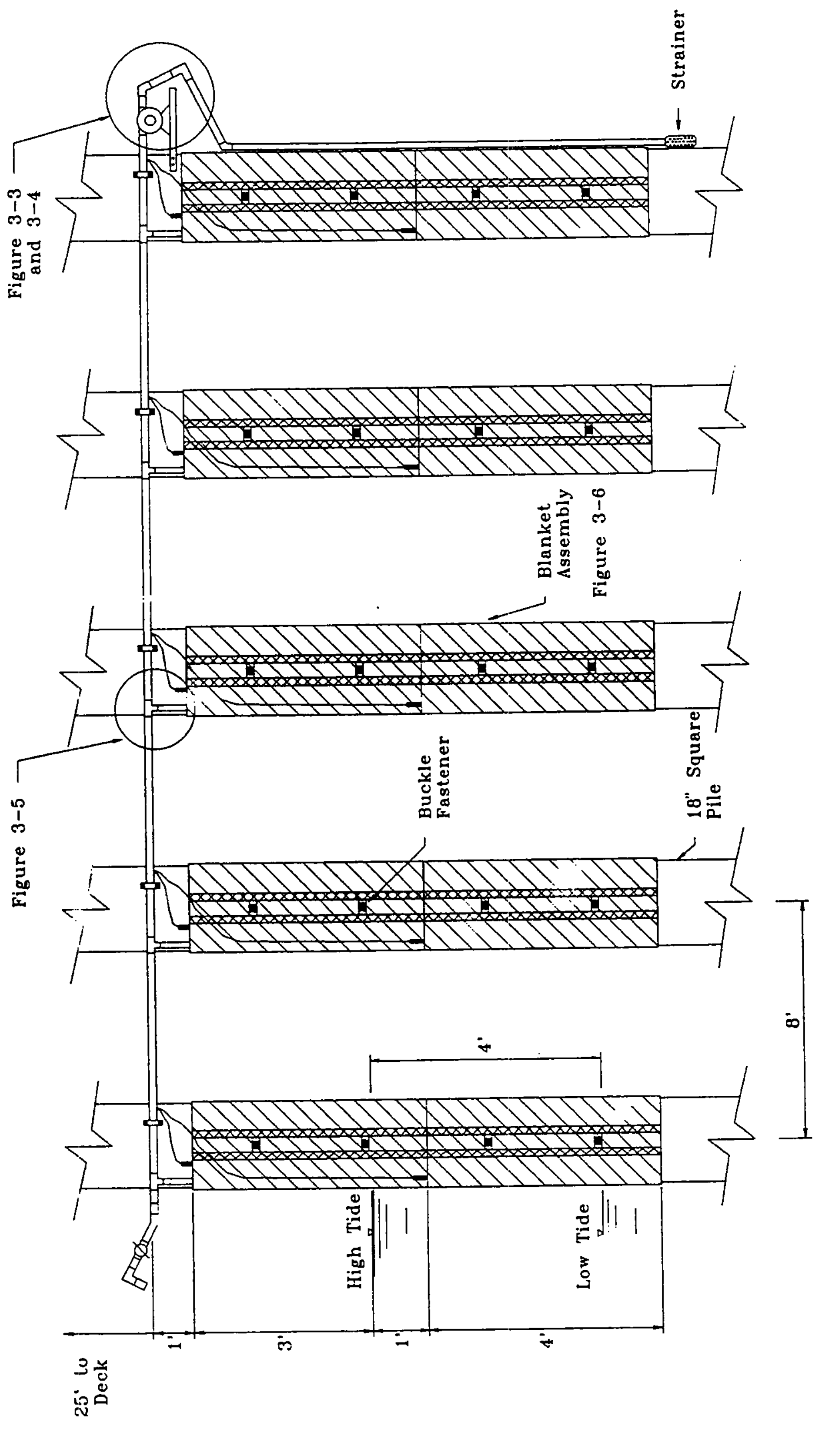


By 1970, corrosion-induced cracks in the splash zone were observed on the piles. The typical cracks ranged from 0.008 to 0.016 in. wide (0.02 to 0.04 cm) and extended from approximately 12 in. (30 cm) above to 24 in. (60 cm) below high tide. In 1986, an experimental impressed current cathodic protection (CP) system using anode mesh in conjunction with a conductive rubber jacket was installed on the piles of Bent 4 of the westbound bridge. In 1990, an experimental galvanic CP system, using a zinc penny blank sheet as the anode, was installed on piles A, C and E of Bent 3 on the westbound structure.

The five piles selected for chloride removal were part of Bent 3 of the westbound bridge. The existing galvanic CP system on piles A, C and E, was dismantled to prepare for the installation of the chloride removal system.

A front view of the chloride removal system is in Figure 3-2. The system consisted of a rectifier, electrolyte distribution system, and chloride removal blankets. The installation of the separate components is highlighted below.

Figure 3-2. Front View of the Chloride Removal System



Concrete Surface Preparation and Inspection

Successful operation of a substructure chloride removal system relies upon the development of an intimate contact between the anode blankets and surface of the concrete. The piles were covered with barnacles which had to be removed prior to system installation. Scraping with the edge of a shovel was generally sufficient to remove the barnacles. The debris that remained was easily washed away by the waves. Cracks on the surface of the columns were visible after cleaning. A brownish color in the cleaned area was found to be mud, not a corrosion product.

Electrolyte Distribution System Installation

This field trial was unique in its attempt to use seawater as the electrolyte. Also unique to this trial was the fact that the recirculating electrolyte operated on a once-through basis. The other trials employed close-looped recirculation or static ponding. The once-through method was necessary due to the proximity of the pilings and also to avoid chlorine gas evolution due to the already low pH of seawater.

Electric Pump

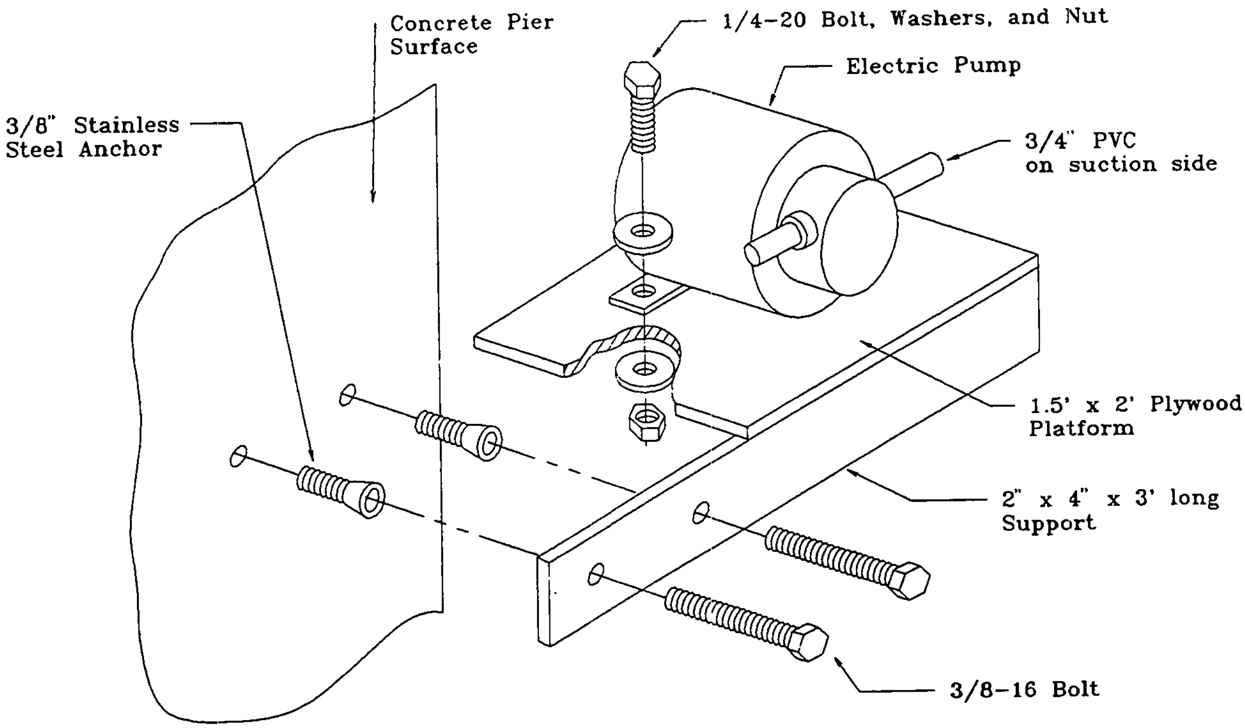
A continuous operation, self-priming electric pump manufactured by ITT Jabsco, Inc. was used to circulate electrolyte through the system. The pump, Model No. 17430, was equipped with a viton impeller and o-rings and was rated for 10.2 gpm (38.6 l/min) at 20 ft (6 m) of hydraulic head. The pump specifications are found in Table 3-1. The intracoastal waterway served as the electrolyte and reservoir for the system.

Table 3-1. Pump Specifications

Specification	Rating
Input AC Voltage	115 V
Input AC Amperes	20 A
Phase	1
Frequency	60 Hz
Horse Power	0.5 hp
Efficiency	63%
Rotation	1725 RPM

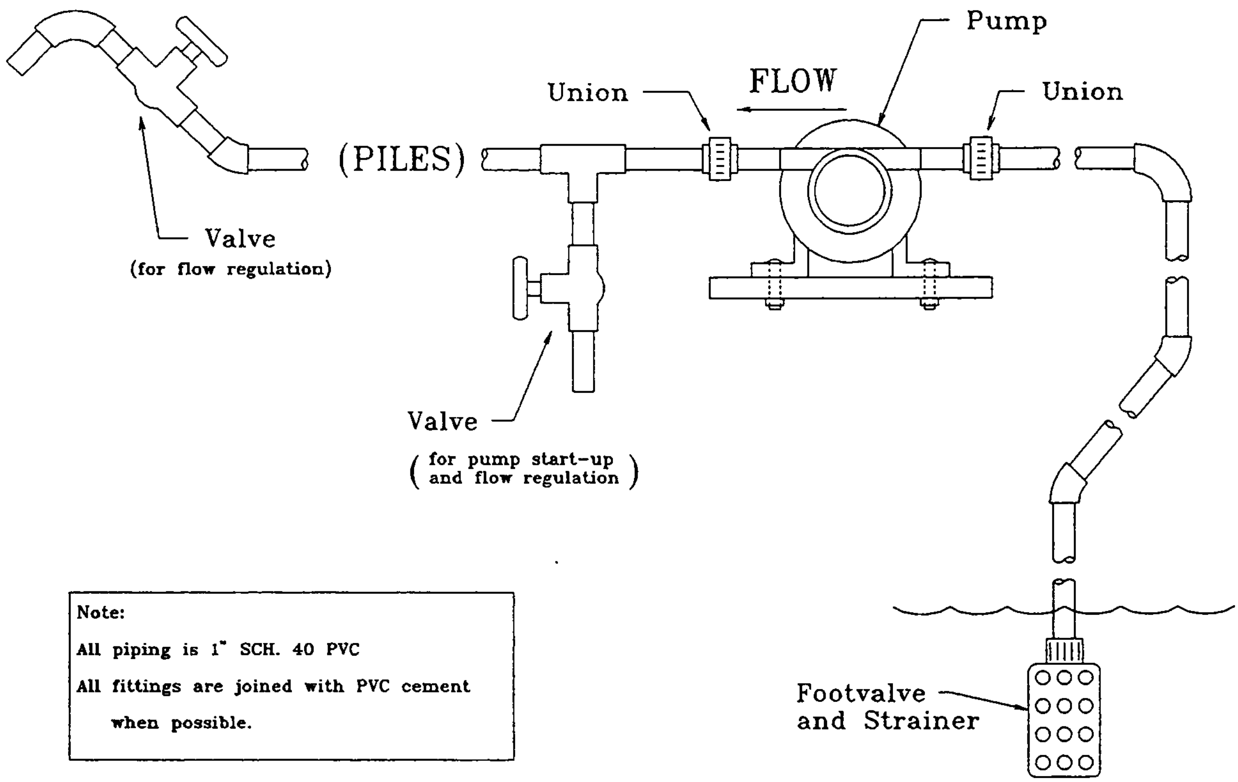
Figure 3-3 illustrates the hardware and pump platform that was mounted to pile E of Bent 3.

Figure 3-3. Pump Mounting Schematic



A foot valve with strainer was attached to the suction side of the pump to prevent the debris from entering the pump. The foot valve remained immersed. Unions were added to the outlet side of the pump to facilitate repair or pump replacement (Figure 3-4).

Figure 3-4. Pump Plumbing Schematic



PVC Manifold

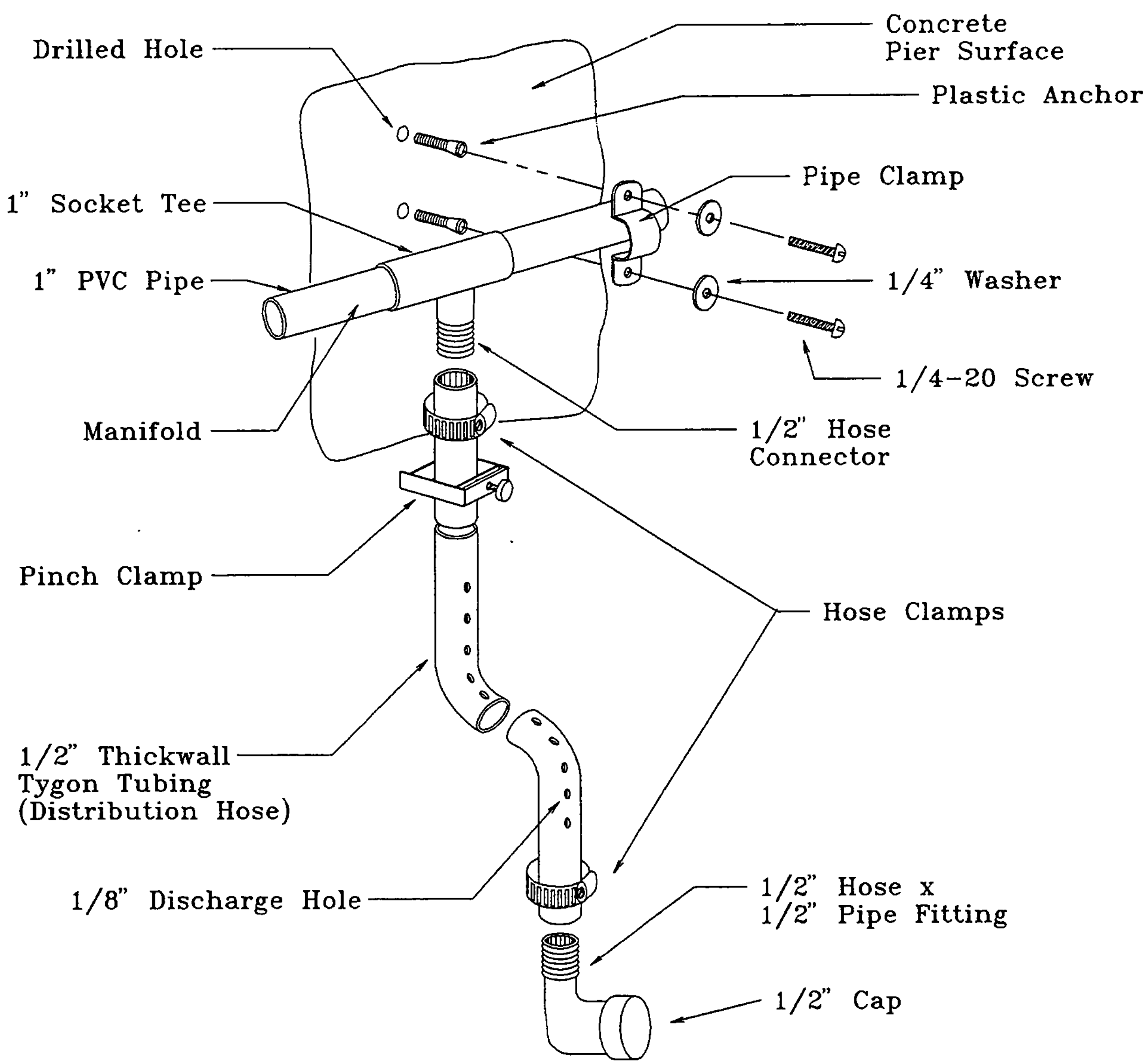
Figure 3-5 shows the PVC manifold which was constructed to distribute the electrolyte to the chloride removal blankets. Electrolyte was pumped continuously into the manifold to keep the blankets wet and electrically conductive.

The PVC electrolyte manifold was attached, five feet above average high tide, to the west face of the piles with pipe clamps. The manifold was connected to the outlet port of the pump that was mounted on pile E of Bent 3. A separate electrolyte distribution hose on each pile was connected to the manifold. A ball valve was installed at the end of the manifold to regulate pressure if necessary. All fittings were primed and glued together using PVC pipe cement.

Electrolyte Distribution Hoses

Figure 3-5 illustrates the 1/4-in. (6-mm) diameter, 7-ft (2.1-m) long, flexible and non-reinforced electrolyte distribution hoses. Eight 1/8-in. (3-mm) diameter holes in each hose allowed equal distribution of the electrolyte. The hose was placed in the top edge of the upper chloride removal blanket. One end of the hose was clamped to a connector from the manifold and the other end was terminated with a plug. Pinch clamps to regulate flow were used on the hoses to each pile.

Figure 3-5. Electroltye Manifold and Distribution Hose Section



Chloride Removal Blanket Installation

The blanket consisted of an inner blanket, outer (anode) blanket, and plastic film wrap. Both inner and outer blankets were 4-ft (1.2 m) high and 6-ft (1.8 m) wide. The blankets were hand sewn into a single unit. The properties of $Sorb_x$ S-92, GTF 350 EX and Polyfelt TS-1000 are found in Table 3-2. A schematic of the chloride removal blanket is in Figure 3-6.

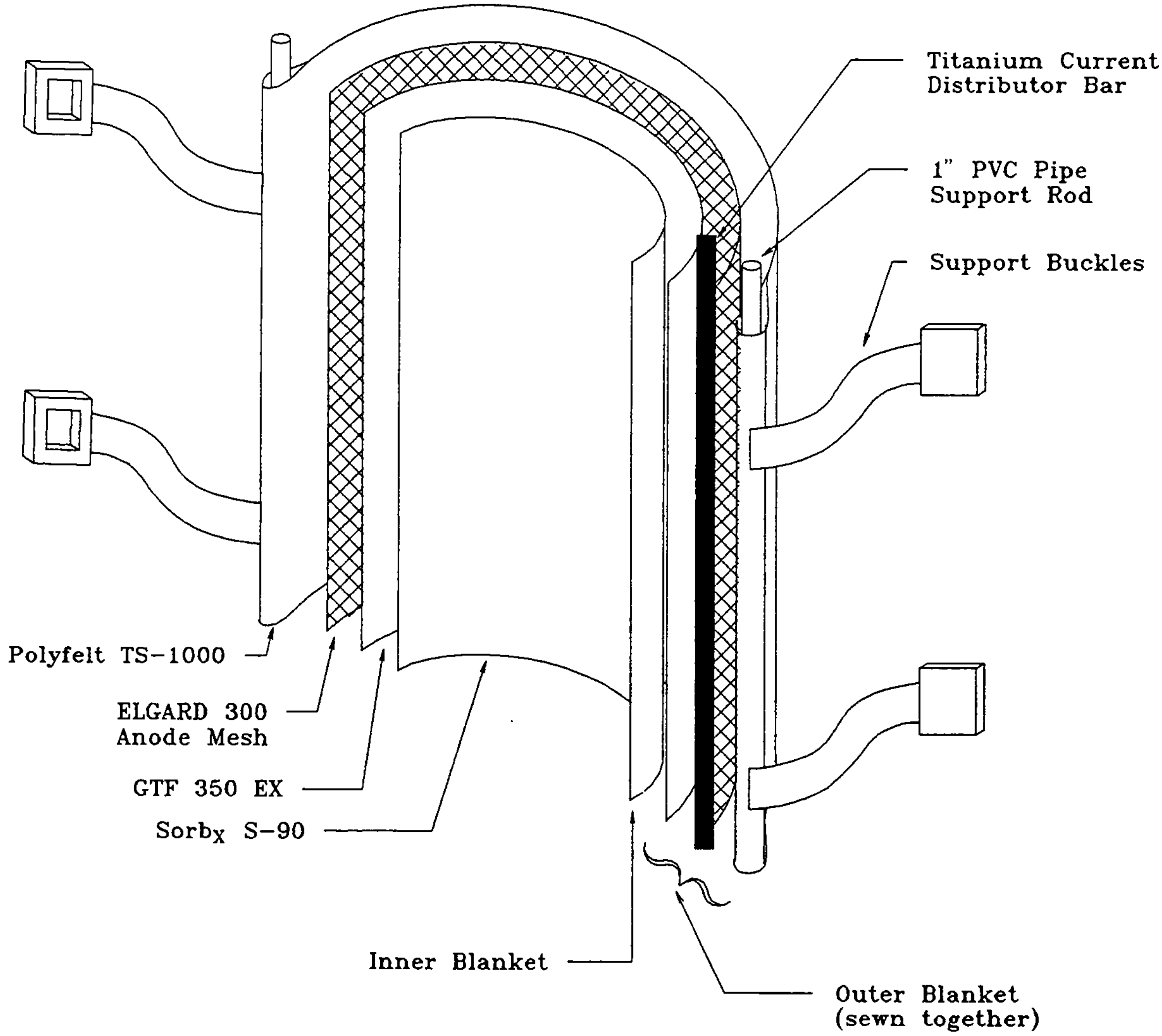
Table 3-2. Chloride Removal Blanket Specifications

Material	Flow Rate (gpm)	Thickness (mils)	Weight (oz/yd^3)	Tear Strength (lbs.)
$Sorb_x$	NA	375	1.4	NA
GTF 350 Ex	50.0	180	16.0	110
Polyfelt Ts 1000	60.0	160	16.2	155

NA: Measurement is not available

Two anode blankets were installed on each pile to treat an 8-ft (2.4-m) continuous, vertical length. As shown in Figure 3-2, the top of the upper blanket was positioned 3 ft (1 m) above average high tide and the bottom of the lower blanket was positioned 5 ft (1.5 m) below the average high tide. The upper blankets were installed at high tide and the lower blankets at low tide.

Figure 3-6. Chloride Removal Blanket Assembly



Inner Blanket

Since the inner blanket served as the path for current flow between the anode and concrete surface, its abiltity to retain electrolyte and conform to irregular shapes was of utmost importance. Based on laboratory tests, $Sorb_x$ S-92, manufactured by Matarah Industries Inc., was chosen for use as the inner blanket. The material was comprised of 33 percent polypropylene and 67 percent celluose which most likely contributed to its moisture retention properties and formability. The blanket was wrapped around the pile and temporarily held in place with duct tape. Due to an inherent structural weakness of the material after wetting, extra care was taken during installation to keep the blanket dry. Once the entire blanket assembly was installed, the outer blanket provided the support to hold the inner blanket in place.

Outer Blanket

The outer blanket of the CRB consisted of two geotextiles and an anode. The ELGARD 300 titanium anode mesh was sandwiched between GTF 350 EX manufactured by Exxon Inc., and Polyfelt TS-1000 manufactured by Gundle Lining Systems. Due to better structural integrity and lower absorbancy than the $Sorb_x$ S-92, the outer blanket was designed to cover the inner blanket to provide anode contact as well as the support to the inner blanket during treatment. The outer blanket was temporarily held in place by belts.

Plastic Film Wrap

A layer of plastic wrapping film was placed around the blanket assembly to minimize current leakage. The plastic wrap was left slightly open at the bottom to allow for circulation. This was necessary to avoid acid buildup at the blanket/pile interface. Six additional plastic bands were installed around the plastic wrap, three per blanket, as further support to prevent the whole assembly from sliding down during treatment.

Electrical Installation

AC Power Source

The rectifier required a 220V-32A, 3ϕ AC service. A 120V, 1ϕ service was required for the electrolyte pump and miscellaneous utilities.

A 3/8-in. diameter (10-mm), 3-ft (1-m) long solid copper rod, driven into the ground, provided an earth ground for the system.

Rectifier

One rectifier from the Ohio trial was used. Output was rated at 0-50 VDC and 0-200 ADC. The specifications of the rectifier can be found in Chapter 2, Table 2-1.

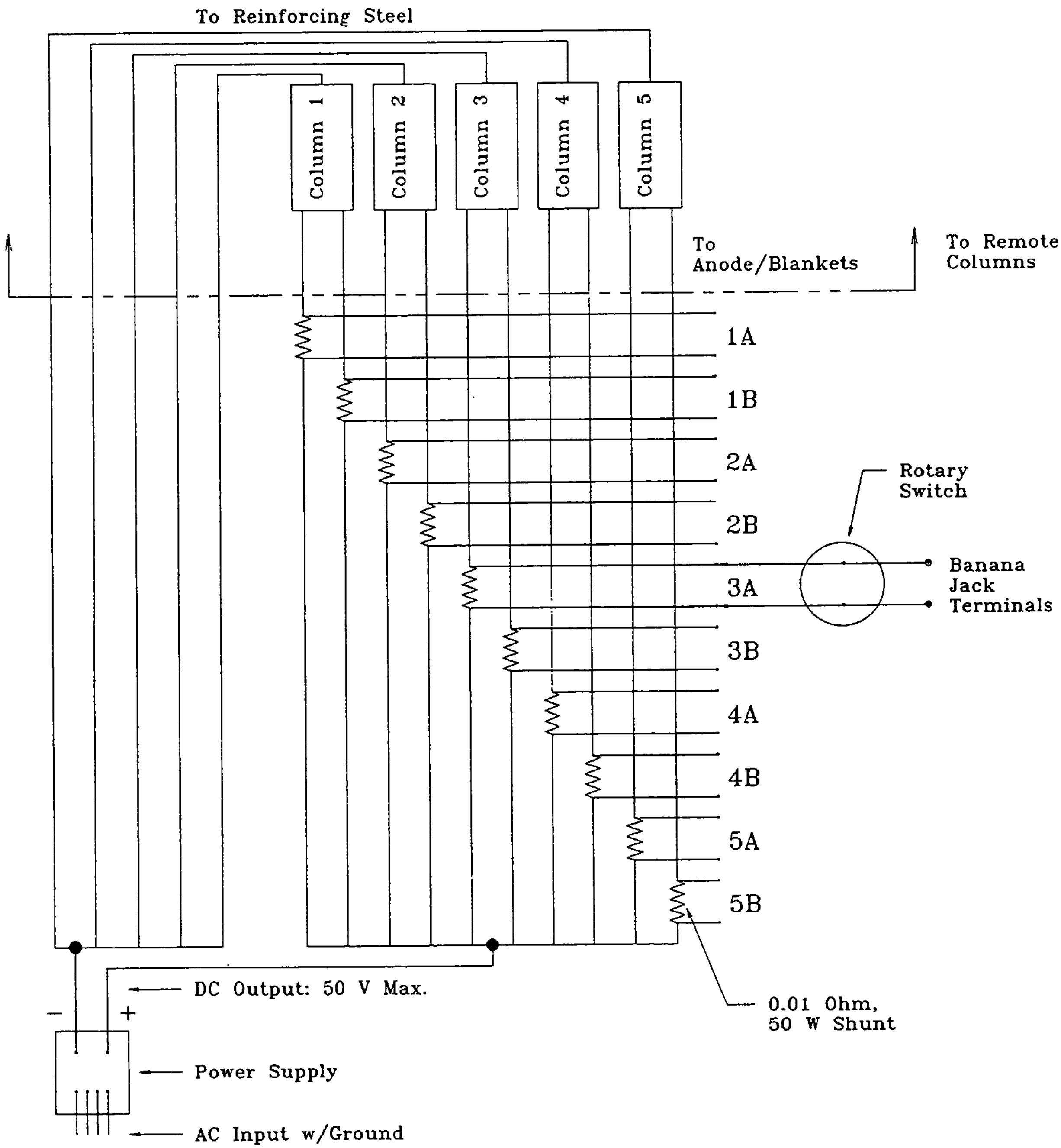
The rectifier was installed on shore as indicated in Figure 3-1. A 4-ft (1.2 m) high, chain-link fence was built around the rectifier to provide safety and discourage vandalism.

Distribution Box

A current distribution box was constructed to provide a means to measure the current, using shunts, distributed to each anode blanket. The distribution box schematic is shown in Figure 3-7. For convenience, the box was mounted on the side of the rectifier. A multi-position switch and labels that corresponded to each anode shunt were mounted on the front. A set of banana jacks on the front panel were provided to monitor current using an external meter.

The positive and negative leads, № 6 (black) and № 10 (red) AWG wires, respectively, were routed through the distribution box from the rectifier to the anode blankets. All leads were sorted and tied to the designated piles, one system negative and two anode leads per pile. The bundled wires were tied to the bridge deck railing supports and the piles.

Figure 3-7. Distribution Box Wiring Schematic



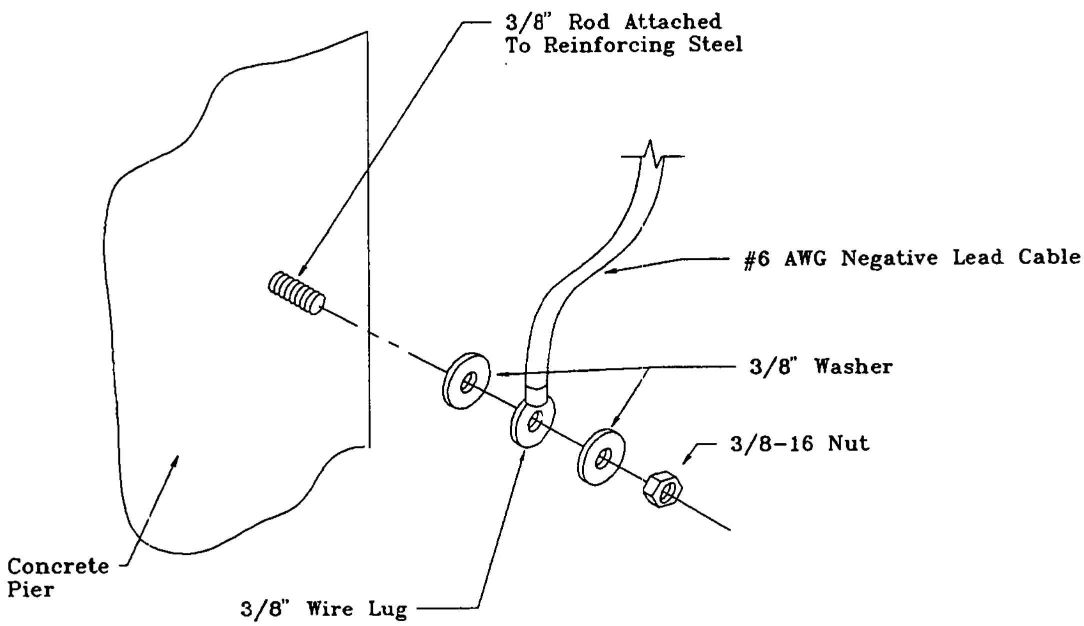
System Positive Connection

Figure 2-4 of Chapter 2 shows a typical system positive connection. Grade 1 titanium current distributor strips, 5.0 ft x 0.5 in. x 0.035 in. (1.5 m x 1.3 cm x 0.09 cm), were spot (resistance) welded to the edge of the anode mesh. Typically, 3 to 4 welds were made per linear foot. All connections to the anode cables were sealed with putty and wrapped with electrical tape.

System Negative Connection

The system negative connection to each pile was made to a 3/8-in. (10-mm) threaded rod extending from the pile. This rod had been been previously installed to make contact with the reinforcing steel for the system negative of a cathodic protection system. The cathodic protection system was removed prior to installation of the chloride removal system. Figure 3-8 shows this system negative connection.

Figure 3-8. System Negative Connection at the Florida Field Trial



Operation

Pre-Treatment Evaluations

Static Half-Cell Potential Survey

A pre-treatment static potential survey was conducted on Bent 3 of the westbound bridge on March 25, 1992. The potentials indicated a significant amount of corrosion was occurring at and below the splash zones. The potentials became less corrosive above sea level. Table 3-3 summarizes the results.

Table 3-3. Pre-Treatment Half-Cell Potential Survey

Potentials = -mV vs $Cu/CuSO_4$ unless Marked +

Pile	Face	4 ft.	3 ft.	2 ft.	1 ft.	0 ft.	-1 ft.	-2 ft.	-3 ft.	-4 ft.
A	East	+30	+34	23	183	293	649	777	808	830
zinc	South	+20	+42	112	266	449	668	795	833	830
removed	West	+33	+25	0	195	398	577	646	739	830
3/25/92	North	+79	+22	78	97	250	548	721	809	830
B	East	+22	+65	26	102	282	476	532	585	830
no zinc	South	+75	+46	28	132	387	479	526	585	830
	West	+69	+53	11	192	312	421	468	580	830
	North	+82	+62	30	70	310	443	539	583	830
C	East	+18	+53	27	185	456	674	711	775	830
zinc	South	+106	+80	29	155	401	545	659	775	830
removed	West	+63	+53	5	174	411	543	706	789	830
3/25/92	North	+98	+52	79	226	426	600	718	788	830
D	East	+79	+78	22	114	370	507	508	551	830
no zinc	South	+113	+63	11	159	419	459	491	550	830
	West	+86	+90	+76	126	376	432	454	552	830
	North	+111	+68	19	152	387	463	506	547	830
E	East	36	+64	24	259	577	806	848	913	830
zinc	South	+35	23	+3	159	539	755	883	910	830
removed	West	+47	+17	81	310	568	717	837	890	830
3/25/92	North	+64	+47	29	192	531	754	848	890	830

All distances are with respect to the average high tide which in this table is denoted by 0 ft.

Even though these potential values are not typical of those obtained on land columns and decks, it is not known if these potentials are typical for marine piles.

Concrete Chloride Content

Pre-treatment cc were obtained for analysis. The pre-treatment chloride concentrations are shown in Table 3-4. No data were available for the location 2 ft (0.6 m) above high tide. Chloride analyses performed on the concrete from cores Nº 6 and Nº 8, showed near or below threshold chloride concentrations (especially at the reinforcing steel level) at elevations of 6 to 8 ft (1.8 to 2.4 m) above high tide. Chloride analyses at elevations of -1 to 1 ft (-0.3 to 0.3 m) above high tide showed significant chloride concentrations, 5 to 16 $^{\#}Cl^-/yd^3$ (3 to 10 kg/m^3). The data indicate that treatment is not needed at elevations higher than 3 ft (1 m) above high tide.

Core Nº 7 was not analyzed but used for a bench scale chloride removal experiment.

Table 3-4. Pre-Treatment Concrete Cl Content of Florida Field Trial Site

LOCATION OF CORE Dist. above high tide (feet)	SAMPLE LOCATION Depth from surface (in.	Cl^- CONCENTRATION lbs./yd^3
-1	0-1	5.36
	1-2	6.60
	2-3	2.11
	3-4	7.75
0	0-1	12.32
	1-2	7.71
	2-3	5.68
	3-4	5.50
1	0-1	15.74
	1-2	15.02
	2-3	16.75
	3-4	11.76
3	average of top 2"	1.61
4	0-½	2.06
	½-1	2.04
	1-1½	1.04
	1½-2	0.67
5	average of top 2"	1.05
6	average of top 2"	1.36
8	0-½	1.15
	½-1	n.a.
	1-1½	1.07
	1½-2	0.65

Values from -1, 0, and 1 ft above high tide were from FDOT analyses.

Laboratory Chloride Removal Test

Core № 7 was obtained 7 ft (2.1 m) above high tide. Since this core contained only approximately 1.2 $^{\#}Cl^{-}/yd^{3}$ (0.7 kg/m^{3}) and still reached the 0.6 A/ft^{2} (6 A/m^{2}) chloride removal current density, it was expected that the area to be treated would reach this current density more quickly if not immediately.

Core Petrographic Analysis

The concrete for core № 7 was characterized as a marginally air-entrained concrete (3 to 4 percent) with a 1-in. (2.5 cm) nominal size gravel coarse aggregate and a natural sand. The coarse aggregate was a siliceous gravel composed of equidimensional, rounded to sub-rounded, sedimentary rock pebbles. Approximate modal percentages were 67 percent quartz arenite and orthoquartzite, 23 percent chert, and 10 percent coarse vein quartz. Chert pebbles were mostly microcrystalline, mottled brown types, with a few fine quartz veinlets. The fine aggregate in the concrete was a fairly well sorted, dominantly coarse to medium, sub-rounded to rounded quartz with only an occasional chert or limonite grain.

There was a tight, uninterrupted bond between the aggregate particles and the cement paste matrix phase. There was no evidence of cement-aggregate reactions. The cement paste phase was of good quality with an estimated water-cement ratio of 0.40 to 0.45.

The core represented good quality concrete.

Field Site Operation

The initial start-up data were collected and is in Table 3-5.

Table 3-5. Initial Operating Data - B. B. McCormick Bridge

Date:	March 26, 1992
Temperature:	55 - 64°F
Time:	4:00 PM
Tide Condition:	1 ft below high tide
System Voltage:	14 V
System Current:	80 A
Amp-hour Reading:	0000.00

Pile	Blanket Assembly	Blanket Current
A	Top	1.7
A	Bottom	13.0
B	Top	1.7
B	Bottom	13.0
C	Top	1.5
C	Bottom	12.9
D	Top	1.9
D	Bottom	13.8
E	Top	1.9
E	Bottom	14.0

Twelve hours after start-up, the viton impeller of the pump was found damaged, possibly due to running dry during initial start-up difficulties. Wetting of the blankets was only by tide water. The impeller was replaced and the pump was restarted.

System Current

The total area of treatment for this trial was 240 ft^2 (24 m^2). The treatment area was comprised of all five piles and was treated as a single zone. The total current supplied to the piles was approximately 80 A or 0.33 A/ft^2 (3.3 A/m^2) concrete.

Maximum system voltage was set at 48 to 50 V. The current was regulated so that the current to any one anode blanket was not greater than 14.4 A, 0.6 A/ft^2 (6 A/m^2), the maximum allowable chloride removal current density. These currents were monitored with the shunts in the current distribution box. With this current regulation scheme, the system voltage was never greater than 20 V. In general, the lower blankets on each piling operated at a much greater current than the upper blankets. This was to be expected since the lower blanket was at least 6 in. (15 cm) in seawater even during low tide.

The trial lasted for 19 days and had an apparent total charge of 135 A-hr/ft^2 (1,350 A-hr/m^2). This charge passage was misleading. A system voltage at 0.6 A/ft^2 (6 A/m^2) was expected to be at least 40 V. The low system voltage, 20 V, suggested that current was lost to a lower resistance current flow path. This path was expected to be from the bottom of the lower blankets to the submerged areas of the piles (or to ground) through the seawater. This would be possible if electrolyte flow distribution was not sufficient to keep the concrete wet.

Post-treatment testing indicated that up to 85 percent of the current was lost to leakage. If this was true, a total charge of only 20 A-hr/ft^2 (200 A-hr/m^2) was achieved.

A summary of the current distribution to the five pilings during the first four days and the second to last day of operation is found below in Table 3-6. Current distributions did not significantly change.

Table 3-6. Current Distributions to the B.B. McCormick Bridge Pilings

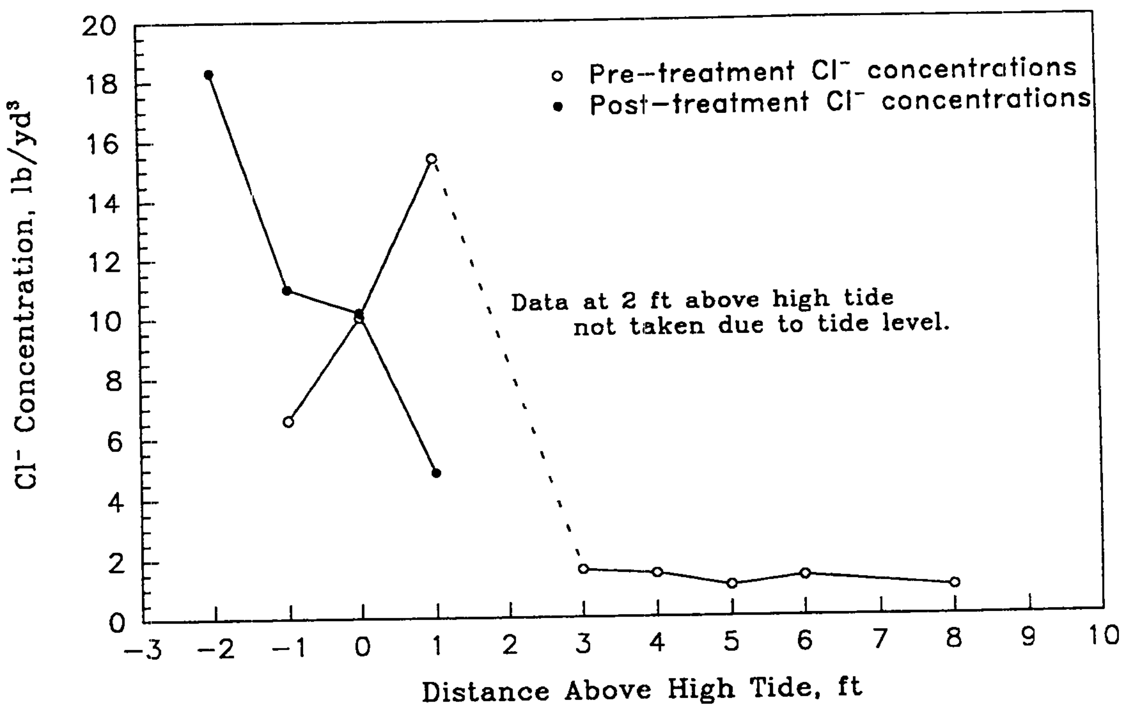
	Pile A (amps)		Pile B (amps)		Pile C (amps)		Pile D (amps)		Pile E (amps)	
Date	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
3-26-92	1.6	12.9	1.6	12.9	1.4	12.8	1.8	13.6	1.7	14.0
3-27-92	2.4	12.6	2.0	10.7	1.6	10.8	2.1	13.1	2.1	14.0
3-29-92	2.5	14.4	1.9	11.3	1.6	10.7	2.1	14.5	1.9	13.9
3-30-92	1.4	15.1	1.1	11.3	1.0	11.2	2.1	14.8	1.9	13.9
4-13-92	3.1	12.6	2.1	8.9	2.4	12.9	3.7	14.0	2.5	9.8
Average Current	2.2	13.5	1.7	11.0	1.6	11.7	2.4	14.0	2.0	13.1
Percentage of Current	14	86	14	86	12	88	17	83	13	87

Post-Treatment Evaluations

Chloride Analyses

Concrete powder was collected from 1/2-in. (12-mm) diameter holes for chloride analysis. Large concrete core samples were not taken for structure reasons. The pre-treatment and post-treatment results of the chloride analyses are shown in Figure 3-9.

Figure 3-9. Pre-Treatment and Post-Treatment Chloride Concentrations



From this data, conclusions about the effectiveness of the removal cannot be made.

Static Potential Surveys

Post-treatment static half-cell potential data were collected at one day (Table 3-7) and seven weeks (Table 3-8) after treatment. There was significant polarization of the steel beneath the lower blanket and less polarization of the steel under the upper blanket.

The post-treatment potentials from Table 3-7, when compared to the pre-treatment potentials from Table 3-3, indicate that all steel was polarized during treatment. Some areas were more polarized than others, and indicates better electrolyte distribution at those areas was likely.

The potential data from Table 3-8, taken seven weeks after treatment, indicate that the steel was still depolarizing. The values are less negative than those from the first set of post-treatment data, but still more negative than those from the pre-treatment data.

The data suggest no effects from the zinc cathodic protection system. No trends were noticed.

Table 3-7. Post-Treatment Half-Cell Potential Survey: One Day After Treatment

Potentials = -mV vs $Cu/CuSO_4$ unless Marked +

Pile	Face	4 ft.	3 ft.	2 ft.	1 ft.	0 ft.	-1 ft.	-2 ft.	-3 ft.	-4 ft.
A	East	247	285	655	766	1031	1083	1082	1093	1091
zinc	South	340	455	667	787	878	1024	1043	1046	1092
removed	West	1114	870	1032	1201	1107	1163	1139	1135	1095
3/25/92	North	890	734	744	1111	1148	1036	1044	1128	1095
B	East	387	268	446	940	1020	1038	1104	1088	1095
no zinc	South	295	363	438	827	1091	1122	1125	1116	1093
	West	984	1002	860	1439	1126	1117	1142	1131	1094
	North	521	541	713	1070	1100	1070	1086	1078	1094
C	East	540	456	712	779	940	977	1030	1040	1095
zinc	South	626	630	953	1061	1084	1081	1066	1084	1093
removed	West	960	730	1043	1350	1155	1131	1160	1141	1096
3/25/92	North	627	630	978	965	1056	1034	1058	1083	1091
D	East	677	670	1090	1070	1080	1100	1088	1089	1097
no zinc	South	660	811	1028	1062	1081	1086	1068	1066	1096
	West	1044	756	1295	1285	1193	1123	1134	1127	1100
	North	773	634	1014	1094	1103	1103	1125	1102	1099
E	East	606	777	1090	1119	1131	1115	1116	1128	1092
zinc	South	590	790	1168	1148	1138	1119	1151	1216	1091
removed	West	1045	811	1033	1097	1135	1118	1111	1135	1090
3/25/92	North	788	662	967	1128	1109	1093	1127	1115	1090

All distances are with respect to the average high tide which in this table is denoted by 0 ft.

Table 3-8. Post-Treatment Half-Cell Potential Survey: 7 Weeks After Treatment

Potentials = -mV vs $Cu/CuSO_4$ unless Marked +

Pile	Face	4 ft.	3 ft.	2 ft.	1 ft.	0 ft.	-1 ft.	-2 ft.	-3 ft.	-4 ft.
A	East	+58	3	162	320	626	901	NA	NA	1066
zinc	South	+2	181	164	336	622	908	NA	NA	1066
removed	West	--	--	--	--	--	--	--	--	--
3/25/92	North	+104	74	141	284	610	909	NA	NA	1066
B	East	120	69	91	232	673	936	NA	NA	1057
no zinc	South	240	235	262	361	616	962	NA	NA	1057
	West	--	--	--	--	--	--	--	--	--
	North	+60	28	13	6	543	970	NA	NA	1057
C	East	+25	28	63	288	526	902	NA	NA	1065
zinc	South	106	123	183	285	382	966	NA	NA	1065
removed	West	--	--	--	--	--	--	--	--	--
3/25/92	North	+52	82	195	258	555	959	NA	NA	1065
D	East	+110	64	164	316	612	898	NA	NA	1056
no zinc	South	75	194	193	367	684	879	NA	NA	1055
	West	--	--	--	--	--	--	--	--	--
	North	+127	73	172	272	560	949	NA	NA	1056
E	East	113	112	205	322	818	1009	NA	NA	1070
zinc	South	32	140	240	391	782	1021	NA	NA	1070
removed	West	--	--	--	--	--	--	--	--	--
3/25/92	North	5	120	179	279	670	1017	NA	NA	1070

All distances are with respect to the average high tide which in this table is denoted by 0 ft.

NA = Reading taken during high tide.

System Removal

Preliminary

Prior to removal, system components were checked for damage. System inspection and removal was conducted from boats.

Lead Wires

The main AC service was disconnected by FDOT electricians. The negative leads were disconnected from the piles. The positive leads were cut off at the distributor strips. The leads were bundled, lifted to the bridge deck, and dropped on the shore. Since the wires were to be reused for other trials, they were carefully inspected for possible damage from removal.

Pump

After the pump was removed, the viton impeller was checked and no damage was found. The wooden platform and its supports were non-reusable and discarded.

Electrolyte Distribution Manifold

PVC pipe, generally manufactured without ultraviolet stablization, became very brittle. The pipe and fittings were removed and discarded. The metal hardware and foot valve were retained for future use.

Chloride Removal Blanket

Although the blankets had not received circulated electrolyte for seven days, they were still wet. The outer blankets were easily removed. Parts of the top inner blankets stuck to the concrete surface and had to be torn off in pieces.

Blanket inspection found the geotextile materials in good condition. The nylon stitching of the blankets was either broken, discolored, or dissolved.

A chalky substance on the concrete surface was found after the $Sorb_X$ was removed. Laboratory tests identified it as calcium carbonate.

Distribution Box Removal

The distribution box was removed from the rectifier and inspected. No damage was detected.

Costs

Materials

A list of disposable and single-use items is tabulated in Table 3-9. The cost per square foot of treatment area for these items was $4/ft^2 ($41/m^2).

Table 3-9. Single-Use Item Costs

Material/Equipment	Description	Quantity	Price, $
Electrical tape	3/4" x 66'	1 roll	2.00
Putty	Waterproof sealant	1 unit	5.00
Cable markers	Numbered tape	1 card	5.50
Wire ties	7" long	2 boxes	17.00
Wrap dispenser	Stainless steel	1 unit	75.00
Plastic strap	1/2" x 200'	1 roll	10.00
Washers	3/4"	10 units	0.50
Washers	1/2"	10 units	0.50
Washers	1/4"	10 units	0.50
Nuts and bolts	1/4-20 x 1"	30 units	3.00
Nuts and bolts	1/2-13 x 1"	10 units	1.00
Steel anchors	3/4"	4 units	8.00
Plastic anchors	1/4"	10 units	0.50
Sorb$_x$ S-92	4' x 6' ($0.40/ft^2)	10 units	96.00
Poles/fencing	Chain link	2 poles/50 ft.	154.36
Set 45 mortar mix	Post foundation	4 bags	14.00
PVC fittings	Electrolyte system		103.20
Pipe/tubing clamps	1" galvanized	5 and 10 units	11.50
Teflon tape	1/2" x 520'	1 roll	0.50
PVC primer and cement		1 quart ea.	13.50
Tube plug	1/2" male elbow	5 units	12.50
Anode/cathode terminals	3/8" and 1/4" lugs	5 and 10 units	6.00
Ground freight	Shipping and handling	750 lbs.	450.00
		Total:	$989.70
		Treatment area:	240. ft^2
		Cost/unit area:	$4.12/ft^2

Table 3-10 lists tools and equipment used for this trial that could be amortized over the course of several treatments. The single-use cost per square foot of treatment area for these items was $31.50/ft^2 ($315/m^2). An amortized cost for these items was $3/ft^2 ($32/m^2).

Table 3-10. Amortizable Item Costs

Material/Equipment	Description	Quantity	Price, $
Shovel	Barnacle removal	2 units	28.00
Rectifier	50 VDC/200 ADC	1 unit	4200.00
Wire	#6 and #10 AWG	400 ft. each	450.00
Electrolyte pump	10 gpm, self-priming	1 unit	750.00
Lock	Security	3 units	30.00
Mechanical sealer	1/2" size	1 unit	80.00
Strap tensioner	1/2" size	1 unit	120.00
Plastic wrap	18" x 500' roll	1 roll	15.00
Polyfelt TS 1000	4' x 6' ($0.29/ft^2)	10 units	70.00
GTF 350 EX	4' x 6' ($0.29/ft^2)	10 units	70.00
ELGARD 300 mesh	4' x 6' ($3.00/ft^2)	10 units	720.00
SCH 80 PVC pipe	1/2" O.D. x 10 ft.	50 ft.	23.00
Titanium strip	5' x 1/2" x .040"	50 ft.	50.00
Blanket buckles	Polyester	20 units	45.00
Blanket sewing costs	Labor/supplies	30 hours	320.00
Shipping crate	Wood	3 units	200.00
Pipe cutter	1/4" - 2 5/8" cap.	1 unit	9.00
Misc. cable connector	#4, #1, and #8	34 units	36.60
Strain relief	#8 - 4 conductor cable	2 units	22.00
Strain relief	#1 welding cable	10 units	4.00
SCE electrode	Test equipment	1 unit	30.00
Multimeter	Test equipment	1 unit	300.00
		Total:	$7,572.60
		Treatment area:	240. ft^2
		Cost/unit area:	$31.52/ft^2
		Amortized cost:	$3.15/ft^2

Total material costs, single-use and amortized, were $7/ft^2 ($70/m^2).

Labor

Table 3-11 summarizes the man-hour requirements for this chloride removal trial. The total labor cost for installation, maintenance, and removal was $\$25/ft^2$ ($\$250/m^2$).

Table 3-11. Man-Hour Requirements

Installation

Crew	Hours	Rate, $/hr	Cost, $
Supervisor/laborer	23	55.00	1265.00
Operator/laborer	28	40.00	1120.00
Laborer	28	25.00	700.00
Laborer	30	25.00	750.00
Laborer	30	25.00	750.00
Total man-hours:	137	Labor cost:	$4585.00

Operation

Crew	Hours	Rate, $/hr	Cost, $
Laborer	5	25.00	125.00
Total man-hours:	5	Labor cost:	$125.00

Removal

Crew	Hours	Rate, $/hr	Cost, $
Supervisor/laborer	6	55.00	330.00
Operator/laborer	7	40.00	280.00
Laborer	8	25.00	200.00
Laborer	8	25.00	200.00
Laborer	7	25.00	175.00
Total man-hours:	36	Labor cost:	$1185.00

Total labor costs:	$5895.00
Treatment area:	240. ft^2
Cost/unit area:	$\$24.56/ft^2$

Man-hour estimates include only the time spent at the site. Installation and removal tasks were discussed earlier in this chapter. Operation tasks were performed on shore and included data collection twice a week and electrical equipment maintenance.

The hourly labor rates were estimated, based on salary and overhead in the year 1991.

Total Costs

The cost of this trial, including single-use materials, amortized materials, and labor, was \$32/ft^2 of treated area (\$320/m^2). This does not include travel expenses, boat use, or standard tools, such as drills and hammers.

The installation and removal labor costs are inflated. A majority of the work was done from boats and tidal currents extended the time required to complete a task. Some work required 4 persons. Most work required only 2 persons, but the other 2 were still present and were included in the cost.

4

New York Land Substructure Field Trial

Summary and Conclusions

The third chloride removal field trial was conducted on the substructure of a bridge over NY Rt. 85 at Hawkins St. in Albany, New York. Work was limited to six columns, each of which were 11 ft (3.3 m) in circumference and 17 ft (5 m) high. Twelve feet (3.6 m) of the vertical dimension were treated. This structure had more distress than the two structures in the previous trials. About 15 percent of the total area was delaminated and required patching. Only 26 percent of the readings from the potential survey were more positive than -200 mV versus CSE, and linear polarization values were in the range where corrosion damage is expected within 2 to 10 years. Chloride concentrations averaged 7.7 lb/yd^3 (4.6 kg/m^3) in the top 2 in. (5 cm) of concrete.

Each column was fitted with three 4-ft (1.2-m) wide, 11-ft (3.3-m) long anode/blanket composites and covered with plastic film. A 0.3 molar sodium borate buffered electrolyte was pumped to the top of the treated area and flowed by gravity down the column and back to a sump. Sealing of the electrolyte collection system around the bottom of the columns proved to be impossible on two of the columns due to fine vertical cracks, and these were left as untreated controls. Current densities on the two remaining columns per zone generally ranged from 0.1 to 0.3 A/ft^2 (1 to 3 A/m^2), and the two zones accumulated total charges of 80 and 93 A-hr/ft^2 (800 and 930 A-hr/m^2).

A post-treatment potential survey showed the steel to be strongly polarized at all locations, indicating good current distribution.

Comparisons of chloride analyses of samples taken before and after treatment were difficult due to very non-uniform distribution of chloride in the columns. Calculation of current efficiencies ranged from 7 to 13 percent, and the amount of chloride removed ranged from 9 to 15 gm/ft^2 (90 to 150 gm/m^2).

Problems at this site included an inability to seal the electrolyte collection system on two of the columns, and overflow of electrolyte on one zone due to rainwater runoff. The mesh anode was dissolved in random locations indicating high localized current densities.

Despite these problems, this chloride removal trial can be considered successful, and the site has been recommended for post-SHRP monitoring.

Background

The Campus Loop Bridge, built in 1962, is over NY Rt. 85 at Hawkins Street, approximately 0.5 mi (0.8 km) North of the NY Rt. 20 and Rt. 85 junction in Albany, New York.

This field trial attempted to treat 6 columns that supported two beam caps of the median pier. The columns were approximately 17 ft (5 m) in height, 3-1/2 ft (1 m) in diameter built on a raft foundation. № 4 and № 9 reinforcing steel were used as their spiral ties and vertical reinforcement, respectively. The bridge was 396 ft (119 m) long and 46 ft (14 m) wide.

Concrete Surface Preparation

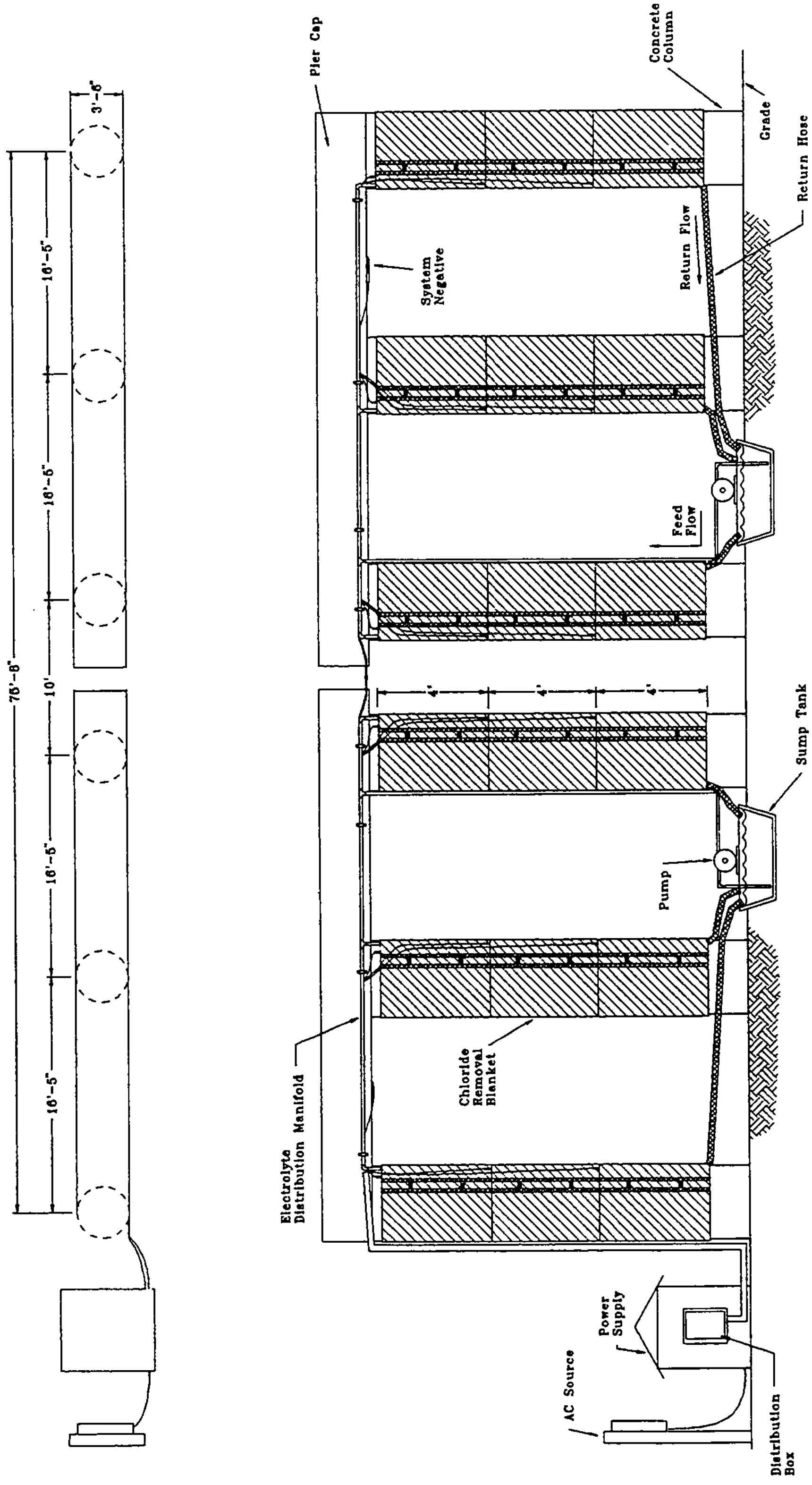
Figures B-1 through B-6 in Appendix B show the location of cracks observed on the columns. Several areas on columns 1, 3, 4 and 6 were delaminated and an estimated 15 percent of the surface required patching. In addition, severe delamination was observed on the bottom face of the cap-beam.

A cementitious material having similar resistivity as the structure concrete was approved for permanent patching repairs. The patches were cured for 30 days and inspected. Wire mesh used for patching was not visible.

Installation

The general set-up of two identical chloride removal systems are presented in Figure 4-1. Each system consists of a rectifier, pump, electrolyte reservoir, electrolyte manifold, chloride removal blankets.

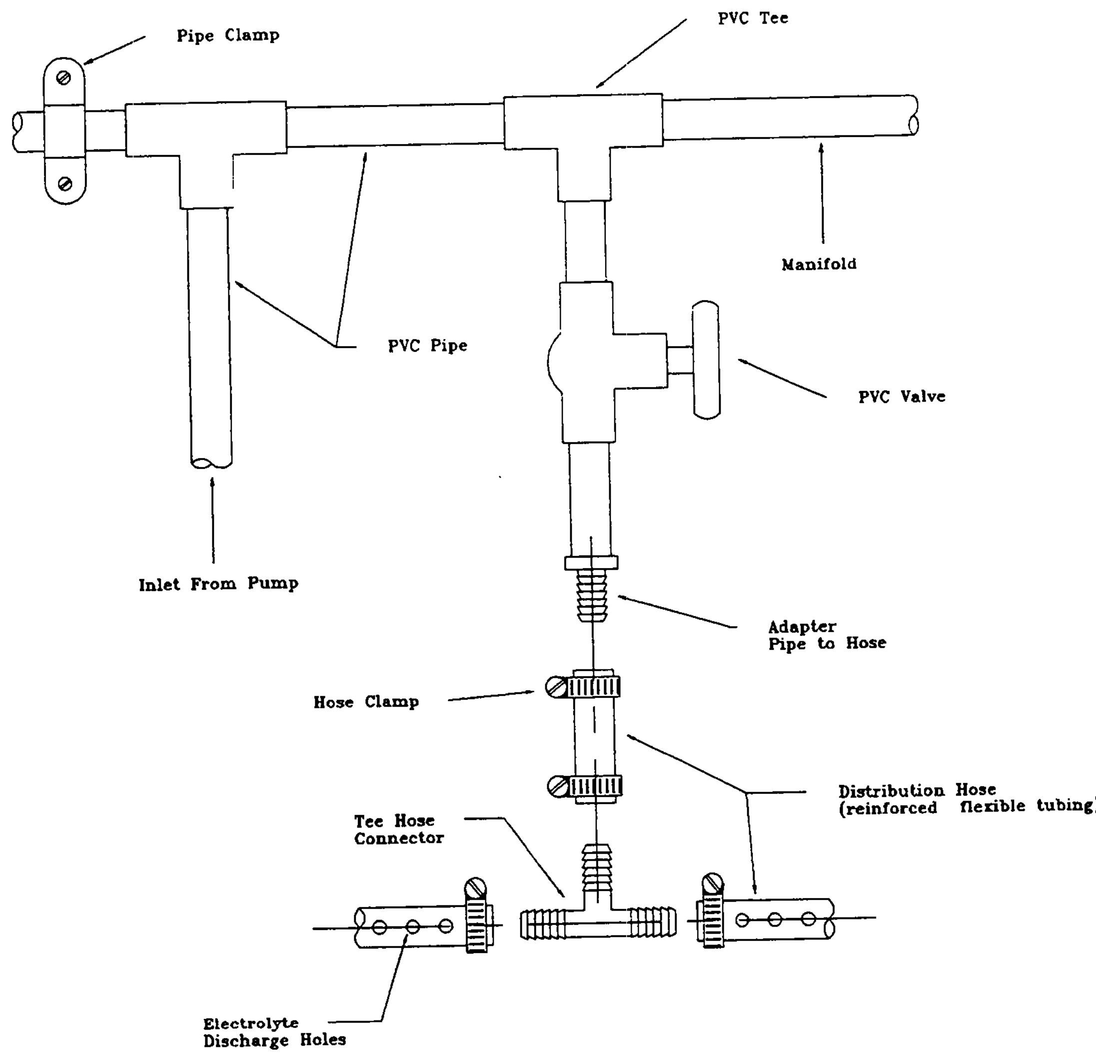
Figure 4-1. Schematic of Chloride Removal Systems



Electrolyte Distribution System

A PVC manifold, shown in Figure 4-2, was constructed to distribute the electrolyte to each column. The electrolyte was pumped from the reservoirs 18 ft (5.4 m) below the manifold to the top of the treatment area. The electrolyte flowed by gravity through the chloride removal blankets to keep them moist and electrically conductive.

Figure 4-2. Electrolyte Distribution Assembly

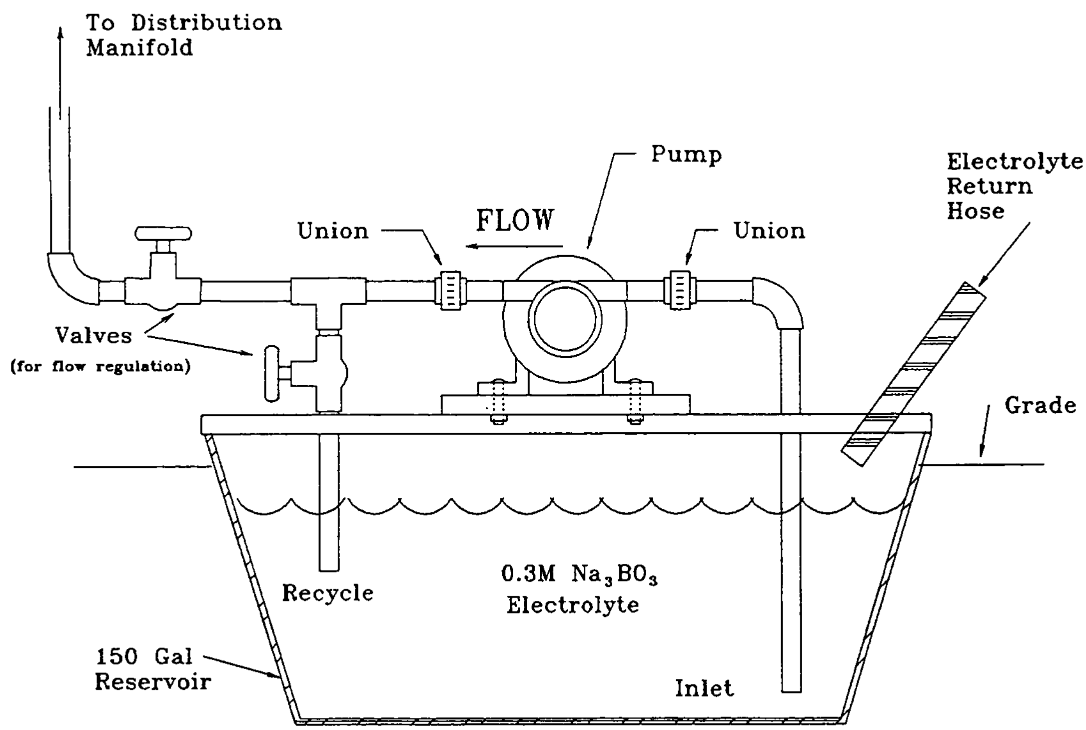


The manifold was held in place by J-clamps that were bolted to the cap-beam and connected to the pump below. A ball valve was inserted into the line feeding each column for flow regulation.

The electrolyte was gravity fed under pressure to an 11-ft (3.3-m) long, 1/2-in. (12-mm) diameter electrolyte distribution hose that wrapped around the top of each column. Twenty, 1/8-in. (3-mm) diameter electrolyte discharge holes were put in each hose. Each hose was connected to the manifold with a tee and fit into the top of the blankets covering the removal area.

An electric pump provided constant electrolyte circulation to the blankets during treatment (Figure 4-3). A PVC union was used on each side of the pump to enable easy removal for repair or replacement.

Figure 4-3. Electrolyte Reservoir and Pump



The electrolyte storage tanks were made of high-density polyethylene which is chemically resistant to sodium borate solutions. Each tank, manufactured by Rubbermaid Commercial Products Incorporated, had a capacity of 150 gal (570 l) and had a bottom drain.

The gravity return of the electrolyte required the tanks to be put into holes at the lowest point in the system (Figure 4-1).

Electrolyte Collection System

Several difficulties were encountered with the installation of the electrolyte collection system at the bottom of the columns. Since a seal between a 2-in. (5-cm) diameter collection hose and the concrete could not be accomplished initially, the system was redesigned. This involved making a 1-ft (30-cm) wide rubber band to fit snug around the column. The ends of the strip strip were vulcanized together after it was wrapped around the column (Figure 4-4).

The bottom of the band was sealed with urethane caulk and secured with plastic banding. The top of the band extended above the bottom of the lower anode blanket and was secured. A 1-1/4 in. (3 cm) diameter semi-rigid plastic tube (Figure 4-5) was under the band and channeled the electrolyte around the column to a bulkhead fitting connected to the return line (Figure 4-6).

Figure 4-4. Vulcanizer Joining Rubber Collector

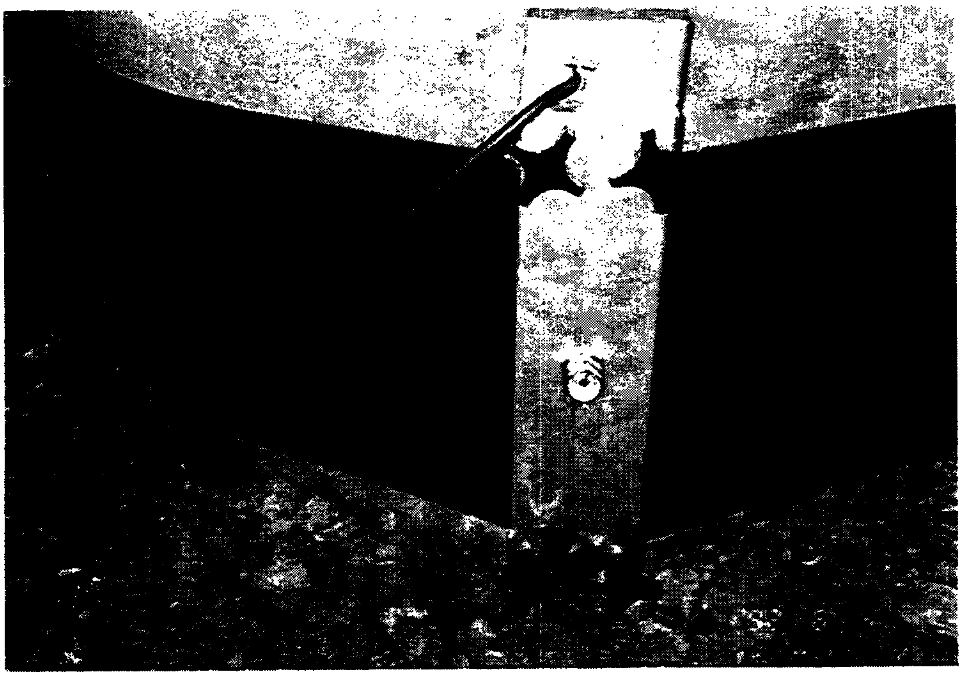
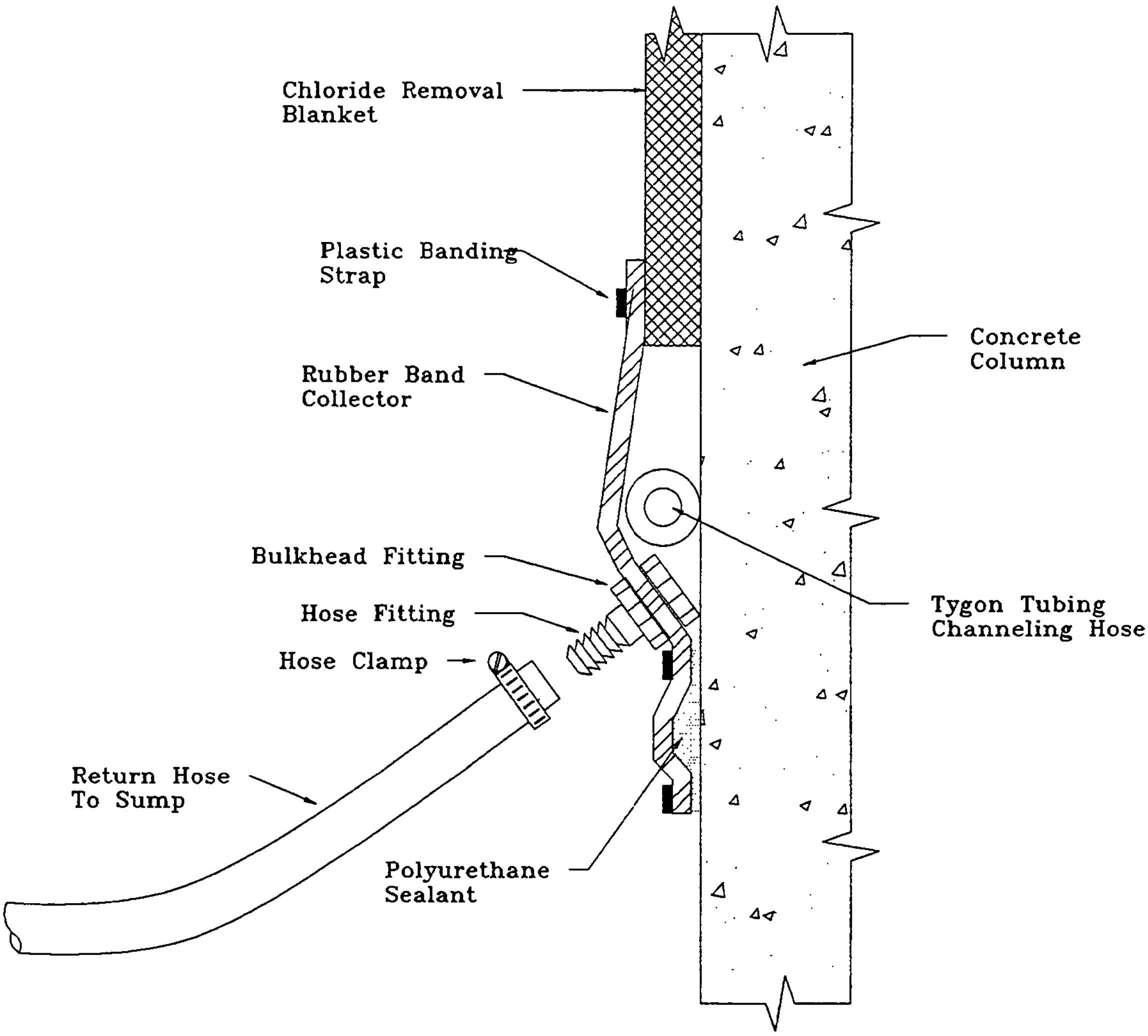


Figure 4-5. Electrolyte Channel Under Rubber Collector

Figure 4-6. Electrolyte Collection Detail



When the system was checked for leaks, two major leaks were found. One was located at a crack in column 4 that traversed the seal at the bottom of the band, and the other was located at the bulkhead seal in the band of column 1. Attempts to repair these leaks were unsuccessful and columns were removed from the system and used as untreated controls.

AC Power

The chloride removal system required 220 V, 3ϕ AC to power the rectifier, and 120 V, single phase AC to operate the pumps. The closest power was located several blocks from the site, so new poles and wires were required.

Rectifiers

Two rectifiers provided the regulated DC power for the chloride removal systems. The rectifiers were equipped with air cooling fans, DC volt and amp meters, and an ampere-hour meter. The operational ratings of the rectifier are listed in Chapter 2, Table 2-1. The rectifiers were at the north side of the bridge as indicated in Figure 4-1. To facilitate data taking, monitoring and adjusting the system currents, all anode blanket leads were wired to a distribution box. The schematic is shown in Figure 4-7. The description of the distribution box is in Chapter 3 of this report. Figure 4-8 is a photo of the AC breaker box, rectifiers, and DC junction box.

Figure 4-7. DC Distribution Box Wiring Scheme

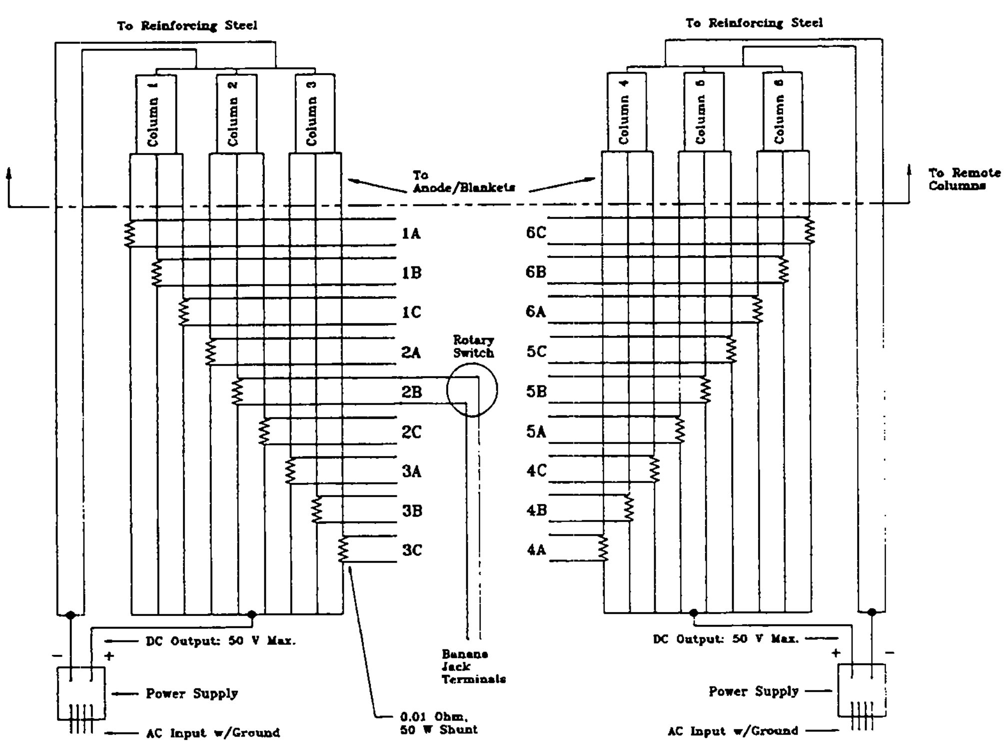
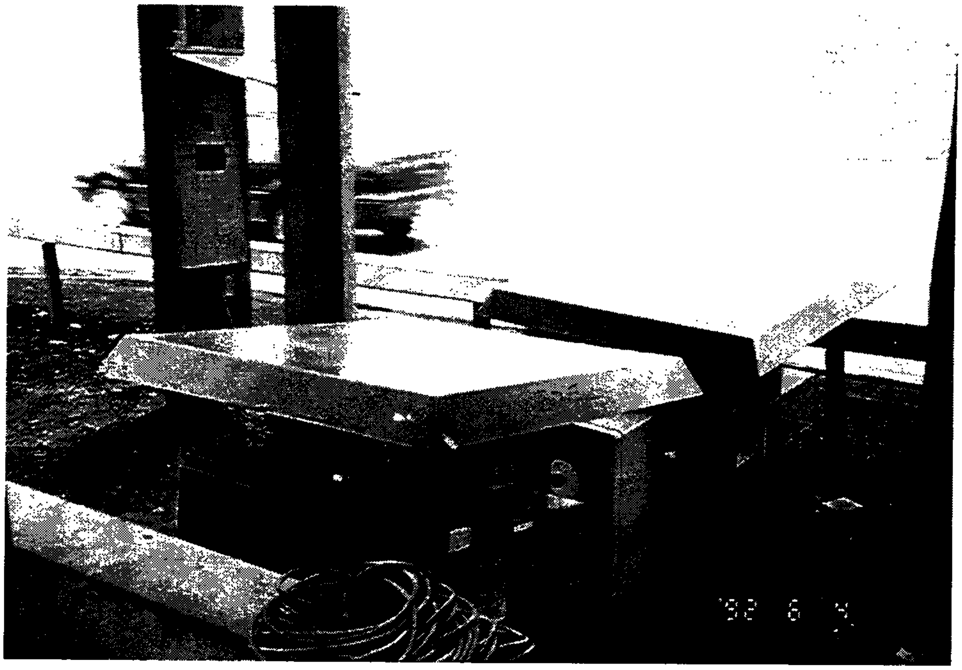


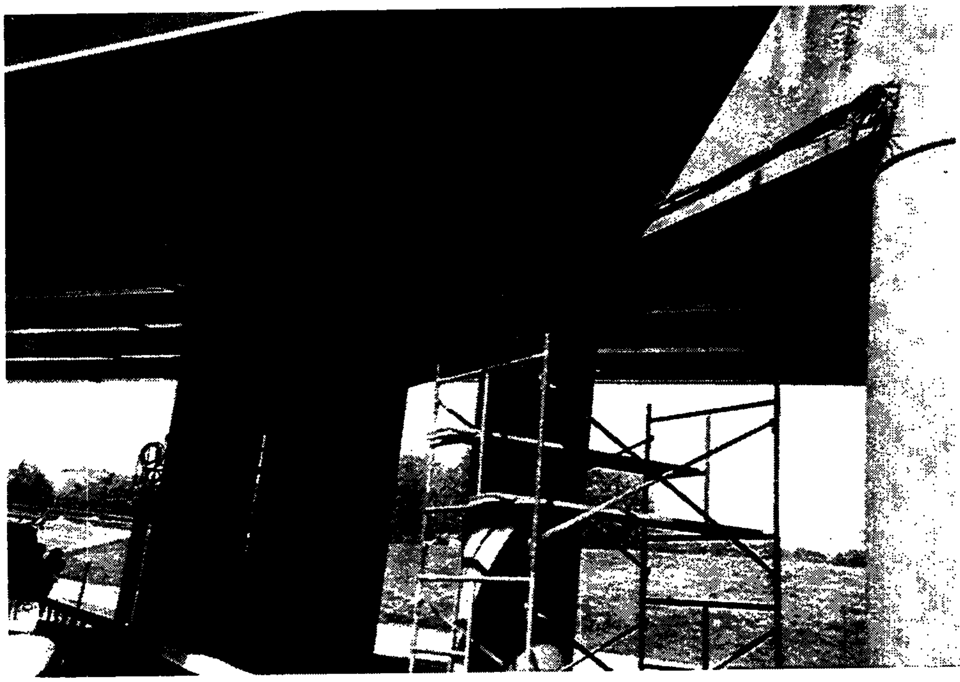
Figure 4-8. Rectifiers, AC Breaker Box, and DC Distribution Box



DC Wiring

The negative and positive (anode) leads were № 6 (black) and № 10 (red) AWG wires, respectively, and were reused from the Florida field trial. The wires were measured, labeled, cut, and bundled together. The bundles were tied to the J-clamps which held the manifold (Figure 4-9). The bundles also contained AC power lines for the pumps.

Figure 4-9. Bundled DC Wires and Electrolyte Manifold Above Columns



Since all steel was found to be continuous, connection to the reinforcing steel was made by exposing the steel at the bottom of the cap-beam. The exposed rebar was ground clean, drilled, and tapped. Two system negative connections were made for each zone system. A typical system negative connection is illustrated in Chapter 2, Figure 2-5.

Figure 2-4 in Chapter 2 shows a typical anode connection.

Chloride Removal Blanket Installation

A description of a typical chloride removal blanket system is described in Chapter 3 and shown in Figure 3-6. The electrolyte gravity return required the blankets to be installed no lower than 2 ft (60 cm) from the ground. Installation of an anode/blanket assembly over the inner blanket of $Sorb_x$ is shown in Figure 4-10. Figure 4-11 shows the installation of three blankets per column.

A layer of 2-ft (60-cm) wide plastic film was wrapped over the outside of the blankets in top-to-bottom spiraling manner to confine the electrolyte. Nine 1/2-in. (12-mm) wide plastic straps, three per blanket, were added for additional reinforcement.

Figure 4-10. Column Wrapped with Inner Blanket and Anode/Blanket Assembly

Figure 4-11. Six Columns with Three Blankets Installed Per Column

Operation

Pre-Treatment Evaluations

Pre-treatment evaluations were conducted, and concrete repairs required were also determined.

Corrosion Measurements

The half-cell potentials were obtained using a $Cu/CuSO_4$ reference cell. The results are tabulated in Table 4-1, and indicate active corrosion.

Linear polarization corrosion rate measurements were obtained at locations without delaminations. At these locations, the values between 1.0 and 10 mA/ft^2 (1 and 10 $\mu A/cm^2$) predict visible corrosion damage in 2 to 10 years (Table 4-1).[4]

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[4]Measurements were taken with the KCC 3LP Device, Kenneth C. Clear, Inc., Virginia

Table 4-1. Pre-Treatment Corrosion Measurements

Column	Height from Ground	Half-Cell Potentials, mV vs $Cu/CuSO_4$ North	East	South	West	3LP i_{corr} mA/ft^2
	10'	-191	-293	-364	-278	east
	8'	-232	-272	-364	-290	at 4'
1	6'	-135	-263	-330	-312	
	4'	-181	-243	-285	-250	1.04
	2'	-214	-226	-222	-215	
	10'	- 81	-207	-116	-226	west
	8'	-133	-239	-113	-257	at 4'
2	6'	-248	-350	-199	-383	
	4'	-208	-301	-165	-426	1.46
	2'	-163	-286	-177	-336	
	10'	-248	-428	-267	-381	east
	8'	-274	-405	-302	-357	at 4'
3	6'	-185	-398	-257	-290	
	4'	-188	-460	-316	-266	1.38
	2'	-214	-443	-321	-290	
	10'	- 87	-120	-102	-192	south
	8'	- 87	-119	-105	-166	at 4'
4	6'	- 99	-163	-147	-194	
	4'	-190	-293	-180	-180	0.28
	2'	-322	-310	-238	-214	
	10'	-236	-402	-211	-310	east
	8'	-220	-342	-186	-270	at 4'
5	6'	-233	-344	-144	-280	
	4'	-233	-316	-155	-240	1.08
	2'	-285	-352	-205	-285	
	10'	-280	-508	-427	-348	east
	8'	-280	-494	-467	-305	at 6'
6	6'	-314	-522	-438	-291	
	4'	-310	-485	-425	-278	1.79
	2'	-309	-375	-450	-285	

Concrete Chloride Content

A chloride content profile was done on a core taken from the south side of Column 3, 2 ft (60 cm) above ground level and part way between the spray zone and no-spray zone. The results are in Table 4-2. The core contained a #9 reinforcing steel bar and had 3.5 in. (9 cm) of concrete cover. The chloride level was below the corrosion threshold at the level of this bar.

Table 4-2. Chloride Content Versus Depth

Average Distance from Surface, in.	#Cl^-/yd^3
0.5	3.80
1.0	2.64
1.5	1.78
2.0	0.94
2.5	0.79
3.0	0.71
3.5	0.67
4.0	0.58

Chloride content on concrete powder samples from the first 2 in. (5 cm) from the surface, on each of the six columns was determined and is in Table 4-3. These samples were taken in the spray zone and one out of the spray zone.

Table 4-3. Chloride Content In and Out of Spray Zones

	Chloride Content, #Cl^-/yd^3	
Column No.	SE Side In Spray Zone	SW Side Out of Spray Zone
1	7.79	8.43
2	4.56	5.08
3	5.00	13.01
4	4.15	10.63
5	8.29	6.39
6	7.46	11.30

Other Core Tests

Two 3-3/4-in. (9.5-cm) diameter cores were obtained for laboratory testing. One core was 4-1/2-in. (4-cm) long and contained a #10 steel bar that was located 3-1/2 in. (9 cm) below the surface. Chloride removal treatment of this core indicated that a current density of 0.3 A/ft^2 (3 A/ft^2) at 50 V would be the approximate field operating parameters.

The second core was 5-in. (13-cm) long and contained no reinforcing steel. Both cores were examined petrographically. The concrete represented by the cores was an air-entrained portland cement concrete containing 1-in. (2.5-cm) nominal maximum size coarse aggregate. The coarse aggregate was a crushed limestone ranging in composition from argillaceous micrites to mud-supported sparse biomicrites. Occasionally sparry calcite veins and vug fillings were present and some particles were composed entirely of sparry calcite. Particles with the fewest fossils were the most argillaceous and/or siliceous.

The coarse sand, 0.08 to 0.19 in. (2 to 4.75 mm), was composed principally of sub-rounded metamorphic rock fragments, mostly gneisses with fewer schist and quartzite granules. Up to 30 percent of the coarse sand was sub-angular to angular dark limestone like that of the coarse aggregate. The bulk of the fine aggregate was sub-rounded, poorly sorted quartz sand that had an average grain diameter of approximately 0.04 in. (1 mm). Inclusions and textures suggested metamorphic quartz as a major part of the sand. A few percent of hornblende, feldspar, mica, and goethite grains were present.

In these core samples, the proportion of fine to coarse aggregate fell within normal bounds and there was good uniformity of distribution of aggregate particles from top to bottom within the cores.

The total air void content was estimated at 5 to 7 percent. The air voids were distributed uniformly from top to bottom in the cores. From the point of view of its intended function, the entrained air system was judged to be of good quality.

In the untreated core, the cement paste was of excellent quality with an estimated water-cement ratio of 0.38 to 0.42. A tight uninterrupted bond persisted between the cement paste phase and the aggregate particles.

A considerable amount of precipitate formed during the operation of the treated core. A section view of this core confirmed that, overall, the treatment had no apparent adverse effect on the structure concrete. The only exception was some very minor cracking of the cement paste phase of the surface.

The concrete of the treated core was very similar to the concrete of the untreated core from all points of view. In the treated core, the cement paste surrounding the steel bar appeared to have been unaffected by the treatment. This paste, adjacent to the bar, had neither discolored or softened as a result of the treatment. With the exception of the surface, there was no new cracking in the core and a tight bond persisted between the cement paste phase and the aggregate particles. There was no evidence of the participation of aggregate particles in cement-aggregate reactions.

The only apparent difference between the untreated and treated cores was a very minor attack of the cement paste phase in the treated core. The paste at the core surface (in contact with the electrolyte) was somewhat softer and more porous. This suggested some involvement or attack of the cement paste with the electrolyte solution. The depth of interaction was less than 0.04 in. (1 mm) from the surface.

These evaluations indicated that chloride removal treatment would not have an adverse effect on the structural integrity of the substructure.

Operation

Initial current densities ranged from 0.1 to 0.3 A/ft^2 (1 to 3 A/m^2) at 49 V. At this setting, power supply fuses were blowing. The voltages were adjusted to 40 volts which prevented the fuses from blowing. Current densities over the first couple of days averaged 0.25 to 0.35 A/ft^2 (2.5 to 3.5 A/m^2), and then steadied at 0.2 A/ft^2 (2 A/m^2) for the balance of the trial.

Zone 1 operated for 24 days, accumulating 80 A-hr/ft^2 (800 A-hr/m^2). The electrolyte pH dropped to 7.6. A leak in the top blanket of one of the columns resulted in the shutdown of this zone.

Zone 2 operated for 17 days, accumulating 93 A-hr/ft^2 (930 A-hr/m^2). Rainwater run-off from the deck overflowed the reservoir even though it was covered. This diluted the electrolyte and caused the pH to fall to 3. This was detrimental to the concrete, and operation was discontinued.

Even though the desired charge was not accumulated on either zone, it is possible that the amount of charge that was accumulated was sufficient to halt corrosion. The corrections to the problems which caused the shutdowns could not be economically justified.

Post-Treatment Evaluations

Pos Treatment Concrete Chloride Content

Cores were taken from the New York field trial columns that were treated. Core 2 was taken from the north side of column 2, and contained a #4 rebar at the fractured end. Core 3 was taken from the south side of column 3 and contained a #4 rebar at the fractured end. Core 5 was taken from the north side of column 5, and contained no rebar. Core 6 was taken from the south side of column 6, and contained no rebar but was located at the edge of a #9 rebar. This core was separated along an existing delamination about 1 in. (2.5 cm) below the wearing surface. All cores were taken 9 ft (2.7 m) above ground level.

The total chloride ion concentration in each core from powder samples at 0 to 1/2 in. (0 to 12 mm), 1/2 to 1 in. (12 to 25 mm), 1 to 1-1/2 in. (25 to 37 mm), and 1-1/2 to 2 or 2-1/4 in. (37 to 50 or 56 mm) depths. These results are shown on Table 4-4.

Table 4-4. Post-Treatment Core Chloride Ion Content

Core No.	Depth, in.	%Cl$^-$ [a]	#Cl$^-$/yd^3 [b]
2	0 to 1/2	0.020	0.78
2	1/2 to 1	0.016	0.63
2	1 to 1-1/2	0.002	0.08
2	1-1/2 to 2-1/4	0.004	0.16
3	0 to 1/2	0.055	2.15
3	1/2 to 1	0.074	2.90
3	1 to 1-1/2	0.084	3.29
3	1-1/2 to 2-1/4	0.039	1.53
5	0 to 1/2	0.152	5.95
5	1/2 to 1	0.232	9.08
5	1 to 1-1/2	0.119	4.66
5	1-1/2 to 2	0.059	2.31
6	0 to 1/2	0.031	1.21
6	1/2 to 1	0.044	1.72
6	1 to 1-1/2	0.034	1.33
6	1-1/2 to 2	0.036	1.41

(a) Based on dry concrete weight
(b) Based on a concrete unit weight of 145.0 lbs/ft^3

Powder samples were obtained from the treated columns adjacent to the pre-treatment sample locations. The samples represent the top 2 in. (5 cm) of concrete, and the data are shown in Table 4-5.

Table 4-5. Post-Treatment Chloride Contents

	Pre-Treatment Chloride Content #Cl$^-$/yd^3		Post-Treatment Chloride Content #Cl$^-$/yd^3	
Column No.	SE Side	SW Side	SE Side	SW Side
1	7.79	8.43	----	----
2	4.56	5.08	2.76	3.30
3	5.00	13.01	5.68	7.84
4	4.15	10.63	----	----
5	8.29	6.39	2.24	3.58
6	7.46	11.30	13.33	6.55

Note: SE side is in spray zone
SW side is out of spray zone

The sample for column 6, southeast side, shows an uncharacteristically higher chloride content after treatment. However, this was located in an area that was patched since the initial samples were obtained. It was not noticed at the time of sampling, but the surface of the patch is likely to have been craze cracked. These cracks would be entry sites for electrolyte with a high concentration of chlorides.

Core Petrographic Analysis

Petrographic examination of the four cores found that this chloride removal treatment had no adverse effect on the quality of the concrete. Cement paste adjacent to the steel bars showed no softening or discoloration relative to cement paste in regions away from the steel. Further examination indicated that the treatment did not aggrevate alkali-silica reactivity despite the fact that the fine aggregate contained ASR materials.

Half-Cell Potentials

Post-treatment half-cell potentials were obtained approximately a week after system shutdown. The same locations as the pre-treatment measurements were used. Values ranged between -700 and -1100 mV versus $Cu/CuSO_4$. These values indicate that the steel was polarized during treatment and is still depolarizing.

System Removal

Electrical System

Before dismantling the systems, all AC power was turned off. All DC lead wires were removed. Since the wires were reusable, they were carefully inspected for damage. The distribution box was removed from the rectifier door.

Electrolyte System

The electrolyte pumps were removed and examined for damage. The wooden platforms for the pumps and related supports were non-reusable and disposed of.

Before removing the electrolyte distribution manifold, all distribution hoses were disconnected and disposed of. The manifold was cut into several small sections for ease of removal. The unions, short PVC pipe segments, and other glued components were considered non-salvageable items and disposed of.

The electrolyte was pumped from the reservoirs into chemical resistant drums. The drums were sealed and removed for testing and proper disposal.

The electrolyte reservoirs were removed and the holes were filled.

Chloride Removal Blanket

All chloride removal blankets were removed and examined. The geotextile materials were in good condition. The lead wire connections to the titanium strip of three of the twelve blankets had partially dissolved possibly due to insufficient insulation.

A couple of 1-in. (3 mm) diameter areas received very high current. This was identified by cement dissolution where tie wires were near the surface of the concrete. The anode in that area also dissolved during the treatment due to high localized current density.

One anode from column 6 dissolved across the 4-ft (1.2-m) width. This was located directly over a large vertical patch in column 6. The resistivity of the patch was much lower than the original concrete and a large amount of current passed into this area.

The vulcanized rubber sheet, bulkheads and return hoses of the electrolyte collection system were removed. Some chalky precipitate was found trapped inside the electrolyte collection system of column 3 in zone 1. Similar compound was found at the bottom of the electrolyte reservoir. This precipitate was noticed in laboratory tests when using 0.3 M sodium borate solution, a near saturated solution.

Costs

Even though the actual treatment area was 528 ft^2, cost calculations were done on the 792 ft^2 that was prepared for treatment. This larger area was fully prepared for treatment, including anode blanket installation, electrolyte circulation system, electrical wiring, and concrete sampling.

Materials

A list of disposable and single-use items is tabulated in Table 4-6. The cost per square foot of treatment area for these items was $3/$ft^2$ ($30/$m^2$).

Table 4-6. Single-Use Item Costs

Material/Equipment	Description	Quantity	Price, $
Plastic anchors	1/4"	10 units	0.50
$Sorb_X$ S-92	4'x11-1/2'	18 units	331.00
Washers	Miscellaneous	20 units	1.00
Nuts and bolts	Miscellaneous	40 units	5.00
Vinyl electrical tape	3/4"x66'x.007"	2 units	4.00
Wire ties	7"	2 boxes	17.00
Plastic wrap	18"x500'	1 roll	15.00
PVC pipe	Sch.80 1"	100 ft	46.00
PVC pipe	3/4"	200 ft	62.00
PVC fittings	3/4"	48 units	137.00
Teflon tape	1/2"	1 unit	0.50
Tubing clamps	1"	10 units	5.00
PVC primer	Oatey	1 quart	5.50
PVC cement	Oatey	1 quart	6.50
3/8" lugs	Anode terminals	18 units	10.50
1/4" lugs	Cathode terminals	4 units	2.50
NaOH	Na_3BO_3	30 kg	68.00
H_3BO_3	Na_3BO_3	15 kg	95.00
Miscellaneous	Materials	-	70.00
Electrolyte disposal	55 gal dums	6 units	1200.00
		Total:	$2082.00
		Treatment area:	792. ft^2
		Cost/unit area:	$2.63/$ft^2$

Table 4-7 lists tools and equipment used for this trial that could be amortized over the course of several treatments. The single-use cost per square foot of treatment area for these items was $20/$ft^2$ ($200/$m^2$). An amortized cost for these items was $2/$ft^2$ ($20/$m^2$).

Table 4-7. Amortizable Item Costs

Material/Equipment	Description	Quantity	Price, $
Wrap dispenser	Stainless steel	1 unit	75.00
Plastic strap	1/2" polyester	1 roll	10.00
Mechanical sealer	1/2" strap size	1 unit	80.00
Strap tensioner	1/2" strap size	1 unit	120.00
J-Clamps	1"	10 units	15.00
Polyfelt TS-1000	4'x11-1/2'	18 units	240.00
GTF 350 EX	4'x11-1/2'	18 units	240.00
Elgard 300 mesh	4'x11-1/2'	18 units	2484.00
Titanium strip	5'x1/2"x.035"	50 ft	50.00
Buckles and straps	Polyester	60 units	90.00
Sewing costs	Labor	30 hours	500.00
Rectifier	Darrah 50VDC-200ADC	2 units	8400.00
Wire	#6 AWG	400 ft	250.00
Wire	#10 AWG	400 ft	200.00
Electrolyte tanks	Rubbermaid, 150 gal	2 units	350.00
Electrolyte pump	10 gpm, self-priming	2 units	1500.00
Nalgene tubing	1-1/4" reinforced	100 ft	520.00
Nalgene tubing	1/2" reinforced	100 ft	160.00
PVC valves	3/4"	10 units	61.00
pH meter	Test equipment	1 unit	100.00
Multimeter	Test equipment	1 unit	300.00
Shipping crate	Wood	2 units	70.00
		Total:	$15,815.00
		Treatment area:	792. ft^2
		Cost/unit area:	$19.97/$ft^2$
		Amortized cost:	$2.00/$ft^2$

Total material costs, single-use and amortized, were $5/$ft^2$ ($50/$m^2$).

Labor

Table 4-8 summarizes the man-hour requirements for this chloride removal trial. The total labor cost for installation, maintenance, and removal was \$8/ft² (\$80/m²).

Table 4-8. Man-Hour Requirements

Installation

Crew	Hours	Rate, \$/hr	Cost, \$
Supervisor/laborer	32	55.00	1760.00
Operator/laborer	33	40.00	1320.00
Laborer	30	25.00	750.00
Laborer	30	25.00	750.00
Total man-hours:	125	Labor cost:	\$4580.00

Operation

Crew	Hours	Rate, \$/hr	Cost, \$
Operator/laborer	20	40.00	800.00
Total man-hours:20		Labor cost:	\$800.00

Removal

Crew	Hours	Rate, \$/hr	Cost, \$
Supervisor/laborer	8	55.00	440.00
Operator/laborer	8	40.00	320.00
Laborer	8	25.00	200.00
Total man-hours:24		Labor cost:	\$960.00

Total labor costs:	\$6340.00
Treatment area:	792. ft²
Cost/unit area:	\$8.00/ft²

Man-hour estimates include only the time spent at the site. Installation and removal tasks were discussed earlier in this chapter. Operation tasks include data collection five times a week, electrolyte maintenance, and electrical equipment maintenance.

The hourly labor rates were estimated, based on salary and overhead in the year 1991.

Total Costs

The cost of this trial, including single-use materials, amortized materials, and labor, was \$13/ft^2 of treated area (\$130/m^2). This does not include travel expenses or standard tools.

5

Ontario Abutment Field Trial

Summary and Conclusions

The final field trial was conducted on the north and south abutments on the Rt. 11 bridge over the Montreal River in Latchford, Ontario, Canada. This structure provided a unique opportunity since there was evidence of severe alkali-silica reactivity (ASR). Ordinarily it would not be considered prudent to conduct chloride removal on such a structure since the treatment process increases alkali at the steel surface and aggrevates ASR. The laboratory studies found that this problem might be controlled with the addition of lithium ions to the electrolyte. The use of a lithium borate (Li_3BO_3) buffered electrolyte at Latchford provided a field demonstration of this finding.

Corrosion potentials were very negative throughout the abutments, with almost all readings being more negative than -0.450 V versus SCE. Chloride contents were well above the corrosion threshold at the reinforcing steel.

Several vertical cracks in the concrete had to be epoxy sealed near the bottom of the abutments to prevent leakage and loss of electrolyte.

A chloride removal anode/blanket composite was installed on each abutment face. The north and the south abutments were separate zones. The total treated area was 168 ft^2 (17 m^2).

A reservoir containing 0.2 M lithium borate elctrolyte was installed at each zone. The electrolyte was pumped to the top of the system, from where it flowed by gravity down the abutment and back to the tank.

The system operated 23 days at 40 V with an average current density of 0.16 A/ft^2 (1.6 A/m^2), accumulating 84 and 89 $A\text{-}hr/ft^2$ (840 and 890 $A\text{-}hr/m^2$) on the two zones.

Post-treatment analysis of the electrolyte and concrete showed that 21 and 14 gm Cl^-/ft^2 (210 and 140 gm/m^2) had been removed from the north and south zone, respectively, at current efficiencies of 19 and 12 percent.

Petrographic analysis of the concrete showed that the treatment had no adverse effect on the alkali-silica reaction occurring in the structure.

Problems encountered included dilution and overflow of electrolyte due to rainwater runoff and corrosion of the titanium conductor bars.

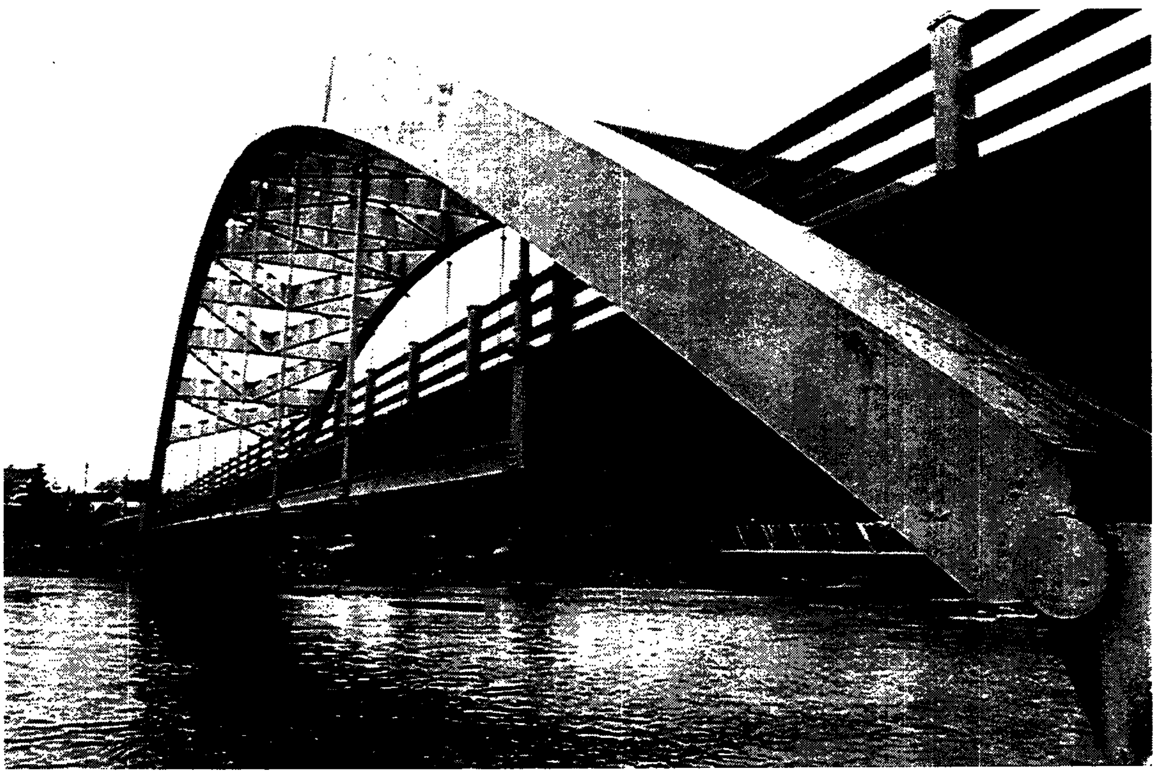
This chloride removal trial is considered a success, especially in view of the severe ASR problem present in the structure. Future post-SHRP monitoring is planned.

Installation

Background

The last chloride removal field trial was in Latchford, Ontario, Canada. The system was installed on the abutments of the bridge over the Montreal River, Site No. 47-58, on Highway 11. Figure 5-1 shows the structure looking toward the north abutment.

Figure 5-1. Bridge Site 47-58, Highway 11 Over the Montreal River



The selection of this structure for a field validation site is significant. The chloride removal process was demonstrated on a vertical flat structure, which is uniquely different from the first three sites. The process may prove to be the only means of rehabilitation for the concrete under bearing seats.

The concrete in this structure contained alkali-silica reactive aggregate. Consequently, this structure was treated using lithium borate (Li_3BO_3) buffered electrolyte, which, in laboratory tests, controls ASR. A core sample from this substructure was operated in the laboratory at 0.6 A/ft^2 (6 A/m^2), and petrographic evaluations confirmed no physical signs of ASR as a result of the treatment.

Epoxy Injection

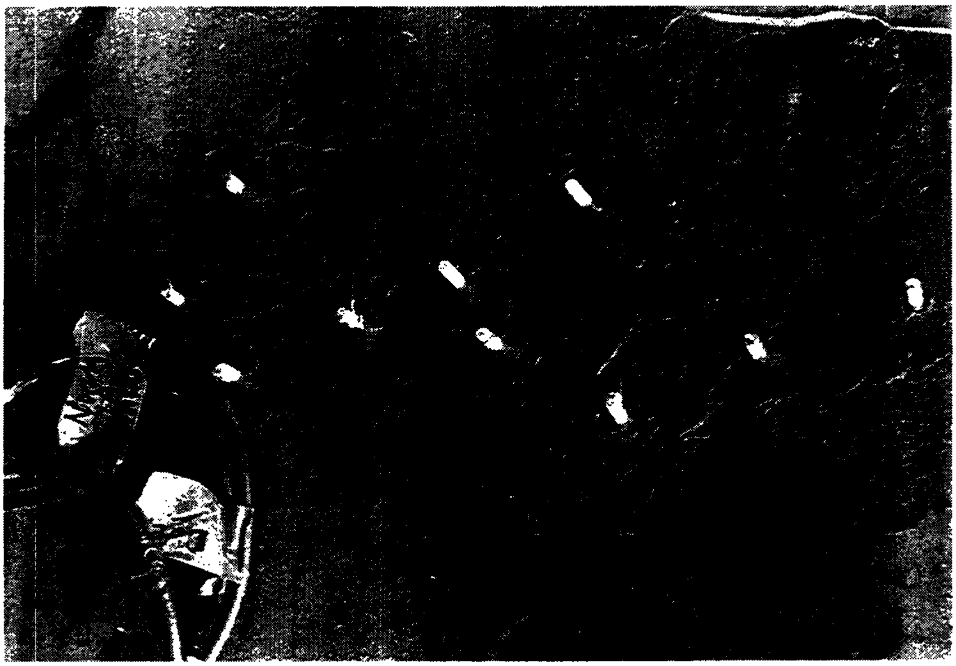
There was a concern about protection of the environment at this site since the bridge spanned the Montreal River, a major fish spawning area. Although the lithium buffer electrolyte was not considered toxic, an electrolyte spill would be likely to enter the river, and would be considered unacceptable. The abutments to be treated were severely cracked, and, based on experience at the New York field trial, sealing the concrete to prevent electrolyte leakage could be difficult.

A conventional epoxy injection system, normally performed to provide structural rebonding, was chosen to seal the cracks at the bottom of the treatment areas. This prevented electrolyte from entering a crack in the abutment and exiting below the treated area. A typical crack is shown in Figure 5-2.

Figure 5-2. Abutment Crack

The surface of the concrete at the cracks was cleaned and roughened with a grinder to accept epoxy surface sealer over the cracks to confine the injection epoxy. Holes were drilled at ı. to 4-in. (7-cm to 10-cm) intervals along each crack to be filled. A 3/8-in. (10 mm) pilot ıe was drilled and enlarged to a 5/8-in. (16 mm) hole. The holes were thoroughly vacuumed to remove any drilling dust that might plug the crack. Polyethylene entry ports were fit into the holes. Capbond EX, a short pot life, 1-hr cure time epoxy was spread over the cracks and around the injection ports to make the seal necessary for injection. Figure 5-3 shows the ports and bonder set along a crack prior to injection.

Figure 5-3. Injection Ports and Epoxy Bonder on Crack



Capweld epoxy #424, a two-component system, was injected into the ports at the end of the crack. A hand-held dispensing gun containing a two-component cartridge and a 32-element, motionless mixing tip, was used for the injection. The first port was injected until the resin flowed out of the next port. The first port was capped, and epoxy was injected into the second port until it flowed out of the third port. This procedure was followed until the entire length of the crack was filled. The epoxy was allowed to harden overnight. The ports and excess epoxy were removed with a grinder until level with the concrete surface. About 45 lin. ft (13.5 m) of cracks were sealed. This injection was successful in that it sealed the cracks and prevented electrolyte leakage. Figure 5-4 shows epoxy being injected into a port midway along a crack.

Figure 5-4. Injection of Epoxy Into Crack

Electrical Installation

AC power, 208 V-3ϕ and 110 V-single phase, was located at both the north and south ends of the bridge.

DC power was supplied to the system through Nº 8 AWG lead wire from the rectifier. A system negative connection was made near each zone by attaching to a 1/4-20 bolt that was threaded into a tapped hole on one of the #12 horizontal reinforcing bars. The anode lead was connected to each titanium anode conductor strip with a 1/4-20 nut and bolt. The northwest and northeast zones were powered by the rectifier at the northwest end of the bridge, and the southwest and southeast zones were powered by the rectifier at the southwest end of the bridge.

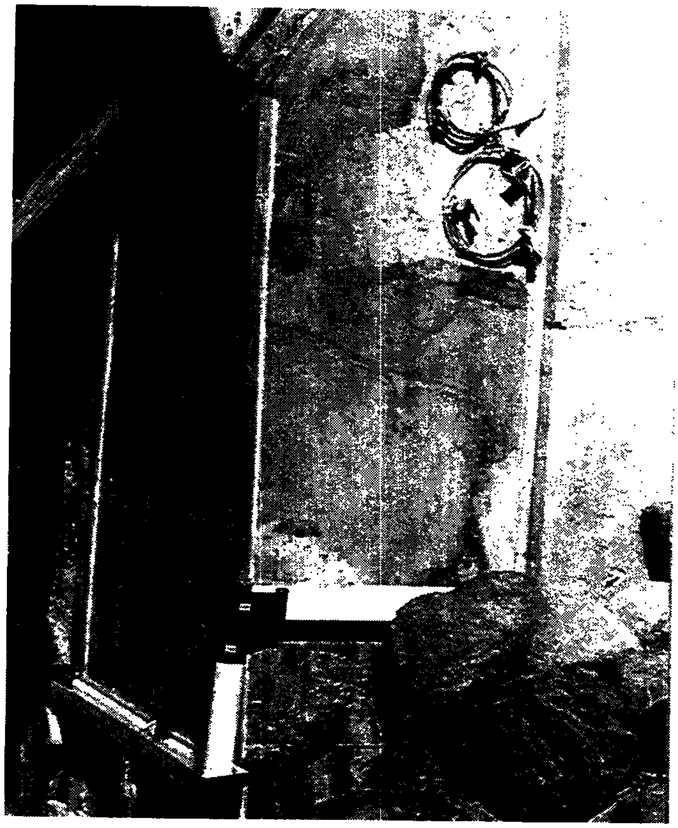
Rectifiers

The same two rectifiers used in the previous trials provided regulated DC power to the chloride removal system. Shunts were installed on the DC output side of each rectifier to measure the current split between the two zones.

Zone Framework

Each zone was made up of two adjacent treatment areas; the trapezoidal face on the side of the abutment and the rectangular face on the front of the abutment. A board framework was mounted to the concrete surface at the perimeter of the treatment areas on each zone. This was done by drilling holes in the concrete, inserting plastic anchors into the holes, and fastening screws through the boards into the anchors. Urethane caulk was used to seal the gaps between the boards and the concrete. The framework was necessary to secure the electrolyte distribution hoses, the electrolyte collection troughs, and the anode blankets. Figure 5-5 also shows the wires from the embedded graphite reference electrodes.

Figure 5-5. Zone Framework, Electrolyte Collection Trough, and Reference Cell Wiring



Electrolyte Feed System

A 150 gal (570 holding tank for electrolyte was located at each end of the bridge, 5 ft from the abutment and approximately midway between the zones. A magnetic drive recirculating pump was mounted on a board spanning the tank and provided electrolyte for both zones.

The end of the inlet line to the pump was fitted with a foot valve so that the pump would stay primed in case there was a power outage.

Figure 5-6 shows the pump, distribution hose lines, and the PVC collection lines for each side of the abutment. Figure 5-7 shows the electrolyte distribution hose fastened to the top of the zone framework.

Figure 5-6. Electrolyte Pump and Piping System

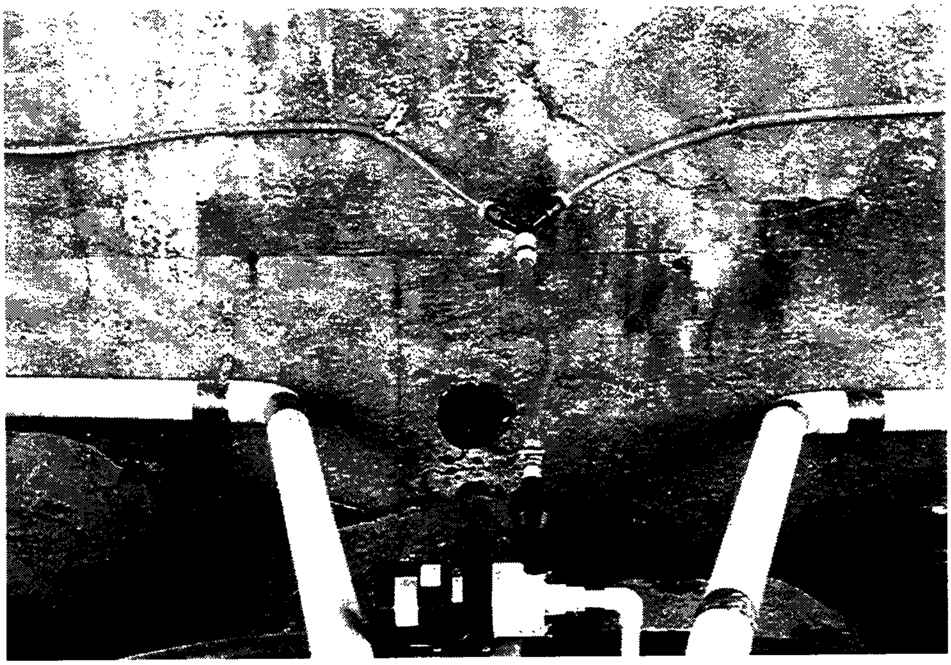
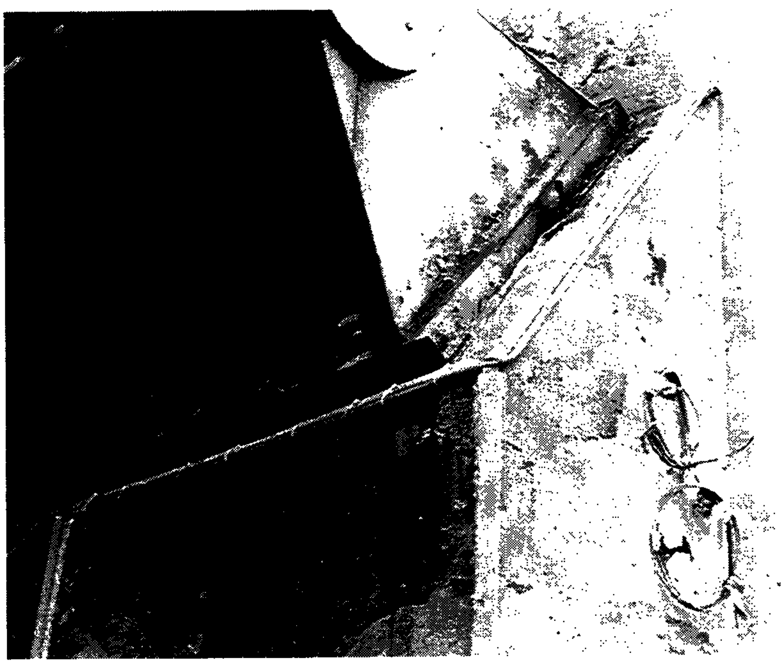


Figure 5-7. Electrolyte Distribution Hose



Water was trucked to the site and 110 gal (415 l) was added to each tank. The system was tested with plain water and found to be sound.

A 0.2M lithium borate (Li_3BO_3) buffered electrolyte solution was made in each tank, by dissolving 11 lb (5 kg) of boric acid (H_3BO_3) and then 22 lb (10 kg) of lithium hydroxide ($LiOH \bullet H_2O$). The tanks were covered with plywood for safety and to minimize evaporation or dilution by rainwater.

Electrolyte Collection System

Plastic gutter was used to collect electrolyte at the bottom of the zones, and piping returned it to the bulk tanks. The gutter was fastened to the bottom board of the framework and urethane caulk was used to seal the top lip of the gutter to the concrete. The ends of the gutter were capped and sealed. (Figure 5-5)

Anode Blanket Installation

Pieces of $Sorb_X$ S-92, GTF 350-EX geotextile, Polyfelt TS-1000 geotextile, and anode mesh were cut to match the dimensions of each zone area. These matching pieces were placed together to form the anode blanket that was secured to the top of the framework. The $Sorb_X$ S-92 was located next to the concrete to maintain electrolyte between the anode and the concrete. The GTF 350-EX was placed next to the $Sorb_X$ S-92. The Polyfelt TS-1000 high strength geotextile covered the assembly.

Titanium conductor strip was welded to the anodes with a resistance welder. The TS-1000 was lifted and the anode was then slipped into place between the geotextiles and held the anode by friction. Figure 5-8 shows the anode blanket configuration, and Figure 5-9 shows the blanket in place against the abutment wall.

Figure 5-8. Anode Blanket Confirguration

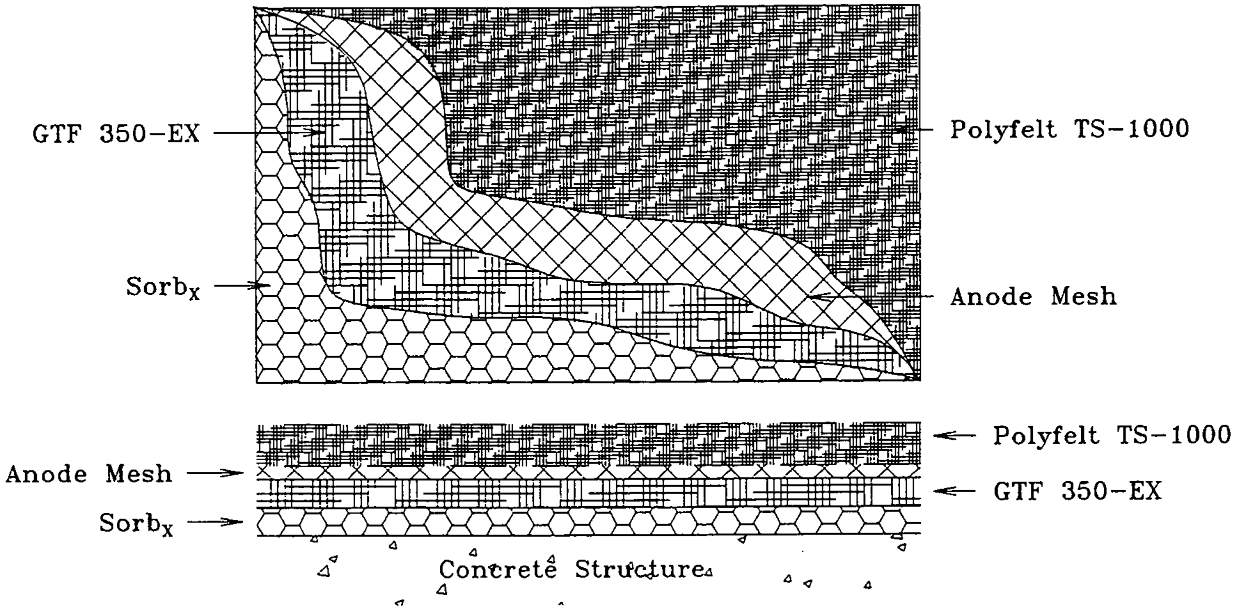


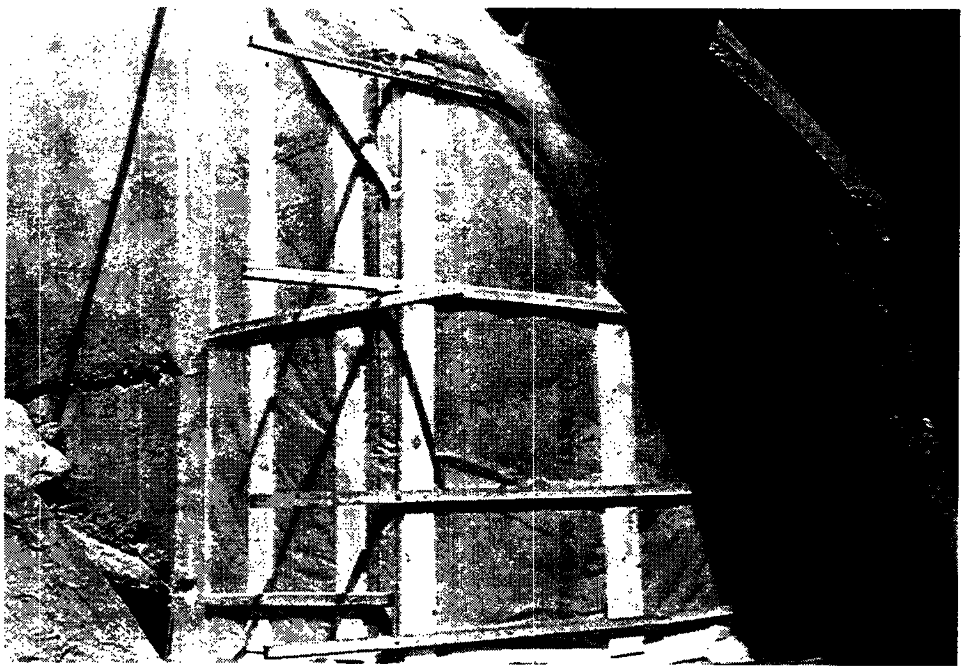
Figure 5-9. Installed Anode Blanket

Thick plastic sheeting was used to confine the electrolyte, and was held in place with staples. The bottom edge of the plastic extended into the gutter.

Wooden slats were used to hold the assembly next to the concrete to ensure good electrolyte retention between the anode and the concrete. Figure 5-10 shows the final assembly.

Another layer of plastic covered the entire zone to minimize rain water from entering the system.

Figure 5-10. Installed Blanket Assembly



Operation

Pre-Treatment Evaluations

The areas treated were the faces forming the corners of the bridge abutments beneath the bridge bearing supports. The area at each of the four corners, or zones (NW, NE, SW, and SE), was approximately 40 ft^2 (4 m^2). Drawings of these zones are in figures 5-11 through 5-14.

The areas to be treated on the north abutment were severely cracked and had several 1 ft^2 (0.1 m^2) areas with concrete missing down to the rebar. There was also significant delamination. The south abutment was not nearly as bad but did contain some cracking and delamination.

Several weeks prior to installation, all delaminated concrete in the areas to be treated was patched with their compatible patching material. Concurrently, concrete cores were taken, and embedded graphite reference electrodes for monitoring were installed.

Figure 5-11. Northwest Abutment and Pre-Treatment Data

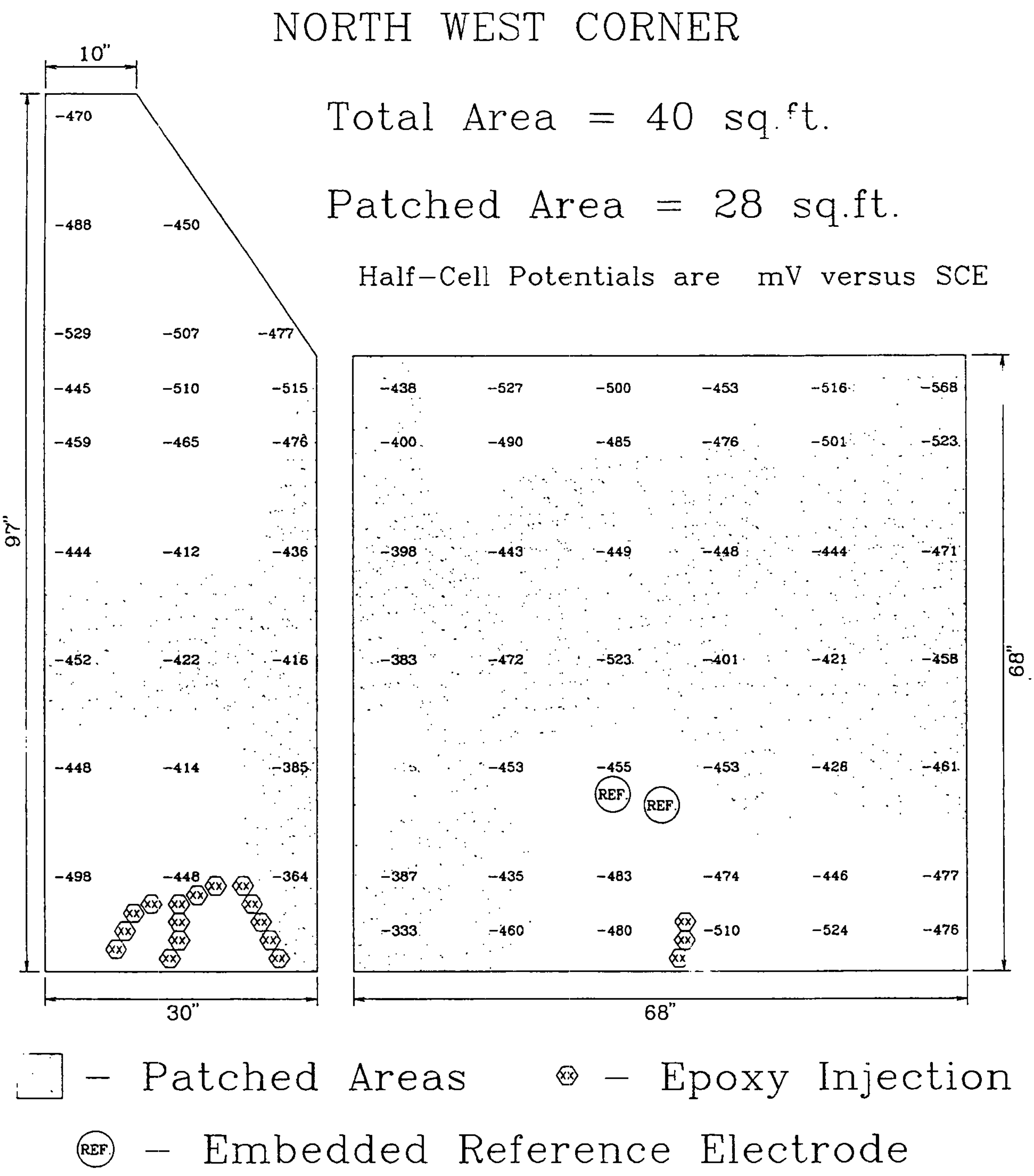


Figure 5-12. Northeast Abutment and Pre-Treatment Data

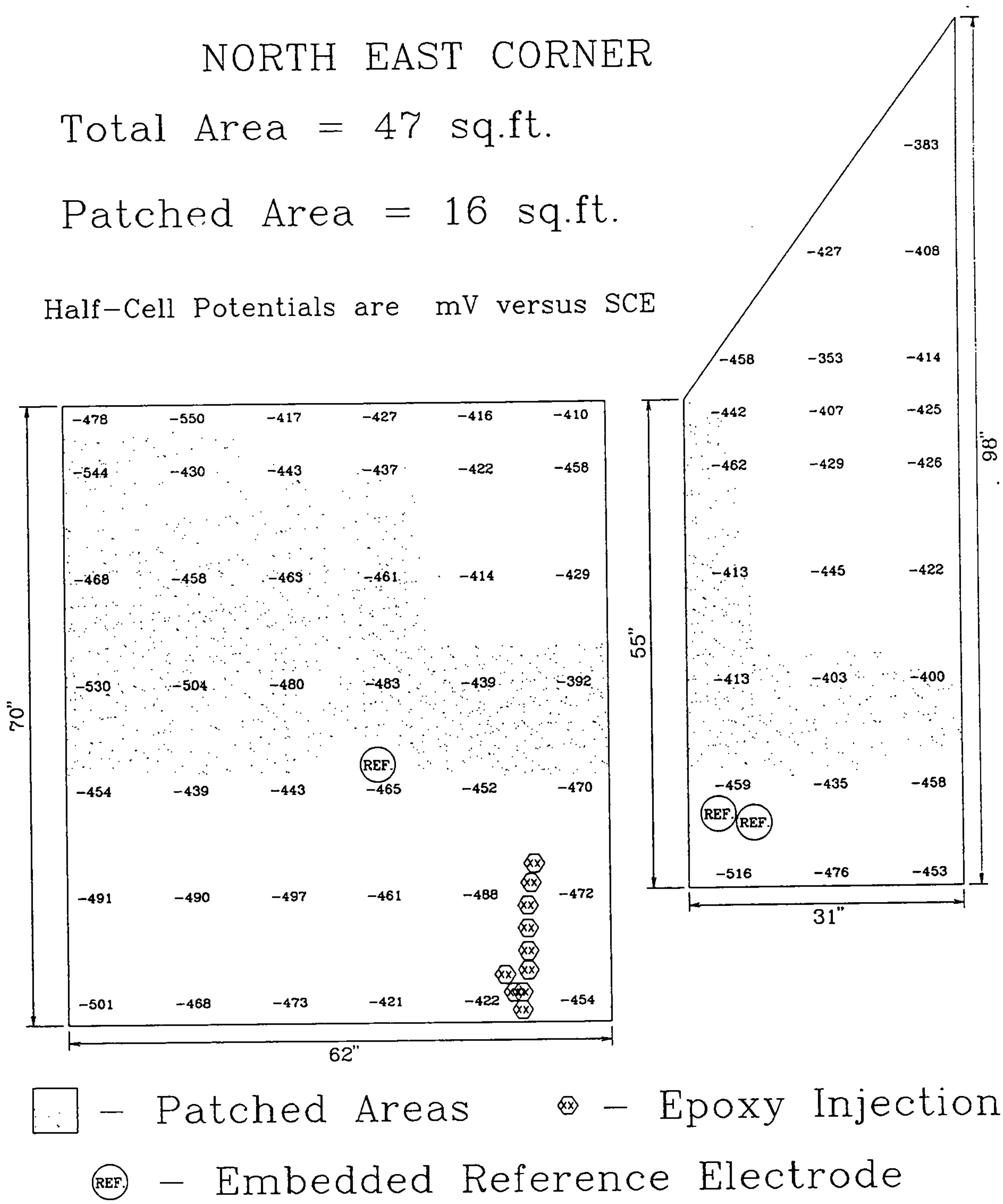


Figure 5-13. Southwest Abutment and Pre-Treatment Data

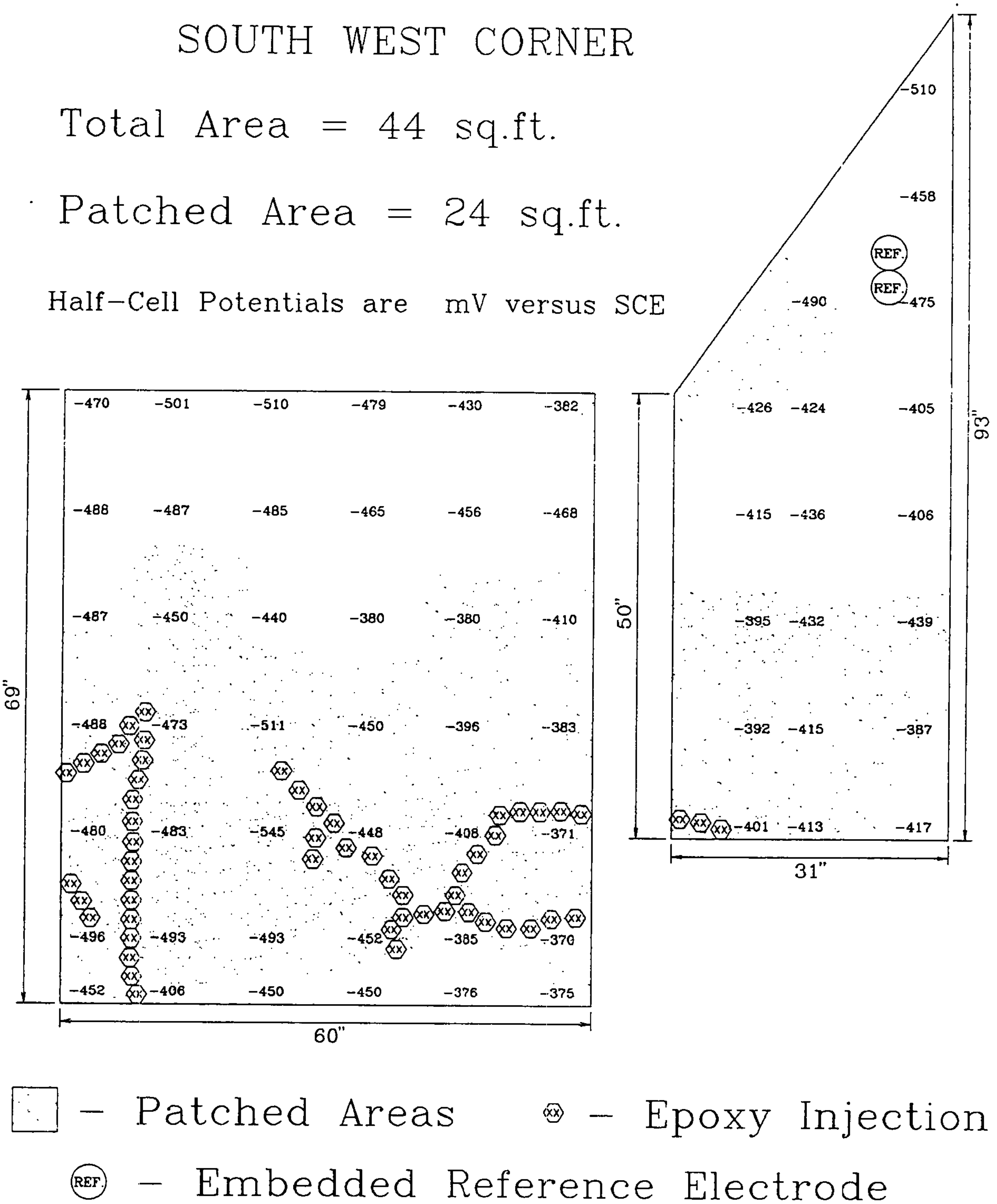
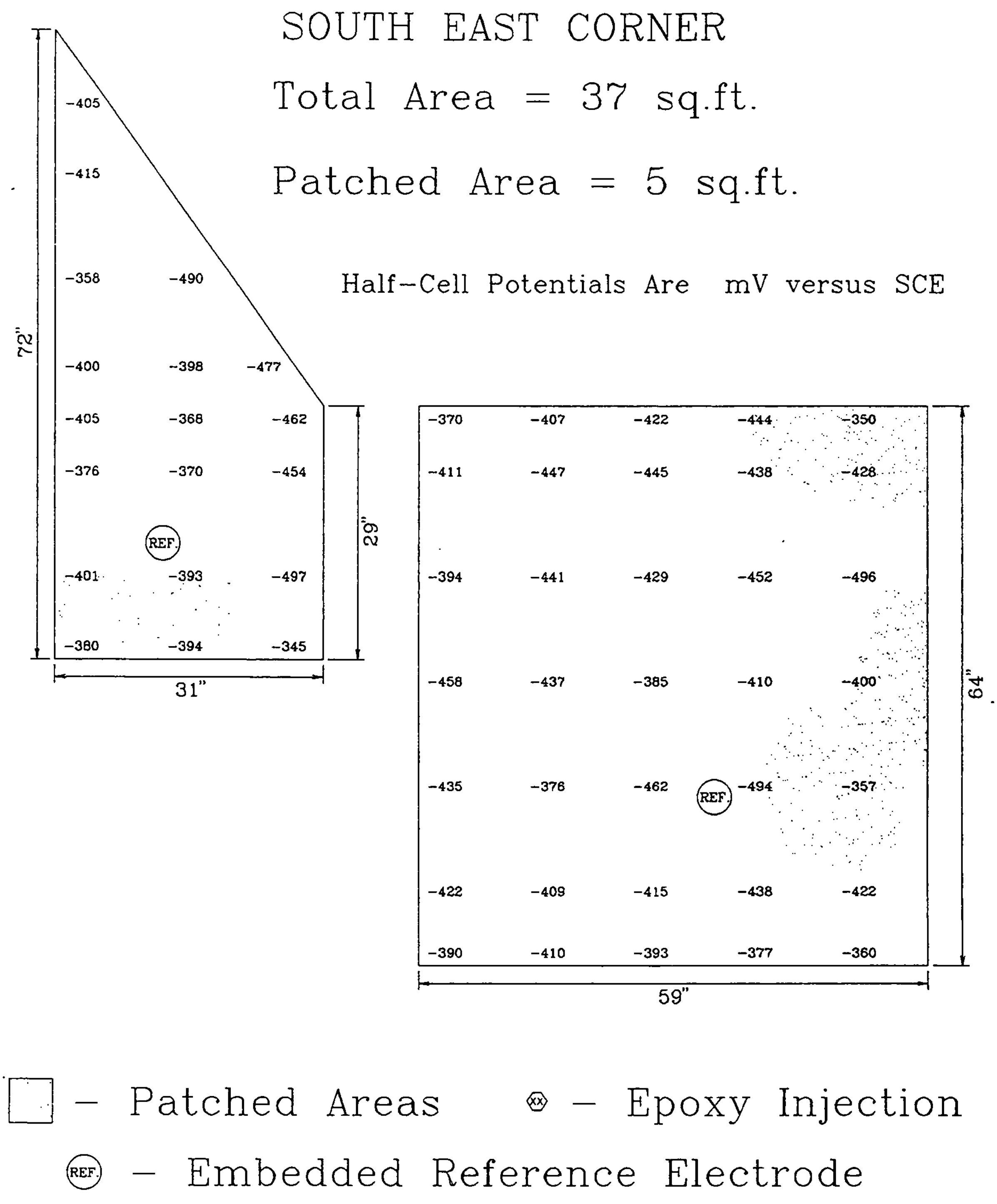


Figure 5-14. Southeast Abutment and Pre-Treatment Data



Half-Cell Potential Survey

A half-cell potential survey was done over each treatment zone using an saturated calomel reference electrode (SCE) and a Fluke 27 multimeter. The results are in figures 5-11 through 5-14. The data show that the reinforcing steel in all areas is actively corroding.

Concrete Resistivity

Since nearly 50 percent of the area to be treated was patched, the resistivities of the structure concrete and patch material were required for confidence that the current would be evenly distributed.

Because an AC resistance meter was not available, another method had to be devised to determine the concrete resistivity. To obtain the data a circuit was wired as shown in Figure 5-15. The current and voltage could be determined by using this test device and two meters.

The formula for resistivity for the Wenner 4-pin method is[5]

$$\text{Resistivity (ohm-cm)} = 2\pi AR$$

where A is the distance in centimeters between the center pins, and R is the resistance in ohms. For the test device the distance between the pins was 1 in. (2.54 cm). A known constant current is applied to the outer pins, and a voltage is measured between the center pins. The value for R is determined by dividing the voltage, in volts, by the current, in amps.

The data obtained indicated that the resistivities of the patched areas are slightly higher than, but are sufficiently close to, the old concrete (Table 5-1). Desirable current distribution was anticipated.

Figure 5-15. Field Assembled Resistivity Device

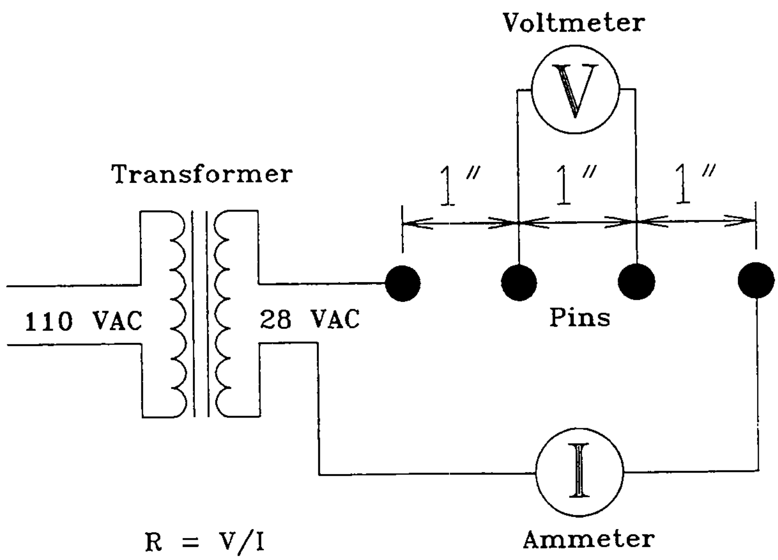


Table 5-1. Resistivity Data on North Abutment

NORTHWEST CORNER

PATCH				CONCRETE			
Potential	Current	Ohms	Ohm·cm	Potential	Current	Ohms	Ohm·cm
1.4	0.0006	2333	37000	1.0	0.0004	2500	40000
1.6	0.0008	2000	32000	0.6	0.0003	2000	32000
1.4	0.0006	2333	37000	0.8	0.0004	2000	32000
1.2	0.0006	2000	32000	0.4	0.0004	1000	16000
1.1	0.0006	1833	29000	1.1	0.0009	1222	19000
1.6	0.0008	2000	32000	0.7	0.0006	1167	19000
2.1	0.0011	1909	30000	1.8	0.0008	2250	36000
Mean		33000		Mean		28000	
Std. Dev.		3000		Std. Dev.		9000	
Coef. of Variation		9%		Coef. of Variation		32%	

NORTHEAST CORNER

PATCH				CONCRETE			
Potential	Current	Ohms	Ohm·cm	Potential	Current	Ohms	Ohm·cm
0.6	0.0010	600	10000	0.4	0.0003	1333	21000
0.7	0.0005	1400	22000	0.3	0.0003	1000	16000
0.3	0.0004	750	12000	0.9	0.0009	1000	16000
0.5	0.0004	1250	20000	0.5	0.0004	1250	20000
0.5	0.0003	1667	27000	0.45	0.0008	563	9000
0.6	0.0008	750	12000	0.9	0.0007	1286	21000
0.5	0.0005	1000	16000	0.7	0.0010	700	11000
Mean		17000		Mean		16000	
Std. Dev.		6000		Std. Dev.		4000	
Coef. of Variation		34%		Coef. of Variation		27%	

Core Petrographic Analyses

Petrographic examinations were conducted on two cores from the abutments prior to treatment. One core was examined "as is." The other core was subjected to laboratory chloride removal before examination.

The concrete represented by the cores had undergone many years of exposure to water and salts and, additionally, may have experienced alkali-aggregate reactivity. The concrete was characterized as a non-air-entrained portland cement concrete containing a 1-1/2 in. (3.5 cm) nominal maximum size gravel coarse aggregate and a natural sand.

The coarse aggregate was dominantly composed of equidimensional, sub-rounded to rounded igneous and metamorphic rock types ranging in size from coarse granules up to 1-1/2 in. (3.5 cm) across. The dominant lithology was granitic gneiss.

The fine aggregate was dominantly composed of sub-rounded sand grains that range in size from coarse silt to granules 0.08 to 0.16 in. (2 to 4 mm). The average grain size fell in the coarse sand range 0.02 to 0.04 in. (0.5 to 1.0 mm). Quartz grains of many types comprised roughly half of the fine aggregate. Compositionally, the sand was a feldspathic litharenite.

Although the lithology of both fine and coarse aggregates was very similar in both core samples, the matrix of the untreated core appeared to contain slightly more silt size mica and other dark minerals. This core also contained more fine, light ASR zones around fine aggregate particles.

The concrete represented by the cores was deficient in several respects; (1) the concrete was not adequately air-entrained, and (2) aggregates have experienced ASR. The water-cement ratio was at an acceptably low level estimated to be 0.40 to 0.45. Both cores showed distress in the form of cracking and delaminations. Although some of the cracking was due to ASR, it is likely that the lack of an adequate entrained air system and corrosion of embedded reinforcing steel contributed to the distress.

The treatment of the treated core was judged to have had no significant adverse effect on the structural integrity of the concrete. The only effect noticed was very minor softening of the cement paste phase of the surface in contact with the electrolyte. Very little chloride was removed in the treatment.

Concrete Chloride Content

Total chloride ion measurements were made on both the treated and untreated cores. The sample taken for chloride ion measurements represents the entire thickness (long dimension) of the cores. The values are presented in Table 5-2.

Table 5-2. Pre-Treatment Chloride Analysis

Core ID	% $Cl^{-(a)}$	lbs $Cl^-/yd^{3(b)}$
Treated	0.009	0.35
Untreated	0.201	7.87

(a) Based on dry concrete weight
(b) Based on concrete weight of 145 lbs/ft^3

These data suggest that the treated core came from a location in the structure not readily accessible to chloride bearing water. At the other coring site, for the untreated core, the average chloride content is relatively high at almost 8 lb/yd^3 (4.5 kg/m^2). It has been reported in the literature that the presence of chloride ions adversely affect the ASR situation. ASR has a gel that absorbs water. This gel would be a path for chlorides to enter the core at an accelerated rate, when compared to a core without gel. This may account, in part, for the greater amount of ASR damage in the untreated core.

Laboratory Chloride Removal

Since the core did not contain reinforcing steel, a 3/8-in. (10-mm) steel rod was inserted into a pre-drilled hole and cemented into place. The core was cured for two weeks at 100 percent relative humidity. Lithium borate (Li_3BO_3) electrolyte was used to duplicate anticipated field conditions. The removal process initially operated at a current density of 0.2 A/ft^2 (2 A/m^2) at 50 V, within two days the current density was 0.6 A/ft^2 (6 A/m^2) at 21 V. A total charge of 170 A-hr/ft^2 (1,700 A-hr/m^2) was passed during the 13-day test period. This testing indicated that a low initial current may be expected at the field trial, and a significant increase could be expected.

Field Site Operation

The electrolyte flow to saturate the anode blankets was checked. The flow rate seemed to be low in a few areas, and was corrected by drilling bigger holes in the distribution hose.

Once the electrolyte flow was satisfactory, the rectifiers were started and current was applied to the system. The south side started at a current density of approximately 0.2 A/ft^2 (2 A/m^2) and 40 V. The north side started up at a current density of 0.27 A/ft^2 (2.7 A/m^2) and 40 V. This was as expected according to core testing in the laboratory.

The systems were monitored daily. Zone currents, system current, system voltage, amp-hr reading, temperature, and electrolyte pH were recorded. Electrolyte samples were occasionally collected for chloride analyses.

A complete set of operating data is summarized in tables 5-3 and 5-4.

Table 5-3. Operating Data Summary; North Abutment

NORTH SIDE

Date	Temp,°C	Electrolyte pH	Zone Amperage NW	NE	Cumulative A-hr/ft^2
8/17	22	10	8.5	13.3	0
8/18	16	10	8.3	16.9	6
8/19	10	10	2.7	11.3	12
8/20	12	10	12.6	13.3	24
8/21	15	10	15.3	17.4	25
8/23	22	10	9.9	9.7	33
8/24	19	8	9.9	9.9	37
8/25	20	8	9.44	9.13	42
8/26	18	10	5.9	5.47	46
8/27	10	10	7.49	8.48	51
8/28	10	10	6.6	7.1	55
8/29	10	8	4.9	4.9	58
8/30	9	8	4.7	4.9	61
8/31	9	10	4.14	3.86	64
9/1	8	8	3.67	4.72	66
9/2	10	8	3.74	4.52	69
9/3	13	6	3.76	4.52	71
9/4	9	6	3.6	4.0	74
9/5	12	6	3.7	4.2	76
9/6	13	6	3.6	4.0	79
9/7	10	6	3.8	4.0	81
9/8	8	6	3.9	4.1	84

Table 5-4. Operating Data Summary; South Abutment

SOUTH SIDE

Date	Temp,°C	Electrolyte pH	Zone Amperage SW	Zone Amperage SE	Cumulative A-hr/ft^2
8/14	22	10	10.9	5.4	0
8/15	18	10	10.8	5.3	4
8/16	19	10	10.7	5.2	8
8/17	22	10	6.3	5.6	14
8/18	16	10	5.1	5.4	17
8/19	10	10	5.9	7.1	22
8/20	12	10	12.6	13.3	26
8/21	15	10	13.8	15.8	35
8/23	21	10	9.3	11.4	43
8/25	20	10	10.55	12.17	54
8/26	18	10	6.54	6.2	56
8/27	10	10	6.12	5.94	60
8/28	10	8	0	5.7	62
8/29	10	8	3.7	4.9	63
8/30	9	8	3.9	4.6	66
8/31	9	10	3.57	4.09	69
9/1	8	10	2.85	5.10	71
9/2	10	10	2.9	5.07	74
9/3	13	9	2.87	5.13	76
9/4	9	9	2.7	4.8	79
9/5	12	9	2.9	4.8	81
9/6	13	9	2.9	4.6	84
9/7	10	9	2.8	4.1	86
9/8	8	9	2.7	4.4	88

Embedded Graphite Electrode Half-Cell Potentials

During operations, daily measurements of the embedded graphite reference cells were taken. The locations of the electrodes are shown in figures 5-11 through 5-14. Tables 5-5 and 5-6 show the data.

The effects of the relatively high operating currents, compared to those used for cathodic protection, on these reference cells are not known. These cells could have become bipolar elements since they were located between the anode and reinforcing steel cathode. If this occurred, the reference cell may have been permanently damaged, and measurements may be unreliable.

Table 5-5. Embedded Graphite Electrode Potential Readings; North Side

North Side Graphite Reference Potentials, -mV

Date	Temp,°C	North 1A Shallow	North 1B Deep	North 2A	North 3 Shallow	North 3 Deep
8/17	23	1095	406	2780	3170	6080
8/18	10	789	746	1749	4380	2590
8/20	12	747	246	2140	5320	3160
8/23	22	1657	1527	1606	3910	1685
8/24	19	366	276	1453	2900	1474
8/25	20	314	251	1374	2490	1190
8/26	18	295	357	1120	1879	920
8/27	10	346	416	1483	2550	1195
8/29	10	364	445	1274	2110	1094
8/31	9	385	447	1204	1866	1014
9/1	8	555	631	1334	2130	1074
9/2	10	816	881	1283	1938	898
9/3	13	473	534	1249	1828	832
9/5	12	861	505	1221	1723	756
9/8	8	394	360	1190	1727	1105
9/9	System Off	522	558	769	887	847

mV vs CSE = mV vs graphite - 155 mV

Table 5-6. Embedded Graphite Electrode Potential Readings; South Side

South Side Graphite Reference Potentials, -mV

Date	Temp,°C	South 4	South 5	South 6	South 7 Shallow	South 7 Deep
8/17	23	4630	2350	1636	2230	2090
8/18	10	379	6100	1150	2270	2230
8/20	12	5530	7600	1904	2960	2980
8/23	22	3800	4060	1257	1309	1349
8/24	19	3900	3900	1440	1477	1519
8/25	20	3550	3710	1365	1424	1487
8/26	18	1567	1970	1041	1093	1126
8/27	10	1438	3040	1161	1188	1217
8/29	10	1455	2450	823	853	843
8/31	9	1385	2010	982	1058	1073
9/1	8	1653	2900	1159	1165	1187
9/2	10	1593	2650	1138	1158	1179
9/3	13	2510	2850	1055	1140	1148
9/5	12	2450	2310	1042	1138	1149
9/8	8	2340	2150	982	1135	1145
9/9	System Off	852	1028	701	825	829

mV vs CSE = mV vs graphite - 155 mV

Electrolyte Management

The electrolyte used was a 0.2M lithium borate (Li_3BO_3) buffered solution. Additional lithium hydroxide ($LiOH \cdot H_2O$) was added to the electrolyte tanks during system operation to maintain the pH of the electrolyte. This was necessary because of dilution of the electrolyte by rainwater. The electrolyte pH data are also in tables 5-4 and 5-5.

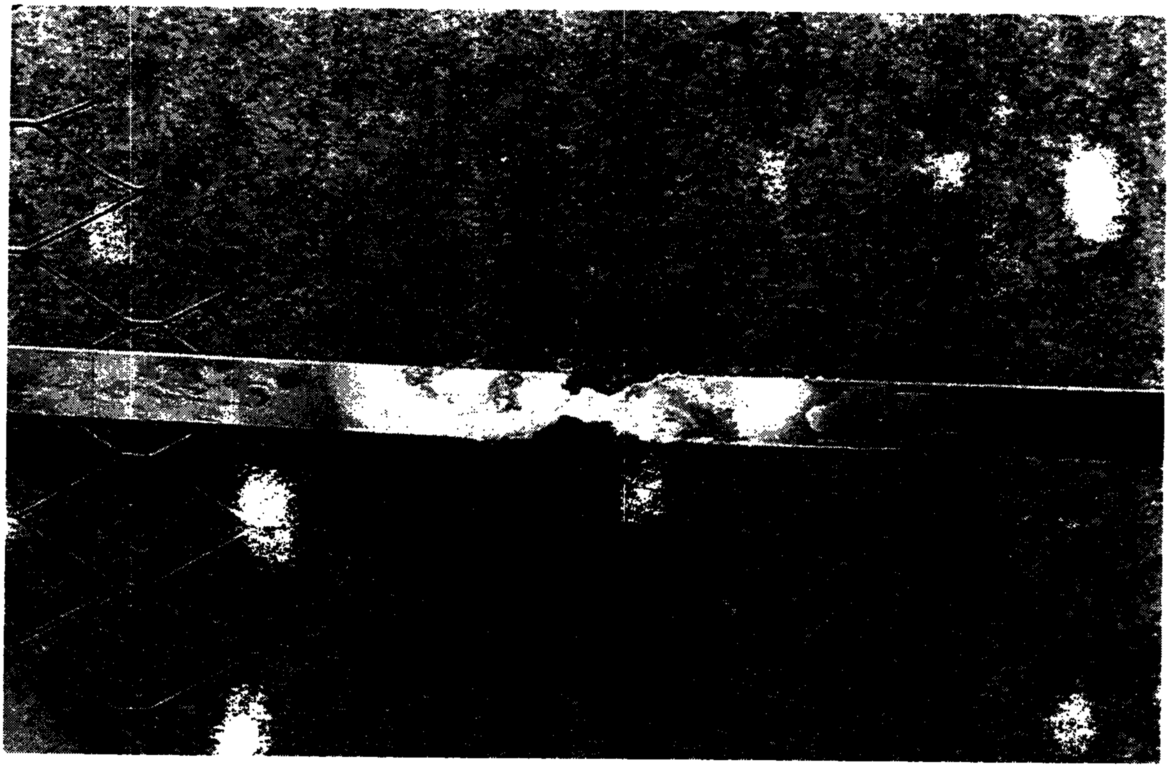
Post-Treatment Evaluations

Anode Inspection

The anodes on both of the north side zones showed no visible signs of degradation. The conductor bar on the northwest corner showed evidence of breakdown in several places and was nearly severed in 7 places. The northeast corner had only slight signs of breakdown. This damage was due to the fact that the conductor bar was not coated, and system voltages were high enough to allow breakdown of bare titanium.

The anode showed minor signs of breakdown near the bottom of the southwest corner. The corroded areas were very small and are not significant. The anode on the southeast corner was intact. The conductor bar on the southeast corner showed ·ıly slight signs of breakdown. The conductor bar on the southwest corner was b. .y corroded, however, and had been completel· ·evered during operation. This break was repaired and did not affect the overall operation of ·: trial. The break is shown in figure 5-16. Coating the conductor bar with the same catalyzed coating that is on the anode could prevent the breakdown of the conductor bars.

Figure 5-16. Conductor Bar Breakdown



Concrete Inspection

V· ..al observation of the treated area after system removal indicated little or no damage to t: ·ncrete surface. Figure 5-17 is a photograph of the surface of the concrete after system removal. Each area had a series of shrinkage cracks in the patched areas. These cracks were present before treatment and were not a result of the chloride removal process.

Figure 5-17. Concrete Surface After Treatment

Half-Cell Potentials

The purpose of this potential survey was to determine the uniformity of polarization, and therefore, the uniformity of current distributed to the steel during treatment. The potential survey is shown being taken in figure 5-22. All potentials were taken using a saturated calomel reference electrode (SCE). The post-treatment potential survey is shown on figures 5-18 through 5-21. These figures show the polarization, and therefore current distribution, to be relatively uniform over most of the treatment area. The exception is the small triangular area on the sides of each corner. These areas were consistently polarized to a less negative value, indicating a lower current density. This was probably due to poor electrolyte circulation, creating a dryer condition in this area, and less current would be passed.

Figure 5-18. Northwest Abutment Post-Treatment Evaluation Testing

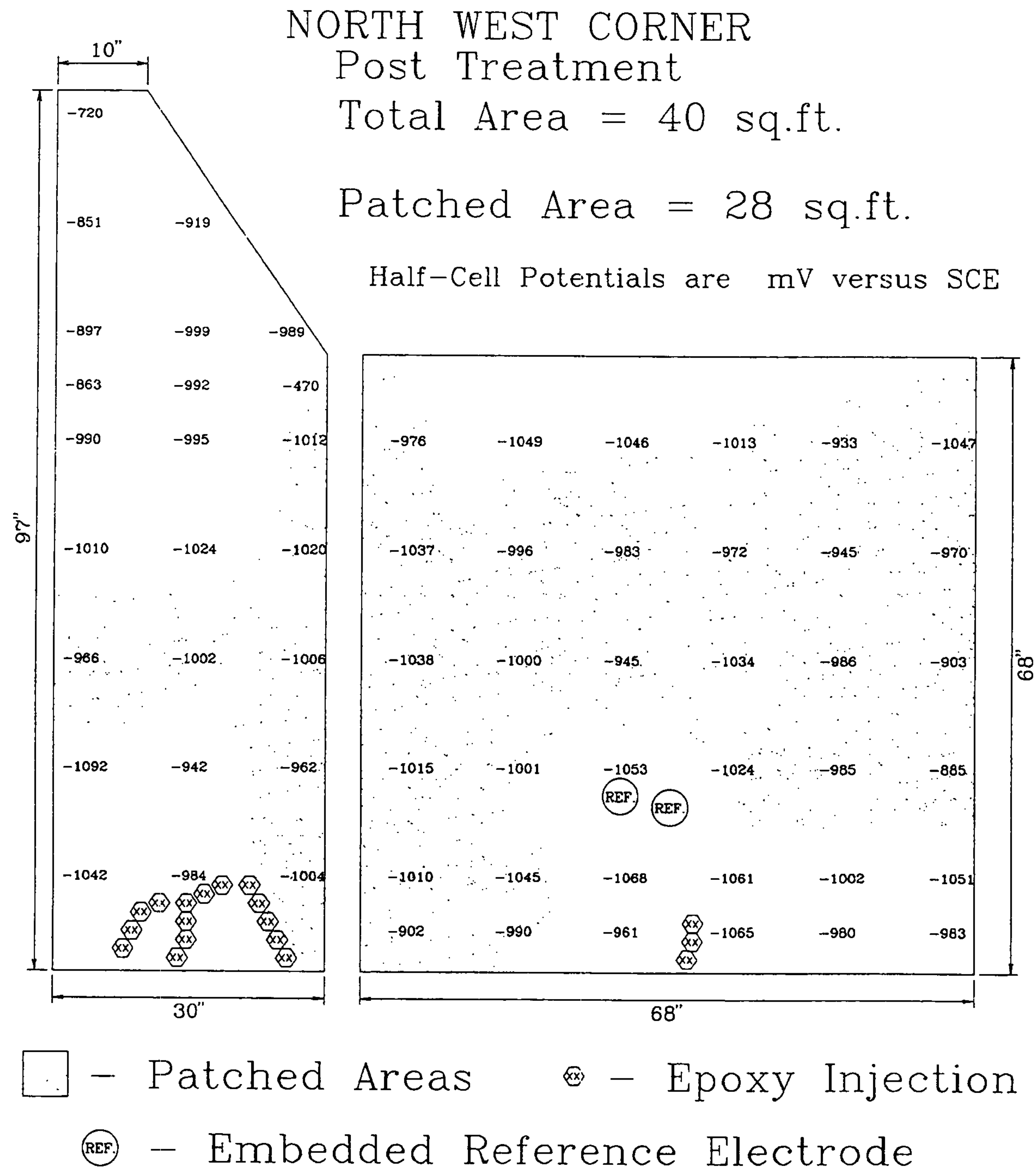


Figure 5-19. Northeast Abutment Post-Treatment Evaluation Testing

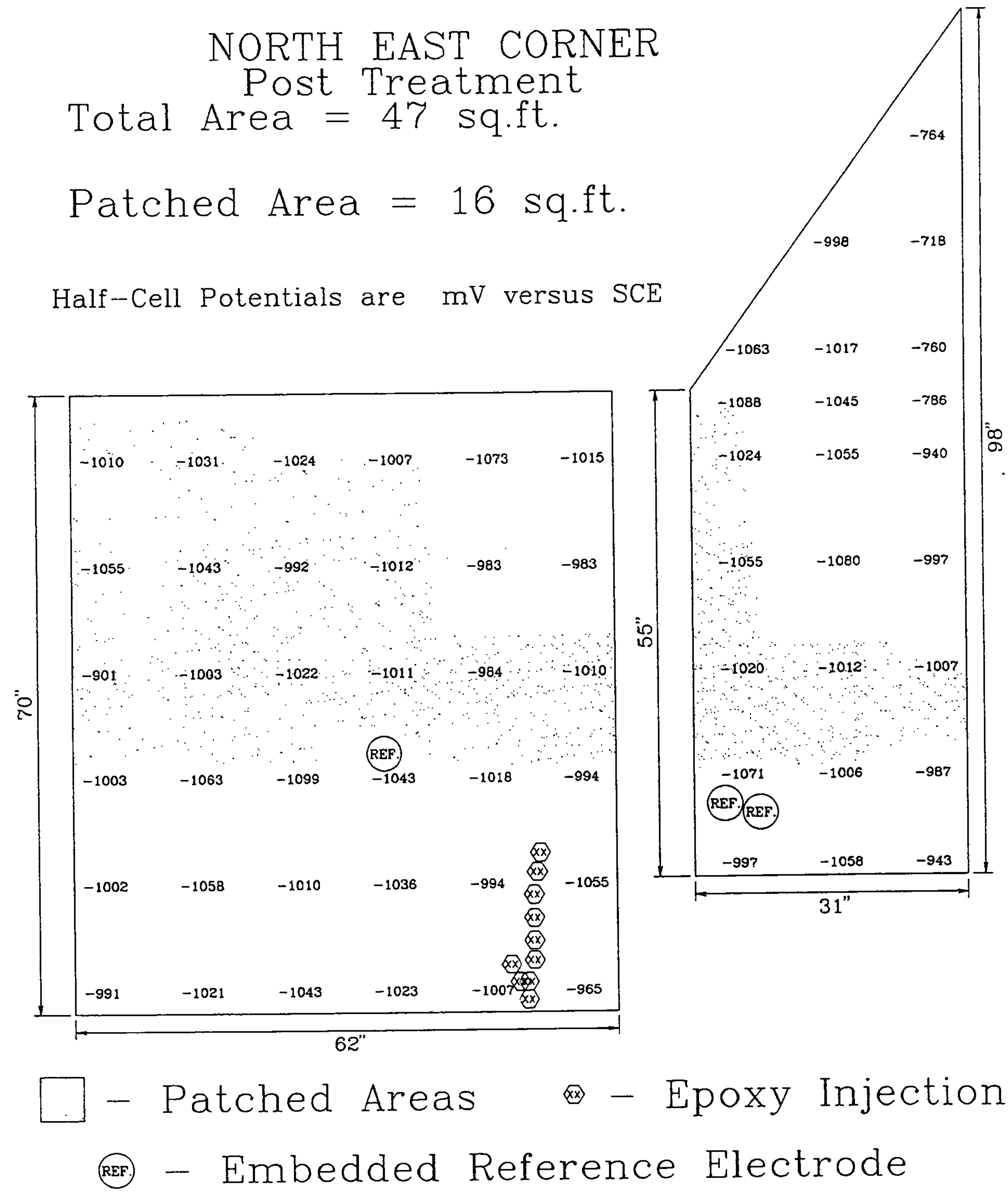


Figure 5-20. Southwest Abutment Post-Treatment Evaluation Testing

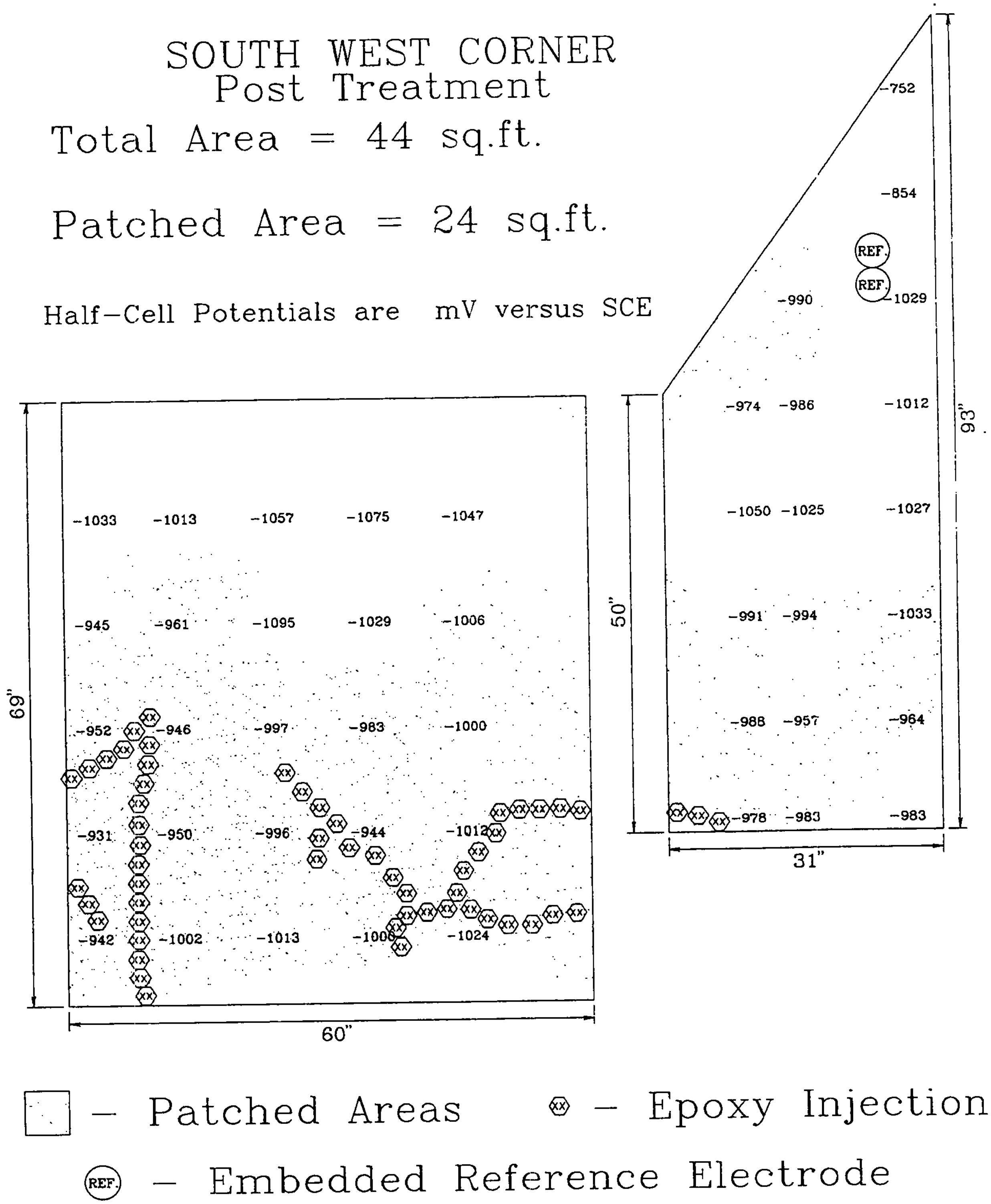


Figure 5-21. Southeast Abutment Post-Treatment Evaluation Testing

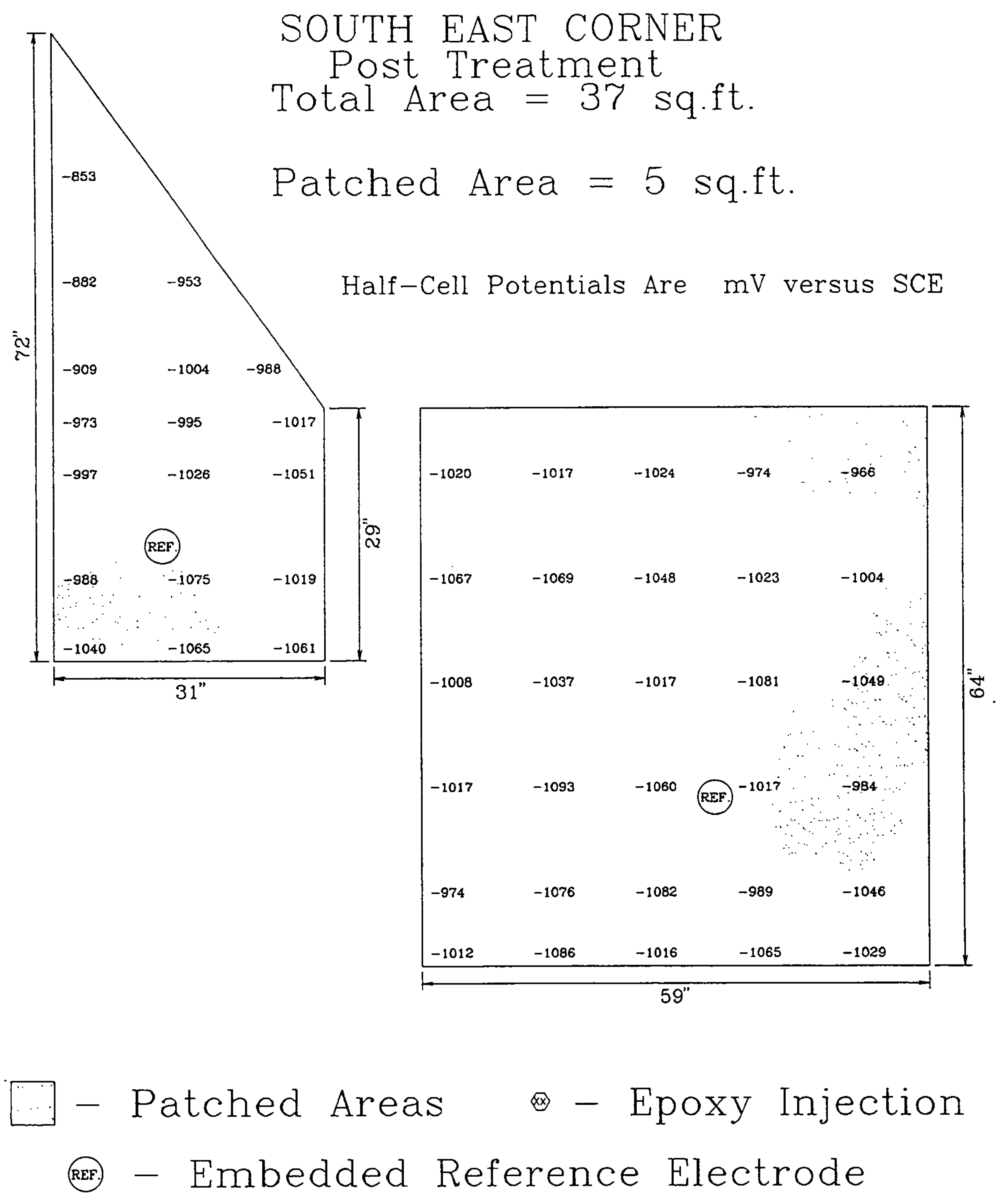


Figure 5-22. Potential Survey

Chloride Analyses

Electrolyte samples were taken periodically during treatment to determine the amount of chloride removed, and the efficiency of the treatment process. This procedure was complicated because the reservoirs overflowed due to rainwater runoff. The amount of overflow was calculated from borate analyses, which in turn allowed an estimate of the chloride removed. A slight inaccuracy was introduced since the exact time of overflow was not known. Analyses showed 4.0 lb (1814 gm) and 2.4 lb (1100 gm) of chloride were removed from the north and south zones, respectively. Based on the chloride removed and the total charge applied for each zone (Table 5-7), current efficiencies were calculated at 19 and 12 percent for the north and south ends, respectively. An efficiency of 15 to 20 percent was expected.

Table 5-7. Chloride Removed and Current Efficiency

	NORTH (87 ft²)		SOUTH (81 ft²)	
Date	Charge A-hr/ft²	Total Cl⁻ Removed, gm/ft²	Charge A-hr/ft²	Total Cl⁻ Removed, gm/ft²
8/17	0	0.00	0	0.00
8/21	25	15.0	35	8.96
8/23	33	18.2	43	11.02
8/24	37	18.34	-	11.22
8/25	42	18.65	54	11.49
8/26	46	19.83	56	12.11
8/27	51	19.99	60	12.23
8/31	64	20.37	-	-
9/3	71	20.63	76	13.44
9/9	84	20.85	89	13.74

North: Total Chloride Removed = 1814 gm Cl^- = 4.0 lbs Cl^- = 6.6 lbs NaCl

Overall Current Efficiency = 19%

South: Total Removed = 1113 gm Cl^- = 2.45 lbs Cl^- = 4.0 lbs NaCl

Overall Current Efficiency= 12%

Chloride analyses were also conducted on concrete cores taken from the north side before and after treatment (Table 5-8). An estimate of current efficiency on the north side was made from these analyses. These indicate a total of 4.0 lb (1800 gm) of chloride removed from the north side, for an overall current efficiency of 19 percent. This compares well with the electrolyte analysis.

Table 5-8. Pre-Treatement and Post-Treatment Core Chloride Analyses

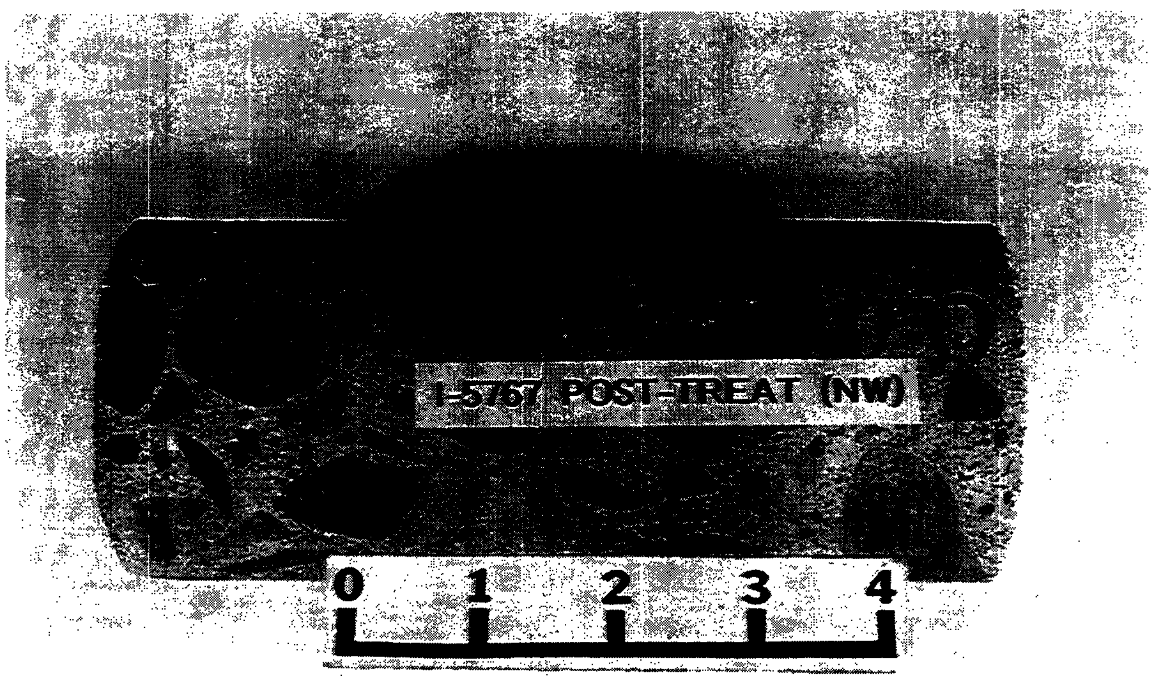
Core Number	Depth, inches	% Cl⁻ (a)	#Cl/yd³ (b)
Pre-Treatment			
1A	0 to ¾	0.383	14.99
1A	1⅝ to 1⅞	0.267	10.45
1A	2⅞ to 3⅛	0.314	12.29
Post-Treatment			
1B	0 to ¾	0.230	9.00
1B	1⅝ to 1⅞	0.193	7.56
1B	2⅞ to 3⅛	0.170	6.66

(a) Based on dry concrete weigh
(b) Based on a concrete unit weight of 145 lb/ft³

Petrographic Analyses

Core 1B, taken from a treated area on the northwest abutment, was 2-3/4 in. (5 cm) in diameter by 6-1/2 in. (16.5 cm) long. It was taken 76 in. (1.93 m) above ground and 38 in. (0.97 m) from the west edge of the abutment. The core, which was extracted in one piece, contained a #12 reinforcing bar, 3-1/8 in. (8 cm) below the surface (Figure 5-23). The entire surface of the core was discolored (rust red); the cause is unknown. Less than 10 percent of the surface showed moderate softening of a thin layer, less than 0.5 in. (1.2 cm), of the cement paste in contact with the electrolyte solution.

Figure 5-23. Core 1B for Post-Treatment Petrographic Analysis



The core had a full-width fracture parallel to the surface at a depth of 1-1/2 to 2-1/4 in. (4 to 6 cm) below the surface. There are heavy deposits of corrosion product along the fracture plane.

No pre-treatment cores were taken immediately adjacent to the post-treatment core. Therefore, there is no direct verification that the corrosion product was there prior to the treatment. However, it was established through examinations of other cores from the pier, and from visual observations of corroding steel in spalled sections of the pier, that there was extensive corrosion of near surface reinforcing steel prior to the treatment.

Previous examinations of cores from this structure confirmed that there was cracking distress in the concrete caused by alkali-silica reactivity. However, in the post-treatment core examined, there was no evidence of any alkali-silica reaction products (gel). This finding indicates that, at this particular coring site, there was no ASR activity prior to or following the treatment despite the fact that the concrete at this site contained alkali-reactive aggregates that were involved with ASR activity at other locations on the structure. The reason that there was no ASR activity at this particular coring site in the structure is not clear. However, it is encouraging that in a structure showing a significant amount of ASR, the use of the treatment did not initiate new ASR activity.

System Removal

When the system was shut down, both sides had good electrolyte flow. Both sump tanks were completely filled and overflowing. The electrolyte had a slight odor of sodium hypochlorite. The electrolyte was pumped into chemical resistant drums for transport and disposal.

The entire removal process, including inspection and post-treatment testing, was accomplished by six persons in about three hours. Removal pictures are in figures 5-24 and 5-25.

Figure 5-24. Removal of System

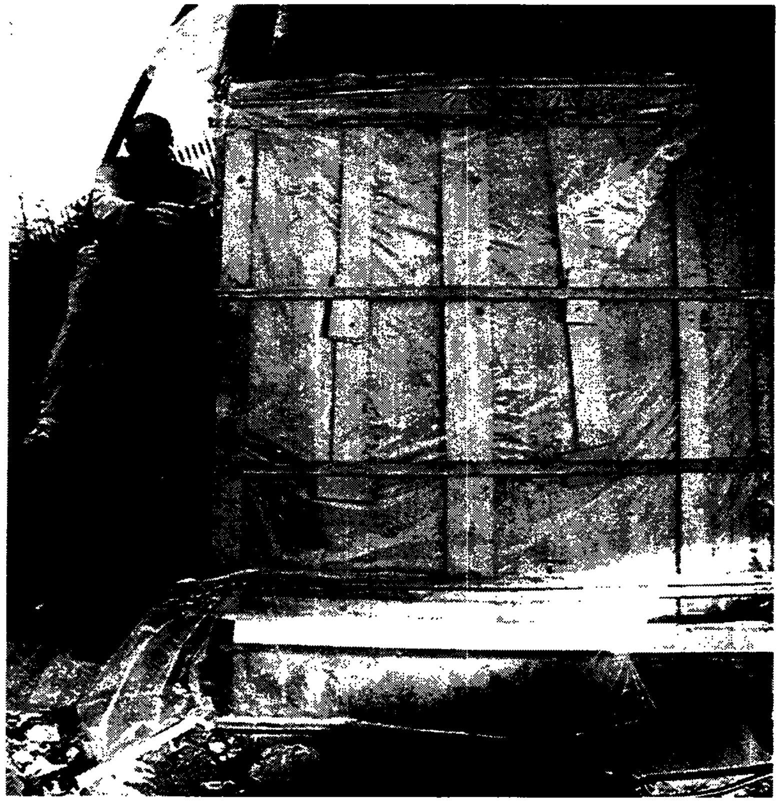


Figure 5-25. Removal of System

Costs

Materials

A list of disposable and single-use items is tabulated in Table 5-9. The cost per square foot of treatment area for these items was $20/ft^2 ($200/m^2).

Table 5-9. Single-Use Item Costs

Material/Equipment	Description	Quantity	Price, $
Epoxy bonder	Capbond EX Gr. Rapid	6 liters	165.00
Injection epoxy	Capweld 424	5 cartridges	119.50
Injection ports	Injection tees	135 units	39.00
Mix tubes	Mixing nozzles	6 units	24.00
Nuts	Mix tube retainers	6 units	4.50
H_3BO^3	Li_3BO_3	10 kg	125.00
$LiOH{\cdot}H_2O$	Li_3BO_3	42 kg	1134.00
Wood	Frames	1 unit	35.50
Gutter & pipe	Electrolyte collection	1 unit	306.50
Hose	Electrolyte pumping	1 roll	56.00
Hardware	Frames and gutters	1 unit	44.00
Plumbing supplies	Electrolyte collection	1 unit	19.00
Caulking tubes	Frame sealant	12 units	38.00
$Sorb_x$ S-92	Anode blanket	168 ft^2	67.00
Electrolyte disposal *	55 gal drums	6 units	1200.00
		Total:	$3377.00
		Treatment area:	168. ft^2
		Cost/unit area:	$20.10/ft^2

* Estimated from electrolyte disposal costs from Ohio and New York trials.

Table 5-10 lists tools and equipment used for this trial that could be amortized over the course of several treatments. The single-use cost per square foot of treatment area for these items was $60/ft² ($600/m²). An amortized cost for these items was $6/ft² ($60/m²).

Table 5-10. Amortizable Item Costs

Material/Equipment	Description	Quantity	Pr[illegible]
Epoxy injection gun	Cartridge dispenser	1 units	80.00
Anode mesh	ELGARD™ 300	168 ft	504.00
Current distribu[illegible]	0.035" x 1/2" x 10'	4 units	1[illegible]
Rectifier	Darrah 50VDC-200ADC	2 units	840[illegible]
GTF 350-EX	Anode blanket	168 ft²	4[illegible]
Polyfelt TS-1000	Anode blanket	168 ft²	[illegible]
Pumps	Electrolyte pumping	2 units	260.00
Holding tanks	Electrolyte storage	2 units	350.00
Multimeter	Test equipment	1 unit	300.00
		Total:	$10,009.00
		Treatment area:	168. ft²
		Cost/unit area:	$59.58/ft²
		Amortized cost:	$5.96/ft²

Total material costs, single-use and amortized, were $26/ft² ($260/m²).

Labor

Table 5-11 summarizes the man-hour requirements for this chloride removal trial. The total labor cost for installation, maintenance, and removal was \$51/ft^2 (\$510/m^2).

Table 5-11. Man-Hour Requirements

Crew	Hours	Rate, \$/hr	Cost, \$
Installation			
Supervisor/laborer	41	55.00	2255.00
Operator/laborer	33	40.00	1320.00
Operator/laborer	33	40.00	1320.00
Laborer	27	25.00	675.00
Laborer	27	25.00	675.00
Laborer	27	25.00	675.00
Total man-hours:	188	Labor cost:	\$6920.00
Operation			
Operator/laborer	25	40.00	1000.00
Laborer	5	25.00	125.00
Total man-hours:	30	Labor cost:	\$1125.00
Removal			
Supervisor/laborer	3	55.00	165.00
Operator/laborer	3	40.00	120.00
Laborer	3	25.00	75.00
Laborer	3	25.00	75.00
Laborer	3	25.00	75.00
Laborer	3	25.00	75.00
Total man-hours:	18	Labor cost:	\$585.00
		Total labor costs:	\$8,630.00
		Treatment area:	168. ft^2
		Cost/unit area:	\$51.37/ft^2

Man-hour estimates include only the time spent at the site. Installation and removal tasks were discussed earlier in this chapter. Operation tasks include data collection six times a week, electrolyte maintenance, and electrical equipment maintenance.

The hourly labor rates were estimated, based on salary and overhead in the year 1991.

Total Costs

The cost of this trial, including single-use materials, amortized materials, and labor, was $78/ft^2 of treated area ($780/m^2). This does not include travel expenses or standard tools.

A large amount of the materials cost is attributable to the type of electrolyte used. The lithium borate electrolyte was necessary or chloride removal could not be performed without fear of significant ASR damage.

The extremely high labor cost was affected by the site's location, the need to seal cracks, and the size of the treatment area. The remoteness of the site to supply stores made acquisition of materials a timely task. Sealing cracks also proved to be a time-consuming task. A contractor that is familiar with the process and already has materials on hand could significantly reduce this cost.

At this particular site, it was felt that an area 5 times the size of the area that was treated would have taken only twice the time and effort.

6

Conclusions and Recommendations

Conclusions

1. The electrochemical chloride removal process can be applied successfully to structures in the field. Success is defined for this conclusion as the passage of the expected amount of current and charge, and the removal of the expected amount of chloride ion at expected efficiency. It is also concluded that the treatment results in no immediately observed detrimental effects. No conclusion can yet be made regarding corrosion control, effective lifetime of the treatment, or the extension of structure life as a result of the treatment on field structures.

2. The anode/blanket composite is a useful system of chloride removal. It is best suited for round, land-based substructure columns. It is more difficult to apply this system on complex structures and structures with large flat surfaces. For those cases a system using a sprayed cellulose fiber to contain the electrolyte may be more appropriate.

3. A ponded electrolyte is useful for chloride removal on flat, horizontal concrete decks. It is not expected that this system will be used frequently because of the need for long treatment time and closure to traffic.

4. Current density for the chloride removal process is likely to be limited to 0.1 to 0.3 A/ft^2 (1 to 3 A/m^2) on field structures. This is a direct result of the need to maintain voltage below 50 VDC for safety reasons, and the resistance of concrete on field structures. Treatment times are therefore likely to be in the range of 10 to 50 days.

5. The cost of chloride removal, conducted routinely on simple land-based substructures, is likely to be less than $15 per square foot ($150/m^2). Achieving this cost requires effective utilization of equipment and careful control of labor and electrolyte disposal costs.

6. A captive electrolyte system offers the possibility of good monitoring and assessment of treatment effectiveness by allowing accurate determination of efficiency and chloride removed. This advantage is balanced by additional difficulty with electrolyte containment and dilution by rainwater.

7. Use of an electrolyte containing sodium (or lithium) borate buffer is capable of preventing the evolution of chlorine gas by maintaining pH above 6. This is true only for a system with a captive, circulating electrolyte.

8. Current leakage away from the treatment area is a problem with structures which extend into seawater. This is a result of the relatively high voltages (up to 50 VDC) used for the chloride removal process. Prevention of leakage is likely to require more sophisticated, and more expensive, system design.

Recommendations

1. Long-term monitoring of field structures subjected to the chloride removal process is recommended. This is especially recommended for the structures of this contract treated in Ohio, New York and Ontario. The true benefits of chloride removal will not be known for these structures until after 5 to 10 years of monitoring.

2. Further development is recommended on the methods of containment of captive electrolytes.

3. Electrochemical chloride removal is recommended for consideration as a commercial rehabilitation technique for simple land-based reinforced concrete substructures. It cannot be recommended for structures which contain prestressed steel, and cannot yet be recommended for structures which contain alkali reactive aggregate.

Appendix A

Ohio Bridge Deck Field Trial Figures

Figure A-1. Static Potential Contour Map

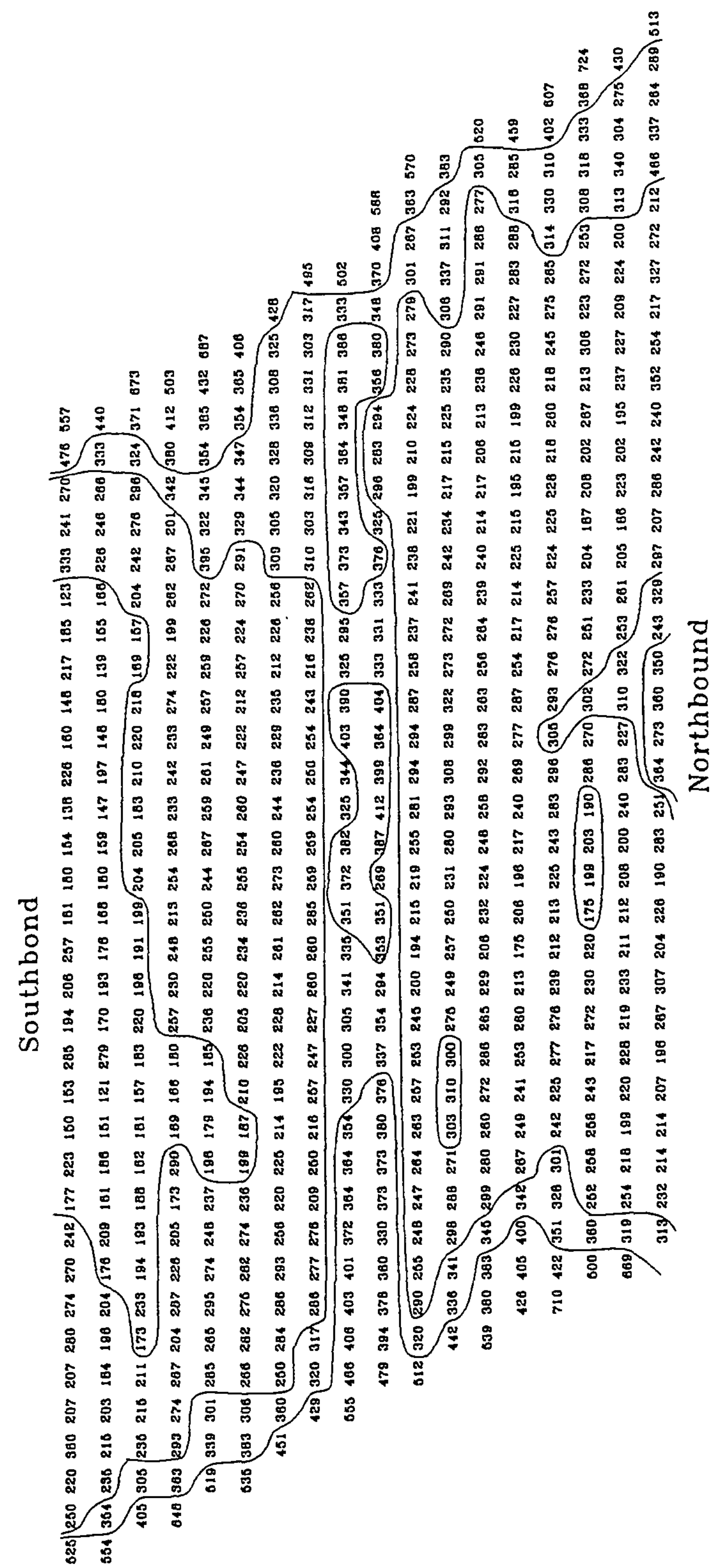


Figure A-2. Sample Data Sheet

FIELD TEST FOR SHRP C-102A; RT.295 TOLEDO, OHIO

Tester:	T.Turk
Date:	9-18-93
Time:	9:00 A.M.
Air Temp:	60°F

SYSTEM DATA

	South Zone	North Zone
Voltage	49.5	49.5
Current	36.0	33.0
Meter A-hrs.	607.2	590.6

ELECTROLYTE DATA

Zone	Sample Obtained	pH	Pond Temp.	Pond Level Start	Pond Level End
South Curb (SC)	Yes	12.56	~60°F	1-3/4"	2-1/16"
South Middle (SM)	Yes	12.61	"	1-13/16"	2-1/4"
North Curb (NC)	Yes	12.58	"	1-1/16"	1-3/8"
North Middle (NM)	Yes	12.53	"	1-1/4"	1-5/8"

HALF-CELL POTENTIALS
(Volts vs. $Cu/CuSO_4$)

		On	Off
(A)	South Curb, high voltage drop	-9.6	-1.59
(B)	South Curb, low steel	-29.5	-2.00
(C)	South Curb, high steel	-26.0	-2.02
(D)	South Middle, low voltage drop	-16.6	-1.84
(E)	North Curb, high voltage drop	-6.9	-1.62
(F)	North Curb, low steel	-27.3	-1.90
(G)	North Curb, high steel	-17.1	-1.66
(H)	North Middle, low voltage drop	-16.0	-1.81
(I)	Control, 50/50 potential (-200 to -350)	-.189	-.087
(J)	Control, low potential (> -200)	-.047	-.222
(K)	Control, high potential (< -350)	-.635	-.669

Observations/comments: Air and pond temps were estimated.
Estimated electrolyte concentration = 0.08 M Na_3BO_3

Figure A-3. Removing Na_3BO_3 from the Reservoirs

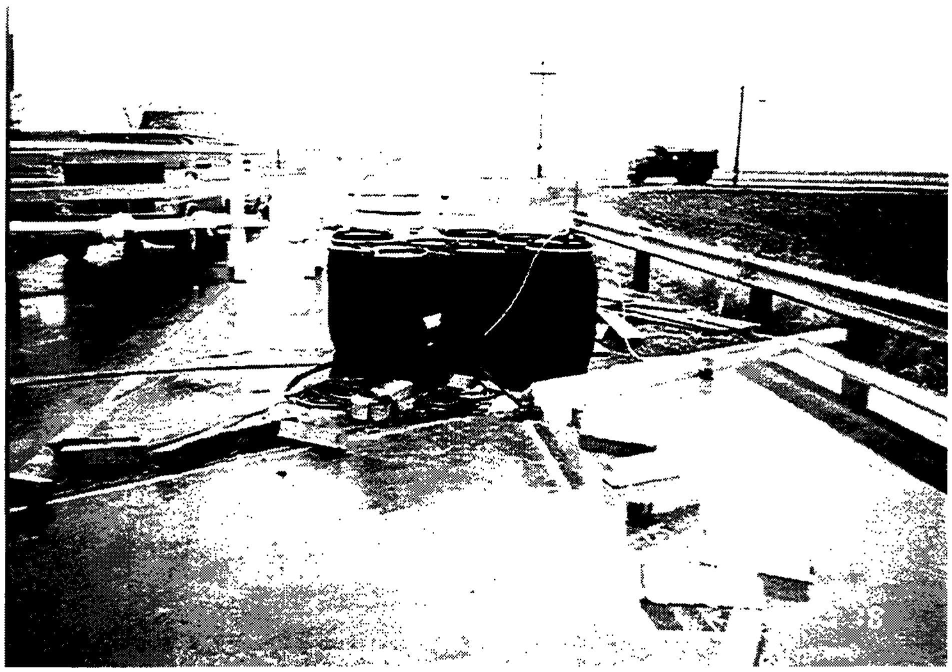


Figure A-4. Sealed Drums Ready for Transport

Figure A-5. Removing Anode Mesh

Figure A-6. Cement Block Removal

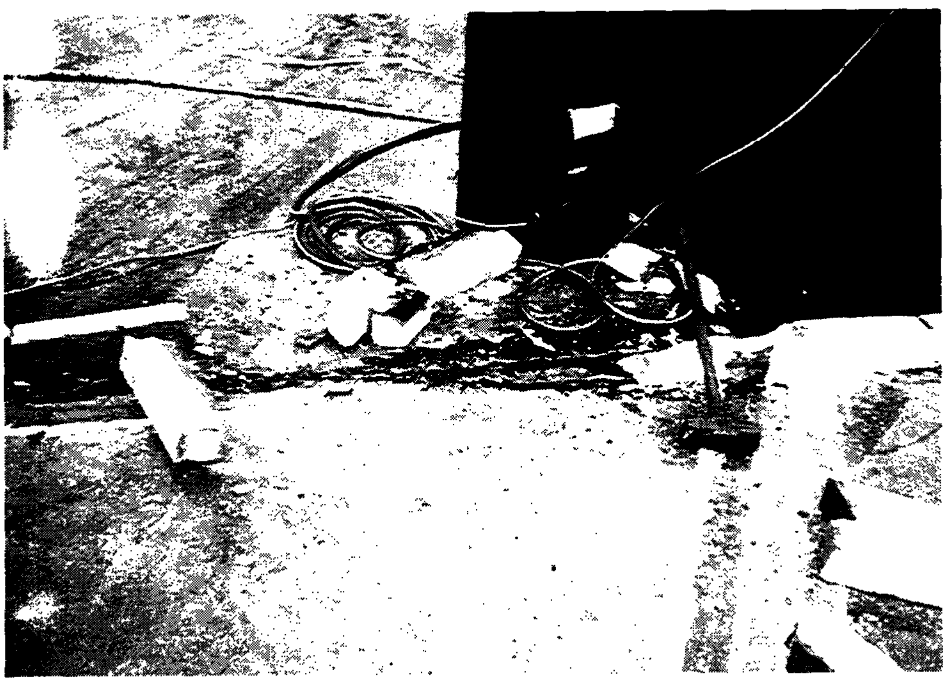


Figure A-7. Removing the Latex Concrete Barrier

Figure A-8. Damage to the Bridge after Removing the Latex Concrete Barrier

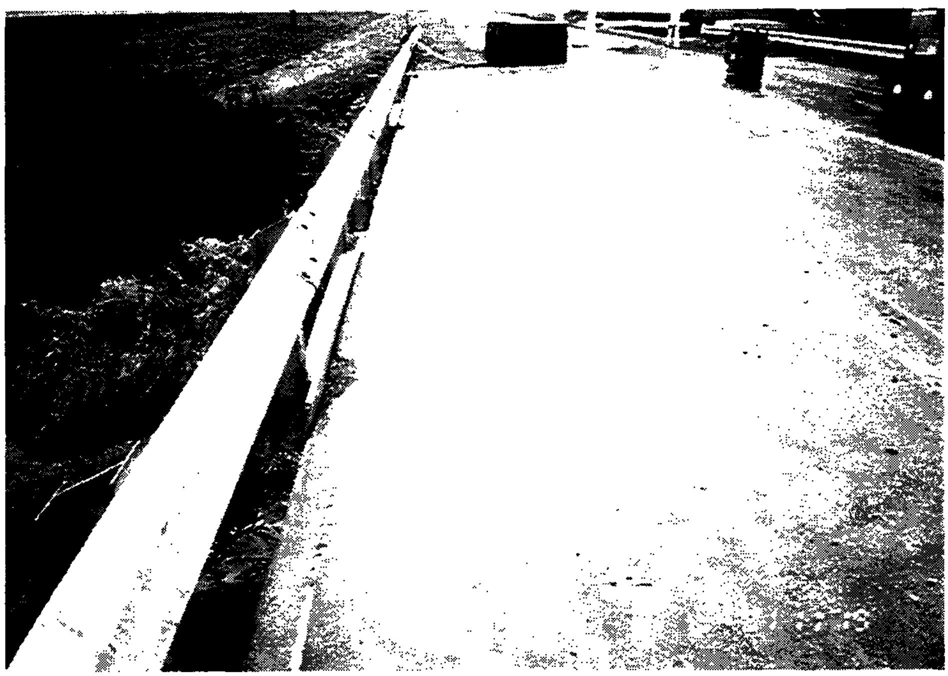


Figure A-9. Bridge Edge Repairs

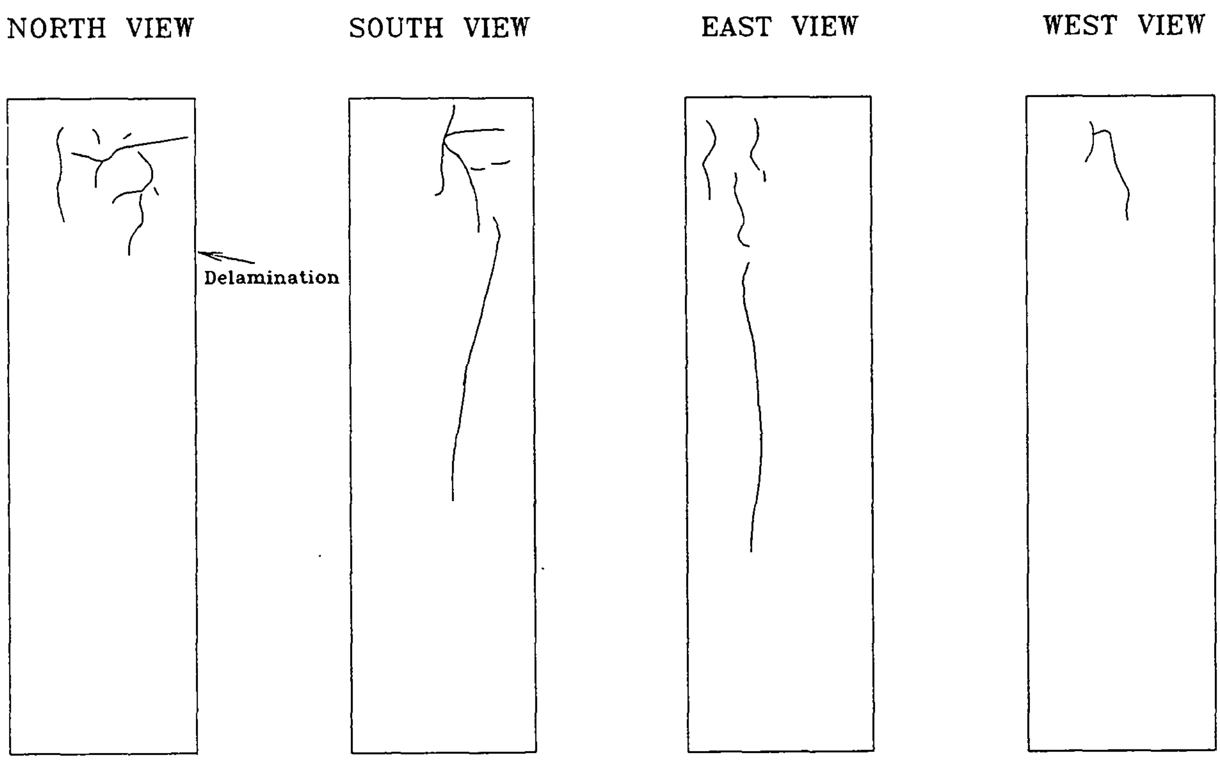
Figure A-10. Preparing Concrete Core Drilling Equipment

Figure A-11. Concrete Core and Patched Hole

Appendix B

New York Substucture Field Trial Column Condition Survey

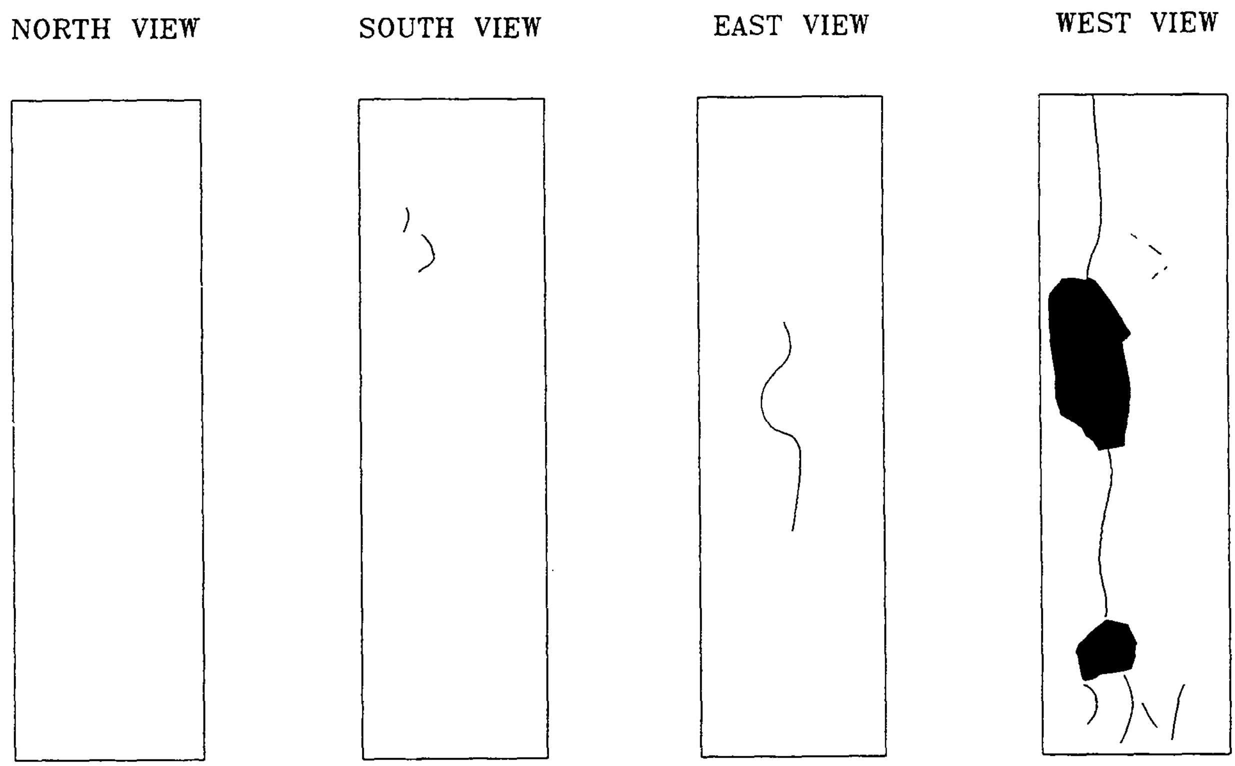
Figure B-1. Column 1 Condition Survey



COLUMN DIAMETER = 3.5 ft

TREATMENT AREA = 132 ft^2/column

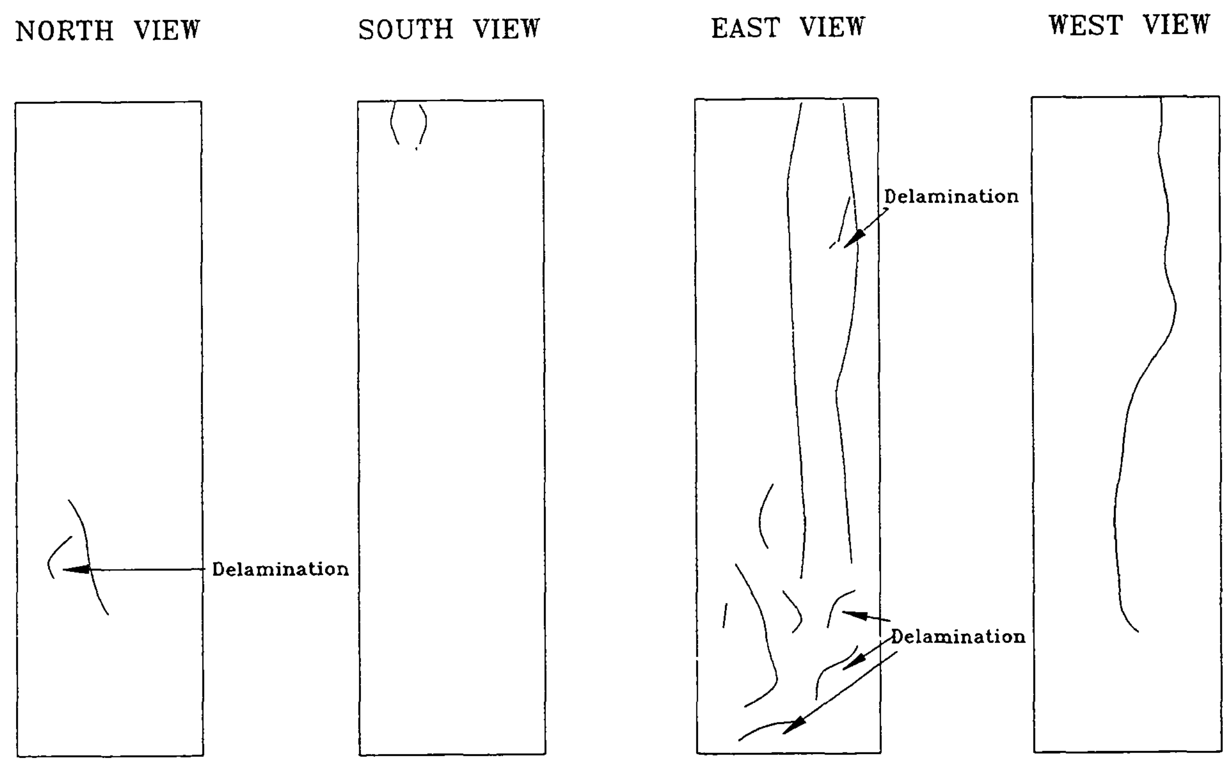
Figure B-2. Column 2 Condition Survey



COLUMN DIAMETER = 3.5 ft

TREATMENT AREA = 132 ft^2/column

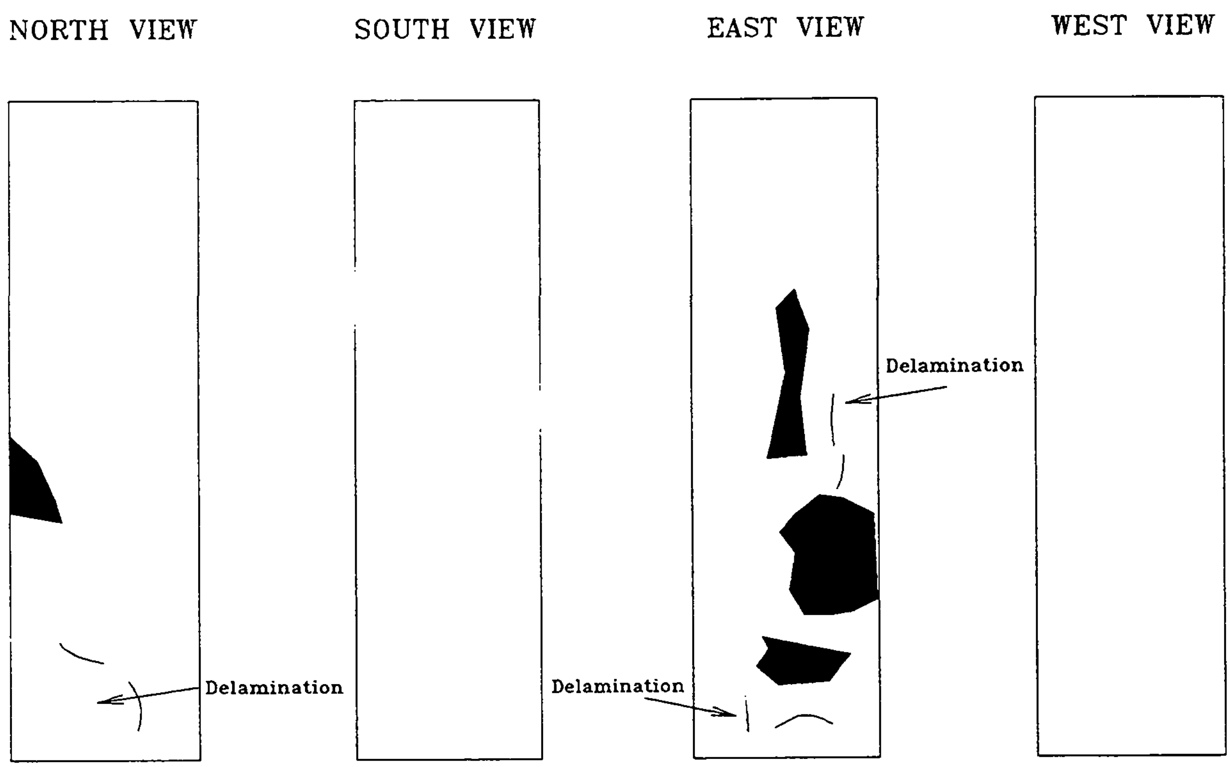
Figure B-3. Column 3 Condition Survey



COLUMN DIAMETER = 3.5 ft

TREATMENT AREA = 132 ft^2/column

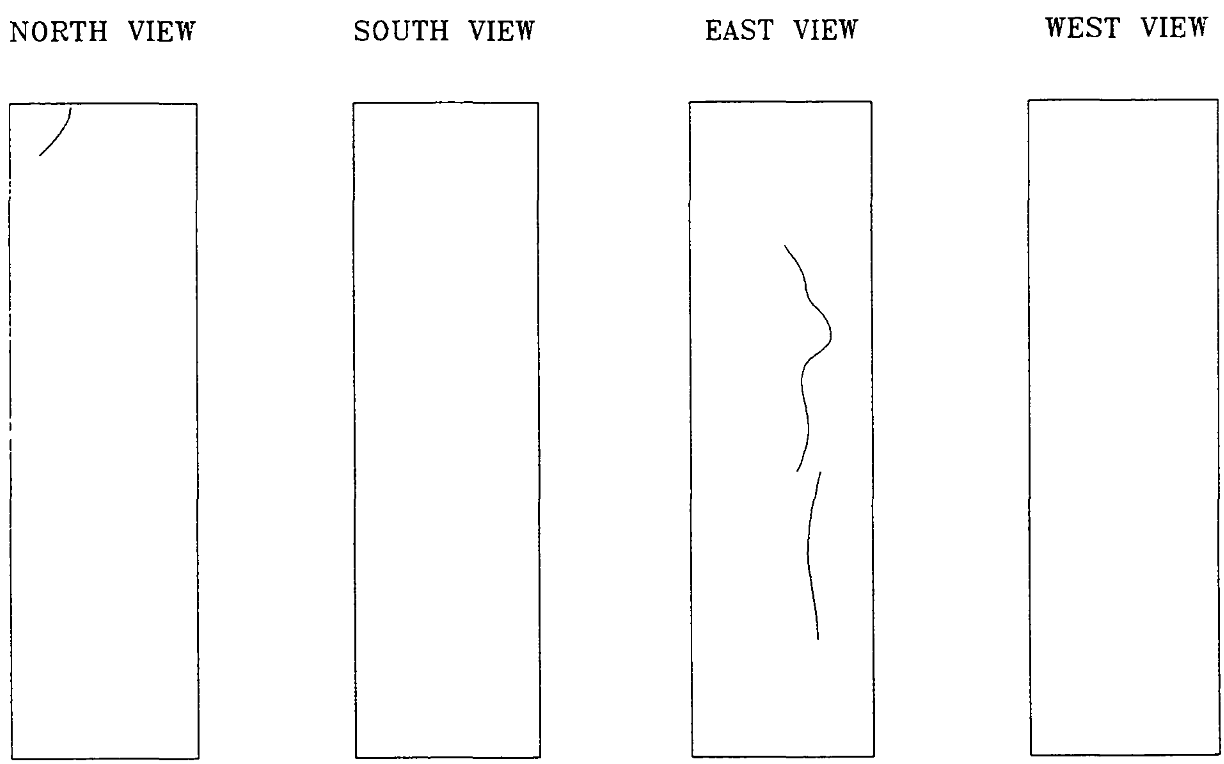
Figure B-4. Column 4 Condition Survey



COLUMN DIAMETER = 3.5 ft

TREATMENT AREA = 132 ft^2/column

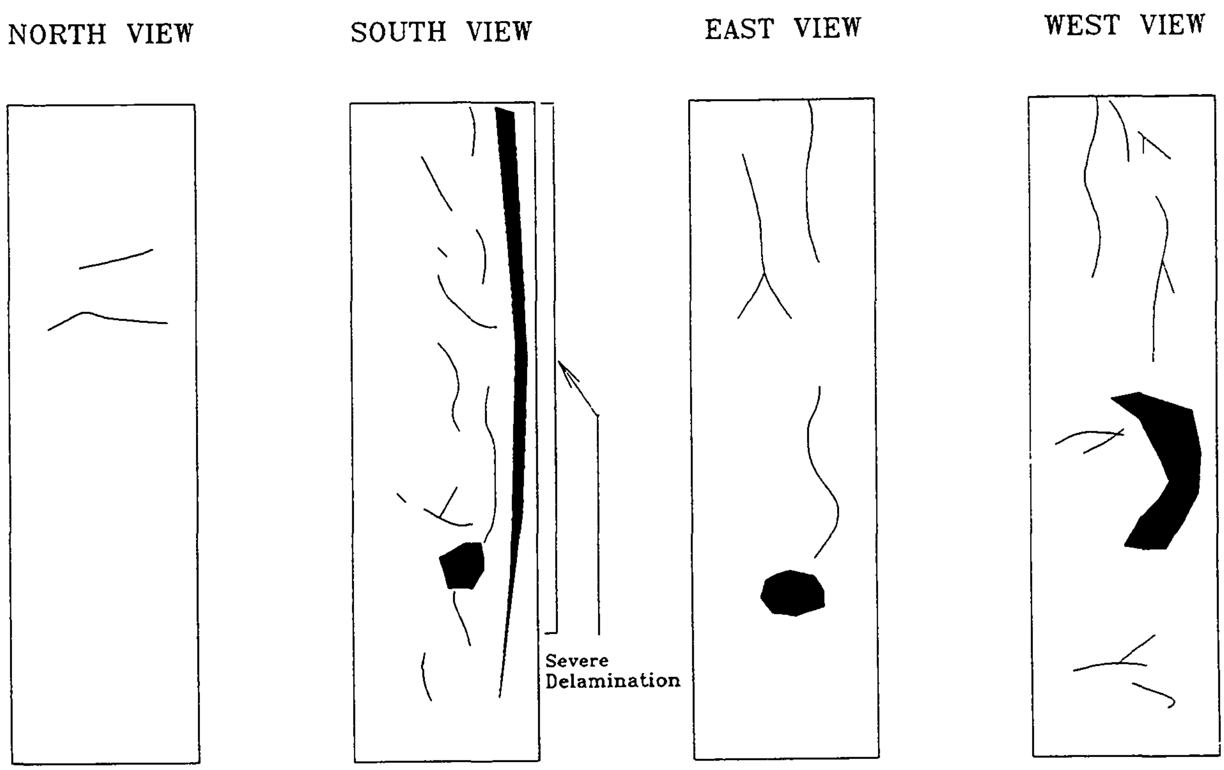
Figure B-5. Column 5 Condition Survey



COLUMN DIAMETER = 3.5 ft

TREATMENT AREA = 132 ft^2/column

Figure B-6. Column 6 Condition Survey



COLUMN DIAMETER = 3.5 ft

TREATMENT AREA = 132 ft^2/column

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