Electrochemical techniques for concrete bridge protection and rehabilitation was one of the research areas of the SHRP concrete and structures technical program. Four reports document the work under SHRP contract C-102A, Electrochemical Chloride Removal and Protection of Concrete Bridge Components. The laboratory studies are described in *Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Laboratory Studies* (SHRP-S-657). The field validation trials completed on a bridge deck, column substructures, and a bridge abutment are described in *Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Field Trials* (SHRP-S-669). The experience gained through that work was used to develop a recommended practice, detailed in *Chloride Removal Implementation Guide* (SHRP-S-347). The fourth report (SHRP-C-620) describes NORCURE™, a proprietary procedure for the electrochemical removal, or extraction, of chloride from reinforced concrete. These four reports constitute SHRP product 2033. The executive summaries from the reports of the laboratory studies and the implementation guide are combined in this brief, followed by some technical details about implementing chloride extraction.

**EXECUTIVE SUMMARY**

Corrosion is recognized as one of the major contributors to the deterioration of steel-reinforced concrete structures. This corrosion is induced primarily by chlorides introduced in the form of de-icing salts or sea water. A secondary source is chlorides in the concrete materials and admixtures. One technique for dealing with this corrosion is the removal of offending chlorides from the concrete. The electrochemical extraction of chloride from concrete structures is accomplished by applying an anode and electrolyte to the external concrete surface, and passing direct current (DC) 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 (Cl⁻) toward the anode, away from the steel and out of the structure.

Under the SHRP contract, the feasibility of chloride extraction from reinforced concrete bridge components was examined, first in laboratory and test yard studies and finally in field validation studies; these methods clearly showed chloride extraction to be an effective technique for arresting chloride-induced corrosion of reinforcing steel. Results of chloride extraction conducted on test yard slabs were particularly impressive. Treatment of these slabs was conducted at a variety of current densities and charges, none of which showed any tendency to return to corrosive conditions 3 1/2 years after treatment. By contrast, the control slab, which was not treated, was badly delaminated and deteriorated.

Initial testing focused on fundamental electrochemical properties not previously reported. The
transference number of chloride ion (a measure of the fraction of current carried by that ion) was established under various conditions. This study showed that the transference number of chloride increases with increasing concentration and temperature, but is independent of current density. This result has considerable practical importance because it means that a small current density applied for a long time will remove the same quantity of chlorides as a high current density applied for a short time, providing the total charge is the same in both cases. In a chloride extraction process, chloride extraction efficiencies are initially about 40%, but decrease as the treatment progresses because there are fewer chloride ions to carry the charge. Overall current efficiencies on a field structure could be expected to be about 20%. In other words, the passage of each amp-hr of charge will extract about 0.25 gm of chloride.

The measure of effectiveness first used to assess the chloride extraction process was the proportion of chloride removed from the concrete. In that regard, the actual amount of chloride removed was disappointing and early technical targets were not met. Even very heavy treatments removed only 40 to 55% of the total chloride present. However, further testing indicated that more complete extraction may not be necessary and that a more appropriate measure of effectiveness is the extent to which corrosion is arrested. The chloride left in the concrete after treatment was positioned between and behind the reinforcing bars, and remained well away from the steel. Chloride content around the top reinforcing steel was greatly reduced by the treatment and showed no significant change after 40 months. Moreover, by removing chloride away from the bars, the treatment also generates hydroxyl ions at the steel surface. This undoubtedly plays an important role in arresting corrosion, since corrosion is dependent on the chloride/hydroxyl ratio rather than on chloride concentration alone. Examination of rebars removed from treated slabs showed only very slight rusting, whereas bars from the untreated control were heavily corroded.

Treatment effectiveness was also demonstrated by 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 and remained near zero 3½ years after chloride extraction. Half-cell potentials of the steel on the control slab were very corrosive, whereas steel potentials on treated slabs were very non-corrosive.

This study also offered dramatic evidence of possible errors when measuring potentials on the top surface of treated slabs. These errors, as great as 200 mV, exist as a result of junction potentials due mainly to differences in pH. This study provided insight into understanding the magnitude and nature of junction potential error.

Concrete compressive strength was not reduced at lower current densities, but concrete treated at high current (20 A/m²) for long periods of time (5000 A-hr/m²) had a softening of the cement paste around the reinforcing steel. This softening probably also caused the loss of bond strength for severely treated specimens and caused one slab to crack and delaminate. For these reasons the regime used in previous studies (up to 20 A/m²) was judged to be excessive, and more modest treatment conditions were used for the 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 structurally insignificant.

The generation of chlorine gas from the anode, which could present a safety hazard, was also studied. 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 the electrochemical treatment of concrete causes an increase in the alkali cation concentration in the vicinity of the reinforcing steel. This study confirmed those results, and demonstrated that serious damage could result if the chloride extraction process was used on concrete containing alkali-reactive aggregate. However, 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.

Based on the laboratory and test yard results, a chloride extraction treatment process was defined which resulted in effective removal of chloride without any damage to the concrete or reinforcing steel. Treatment current density is limited to less than 5 A/m² of concrete. System voltage is also limited to less than 50 volts for safety reasons. Under these conditions, treatment time for chloride extraction can be expected to be from as little as two to four weeks up to about eight weeks. Typical applied charge will be 800 to 1200 A-hr/m². Treatment times and charges greater than these will probably yield little additional benefit in terms of chloride extracted or corrosion prevented. In light of the time frame, treatment is more suitable for substructures rather than bridge decks, which are difficult to close to traffic for a relatively long period of time.

Chloride extraction is recommended for structures with active corrosion but in which the concrete has little damage, no prestressed steel, and for which a five- to ten-year extended service life is adequate. Prior to treatment, potential and delamination surveys should be conducted and chloride analysis should be used to establish a chloride contamination profile. Reinforcing steel must be tested for electrical continuity and petrographic analysis can identify alkali-silica reactive aggregates in the concrete.

The chloride extraction system uses an anode/blanket composite; an inert catalyzed titanium anode applied to the surface of the concrete together with a blanket material containing electrolyte. The blanket is a composite of a reusable geotextile outer blanket and an inner water-absorbent layer. The anode/blanket composite is prefabricated as well as partially reusable.

The electrolyte is a sodium borate (Na₃BO₃) or lithium borate (Li₃BO₃) buffered solution designed to maintain a basic pH for the duration of the process. This pH maintenance prevents etching of the concrete and the evolution of gaseous chlorine. Lithium borate electrolyte, which is more expensive, is used only when the structure contains potentially alkali-silica reactive aggregate.

The chloride extraction process discussed in the technical highlights uses about 980 l of 0.2 molar sodium (or lithium) borate buffer solution per 300 m² of treated surface. The electrolyte is prepared on site by mixing 24.0 gm of sodium hydroxide with 12.4 gm of boric acid per litre of solution. The treatment process uses a current of 1.0 to 5.0 A/m² of concrete at a maximum of 50 volts. A treatment time of 10 to 50 days and a total charge of 600 to 1500 A-hr/m² is considered normal. The process is monitored daily during this time.

This process will extract about 20 to 50% of the chloride present in the concrete. The amount of chloride removed depends on several factors, including the amount of chloride present, the distribution of chloride in the concrete, and the design of the reinforcement. After the treatment is complete, chlorides remaining in the structure are usually sufficient to reinstate corrosion. These chlorides are usually distributed well away from the steel, however, and a long time is required for redistribution to take place. The return to corrosive conditions is further delayed by the build-up of alkalinity that takes place at the steel surface.

Alternate systems include a procedure that uses a ponded electrolyte on horizontal surfaces such as decks, and a proprietary system that uses a sprayed matrix of cellulose fibre to support the electrolyte. Each of these systems has its own attributes for particular types of structures and may be used efficiently.

Post-treatment testing is normally conducted to determine the effectiveness of the process and its effect on the concrete in the structure. Application of a sealer is recommended following treatment to prevent the ingress of additional chlorides and intrusion of moisture into the concrete.

Chloride extraction from reinforced concrete bridge components is judged to be both feasible and technically practical. At this time, it is difficult to judge for how long this process will be effective. It appears that the procedure will prevent corrosion for at
least five years, and possibly for ten years or more, provided contamination with new chlorides is prevented. Additional field experience is needed for a better understanding of the chloride extraction process, its effective life and its effect on the structure.

### CHLORIDE EXTRACTION IMPLEMENTATION - TECHNICAL HIGHLIGHTS

This section outlines criteria for candidate structures for chloride extraction and then describes how to carry out the process, dependent on the field configuration to be treated. A detailed chloride extraction implementation guide is provided in SHRP-S-347.

1. **Active chloride-induced corrosion** will likely be present in a candidate structure and can be verified by a combination of commonly-used survey techniques. Half-cell potential surveys should be done; potentials more negative than -0.35V versus a copper/copper sulfate reference electrode indicate greater than 90% probability that reinforcing steel corrosion is occurring in the area at the time of measurement. Chemical analysis should be used to verify that corrosive levels of chloride are present at the level of reinforcing steel. Many highway agencies and corrosion engineers use a total chloride ion content of 0.03 % by mass of concrete as the corrosion threshold limit.

Chloride extraction is best applied on structures with contamination near the concrete surface and lower, near the reinforcing steel. During treatment, most of the current flows between the steel and concrete surface and because this is where most ionic movement takes place, chloride content should be determined as a function of depth prior to treatment. Visual inspection, sounding for delamination and corrosion rate measurements are also useful.

2. **No prestressed steel**: The chloride extraction process will generate hydrogen at the reinforcing steel, and may cause hydrogen embrittlement in prestressed steel structures.

3. **No alkali-reactive aggregates** should be exposed to chloride extraction because it may aggravate the expansive reaction associated with these aggregates. Laboratory tests and one field trial suggested that lithium ions in the electrolyte can control this reaction, but the effectiveness of the lithium ions remains undetermined and its use is still experimental. A concrete core sample should be taken and submitted for petrographic analyses if the presence of alkali-reactive aggregates is unknown.

4./11. **Electrical steel continuity** is required to distribute current evenly and prevent rapid corrosion of unconnected steel in the structure. While most structures have adequate electrical continuity, very old ones can be problematic. To verify electrical continuity, a high-impedance voltmeter (10 megohm minimum) with a resolution of 0.1 mV is used. Electrical continuity exists when a voltage difference no greater than 0.1 mV is measured by leads connected to two pieces of steel being tested.

5./12. **Concrete resistance** must allow for the chloride extraction current to flow easily. High resistance results in lengthy treatment times. Latex-modified concrete, very dense good-quality concrete and a high concrete cover over the reinforcing steel may all contribute to high resistance. Concrete resistivity can be determined using an AC resistance meter and the “Wenner Four Pin” method. Conductivity usually ranges from 10,000 to 50,000 ohm-cm. Concrete resistance in the high range requires a longer time to pass a given amount of charge, and attendant costs will be higher.

6. **Minimum concrete damage** is desired for effective chloride extraction. Loose and delaminated

### CRITERIA FOR CANDIDATE STRUCTURES

In order to consider treating a structure for electrochemical chloride extraction, certain conditions must be met:

<table>
<thead>
<tr>
<th>Required conditions</th>
<th>Desired conditions</th>
</tr>
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<tbody>
<tr>
<td>2. No prestressed steel</td>
<td>7. No coatings or overlays</td>
</tr>
<tr>
<td>3. No alkali-reactive aggregate</td>
<td>8. Minimum exposed steel</td>
</tr>
<tr>
<td>4. Reasonable steel continuity</td>
<td>9. Minimum traffic disruption</td>
</tr>
<tr>
<td>5. Reasonable concrete resistance</td>
<td>10. Available AC power</td>
</tr>
<tr>
<td>11. Excellent continuity of steel</td>
<td>12. Low concrete resistance</td>
</tr>
<tr>
<td>13. Simple geometry</td>
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</table>

11. Excellent continuity of steel

12. Low concrete resistance

13. Simple geometry
concrete should be removed and these areas should be patched before treatment. After patching and curing for 28 days to ensure a stable resistivity, tests should be done to ensure that the resistivity of the patch closely matches that of the parent concrete. A good match allows for uniform current flow.

If cracks exist perpendicular to the concrete surface, use of a captive electrolyte will be difficult. Cracks can be deeply sealed by epoxy injection, but this process involves additional expense. If chloride extraction is to be conducted on an extensively cracked structure, a system using a sprayed cellulose fibre that does not use a recirculating confined electrolyte is recommended.

7. No coatings or non-conductive overlays should be present since they result in a high electrical resistance and prevent the flow of enough current at acceptable voltages. Such coatings can be removed before treatment but removal sharply increases costs.

8. Minimum steel exposure at the surface is desired in candidate structures because exposure could cause a short circuit between the steel and the anode. Even if a short does not occur, a high current may flow to the exposed steel, which will stop chloride extraction from the adjacent concrete and cause inefficiency.

9. Minimum conflict with traffic is necessary since the chloride extraction process can take 10 to 50 days, depending on the electrical resistance of the concrete and the extent of chloride corrosion. The process is more applicable to substructures than decks since procedures have not been developed that allow traffic over a deck system during operation. Some substructures may require traffic control during system installation and extraction.

10. AC power availability should be ensured since the power requirement for maximum current flow, 5 A/m², is about 250 W/m². For large structures, 240 or 480 V, 3—phase AC power is usually required. If sufficient AC power is not available, a generator can be used but equipment, fuel and labour costs will increase.

13. Simple geometry is another consideration, because of the design of the process; the system using an anode/blanket composite is best suited for round columns while the system using sprayed cellulose fibre is more easily adapted to flat surfaces. Large horizontal decks are easily handled by constructing an electrolyte pond.

CHLORIDE-EXTRACTION PROCEDURES

Those structures which meet the above criteria for electrochemical chloride extraction can undergo treatment. Following the laboratory studies, chloride extraction processes were developed for three different field configurations. These design concepts are for the three most common concrete bridge elements that would be subjected to chloride extraction treatments: 1) land column, 2) marine column and 3) deck. The design for chloride extraction in column structures is first described since it has the widest possible application. Alternative designs for decks using a ponded system or a sprayed fibre system on large, flat structures follow.

ANODE/BLANKET COMPOSITE

For concrete columns, located on land or in a marine environment, a prefabricated and reusable anode/blanket composite is wrapped around the column and held in place for the chloride-extraction process. For a column on land, electrolyte is contained in a reservoir on the ground; it is pumped to the top of the treatment area, flows by gravity over the anode and returns to the reservoir. The marine column concept is similar but no reservoir is needed at the base of the column because the constant supply of fresh sea water serves as the electrolyte feed. Polyvinyl chloride (PVC), polyethylene and polypropylene piping or hose are all recommended materials for the circulation system, which is depicted in Figure 1.

The anode-blanket composite has three components: the anode mesh, an inner blanket and an outer blanket, as shown in Figure 2. The anode is a flexible, highly expanded mesh that will conform easily to a variety of surfaces. For the field trials, ELGARD 300 titanium mesh with EC-100 coating was used; it is supplied with an

1 Wherever possible, the units reported in this brief are those used in the source document. Where both SI and imperial units are reported, the SI units have been converted from the imperial. Readers are advised to make reference to the original imperial units for any subsequent analysis or interpretation or when discrepancies may appear in the equivalency.
electrical resistance of 0.026 Ω/m. A catalyzed coated titanium current distributor strip is spot resistance welded to the edge of the anode mesh in 10 to 13 spots per linear metre (3 to 4 per lin. ft).\(^1\)

The inner blanket serves as the main path for current flow between the anode and the reinforcing steel. Its ability to retain electrolyte for long periods of time and to conform to irregular concrete surfaces is of utmost importance. Sorb\(_X\) S-92, manufactured by Matarah Industries Inc., is composed of 33 percent polypropylene and 67 percent cellulose fibre and was selected for the inner blanket. The inclusion of cellulose fibre allows for moisture retention. If electrolyte flow to the system is interrupted, the Sorb\(_X\) fibre will retain enough electrolyte to allow the treatment to continue for several hours. This material is friable and is not reusable.

The outer blanket, however, is composed of several components sewn together and forms a reusable unit. It is comprised of GTF 350 EX, manufactured by Exxon Inc., which is placed between the Sorb\(_X\) inner blanket and the anode mesh, and an outer lining made of Polyfelt TS-1000, manufactured by Gundle Lining Systems. A plastic film can also be wrapped around the composite to minimize evaporative losses or dilution of electrolyte caused by rainwater entry. The Polyfelt material is particularly strong and will support straps to secure the system. Depending on the geometry of the member being treated, additional bands or other means of securing the system may be needed. Close and uniform contact between the inner blanket and the concrete is essential.

To confine the electrolyte at the bottom of the system, a heavy application of caulking material between the concrete surface and the collection element was required. Columns were sealed with a 30 cm wide rubber band that was vulcanized together as it wrapped around the column. The rubber band was further secured with urethane caulking material and plastic banding. Vertical cracks in the concrete may need to be sealed by epoxy injection to prevent significant loss of electrolyte.

The electrolyte composition should be pH-buffered to prevent it becoming too acidic; sodium borate (Na\(_3\)BO\(_3\)) is recommended for its buffering capacity, cost, safety and environmental impact. Generally, 0.2 moles of sodium borate will neutralize the acid generated...
by 100 A-hr. An electrolyte containing 0.2 moles/litre sodium borate will contain 25.56 gm/l of the salt. The electrolyte can be made on site by adding 24.0 gm sodium hydroxide and 12.4 gm boric acid per litre. For structures with known alkali-silica reactive aggregates, lithium borate electrolyte is recommended. A 0.2 molar (15.93 gm/l) Li₃BO₃ solution is prepared by adding 14.4 gm lithium hydroxide and 12.4 gm boric acid per litre.

It is also necessary to determine the amount of total charge needed for the chloride extraction process. Typically, a total charge of 600 to 1500 A-hr/m² is sufficient, although there may be cases in which more or less charge is used. The maximum current used for the chloride extraction process is 5.0 A/m² of concrete. This level assumes a steel-to-concrete surface area ratio of about 1:1. This maximum current can be reached while remaining under 50 V when the concrete is very conductive but current and voltage requirements should be determined prior to treatment by conducting a chloride extraction laboratory test on a core removed from the structure.

Once the charge and expected current have been determined, it possible to predict the treatment time. Time is calculated by dividing the total charge (A-hr/m²) by the current (A/m²). A treatment time of 10 to 50 days is considered normal.

### SPRAYED CELLULOSE FIBRE SYSTEM

The sprayed cellulose fibre system is used for large, flat, principally vertical surfaces. Cellulose fibre is sprayed wet onto the surface, a steel anode is installed over the fibre and more cellulose fibre covers the anode. Periodic wetting of the surface with water is needed to maintain an electrically conductive path between the anode and the concrete. An operating current density of approximately 1.0 A/m² is recommended. This continues until 600 A-hr/m² of charge has passed.

More details and analysis of this proprietary procedure, known commercially as the NORCURE™ process, are reported in SHRP-C-620, Evaluation of NORCURE Process for Electrochemical Chloride Removal from Steel-Reinforced Bridge Components. Vector Construction in Winnipeg, Manitoba is the Canadian licensee for the procedure. The procedure was first tested on a section of Pier S-19 of the Burlington Skyway in Ontario during the summer of 1989. Evaluation under the SHRP contract showed the NORCURE™ process to be simple and relatively easy to install. The wet cellulose mat was an effective electrolyte for the chloride extraction process. Unsightly stains from the corrosion products of the steel anode were easily removed by subsequent grit blasting. The treatment process was completed without any evidence of mechanical or chemical distress to the concrete. Chloride extraction efficiencies and post-treatment corrosion data were similar to other slabs subjected to chloride extraction, but under slightly different conditions. Rate-of-corrosion measurements taken annually up to October 1994 by the Ontario Ministry of Transportation have shown the treatment was effective in arresting corrosion in the five years following treatment.

### PONDED ELECTROLYTE SYSTEM

An alternative design has been developed for use on horizontal or near horizontal surfaces such as bridge decks. It should be noted, however, that the time required for treatment is quite long and no traffic may use the bridge deck during treatment. This restriction renders the process of electrochemical chloride extraction from concrete bridge decks impractical in most cases. The ponded electrolyte system used on horizontal surfaces is shown in Figure 3. A dam of concrete or some other suitable material is constructed around the perimeter of the treatment area. A catalyzed titanium inert anode mesh is embedded in a sand backfill over the treatment area. Most decks slope from the centreline to the edge, enabling

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**Figure 3 – Conceptual Layout of Deck Configuration**
the electrolyte to be pumped from a reservoir electrolyte distribution system. The electrolyte would travel through the sand and over the anode by gravity to a gutter collection network at the edge of the deck, which is then channelled back to the reservoir.

A pond approximately 5 cm deep is recommended, holding approximately 1650 l of electrolyte per 300 m². A cover is recommended over the treatment area to prevent dilution or evaporation of the electrolyte which must be maintained at a constant level throughout the treatment.

**DEMONSTRATIONS**

The chloride removal process was demonstrated in field validation trials conducted on four structures, including one substructure in Latchford, Ontario. All four trials judged the process to be successful and it was recommended that these structures be monitored for a period of five years.

A showcase contract for electrochemical extraction has been initiated by the US Federal Highway Administration. The states of Virginia and South Dakota have agreed to apply the concept on several bridges.

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**SHRP S-347**
Chloride Removal Implementation Guide
J. Bennett, T.J. Schue, ELTECH Research Corporation, Fairport Harbor, Ohio
Strategic Highway Research Program
National Research Council
Washington, DC 1993

**SHRP C-620**
Evaluation of NORCURE Process for Electro-Chemical Chloride Removal from Steel-Reinforced Concrete Bridge Components
J. Bennett, T.J. Schue, ELTECH Research Corporation, Fairport Harbor, Ohio
Strategic Highway Research Program
National Research Council
Washington, DC 1993

**SHRP S-657**
Electrochemical Chloride Removal and Protection of Concrete Bridge Components: Laboratory Studies
Strategic Highway Research Program
National Research Council
Washington, DC 1993

**SHRP S-657**
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