Electrochemical Treatments for Reinforcement Corrosion in Concrete Road Bridges in New Zealand

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An Important Note for the Reader

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This report represents the first stage of an evaluation of the long-term performance of proprietary patch repair/surface treatment systems and electrochemical treatments used to rehabilitate concrete bridges suffering from corroding reinforcement. The findings will enable New Zealand bridge asset managers to select appropriate repair technologies to suit the needs and circumstances of individual structures, thereby optimising cost and long-term performance requirements. The information will also allow bridge owners to furnish more accurate information for their long-term financial strategies.

Scope of Report

This report summarises the main technical features of electrochemical treatments and opportunities for their use on New Zealand bridges. It is written to overcome a lack of knowledge about and confidence in using techniques that are quite different to familiar patch repair techniques. They have not been widely used in New Zealand, although they have a history of successful application overseas. It describes the factors that need to be considered when deciding on an appropriate course of treatment for an individual structure and is designed to alert managers to features that might be relevant when they are considering the options for rehabilitating a structure rather than to provide a comprehensive guide. The information presented is drawn from a review of international technical and trade literature, and from discussions with designers and suppliers of electrochemical treatments, both of which were carried out during 2001-2002. Readers are directed to consult technical literature, standards and suppliers for more detailed information when considering specific applications of electrochemical treatments.

Electrochemical Treatments

Cathodic protection (CP), chloride extraction and realkalisation are electrochemical treatments for concrete damaged by reinforcement corrosion. They are designed not to repair the damage but to prevent further deterioration for considerably longer than the typical 10-year repair cycle offered by traditional patch repair techniques. They do not require the extensive removal of contaminated but sound concrete that is required by patch repair. They can also be applied as preventive treatment before damage occurs, although this aspect of their use is beyond the scope of this report.

Reinforcement corrosion is the most common and significant durability problem on New Zealand's concrete road bridges. The nature and uniformity of the bridge design and construction makes them ideal candidates for electrochemical treatments. The similarity of many structures means that, although initial applications of electrochemical treatments will involve steep learning curves and there will always be aspects specific to individual structures, lessons learned on each structure will be applicable to subsequent applications.

Rebar corrosion severe enough to necessitate repair is usually caused by chloride contamination. Depending on exposure conditions and the intended remaining life of the structure, either CP or chloride extraction could be appropriate treatments for chloride contamination.

CP systems offer permanent treatment, i.e. for the remaining life of the structure, although they require continued monitoring throughout their service life, and, like a car, components within the system have a finite life. Systems can be designed to suit all parts of a concrete structure in any exposure zone: inland (A2), coastal (B1 and B2), tidal/splash (C) or submerged (NZS 3101: 1995 exposure categories). CP can be used to protect rebar in reinforced and prestressed concrete, although particular care must be taken to avoid damaging prestressing strands and tendons. CP can also be used to protect pretensioning strands but tendons used to post-tension concrete cannot be cathodically protected. Impressed current (IC) CP offers greater control and flexibility, while galvanic systems may be more economic because less hardware is needed to control their performance. CP has an extensive history of use over the last twenty years that is well documented in the literature.

A proprietary galvanic anode system designed to prevent incipient anode effects in patch repair could increase the life of patch repairs by an estimated 10 years depending on conditions.

How long **chloride extraction** remains effective will depend on the individual circumstances of each structure but, if sufficient chlorides are removed and recontamination is prevented, then the treatment could remain effective for 20-30 years. Treatment takes up to four months and no long-term maintenance is required. Chloride extraction is best suited to elements not in direct contact with seawater, i.e. those in the coastal exposure zone (B1 and B2 zones, NZS 3101:1995), which can be protected from recontamination by coating after treatment. It cannot be applied to pretensioned concrete. Under some circumstances it can be applied to protect the rebar in post-tensioned concrete, but not the tendons. Particular care must be taken when applying it to round (undeformed) rebar, and to concrete containing alkali-reactive aggregates. Chloride extraction has rapidly gained favour since its introduction in the late 1980s, particularly for removing de-icing salt contamination. However fewer case studies are reported of treatments to concrete exposed to marine conditions.

For concrete that is extensively carbonated, **realkalisation** offers a permanent solution. Treatment takes two to three weeks and no long-term maintenance is required. It is best suited to concrete that is not chloride-contaminated, i.e. in inland exposure zones (A2 zone, NZS 3101:1995), but can be applied in conjunction with chloride extraction if necessary. Application to prestressed concrete has the same limitations as chloride extraction. Although realkalisation is a technically sound treatment, in practice it is unlikely to find a large market on New Zealand bridges because carbonation-induced corrosion is not a major problem, and can usually be effectively treated with patch repair. Indeed a search of international literature found only one reported case study of application to bridges.

Details of Australasian designers and suppliers of the electrochemical treatments, and of installations similar to possible New Zealand bridge applications are given in the report.

Cost Benefits

The next stage in evaluating the potential for using cathodic protection, chloride extraction, and realkalisation on New Zealand bridges is to compare their up-front and long-term costs with those of patch repairs. This constitutes the second stage of the research, which will be carried out in 2002-2003. Note however that repair options for individual structures will always need to be evaluated for the particular structure concerned.

Future Research

A possible area for future research is to identify the need for some sort of independent database of Australasian installations of electrochemical treatments. This record could make it easier in the future for designers and asset owners to find information on long-term performance, given that relatively few case histories are likely to be reported more than 10 years after installation.

The 2002-2003 research is likely to identify shortcomings in knowledge that could be addressed by further research. Similarly, technical or practical issues related to electrochemical treatments may arise as they become more widely used. Future research could be directed at refining the technology to make it more practical, durable, efficient or economical as required.

Abstract

Reinforcement corrosion is the most significant durability problem affecting New Zealand concrete bridges. Cathodic protection (CP), chloride extraction and realkalisation are electrochemical treatments that are designed to prevent further deterioration for considerably longer than the typical 10-year repair cycle offered by traditional patch repair techniques. They do not require extensive removal of contaminated but sound concrete. To inform New Zealand bridge asset managers about the potential benefits of these techniques, their technical features are summarised and opportunities and limitations for their use on New Zealand bridges are identified in this report, prepared in 2001-2002. Case studies of overseas applications similar to possible New Zealand bridge applications are presented, and Australasian designers and suppliers of treatments are listed. These data were current to July 2002.

Evaluation of data from the case studies and from a literature review suggests that CP offers protection for the remaining life of a structure, although it must be continuously monitored and maintained throughout that time. It is suggested as suitable for structures affected by chloride-induced contamination. Chloride extraction was considered to offer up to 20 to 30 years of protection, and is suggested as suitable for concrete exposed to atmospheric chloride contamination. Realkalisation was considered to offer permanent protection from carbonation-induced corrosion, although this is not a major problem on New Zealand bridges.

1. Introduction

1.1 Background

Corrosion of steel reinforcement is the most serious and common deterioration problem affecting reinforced concrete structures in New Zealand. Steel will corrode when exposed to moisture and oxygen, and corrosion is accelerated in the presence of chloride ions, which are present in seawater. Normally the surrounding concrete provides a relatively impermeable barrier to prevent moisture, oxygen and chlorides reaching the steel. It is also highly alkaline, which prevents the corrosion reactions occurring. But if insufficient concrete surrounds the reinforcement, or if the concrete is of poor quality and easily transmits air and water, then the reinforcement will start to corrode. The corrosion products occupy a greater volume than the original steel, and their formation will first crack then break off the overlying concrete, exposing the steel to the elements. As the reinforcing bar corrodes, its diameter and consequently its strength both decrease, until eventually the load capacity of the structure is lost. It is therefore important to repair damage caused by reinforcement corrosion in order to maintain structural capacity and prevent damage to people, property, vehicles, etc. by any concrete that may fall off the structure.

All types of reinforced concrete structures, including bridges, are prone to corrosion damage. Those exposed to seawater or sea spray are at greater risk, as are surfaces exposed to rain or run-off. Road bridges are affected because many (60% of state highway bridges and 45% of local authority bridges) are in coastal environments, and because they all have surfaces exposed to water. Older bridges are more likely to be affected, first because construction quality was often poorer before 1950, and second because the corrosion damage increases with time. In New Zealand, over 30% (approximately 770) of state highway concrete bridges and 14% (approximately 1180) of local authority concrete bridges are more than 50 years old. Although many are still in acceptable condition, the incidence of deterioration caused by reinforcement corrosion is likely to increase as they age further, increasing the overall maintenance costs for concrete bridges. Transit New Zealand's National State Highway Bridge Asset Management Plan (Transit New Zealand 2000) estimates the annual cost of maintenance over the next 10 to 20 years to be (NZ)$6 million for all bridges with more than $3 million to be spent on structural bridge maintenance.

Technology for repairing concrete structures affected by reinforcement corrosion has advanced significantly in recent years and several different approaches are commercially available. The electrochemical processes known as cathodic protection, chloride extraction and realkalisation have a high initial cost but are promoted as providing a permanent solution, while conventional systems, which combine patch repairs and surface treatments, are cheaper to install but have a limited life.

Different techniques are used depending on whether the corrosion was initiated by chlorides or loss of alkalinity. Sometimes the repair needs to be permanent, and sometimes it may only be needed to serve for a finite time before major modifications or reconstruction are carried out. Consequently, when repair is needed asset managers need to identify the most effective and economic method for each particular case, taking into account the initial cause of the corrosion, the anticipated functional remaining life required for the structure, and the long-term cost and predicted life of the repair.

To do this, they need to be familiar with the long-term performance and costs of these repair systems, and yet most systems are too recent for individual manufacturers or users to have built up extensive experience with them. Research by Bruce et al. (1999) suggested that bridge managers in New Zealand need more up-to-date information on corrosion treatments, and that lack of local evidence of performance is a major obstacle to the uptake of new repair technologies such as electrochemical techniques.

Logistics preclude installing and monitoring repairs as long-term trials in New Zealand. Many case histories in the international literature report the development, selection and installation of particular systems, but fewer reports on their long-term performance are available. No large-scale investigations of current repair technologies are in progress in New Zealand, although some individual asset owners have initiated limited trials for their own purposes. Literature review therefore remains the best source of information on the various repair options, although there is a lack of pragmatic information about their long-term performance.

1.2   Scope of Research

The research reported here was carried out in 2001-2002. It represents the first stage of a project that aims to evaluate existing evidence on the long-term performance of proprietary patch repair/surface treatment systems and electrochemical treatments used to rehabilitate concrete bridges suffering from corroding reinforcement. The findings will enable New Zealand bridge asset managers to select appropriate repair technologies to suit the needs and circumstances of individual structures, thereby optimising cost and long-term performance requirements. The information will also allow bridge owners to furnish more accurate information for their long-term financial strategies.

This report summarises the main technical features of electrochemical treatments. It is written to improve knowledge about and confidence in using techniques that are quite different to familiar patch repair techniques and that have not been widely used in New Zealand, although they reportedly have a history of successful application overseas.

It describes the factors that need to be considered when deciding on an appropriate course of treatment for an individual structure. It is designed to alert managers to features that might be relevant when they are considering the options for rehabilitating a structure, rather than to provide a comprehensive guide.

The information is drawn from a review of international technical and trade literature, and from discussions with designers and suppliers of electrochemical treatments, both of which were carried out during 2001-2002. Readers will still need to consult technical literature, standards and suppliers for more detailed information on design, specification, construction and maintenance when considering specific applications of electrochemical treatments.

Part of the original scope of the project was to identify further research needs in this area. Funding for the second stage of this investigation, to be carried out in 2002-2003, has been approved. This work will involve a similar review of patch repair technology and a comparison of the short- and long-term costs involved in patch repair and electrochemical treatments.

2. General Principles of Corrosion

'Corrosion' can be defined as the destruction or deterioration of a material by reaction with its environment. It can refer to the process or to the damage caused, and applies to metals and non-metals. In this report 'corrosion' refers to the corrosion of steel reinforcement in concrete.

Metals are normally found in nature as oxides, called ores. This is their most stable (or lowest energy) form. To obtain the metal, energy is applied to separate the chemical elements present in the ore. More energy is then applied to shape the metal into a product. The finished metal product has more energy than it needs to maintain equilibrium in the natural environment, and so tends to release this extra energy and return to its natural, low energy state. This is the process of corrosion. For example, heat and mechanical energy are applied to produce steel from iron oxide, and on exposure to moisture and oxygen the steel corrodes back to stable iron oxides, releasing energy in the form of electrical corrosion currents.

Metallic corrosion occurs by electrical charges moving between sites on a metal surface to balance charges generated by chemical reactions at each site. Both electrical and chemical processes are involved, so corrosion is referred to as an 'electrochemical' process.

Metallic corrosion has four requirements:
- two sites with different potentials for releasing energy;
- a metallic connection that allows the flow of electrons (electric current) between them; and
- an electrically conductive solution (electrolyte) in contact with both sites that allows the flow of ions.

2.1 Anodes and Cathodes

The two metallic sites are called the electrodes. One, the anode, releases energy in the form of electrons. The other, the cathode, receives the electrons released at the anode. The difference in energy between the electrodes is the voltage, or electrochemical potential, and this is what drives the corrosion reactions. The amount of material lost from the corroding electrode is determined by the amount of corrosion current generated. This is a function of the voltage between the two electrodes and the electrical resistance of the materials through which electrons and ions must flow.

Features of the two electrodes, and the chemical reactions that occur at them are as follows.

The *anode* has a greater potential to release energy. It dissolves, releasing energy in the form of electrons. The chemical reactions are called oxidation reactions. They are expressed as:

Metal → metal ions (dissolved in the electrolyte) + electrons (e^-)   (1)

M   → M^{n+} + ne^- (n = the number of electrons involved in the reaction)
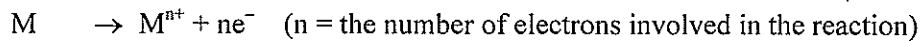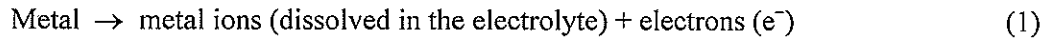
The anode has a positive charge because it loses negatively-charged electrons.

The *cathode* has less energy. It accepts the electrons released by the anode, and takes them up in chemical reactions called reduction reactions. They do not necessarily involve the metal itself. They include:

In aerated neutral or alkaline solutions (and cement paste is usually alkaline):

Oxygen (dissolved in the electrolyte) + water + electrons → hydroxyl ions   (2)
$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$

Metal ion + e^- → metal, or metal ion with lower charge   (3)
$M^{n+} + e^- \rightarrow M^{n-1}$

In acid solutions:

Hydrogen ions + e^- → hydrogen gas   (4)
$2H^+ + 2e^- \rightarrow H_2$
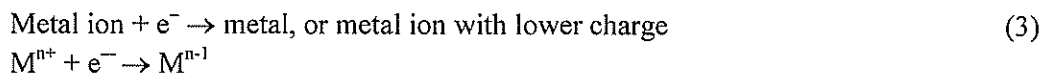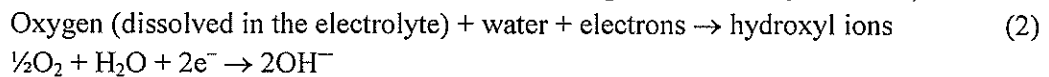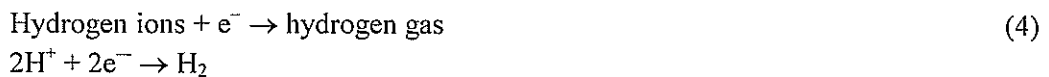
In neutral conditions in the absence of oxygen:

Water + e^- → hydroxide ions and hydrogen gas   (5)
$2H_2O + 2e^- \rightarrow 2OH^- + H_2$
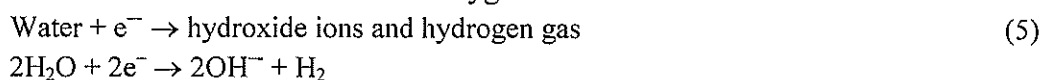
The cathode has a negative charge because it gains electrons.

Reactions (2) and (5) are sometimes called electrolysis reactions.

When steel corrodes, the positive iron ions generated at the anode react with the negative hydroxyl ions generated at the cathode, to form iron hydroxides. These eventually form the orange coloured product we recognise as rust.

Any metal with a higher potential energy can release energy to any metal with lower energy, and thereby corrode. Similarly, any metal with lower energy can receive energy from any metal with higher energy, and thereby be protected from corrosion. The relative energies of various metals are given in tables known as the Galvanic Series and the Electrochemical Series.

The Galvanic Series ranks metals in order of their tendency to dissolve in a given environment. The further apart the two metals are on the list, the greater the driving force of the corrosion reaction. 'Galvanic corrosion' is the term given to corrosion driven by an energy difference between two different metals.

The Electrochemical Series lists the differences in energy between a metal and a reference electrode under standard conditions. It can be used to calculate the energy

difference between any two metals and hence estimate the driving force (measured in millivolts) of the likely reaction between them.

A metal's potential energy, or tendency to dissolve, depends upon its immediate environment, particularly the availability of oxygen, water, and contact with chemicals that it (or its ions) might react with. A single piece of metal is often exposed to slightly different conditions over its surface area. If these differences are large enough, anodes and cathodes will be set up on its surface and it will corrode even if not in contact with another metal. Inclusions of other metals exposed on the surface of an alloy, or local differences in the metal's grain structure caused by working (welding, cutting, bending, etc.) can have the same effect.

In the usual situation where no other metals are present, these effects cause steel reinforcement in concrete to develop anodes and cathodes and then corrode. The anode and cathode can be the on same piece of reinforcement or on different pieces, as long as a conducting material connects them. The variations in the immediate environment of the reinforcement include availability of oxygen and moisture, chloride ions, and alkalinity of water in contact with the steel.

2.2   Electrical Conductor

The metallic conductor in reinforced concrete is the reinforcement itself.

2.3   Electrolyte

Moisture in the concrete provides the electrolyte through which ions are transported. The lower the moisture content, the higher the electrical resistivity of the concrete, because ion transport is restricted. The resistivity of concrete determines the rate of corrosion. Resistivity is also related to the chemical composition of the water in the concrete pores (i.e. the 'pore solution').

2.4   Corrosion Potential of Steel in Concrete

Steel does not normally corrode in concrete because the high alkalinity of Portland cement paste causes a film of iron oxide to develop on the steel surface. The steel is then said to be in a passive state or passivated. In normal concrete conditions the oxide film is stable enough to protect the steel against small variations in environment, but it becomes unstable in the presence of chloride ions or if the alkalinity of the pore solution is reduced by carbonation. Thus chloride ion contamination (such as in marine environments), carbonation, and large variations in the concrete environment (e.g. areas of poor compaction) will lead to corrosion of the reinforcement. If the alkalinity of the pore solution is restored or chloride contamination removed, the oxide film will be reinstated, thereby repassivating the steel.

3. Electrochemical Treatments for Reinforcement Corrosion

3.1 General Principles

Traditional *patch repair* methods of treating concrete damaged by reinforcement corrosion repair the damage caused by corrosion but do not remove the original cause. That is, they involve replacing cracked or spalled concrete surrounding the damaged reinforcement, which may or may not be replaced itself depending on its condition. In carbonated or chloride-contaminated concrete this does not necessarily stop further corrosion for two reasons. First, rebar corrosion will continue in the original concrete because the carbonation/chloride contamination is still present. Second, the rebar adjacent to a new repair will start to corrode because it is now in relatively more aggressive surroundings than the rebar encased in the new repair material (this is known as the incipient anode effect). To avoid these two effects all the carbonated or chloride-contaminated concrete needs to be replaced, even where corrosion has not caused significant damage. This is rarely practical.

Electrochemical treatments remove the cause of corrosion by modifying the electrochemistry of the reinforcement and surrounding concrete. With these treatments only the cracked or spalled concrete needs to be replaced. Carbonated or chloride-contaminated concrete that is otherwise sound does not need to be removed. This offers a significant advantage, not only in cases of severe damage and contamination where a large volume of concrete would otherwise need to be replaced, but also in slender sections such as architectural panels where removal of even a small amount of concrete could significantly reduce the load-bearing capacity of the structural element. Electrochemical treatments avoid incipient anode effects and treat large areas of a structure.

Three types of electrochemical treatment are available commercially[1]. All turn the reinforcement into a cathode. They are:

Cathodic protection (CP) turns the reinforcement into a permanent cathode by maintaining a permanent potential difference (voltage) between it and a new anode material that is electrically connected to the reinforcement. The current is strong enough to override other effects that may generate anodes and cathodes on the rebar.

Chloride extraction removes chloride ions from around the reinforcement by applying a temporary current through surface-mounted anodes to drive chloride ions towards the anode.

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[1] While this report was in the final stages of editing, an item about a new proprietary electrochemical system appeared in the UK Concrete Society's journal *Concrete* (*Trade News* section, October 2002 edition). The suppliers claim that the treatment combines cathodic protection and electro-osmosis to reduce moisture content and thereby control reinforcement corrosion. This treatment is not included in this report.

Realkalisation restores the high pH of carbonated concrete by applying a temporary current through surface-mounted anodes to generate alkalis at the reinforcement and to transport alkali metal ions into the concrete. A supplementary electrolyte is applied temporarily to the surface around the anodes during chloride extraction and realkalisation.

The main features of the processes are summarised in Table 3.1 (pp. 20-21), and Section 3.2 describes the factors that need to be considered when deciding on an appropriate course of treatment for an individual structure. Each treatment is described in more detail in Chapters 4 to 6 of this report.

Some concrete repair is normally needed before installing an electrochemical treatment. The repair materials must have appropriate strength, shrinkage and elastic properties to remain sound, just as for conventional patch repair. They must also have similar electrical resistivity to the original concrete. Patch repair materials are the subject of Stage 2 of this research, which will be carried out in 2002-2003, and are not discussed in this report. The selection of suitable materials to be used in conjunction with electrochemical treatments should be part of the specification for the electrochemical treatment.

Modified CP systems can be installed in high-risk structures at the time of construction to prevent corrosion. This application is known as *cathodic prevention*. It is not described in this report, but is basically a CP system operated at very low current density, typically 0.2-2 mA/m^2 of rebar, to maintain the rebar in a passive state.

Electrodes can also be cast into new concrete as a *corrosion monitoring* system. Typically these monitor corrosion potentials, corrosion rates and/or the ingress of chlorides or other contaminants. Monitoring does not provide any protection itself but warns of corrosion damage earlier than the cracking and spalling of cover concrete, which is usually the first evidence of reinforcement corrosion. The early warning allows the application of preventive treatments, such as coatings or CP, before the damage becomes significant. Preventive corrosion monitoring systems are not the same as those used to monitor processes in electrochemical treatments for damaged concrete and are not described in this report.

Electrochemical treatments are highly specialised processes. Each application must be individually designed and installed by specialists with experience in corrosion prevention. Information about Australasian designers and suppliers of electrochemical treatments is given in Chapter 8 of this report.

3.2   Selection of Repair Methods

Benefits, applications and shortcomings of cathodic protection, chloride extraction and realkalisation are described in Chapters 4, 5 and 6 of this report. The decision whether concrete should be patch-repaired or receive an electrochemical treatment should be based on a combination of technical and economic factors. These will be described in the report from the 2003-2003 research. In the interim, Figures 3.1 to 3.3 (pp. 22-24) summarise the decision processes involved in selecting appropriate rehabilitation techniques for concrete affected by reinforcement corrosion. The Australian Concrete Repair Association (ACRA 1996) and the Building Research Establishment (BRE 2000) also offer guidelines to the inspection, assessment and selection of repair strategies for reinforced concrete structures.

Chloride extraction and realkalisation can be performed sequentially. This was originally proposed for the National War Memorial Carillon in Wellington. A pilot study of the combined treatment found that its efficiency was compromised by the presence of a coating material, and additional testing to monitor the process revealed that chloride contamination was more widespread than originally estimated. Local application of CP where steel was actively corroding was found to be the most cost-effective option (Broomfield et al. 2000, CCANZ 1999, Mandeno 1999).

Table 3.1 Comparison of electrochemical treatments.

Attribute	Galvanic Cathodic Protection	Impressed Current Cathodic Protection (ICCP)	Chloride Extraction	Realkalisation
Main application	To inhibit chloride induced corrosion in marine concrete.	To inhibit chloride-induced corrosion in marine concrete.	To remove chloride ions in non-marine concrete.	To reverse effects of carbonation.
Method of corrosion control	Sacrificial corrosion of a suitable metal, such as zinc, instead of rebar.	Changes the corrosion potential of the rebar.	Removes chlorides to restore passivity of rebar.	Reinstates alkalinity to restore passivity of rebar.
Duration of installation	Permanent, with maintenance.	Permanent, with maintenance.	Up to 12 weeks.	Up to 20 days.
Current density*	Controlled by chemistries of anode and environment.	Typically 2–20 mA/m^2 of rebar for structures exposed to the atmosphere; 0.1-5 mA/m^2 of rebar for submerged concrete.	Up to 3 A/m^2 of concrete surface (approx 0.4-2.0 A/m^2 of rebar).	Up to 3 A/m^2 of concrete surface (approx 0.4-2.0 A/m^2 of rebar).
Voltage	Determined by corrosion potential of anode.	5-40 V	5-40 V	2-30 V
Anode systems	Thermally sprayed zinc or zinc alloy; Adhesive zinc sheet; Zinc mesh; Cast zinc/aluminium discrete anodes.	Titanium mesh in mortar overlay; Conductive coatings; Slotted anodes; Discrete internal anodes.	Titanium mesh; Mild steel.	Titanium mesh; Mild steel.
Electrolyte	Water in concrete pores.	Water in concrete pores.	Alkaline solution or water applied to concrete surface.	Sodium carbonate solution applied to concrete surface.

3. *Electrochemical Treatments for Reinforcement Corrosion*

Attribute	Galvanic Cathodic Protection	Impressed Current Cathodic Protection (ICCP)	Chloride Extraction	Realkalisation
Advantages	No power supply needed;	Long anode life;	Temporary process;	Temporary process;
	Monitoring or maintenance minimal;	Variable operating parameters suit a wide range of current requirements and concrete resistivities;	Universal protection over treated surfaces;	Universal protection over treated surfaces;
	Electrical isolation not needed;		No further maintenance required if coated after treatment, although coating will need to be maintained.	No further maintenance required if coated after treatment, although coating will need to be maintained;
	Safer for prestressed concrete;	Protection can be universal or local;		
	Substrate cutting and anode encapsulation not needed;	Extensive track record;		Permanent solution.
	Protection can be universal or local;	Proven technology with well-developed standards;		
	Permanent solution with appropriate maintenance of anode.	Permanent solution with appropriate maintenance of anode and other hardware.		
Disadvantages	Shorter anode life;	Ongoing monitoring and maintenance required;	Cannot use for prestressed concrete because of high current density;	Cannot use for prestressed concrete because of high current density;
	Current delivery not controlled;	Electrical isolation of anode and rebar required;	High current density can cause more problems than CP;	High current density can cause more problems than CP;
	Most suitable for low-resistivity concrete.	Power source and wiring required;	Recontamination possible;	New technology so few standards and long-term performance not well-defined.
		Potentially risky for prestressed concrete.	New technology so few standards and long-term performance not well-defined.	

* For CP, current density at the cathode is expressed as current per area of steel being protected, and current density at the anode is expressed as current per anode area. For chloride extraction and realkalisation, current density is expressed as current per area of concrete surface. This is because CP treats the steel surface, while chloride extraction and realkalisation treat a volume of concrete (cover depths are assumed to be approximately uniform so that the surface area of concrete determines the current requirements). The current density values quoted by different sources vary considerably, so the data quoted here should be considered only as the order of magnitude.
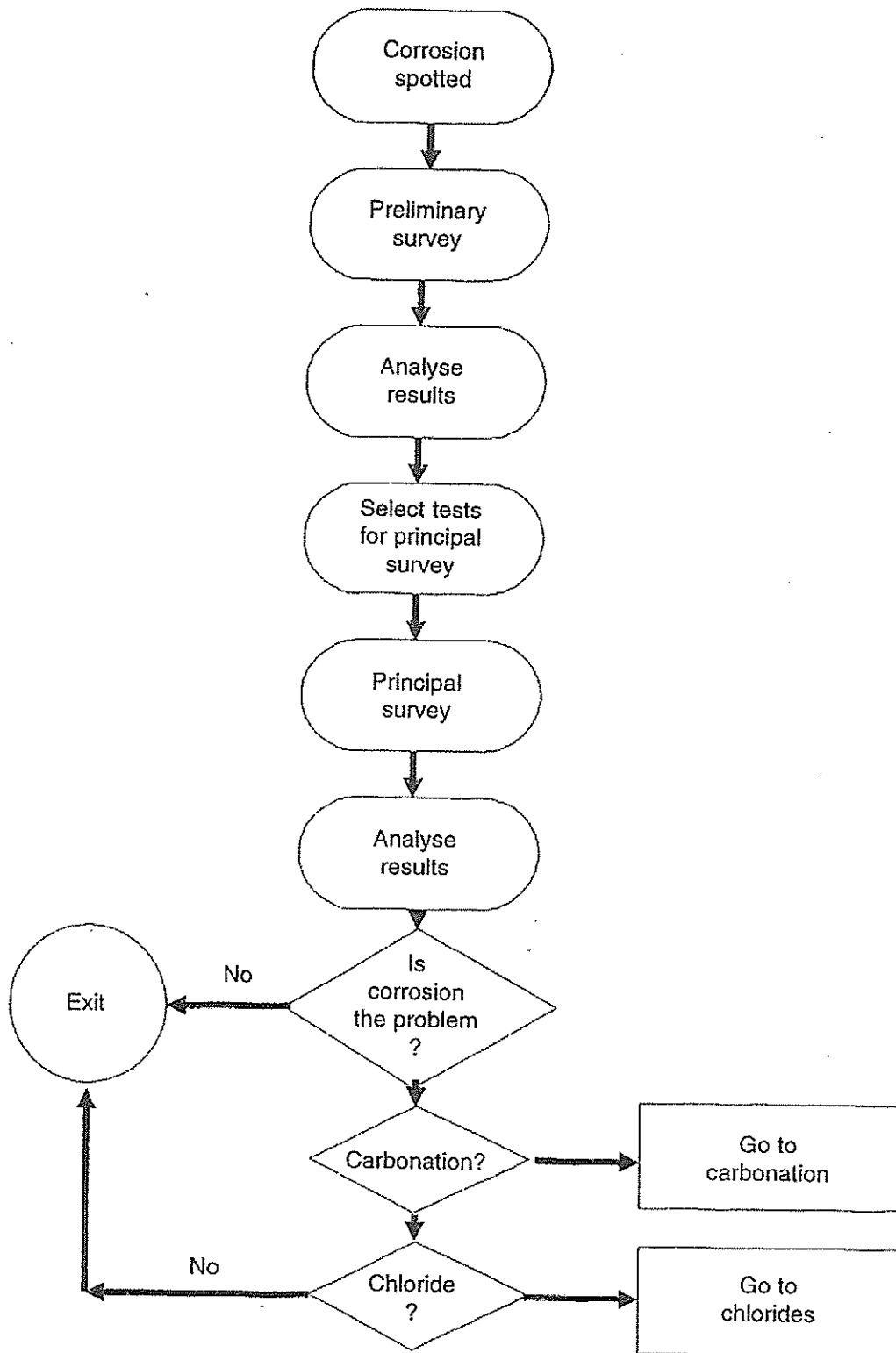
Figure 3.1   Methodology   for   selecting   a   repair   or   rehabilitation   method (Broomfield 1997).
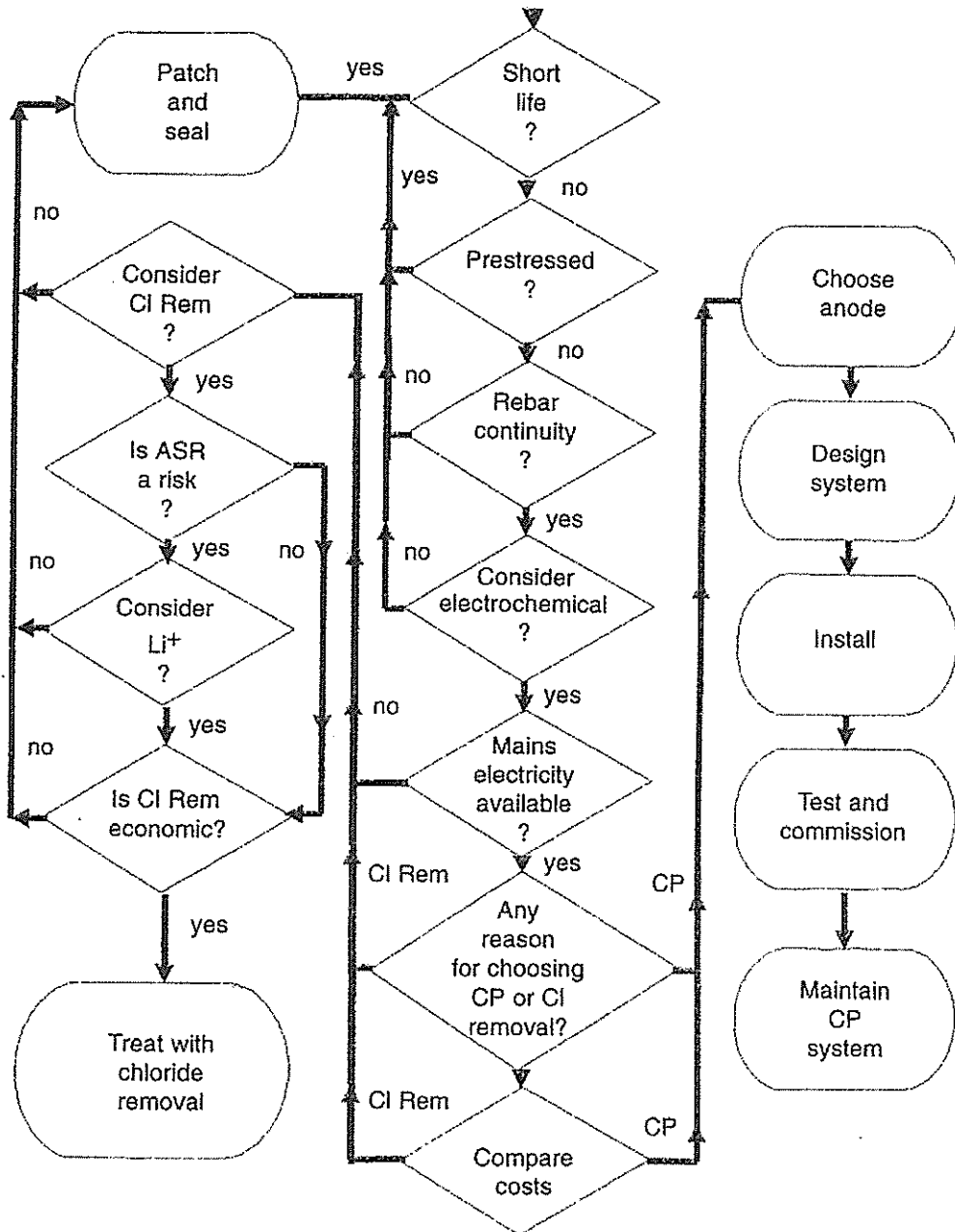
Figure 3.2   **Methodology for selecting a treatment for corrosion caused by chloride contamination (Broomfield 1997).**

ASR = alkali silica reaction, Li$^+$ = lithium treatment, Cl rem = chloride removal
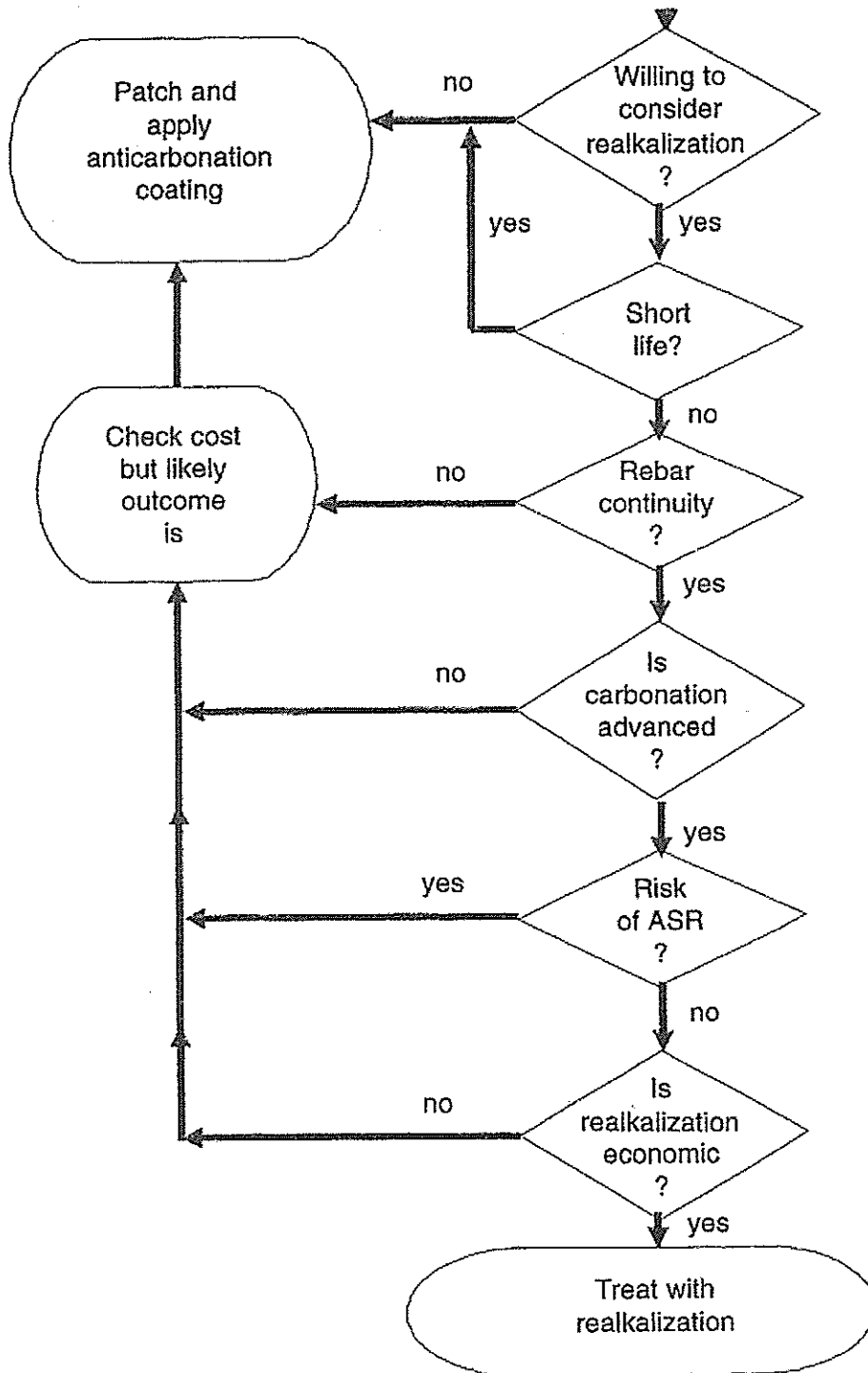
Figure 3.3 Methodology for selecting a treatment for corrosion caused by carbonation (Broomfield 1997).

ASR = alkali silica reaction.

4.   Cathodic Protection (CP)

Cathodic protection (CP) is defined as the reduction or elimination of metal corrosion by changing the metal from a current-supplying anode to a current-receiving cathode, either by an impressed direct current or by connecting it to a sacrificial anode. Cathodic areas do not normally corrode. If all the naturally anodic metal is forced into a cathodic state then the entire metal structure becomes a cathode and corrosion is controlled. As long as the metal is maintained at an appropriate potential it will remain a cathode. Only those parts of the metal to which the potential is applied will be protected.

CP will prevent corrosion from the time it is applied, but it will not replace metal that has already been lost from the component or structure to which it is applied.

CP will stop reinforcement corrosion in concrete structures **provided it is properly installed and operated** (Eltech 1993).

AS 2832.5-2002[2] provides a comprehensive description of cathodic protection of steel in concrete structures. It covers the assessment and repair of structures, design, installation, commissioning and operation of CP systems, and should form the basis for any Australasian specification. Guidelines are also given by NACE RP 0290-2000, and BS/EN 12696:2000. Bennett et al. (1993) provide a detailed manual of practice. These references give more detail than the owners of structures need, but they do give a valuable insight into the technology involved and the issues that need to be considered when installing CP systems.

All aspects of CP design and installation, including specification, must be undertaken by specialists.

4.1   Impressed Current CP (ICCP)

4.1.1   Principles

In ICCP, a direct current (DC) power supply creates a potential between an anode and the reinforcement. The anode may be attached to the concrete surface, or embedded in the concrete.

The power supply generates sufficient current to stop the reinforcement dissolving (reaction 1[3]) and to instead produce the cathodic reaction at the rebar:

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \tag{2}$$

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[2]   Standards Australia (SA). 2002. Cathodic protection of metals – Part 5:
      Steel in concrete structures. *AS 2832.5-2002*
[3]   In this section, chemical reactions are identified by the same numbering system as that used in
      Chapter 2 of the report.

If the potential gets too negative, i.e. if the supply of oxygen at the reinforcement is depleted and/or if too much current is applied, hydrogen atoms or hydrogen molecules can be generated at the reinforcement:

$$H_2O + e^- \rightarrow OH^- + H \tag{5a}$$

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \tag{5b}$$
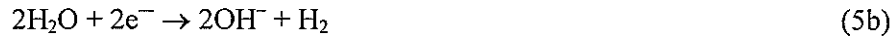
The hydrogen atoms produced in reaction 5a can diffuse into the steel at defects and crystal boundaries, resulting in hydrogen embrittlement. The problem is not usually significant for mild steel reinforcement, which is rarely heavily loaded. However the high tensile steel used to prestress concrete is loaded to a large proportion of its tensile strength and is susceptible to hydrogen embrittlement, which can lead to sudden failure of an element.

Hydrogen gas produced at the steel-concrete interface (reaction 5b) can reduce bond strength and crack cover concrete.

Hydrogen atom or gas evolution can usually be avoided by careful control of the potential of the steel. However in pits or crevices at the steel surface, local conditions can be quite different, often acidic, and therefore present a much higher risk of hydrogen evolution (reaction 4) than indicated by the measured potential, which represents the overall condition of the bar.

$$2H^+ + 2e^- \rightarrow H_2 \tag{4}$$
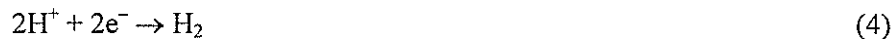
The hydroxyl ions generated at the steel in equations 2, 5a and 5b will increase the alkalinity of the concrete pore solutions and allow the stable iron oxide film to regenerate on the rebar surface. In the long term, sodium and potassium ions will migrate to the steel, being attracted by its negative charge. Cement silicate hydrates become soluble in very highly alkaline solutions, and so the accumulation of these ions could be associated with weakening of the cement paste and its bond to the steel (Page 1992). If the concrete aggregate is alkali-reactive, alkali aggregate reaction (AAR) can occur close to the steel-concrete interface, and this might also affect bond strength. The operating criteria can also be affected, depending on the effect of chloride ions on the properties of the gel produced by AAR (Shayan & Zu 2001).

The actual effects of alkalis on bond and AAR are not well understood, although Page & Sergi (2000) comment that uniform, low-current densities minimise the risk of bond degradation and AAR. Broomfield (1997) considers that, in most practical applications, the major part of the bond is supplied by ribs on a deformed bar and interfacial chemical effects are relatively insignificant. Impregnation of the concrete with lithium compounds (which generate non-deleterious AAR) may be a way to reduce the risk of AAR damage. Broomfield (1997) also reports a suggestion that, if a structure is suffering from AAR and corrosion, corrosion should be treated as the first priority, but comments that such decision should be made on a case-by-case basis.

The anode in an ICCP system generally does not react itself, but allows the reverse of the normal cathodic reaction (2) to occur, reducing the concrete alkalinity:

$$2OH^- \rightarrow \tfrac{1}{2}O_2 + H_2O + 2e^- \tag{6}$$

If all the hydroxyl ion is consumed, water is then oxidised and acid (represented as the hydrogen ion H^+) is produced:

$$H_2O \rightarrow \tfrac{1}{2}O_2 + 2H^+ + 2e^- \tag{7}$$
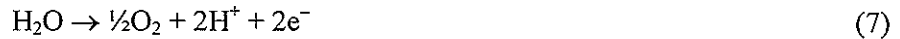
This can lead to acid attack of the concrete surface or encapsulating material at the anode, particularly with carbon-based or graphite-encapsulated anodes where the carbon is oxidised to carbon dioxide. The anode should be surrounded by a highly alkaline material to reduce this risk. Acid evolution is more likely to be generated in systems that operate at high current densities such as those with titanium-based anodes, rather than those based on surface coatings or sprays.

Chloride ions, being negatively charged, are repelled from the negatively charged reinforcement and attracted to the anode, where with carbon-based anodes (Broomfield 1997) they can be oxidised to form chlorine gas:

$$2Cl^- \rightarrow Cl_2 + 2e^- \tag{8}$$

In alkaline conditions the chlorine gas dissolves in the electrolyte and forms hypochlorous acid and hypochlorite ion (NACE 2001):

$$Cl_2 + H_2O \rightarrow HClO + Cl^- + H^+ \tag{9a}$$

$$HClO \rightarrow ClO^- + H^+ \tag{9b}$$

An anode system needs to be designed to avoid the build up of gas and acid and resist attack from the oxygen, chlorine and acid that are produced at its surface.

In designing a ICCP system the aim is to optimise the operating conditions so that:
- The voltage is large enough to overcome the natural corrosion potentials;
- The current is small enough to avoid acid attack of the anode and surrounding concrete;
- The potential of the steel is low enough to avoid hydrogen evolution.

The current required will reduce with time because of changes in the electrochemistry of the anode and cathode.

4.1.2   Equipment

4.1.2.1 *General*

An ICCP system requires the following components:

- External DC *power source and controller* (rectifier): The steel to be protected is connected to the negative terminal of the power source and the anode is connected to the positive terminal. The output may be constant voltage,

constant current, or (less commonly) constant potential against a reference half cell, and is continuously monitored. The power supply must be of appropriate capacity and sensitivity to stop corrosion and to allow the small adjustments that will be needed during the life of the system. Capacity is determined by the steel current density required for protection, with allowances for current drops due to the resistance of wiring, reinforcement and concrete. The power supply can be remote controlled and can be sourced from mains or battery, or wind- or solar-powered. It must be protected from effects of the weather and from vandals, and not present a hazard to operators, the public or livestock.

- *Anode* to distribute current: The anode must convert the electrical current to a flow of ions that reaches all areas of the rebar that need to be protected. Anodes are thus distributed over the concrete surface, either embedded at regular intervals in the concrete or applied as a surface covering. Materials used to attach the anode to the concrete need to be gas-permeable to prevent a build up of the gases generated (equations 6, 7, and 8 in Section 4.1.1), which could disbond the anode from the concrete when high current densities are applied.

- *Electrolyte* (concrete): Water in the concrete pores acts as the electrolyte in concrete. The lower the moisture content of the concrete the higher will be its resistivity and the higher the driving voltage required. The electrolyte conducts ions, so any repair material must also be ionically conductive, i.e. of low resistivity, but it must not be electrically conductive. Metal- or carbon-fibre reinforced repair materials are not suitable.

- *Cathode* (reinforcing steel): The cathode must be electrically continuous to allow current to flow, and must be electrically separated from the anode by the electrolyte.

- *Electrical connections*: These are the connections from negative terminal of power supply to cathode and from anode to positive terminal of power supply, and to reference cells and monitoring systems. Connections must be both electrically and mechanically robust and remain accessible for inspection.

- *Monitoring and recording devices*: Reference electrodes and other sensors monitor the effectiveness of the applied protection and allow the operating parameters to be adjusted as necessary. Reference electrodes measure the potential of the reinforcing steel/concrete interface.) They are either permanently embedded in the concrete or applied to its surface and include silver/silver chloride, copper/copper sulphate, mercury/mercury oxide, lead/lead oxide, manganese/manganese oxide and saturated calomel, the choice depending on the operating conditions of the system, the method of application and the environment. Other sensors include steel coupons and probes (called 'macrocells') used to monitor current at the reinforcement, and various probes used to monitor corrosion rate (which should be negligible if the system is operating properly), and to enable future recalibration of embedded reference

electrodes. Data can be recorded manually or by data logger, which may be part of a remote monitoring and control system.

Selection of components will be determined by operating conditions and intended service life.

Eltech (1993) and, more recently, Kepler et al. (2000) reviewed in detail the development of ICCP and galvanic systems in the USA. Broomfield (1997) gives a more general review.

Bennett et al. (1993) describe equipment for ICCP and galvanic CP in detail. Only the anode systems are described in this report because CP systems are usually categorised by anode.

4.1.2.2 Anode systems

Proprietary CP systems are usually distinguished by anode type, which can be categorised by material or application.

The principal anode materials are:

- *Activated titanium/niobium*: Titanium or niobium substrate coated with oxides of a mixture of metals (MMO), are suitable for high current density applications (110 mA/m^2 of anode is a typical operating current (Solomon et al. 1999)) and where a long life is required. Different oxide combinations will produce different performance characteristics, for example some do not evolve chlorine gas. The MMO coating acts as the anode and slowly oxidises, while the titanium substrate remains passive and is not consumed. The potential durability and versatility of titanium-based anodes make them the most widely marketed products at present. Titanium-based anodes can be applied as:

- surface mesh or grid, generally embedded in a cementitious overlay. Mesh was first introduced in the mid-1980s;

- mesh ribbons recessed in slots or grids in the cover concrete, electrically connected with titanium bars and embedded with a non-shrink cementitious backfill. The most commonly used system in Australia at present (Green 2001);

- embedded as a discrete strip, mesh, or rod into new or existing concrete, repair material, or conductive graphite backfill;

- thermally sprayed surface anode, overcoated with catalyst that can be renewed at a later date (Green 2001). First introduced in the mid-1990s.

- *Conductive organic coatings*: Solvent- or water-based paint coatings containing a carbon conductor, connected to the power source with conducting wires (called primary anodes) of carbon fibre, activated titanium, or platinised niobium copper which distribute the current within the coating. Conductive organic coatings are black, but decorative coatings can be applied over the conductive coating. They will not withstand continuous wetting, wear or

abrasion. Suitable for low current density applications (up to 30 mA/m² of anode, Solomon et al. 2001) rather than marine applications. They were developed in the early 1980s.

- *Conductive cementitious materials*: Cement-based materials containing carbon granules or fibre and with a metal (e.g. nickel) coating. Current is supplied through platinum niobium wire or catalysed titanium ribbon attached to the concrete surface before application of the overlay. Introduced in the late 1980s.

- *Metallic coatings*: Thermally sprayed zinc, zinc alloys or titanium, attached to the power source with connectors of copper, copper-zinc or titanium. Can be applied to damp surfaces. Zinc anodes are consumed and require moisture. Titanium tolerates dry conditions better than zinc. Suitable for low current density applications (up to 20 mA/m² of anode for zinc, Solomon et al. 2001). Arc-sprayed zinc anodes were introduced in the mid-1980s. Thermally sprayed titanium was introduced in the mid-1990s.

- *Conductive ceramics*: Rods of titanium suboxides are embedded into the concrete, usually with a cementitious grout. They can be operated with higher current densities than other systems if provided with a gas venting facility (typically up to 500 mA/m² of anode, Solomon et al. 2001). First introduced in the mid-1980s.

- *Conductive asphaltic overlays*: The earliest applications of ICCP were on bridge decks in the USA in the mid-1970s, where Caltrans used high silicon cast-iron primary anodes overlaid with a conductive coke/asphalt mixture, which was in turn overlaid with an asphaltic concrete wearing surface[4]. Similar materials are still used as anodes in soil to cathodically protect buried pipelines.

- *Conductive polymers*: Carbon-loaded polymers can be used as a backfill or overlay for activated titanium or niobium anodes. Conductive asphaltic overlays were succeeded by platinised wire anodes placed either in slots cut into the bridge deck and backfilled with conductive polymer grouts poured into the slots, or laid on the bridge deck surface and covered with the conductive polymer. The carbon will oxidise to carbon dioxide with time so durability is limited, and the polymer is subject to acid attack at high current densities. Conductive polymer cable anodes were once widely used but have been withdrawn from the market.

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[4] Overlay systems incorporate two types of anodes. The 'primary anode' (sometimes called the 'anode conductor') is a discrete anode that distributes current from the power supply to the 'secondary anode'. The secondary anode is the overlay. It distributes the current to the entire surface of the structure being protected.

In terms of the method of application, anodes can be categorised as:

- *Encapsulated*:
  - Continuous mesh anodes embedded in an *overlay*. Suitable for surfaces subject to abrasion or erosion. Overlays will increase the dead load, change the profile, can reduce clearances and can be difficult to apply in restricted areas or to complicated geometries. Careful surface preparation is required to ensure good bonding to the substrate. The overlay must be durable in the anticipated service conditions. One proprietary system for piles consists of a prefabricated fibreglass jacket with catalysed titanium mesh attached to the inside. The jacket is attached to the pile and the void between the jacket and the concrete surface is filled with a cementitious grout. Titanium mesh fibreglass pile jacket systems have been used since the early 1990s.

  - Interconnected ribbon or wire anodes *embedded in slots* cut in the concrete surface. Can be used on wearing surfaces where overlays are unsuitable. Sufficient depth of concrete cover is required to ensure that the anode is separated by at least 15 mm from the reinforcement. A slotted system based on platinised wire embedded in conductive backfill was introduced in the mid-1970s. More recent developments were to embed the wires in coke breeze epoxy, to run wires in two directions to form a grid, and the introduction of titanium-based ribbon, which has become the most widely used system in Australia.

  - *Discrete internal anodes* inserted into holes cut in the concrete. These include titanium ribbon mesh anodes that are backfilled with non-shrink cementitious grout, ceramic anodes that can be backfilled with cementitious material or not backfilled, and titanium wire with a carbon-rich backfill. Sufficient depth of concrete cover is required, so they are not suited to thin concrete sections. Individual anodes can also be used to supplement other anode systems, e.g. where current requirements are locally elevated or complex shapes prevent use of ribbon or mesh anodes. Discrete internal anodes may require higher current densities than ribbon or mesh anodes, but should be limited to 220 mA/m^2 of anode to avoid acid attack of the surrounding concrete. After titanium mesh slotted systems they are the most commonly used system in Australia (Green 2001).

- *Surface-applied*: Conductive coatings can be used where overlays or embedded anodes are unsuitable, but they have limited resistance to wear and frost damage and, except for zinc-based coatings, do not tolerate moisture. They are easy to apply to vertical or soffit surfaces and to complex shapes. The whole surface may be treated, or just the part that needs protection. Careful surface preparation is required. Clamp-on systems containing zinc or titanium mesh anodes have also been developed for used in immersed or splash zone concrete. They are relatively simple to replace.

- *Immersed/remote*: To protect continuously immersed or buried concrete, anodes can be mounted or suspended in the surrounding medium remote from the concrete, much as in traditional CP systems for protecting buried steel structures. Immersed anodes are made of MMO titanium, high silicon iron or lead/silver/antimony and are sometimes referred to as water/soil anodes. 'Groundbed' anodes are buried in the ground some distance from the structure itself and are connected electrically to it.

Whichever type of anode is chosen, the anode system design should (Bennett et al. 1993):

- Be physically rugged and not easily damaged during installation or service;
- Include redundancy in current-carrying pathways so that future cracking or damage such as careless coring will not stop the system functioning;
- Produce a uniform distribution of current to the steel.

4.1.3 Long-term Performance

ICCP components have a finite life, and ICCP systems must be continuously monitored and maintained after installation (see Section 4.1.4 of this report).

Developments in equipment technology will continue, particularly for anodes (Section 4.1.2.2.) and monitoring systems, so it might be necessary or desirable to upgrade the system or some of its components during the life of a treated structure. For example, developments in telecommunications will probably make it possible to transfer larger amounts of data from a remote site, which will increase the level of control achievable.

Table 4.1   Summary of anode durability (based on Broomfield 1997).

Anode Type	Estimated Life (years)
Ti mesh in cementitious overlay	$20+^1$, $30+^2$, 35^7, 75^3
Silicon iron in coke breeze/asphalt	$20+^{1,7}$, $10-20^5$
Ti ribbon mesh in slots	$20+^1$, 75^3
Ti ribbon mesh discrete internal anode	40^3
Conductive concrete	$10-20^1$, 20^7
Conductive polymer grout	10^1
Conductive ceramic	$50+^4$
Conductive organic coating	5^7, $10+^1$, $10-15^{2,3}$, $5-15^{4,5}$
Sprayed zinc and zinc alloys	10^1, $10-15^3$, 15^7, $15-30^4$
Sprayed Ti	$20+^1$, 40^6, $>100^3$
Clamp on	10^1
Embedded rods	10^1

1.	Broomfield (1997)	5.	Wyatt (1995)
2.	ACRA (1996)	6.	Kepler et al. (2000)
3.	Green (2001)	7.	Bennett et al. (1993)
4.	Solomon et al. (1999)		

Anode life is often quoted as the life of an ICCP system, even though the system will still be effective after the anode is replaced. The long-term performance of common anode types is summarised in Table 4.1. Operating at high anode current densities can shorten the life not only of the anode itself but also of the concrete at the anode interface, the backfill, cable connections and insulation and of surface coatings.

Where a graphite or conductive polymer backfill or anode is used, the graphite will be consumed before the anode by reaction with oxygen to form carbon dioxide. This occurs within 10-15 years and so the graphite must be treated as the anode in calculating performance life (Solomon et al. 1999). Acid attack of cementitious backfills to titanium anodes can shorten the life of systems operated at high current densities (>100 mA/m^2 of anode, Page & Sergi 2000).

Boam (1993) commented that the life expectancies of anode systems quoted by manufacturers are based on laboratory tests involving different environments to those that will be experienced in-situ, and are probably over-estimated. Without data on anode durability in practice he suggested assuming a ten-year anode life for costing purposes. Although anode systems have changed since then, it may still pay to be conservative when estimating life cycle costs.

Voon et al. (2001) consider that systems that have become available in the last 10 years can extend a structure's life by 30 or more years. They report that the first New Zealand installation of ICCP, in 1990, is still performing as designed, and that the designers anticipate a further 10 'trouble-free' years from it.

Reference probes can have relatively short lives compared to the remainder of the CP system (Eltech 1993). Rectifier malfunctions are often related to changes in the system operation caused by external events such as power surges, although recurring problems may be related to the design of the system (Eltech 1993).

4.1.4   Design, Specification and Management Issues

Specifications for the design and installation of CP systems for concrete structures in New Zealand should be based on AS 2832.5.

Different systems are needed for structures and parts of structures in different environments. Aspects that need to be considered when designing a CP system are the method of application, current demand to achieve protection, rebar continuity and density, environmental issues (e.g. zinc is toxic so the work area must be enclosed and workers protected while applying a zinc spray), exposure of the concrete to moisture and chlorides, risk of AAR or other deleterious reactions, physical robustness of the system, monitoring requirements, design life of components, ease of maintenance, and appearance.

Surface coatings or overlays may need to be removed before the CP system is installed, as may polymer crack injection materials and epoxy patch repairs, because they will disrupt the current flow between anode and reinforcement.

Embedded steel components such as tie wire must not come into contact with the anode because they will cause shorting.

Different operating parameters are normally needed for concrete with different moisture/chloride/oxygen availability, concrete resistivity, or steel potential. For example, on a marine structure, different operating parameters will be needed for concrete in the splash zone, the tidal zone, the submerged zone and the zone exposed to sea spray. Different CP systems can be used in these zones as appropriate.

All reinforcement to be protected by a single system must be electrically connected. Rebar continuity must be checked before installation and extra connections made if necessary. Zones defined by the above conditions can be sub-divided to allow optimum operating parameters (e.g. number and type of anodes and reference cells, current density) for individual components to accommodate variations such as densities of rebar, varying cover depths or intermittent presence of electrically shielding materials. Most structures will need several independently powered and controlled zones. The smaller the individually-controlled zones the lower the risk of under- or over-protection. Each zone must be electrically separated from its neighbours by at least 25 mm.

The presence and location of pretensioning strands and post-tensioning tendons must be established, and the degree of shielding afforded to the latter by ducting identified.

Stray direct currents from other power supplies may need to be accommodated, and care must be taken to avoid interference from the CP system to adjacent structures. Such currents can cause corrosion in the adjacent structures, or interfere with their operation or that of the CP system. With buried structures, interference is commonly associated with telecommunications and signalling systems, pipelines and electrified transportation systems. On concrete above ground, metallic brackets, fasteners, pipe or conduit attached to or passing through the protected concrete can cause interference. Stray currents between reinforcement and high tensile prestressing strands/tendons can put the prestressing steel at risk.

Protection criteria are usually expressed as functions of steel potential, e.g. potential shift, absolute potential (instant off potential), potential decay, and absolute passivity. Glass et al. (2000) recommend using a current density criterion in tidal/splash zones, and potential-based criteria for submerged concrete and concrete exposed to atmospheric chlorides. Reducing the current as the system polarises with time (Section 4.1.1) will help to prolong the anode life.

Specification for a CP system should include requirements for:

- *Installation*: Initial assessment of structure and CP suitability, rebar continuity, location of reference electrodes, substrate preparation, anode installation, connections to rebar and anodes, testing, concrete repair.

- *Commissioning*: Initial inspections, application of current, adjustments, performance assessment and monitoring by the supplier for a fixed period after installation to ensure that the system is operating as designed. The system should be providing protection within 6 months of installation. (Solomon et al. 1999).

- *Documentation*: The owner must be provided with records of design calculations and drawings; specifications for materials, installation, testing; records of quality, testing, installation and commissioning; operating and maintenance requirements.

- *Data management*: Methods of collecting, collating and presenting performance data during operation.

- *Training*: The owner must be taught how to manage the system. This could involve maintaining and operating it, but is more likely to involve developing a management system that ensures that the CP system is operated and maintained by appropriately trained personnel.

The system must be regularly monitored and maintained according to the supplier's instructions for as long as it is in operation. Solomon et al. (1999) indicate that power supply should be checked weekly and performance monitoring undertaken every 3-6 months. The full system must be reviewed, including calibration of reference electrodes, every 12 months. Many performance checks can be carried out remotely if a modem is installed. Visual inspections are also recommended, particularly for structures exposed to harsh environments or vandalism. These should be inspected monthly (Gower & El-Belbol 2001). Inspections should be incorporated into the routine inspection programme for the structure.

New construction on or near a cathodically protected structure will increase the risk of physical damage to the CP system. Environmental conditions affecting the operation of the system may also change. The system may need to be modified to accommodate these effects.

4.1.5   Benefits and Applications

Provided it is correctly designed, installed, operated and maintained, ICCP prevents reinforcement corrosion where chloride-contaminated concrete cannot all be replaced and where recontamination cannot be prevented. The long-term performance of an ICCP system depends on the longevity of its components. Commercial systems offering service lives from 10 to more than 50 years are available. Systems can be

designed with remote monitoring and adjustment capability to reduce the need for frequent on-site inspection.

ICCP can offer economic advantage where the structure is expected to meet functional requirements for the foreseeable future, and/or where the cost of one or more cycles of patch repair during its remaining functional service life would be prohibitive because of the extent of repair and/or access issues.

ICCP is typically used in reinforced concrete exposed to the atmosphere, or in tidal/splash zones. It can be applied to concrete containing materials that will shield the reinforcement from the applied current, such as electrically conductive fibres, meshes or plates, or electrically non-conductive sheets, rebar coatings, or repair materials, but their effects must be accounted for in the design of the system.

ICCP is applied to reinforcement in pretensioned concrete with extreme care because of the risk of hydrogen embrittlement of the high tensile strand (even though the strand itself would not be connected to the power source, it could come into contact with stray currents). Some authors (e.g. Pocock (1995), Miller (1999)) consider that it can be applied safely to protect rebar in post-tensioned structures provided the ducting protects the tendons, is shielded by (i.e. behind) the reinforcement, and the steel is cold-drawn and not chromium-alloyed. The post-tensioned tendons themselves cannot be protected because they are shielded by the ducting (Faraday effect). In contrast, Kepler et al. (2000) consider that ICCP can be applied to prestressing steel in pretensioned concrete provided that concrete resistivity is relatively uniform and voltage is kept below that required for hydrogen generation.

ICCP can be carried out on structures that comprise prestressed and non-prestressed elements provided that the prestressed elements are electrically isolated from those that are not prestressed. The key is to avoid inadvertent damage to the high tensile strands and tendons and to post-tensioning ducts. This includes damage from stray currents, which present a particular hazard where stirrups pass close to the prestressing components. To maintain uniform resistivity within the concrete being treated and thus reduce the risk of over-protection and consequent damage to the prestressing, features designed to remove water from the surfaces of the structure must be well designed and properly maintained. Prestressed structures treated with ICCP must be continuously monitored to ensure that safe operating conditions are maintained.

Compared to galvanic CP (Section 4.2 of this report), ICCP offers more control over the operation of the system, and the potential for a longer period of operation without major maintenance.

4.1.6   Shortcomings

Technical shortcomings of ICCP are, as outlined in Section 4.1.1, possible acid attack of the concrete at the anode, and possible increased risk of alkali aggregate

reaction, reduction in steel-concrete bond and/or hydrogen embrittlement at the cathode. However these effects should not occur in a well designed, operated and maintained system.

ICCP involves the permanent installation of hardware and the original profile or appearance of the concrete surface will be altered, although the effect on overall appearance can be minimised.

Application to reinforcement in prestressed structures must be undertaken with extreme caution.

From a management side, ICCP systems must be designed and installed by specialists, require routine monitoring and maintenance, and components do need to be replaced over the lifetime of the system. These features mean that ICCP is not cheap to install or operate, but in some circumstances will still be cheaper than repeated patch repair over the life of the structure.

4.2   Galvanic CP

Many of the aspects described for ICCP in Section 4.1 of this report also apply to galvanic CP. Details particular to galvanic CP are described in this Section 4.2. The numbering used in this section to identify the chemical reactions continues the numbering system begun in Chapter 2.

4.2.1   Principles

In galvanic CP (sometimes called sacrificial anode cathodic protection, or SACP), a sacrificial anode system uses a more reactive metal anode such as zinc, aluminium or magnesium to create the flow of current from the anode to the cathode. The current is generated by the energy difference between the anode and the reinforcing steel to which it is connected. The sacrificial anode corrodes and is consumed:

$$M \rightarrow M^{n+} + ne^- \tag{1}$$

Anodes must be selected and installed with care to ensure that the voltage between the anode and cathode provides sufficient current to protect all of the reinforcement, despite variations in conditions over the steel surface and changes in the concrete that affect its resistivity, such as moisture condition and chemistry. Build up of corrosion products at the anode ('concentration polarisation') increases the resistivity of the system, and drying exacerbates this. Laboratory and field trials reported by Cramer et al. (2002) suggest that applying a lithium-based humectant to the anode surface to keep it moist reduces resistivity and increases the service life of the anode.

4.2.2   Equipment

4.2.2.1 General

Galvanic CP requires the following components:

- *Anode*: In theory any metal with more energy than iron in the galvanic or electrochemical series can be used, although in practice zinc, aluminium, magnesium or their alloys are preferred.

- *Electrolyte*: Like ICCP, the pore water in the concrete provides the electrolyte for the passage of ions from anode to cathode. Some attempts have been made to lower the concrete resistivity by applying a solution of hygroscopic salts in association with a surface-applied anode, but it is not known whether this is effective in the long term (Broomfield, 2000). In immersed or buried structures, water in the surrounding medium also forms part of the electrolyte.

- *Cathode* (reinforcing steel): Like ICCP, only the reinforcing steel that is electrically continuous and connected to the anode will be protected.

- *Electrical connection* from anode to cathode: The anode can be in direct contact with the cathode (as in galvanised steel), although in buried or submerged concrete the anodes can be remote from the structure being protected.

- *Monitoring and control devices* (probes, reference cells, controllers): Current and voltage cannot be controlled, so maintenance of the system is by regular measurement of the amount of remaining anode. If desired, the system's effectiveness can be monitored by measuring the amount of current flow into a selected part of the reinforcement by installing an ammeter.

No external power source is needed.

Eltech (1993) and, more recently, Kepler et al. (2000) have reviewed in detail the development of ICCP and galvanic systems in the USA. Broomfield (1997) gives a more general review.

Bennett et al. (1993) describe equipment for galvanic CP in detail. Only the anode systems are described in this report because CP systems are usually categorised by anode.

4.2.2.2 Anode systems

As with ICCP, proprietary systems for galvanic CP are most often distinguished by the type of anode.

Zinc galvanic anodes have been widely and successfully used since the 1970s. Aluminium or zinc-aluminium-indium alloys became available in the mid- to late 1990s and are reported to remain active in drier conditions than sprayed zinc (Green 2001). Zinc anodes are more efficient in moist environments, where zinc oxides do not build up on the anode surface. Aluminium and magnesium alloys are also

available. They are lighter than zinc anodes but their corrosion products are more voluminous than those of zinc and could damage the concrete (Broomfield 2000).

Methods of application are the same as for ICCP:

- *Encapsulated* in a cementitious material: One supplier provides a zinc mesh attached to formwork that is then filled with proprietary grout to jacket piles in the tidal/splash zone. The same supplier provides a zinc pellet encapsulated in a hardened proprietary mortar that is impregnated with alkalis for inclusion as a discrete internal anode in patch repairs to prolong their effectiveness by preventing incipient anodes.

- *Surface-applied,* usually as metal spray. One system, developed in the mid-1990s, consists of a zinc sheet backed with a conductive adhesive gel. The sheet is simply pressed onto a smooth concrete surface. The edges must be sealed to protect the gel coming into direct contact with water during service or the adhesive will swell and disbond (Green 2001). Zinc-rich paint coatings applied to the reinforcement provide a form of galvanic CP. Clamp-on systems have also been used.

- *Immersed*: Cast zinc or aluminium anodes may be submerged adjacent to permanently immersed concrete. These will protect concrete in the submerged zone and in parts of the tidal zone.

4.2.3   Long-term Performance

The comments made in Section 4.1.3 about long-term performance of ICCP also apply to galvanic CP.

Estimates of service life for anodes for galvanic CP systems are included in Table 4.1 (Section 4.1.3 of this report). The encapsulated anode for patch repairs has a design life of 10 years. From field trials, Kepler et al. (2000) considered that the encapsulated zinc mesh pile jacket system could have a service life of at least 45 years, and that sprayed alloy anodes could have service lives of more than 15 years.

4.2.4   Design, Specification and Management Issues

As for ICCP. Anode consumption must be monitored and provision made for renewal of consumed anodes.

4.2.5   Benefits and Applications

Galvanic CP offers similar technical and economic benefits to ICCP.

Unlike ICCP there is no need to maintain a power supply and hardware for monitoring and controlling the system, which can be advantageous on remote sites and those exposed to aggressive environments or vandalism.

Galvanic CP can possibly be used more safely than ICCP on prestressed concrete because the lower driving voltage reduces the risk of hydrogen evolution. It is suitable for use on concrete that is buried or submerged, or where the electrolyte resistivity is low for other reasons, and where oxidation products can be removed from the anode so that it maintains its potential and does not become passivated. Its low driving voltage means it can be suitable for protecting single mats of steel, such as on bridge substructures (Daily 1999). The encapsulated zinc discrete internal anode protects against incipient anode effects in concrete repairs.

4.2.6   Shortcomings

The inability to control the protective current is the main technical shortcoming. Anode life is shorter than many of the ICCP anodes, which may be a disadvantage where access to replace anodes is expensive. Like ICCP, galvanic CP involves installing anodes and the original profile or appearance of the concrete surface may be altered.

Shorting can occur when a surface-applied anode comes into contact with embedded steel components that extend to the surface. These could include tie wires, or reinforcement exposed at cracks.

Galvanic CP cannot be used in high resistivity concrete, other than where discrete internal anodes are used to prevent incipient anodes in concrete repairs.

As with ICCP, the up-front costs of installing and maintaining a galvanic CP system are generally greater than those of patch repair, and its economic benefits need to be assessed over the whole of the remaining life of the structure.

5.   **Chloride Extraction**

Chloride extraction is also known as electrochemical chloride extraction (ECE), dechlorination, chloride removal, chloride migration, chloride neutralisation and desalination. Following the lead of Mietz (1998) and NACE (2001), who provide detailed objective reviews of the process, it is referred to herein as 'chloride extraction' to avoid confusion with desalination of seawater and the implication that all chlorides are removed.

5.1   **Principles**

Chloride extraction involves both removing chloride ions from the concrete and increasing its alkalinity around the reinforcement to repassivate the steel (see Section 2.4 of this report).

Chloride extraction is a similar process to cathodic protection. Each layer of reinforcement is connected to the negative terminal of a DC power supply, and a temporary external anode, within an electrolyte covering the concrete surface, is connected to the positive terminal. Current runs through the reinforcement, creating an electric field in which the chloride ions are pulled away from the negatively charged reinforcement towards the positively charged anode. They are absorbed by the electrolyte, which is removed at the end of the process. This typically takes about three months. As shown in Table 3.1, the current densities applied are much higher than those used for ICCP. Chloride ions migrate fastest in the zone directly between the outermost reinforcement and the anode, slower in the cover zone between individual bars, and very slowly in the concrete beneath the outermost layer of rebar.

The chemical reactions that occur at the anode and cathode are similar to those generated in CP. The electrolyte can be one of many solutions, including calcium hydroxide, sodium borate, sodium hydroxide or tap water. The choice of electrolyte will affect the chemical reactions at the anode and cathode, although they are closely related to those generated by CP. The numbering used in this section to identify the chemical reactions continues the numbering system started in Chapters 2, 3 and 4 of this report.

At the rebar (cathode), hydroxyl ions are formed in the presence of oxygen and water:

$$\tfrac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \qquad (2)$$

If the supply of oxygen at the cathode is limited, hydrogen atoms or molecules are generated:

$$H_2O + e^- \rightarrow OH^- + H \qquad (5a)$$

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \qquad (5b)$$

The cathode is negatively charged and negatively charged chloride ions are repelled from it. The hydroxyl ions generated at the cathode will increase the alkalinity of the water in the concrete. The threshold chloride concentration for corrosion increases with the concentration of hydroxyl ions, so if enough chloride ions are removed from the concrete and/or enough hydroxyl ions are added, the steel surface will repassivate.

Problems associated with hydrogen evolution and concentration of alkalis at the reinforcement that were described for ICCP in Section 4.1.1 of this report can be exacerbated with the higher current density used in chloride extraction.

As with CP, the evolution of hydrogen presents a risk of hydrogen embrittlement of prestressing steel and so chloride extraction is not recommended for prestressed structures. Some authors, e.g. Pocock (1995) and Miller (1999), consider that it can be applied, with care, to protect the reinforcement in post-tensioned structures under certain circumstances and particularly if some load is removed from the tendons during treatment. Excessive hydrogen gas evolution can cause microcracking of the concrete because of build up of gas pressure. The ductility (elongation) of mild steel has been observed to reduce temporarily when the steel is exposed to high current densities. This has been attributed to the absorption of hydrogen, which is rapidly released when the current is switched off, thus restoring ductility (Mietz 1998).

Well recognised problems associated with the concentration of alkalis at the reinforcement include reduction in steel-concrete bond strength and alkali aggregate reaction.

Broomfield (1997) considers that the potential effect on steel-concrete bond may be to eliminate improvements in bond that resulted from the development of corrosion products, rather than to reduce bond below that of an uncorroded bar. Broomfield also suggests that the rate of bond loss is faster than can be accommodated by concrete creep and thus produces a layer of weakness around the rebar. As in CP, this effect could be significant for smooth bars, but would be overridden by the extra physical bond provided by deformed bar.

Similarly, there is an increased risk of alkali aggregate reaction in the concrete near the reinforcement if the concrete contains reactive aggregates. Use of a lithium-based electrolyte will reduce this risk (see Section 4.1.1).

Bertolini et al. (1996) raised the additional question of possible deterioration due to secondary ettringite formation caused by elevated concentrations of sulphate ions in the pore solutions close to the cathode. (Ettringite has a larger volume than the reactants from which it is produced so its formation in hardened concrete causes expansion and cracking, much like alkali aggregate reaction.)

The anode may be sacrificial or inert. If sacrificial, the anode dissolves:

$$M \rightarrow M^{n+} + ne^- \qquad (1)$$

If the anode on the concrete surface is inert and surrounded by an alkaline solution, the hydroxyl ions are converted to oxygen and water:

$$2OH^- \rightarrow \tfrac{1}{2}O_2 + H_2O + 2e^- \qquad (6)$$

If the anode is inert and the electrolyte is neutral (such as water), oxygen gas and acid (H^+) are produced:

$$H_2O \rightarrow \tfrac{1}{2}O_2 + 2H^+ + 2e^- \qquad (7)$$

In very acid conditions (pH less than 4), excess chloride ions will be released at the anode as chlorine gas:

$$2Cl^- \rightarrow Cl_2 + 2e^- \qquad (8)$$

Reactions 7 and 8 are not desirable. The acid will be attracted to the cathode, and will attack the concrete, and chlorine gas is a health hazard. Consequently an alkaline electrolyte is often used to prevent these reactions. The small amount of chloride gas that is evolved under these conditions dissolves in the electrolyte and forms hypochlorous acid and hypochlorite ion (NACE 2001):

$$Cl_2 + H_2O \rightarrow HClO + Cl^- + H^+ \qquad (9a)$$

$$HClO \rightarrow ClO^- + H^+ \qquad (9b)$$
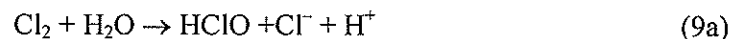
The rate of chloride extraction decreases with time. One reason for this is that hydroxyl ions produced at the cathode are also attracted to the anode, and the rate of removal of chlorides from around the anode accordingly decreases with the increase in hydroxyl ion concentration.

Chloride extraction is sometimes carried out in stages. Between each stage the current is turned off, and when it switched on again, the rate of chloride extraction is higher than it was at the end of the previous stage. This phenomenon is related to the binding of chloride ions by aluminate compounds in the hydrated cement paste. When chlorides are removed from the pore solutions, the aluminates gradually release the bound chlorides. These are then removed when the current is turned on again. Tritthart et al. (1993) found that bound chlorides are released more rapidly than otherwise during application of a direct current, so even if the process is carried out in one stage a significant amount of bound chloride can be removed.

Extraction efficiency increases with increasing temperature.

After treatment, the area around the outer layer of rebar is left virtually chloride free. Chlorides will not be removed from behind the reinforcement. Computer model studies described by Manning & Ip (1994) suggest that, if current is applied

intermittently, chlorides behind the reinforcement will diffuse into the cover zone and migrate to the surface when the current is turned on again. However they consider that the diffusion rate may be too slow for this to be a practical approach. Laboratory trials by Arya et al. (1996) suggest that for a single layer of reinforcement, these 'internal' chlorides might be removed by applying an anode to a surface remote from the original source, or by applying an external cathode to the surface opposite to the anode.

Between 40-95% of chlorides are removed. After treatment, chlorides remaining in the concrete will eventually diffuse back into the treated area, either from within the concrete or, unless the exposed surface is waterproofed, from an outside source.

5.2   Equipment

The equipment requirements are similar to those of ICCP: a DC power supply (rectifier), an electrolyte, an anode, a cathode, and an electrical connection between them. Connections must be corrosion-resistant. Anodes, electrolytes and the method used to support them are the principal features of proprietary systems.

5.2.1   Anode Systems

As with CP, proprietary systems are usually differentiated by the anode system. Anodes include:

- *Sacrificial steel mesh*: Does not generate acid or chlorine, but can corrode unevenly, leading to uneven treatment, and can stain the concrete surface.

- *Coated titanium mesh*: The most commonly used anode because it can withstand the high operating current densities, does not cause staining and can be used several times until the surface coating is consumed. Titanium strips are used for electrical connections.

- *Aluminium foil*: This is discussed by Mietz (1998) as a means of overcoming uneven current distribution requirements on a surface, due perhaps to uneven cover depths. The anode is sacrificial. Where current density is highest, e.g. at sites of low cover or resistivity, it will dissolve fastest, eventually leaving a hole in the foil which reduces the current density in the concrete under the hole so that the rate of chloride extraction becomes more uniform.

5.2.2   Electrolytes

Electrolytes include:

- *Water*: Inexpensive, readily available and easy to dispose of but significant acid and chlorine can be generated if used with an inert anode in a closed system unless the water is replaced regularly.

- *Calcium hydroxide (lime)*: More suitable than water for use with an inert anode because its high alkalinity provides a buffer against acid and chlorine

generation. It has a low solubility in water so if a reservoir of solid calcium hydroxide is provided, it will replenish the solution as the dissolved material is neutralised. It may reprecipitate in the concrete pores, particularly upon drying after treatment, thus reducing the permeability of the concrete and increasing its resistivity. Sodium borate has also been used.

- *Lithium borate*: Lithium borate has been reported to be better than calcium hydroxide at maintaining alkalinity at the anode (Mietz 1998). Lithium compounds are used to reduce the risk of alkali aggregate reaction. Safe disposal of used lithium electrolyte may raise concerns.

Note that sodium carbonate solutions, as are used in realkalisation, will increase concrete resistivity and reduce the efficiency of chloride extraction (Polder et al. 1995).

5.2.3   Electrolyte Media

A variety of methods is used to maintain the electrolyte on the concrete surface for the duration of the extraction process:

- *Paper mâché (cellulose fibre)*: This is sprayed onto the concrete surface to which the anode has been fastened, and is kept wet during the period of operation. Can be applied easily to surfaces of any shape and can allow greater anode spacing, but on vertical surfaces the electrolyte can run to the bottom of the fibre layer. Both the application of the sprayed material and its disposal at the end of the process are messy, and may sometimes be undesirable for environmental reasons.

- *Surface-mounted tanks*: Purpose-built reservoirs (cassettes) containing the anode and electrolyte are attached to the concrete surface. The reservoirs need to be small to accommodate changes in surface profile and need to be well-sealed or replenished regularly. The reservoir system is suitable for dry, porous concrete and for large applications where the reservoirs can be reused.

- *Blankets*: The anode mesh is encased in electrolyte-saturated fabric (e.g. felt) that is kept wet during the treatment, either from a reservoir of electrolyte, or by covering the blanket with plastic film to prevent evaporation (or dilution with rainwater). This system can be difficult to secure to large vertical surfaces, but can be strapped to columns. Easy to dismantle and can be re-used.

5.3   Long-Term Performance

Early trials of chloride extraction in the 1970s were considered unsuccessful because of problems associated with the high voltages that were used (Mietz 1998). Chloride extraction was first applied in its present form in the mid-1980s so little is known about its long-term performance beyond 10-15 years. Many of the case studies recorded in the literature were reported 5-10 years after application.

Diffusion of chlorides remaining in the concrete after chloride extraction means that a single treatment does not remain effective forever. Experience reported to date suggests chloride extraction remains effective for at least 5-10 years. The ultimate duration of its effectiveness will be determined by the amount of chloride remaining in the concrete after treatment, the exposure to subsequent chloride contamination, moisture and drying experienced by individual components, their geometry and reinforcement configuration, and on chloride diffusion coefficients of the concrete, which are determined by cement type and concrete quality. Long-term performance can therefore be difficult to predict. The FHWA considers that the treatment can extend the life of a bridge by 5-10 years (NACE 2001). Broomfield (1997) considers that, if further ingress can be prevented the treatment may remain effective for 10-20 years. Repeat treatments, if required, could extend the life further.

Reduction of the chloride ion to hydroxide ion ratio at the steel as a result of hydroxyl ions being produced during treatment means that, even if the chloride content exceeds corrosion threshold values, actual corrosion rates may still be very slow. SHRP trials showed low corrosion rates and potentials 10 years after treatment even with modest amounts of chloride removed (NACE 2001).

Treatment on piers of the Burlington Skyway in Toronto, Canada, in 1989, has reportedly remained effective (Decter et al. 1998, NACE 2001). On this structure the principal source of contamination, leaking deck joints, was removed but the piers were still exposed to wetting and drying.

Miller (1999) reported that no structure treated by modern chloride extraction techniques had shown signs of renewed corrosion activity since they became available in the late 1980s.

5.4   Design, Specification and Management Issues

Electricity, water and physical access to all concrete surfaces to be treated must be available.

Before treatment the structure needs to be cleaned to remove surface contaminants. Chloride extraction will be affected by previous applications of overlays, waterproof or hydrophobic surface coatings or treatments or crack repair materials, and trials will be needed to establish the presence and likely effects of any such materials.

The presence of prestressing steel, undeformed reinforcement or alkali-reactive aggregates must be established before considering chloride extraction as a repair option.

The effect of the treatment on electrically connected components of metals that could produce a galvanic reaction, e.g. aluminium conduit, must be considered.

If the electrolyte makes direct contact with the reinforcement, it will become the path of least resistance for current flow, and all current will pass through this route, creating a short circuit and preventing current flow through the concrete. Before treatment, cracks, delaminations and voids (e.g. honeycombing) must be repaired with materials that will allow ionic transfer. Impermeable, non-conductive materials such as surface coatings, crack injection materials and epoxy patch repairs must be removed.

Potential stray current effects must be identified and eliminated.

The application of chloride extraction is unique for each structure and features that will affect the performance of the treatment need to be taken into account in the design for each application. The efficiency of the process can be expressed as:

$$Cl_{ex} = I \times t \times CRE \times G/F$$

where: Cl_{ex} = amount of chloride extracted per m^2 of concrete surface
            I   = current density
            t   = time of current flow
            CRE = chloride removal efficiency factor ('chloride transference number')
            G   = geometric factor
            F   = Faraday constant

The geometric factor accounts for the ratio between the surface area of the steel and the surface area of concrete to which the treatment is applied.

The chloride transference number defines the proportion of the total current that is carried by chlorides and is related to chemical parameters of ion mobility, ionic charge and concentration. It ranges from 0.05 to 0.4, increasing with increasing chloride concentration and decreasing concentration of other ions.

Operating parameters (current and charge requirements, electrolyte, chloride removal efficiency, alkali reactivity of aggregates) and an estimate of the duration of treatment are often established by laboratory testing of concrete cores from representative parts of the structure as part of the design process.

As with CP, electrical continuity of reinforcement over the parts of the structure to be treated must be measured before the system is designed. The closer the reinforcement spacing the more effective chloride extraction will be. The relationship of reinforcement to accessible surfaces (cover depth, spatial distribution) will also determine its effectiveness and needs to be established.

The amount of contamination in cover concrete and beyond the reinforcement needs to be established, as does the likely amount of chloride bound by the cement hydrates. Bound chlorides and chlorides beyond the outer rebar are harder to remove.

Carbonated concrete is less permeable and its electrical resistance is higher than non-carbonated concrete. Carbonation depths therefore need to be identified when designing a chloride extraction system.

Reducing dynamic loads on the structure during the treatment, e.g. by introducing weight and speed limits, might be appropriate because of the possible reduction in reinforcement elongation when current is applied (see Section 5.1 of this report).

Operating requirements will change during the process with changes in the resistivity of the concrete, so a continuous monitoring system is required to optimise treatment time. Either current or voltage can be controlled. The smaller the individually controlled zones the more effective the treatment will be.

One of the critical aspects in chloride extraction is determining when the process should terminate. This is decided by one or more of the following methods:

- Defining an 'end point' chloride concentration, decrease in chloride concentration, or chloride/hydroxyl ion ratio for the concrete at the level of the reinforcement, and regularly measuring concrete chloride contents until this value is achieved.

- Defining an 'end point' chloride concentration, decrease in chloride concentration, or chloride/hydroxyl ion ratio for the electrolyte at the anode, and regularly measuring electrolyte contents until this value is achieved.

- Monitoring electrical resistance and turning the system off when it reaches a defined maximum (related to the decrease in chloride ions in the concrete pore solution).

- Monitoring changes in corrosion rate or steel potential, and allowing several months for the rebar to depolarise after current is switched off.

- Turning the system off once an amount of electrical energy, predetermined by experience, has been passed.

Sampling techniques and regimes must be appropriate for the accuracy required to identify the end points determined by chloride concentrations.

Manning & Ip (1994) believed that a performance criterion such as reduction in corrosion current is more appropriate than a prescriptive criterion such as chloride concentration, for which the acceptance value will vary from structure to structure.

Treatment time is typically between a few weeks to three to four months, depending on the amount and distribution of chlorides in the concrete, their source, concrete quality, reinforcement distribution and current distribution. Uneven current

distribution related to reinforcement configuration and uniformity of concrete quality and contamination will reduce the efficiency of the system.

Unless external sources of chloride contamination can be eliminated, chloride extraction needs to be followed by application of a surface treatment to prevent recontamination. Treatments range from breathable sealers or waterproofing to prevent ingress of chloride solutions, to cementitious overlays to increase the effective cover depth over reinforcement. Selection of the surface treatment will depend on exposure to moisture and abrasion. A period of drying may be required between completion of chloride extraction and application of the surface treatment. Maintenance of the surface treatment must be considered when assessing long-term costs.

With time, chlorides behind the treated bar and chlorides remaining in the bulk of the cover concrete could diffuse to the steel surface. At the same time, alkalis could diffuse away from the steel. These effects can depassivate the steel eventually, so chloride ion distributions and/or corrosion activity need to be monitored as part of the long-term management of treated structures.

Successive chloride extraction treatments as needed could be considered. This approach requires ongoing monitoring of chloride contents and/or corrosion activity.

5.5   Benefits and Applications

Chloride extraction will reduce or prevent the corrosion of reinforcement caused by chloride contamination of the concrete.

It can be used where it is not practical to remove all chloride-contaminated concrete, either because the volume of material concerned makes the cost prohibitive or raises structural concerns, or because the noise, dust and disruption during conventional patch repair is unacceptable to the users of the structure.

It does not involve the permanent installation of hardware or the ongoing maintenance of CP systems, and the appearance of the concrete surface is not permanently altered by the treatment.

It is an effective alternative to CP on structures where contamination is limited to the cover concrete, where recontamination can be prevented by sealing the concrete surface after treatment or removing the source of chlorides, where the predicted time to significant recontamination is longer than the intended life of the structure or of traditional patch repairs, or where the concrete is relatively dry.

If the risk of chloride-induced corrosion is identified before damage occurs, chloride extraction can be applied as a preventive treatment. This is possibly where it is most cost effective because no concrete repair is necessary.

Overseas, chloride extraction has been applied on structures contaminated with de-icing salts, such as bridge decks and car park buildings, or with chlorides added at the time of construction to accelerate strength development. It is also suitable for concrete contaminated by industrial processes that use chloride salts in manufacturing, wash-down, cooling or fire-fighting. It can be applied to concrete containing materials that might shield the reinforcement, such as epoxy coating applied to the rebar, provided these are identified and accounted for in the design.

5.6   Shortcomings

As noted in Section 5.1 of this report, it is not possible to remove all chlorides, and significant contamination can remain beyond the surface reinforcement after treatment. Neither does the process prevent recontamination. It is not suitable therefore for components such as piles or piers that are directly exposed to seawater, or for components that are deeply contaminated and exposed to rain or run-off.

It is not an appropriate treatment where deterioration is related to low cover, especially where concrete beyond the outer layer of rebar is contaminated because of the reduced efficiency of removal between bars. Neither is it appropriate where contamination is related to poor consolidation of the concrete, because extensive repair will be needed before treatment to prevent short-circuiting from direct contact between reinforcement and electrolyte.

Chloride extraction should not be used on concrete containing potentially alkali-reactive aggregate without taking precautions to minimise the risk of alkali aggregate reaction.

Neither should it be used on pretensioned concrete because of the risk of hydrogen embrittlement of the prestressing strands, but it might be possible to use it with extreme care on post-tensioned concrete where the tendons are protected by ducting, particularly if some load can be taken off the tendons during treatment. Strands and tendons themselves cannot be protected by chloride extraction. There must be good electrical continuity of reinforcement over the components to be treated otherwise extra connections will need to be made.

The surfaces being treated cannot be trafficked during the process.

The present lack of information about its long-term performance may also be a barrier to the initial use of chloride extraction but this should be overcome with time.

6.   Realkalisation

Mietz (1998) provides an extensive and independent review of realkalisation. A joint state-of-the-art review by NACE and the UK Corrosion Prevention Association is in preparation (Broomfield 2002).

6.1   Principles

The numbering used in this section to identify chemical reactions continues the numbering system that was applied in Chapters 2, 3, 4 and 5 of this report.

Carbonation is the chemical reaction of alkaline hydroxides in concrete pore water with atmospheric carbon dioxide that is dissolved in the pore water:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{10}$$

The reaction neutralises the alkalis so that the pH of the concrete drops to a level where the steel reinforcement is no longer passivated (see Section 2.4) and will corrode in the presence of sufficient moisture and oxygen.

Realkalisation reinstates high alkalinity in carbonated concrete, allowing a passive film to redevelop on the surface of the steel reinforcing and thus preventing further corrosion.

Realkalisation is a very similar process to chloride extraction. Each layer of reinforcement is connected to the negative terminal of a DC power supply and a temporary external anode, within an electrolyte covering the concrete surface, is connected to the positive terminal.

As shown in Table 3.1, the current densities applied are much higher than those used for impressed current CP.

The chemical reactions that occur at the anode and cathode are similar to those generated in CP.

At the rebar (cathode), hydroxyl ions are formed in the presence of oxygen and water:

$$\tfrac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \tag{2}$$

After the available oxygen has been consumed, hydrogen atoms or molecules are also generated:

$$H_2O + e^- \rightarrow OH^- + H \tag{5a}$$

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2 \tag{5b}$$
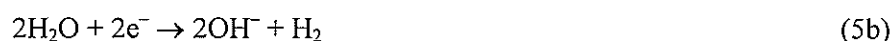
The hydroxyl ions produced in reactions 2, 5a and 5b will increase the alkalinity of the water in the concrete, allowing the steel surface to repassivate.

The potential problems associated with hydrogen evolution and the build up of hydroxyl ions are the same as described for ICCP (see Section 4.1.1) and chloride extraction (see Section 5.1). The risk is higher than for CP because higher current densities are used, but less than for chloride extraction because the treatment time is shorter and therefore less electrical energy is used in total.

The anode may be sacrificial or inert. If sacrificial, the anode dissolves:

$$M \rightarrow M^{n+} + ne^- \tag{1}$$

If the anode on the concrete surface is inert and surrounded by an alkaline solution, the hydroxyl ions are converted to oxygen and water:

$$2OH^- \rightarrow \tfrac{1}{2}O_2 + H_2O + 2e^- \tag{6}$$

If the anode is inert and the electrolyte is neutral (such as water), acid (H^+) is produced:

$$H_2O \rightarrow \tfrac{1}{2}O_2 + 2H^+ + 2e^- \tag{7}$$

Reactions 2, 5, 6 and 7 are sometimes referred to as electrolysis reactions.

Although the production of hydroxyl ions at the cathode (reaction 2) is the most important process in realkalisation, several ionic transport processes are also involved and can be used to assist the ingress of an alkaline electrolyte:

- *Electromigration (electrophoresis)*: Under the influence of the applied electric field, negatively charged hydroxide ions in the pore solution will move towards the anode and positive ions, such as sodium, will move towards the reinforcement. This process is also utilised in chloride extraction.

- *Electro-osmosis*: It has been suggested that the liquid electrolyte is drawn into the concrete by osmosis to reduce increased ionic concentration at the cathode, or by electro-osmosis due to attraction to the negatively charged steel. This attraction is related to the positively charged outer surface of water (or other electrolyte) adsorbed on the pore walls. Miller (1999), the designer of one proprietary system, claims that this process is the principal means of introducing sodium carbonate electrolyte, which is used to prevent further carbonation (see below). Mietz (1998) reports a lack of evidence of this effect.

- *Absorption*: Depending on the moisture content of the concrete at the time of treatment, electrolyte will be absorbed from the concrete surface. This process can be utilised to realkalise the concrete by simply saturating the surface with an alkaline solution without connection to a power supply, although this will take a month or more (Miller 1999).

- *Diffusion*: Ions will diffuse through pore solutions from areas of high concentration to areas of low concentration. The rate of diffusion is probably too slow to be critical to the performance of electrochemical realkalisation but after treatment alkalis can diffuse away from the reinforcement, potentially reducing the corrosion protection with time. The diffusion process by itself has been used to redistribute alkalis in concrete tunnels, chimneys and deck soffits by saturating the concrete then sealing it. The process takes about a year (Miller 1999).

BRE (2000) considers absorption and diffusion to be the principal mechanisms of electrolyte penetration. Andrade et al. (1998) describe the sources of variation in surface electrochemistry that could contribute to conflicting observations of different investigators.

After treatment, the hydroxide ions generated at the cathode can react with dissolved atmospheric carbon dioxide to form sodium carbonate:

$$2Na^+ + 2OH^- + CO_2 \rightarrow Na_2CO_3 + H_2O \qquad (11)$$
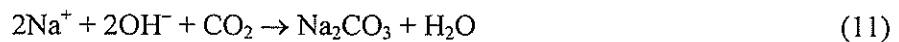
The sodium carbonate then reacts with dissolved carbon dioxide to form sodium bicarbonate:

$$Na_2CO_3 + CO_2 + H_2O \rightarrow 2NaHCO_3 \qquad (12)$$
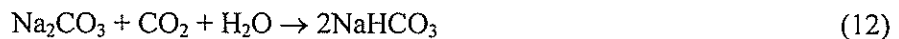
This prevents the significant reduction in pH after treatment that reaction 11 alone would produce. In addition, it is a reversible reaction, and once the carbon dioxide supply is reduced, e.g. by applying a coating, sodium carbonate is regenerated to maintain a buffer against subsequent ingress of carbon dioxide.

6.2   Equipment

Equipment requirements are the same as for chloride extraction.

Steel mesh anodes can be used because the treatment time is shorter and the problems of anode corrosion are reduced.

The electrolyte is generally sodium carbonate. After treatment, the sodium carbonate that was drawn into the concrete pore solutions will react with incoming carbon dioxide as shown in reaction 12 above. This prevents consumption of the hydroxyl ion that is needed to passivate the reinforcement. Potassium carbonate can be used as an alternative.

Calcium hydroxide electrolytes can also be used. When calcium hydroxide in the pore solution reacts with carbon dioxide, calcium carbonate is produced (reaction 10). The reaction is not reversible, so hydroxide ions are consumed and there is not the long-term buffering effect that is offered by sodium carbonate.

Tap water can also be used as an electrolyte and, as with chloride extraction, lithium compounds have been proposed for use on concrete containing alkali-reactive aggregates.

6.3 Long-term Performance

Like chloride extraction, realkalisation has only been applied since the mid-1980s so little is known about its performance beyond 10-15 years.

In theory, the effects of realkalisation should be permanent, particularly if sodium carbonate electrolyte is used and treatment is followed by applying a waterproof carbon dioxide barrier coating to the concrete (the coating will require maintenance however). BRE (2000) suggest that unless sufficient electrolyte penetrates by absorption or diffusion to the depth of the reinforcement, realkalisation might be limited to the area immediately around the bar, which may allow subsequent diffusion of alkali away from the steel.

Decter et al. (1998) report that protection was maintained seven years after realkalisation and subsequent surface coating treatment of one building.

6.4 Design, Specification and Management Issues

Many of the considerations for chloride extraction (see Section 5.4) also apply to realkalisation.

The treatment is applied until sufficient charge has been passed to generate the required amount of hydroxide at the cathode. The time required is determined by the carbonation depth, concrete quality, cover depth, distribution of reinforcement and uniformity of current distribution.

The process is terminated when concrete alkalinity has been restored to a pre-determined level, usually within two weeks. Carbonation depths are usually measured with phenolphthalein indicator, which turns pink as pH increases above 8. Steel passivation requires a pH of 10 or more (higher in the presence of chlorides), so a more accurate means of identifying the end of treatment is required.

One option is to use other chemical pH indicators with obvious colour changes at higher pH than phenolphthalein. Another option is to measure the sodium concentration of the pore solution. This will indicate the pH once chemical equilibrium between carbon dioxide, sodium carbonate and bicarbonate is achieved. However it is difficult to extract the pore solution without altering its chemistry in some way, and sodium concentration is not a direct measure of actual steel passivity. A third option is to monitor changes in steel potential, provided that the measurement accounts for the decrease in potential caused by sodium carbonate introduced during treatment, and for polarisation of the steel that may remain for weeks or months after

treatment. The presence of a homogeneous potential field is considered to indicate that the steel has been repassivated. Yet another approach is to measure anodic polarisation of the steel.

Although further carbonation after treatment is unlikely, particularly if sodium carbonate electrolyte was used, it is prudent to treat the concrete surface with a carbon dioxide-resistant coating after realkalisation. A surface coating will also prevent alkalis being washed out of the concrete by rain or run-off. Coatings will, however, require ongoing maintenance.

6.5   Benefits and Applications

Realkalisation offers a permanent solution to concrete that has been carbonated to a degree that allows the reinforcement to corrode.

Carbonated but otherwise sound concrete does not need to be broken out and replaced. Therefore realkalisation can be used where removal of all carbonated concrete is not practical, either because the volume of material concerned makes the cost prohibitive or raises structural concerns, or because the noise, dust and disruption during repair is unacceptable to the users of the structure. Concrete thickness does not have to be increased where cover is low, and the treatment does not involve the permanent installation of hardware or the ongoing maintenance of CP systems, so the profile, weight and appearance of the concrete is not altered by the treatment.

Realkalisation is suitable for treating structures where poor concrete quality and/or low cover depths have led (or will lead) to carbonation-induced reinforcement corrosion. Patch repair followed by surface coating is a valid option where the deterioration is localised and/or the structure's remaining life is limited by functional requirements, but realkalisation should be considered where carbonation is extensive and an indefinite service life is required. Like chloride extraction, realkalisation offers the greatest benefits if applied before corrosion damage appears, when little or no concrete repair is needed. Even once the concrete is damaged, the disruption and cost of repair will be less than for patch repair because less concrete will need to be replaced.

Realkalisation can be applied in conjunction with chloride extraction (see Section 3.2 of this report and Woodhouse 2000).

6.6   Shortcomings

Realkalisation is not appropriate for concrete that is contaminated with chlorides unless chloride extraction is applied first. Neither is it appropriate for concrete that is highly porous (e.g. due to poor consolidation) because extensive repair will be needed before treatment to prevent short-circuiting from direct contact between

reinforcement and electrolyte. There must be good continuity of reinforcement in the components to be treated otherwise extra connections will need to be made.

Sodium carbonate electrolyte and its residues will soften some surface coatings, particularly oil-based ones, and can damage wood finishes. These effects are unlikely to be of concern on bridges. Water can be used as the electrolyte if compatibility with coatings is an issue.

When sodium carbonate electrolyte is used, some efflorescence will develop on the concrete surface after treatment as the concrete dries. This may need to be removed. The high alkalinity of the surface means that some decorative paints cannot be used.

Realkalisation should not be used on pretensioned concrete because of the risk of hydrogen embrittlement of the tendons, but it might be possible to use it with extreme care to protect the reinforcement in post-tensioned concrete where the tendons are protected by ducting. It cannot be used to protect tendons themselves. However carbonation should rarely be a problem on prestressed structures because they usually use high strength, high cement content, low water/cement ratio concretes that are resistant to carbonation.

Realkalisation should not be used on concrete containing alkali-reactive aggregates without prior investigation to ensure that the risk of inducing alkali aggregate reaction is minimal.

7.   Scope for Use of Electrochemical Treatments on New Zealand Bridges

This chapter identifies the scope for cathodic protection, chloride extraction or realkalisation to provide sound alternatives to patch repair of concrete on New Zealand bridges damaged by reinforcement corrosion.

7.1   Incidence of Reinforcement Corrosion

About 20% of all bridges owned by Transit New Zealand and by a selection of local authorities have been found to need some remedial work because of reinforcement corrosion (Rowe & Freitag 1984, Bruce et al. 1999).

These investigations found that reinforcement corrosion is more common on bridges older than 50 years, and is usually related to construction defects in these pre-1950 structures. The 1999 investigation showed that bridges more than 50 years old comprised 32% of the approximately 2300 state highway bridges with concrete superstructures, and an estimated 14% of the approximately 8500 local authority bridges with concrete superstructures. Thus New Zealand has approximately 1920 bridges with concrete superstructures over 50 years old.

Bruce et al. (1999) also found that the incidence of reinforcement corrosion increases with increasing exposure to seawater and seaspray, and that 61% of state highway bridges and 45 % of local authority bridges are in the coastal perimeter (B1), coastal frontage (B2) and tidal/splash (C) zones (which are defined by NZS 3101:1995).

These data suggest that there could be plenty of opportunity to use electrochemical treatments on concrete bridges damaged by reinforcement corrosion.

Of all reinforced concrete structures, bridges represent some of the most likely subjects for electrochemical treatments because of their well developed, uniform design and good continuity of reinforcement. Many of the pre-1950 bridges were built in the 1930s to a common design. Experience gained with electrochemical treatment on the first few bridges should therefore be applicable in subsequent installations. This should mean that once asset owners become confident in the technology and start to apply it, design and installation should become increasingly efficient with subsequent applications.

7.2   Technical Considerations for All Electrochemical Treatments

The risk of alkali aggregate reaction (AAR) must be considered in the design of electrochemical treatments for structures made from concrete containing potentially alkali-reactive aggregates as identified by CCANZ (1991). Aggregates known to have caused significant AAR in structures and therefore of particular concern are

Waikato River sands and other rhyolitic material, and andesites from Taranaki and the central North Island.

Table 7.1 summarises the recommended use of each electrochemical technique in relationship to the types of reinforcement that a bridge might contain. These recommendations are based on comments made in the literature and described in the previous sections of this report. They will need to be reviewed as the technologies develop and more becomes known about managing the risks of bond loss and hydrogen embrittlement.

Table 7.1   Recommended application of electrochemical treatments to protect rebar and strand/tendons in reinforced and prestressed concrete.

Treatment	Reinforced concrete		Pre-tensioned concrete		Post-tensioned concrete	
	deformed rebar	plain rebar	rebar	strand	rebar	tendon
ICCP	yes	yes	with care[2]	with care[2]	with care[2]	no[2]
Galvanic CP	yes	yes	with care[2]	with care[2]	with care[2]	no[2]
Chloride extraction	yes	with care[1]	no[2]	no[2]	with care[2]	no[2]
Realkalisation	yes	with care[1]	no[2]	no[2]	with care[2]	no[2]

1.   Risk is of bond loss due to high alkalinity at the steel-concrete interface.

2.   Risk is of overprotection causing hydrogen embrittlement of high tensile steel strand and tendons. Risk should be minimal with zinc-based galvanic CP. Note that although ducting might protect post-tensioning tendon in theory, in practice it may have been damaged during construction, or indeed be corroding itself. Stray currents also present a significant risk. The position of strand/tendons in relation to the reinforcement will contribute to the level of risk. The suitability of application to prestressed concrete must be considered on a structure-by-structure basis.

7.3   Cathodic Protection

CP offers the only permanent treatment for reinforcement in chloride-contaminated concrete in the tidal/splash (C) zone defined by NZS 3101:1995. It can also be used on concrete not in direct contact with seawater, i.e. on bridge elements in the inland (A2), coastal perimeter (B1), or coastal frontage (B2) zones, although in these zones the other techniques could also be considered.

ICCP is the most versatile CP treatment. The wide variety of anode materials and configurations mean it can be applied to any part of a structure in any exposure conditions, and individually controlled zones can be tailored to any size required to accommodate variations in the design and condition of the elements being protected. Chloride-contaminated concrete in the atmospheric and tidal/splash zones is most effectively treated with ICCP. Concrete immersed in seawater can be treated with either ICCP or galvanic CP. This includes rebars and strand in pretensioned concrete and rebar in post-tensioned concrete. Titanium-based anodes offer the best protection to chloride-contaminated concrete in the tidal/splash (C), and coastal (B1 and B2) zones. Surface anodes are suitable for inland (A2) environments.

Galvanic CP offers a more economic option for elements that are permanently wet, such as piles below low tide level or surfaces that are exposed to frequent splashing. It is less effective on concrete that is exposed to drying because of the low current densities it generates, although anodes that can tolerate non-saturated concrete are available and these would be suitable for substructures in inland (A2) areas.

Rebar in prestressed concrete can be treated with either ICCP or galvanic CP. ICCP allows close control of the potential developed by strand, tendons or ducting, while the low current densities generated by the low driving potentials of galvanic CP systems present an overall lower risk. To avoid hydrogen evolution with either system the output must be closely controlled, stray currents avoided, and the drainage of water from the structure carefully controlled to maintain uniform concrete resistivity. Pretensioning strand itself might best be treated with ICCP because of the degree of control achievable.

The proprietary encapsulated discrete internal zinc anode designed to prevent incipient anode effects in patch repair has obvious application in any chloride-contaminated structure where the service life or level of damage does not warrant the cost of CP or chloride extraction. It will only be effective until it is consumed. It would be difficult to replace, so the patch repair would then be left as the sole means of protection to the rebar. Nevertheless, with an estimated anode life of 10 years, this would still significantly prolong the life of many patch repairs, possibly for a further 10 years depending on exposure conditions.

For a quick comparison of anodes for ICCP and galvanic CP see Table 7.2. Note that different authors use different terminology to describe anode products and systems and there may be some inconsistency between the terminology in this table and that used elsewhere. The surface-applied ICCP anodes are more suitable for low current density applications, such as inland (non-chloride contaminated) structures.

Table 7.2   Comparison of anodes for ICCP and galvanic CP (based on Green 2001).

Method of Application	ICCP	Galvanic CP
Surface-applied	Conductive coating; Thermally sprayed zinc; Thermally sprayed titanium; Conductive cementitious overlay.	Thermally sprayed zinc; Thermally sprayed aluminium-zinc-indium; Zinc adhesive anode.
Encapsulated	Titanium anode mesh overlay; Titanium ribbon mesh (slotted); Discrete internal anodes; Titanium mesh integral pile jacket.	Zinc mesh integral pile jacket; Discrete internal zinc anode for patch repairs.
Immersed	Remote anodes of: • Mixed metal oxide titanium; • High silicon iron; • Lead/silver/antimony.	Cast aluminium or zinc.

7.4   Chloride Extraction

The international popularity of chloride extraction is largely because of its ability to prevent corrosion caused by ingress of de-icing salts. The most obvious New Zealand application for chloride extraction is to protect the reinforcement in bridge elements that are exposed to seaspray but not seawater, i.e. elements on bridges in the coastal perimeter (B1) or coastal frontage (B2) zones, defined by NZS 3101:1995. These elements can be coated after treatment to prevent subsequent recontamination. It would be particularly useful for such elements where removal of large amounts of contaminated concrete would create an unacceptable nuisance to nearby residents, or incur excessive costs associated with compliance with the Resource Management Act. It could also be applied to the same types of element as a preventive treatment.

If the recontamination risk and environmental aspects suggest that chloride extraction is a realistic option, then its technical suitability needs to be assessed. This is determined by the extent of damage, and by the physical features of the individual elements of the structure as described in Section 5.4, such as cover depths, rebar continuity, uniformity of steel/surface relationship and contamination.

The final stage of the assessment depends on the whole of life cost of the treatment. International experience reported to date suggests it might be reasonable to consider chloride extraction for medium term application, e.g. 20-30 years, for which more than one cycle of patch repair would probably be needed. CP offers protection for longer periods, say 50 years or more, with lower risk.

7.5   Realkalisation

Realkalisation could be a realistic option for protecting reinforcement where concrete is not chloride-contaminated but is carbonated over a wide surface area because of its poor overall quality (but not so porous that extensive repair is needed to avoid short-circuiting). Treated with the right electrolyte, the concrete should not carbonate again.

In practice, opportunities for applying realkalisation on New Zealand bridges are probably more limited than those of CP and chloride extraction. In the inland (A2) and coastal perimeter (B1) zones defined by NZS 3101:1995, carbonation does sometimes cause a loss of alkalinity at the rebar on concrete bridges. However corrosion in this environment tends to be slow and the damage minor, particularly on substructure surfaces that are not exposed to rain or run-off. In addition, concrete in bridges is generally of reasonable quality. Corrosion in the A2 zone is usually related to construction defects such as low cover and poorly consolidated concrete, which tend to be localised and can often be patch repaired quite effectively. Corrosion in the B1 zone is often of a similar nature but there is an additional risk of chloride contamination that depends on exposure and needs to be investigated for the

individual structure. Depending on relative costs, realkalisation could be considered as a preventive treatment, either with or instead of a coating.

Prestressed concrete is an unlikely candidate for realkalisation because the quality of concrete should prevent significant carbonation. Rebar in post-tensioned concrete could be protected by realkalisation if necessary.

Reinforcement corrosion is most common and severe in concrete exposed to salt water and sea spray, i.e. in the coastal frontage (B2) and tidal/splash (C) exposure zones defined by NZS 3101:1995. In these environments, CP and desalination are the appropriate electrochemical treatments because the corrosion is induced by the ingress of chlorides.

7.6   Barriers to the Use of Electrochemical Treatments

CP became widely accepted in the US in the mid-1970s for protecting bridge decks that were corroding because of chloride contamination from de-icing salts. In the UK CP took much longer to be accepted, even though bridges were also suffering from de-icing salt contamination. Boam (1993) reviewed the reasons why CP met with so much more resistance in the UK and it is interesting to examine them here in the context of introducing it (and the other techniques) into New Zealand some 12 years later (his paper was actually presented in 1989). It must be noted however that a major reason why electrochemical treatments are rarely considered for New Zealand bridges at present is that the economic benefits of the treatments are based on whole-of-life costs, while current procurement policy favours lower installation and short-term costs.

One of the reasons for slow acceptance that Boam quoted was a lack of interaction between corrosion engineers and civil engineers. In recent years corrosion prevention specialists have recognised the potential market for their skills in rehabilitating civil engineering structures. This was reflected at the Australasian Corrosion Association's 2001 conference, where about 15% of papers presented were related to concrete. Their interest has helped to close the gap between the two technologies.

Another reason was engineers' desire for categoric proof that CP would work without any adverse side effects, and the lack of quantitative data available from earlier US experience. This may be because the actual process is invisible and the engineer must rely on indirect proof that it is functioning. Boam found this expectation of performance difficult to understand in the light of the poor performance achieved with repair techniques that were considered acceptable, and felt that engineers should accept that success is not guaranteed with CP either. He considered that CP should be considered as an option if it is technically appropriate and cost-effective, and if the client and engineer appreciate that the job is not over once the installation has been commissioned. These same comments about expectations could apply here. In addition, New Zealand can now benefit from at

least 25 years of US and UK experience, as well as from more recent experience with up-to-date systems in Australia. Thus the risk of unsatisfactory performance should be somewhat lower than it was in 1989. Case histories are given in Sections 8.3 and 8.4 of this report.

A third reason was that the service life expected from the US bridges was only 40 years compared to the 120-year design life for UK bridges. US engineers considered a further 15 years service from the time of CP application to be adequate. Thus US expectations of continued operation of the system and prevention of further deterioration (as distinct from prevention of corrosion) were based on a much shorter period, and an installation considered successful in the US might not have been considered successful in the UK. Nowadays the service lives of the components are better understood, and their replacement is factored into the whole-of-life cost. Anodes with service lives appropriate to 100+ year service lives of structures are also available now.

A fourth reason was a lack of skilled installers and a lack of support from equipment suppliers. Boam compared this to the way in which inappropriate patch repair materials were promoted by their manufacturers, which led to widespread failures. This problem has been overcome with experienced corrosion engineers taking responsibility for the design and operation of CP systems and the use of licensed applicators for their installation (see Section 8.2 of this report).

Although these comments related specifically to CP, they could equally apply to chloride extraction and realkalisation.

8.   Suppliers, Installations and Case Histories

8.1   Sources of Information

Part of the resistance to adopting a new technology is lack of confidence about its performance. Electrochemical treatments do now have a history of previous application, albeit relatively short, and so the best way to overcome uncertainty about their installation and long-term performance will come from experience gained in previous applications. This can be obtained by direct enquiry to designers, suppliers, operators and owners of existing installations. Organisations with an interest in corrosion control, such as the US-based National Association of Corrosion Engineers (NACE International), the Corrosion Prevention Association (CPA) in the UK and, in New Zealand, the Australasian Corrosion Association (ACA)[5] will provide a starting point for making appropriate contacts. Up-to-date codes of practice and standards will also incorporate recent industry experience.

Case studies reported in the literature also provide useful information about the types of protection that have been used in various environments. However papers reporting long-term performance will always be limited even for mature technology. This is generally because of commercial pressures: sensitivity about the deterioration of a structure or about treatments that do not meet expectations, or simply that low priority is given to publicising something done many years ago that is still performing as designed.

Attempts were made to find out how many installations of CP, chloride extraction and realkalisation had been made by major Australasian suppliers, and on what types of structure, but were not entirely successful. Several companies can be involved in the same installation so the data received were not clear enough to establish precisely who had done what. Similarly, global data is often expressed as total surface area treated, rather than as numbers of individual applications.

Information on long-term performance is probably best obtained directly from owners of treated structures. Consequently there may be a role for a database of local installations to help owners evaluate the suitability of a treatment for a particular structure. This would involve minimal effort on the part of owners of treated structures to make their experiences available to others, and would provide a source of independent information to other prospective purchasers (see Chapter 10 of this report).

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[5] In 2002 the ACA introduced a two-day course on corrosion and electrochemical protection of concrete structures for asset managers. The New Zealand branch of the ACA hopes to run this course in New Zealand during 2003.

8.2 International Experience

CP was first applied to reinforced concrete in 1973 when it was used by Caltrans (USA) to protect a bridge deck. Since then it has been widely accepted internationally as a means of overcoming corrosion problems caused by the ingress of chloride ions from de-icing salts and exposure to marine conditions.

Miller (1999) estimated that CP had been applied to more than 2 million m^2 of concrete surface. Broomfield (2002) estimated that 2 to 3 million m^2 of concrete surface had been treated with ICCP. Corrpro Companies Inc. claims involvement in the design/installation of more than 500 CP projects, involving around 1,300,000 m^2 of concrete surface. GHD (formerly Taywood Engineering Ltd Australia) claims involvement with 75 CP installations. Fosroc Limited claims that Galvashield XP (a sacrificial discrete internal anode designed to prevent incipient anode effects) has been installed on around 130 structures, mostly in the UK.

CP technology has been evolving continuously as operating systems are improved and the shortcomings of early systems are identified and addressed. Because most systems currently available are relatively new, little data is available about their long-term performance.

Proprietary chloride extraction systems became available in the mid- to late 1980s and have been widely used since then in both Europe and North America.

Realkalisation also became available in the mid- to late 1980s, after the realisation that the technology used for CP and chloride extraction would also increase the alkalinity of the pore solutions at the reinforcement. It has been widely used in Europe and the Middle East, but not in North America. Whether this means carbonation-induced corrosion is not a problem in the US, or whether it is over-shadowed by the problem of chloride-induced corrosion is uncertain (Broomfield 1997).

International applications of realkalisation and chloride extraction up to 1995 are summarised in Table 8.1. Broomfield (2002) estimates that 40,000 m^2 of concrete surface have been treated with chloride extraction and 170,000 m^2 have been treated with realkalisation. Miller (1999) reported that more than 250 structures had been treated by chloride extraction and realkalisation. Martech Services (UK) claim involvement in more than 110 realkalisation projects and over 70 chloride extraction projects between 1991 and 1999.

Like CP, little information is available on the long-term performance of current chloride extraction and realkalisation systems, although the technology involved in their design and installation is well documented, as is their performance for up to 10 years after treatment.

More information may become available with time, although this will depend on owners and operators being sufficiently interested and motivated to publish the information.

Table 8.1   Applications of chloride extraction and realkalisation up to 1995 (Pocock 1995).

Sector	Realkalisation Projects	Chloride Extraction Projects	Total
Buildings	37	10	47
Highways	18	17	35
Housing	13	4	17
Car-parks	2	9	11
Industrial	1	4	5
Water	5	0	5
Jetties	0	3	3
Total	**76**	**47**	**123**

8.3   Australasian Suppliers/Designers

Major suppliers and designers of electrochemical treatments for concrete in Australasia are listed in Table 8.2. These companies can design and commission CP systems and some also supply anodes. Some of the companies also install CP systems although independent contractors often do the actual installation. Fosroc Ltd in New Zealand supplies proprietary products but does not design, install or commission the systems. There are similar suppliers in Australia but they are not listed because New Zealand installers are more likely to purchase from a local supplier. The list does not include consultants who specify but have no detailed design experience.

The Australian companies listed in Table 8.2 can all operate in New Zealand, as can designers from further afield such as Europe and North America. Thus CP contracts in New Zealand can be let using an open tendering process where overseas designers partner with local contractors. For example the CP system on the National War Memorial Carillon in Wellington was designed by Global Corrosion (a UK company), which employed international expert John Broomfield, and was installed by Surface Technologies Ltd, with Opus International Consultants Ltd as specifier, project manager and technical advisor to the client.

Australian-based CP designers can each claim involvement in at least 20 installations, and approximately 100 CP systems are operating at present on reinforced concrete structures in Australia. However it is not possible to list projects carried out by each company because each project tends to involve more than one designer. For example, one designer may develop the specification for the client, and a principal contractor takes overall responsibility for the project, employing an independent designer to prepare the detailed design.

Table 8.2   Australasian designers and suppliers of electrochemical treatments.

Company	Contact details	Capability
Solomon Corrosion Control Services Pty Ltd	www.solcor.com.au	Supply of CP anodes; Design, installation and commissioning of CP systems.
GHD Pty Ltd (Materials Technology group)[1]	www.ghd.com.au	Detailed design and commissioning of CP systems; Design and commissioning of chloride extraction and realkalisation systems.
R M Watson	www.rmwatson.com.au	Installation of CP, chloride extraction and realkalisation systems.
Savcor ART Pty Ltd[2]	www.savcorart.com.au	Supply of CP anodes; Design, installation and commissioning of CP systems; Design, installation and commissioning of chloride extraction and realkalisation systems (Norcure licensee).
Construction Techniques Group Ltd	info@contech.co.nz	Supply of CP anodes; Design, installation and commissioning of CP systems; Design, installation and commissioning of chloride extraction and realkalisation systems (Norcure licensee).
Fosroc Ltd	www.fosroc.co.nz	Supply of ICCP anodes; Supply of Norcure chloride extraction and realkalisation technology and hardware; Supply of 'Galvashield' galvanic anode systems.

1.   GHD Ltd Material Technology group includes staff formerly with Taywood Engineering Ltd who joined GHD after the closure of Taywood in Australia.

2.   Savcor ART Pty Ltd was formerly Remedial Engineering Ltd but was recently acquired by Savcor Group from Finland. Savcor Australia has recently acquired Finn International Pty Ltd, a CP installer and Norcure licensee, and Corrpro Companies' Australian and New Zealand operations.

8.4   New Zealand Installations

New Zealand CP installations to 2002 are listed in Table 8.3.

Table 8.3   New Zealand installations of CP.

Site (Structure)	Location	Date installed	Type	Designer / installer	Anode type
Westminster Court apartments (façade)	Auckland	1990	ICCP	Construction Techniques	Titanium mesh with plaster overlay
Axon House (basement walls)	Wellington	mid 1990s	ICCP	Construction Techniques	Titanium mesh and slotted anodes
Wool House (basement slabs and columns)	Wellington	mid 1990s	ICCP	Construction Techniques	Slotted anodes
Bledisloe Wharf (prestressed beams)	Auckland	Late 1990s	Galvanic CP	Construction Techniques	Sprayed zinc
National War Memorial Carillon (belfries)	Wellington	1999	ICCP	Global Corrosion (UK) / Surface Technologies Ltd	Discrete internal anodes
Axis Fergusson Wharf (beams)	Auckland	1999	ICCP	Construction Techniques	Slotted anodes
Seaview Wharf (head beams)	Wellington	2000	ICCP	Construction Techniques	Slotted anodes
Seaview Wharf (approach structure beams)	Wellington	2002	ICCP	Construction Techniques	Slotted anodes

The recent increased rate and size of CP installations could indicate increasing acceptance of the technology by owners, perhaps because of better understanding of the potential benefits, or increased interest in whole-of-life performance. Partnering arrangements between New Zealand contractors and overseas CP designers, such as those used on the Seaview Wharf and Carillon projects, should open the way for a more competitive tendering environment in future.

CP has not been installed on bridges in New Zealand, but in Australia has been installed on bridges by RTA, VicRoads, Queensland Main Roads and the Tasmanian Department of Infrastructure Energy and Resources, and various local authorities. It is estimated that at least 30% of Australian CP systems are installed on bridges.

Fosroc's proprietary galvanic system 'Galvashield XP' has been used on about 5 structures in New Zealand and 10 in Australia.

To date there have been about 10 applications of chloride extraction/realkalisation in Australia. There have been none in New Zealand, although trials were carried out on the Carillon before CP was installed.

8.5   Case Histories

The following sections list some case studies from the literature that describe CP, chloride extraction and realkalisation applications that are relevant to New Zealand bridges. This is not an exhaustive list of such applications. The performance of some of these installations may be reviewed again at a later date and so these papers could form the basis of a future literature search.

8.5.1   Cathodic Protection

Most case studies in the literature are of bridges contaminated by de-icing salts. The case studies summarised here are limited to coastal applications.

Coastal reinforced concrete bridges, Oregon (Cramer et al. 2002):
- More than 40,000 m^2 of bridge surface repaired by ICCP and galvanic CP with zinc anodes, plus demonstration projects with other surface anodes;
- Compared different types of surface anodes for ICCP and galvanic CP;
- Examined effect of treating anodes with humectants to keep them moist;
- Investigated tools for assessing potential corrosion problems in structures;
- Discussed applications for supplementary cementitious materials and stainless steel rebar in coastal bridges.

Canvey Island Bridge, Essex, UK (El-Belbol & Das 2001):
- Built 1973 in tidal zone;
- Reinforced concrete abutments, piers, and bored cast in-situ piles with chloride-induced corrosion evidenced by rust stained cracks;
- Abutments and piers protected by remotely controlled ICCP, installed 1999;
- Abutments and parts of piers in mud zones protected by MMO/titanium groundbed anodes embedded in carbonaceous backfill;
- Parts of piers in atmospheric and tidal exposure zones protected by ribbon anode system.

Lynch's Bridge, Victoria, Australia (Green et al. 2001):
- Piers in brackish tidal water protected by ICCP with discrete internal anodes in the atmospheric and tidal zones, and with remote anodes in the submerged zone (1999);
- Discusses design, installation, monitoring and performance of the system.

Endeavour, Windang and Cathie bridges, NSW, Australia (Cheaitani et al. 1996):

- Reinforced concrete deck beams on Endeavour Bridge protected by ICCP with combination of slotted titanium ribbon mesh anode and discrete internal anode;
- Reinforced concrete pile on Windang Bridge protected by ICCP with combined internal and strip anodes (see also Godson & Cheaitani 1998);
- Failed epoxy patch repairs on piles of Cathie Bridge replaced and piles protected by strip anodes (1995).

Windang Bridge, NSW, Australia (Godson & Cheaitani 1998):

- Reinforced concrete piles in marine environment protected by ICCP;
- Combined strip anodes in tidal zones, supplemented with discrete internal anodes as required to accommodate variations in corrosion activity.

Mission River and Andoom Creek Bridges, Queensland, Australia (Godson & Cheaitani 1998):

- Bridges built early 1970s, deterioration evident by early 1980s;
- Chloride-contaminated reinforced concrete headstocks and pilecaps, prestressed concrete piles protected with remote controlled and monitored ICCP;
- Discrete internal anodes protect headstocks, pilecaps and piles above mean high water level;
- Water anodes protect piles below mean high water level. To avoid overprotection, potential at every anode is automatically monitored and current output adjusted every 5 minutes. Anodes tested every 24 hours.

Fremantle railway bridge, Western Australia (Godson & Cheaitani 1998):

- Built early 1970s, deterioration evident in 1985;
- Chloride-contaminated reinforced concrete piers;
- Pier headstocks and columns protected by ICCP using discrete internal anodes, individual pier monitoring and control.

Tasman Bridge, Tasmania (Godson & Cheaitani 1998):

- Built 1965;
- Remote controlled and monitored ICCP installed 1994 to protect lower pier columns on western interchange section where patch repair had failed;
- Water/soil anodes used on submerged/buried parts of columns, with zinc reference electrodes for monitoring;
- Discrete internal anodes used above mean high water, divided into independent zones for splash and atmospheric exposure.

Deep Creek Bridge, Victoria, Australia (Andrews-Phaedonos et al. 1992, 1997):

- Built 1970, pier columns corroding due to chloride contamination, piles and pile caps chloride-contaminated but not visibly corroding (due to low oxygen availability), pier caps and superstructure not corroding;

- One galvanic CP system (water anode) trialled for protecting submerged zones;

- Two galvanic CP systems (unshielded zinc anode, zinc anode shielded from contact with submerged concrete), and two ICCP systems (slotted MMO/titanium wire, surface-applied MMO titanium mesh/conductive tape shielded from submerged zone) trialled in tidal/splash and atmospheric zones;

- Preliminary findings indicated all systems trialled would be suitable for small to medium size columns/bridges where aesthetics are not an issue; that shielding both the ICCP and the galvanic anodes in tidal zone from submerged concrete was beneficial, that the galvanic systems were cost effective and providing protection in tidal/splash zones and possibly also in atmospheric zones although they were sensitive to tidal activity.

Moody's Inlet Bridge (Andrews-Phaedonos et al. 1997):

- Sprayed zinc galvanic CP system was applied to six columns in tidal water and three in tidal mud, with galvanic zinc anodes buried or immersed to protect the submerged or buried parts of the columns and to minimise consumption of the sprayed material in the lower parts of the application.

Sunshine Tip Roadway (Andrews-Phaedonos et al. 1997):

- Reinforced concrete piles were cracked during pile driving, exposing reinforcement to soil electrolyte;

- ICCP using MMO/titanium groundbed anodes in carbon backfill installed to protect cracked piles;

- Full protection achieved within a week.

Mile Bridge, Victoria, Australia (Andrews-Phaedonos et al. 1997):

- 1995 installation;

- Slotted titanium anode system protects pier wall above mean high water level;

- A water/soil titanium anode in conductive backfill protects tidal/submerged parts of pier wall.

Mordialloc Creek, Victoria, Australia (Andrews-Phaedonos et al. 1997):

- Zinc anodes submerged in water to protect submerged/buried and tidal sections of columns;

- Galvanic CP anodes considered appropriate for submerged/tidal zones in small/medium columns but ICCP water anodes would be more effective in larger sections because of the greater amount of steel that needs to be protected.

8.5.2   Chloride Extraction

Bridge pier, Sydney, Australia (Collins & Kirby 1992):

- Base, in tidal/splash zone, was treated for 36 days but was significantly contaminated again after 16 months;

- Upper part, in atmospheric exposure zone, was treated for 65 days and remained uncontaminated after 16 months,

Orealla Crescent overpass, Noosa, Australia (Cheaitani & Carse 1998):

- Reinforced concrete piers and pier caps in atmospheric exposure zone;

- Prestressed beams were more contaminated but not treated;

- Compared different electrolyte media;

- Identified factors that affected efficiency of chloride removal;

- Promised update on long-term effectiveness.

Burlington Skyway, Toronto, Canada (described by many authors; Decter et al. (1998) report 8-year data):

- Treatment applied in 1989 to pier exposed to run-off from leaking deck joints;

- Leaks repaired;

- No new contamination or migration of chlorides after 8 years.

Salvoy Bridge, Norway (Nustad & Decter 1997)

- Coastal/marine environment;

- Treatment applied in 1995.

8.5.3   Realkalisation

The literature search carried out as part of this review uncovered several case studies of realkalisation on buildings but only one application to a bridge. This may reflect higher cement contents and lower water/cement ratios being used in bridges for structural reasons compared with that used for architectural purposes. Mietz (1998) also commented on the lack of documented site applications, and indeed many of those that are reported are described by different authors in different papers.

Wardell Road Bridge, Sydney, Australia (article in *Concrete in Australia*, 2002):

- Girders, cross-beams and deck carbonated with extensive damage on edge girders, and pier columns and tie beams subjected to high levels of chloride ingress;

- Life-cycle cost analysis used to select repair methods and tests show the bridge's service life should be extended by at least 25 years;

- In 2001-2002 edge girders realkalised, internal superstructure patch repaired and CP applied to pier columns and tie beams.

9. Conclusions

9.1 General

Cathodic protection (CP), chloride extraction and realkalisation are electrochemical treatments for concrete damaged by reinforcement corrosion. They are designed not to repair the damage caused but to prevent further deterioration for considerably longer than the typical 10-year repair cycle offered by traditional patch repair techniques. They do not require the extensive removal of contaminated but sound concrete that is required by patch repair.

Reinforcement corrosion is the most common and significant durability problem on New Zealand's concrete road bridges. The nature and uniformity of their design and construction makes them ideal candidates for electrochemical treatments. The similarity of many structures means that, although initial applications will involve steep learning curves, lessons learned on one structure will be applicable to others.

Rebar corrosion severe enough to necessitate repair is usually caused by chloride contamination. Depending on exposure conditions and the intended remaining life of the structure, either CP or chloride extraction could be appropriate treatments for chloride contamination.

9.2 Cathodic Protection (CP)

CP systems offer permanent treatment, i.e. for the remaining life of the structure, although they require continued monitoring throughout their service life, and, like a car, components within the system have a finite life.

Systems can be designed to suit all parts of a concrete structure in any exposure zone: inland (A2), coastal (B1 and B2), tidal/splash (C) or submerged.

CP can be used to protect rebar in reinforced and prestressed concrete, although particular care must be taken on prestressed concrete to avoid damaging prestressing steel or ducting. CP can also be used to protect pretensioning strand but not tendons used in post-tensioning.

Impressed current CP (ICCP) offers greater control and flexibility, while galvanic systems may be more economic because less hardware is needed to control their performance.

A proprietary galvanic anode system designed to prevent incipient anode effects in patch repair could increase the life of patch repairs by an estimated 10 years depending on conditions.

CP has an extensive history of use over the last twenty years that is well documented in the literature.

9.3 Chloride Extraction

How long chloride extraction remains effective will depend on the individual circumstances of each structure, but if sufficient chlorides are removed and recontamination is prevented, then the treatment could remain effective for 20-30 years. Treatment takes up to four months and no long-term maintenance is required.

Chloride extraction is best suited to elements not in direct contact with seawater, i.e. those in the coastal exposure zone (B1 and B2), that can be protected from recontamination by coating after treatment.

It cannot be applied to pretensioned concrete. Under some circumstances it can be applied to protect the rebar in post-tensioned concrete, but not the tendons. Particular care must be taken when applying it to round (undeformed) rebar, and to concrete containing alkali-reactive aggregates.

Chloride extraction has rapidly gained favour since its introduction in the late 1980s, particularly for removing de-icing salt contamination. However there are fewer reported case studies of treatments to marine concrete.

9.4 Realkalisation

For concrete that is extensively carbonated, realkalisation offers a permanent solution. Treatment takes two to three weeks and no long-term maintenance is required.

It is best suited to concrete that is not chloride-contaminated, i.e. in inland (A2) exposure zones, but can be applied in conjunction with chloride extraction if necessary.

Application to prestressed concrete has the same limitations as chloride extraction.

Although realkalisation is a technically sound treatment, in practice it is unlikely to find a large market on New Zealand bridges because carbonation-induced corrosion is not a major problem, and can usually be effectively treated with patch repair. Indeed a search of international literature found only one reported case study of application to bridges.

10. Recommendations for Future Research

The next stage in evaluating the potential for using cathodic protection, chloride extraction, and realkalisation on New Zealand bridges is to compare their up-front and long-term costs with those of patch repairs. This constitutes Stage 2 of the research, which is being carried out in 2002-2003. Note however that repair options will always need to be evaluated specifically for individual structures.

A possible area for future research is to identify the need for some sort of independent database of Australasian installations of electrochemical treatments. This record could make it easier in the future for designers and asset owners to find information on long-term performance, given that relatively few case histories are likely to be reported more than 10 years after installation.

The 2002-3 research is likely to identify shortcomings in knowledge that could be addressed by research. Similarly, technical or practical issues related to electrochemical treatments may arise as they become more widely used. Future research could be directed at refining the technology to make it more practical, durable, efficient or economical as required.

11. References

Andrade, C., Castellote, M., Alonso, C. 1998. An overview of electrochemical realkalisation and chloride extraction. Pp. 1-12 in *Rehabilitation of Structures*. Eds: Ho, D.W.S, Godson, I., Collins, F. Melbourne: RILEM/CSIRO/ACRA. 632 pp.

Andrew-Phaedonos, F., Solomon, I., Payne, D.J. 1997. Repair and protection of concrete bridges, the VicRoads experience – a current update. Pp. 363-377 in *Bridging the Millenia*. Proceedings of Austroads Bridge Conference, Sydney. *Austroads Publication AP-54/97.*

Andrew-Phaedonos, F., Solomon, I., Phang, B. 1992. Trial sacrificial anode and impressed current cathodic protection installations for bridge columns. Pp. 201-212 in *Rehabilitation of Concrete Structures*. Eds: Ho, D.W.S., Collins, F. Melbourne: RILEM/CSIRO/ACRA. 486 pp.

Arya, C., Sa'id-Shawqi, Q., Vassie, P.R.Q. 1996. Factors influencing electrochemical removal of chloride from concrete. *Cement and Concrete Research 26(6)*: 851-860.

Australian Concrete Repair Association (ACRA). 1996. *Guide to concrete repair and protection*. ACRA/CSIRO/Standards Australia/Standards New Zealand.

Bennett, J.E., Bushman, J.B., Clear, K.C., Kamp, R.N., Swial, W.J. 1993. Cathodic protection of concrete bridges – a manual of practice. *Strategic Highway Research Program Report SHRP – S-372.* 270 pp.

Bertolini, L., Yu, S.W., Page, C.L. 1996. Effects of electrochemical chloride extraction on chemical and mechanical properties of hydrated cement paste. *Advances in Cement Research 8(31):* 93-100.

Boam, K.J. 1993. Impact of cathodic protection on civil engineering. Pp. 278-292 in *Cathodic protection theory and practice*. Eds: Ashworth, V., Googan, C. Chichester: Ellis Horwood Ltd. 358 pp.

British Standards Institute (BSI). 2000. Cathodic protection of steel in concrete. *BS/EN 12696:2000.*

Broomfield, J.P. 1997. *Corrosion of steel in concrete – understanding, investigation and repair*. London: E & F Spon.

Broomfield, J.P. 2000. The principles and practice of galvanic cathodic protection for reinforced concrete structures. *Corrosion Prevention Association, Monograph No. 6.* 4 pp.

Broomfield, J.P. 2002. Report to focus on electrochemical realkalisation of reinforced concrete. *Materials Performance 41(4): 69.*

Broomfield J.P., Jacob, W.R., Mandeno, W.L., Bruce, S.M. 2000. Cathodic protection of the National War Memorial Carillon tower, Wellington, New Zealand. Paper 22 in *Corrosion and Protection 2000*, Australasian Corrosion Association.

Bruce, S.M., Freitag, S.A., Hickman, W.E. 1999. Durability of concrete road bridges in New Zealand. *Transfund New Zealand Research Report No. 129*. 88 pp.

Building Research Establishment (BRE). 2000. Corrosion of steel in concrete – protection and remediation. *BRE Digest 444 Part 3*. BRE Centre for Concrete Construction, UK.

Cement and Concrete Association of New Zealand (CCANZ). 1991. Alkali aggregate reaction – minimising the risk of damage to concrete. *CCANZ Technical Report TR3*. 64 pp.

Cement and Concrete Association of New Zealand (CCANZ). 1999. Case study – the National War Memorial Carillon. *New Zealand Concrete, June 1999*: 16-17.

Cheaitani, A., Carse, A. 1998. The electrochemical desalination of a coastal road bridge. Pp. 173-179 in *Rehabilitation of Structures*. Eds: Ho, D.W.S., Godson, I., Collins, F. Melbourne: RILEM/CSIRO/ACRA. 632 pp.

Cheaitani, A., Tickner, N.D., Morris, H., Godson, I. 1996. Cathodic protection of concrete bridges. Pp. 400-409 in *Concrete Repair and Rehabilitation*. Eds: Dhir, R.K., Jones, M.R. London: E & F Spon.

Collins, F.G., Kirby, G.A. 1992. Electrochemical removal of chlorides from concrete. Pp. 171-177 in *Rehabilitation of Concrete Structures*. Eds: Ho, D.W.S., Collins, F. Melbourne: RILEM/CSIRO/ACRA. 486 pp.

Cramer, S.D., Covino, B.S., Bullard, S.J., Holcomb, G.R., Russell, J.H., Nelson, F.J., Laylor, H.M., Soltesz, S.M. 2002. Corrosion prevention and remediation strategies for reinforced concrete coastal bridges. *Cement and Concrete Composites 24:* 101-117.

Daily, S.F. 1999. Using cathodic protection to control corrosion of reinforced concrete structures in marine environments. *Corrpro Companies Inc., Technical Paper CP-49*. 8 pp.

Decter, M., Nustad, G.E., Miller, J.B., McKee, W. 1998. Desalination and realkalisation – a study of the durability of treatment. Pp. 154-162 in *Rehabilitation of Structures*. Eds: Ho, D.W.S, Godson, I., Collins, F. Melbourne: RILEM/CSIRO/ACRA. 632 pp.

El-Belbol, S., Das, S.C. 2001. Cathodic protection in marine environments. *Concrete Engineering, Summer 2001*: 67-70.

Eltech Research Corporation (Eltech). 1993. Cathodic protection of reinforced concreter bridge elements: a state of the art report. *Strategic Highway Research Program Report SHRP – S-337*. 81 pp.

Glass, G.K., Hassanein, A.M., Buenfeld, N.R. 2000. CP criteria for reinforced concrete in marine exposure zones. *Journal of Materials in Civil Engineering 12(2)*: 164-171.

Godson, I., Cheaitani, A. 1998. Electrochemical treatment of reinforced concrete structures in Australia. Pp. 569-576 in *Rehabilitation of Structures*. Eds: Ho, D.W.S., Godson, I., Collins, F. Melbourne: RILEM/CSIRO/ACRA. 632 pp.

Gower, M., EL-Belbol, S. 2001. Monitoring and maintenance of conductive coating anode cathodic protection systems. *Corrosion Prevention Association, Monograph No. 4*. 4 pp.

Green, W.K. 2001. Australian experiences with cathodic protection of concrete structures. Paper presented as part of promotional seminar by Corrpro Companies New Zealand Pty Ltd.

Green, W., Andrews-Phaedonos, F., Brewster, G., McCormick, D. 2001. Lynch's Bridge – a case study in the cathodic protection of reinforced concrete. Paper 53 in *Corrosion and Protection 2001*, Australasian Corrosion Association.

Kepler, J.L., Darwin, D., Locke, C.E. 2000. Evaluation of corrosion protection methods for reinforced concrete highway structures. *Kansas Department of Transportation Report K-Tran: KU-99-6*. 234 pp.

Mandeno, W.L. 1999. Electrochemistry to the rescue: NZ War Memorial refurbishment. *Corrosion and Materials 24(4)*: 6-7.

Manning, D.G., Ip, A.K.C. 1994. Rehabilitating corrosion damaged bridges through the electrochemical extraction of chloride ions. Paper 12 in *Concrete Bridges in Aggressive Environments. American Concrete Institute Special Publication SP-151*.

Mietz, J. (Ed.). 1998. Electrochemical rehabilitation methods for reinforced concrete structures – a state of the art report. *European Federation of Corrosion Publications No. 24*. 58 pp.

Miller, J.B. 1999. A milestone in concrete infrastructure repair – desalination and realkalisation. Paper presented at New Zealand Concrete Society Conference, October 1999.

NACE. 2000. Cathodic protection of reinforcing steel in atmospherically exposed concrete structures. *NACE Standard RP 0290-2000*.

NACE. 2001. Electrochemical chloride extraction from steel reinforced concrete – a state of the art report. *NACE International Publication 01101, Item 24214*. 14 pp.

Nustad, G.E., Decter, M. 1997. Electrochemical repair of concrete, review of realkalisation and desalination – 10 years on. Pp. 313-318 in *Concrete 97*, Concrete Institute of Australia 18th biennial conference, Adelaide, Australia.

Page, C.L. 1992. Interfacial effects of electrochemical protection methods applied to steel in chloride-containing concrete. Pp. 179-187 in *Rehabilitation of Concrete Structures*. Eds: Ho, D.W.S., Collins, F. Melbourne: RILEM/CSIRO/ACRA. 486 pp.

Page, C.L., Sergi, G. 2000. Developments in cathodic protection applied to reinforced concrete. *Journal of Materials in Civil Engineering 12(1)*: 8-15.

Pocock, D. 1995. Chloride extraction and realkalisation – six years on. *Construction Repair-Concrete Repairs 9(2)*: 42-47.

Polder, R.B., Walker, R.J., Page, C.L. 1995. Electrochemical desalination of cores from a reinforced concrete coastal structure. *Magazine of Concrete Research 47(173)*: 321-327.

Rowe, G.H., Freitag, S.A. 1984. Concrete quality in some New Zealand bridges. *National Roads Board Road Research Unit Bulletin 73*: 119-122.

Shayan, A., Xu, A. 2001. Some electrochemical effects of CP on concrete cracked due to AAR and contaminated by chloride ions. Paper 65 in *Corrosion and Protection 2001*, Australasian Corrosion Association, Newcastle, NSW.

Solomon, I., Cope, M., Vimpani, P. 1999. Key design factors and criteria for successful reinforced concrete CP systems. Paper 39-021 in *Corrosion and Protection 1999*, Australasian Corrosion Association.

Standards Australia. 2002. Cathodic protection of metals – Part 5: steel in concrete structures. *AS 2832.5–2002*.

Standards New Zealand. 1995. Concrete Structures Standard. *NZS 3101:1995, Parts 1 and 2*.

Transit New Zealand. 2000. National State Highway Bridge Asset Management Plan.

Tritthart, J., Pettersson, K., Sorensen, B. 1993. Electrochemical removal of chloride from hardened cement paste. *Cement and Concrete Research 23*: 1095-1104.

Voon, Y.L., Lim, C.B., Lawson, M.J., Irwin, R.W. 2001. Long term rehabilitation technology for concrete marine structures using impressed cathodic protection systems. Paper presented at *Construction Technology Conference – Contec – 2001* Kota Kinabala, Malaysia, October 2001.

Woodhouse, J.J. 2000. Norcure electrochemical concrete repair of British Telecom Tower Podium Buildings, London. Paper presented at *Developments in repair and maintenance of concrete structures*, Aston University, Birmingham, UK, 27 September 2000. 5 pp.

Wyatt, B. 1995. Cathodic protection of steel in concrete. *Construction Repair July/August 1995:* 33-40.

[no author]. 2002. Electrochemistry used in bridge restoration. Project report, *Concrete in Australia, June-August 2002.* 11.