CATHODIC PROTECTION FOR THE

REHABILITATION OF

CONCRETE PARKING STRUCTURES

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Date: MARCH, 1990

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This publication is one of the many items of information published by CMHC with the assistance of federal funds.

PREFACE

This document is intended as a reference document for individuals who desire a technical understanding of the evaluation and use of cathodic protection in deteriorating parking structures.

There are no generally accepted standards for cathodic protection of reinforced concrete. There is no way to assess visually whether a system is performing acceptably. A purchaser therefore requires a somewhat higher level of understanding of the theory and application than for most products in order to make an informed decision about cathodic protection.

The information contained in this report is based upon a review of the literature, discussions with building owners and with suppliers of cathodic protection systems, and the authors' direct experience with several installations. It is believed to be current at the time of writing. Ongoing developments will likely improve the technical understanding of the processes involved and create new products. These factors may in the future affect the validity of some of the contents of this report.

The decision about whether or not to use cathodic protection should be made with the involvement of a knowledgeable specialist. This report does not provide all the necessary information about cathodic protection, or about concrete repair options, upon which to base this decision.

The funding for this report was provided by Canada Mortgage and Housing Corporation, but the contents represent the author's review of available literature and no responsibility for them should be attributed to the Corporation.

ACKNOWLEDGEMENTS

The author wishes to thank the following people for their assistance in the preparation and review of this report:

Mr. Bob Gummow (Corrosion Services Ltd.) for his critical analysis of both the writing and technical content.

Dr David Manning (MTO), Mr. E. Sanderson, P.Eng. (OHC), Gerald Lichty, P.Eng. (MTHA) and Dr Stephen J. Clarke (Research and Productivity Council of New Brunswick) for their very useful critical reviews of the drafts of this document.

Mr. J.A. Bickley, P.Eng., reviewed this report as it applies to the CSA Standard S413M - Durable Parking Structures.

Mr. Alvin Houston (CMHC) for his assistance in sourcing references and advice in developing the text with a non-technical reader in mind.

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1. OBJECTIVES

1.1

The purpose of this report is to document the present state of knowledge about cathodic protection (CP) systems for concrete parking structures. It is intended as a reference document for individuals who wish to develop a thorough understanding of the theory and application of the process. A shorter companion report "A User's Guide to Cathodic Protection for Rehabilitation of Concrete Parking Structures" has been produced to provide an overview of the topic for less involved readers.

1.2

Section 2 Theory explains the principles behind cathodic protection of reinforced concrete. For a description of basic terms, refer to the glossary in Appendix E.

1.3

Section 3 covers the basic design considerations, and the systems currently available.

1.4

Section 4, Structure Evaluation Requirements, outlines the information which should be obtained about a specific structure, to evaluate rehabilitation strategies and the suitability of cathodic protection.

1.5

Criteria that can be used to compare cathodic protection to other rehabilitation methods are presented in Section 5 - Evaluation Criteria. Section 6, Implementation/Operation, contains recommendations for the physical installation and the monitoring and operation phases.

2. THEORY

2.1 GENERAL

Corrosion of steel in concrete involves a complex interaction of non-uniform materials and varying environmental conditions. A reinforced concrete structure contains steel reinforcing bars embedded in concrete. The steel is cost-effective at resisting tension, and the concrete is efficient at resisting compression. The two must be bonded for the structure to work. The following components and processes are pertinent to the cathodic protection of steel in concrete.

a) Concrete

Concrete is a solid mixture of stone aggregates and portland cement paste. The paste is created by a reaction between water and the aluminas, silicas and lime in portland cement. The results is a structure with various sized of pores or voids in which water exists. The smallest pores contain GEL WATER. Adhered gel water does not evaporate when concrete is dried; the remaining gel water can be evaporated. CAPILLARY WATER exists in small natural pores spaces within the mortar. This water can evaporate. Finally, large voids, often intentionally introduced as entrained air to prevent frost damage in hardened concrete, contain FREE WATER. The composition and water content of the paste can vary significantly across small distances in concrete.

b) Steel

The mild, low-carbon steel used in normally reinforced concrete is a solid alloy solution of nickel, silicon, chromium, etc. in iron and iron carbide. The alloy does not have a perfectly uniform composition, and threfore, even without variability in concrete properties, the interface between steel and concrete will vary. The steels used in prestressed concrete have much higher strength than "normal reinforcing". This is created by a higher carbon content and different crystal structure. There are two basic types used - "cold-worked, stress relieved (ferritic-perlitic)" in North America and "heat treated, tempered (martensitic)" in Europe.

c) Passivation

The initial reaction on the surface of steel in concrete results in the formation of a film of ferrous oxide (Fe_2O_3). In a stable, alkaline environment such as is found in uncontaminated concrete, this film will adhere to the surface and isolate the iron in steel from oxygen. This is passivation. Corrosion essentially does not occur on a passivated surface. The introduction of chlorides to the reaction leads to the creation of ferric oxide which does not form a film and allows more iron on the surface to react. This effect of chloride is called depassivation.

d) Electrochemical Reaction

An ELECTRICAL CELL consists of an anode and a cathode in an electrolyte (Figure 1). There is a potential (voltage) difference between the two, which is the sum of the potentials at the anode/electrolyte and cathode/electrolyte interfaces. Each of these is a HALF-CELL.

Negatively charged ions in the electrolyte move towards the anode and positively charged ions move towards the cathode at rates dependant upon their mobility in the electrolyte. This movement of ions represents a current. Whether or not the anode and cathode are connected, there is still a POTENTIAL for the flow to occur. The magnitude of the potential at the anode, which is measured in volts, in a measure of the tendency for the anode surface in contact with the electrolyte to corrode. Electronic current flows between the anode and cathode if they are connected by a conductor.

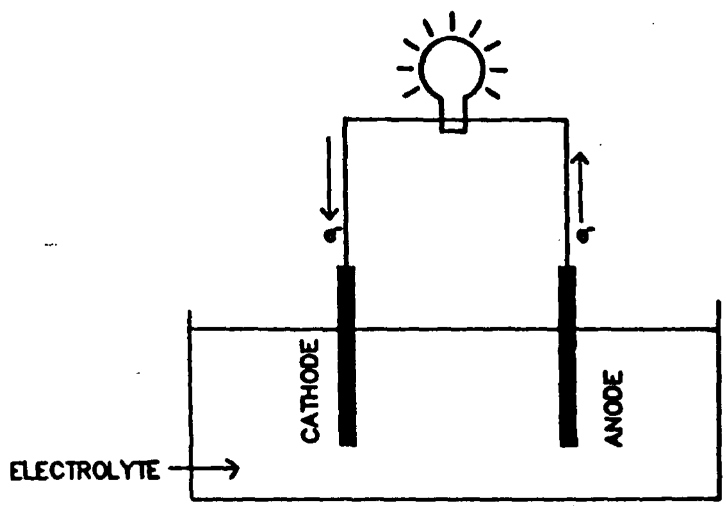


FIG. 1 ELECTROCHEMICAL CELL

An electrochemical reaction involves two (or more) partial reactions, called oxidation and reduction. Electrochemical reactions occur at ELECTRODES, which are generally metallic conductors, in an ELECTROLYTE (an ionic solution). Ions (charged chemical compounds or elements) flow through the electrolyte. Chemical changes occur in the electrolyte in the regions of the electrodes in a process termed ELECTROLYSIS. The donor of electrons to the electrolyte is the CATHODE and the reaction is REDUCTION, including metal deposition (as opposed to corrosion), hydrogen liberation and formation of an alkaline substance (ie. hydroxyl ions). Positive ions are generated (electrons are removed) at the ANODE. The reaction is known as OXIDATION, including dissolution of the anode (corrosion), the production of oxygen molecules and an acid or liberation of a non-metal.

e) Corrosion

Corrosion, for our purpose, is the destructive chemical reaction in which the elemental form of a metal is converted to a combined form. For reinforcing steel in concrete, the elemental metal which corrodes in steel is iron (Fe). The iron reacts with oxygen (O_2) and hydroxyl ion (OH-) to form ferrous (Fe^{+2}) and ferric (Fe^{+3}) compounds, commonly known as rust (Figure 2). The increase in volume between iron and rust creates stresses which can fracture concrete and eliminate the bond between the steel and concrete. This fracturing, loss of bond and reduction of the area of the reinforcing weakens the structure.

ELECTROCHEMICAL CORROSION of a metal occurs when it is the site of the oxidation reaction in an electrochemical reaction and there is current flow. The corrosion rate is governed by many factors and can be measured by the current flow.

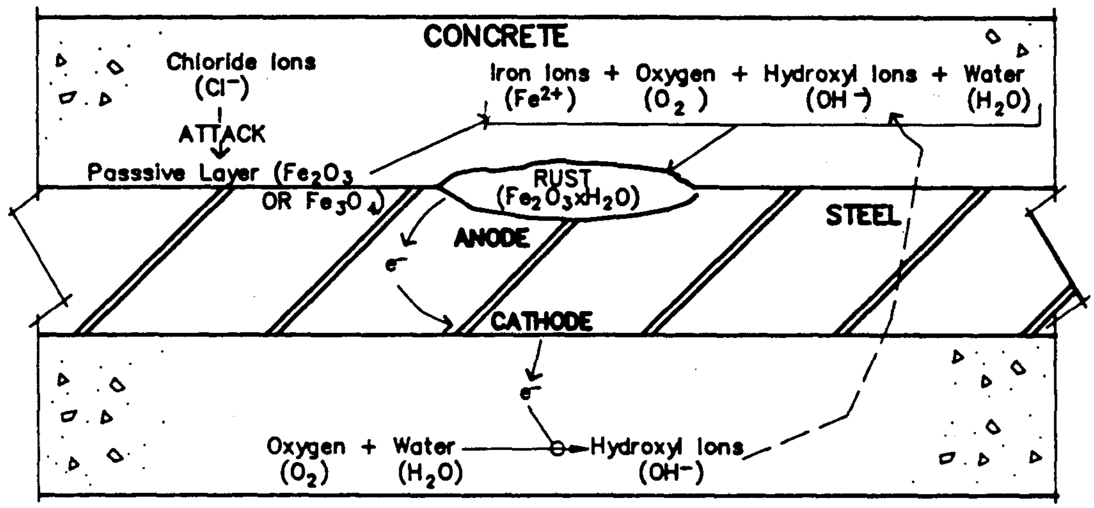


FIG 2. ELECTROCHEMICAL CORROSION MECHANISM OF STEEL IN CHLORIDE CONTAMINATED CONCRETE.
(NOT ALL CHEMICAL REACTIONS ARE INCLUDED)

f) Reference Half-Cell

If the potential of one half-cell in an electrochemical corrosion cell is a known constant and the voltage between the two half-cells is measured, then the potential at the other half-cell can be calculated. A REFERENCE HALF-CELL consists of an electrode in an electrolyte for which the electrochemical reaction is reproducible (ie. in thermodynamic equilibrium).

When a reference half-cell is placed in contact with concrete, an electrical cell is created with the concrete/steel half-cell. The potential of the concrete/steel half-cell at different locations can be compared by measuring the voltage between the electrode in the reference half-cell and the reinforcing steel in the concrete. Typical reference half-cells are Copper in Copper-Sulphate ($Cu/CuSO_4$ or CSE), Saturated Calomel (SCE) (actually a mercury based half-cell), and Silver in Silver Chloride (Ag/AgCl).

Carbon or graphite probes are also commonly used. These are sometimes called a pseudo-reference electrodes. The potential generated at this type of electrode is due to the oxygen reduction reaction as opposed to chemical reaction with an electrolyte. Testing has found these to produce stable readings in the concrete environment, however careful calibration and interpretation are required.

g) Polarization

As an electrochemical reaction proceeds, the ionic flow in the electrolyte can lead to an accumulation of charged particles at the anode and/or cathode. This can create a potential drop across the electrolyte/electrode interface which reduces current flow. This process is termed POLARIZATION. In cathodically protected concrete, migration of chloride ions to the anode and hydrogen ions to the cathode (steel) is believed to be the major polarization process.

2.2 CORROSION OF STEEL IN CHLORIDE CONTAMINATED CONCRETE

The electrochemical principles used to describe corrosion in concrete are based upon the analysis of laboratory experiments on small, well defined samples. The extrapolation of these results to a complex chemical system such as a parking structure will, at best, give a rough guide as to the processes that are taking place.

Concrete is a very alkaline material (pH of 12 to 13). At this level, the passivation process is supported and corrosion is negligible. Chloride can enter concrete from road salt (NaCl), from chemical admixtures used in the production of concrete (eg. calcium chloride) or from contaminated aggregate (although most of this will be unavailable for the corrosion reaction because it does not enter the pore water). Chlorides act to disrupt the stable oxide film on passivated steel. The pH level immediately adjacent to the steel is reduced by the corrosion products. (It is not reduced throughout the concrete). Where the passive film is broken, electrochemical corrosion reactions develop between the concrete and steel.

The anodes and cathodes in the electrochemical corrosion cells in reinforced concrete are formed at different sites on the reinforcing steel. There are generally considered to be two types of corrosion cells in reinforced concrete, often referred to as MACROCELLS and MICROCELLS (Figure 3).

Macrocells exist between sites which are more than a few millimetres apart - either on the same bar or on different bars. An example of a macrocell would be between the steel in the top of the slab and that in the bottom. The anodic layer is in chloride contaminated concrete (generally the top in parking structures) and the cathode is the layer(s) of steel in less contaminated or uncontaminated concrete. The electrolyte is the concrete.

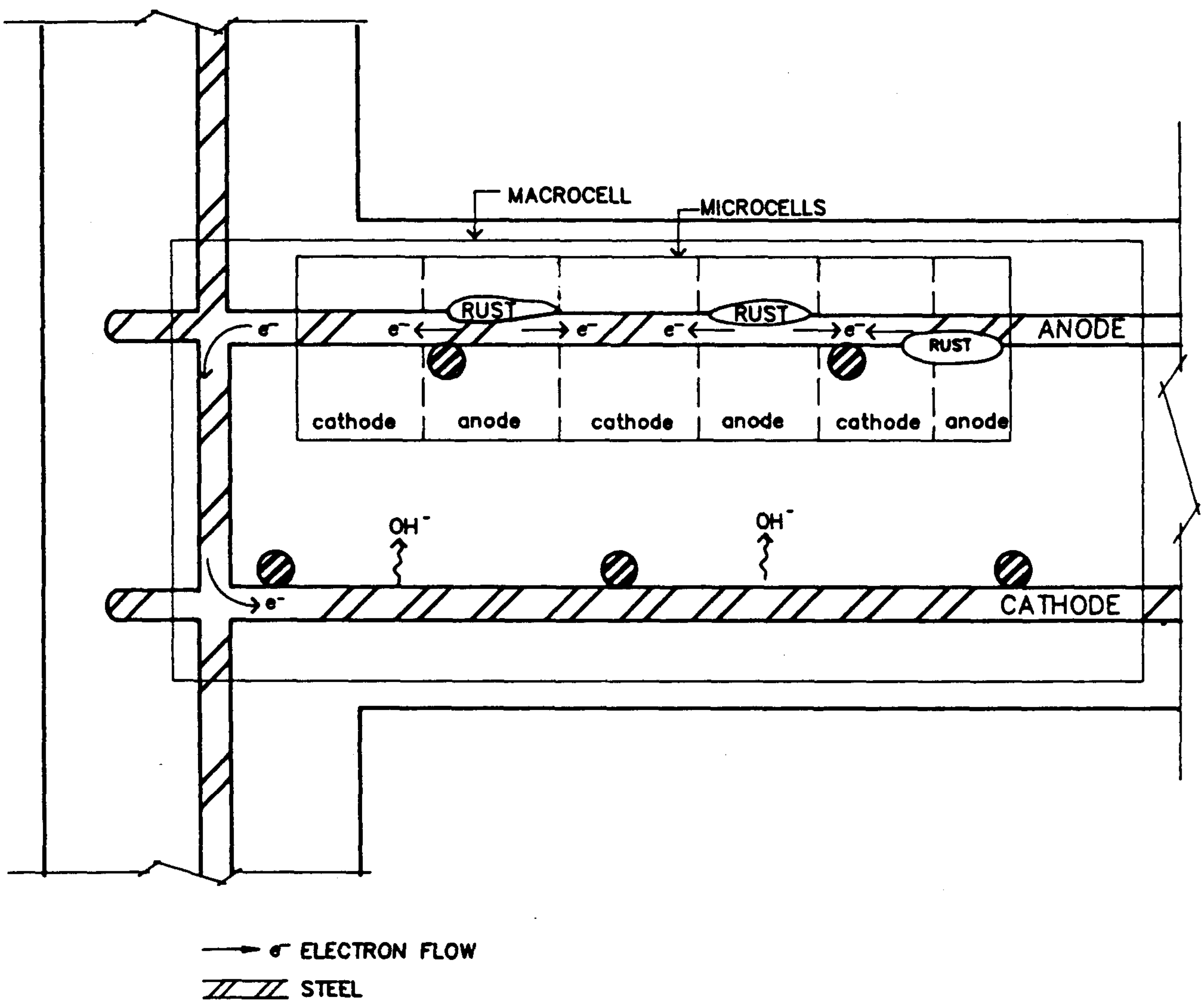
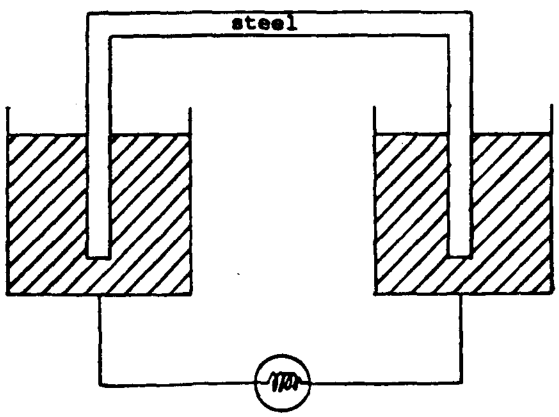
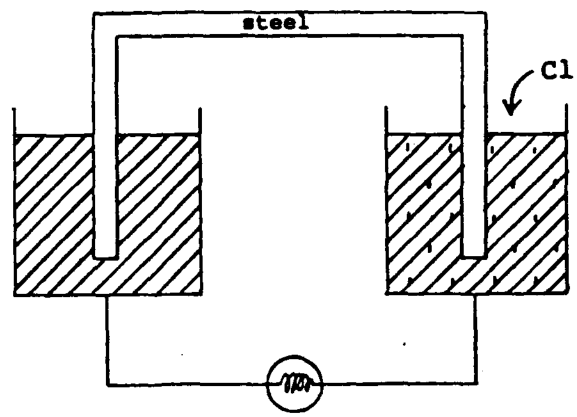


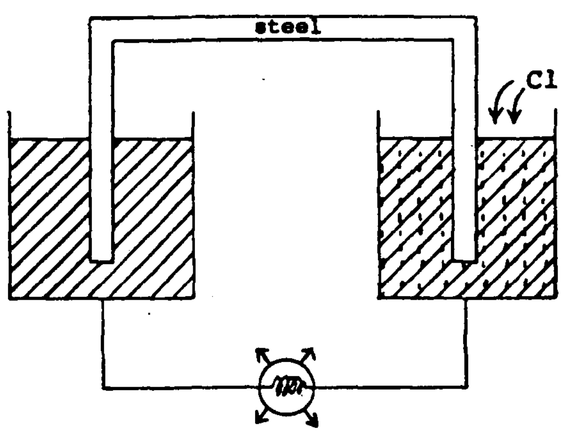
FIG 3. SCHEMATIC DIAGRAM OF MACROCELL AND MICROCELL CORROSION CELLS IN REINFORCED CONCRETE STRUCTURES CONTAMINATED BY CHLORIDES. (MICROCELLS ARE ACTUALLY VERY SMALL)



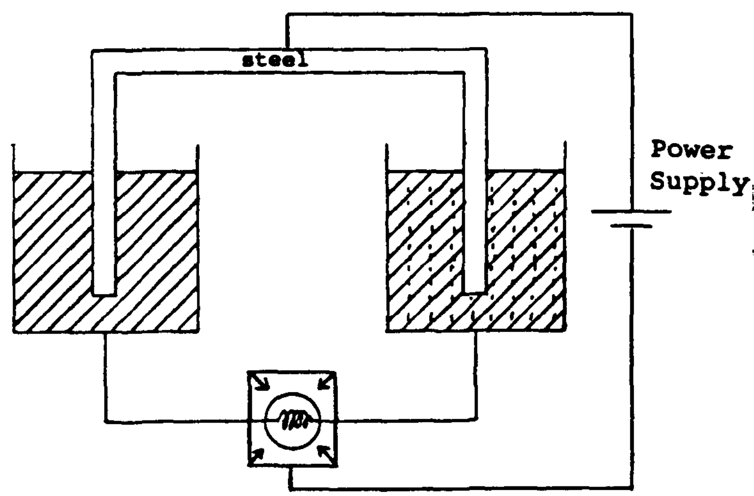
1) Steel in uncontaminated concrete - same electrodes, same electrolyte - no current



2) Slight contamination of 1 electrolyte, not enough difference for current flow



3) Significantly greater contamination of electrolyte, corrosion reaction at anode, electric current flows between electrodes



4) Cathodic Protection

FIG. 4 CORROSION CELL & CATHODIC PROTECTION

2.4 THE EFFECT OF CATHODIC PROTECTION ON THE CORROSION PROCESS

In order to turn the corrosion sites on reinforcing steel into cathodes, sufficient current must flow from the anode into the steel through the concrete (current flows from + to -) (Figure 5). For effective cathodic protection, the impressed current draws electrons from the steel, countering both microcell corrosion (by making both layers of steel electron donors to the concrete electrolyte) and microcell corrosion (by shifting the potential along the entire surface of the steel sufficiently to make all sites electron donors). The oxidation reaction of the iron is inhibited because of the supply of electrons takes away the tendency for iron to become more positive, as is required for rusting. It is not believed that there is any tendency for passivation as a result of cathodic protection. (This would require anodic protection.)

The power supply of a cathodic protection system is connected at a few locations to the reinforcing steel of the treated structure. Only the steel which is electrically connected to the power supply is protected by the applied current. If steel which is not connected ("discontinuous steel") exists between the anode and the connected reinforcing, some of the current flowing from the anode to the steel will flow through the steel instead of the more resistive concrete (Figure 6). A local cathode is formed where this current enters the discontinuous steel. Where the current leaves, a local anode is formed and the steel will corrode.

To prevent structural weakening, all of the reinforcing steel must be electrically connected to the continuous steel. The continuity of the reinforcing is typically checked by comparing the output readings from a half-cell on the surface of the concrete when the rebar connection is moved from location to location. If the reinforcing steel cannot be made continuous, cathodic protection cannot be used.

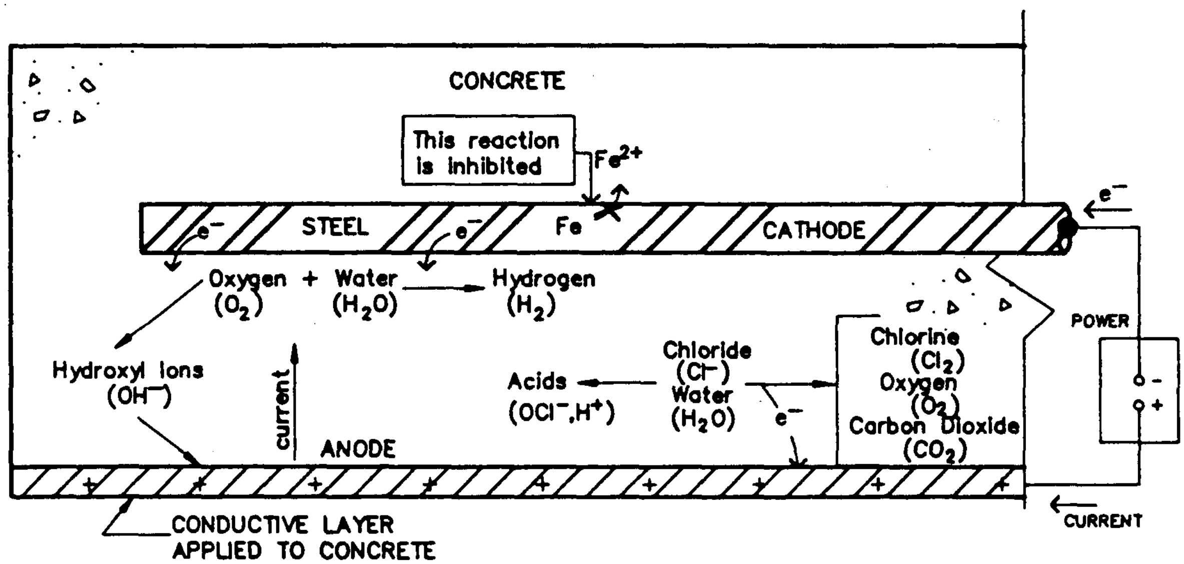


FIG. 5. SCHEMATIC DIAGRAM OF IMPRESSED CATHODIC PROTECTION OF STEEL IN CONCRETE.

NOTES: CHLORINE GENERATION ONLY AT ANODE VOLTAGES OVER ABOUT 1V (CSE)
: OCl^- = HYPOCHLOROUS ACID

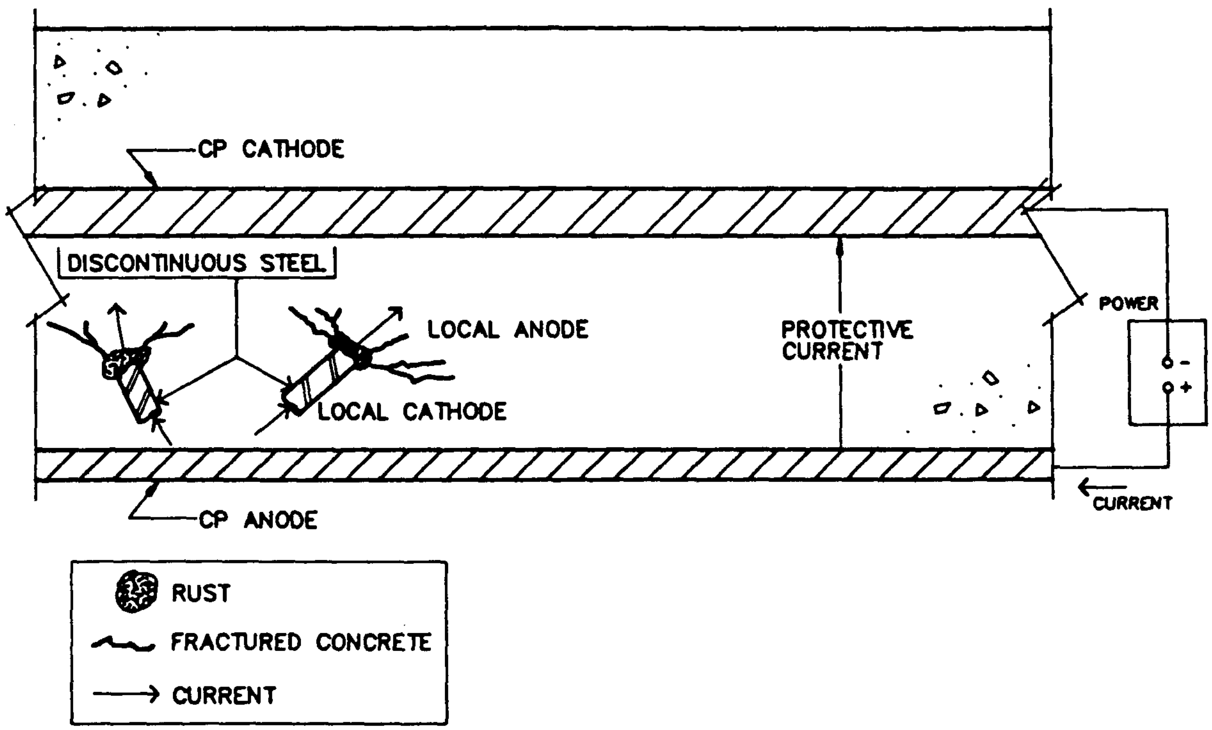


FIG. 6. CORROSION OF DISCONTINUOUS STEEL IN IMPRESSED CATHODIC PROTECTION SYSTEM

There is often other metal, embedded in slabs, such as construction debris left in the forms, which cannot be identified prior to installation and therefore corrodes after the system has been in operation. The significance of this situation depends upon the amount of steel involved. The likelihood of delaminations on the soffit can be significant.

If there is steel, or other conductive material, in electrical contact with both the anode and the cathode, a short circuit will exist. The applied current will mostly flow through the low resistance route instead of through the concrete. Therefore, there will be relatively little current across the rebar/concrete interface and relatively little cathodic protection.

3. SYSTEM DESIGN PARAMETERS

3.1 SYSTEM COMPONENTS

The basic components of an impressed cathodic protection system in reinforced concrete are:

a) the reinforcing steel with its supports and connectors installed during original construction;

b) the original concrete and any new patch materials installed during structural repairs;

c) a power supply comprising a rectifier for each zone, which converts AC (mains) power to DC, control circuity which adjusts the amount of current or voltage applied to the system and conductors connected between the power supply and the anode, and between the supply and the reinforcing steel;

d) an anode applied to the surface of the member(s) to be protected;

e) reference half-cells to provide repeatable corrosion potential readings at a known point and/or to provide a reference for rectifier output control.

3.2 CURRENT SUPPLY

3.2.1 Current Densities

To be effective a cathodic protection system must cause a suitable amount of current to flow into the reinforcing steel from the concrete. There are basically two stages to this:

a) distribution of electronic current through conductors from an external power supply to the anode and from the steel to the power supply; and

b) distribution of ionic current through the concrete.

In general terms, the conversion between ionic and electronic conduction occurs at the interfaces between the steel and concrete and between the anode and concrete. The relationships between current, voltage (potential) and resistance are reasonably well understood and uniform in the electronic flow components. The ionic flow, however is affected by many poorly understood and non-uniform factors.

The current density at the cathode is the amount of current flow per area of reinforcing steel surface. Current density at the anode is measured either at the surface of the anode material, or at the surface of the concrete where the layer of material which contains the anode is bonded.

The rectifier output required to produce a given average current density over a section of anode is affected by the resistivity of the concrete and the distribution of steel within the concrete. In the case of steel in concrete it has been found that a current density of about $10mA/m^2$ to $20mA/m^2$ ($1mA/ft^2$ to $2mA/ft^2$) of concrete surface is sufficient to achieve cathodic protection (89, 93, 114, 124, 150). The local values may range from about $5mA/m^2$ to $100mA/m^2$. Acid damage to the concrete is prevented by keeping maximum concrete current density less than $108mA/m^2$. These figures are not a steady state operating current density; rather they are an indication of the current likely to be needed in order to "polarize" the steel, and hence are used in sizing the rectifiers.

Typical operating steady-state current densities are reported to be between 1 to $8mA/m^2$ of concrete surface (99, 109, 114). At this time, the correct design parameters for cathodic protection are empirical. Variations in current density reaching the steel can result under-protection of some sections of steel.

In a typical flat slab parking structure, the ratio of steel surface area to concrete surface area would be about 0.5. About 40% to 55% of the steel would be in the top mat. Considerable variations from this can be expected with changes in codes and local practices. For sufficient current to reach the steel furthest from the anode, the nearer mat of steel must be overprotected. Field measurements (99, 131) have reported 20 to 30% of current applied reaches the further steel.

3.2.2 Current Distribution

The amount of current flow to the embedded steel at different locations is affected by variations in:

- the current flow within the anode;
- the density of steel in the slab;
- the electrical resistance of concrete at various locations;
- the resistance at the interface between the steel and concrete (which is affected by the chemical effects of carbonation); and
- the distance between the steel and the surface to which the anode is applied.

Most anode systems used at present are in the form of coatings or meshes covering the entire slab surface. Ideally, current from the rectifier would be distributed into the anode in a manner which provides even distribution of current to the steel. As steel density varies between different locations and between top and bottom mats, it may be desirable to vary the anode current density to suit. In practice, this is not done and the objective is to achieve relatively even current densities in the anode. Current is supplied to the anode by conductors (often called primary anodes). The distance between conductors and between connections to the anode governs the variations in current which will occur in the anode. The total flow is not governed by the resistances in the conductors and anode because they are generally orders of magnitude less than the concrete resistances.

Concrete resistivity is generally found to be in the range of 5,000 to 50,000 ohm-cm. Shotcrete resistivity in one study was found to range from 50,000 ohm-cm to 160,000 ohm-cm. It is differences in resistivity, not absolute resistance, which is believed to affect the protection provided. Patching can therefore create problems with current distribution.

The conductivity of concrete is proportional to the ratio of water to cement in the manufacture of the concrete and the in service moisture content of the concrete at a particular time. The ability to absorb water, and thus chloride permeability, also increase with the water:cement ratio. The conductivity of concrete is increased by chlorides added to the concrete during manufacture or contained in water absorbed by the concrete in service by increasing the free ion contamination.

Good design practice calls for installing separate anode systems, energized by separate power supplies, operating in parallel. This procedure enables sections of slab that require higher amounts of current to be satisfied without overprotecting other areas. One power supply circuit per $1000m^2$ of surface is a common design value (79, 97).

3.2.3 Power Supply

The total amount of current supplied by an impressed cathodic protection system is a function of the applied voltage and the circuit resistance. In order to ensure that the protection is being maintained, the power supply must have a control system which reacts to changes in the current/voltage/resistance relationship brought about by environmental, material and/or electrochemical changes in the concrete.

In addition, there is a polarization effect whereby the current received by the cathode is reduced by accumulation of positive ions around the steel. Because the time required to achieve "polarization" cannot be predicted, a control mechanism is needed to adjust the current output from the rectifier to the designed value from time to time (131, 133).

The most basic control procedure for impressed current cathodic protection involves a feedback loop to adjust the current flow as necessary to maintain the desired potential of the steel. This feedback process can, in principle, be performed automatically using a suitable reference half-cell to measure the potential of the steel and a constant voltage power supply, which is a rectifier with control circuitry which adjusts the current to maintain a constant potential. However, the reference half-cell potential indicates only a local condition within the area of slab being controlled. Thus, to control a system with reference half-cells, a large number would have to be installed in the slab, with a procedure established for scanning them and performing a statistical analysis on the range of measured potentials.

In practice, system control is not based upon embedded half-cells. Instead, technicians measure the steel-to-concrete potentials at many sites on the surface of the slab periodically with a portable reference half-cell. The rectifier output is adjusted manually, depending upon the results obtained. Constant current power supplies are used as they are less expensive than constant potential rectifiers (131, 133).

3.3 MOUNTING LOCATION

The anode can either be applied on the top surface or bottom surface of the slab. Each location has advantages and disadvantages, as follows.

Soffit mounted systems have two primary disadvantages. Exposed supports for the reinforcing and debris such as nails and wire are relatively more abundant on the underside of a typical slab than the topside, so soffit mounted anodes have a greater potential for short circuits and discontinuous steel corrosion than the top surface anodes. The other primary concern is that whereas it is typically the top layer of steel which requires the greatest protection from the cathodic protection system because of higher chloride contamination, the bottom layer of steel receives most of the protective current in soffit mounted systems (see 3.2.1).

A less immediate potential problem with soffit mounted systems is that the impressed current flow can draw chloride ions from the top of the slab down into previously uncontaminated concrete. Application problems include the interference associated with soffit mounted conduit, piping and lighting.

There are several advantages to mounting the anode on the soffit. There is no physical wear of the anode on the soffit. The anode is above existing headroom restrictions. Soffit systems can often be installed during hours when the facility is closed to traffic, whereas top surface installation requires closure of parking stalls for some time.

The primary advantage of top mounted systems is that they are closest to the steel in most need of protection (ie. the top layer). In some types of structure (eg. waffle slab or beam/joist systems), the underside has much more surface area over which the anode has to be applied than the topside.

Top surface installations are particularly suitable for these types of structures. Top surface installations require the removal of existing surface treatments and contaminants which would affect bond of the anode. They must resist tire wear with as little thickness (to minimize headroom loss) and weight addition as possible.

3.4 ANODE TYPES

The cathodic protection principles applied to reinforced concrete parking structures have evolved from the systems developed and used in concrete bridge decks and substructures, and offshore seawater structures. Bridge deck cathodic protection was proposed and tested in the late 1950's. Parking structures, although constructed of similar materials, differ from bridges, in that they are typically lighter, have less load capacity, have restricted headroom, and need waterproofing to prevent damage to cars below. For this reason, anodes which may be acceptable for bridge decks may not be optimal for parking decks, and vice versa.

The four basic types of anodes used in parking structures are:

- conductive coatings
- surface treated titanium mesh
- conductive polymer mesh
- conductive membrane

3.4.1 Conductive Coatings

a) General

These systems use a relatively thin, electrically conductive coating to function as the distributive anode (Figure 7). Coatings currently in use are either solvent or latex (water based) paints with carbon/graphite filler. (Sprayed, metallized zinc is a type of coating being tried on bridge abutments, but not in parking structures.) The coating is generally applied to the underside (soffit) of the deck to be protected. Current is usually distributed to the coating along platinum niobium-coated copper wire set in either gel or grout. A decorative top-coat, usually water-based acrylic paint, is applied overtop to protect the anodic coating and improve the appearance without significantly inhibiting vapour flow.

One trial of a conductive coating applied to the top surface beneath a membrane has been installed in Toronto.

b) Installation

The surface to be protected is cleaned of all existing coatings or unsound material which would inhibit bond and/or current flow. Sandblasting or high pressure waterblasting can be used. Short circuits, leaking cracks and isolated steel are identified and electrically insulated as fully as possible. The coating is applied (spray, brush or roller depending on material) to the required thickness. Distribution wires are mechanically fastened to the concrete and connected to the power source. A white top coat is then applied.

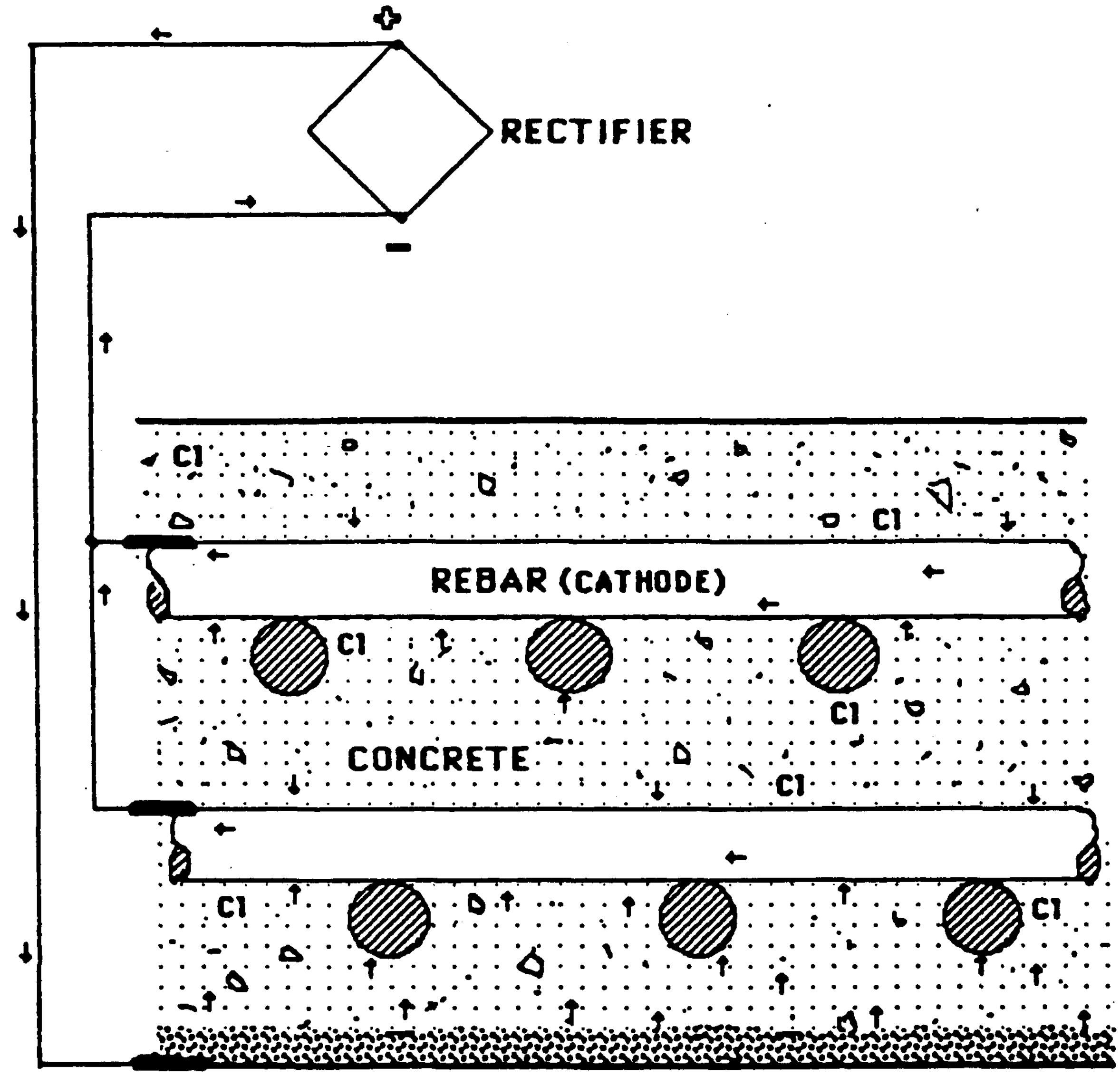


Figure 7: Schematic Diagram of Conductive Coating System (From Porter Coatings)

c) Advantages of Conductive Coatings

These systems are lightweight and do not reduce headroom. A uniform coating for even current distribution is provided. Application and material costs are the lowest of available systems. The lifespan of the anodic coating can be estimated by calculating the rate of consumption of the consumed anode component (ie. carbon) at the designed current densities.

d) Disadvantages of Conductive Coatings

Acid conditions generated at the anode (eg. hypochlorites) may adversely affect these coatings (particularly acrylic latexes) and their bond to concrete. Chloride gas is evolved at the anode. The conductive coating is consumed in the anodic reaction. The materials are typically not resistant to water. Solvent based coatings require special precautions against odour and fire during application.

3.4.2 Titanium Mesh In Mortar

a) General

Alloys of titanium (Ti) can be economically viable, strong and reasonably ductile for producing a conductive mesh. Their surface, however is normally highly passivated. Thin films of the platinum metals or their oxides can be metallically bonded to a titanium surface, resulting in an inert but electrochemically active surface. These electrodes have been developed for the production of chlorine gas and are now being applied to reinforced concrete cathodic protection. Anodes used for cathodically protecting reinforcing steel are made from sheets about 1mm thick, expanded into diamond shaped mesh which is formed into rolls for transport and storage (Figure 8).

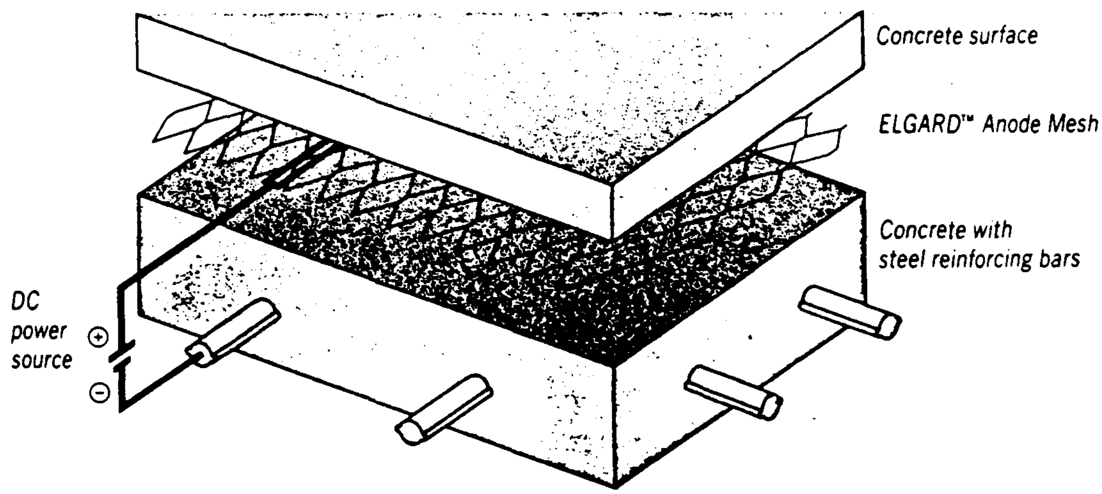


Figure 8: Schematic Diagram of Mesh Anode System (From Eltech Corp.)

b) Installation

Once the surface has been cleared of short circuits and exposed steel, the anode mesh is unrolled over it. Because the diamond shaped voids are extendible to a certain extent, it is possible to stretch the mesh over a contoured surface. The sheets are held in place with plastic cleats that are inserted in holes drilled into the concrete surface. Once the sheets are installed, adjacent sheets are brought into mutual electric contact either using strips of Ti that are spot welded to the nodes at the sheet edges or by simple overlap of the mesh, depending upon the system. The Ti strips serve to bring current to the anodes and to ensure that there is adequate electrical contact from sheet to sheet. In either system, multiple redundant current paths are set up, so that the performance of the anode will not suffer if some strands or mesh are ruptured during installation.

Once the mesh is installed it is covered with a layer of a cementitious product that is ionically conducting and otherwise suitable (ie. resistant to wear, able to bond to the concrete, waterproof, cost effective). If the mesh is soffit-mounted then the overlay is sprayed on. It is important to ensure that the mortar is in good electrical contact with both the mesh and the concrete slab.

c) Advantage of Titanium Mesh Electrodes

The prepared titanium surface is inert to anodically generated chemicals (hydrated oxy-chloro compounds). Mesh distribution can be varied to suit distribution of reinforcing steel. Top surface or underside application is possible. The relatively large effective area of the mesh ensures an even distribution of current to the steel to be protected.

Visual inspection is generally sufficient to prevent short circuits from occurring during installation because the anode does not penetrate the surface of the concrete. Because the mesh is embedded in mortar it is well protected from abrasion damage. The indications are that the mesh material will have a maintenance free life of at least 20 years. (Platinized titanium anodes used for protecting underground pipelines have lasted for 20 years and more.)

d) Disadvantage of Titanium Mesh Anodes

The mesh material is relatively expensive and the mortar topping is expensive in both labour and material. A good deal of preparatory work is required to ensure bonding of the mortar. Although the Ti mesh can be soffit mounted, this option would normally only be feasible in a building under construction, before fixtures such as lights and sprinklers are installed. Top surface mounting requires that the mesh is applied directly to the concrete surface. If this is already covered with a membrane/asphalt system then this would have to be removed prior to the installation of the mesh. Repairs to the anode require removal and replacement of the protective overlay(s), increasing repair and examination costs.

3.4.3 Conductive Polymer Mesh In Concrete

a) General

To make polymers, such as polyethylene or polyvinyl chloride conductive, they are blended with carbon black of sufficient particle size and quantity that continuous conductive paths exist within the polymer matrix. To make anodes for cathodic protection systems, the conductive polymer is extruded over a copper wire, so that the finished product is similar to regular cable in appearance. Properly selected carbon fillers/polymer combinations allow current to pass from the coating surface into the environment (ie. chloride laden concrete) without appreciable deterioration occurring upon the electrode surface. Also, although the coating is conductive, its resistance is high enough to ensure that current is available from the copper conductor along its entire length. It is possible to form a mesh by connecting pairs of individual wires with conductive clips, to create a configuration with multiple redundant current paths.

b) Method of Installation

The method of installation of these anode systems is very similar to that of the expanded titanium mesh anodes. They have to be anchored to an exposed concrete surface and then covered with a layer of mortar. The procedure must prevent damage to the conductive coating, otherwise the copper conductor will be exposed to the environment, which would cause rapid corrosion of the copper. A method for overcoming this problem is to interconnect cables using conductive fasteners. However, because the resistance of the coating is high very little current can be transferred from cable to cable by this technique.

c) Advantages of Polymer Mesh

The anode system has low mass and hence can be used on any suspended slab, if it is embedded into the existing thickness of the slab (ie. not inside a concrete topping). Cable type anodes are flexible and can be installed on uneven surfaces. The conductive polymer surface is presumably inactive in the electrochemical environment generated after several months of operation. Because the wires are embedded in mortar or concrete they are more or less immune to mechanical damage during operation except for cracking of the concrete.

d) Disadvantages of Polymer Mesh

The anode material is relatively expensive. There is only one supplier. Extensive preparatory work is needed. The mortar is expensive in labour and material. Damage to the conductive coating is liable to allow electrolyte to make direct contact with the copper conductor which would corrode at that point. Individual cables have to be installed at close centres to ensure good current distribution to the underlying rebar system. This requirement increases the installation time, and is an item that must be closely monitored to ensure that it is done properly because it is difficult to add extra anodes once the concrete has been poured. The conductive coating becomes brittle with time, and there is a danger that vibration could shake it loose, exposing the copper conductor, even with the anode embedded in concrete.

3.4.4 Conductive Membrane

The concept of combining the anode with a waterproofing membrane is intuitively appealing. In principle conductive membranes can ensure very effective current distribution over the slab and performance would be little effected by minor damage or imperfections. We have identified two small installations in Canada, one with a conductive coating applied to the top surface of a slab and a membrane applied over, and one which the membrane itself is conductive. Neither system is in production so only general comments can be made. In a 1989 test installation in Kansas City, two systems were operated, one of which apparently performed well.

Various problems remain to be addressed for these materials. Adding conductive fillers to a membrane typically reduces the membrane's flexibility and increase its permeability.

Elastomers (usually synthetic rubber based compounds) are not usually resistant to the highly oxidizing environment. The surface of an anode system in an alkaline environment contaminated is a highly oxidizing environment. Unless special precautions are taken the material is liable to lose its flexibility. This could adversely affect the bond, electrical continuity and waterproofing ability of the membrane.

Membranes are normally applied in the liquid phase, so that they can flow down into cracks or imperfections in the surface and may short circuit the system. The detection of such paths prior to installation could be difficult.

3.5 STRUCTURAL REPAIR TECHNIQUES

It is not clear from the literature what repair materials should be avoided in a structure which will have cathodic protection applied. If bare steel is to remain, the patch material should be about as conductive as the original concrete to allow even current distribution. This may not be the case for some modified mortars. Epoxy bonding agents may reduce current flow into a patch. Coated tie wires or support bars with exposed ends may create small anodes.

Epoxy coating the steel is not required but will not prevent cathodic protection from working as long as the coated bars are electrically connected. The coating reduces the surface area of steel to be protected. Removing chloride contaminated, but intact concrete fully around steel as is typically done in garage repairs is not required. (Fractured concrete should be replaced for structural integrity.) Steel need not have all rust removed, only enough to ensure no loose surface scale remains to impair the bond to the concrete. All of these factors should significantly reduce the cost of concrete repair if cathodic protection is to be the primary method of maintaining a durable structure.

4. STRUCTURE EVALUATION REQUIREMENTS

4.1 STRUCTURAL LAYOUT AND CONDITION

4.1.1 Structural Layout

The first step in structural evaluation is to establish the design principles for the garage. The following factors should be considered:

- The type of reinforcing is of interest primarily for its susceptibility for hydrogen embrittlement.

- The location of reinforcing may be useful in establishing current density variations and suitability of top vs. bottom applied system.

- The type of slab, beam and/or joist system will affect the number of protection zones and the concrete/steel surface area ratios.

- The location of expansion joints may lead to electrical isolation between sections of the structure (but often does not).

- The number of different pours should be recorded for reference in analyzing results because different pours often represent very different concrete properties.

- An estimate of the anticipated response of the structure to added dead load should be made to evaluate suitability of different systems. The flexibility of the structure may also affect the decision on selection of alternatives.

4.1.2 Structural Condition

The extent of concrete deterioration, and if possible its progression over time, is required to determine the cost of the structural repairs required prior to cathodic protection installation. Cathodic protection does nothing to replace structural integrity, so the cost for cathodic protection is over and above that for structural repair. The structural repairs required for a structure protected by a cathodic protection system may be less costly than those required for a program which does not incorporate cathodic protection (see 3.5).

The cost of reinstating lost cross-sectional area of reinforcing must be evaluated. This is necessary whether or not cathodic protection is employed. The loss of section of reinforcing in corroding, but not delaminated, areas can generally be assumed to be minimal except at leaking cracks.

4.2 CORROSION POTENTIAL

It is often suggested that any concrete which is chloride contaminated will eventually deteriorate because of corrosion. This has not been verified. Many buildings have chloride contaminated concrete superstructures which may delaminate on the exterior face but not on the interior. Therefore, reproducing the conditions of a building interior, which presumably involves keeping the moisture content of the concrete below some critical threshold, should prevent the initiation of corrosion.

Unpublished results from monitoring of existing garage repairs indicate that where a contaminated slab is protected from moisture, corrosion does not develop to a significant degree in areas which were not corroding before the access to moisture was cut off. Therefore, if a slab has relatively little corrosion activity outside areas in need of structural repair, cathodic protection would have little benefit.

The effectiveness of cathodic protection is in controlling corrosion in those parts of the structure which do not require structural repair. For example, if 60% of a slab is actively corroding, cathodic protection may be cost-effective if 5% is delaminated, but not if 40% is delaminated and needs repaired. Conversely, if only 5% is actively corroding, and if passive protection can stabilize the slab at this level, cathodic protection is not likely to be cost-effective. Therefore, the extent of corrosion activity, based upon a reasonable sample of surface, must be measured.

4.3 MISCELLANEOUS

The amount of miscellaneous metal in the concrete which is either discontinuous with the reinforcing or in contact with both the surface receiving the anode and the reinforcing (ie. creating a short circuit) will affect the performance of cathodic protection. This can not be accurately assessed visually, but should be considered in general terms for evaluation of likely cathodic protection performance.

It is still not known how much effect the chloride content has on cathodic protection performance, but records of the concentration could be useful for future evaluation.

5. EVALUATION CRITERIA

5.1 GENERAL

To evaluate repair strategies objectively, it is important to categorize the types of work involved in the rehabilitation program. Examples of decision tables for concrete structure rehabilitation have been published (12, 18, 84; Ontario Ministry of Housing - 1988) but a particular program is only appropriate for that structure and facility manager. Cathodic protection will likely be combined with other repair methods, such as concrete patching, waterproofing or sealers. The preferred combination should be arrived at with the guidance of a consultant specializing in this field.

A typical parking structure rehabilitation program addresses several issues, not all of which are related to the choice of corrosion treatment. Improvements to traffic flow, ventilation, etc. may affect the performance of repairs, but they will generally represent a common fixed cost added to any program.

This discussion is intended to address items which affect the relative costs of different strategies. There are three fundamental components of the discretionary part of the program: structural repair, corrosion control and occupancy needs. These are not independent, but should be evaluated separately to select from among available alternatives. The criteria to be used in evaluating the alternatives can be used in a wide variety of ways and with different importance attributed to them by different users.

5.2 STRUCTURAL REPAIR

The extent of repair required to reinstate a "safe" structure should be outlined. The types of damage should be separated into those caused by corrosion and those with other causes. The repair of structural damage not caused by corrosion may be affected by the corrosion treatment strategy. (For example replacement of the top surface of the slab could eliminate the need to repair frost damaged concrete, while separate repair of frost damage would be needed if soffit mounted cathodic protection were used to deal with corrosion.) In many cases, the damage would not be repaired as part of the corrosion treatment.

There will generally be deterioration which does not constitute an unsafe situation at the time of the evaluation, but which would be expected to progress and require repair in the near future to maintain structural integrity.

There will be some structural work which is necessary to allow other work to proceed (eg. surface repairs for membrane, anode, sealer and/or paint application, repairs at penetration locations such as expansion joint nosings or drains) or to make use of the facility safe (ie. intact concrete surface for pedestrians, elimination of the hazard of loose overhead concrete falling).

5.3 PROTECTION STRATEGY

The various approaches to dealing with the potential for future damage are generally as follows:

a) Do Nothing: Carry out repairs to meet immediate needs, hopefully without creating new problems, and wait to see what happens. This approach assumes little faith in the ability to predict the effect of present treatments. It also assumes that the cost of trying a preventative measure is not likely to be less than the costs of dealing with future deterioration. A belief in the improvement of technology and/or knowledge of existing systems is often associated with selecting this approach.

b) Apply Surface Protection: A membrane essentially excludes new water, salt contaminated or clean, from entering the top surface. Most membranes will also not allow existing moisture in the slab to evaporate. Studies have shown both a reduction in corrosion activity below membranes applied to corroding slabs, and a continuation of delamination formation. It is not possible to predict the relative contribution of each, so estimating the future costs associated with membrane application is based on subjective interpretation of available data. Sealer application (with effective products) permits visual observation of the surface, does not trap moisture, reduces water and chloride ingress, costs less than membrane application and should allow application of different surface treatment (eg. anode or membrane) with minimal cost. Cementitious overlays have properties which are combinations of sealers and membranes at much higher costs.

c) Remove Concrete from around Corroding Steel: This process, termed potential based removal, is based upon the belief that corrosion activity is reduced by applying a membrane. If concrete is removed in areas with potentials at the level associated with corrosion damage, and if the steel is electrically isolated before applying the membrane, future delamination formation should be minimal. This is subject to errors in measuring potentials and deciding the threshold level for removing concrete (too much or too little could be removed), but these should not be significant as the condition of the steel can be inspected as it is removed.

d) Remove all Contaminated Concrete: This approach assumes that any steel in chloride contaminated concrete will eventually deteriorate or that the process of patching will initiate corrosion in contaminated areas that were not previously corroding. This is a very conservative approach but one which has the highest chance of eliminating all further corrosion activity if this is the desired result of the repair.

e) Cathodic Protection: This is the only approach to corrosion control intended to actively combat corrosion without removing the concrete in affected areas. It typically has no other benefits (ie. no leakage control or structural rehabilitation). To rely on it as a solution requires a belief in the ability of available technology to make electrochemical theory work in reinforced concrete structures for a reasonable length of time without creating deleterious side-effects.

5.4 OCCUPANCY NEEDS

Parking structure deterioration is often first perceived as leakage. Paint damage on cars is a serious problem for garage operators, particularly where parking spaces are repeatedly used by the same vehicle so accumulation of leakage deposits is noticed. The cost of leakage control is likely to be common to any approach to corrosion control.

Lighting levels required for safety of garage users can be affected by different surface finishes or anodes. Ponding is often a user complaint which may be more easily rectified by some treatments (eg. top surface overlays) than others (sealers or soffit mounted cathodic protection).

5.5 CRITERIA

5.5.1 Facility Service Life

The intended, desired or required service life of the parking structure needs to be considered in the selection of an appropriate repair strategy. In some cases, the relative cost of different alternatives may affect the owner's decision about the desired service life, if it is flexible. Implicit in this criterion is the consideration of the cost of replacing the structure (ie. the 0 lifespan option), which is generally considered when massive repairs are contemplated.

5.5.2 System Durability

The installation of cathodic protection systems applied to parking structures have a history of less than five years. The monitoring programs in parking structures appear to have been more limited than those of the publicly funded bridge deck systems. In the absence of well documented history, the functional lifespan and maintenance costs over the lifespan of a system can only be estimated. The following factors are believed to have the major influence on durability:

a) Anode consumption: The anode can either be consumable or electrochemically inert. At consumable anodes, typically based on carbon, electrons are produced in the corrosion (oxidation) reaction of the steel. The rate of consumption is proportional to the current flow. The lifespan for a given rate is governed by the amount of material available for consumption. Because long-term current flow is not yet known, consumption estimates are educated guesses at best. The effects of consumption on anode bond or interface chemistry will not be known for some time. At so-called inert electrodes, oxygen and/or chlorine gases are formed. Advertised anode life expectancy is based on consumption of the metal coating on the surface of the essentially inert core.

   The primary reaction at the cathode is hydroxyl ion (OH^-) generation. If oxygen supply is adequate, hydroxyl formation is by oxygen reduction. If oxygen availability is restricted, hydrogen evolution through electrolysis of water occurs. Hydrogen evolution requires less applied current to maintain the same potential with respect to the electrolyte. Therefore, cathodic protection becomes more efficient, and the anode more durable, as oxygen availability is reduced.

b) Ion Migration: Chlorine migration to the anode and hydrogen migration to the steel are cause for concern about the effect on the bond of each to the concrete. Hydrogen evolution is controlled by limiting the applied voltage to below 1.1V, which is said to be the level required for the process of combining hydrogen ions (140). Water may move away from the anode, leading to desiccation, which will increase the resistance at the interface and thereby reduce the applied current for a given applied voltage.

c) Electrical components: These are relatively standard items that should not govern the overall lifespan of cathodic protection systems.

d) Concrete: Acid formation at the anode may create material degradation problems for the anode and/or the concrete. Hydroxyl ion formation at the cathode could conceivably produce alkali reactions in some concrete but this is not believed to be a major concern.

5.5.3 Performance History

Performance history is at least implicitly used in all evaluations of repair options but is highly subjective. This report is intended to reduce subjectivity about cathodic protection, but the present lack of extensive monitoring data means that the subjective aspect of evaluation will continue to be important. Published results from monitoring programs of the effectiveness of repairs are scarce. The technology employed in repairs is changing rapidly, making the performance of some older repairs not relevant to present strategies. The technology of cathodic protection in parking structures is changing rapidly and there is even less performance data available than for standard repairs because of its shorter history of use.

5.5.4 Technical Support

Cost effective decisions on repair programs, with or without cathodic protection, should draw on the experience of personnel with considerable experience and current state-of-the-art knowledge.

Given the experimental nature of cathodic protection in parking structures, the evaluation of alternatives should include an assessment of the skills of the system vendor in recognizing, accepting and correcting problems. This is difficult to quantify but the decision making process should include recognition of the system supplier's experience with similar installations, including short circuit and discontinuous steel identification, anode bonding, moisture effects on performance, monitoring procedures, report presentation, etc. The quality of technical support provided by the installer/supplier is likely to be critical in obtaining satisfactory performance.

5.5.5 Project Duration

Different options can have widely differing construction periods. This criterion is complicated by the differing affects on use within the same category of options. For example: top surface cathodic protection requires closing access to parking whereas soffit installations may be done in some garages outside normal hours of operations. Duration may be measured in parking stall days lost or in total length of disruption of the facility or in terms of fitting into a budget period.

5.5.6 Finished Product Appearance

A parking facility which obviously has signs of being repaired may be a liability in some instances. In these situations, a membrane or other opaque covering has an advantage over sealer protection. Conversely, the ability to see the surface condition is sometimes considered to be a benefit. These are subjective opinions which have major impacts on options evaluation.

5.5.7 Cost

a) General

Cost is obviously the most quantitative evaluation criterion for an Owner. As long as the options have no associated operating and maintenance costs, such as when a building will be sold or when these costs can be recovered, the evaluation process may be a direct comparison of initial capital cost. For most long term ownership though, costs to be evaluated include capital, operating, maintenance and disruption.

b) Capital Cost

Appendix C contains a summary of typical costs of different types of repair. From this, it can be seen that cathodic protection is in the order of half the unit area cost of concrete replacement. Therefore, if cathodic protection is being compared to replacement of less than half the slab surface, cathodic protection would not be cost-effective, all other things being equal, because cathodic protection is applied over the entire surface of the slab. The unit cost for concrete repair procedure could be reduced if cathodic protection is applied, although probably not enough to significantly alter the basic cost relationship.) Similarly, surface protection applied with cathodic protection may be a sealer, whereas if the top surface were replaced, a membrane would likely be applied, creating a $\$10/m^2$ to $\$20/m^2$ relative saving for a program which includes cathodic protection. This advantage, however, could be eliminated if occupancy needs dictated the use of a membrane with cathodic protection.

c) Operating Cost

Cathodic protection is an active system with necessary operating costs. By comparison, concrete and membranes do not consume energy or contain feedback systems. Some newer cathodic protection systems do not have sufficient history to have had operating procedures full developed. The "maintenance programs" offered by most suppliers would be better termed operations contracts.

d) Maintenance Costs

Maintenance costs are those costs associated with either replacing worn out components or providing treatment to keep a system operational. Membrane system maintenance requirements vary with use, wear course properties, etc. Sealers are considered by some to wear off but their effectiveness cannot be easily tested so maintenance, short of reapplication, is basically impossible. The associated leakage control procedures (ie. cracks sealing) do have maintenance needs, but the costs are typically very small. For cathodic protection, it is difficult to separate maintenance from operating, and most systems have not been functional long enough to establish the durability of different components.

e) Replacement Costs

None of the systems used in garage structural repair, protection or corrosion control has a long enough history to predict when replacement would be required. Appendix C includes some ranges we have encountered. Costs involved depend upon how much, if any, removal of the component is involved. This should be discussed as part of the evaluation, but given the uncertainties involved, is not likely to be a significant factor.

6. IMPLEMENTATION/OPERATION

6.1 CONTRACT REQUIREMENTS

6.1.1 Bid Process

The bid documents for cathodic protection systems are fundamentally performance based, to allow competition between suppliers of different products. This has merit given the relatively short history of commercial installations. The different attributes of the available system can either be compared after tendering and factored into the cost/benefit analysis of each proposal, or the desirable systems(s) could be selected prior to obtaining prices. In practice, some combination of these two extremes will normally be practised.

6.1.2 Specifications

a) General Conditions

Cathodic protection can be considered effective if corrosion is reduced to a level which does not result in structural deterioration for the specified life of the cathodic protection system. For this to be considered true, three conditions must be met:

i) The system must supply sufficient, properly distributed current to the steel to reduce the corrosion rate of all of the steel to an adequately low level.

ii) The system must remain operational for the period used in the economic evaluation.

iii) The system must not create other deleterious side-effects which require its use to be stopped.

Each of these criteria should be specified, including means of assessment and liabilities for failure to meet them. It is obvious that payment cannot be tied to long term performance though. If a system is being installed as a trial, then the supplier's responsibility would be limited to defects in materials or installation procedures with respect to those specified.

Conditions typical to any parking structure retrofit, such as access to the site, available work areas and protection of existing facilities during the surface preparation and system installation, are needed.

Each system will have slightly different impacts on the routine maintenance of the facility, and the contractor should make any conditions for maintenance procedures clear in the bid and contract documents.

b) Materials

The materials which comprise the cathodic protection system are given in section 3.1 above. Of these the electrolyte and cathode are not supplied by the contractor, however electrolyte (concrete) resistances should be measured as part of the installation and the electrical continuity of the cathode (reinforcing steel) must be verified. The system software (including monitoring procedures, reporting frequency, adjustment procedures) must also be specified. Remote monitoring and plotting facilities for voltage, current, temperature and humidity sensors should also be considered.

Cathodic protection rectifiers are normally supplied with a built-in interrupter to enable the system to be shut off momentarily while readings are taken. This is done to eliminate the IR drop in the concrete from the potential readings.

c) Execution

This section of the documents will be specific to the type of anode system with a few exceptions. The control system requirements, such as whether the control is either current or voltage based, the area of surface for each power supply, the pre-installation survey, system operation and post installation monitoring program are relatively independent of the system type. Without accurate history of performance records for the various cathodic protection systems, it is difficult to specify the size of each zone, the required current density etc. These are affected by construction and materials which differ between sites.

As discussed above, the potential drop between the anode and cathode is a function of many variables. A short circuit at one location will reduce protection provided in the vicinity but will not draw all the current from an anode. It is therefore difficult to determine whether current loss is through a large area of concrete, a local short circuit or a section of steel with high current demand. Infrared thermography can be used to detect hot spots created by concentrated current flow once the system is installed. The typical procedure to locate short circuits before installing an anode is to apply a large voltage (3,000V to 10,000V) to the reinforcing steel and pass an electrical contact (spark brush) over the concrete. When anodes are applied in liquid form, they may penetrate cracks and create shorts which are not apparent in a survey of the concrete surface.

System-specific aspects of execution include:

- surface preparation
- anode installation
- contact medium application

Installation must comply with applicable electrical, safety or other codes and by-laws. The security required for the rectifier and monitoring sites may vary with the type of user of the garage.

The use of the garage may dictate the times and locations of on-site monitoring, which should be considered in the original contract (and be written into the operation contract for the garage).

6.2 MONITORING PROCEDURES

6.2.1 General

The true long-term test of whether or not a cathodic protection system is working is how much delamination develops over time (assuming no side-effects develop). This can be tested by a delamination survey. However, delaminations take years to form after the onset of corrosion. Other methods are therefore required to monitor cathodic protection performance.

In buried pipelines and storage tanks, the inability to access the structure for visual inspection has led to the creation of electrochemical test criteria. Our review of the literature indicates that these criteria are basically empirical. Five criteria are included in the NACE Standard for pipelines (NACE Standard RP-0169-76, rev. 1983). Only one is referenced in the equivalent British Standard, and the largest British pipeline operator uses yet a different criterion (150). Despite the widespread acceptance of cathodic protection in pipeline protection, which provides the basis for much of the sales literature for cathodic protection in concrete, there is hardly a consensus on appropriate monitoring procedures.

6.2.2 Empirical Criteria

i) Absolute Potential: 850mV and 770mV CSE

Two levels of potential measured with the cathodic protection system installed are mentioned in the literature. In cathodic protection of pipelines, it has been found that creating a -850mV CSE potential resulted in effective control of corrosion (140, 150). Vrable et al (140) applied increasing potentials to test samples of steel in chloride environments and found that corrosion was controlled at potentials of -770mV CSE, and suggested this as a possible criterion, with the provision that it would probably be excessive because the test conditions were extreme.

ii) 300mV CSE Relative Potential Shift

Another empirical pipeline criterion is a negative shift of 300mV in the potential from the static readings taken before cathodic protection to the readings taken after cathodic protection is applied. This is apparently a criteria applied to protection of uncoated pipe.

iii) 100mV Decay

Another empirical criterion for uncoated pipe is that the change (in the positive direction) between the potential) measured immediately after turning a cathodic protection system off (ie. eliminating the IR component) and some time later must be 100 mV. This change, or decay, should be a measure of the polarization (overpotential) created by ions collected at the cathode (particularly OH^-), which dissipates with time without an impressed current. Its use infers a belief that if 100 mV polarization is produced, then enough current is reaching the steel to reduce corrosion to acceptable levels.

6.2.3 Theoretical Criteria

There appear to be three categories of theoretical cathodic protection criteria, contained in the literature under various headings (128, 131, 140, 152).

i) Potential/pH or Pourbaix Diagram

This diagram (Figure 9) shows regions of passivity/immunity, corrosion and cathodic protection for iron, iron oxides and water. Viable found that this diagram appeared to apply even in the presence of chlorides, and that corrosion was not sustained after equilibrium was reached at pH greater than 8. Therefore, the potential required to create cathodic protection would be in the 0.9V CSE to 1.0V CSE. This is generally considered to be an excessive requirement.

ii) Mixed Potential Theory

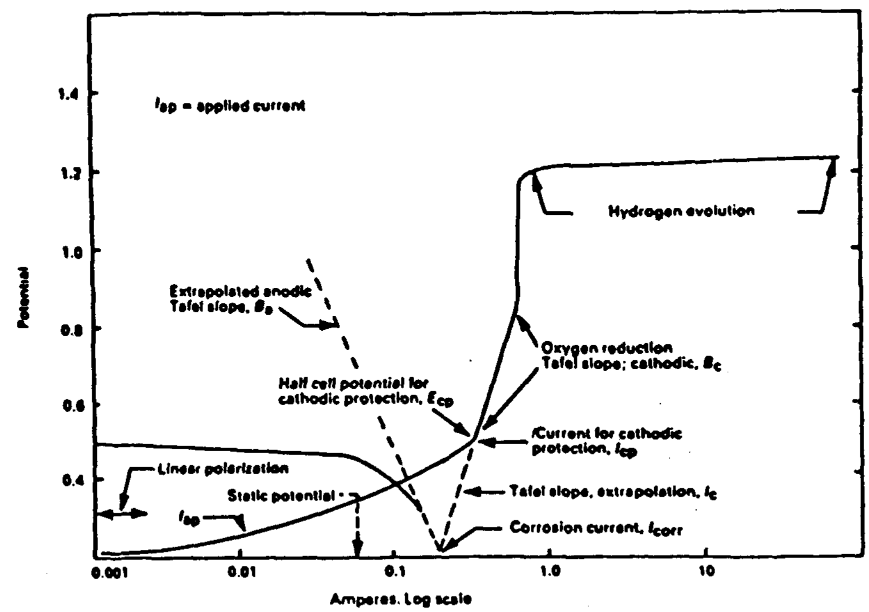
Lacque (1969) showed that once the entire metal surface has been made cathodic, hydrogen evolution replaces oxygen reduction as the prime cathodic reaction and there is a marked change in potential with increasing current density. This is a pH related phenomenon which is difficult to apply to concrete (128).

iii) Overpotential/E-Log i Curve

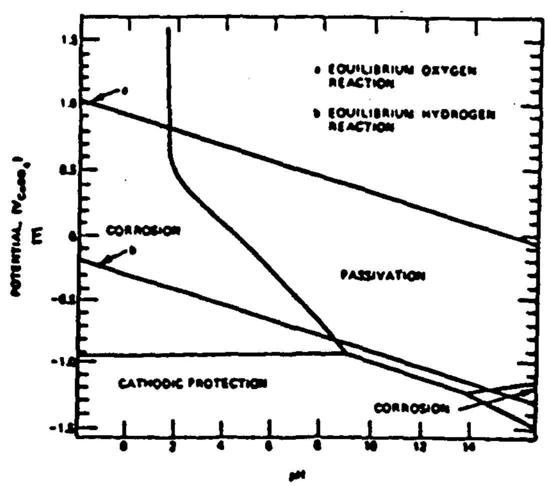
The potential applied to a corrosion cell (E_I) equals the sum of the equilibrium (zero current) potential (E_o), plus the IR drop in the circuit, plus an entity termed "overpotential (n)" which is the measure of polarization.

$$E_I = E_o + IR + n$$

Overpotential is a function of the electrolyte, electrodes, current density and polarization effects. There are two types of polarization - activation and concentration. Activation polarization (na) is a function of the rate of reaction at the electrode in terms of current density. In the laboratory, na = $\pm$ B log i/i_o where i is the closed circuit current density, and i_o is the rate at electrodes in equilibrium, and B is a constant. Concentration polarization is the effect of concentrations of reactive ions at the electrode, primarily the cathode. In impressed



E Log I Curve
(From Stratfull, June '83)



Pourbaix Diagram for Iron
From Vrable; Wild, March '79

FIGURE 9

cathodic protection systems, polarization is an indication of the amount of protection provided. If the slope of the relationship were known (ie. the variables affecting n were determined), this would produce a theoretically accurate method of establishing how much current per area of steel is required to provide a suitable drop in corrosion current.

The relationship is determined by applying a current to a corrosion cell and plotting the current density (or often just the current) on a log scale against the potential measured over the most negative anode prior to application, less the IR drop in the concrete (ie. with the system off) (Figure 9). The straight-line portion of the curve is the "Tafel slope" which is the oxygen reduction portion (in the absence of diffusion processes). The current density required to effect cathodic protection is that associated with the starting of the Tafel slope. Several parties have attempted to produce these for structures reinforced concrete but the results are inconclusive (124, 128, 131). From electrochemical theory, this could provide useful data, but the variability in concrete is too great for this procedure to be applied effectively.

6.2.4 Present Practice

There is now a consensus in the NACE Proposed Standards (37, 101) to use the 100 mV decay criteria as evidence of successful cathodic protection. This is measured over a test area with many points and the decay at each point is plotted. It is not clear how the results are to be statistically analyzed.

6.3 STAFF TRAINING

6.3.1 Non-Technical Staff

To the casual observer, a garage protected with cathodic protection would not have any particularly identifiable characteristics. Therefore, all staff who will control or carry out maintenance in the garage must be made aware of the existence of the power supply and anode distribution system.

Normal maintenance procedures such as painting, cleaning and lighting replacement must be reworked in accordance with the system requirements.

6.3.2 Technical Staff

The operation of a cathodic protection system is generally handled by a "qualified" corrosion specialist, who is generally working for or with the installation contractor. In order that the Owner of the system has a degree of comfort in the reliability of the information being supplied, the Owner can either train a person in-house, which may be appropriate for an Owner of many protected facilities, or engage the services of an independent specialist to advise on the suitability of the data supplied. An on-site representative should be trained as part of the installation contract to recognize damage to components and whether the system is energized so that the appropriate corrective actions can be taken.

APPENDIX A

BIBLIOGRAPHY

In compiling the bibliography, the central goal was to obtain material on parking garage repair methods, criteria for selection of method, and evaluation of repair methods in place, including Cathodic Protection.

C.P. systems in parking structures have not been reviewed as closely as those in other reinforced concrete structures. In particular, considerable experience and material exists on highway (bridges and pavements) and marine environment structures. Relevant studies have been included.

Literature searches using NTIS at CMHC and DOBIS (of CISTI) at NRC were carried out.

The following sources were used to obtain literature:

1. Corrosion Service Company Limited, Downsview, Ontario
2. Ontario Ministry of Transportation and Communications, Downsview, Ontario
3. University of Toronto Library, Toronto, Ontario
4. Canada Mortgage and Housing Corporation, Ottawa, Ontario
5. National Research Council Library, Ottawa, Ontario
6. Metropolitan Toronto Housing Authority, Toronto, Ontario
7. American Concrete Institute, Ontario Chapter, Toronto, Ontario

For help with obtaining and recommending material, we have to thank Halina DeMaurivez (CMHC), Carol Fairbrother (NRC), Glen Coley, Harry Webster (Corrosion Serv. Co. Ltd.), Frank Alaimo (ACI), Gerald Lichty (MTHA), Hannah Schell (OMTC).

All publications listed are available in the Robert Halsall and Associates Limited library.

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APPENDIX B

APPENDIX B

LIST OF SYSTEM SUPPLIERS FOR PARKING STRUCTURES

B.1 Conductive Coatings

a) **Name:** DuoDac 85
Anode: Carbon in Solvent-Based Co-Polymer Acrylic Anode
Manufacturer/Supplier: Corrosion Service Company Limited
369 Rimrock Road
Downsiview, Ontario
M3J 3G2
Phone: (416) 630-2600
Fax: (416) 630-2393/8161
Tlx: 06-218984

b) **Name:** Electrodag 8050 or RW 23698
Anode: Carbon in Water-Based Acrylic Resin Anode
Manufacturer/Supplier: Acheson Colloids Company
P.O. Box 611747
Port Huron, Michigan
48061-1747
Phone: (313) 984-5581
Fax: (313) 984-1446
Twx: (810) 231-5265

Canadian Distributor: Corexco Inc.
622 Avenue Meloche
Dorval, Quebec
H9P 2P4
Phone: (514) 636-0085

c) **Name:**
Anode: Solvent-Based
Manufacturer/Supplier: Royston Laboratories Inc.
128 First Street
Pittsburgh, PA
15238
Phone: (412) 828-1500
Tlx: 86-5541

Canadian Distributor: Can-Con Gas Services Ltd.
101, 9333-45 Avenue
Edmonton, Alberta
T6E 5Z7
Phone: (403) 436-1937

d) **Name:** Electro-Coat 30-86
Anode: Carbon in Water-Based Polymer Anode
Manufacturer/Supplier: Pascorr Cathodic Systems Limited
521 Piercy Road
Unit 7
Bolton, Ontario
L7E 5B5
Phone: (416) 857-0583

e) **Name:** Sprayed Zinc
No Suppliers

B.2 Titanium Mesh in Mortar

a) **Name:** Tectrode
Anode: Platinized Expanded Titanium Mesh
Manufacturer/Supplier: ICI Americas Inc.
Wilmington, Delware
19897
Phone: (302) 575-3708
Fax: (302) 984-5010

b) **Name:** Lida Net
Anode: Metal Oxide Coated Expanded Titanium Mesh
Manufacturer/Supplier: Dow Chemical U.S.A./Oranzio de Nora S.A.
400 West Sam Houston Parkway South
P.O. Box 3387
Houston, Texas
77253-3387
Phone: (713) 978-3925
Fax: (713) 978-3930
Tlx: 775437

c) **Name:** Elgard Anode Mesh
Anode: Metal Oxide Coated Titanium Strip or Expanded Mesh Anodes
Manufacturer/Supplier: Elgard Corporation (division of Eltech Co.)
470 Center Street
Chardon, Ohio
440224
Phone: (216) 285-1439
Fax: (216) 285-1408

B.3 Conductive Polymer Mesh in Concrete

a) **Name:** Ferex
Anode: Conductive Polymer Cable/Mesh Anodes
Manufacturer/Supplier: Elgard Corporation (division of Eltech Co.)
470 Center Street
Chardon, Ohio
44024
Phone: (216) 285-1439
Fax: (216) 285-1408

APPENDIX C

APPENDIX C

The following is a list of approximate cost factors. Actual costs vary with each installation. We have contacted various construction management firms in Montreal, Calgary, Edmonton and Vancouver and the regional variance did not exceed 20%.

	Approx. Unit	Operating (Annual)	Maintenance (Annual)	Life
<u>CONCRETE REPLACEMENT</u>				
Top Surface				
Jackhammer	$140/m^2			
Hydrodemolition	$220/m^2	N/A	N/A	
Full Slab	$280/m^2			
<u>SURFACE PROTECTION</u>				
Penetrating Sealer	$ 10/m^2	0	Hi	10 years
Asphaltic Membrane Systems	$ 25/m^2	0	Med	15 years
Elastomeric Membrane Systems	$ 35/m^2	0	Low	15 years
<u>CATHODIC PROTECTION</u>				
Titanium Mesh in Mortar				
Top Surface	$ 80/m^2	?	Unknown	25 years
Soffit				
Conductive Coating-Soffit	$ 50/m2	$.50-$1/m^2	Unknown	15 years
Conductive Polymer Mesh	$ 70/m^2	?	Unknown	
Sprayed Zinc	$ 90/m^2	?	Unknown	

APPENDIX D

APPENDIX D

KNOWN PARKING STRUCTURE INSTALLATIONS

The following is a list of known installations of cathodic protection systems in Canada. They are listed in order of year of known (first) installation.

The following abbreviations are used:

1. Ach. = Acheson Colloids (Coating)
2. Capp. = Cappar Products (Coating)
3. Corex = Corexco Inc.
4. CorServ = Corrosion Services Ltd.
5. Pass = Passcorr Cathodic Systems Ltd.
6. Roys = Royston Laboratories Inc.
7. Raychem = Raychem Corp.

DATE	SITE	SYSTEM(S)	APPROX.AREA CP
1981	PSAC Building Ramp, Ottawa	Wires in Slabs	120m^2
Aug.1982	Manulife, Toronto, Ont.	Pass./Ach.	1,000m^2
Aug. 1984	Louisburg, Quebec	Pass/Ach.	3,400m^2
Nov.1984	Dufferin Mall, Toronto, Ont.	Raychem	500m^2
Mar.1985 (1986/88)	Guardian Towers, Toronto, Ont.	Pass./Ach./Capp	8,000m^2
Aug.1985	Sutton Place, Toronto, Ont.	Pass./Ach.	900m^2
Oct.1985	Dundas St., Toronto, Ont.	CorServ	200m^2
Sept.1985 (Nov.86)	Place Bell Mall, Ottawa, Ont.	Pass./Ach.	16,000m^2
Dec.1985	Charles St.W., Toronto, Ont.	Pass./Ach.	3,200m^2
Apr.1986	Benvenuto Place, Toronto, Ont.	Pass./Ach.	1,000m^2
Aug.1986	Brentwood Towers, Toronto, Ont.	Pass./Ach.	17,000m^2
Sept.1986	50 Baif Blvd., Richmond Hill, Ontario	CorServ	10,000m^2
Oct.1986	80 St. Clair Ave.W., Tor., Ont.	Pass./Ach.	4,000m^2

Dec.1986 (1987)	Main St. W., Hamilton, Ontario	CorServ	8,800m^2
Dec.1986	Carlton St., Toronto, Ontario	CorServ	1,000m^2
Jul.1987	Prudential Dr., Scar., Ont. (Disconnected)	CorServ	500m^2
Nov.1987	Blackthorn Dr., Toronto, Ont.	CorServ	7,000m^2
Nov.1987	William St., Oshawa, Ontario	CorServ	8,000m^2
Nov.1987	Rathburn St., Mississauga, Ont. (Disconnected)	CorServ	200m^2
1987	5 Brahms, Don Mills, Ontario	Pass.	300m^2
Apr.1988	Bayview Ave., Toronto, Ontario	CorServ	200m^2
June 1988	L'Hotel Classic, Laurier Blvd. St. Fois, Quebec	CorServ	4,500m^2
Sept.1988	Wellesley St., Toronto, Ont.	CorServ	6,500m^2
Sept.1988	Graydon Hall, Don Mills, Ont.		5,300m^2
Sept.1988	Don Mills Rd., Don Mills, Ont.	CorServ	1,600m^2
Dec.1988	Eastdale, Toronto, Ontario	CorServ	6,000m^2
1988	Delta Chelsea Hotel, Tor., Ont.	Pass.	
1988	Place d'Youville, Hull, Quebec	Corex/Roys	25,000m^2
1988	Society D'Insurance D'Health Hull, Quebec	Corex/Roys	2,000m^2