RESEARCH REPORT

Factors Affecting Consideration & Use of Cathodic Protection in Rehabilitation of Reinforced Concrete Parking Structures

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FACTORS AFFECTING THE CONSIDERATION AND USE OF CATHODIC PROTECTION IN THE REHABILITATION OF REINFORCED CONCRETE PARKING STRUCTURES

Prepared for: THE RESEARCH DIVISION
CANADA MORTGAGE AND HOUSING CORPORATION
682 Montreal Road
Ottawa, Ontario
K1A 0P7

Submitted by: ROBERT HALSALL AND ASSOCIATES LIMITED
Consulting Engineers
6th Floor
188 Eglinton Avenue East
Toronto, Ontario
M4P 2X7

Tel. (416) 487-5256
Fax. (416) 487-9766

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Principal Consultant: Peter Halsall, M.A.Sc., P.Eng.

CMHC Project Manager: Alvin J. Houston
Research Division

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Cathodic Protection of Parking Structures

CAUTION

The information contained in this report is based upon a review of the literature, discussions with building owners and 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 future affect the validity of some of the contents of this report.

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TABLE OF CONTENTS

1. INTRODUCTION

A rehabilitation program to reinstate the structural integrity of a corrosion-damaged parking structure and to control future corrosion typically comprises many different procedures. Cathodic protection is one possible procedure. It is specifically intended to control corrosion.

Successful operation of cathodic protection systems require consideration of electrical characteristics not recorded when the structure was built and normally not considered prior to structural repair.

This document is intended to provide building owners and managers with an introductory description of the principles involved in the use of cathodic protection for corrosion-damaged, reinforced-concrete parking structures. (A more detailed discussion is available in the CMHC document "A Report on the State of the Art of Cathodic Protection Systems for the Rehabilitation of Concrete Parking Structures".)

Concepts addressed in this document are:

a) the basics of the corrosion process in steel-reinforced concrete;
b) principles of cathodic protection as applied to corrosion-damaged parking structures;
c) factors affecting the selection of cathodic protection for such facilities;
d) factors affecting design and installation of cathodic protection systems; and
e) the monitoring and maintenance considerations for any structures having cathodic protection.

2. CORROSION OF REINFORCING STEEL IN CONCRETE

2.1 Corrosion Mechanism

The primary cause of structural deterioration in concrete parking structures is corrosion of embedded reinforcing steel. Rust is the corrosion product of iron in the presence of oxygen and water. Iron is the principle component of reinforcing steel. Rust has a larger volume than iron. If corrosion occurs on steel in concrete, it produces rust and this creates stresses within the concrete. If the stresses produced exceed the concrete strength, the concrete will fracture. Fractures radiate from the steel in a pattern that can lift the surface of the concrete. This separation is called a delamination (see Figure 1).

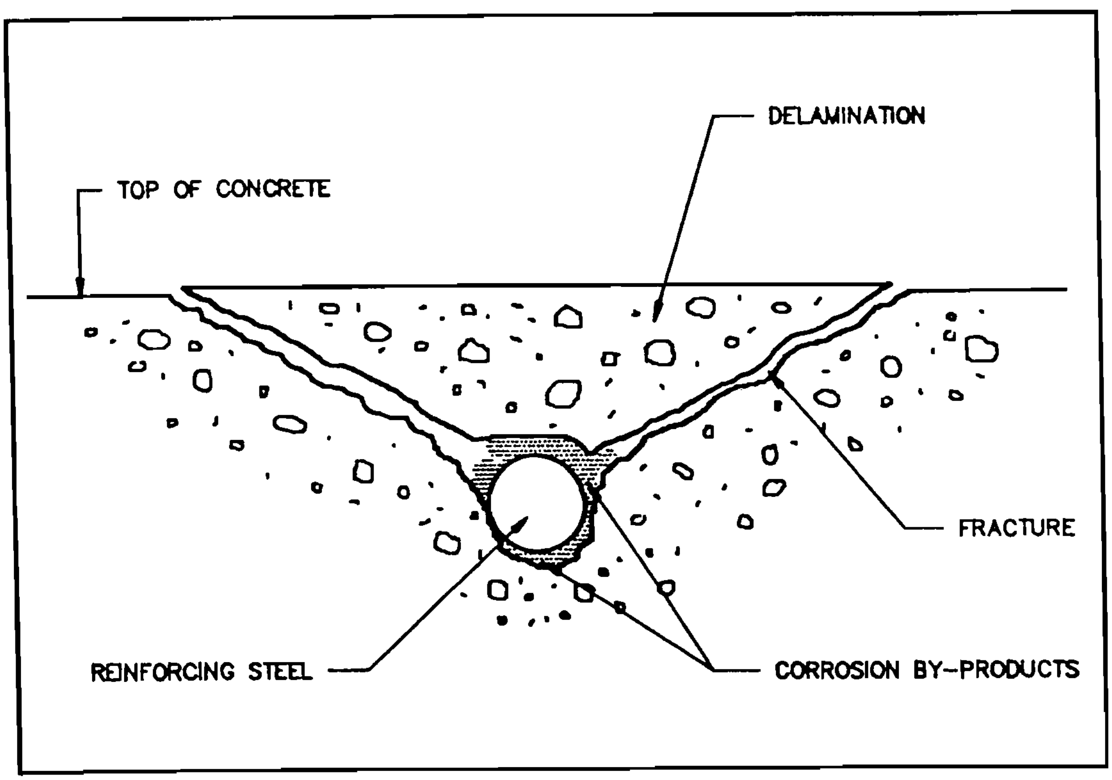


FIGURE 1 DELAMINATION

Concrete contains many microscopic pores. In uncontaminated concrete, iron in the reinforcing steel reacts with oxygen and water in these pores to form a stable "passive layer" on the surface of the steel. This passive layer is known to protect the reinforcing steel from corrosion. This means that reinforced concrete structures do not suffer corrosion damage as long as this layer is intact. If the water in the pores contains high enough concentrations of chloride ions, the chlorides will interfere with the passive layer on the steel. This interference encourages corrosion.

Chlorides can enter the pore water in concrete from four common sources: road salt (sodium chloride) from slush melting off cars or applied directly to the slab; chloride-contaminated aggregate; calcium chloride added to the mix during winter construction as a strength accelerator; or finally, deicers used on construction formwork.

Corrosion is an electrochemical process, which involves changes in the chemistry of elements and metallic compounds, including steel. These harmful corrosion reactions can occur on the surface of steel in concrete when there are sufficient differences in the chemical composition of the steel and/or the concrete at different locations along the interface between them. The conditions which create these differences include variations in:

- oxygen and moisture content of the concrete pores
- chloride content of the concrete pore water
- microscopic composition of the steel and
- consolidation of the concrete around the steel (e.g voids often exist beneath the steel as concrete settles during placement)

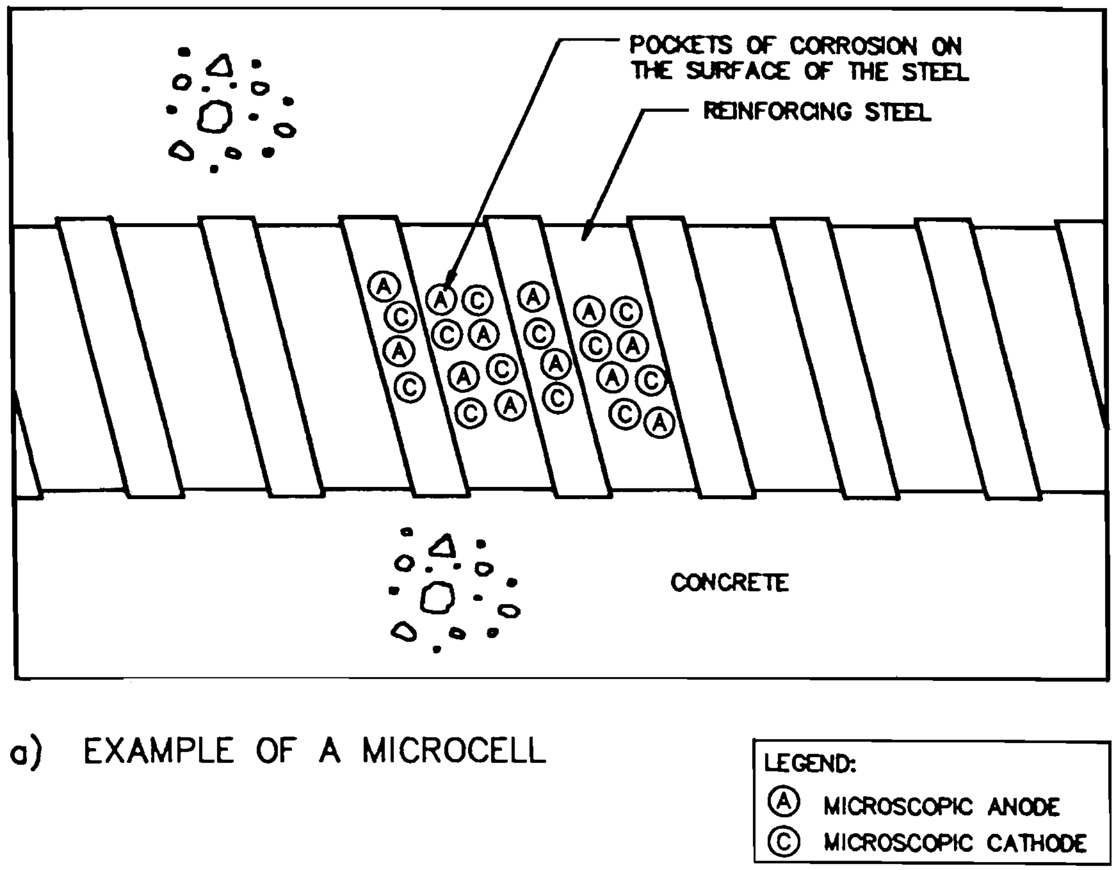
The electrochemical process occurs between two separate but adjacent locations on the steel, technically called half-cells. One half-cell has a corrosion reaction (the "anode"), the other half-cell is non-corroding (the "cathode"). If different chemical conditions exist across microscopic distances, usually on the same bar, "microcells" are formed (see Figure 2). If there are larger distances (several millimetres or more) involved, for example between the top layer of steel (encased in concrete with high chloride levels from road salt) and the bottom layer (with low chloride levels), a "macrocell" exists. It is not known which type of cell creates more damage, or how they interact in reinforced concrete.

3. CATHODIC PROTECTION

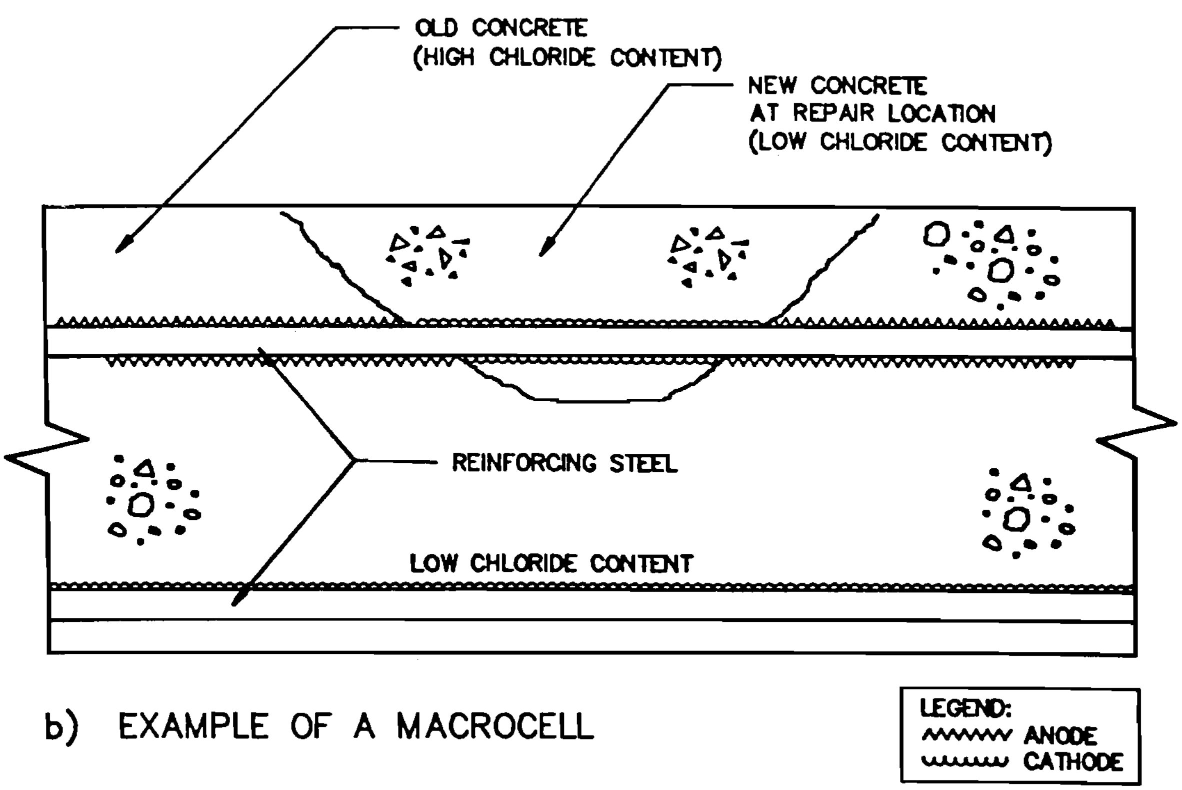
3.1 General Description

The corrosion reaction occurs where current leaves a surface. Cathodic protection changes the location of this reaction from the surface of the reinforcing-steel to the surface of an externally applied conductive layer applied to the concrete. The various types of conductive layers used are described in Section 5.2. The process used in reinforced concrete is impressed current cathodic protection. In this process, a current is applied from an external power supply to a conductive layer (an "impressed current anode") on the surface of the structure being protected (Figure 3). Material in the conductive layer is consumed, at a slow rate related to properties of the conductive layer material and the current flow in the system.

One effect of applying a current through the concrete to the steel is that a difference in electrochemical charge, a voltage "potential", is created across the steel/concrete interface. This potential is called the polarization potential.



a) EXAMPLE OF A MICROCELL



b) EXAMPLE OF A MACROCELL

FIGURE 2 MICROCELLS AND MACROCELLS

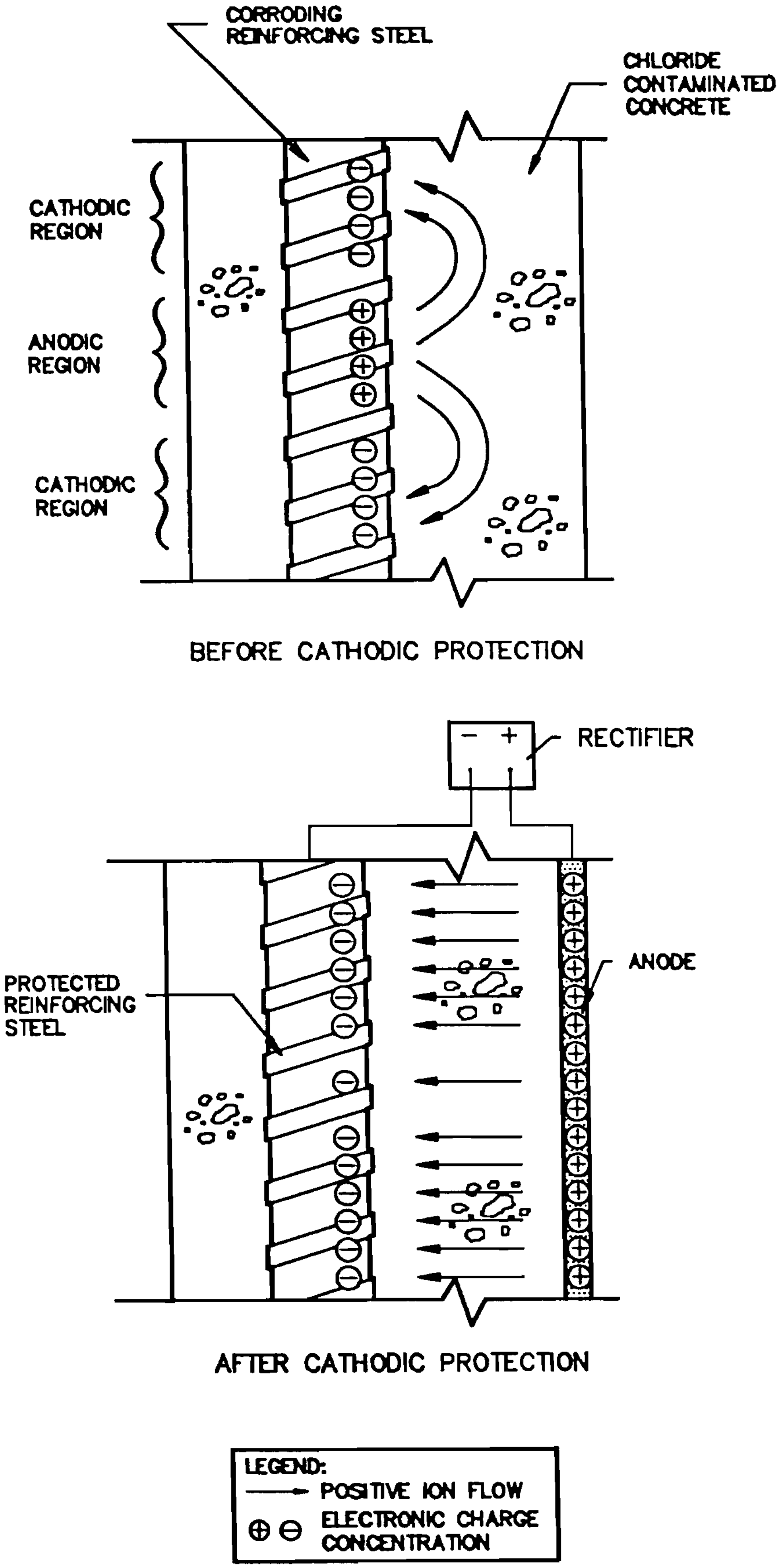


FIGURE 3 IMPRESSED CURRENT CATHODIC PROTECTION

Potentials can be readily measured at a large number of locations across the surface of a slab. However, the actual rate of the corrosion process - corrosion current flow, corrosion rates, or loss of steel area - are difficult to measure in the field. The performance monitoring of cathodic protection systems is thus based on measurements of polarization potential. The industry has reached a consensus that a 0.1 volt (100 millivolt) polarization potential indicates effective cathodic protection.

3.2 System Components

The basic components of a cathodic protection system for a parking structure (other than the embedded reinforcing steel which is to be protected and the structural concrete which must carry the current to the steel) are: a power supply; the applied anode; reference electrodes; electrical connections between components; and control systems to govern the voltage and/or current output. Power for the cathodic protection system comes from a rectifier. This device converts alternating current (AC) from the building's electrical system to direct current (DC). The power supply will typically have several different output circuits. The positive pole of each is connected to a section of the conductive layer (anode). The negative pole of each output circuit is connected through wire leads to several locations on the embedded steel within each section (Figure 4). The area of each section is limited in size to make fault location easier after system start-up and to limit the impact of a short circuit. The applied voltage supports current flow from the conductive layer through the concrete to the steel. The effectiveness of cathodic protection depends on the amount of current reaching the surface of the steel in need of protection. The amount of current is governed by the voltage applied, the resistance of the concrete through which the current must flow, the surface area of the steel being protected and the distribution of current between and across different layers of steel.

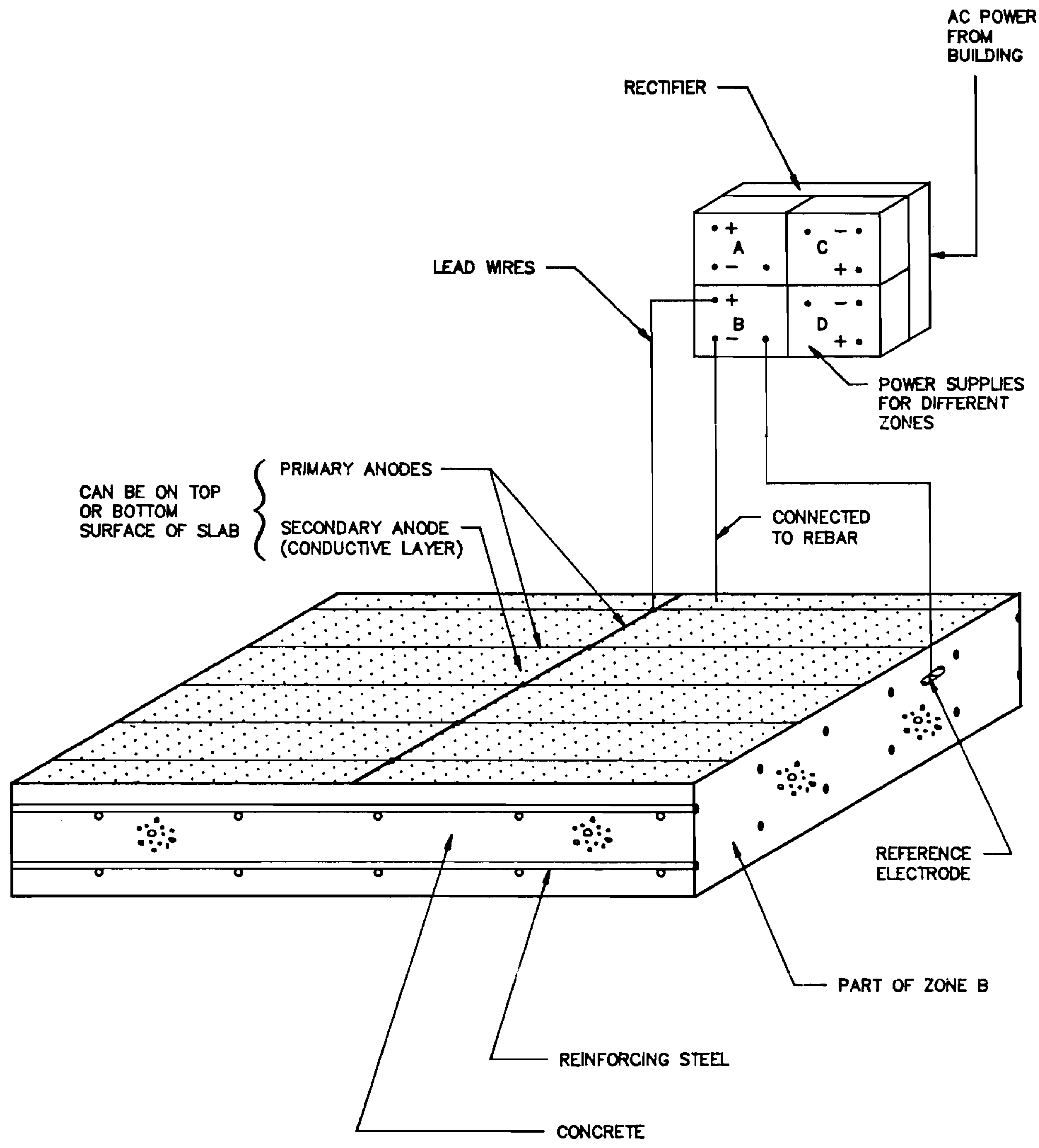


FIGURE 4 COMPONENTS OF A CATHODIC PROTECTION SYSTEM FOR A PARKING STRUCTURE

3.3 Practical Considerations in Reinforced Concrete Structures

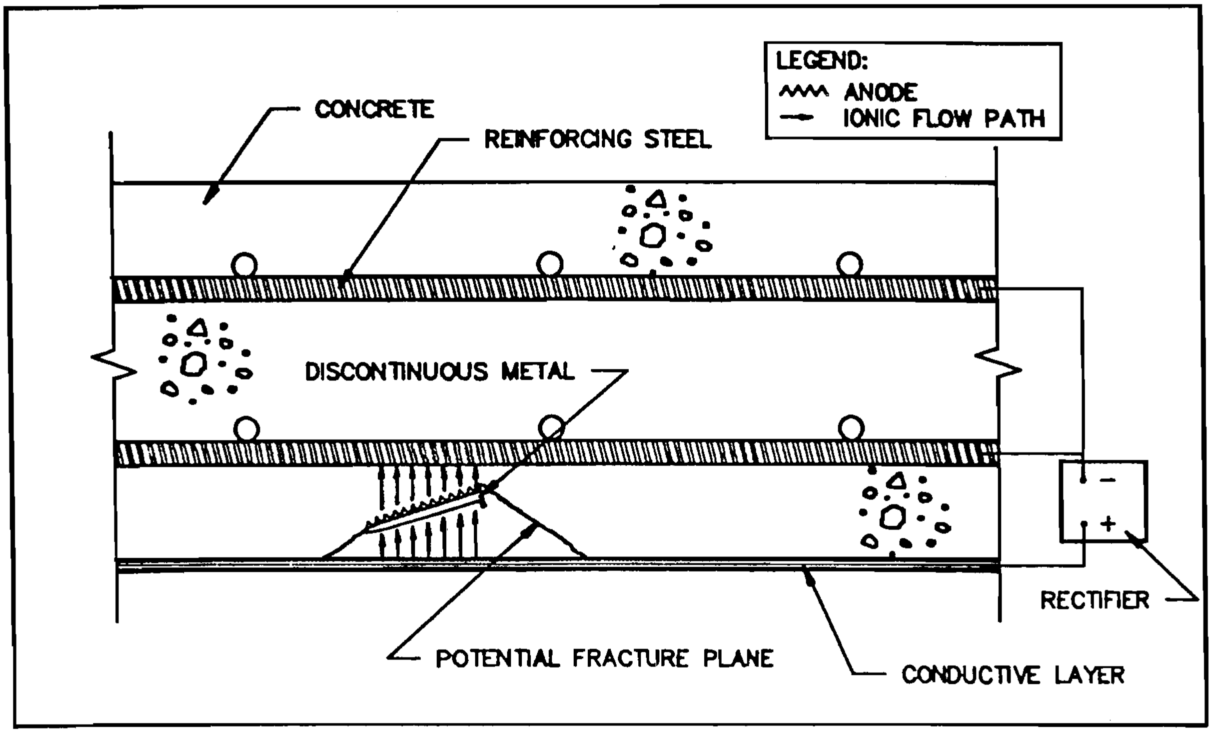
3.3.1 Concrete Resistivity

The amount of protective current reaching a local section of reinforcing steel varies with the resistivity of the concrete and with the amount of moisture and chloride in the concrete. This variability can cause differences in the amount protective current flow, and therefore in the amount of polarization achieved, at different locations in the slab.

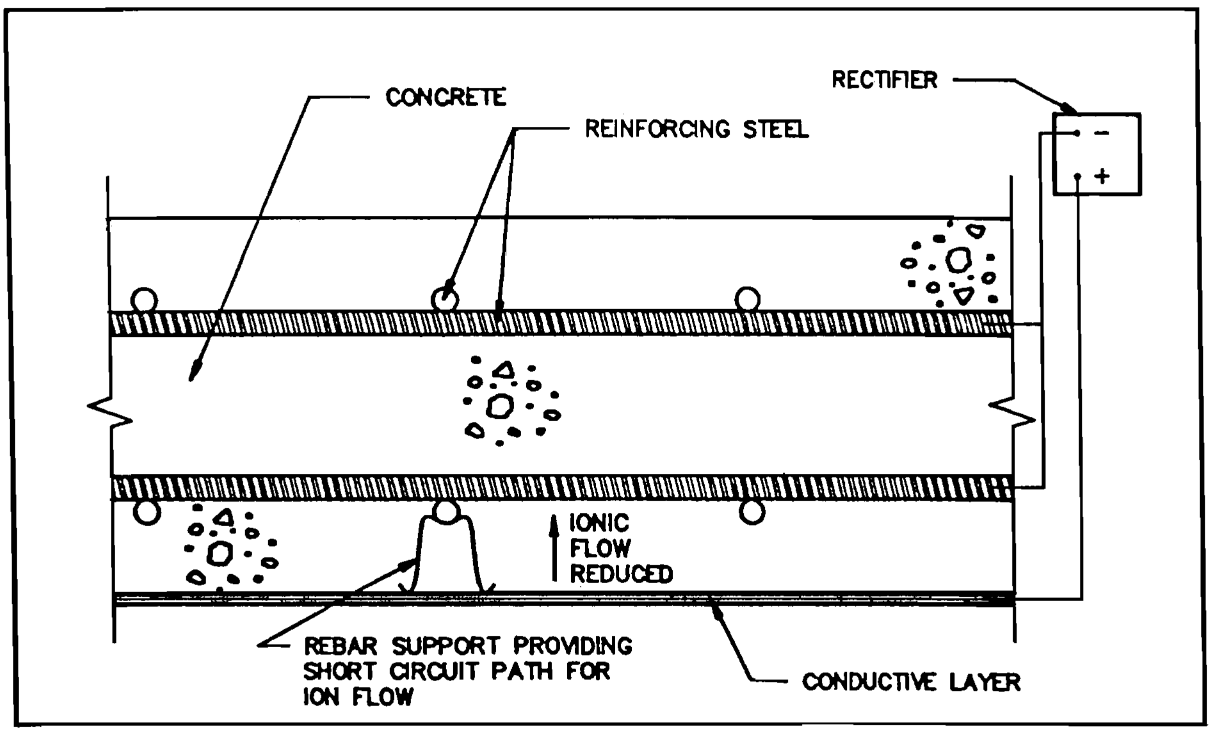
Both corrosion activity and impressed current flow should be higher in regions of elevated moisture or chloride content in the concrete. It has been argued that this relationship means that cathodic protection current flows more to where it is most needed. This cannot be accepted as a general condition, however, as corrosion activity depends upon resistivity at the steel/concrete interface, while the impressed current must flow through a mass of concrete which may have different resistivity than exists in the concrete around the steel.

3.3.2 Steel Continuity

Corrosion will occur on metal which is not connected to the negative pole of the power supply ("discontinuous metal"). This random corrosion often leads to uncontrolled delamination (see Figure 5). If large sections of the reinforcing steel are not connected to the rest of the steel or directly to the power supply, the use of cathodic protection could be destructive.



a) DISCONTINUOUS METAL



b) SHORT CIRCUIT

FIGURE 5 DISCONTINUOUS METAL AND SHORT CIRCUIT

3.3.3 Short Circuits

The ends of wires used to tie rebar in place during construction and metallic supports holding the reinforcing-steel off the construction formwork are often exposed at the surface of the slab, which makes them possible causes of short circuits between the conductive layer on the concrete surface and the reinforcing steel. Short circuits reduce the amount of current flowing through the concrete, and reduce or negate the overall effectiveness of cathodic protection. They must therefore be detected and eliminated during installation or detected during commissioning of the cathodic protection system.

4. SELECTION OF APPROPRIATE STRUCTURES FOR APPLICATION OF CATHODIC PROTECTION

This report will not compare cathodic protection with other treatment options, as many factors influence the decision about when to include cathodic protection in a repair program for a steel-reinforced concrete parking structure. The evaluation of options should be made with the involvement of a professional engineer who is a specialist in this field. If a comparison of repair options shows that cathodic protection would be a cost-effective alternative to consider, the measurements required to assess its technical viability should be performed and/or assessed by a qualified, and preferably independent, cathodic protection specialist. The types of measurement could be grouped into problem assessment, electrical characteristics, slab configuration and economic factors, but they are interrelated.

4.1 Problem Assessment

It is ultimately the amount of actively corroding steel which remains in the slab after structural repairs are performed which determines whether or not cathodic protection should be considered. The area of concrete which requires repair for structural integrity and user safety is measured by visual inspection, materials testing, and surfacing sounding. The American Concrete Institute has published guidelines and standards covering the assessment process. The amount of corrosion activity is measured by means of a "half-cell potential" survey. The instrumentation for this is outlined in an industry standard (ASTM C876-87). The number, location and environmental conditions during readings will vary between consultants and facilities.

4.2 Electrical Characteristics

Electrical characteristics, which are not typically considered in a structural condition survey, but which need to be evaluated prior to installing a cathodic protection system include:

a) Electrical Continuity of Reinforcing Steel - General continuity of the reinforcing steel can be checked with a half-cell connected to different locations on the steel. Small pieces of metal dropped into the forms or used to support the reinforcing are not detected by a half-cell survey. These have taken a long time to identify for many installations.

b) Epoxy Coated Steel - Epoxy-coating applied to portions of steel exposed in delamination repairs isolates the steel from the corrosion process, and so the coated steel will not receive current (except at defects in the epoxy coating). This should allow more current to reach the uncoated sections of bar which is where protection is required. However, the steel must still be electrically continuous. If a slab is originally built with epoxy-coated steel, electrical continuity of the assembled steelwork is unlikely.

c) Short Circuits - Various procedures are being used to locate short circuit paths, including electric arc brushes before installation and thermography after installation. Once located, the short circuit must be electrically isolated from the anode to ensure effective performance of the system.

d) Conductivity of Concrete - If the steel conditions are appropriate for cathodic protection, the ability of the original and repair concrete to conduct an applied current should be determined. There are no standard procedures for doing this over a representative sample of the slab to be protected, nor is conductivity easily monitored over time.

4.3 Slab Configuration

The conductive layer forming the impressed current anode can either be applied to the top or bottom surface of a slab. The most actively corroding steel is typically near the top surface. The amount of steel in the current path between the most actively corroding steel and the conductive layer should be considered in the evaluation. Application to the top surface requires the conductive layer to be protected from or be capable of resisting abrasion, salt and water, usually with a mortar topping. A topping will reduce headroom and add load, which may make these systems unsuitable for some facilities. With bottom surface applications the conductive layer is protected from traffic, however beams, joists or slab thickening around columns increase the surface area to be coated, which increases both the amount of conductive material required and the amount of concrete the current must flow through to reach the top steel.

Cathodic protection has not been used commercially on prestressed slabs, primarily because of concern for the potential for damage to some types of steel which can result from hydrogen evolution which occurs if current density is allowed to rise above a threshold level. Research is ongoing in this field. There is also a potential problem with continuity when the steel is coated.

4.4 Economic Evaluation

Comparing repair costs with and without cathodic protection for a particular structure requires estimating initial and future costs. Data upon which to evaluate these factors is growing for all repair techniques, including cathodic protection, but the comparison between options is still highly dependent upon the experience of the estimator. The largest unknown in this evaluation is the progression of corrosion activity. If a cathodic protection system is successful, there will be insignificant future costs for structural repair. The amount of delamination which develops following sealer or membrane protection will depend upon the sealer or membrane used, the type and quality of concrete repair, the area of corrosion activity remaining in the slab following repair and various environmental factors. As an objective selection will be required, the evaluation should be provided by a specialist independent of system vendors.

The initial cost of a cathodic protection system includes the site survey, system installation, activation, associated debugging such as short circuit and discontinuous metal detection and verification of performance for a period of time. Ongoing costs include those for monitoring of polarization potentials, rectifier output and various other operating parameters, as required, to ensure continued protection of the structure. Over time, some maintenance of the system will be required, but this cost component, although not predictable, is not believed to be significant.

5. SYSTEM DESIGN AND INSTALLATION

5.1 General

The principles of cathodic protection have been employed for many years to control corrosion in various wet environments (such as underground tanks and pipelines). Cathodic protection has been successfully used and monitored on reinforced concrete bridge decks for about 15 years; however the bridge-deck system most commonly used is too thick and heavy for most parking structures. The technology for the application of cathodic protection to parking structures is still in the development stage and data on the effectiveness or durability of available systems over their intended lifespan is still being collected. Any current/existing parking garage installation must therefore be considered somewhat experimental.

5.2 Types of Conductive Layers (Impressed Current Anodes)

5.2.1 Conductive Coatings

Systems based on conductive coating anodes incorporate a relatively thin carbon or graphite-based paint applied to the bottom surface (soffit) of the slab to be protected. Current is distributed to the coating through wires (sometimes called primary anodes) set in the coating, which is called the secondary anode. The conductive paint is black; a light-coloured top-coat is applied to improve light levels in the facility.

Conductive coating systems are lightweight and do not reduce headroom. Application and material costs are the lowest of available cathodic protection systems. The commissioning period is typically governed by the time required to isolate short circuits.

In conductive coatings the carbon is the material which is consumed in the anodic reaction (see Section 3.1), resulting in a theoretical service life which is proportional to the thickness of the coating. Other factors which can affect service life such as the durability of the other components in the coating and the chemical processes at the concrete/coating interface, have not yet been quantified.

5.2.2 Titanium Mesh in Mortar

For these systems, a 1mm-thick diamond-shaped mesh of titanium coated with a reactive metal is set in a layer of latex modified mortar applied to the top surface of the slab. Distribution of the current from the power supply is primarily through the mesh. One system has separate conductors connected to the different sections of mesh. The mesh is held in place with plastic cleats to resist movement while the mortar is being placed.

Consumption of material in these types of anodes is extremely slow. Laboratory tests indicate that the mesh material should have a service life of over 50 years. The durability of the mortar exposed to the anode current density is not known but is the subject of some concern and investigation. The chemical reaction at the anode is affected by the type of reactive metal coating. Repairs to the anode require chipping into the mortar, increasing examination and repair costs over those for conductive coatings.

5.2.3 Conductive Polymer Mesh in Concrete

This anode material is made from a carbon-loaded conductive polymer, extruded over a copper wire. A mesh formed by fastening individual wires together is anchored to the concrete and covered with a layer of mortar. The carbon in the conductive polymer is consumed in the anode reaction and the polymer becomes brittle with time. The durability of the mesh connectors is being questioned. This system is typically more expensive than the titanium anodes, but the anode is more flexible and rugged than titanium mesh and therefore may be economically viable on rough surfaces.

5.2.4 Conductive Membrane

The concept of combining the anode with a waterproofing membrane is intuitively appealing; however, the quantity of carbon required to make a membrane conductive tends to make it relatively porous and brittle. There have been small trial installations of liquid-applied and preformed sheet membranes but performance data is not generally available and no system has been widely marketed yet.

5.3 Electrical Parameters

Most electrical characteristics of the steel-reinforced slab to be protected should have been evaluated in the selection stage (see section 3.3). Further measurements may be required to design the rectifier sizes for the different sections of anode being supplied.

6. PERFORMANCE EVALUATION

6.1 Delamination Measurement

The direct measure of the performance of a repair is whether or not delamination of the steel-reinforced concrete continues to occur. As delamination formation can take several years, it is useful to have other short-term tests to measure the effectiveness of protection systems.

6.2 Electrical Measurements

As described in 3.1, polarization of the steel, as measured by corrosion potential readings taken on the concrete surface with a half-cell, is the most widely used measure of performance for cathodic protection of reinforced concrete.

To measure polarization, corrosion potential readings are taken across the surface immediately after turning off the system and then about four hours later. The initial (or instant off) readings give the electrical potentials of the reactions which are occurring with the protective current flowing (but without the applied voltage). The later readings reflect the conditions in the slab without the influence of the protective current. A difference, which is called a shift or decay, of 0.1 volt (100mV) between these readings (with the initial reading being more negative than the later one) is considered to represent effective protection. There appear to be different opinions in the industry about how many readings should be taken, how many have to shift and whether only the readings in areas which were originally corroding have to undergo this shift. Collection and evaluation of laboratory and field studies over the next several years will be required to correlate polarization levels with performance in the field.

6.3 Durability

In Canada, only systems using soffit side conductive coatings and a system using a polymer mesh anode have much history. Performance of these systems have not yet been statistically analyzed and published. Expected service life based on this history can only be estimated at this time.

6.4 Technical Support

Experienced personnel are required to keep cathodic protection systems functional. In a developing field such as this, only a few such people are available, and this may restrict the initial use of cathodic protection to large urban centres.

6.5 Cost

Initial application costs vary from about $40/m^2 to about $80/m^2 (1990). The longer term costs of maintenance and operation will only be known with confidence after several systems have been operational for many years.

7. IMPLEMENTATION AND OPERATION

7.1 Standards

Various bodies, including the Canadian Standards Association (CSA), National Association of Corrosion Engineers (NACE), National Reinforced Concrete Cathodic Protection Association (NRCCPA) and the Concrete Society of Britain have standards in development or circulation for use in specifying cathodic protection. As these have not yet received general recognition, the criteria used to evaluate system performance will vary.

7.2 Monitoring

The frequency of performance tests of a system will vary to suit the installation. Any installation contract should cover these costs for a suitable period as well as the costs of any corrections required to the system. Most installations now have computer-based monitoring programs which allow some operating parameters, such as voltage and current output, to be checked and even adjusted from a terminal linked to the facility by telephone line. On-site measurements of corrosion potentials and delaminations are still required at intervals which will depend upon the general performance of the system.

7.3 Staff Training

The facility maintenance staff must be made aware of the procedures to be used when working in the vicinity of the cathodic protection systems. Cleaning, painting, sprinkler testing and lighting maintenance or modification could all have impacts on the system. Appropriate personnel who are routinely at the site should also be trained to make observations of the system for evidence of conditions which should be addressed by the installation or maintenance company.