Evaluating the Performance of Conductive Coating Cathodic Protection Systems Applied to Reinforced Concrete Parking Decks

by

R.A. Gummow, P.Eng.
Consulting Engineer in Corrosion
***Correng Consulting Service Inc.**
Downsview, Ontario

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**A subsidiary of Corrosion Service Company Limited*

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INTRODUCTION

A 1985 study conducted by the Canada Mortgage and Housing Corporation stated that the overall cost of repairs to damaged parking structures in Canada was estimated at 1.5 to 3.0 billion dollars.[1] Little has been done in the intervening years to reduce these costs on existing parking structures.

In fact repair costs have escalated not only due to inflation but owing to more rigorous repair techniques since it is now recognized that the old methods of simply repairing a delamination does little to reduce overall corrosion. Unless all concrete containing greater than a threshold concentration of chlorides is removed, then corrosion continues unabated in non-repaired areas. It is now apparent that unless chloride contaminated concrete is removed corrosion activity continues as long as the relative humidity remains above 50% at the reinforcing steel surface[2] even if a membrane or sealer is applied since the chloride ions are not consumed in the corrosion process. Because of this, repairs have become more extensive and expensive, often involving hydrodemolition of large areas of a parking deck and in extreme cases complete removal and replacement of the slab. Many of these costly measures could have been avoided at considerable savings to the owners if cathodic protection had been used.

The civil and structural engineering community has, with a few minor exceptions, viewed cathodic protection, as it is applied to reinforced concrete decks, as an experimental and largely unproven technique. This conservative attitude has continued even though the Federal Highways Administration endorsed cathodic protection in 1981 as the only proven method of controlling corrosion in chloride contaminated concrete bridge decks[3]. Since the early 1970's cathodic protection has been applied to over 400 bridge decks in North America. Despite the reluctance of the concrete restoration industry to embrace cathodic protection as a viable tool to control corrosion in parking structures, it nevertheless has been applied to over 500,000 m^2 of parking slabs[4]. Most of these installations have been made over the last 5 years and the conductive coating method, wherein a carbon based conductive coating is applied to the soffit of the reinforced concrete deck, constitutes the vast majority of applications.

The cathodic protection industry is, in part, responsible for the limited acceptance by owners and the concrete repair and restoration industry. It is only recently that consensus standards have been produced for the installation and operation of cathodic protection systems and even today research work continues into establishing more empirically derived protection criteria.

One cathodic protection organization, the National Reinforced Concrete Cathodic Protection Association has produced both a User's Guide[4] which describes the various types of systems available and a standard[5] which provides guidelines for applying cathodic protection using the conductive coating method. As useful and informative as these documents may be, there remains a momentum of skepticism in the minds of many involved in the restoration industry. Accordingly, the data presented herein will describe case history results on several cathodically protected structures based primarily on results of delamination surveys conducted by a number of civil and structural consultants.

PROTECTION CRITERIA

Thermodynamic Considerations

The possibility of corrosion occurring on steel in a particular electrolyte is predetermined by the energy relationships between the steel and the solution in contact with it. These energy relationships can be determined by calculation using thermodynamic principles. A result of such an exercise for iron in contact with water can be illustrated in graphical form as in Figure 1.

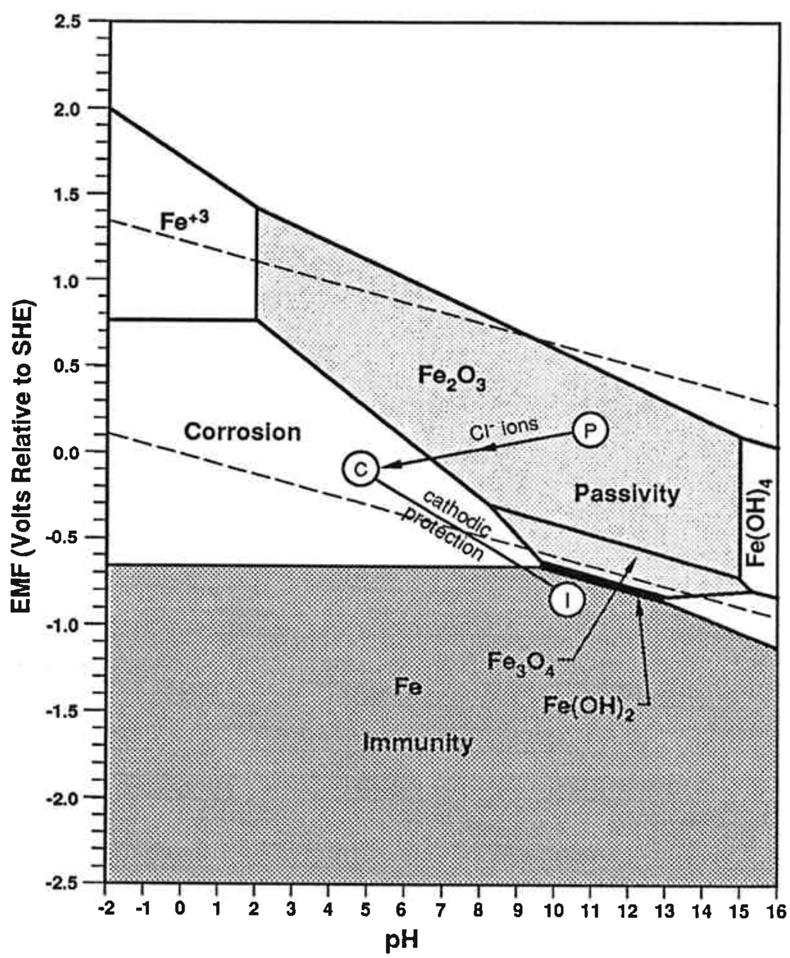

FIGURE 1 - CALCULATED EMF DIAGRAM FOR IRON AT A TEMPERATURE OF 298 K WITH ALL IONS AT AN ACTIVITY OF 10^{-6}[6]

Iron can theoretically exist in three different zones, namely; corrosion, passivation or immunity, depending on the solution potential and pH. Steel in concrete normally resides in the passivation zone (point P) in which the steel is protected by a passive film of Fe_2O_3 and Fe_3O_4 and corrosion activity proceeds only at a small rate sufficient to maintain the passive film. Chloride ions disrupt the passive film which accelerates corrosion, lowers the pH and with increasing chloride ion concentration shifts the iron potential progressively in the electronegative direction as shown in Figure 2.

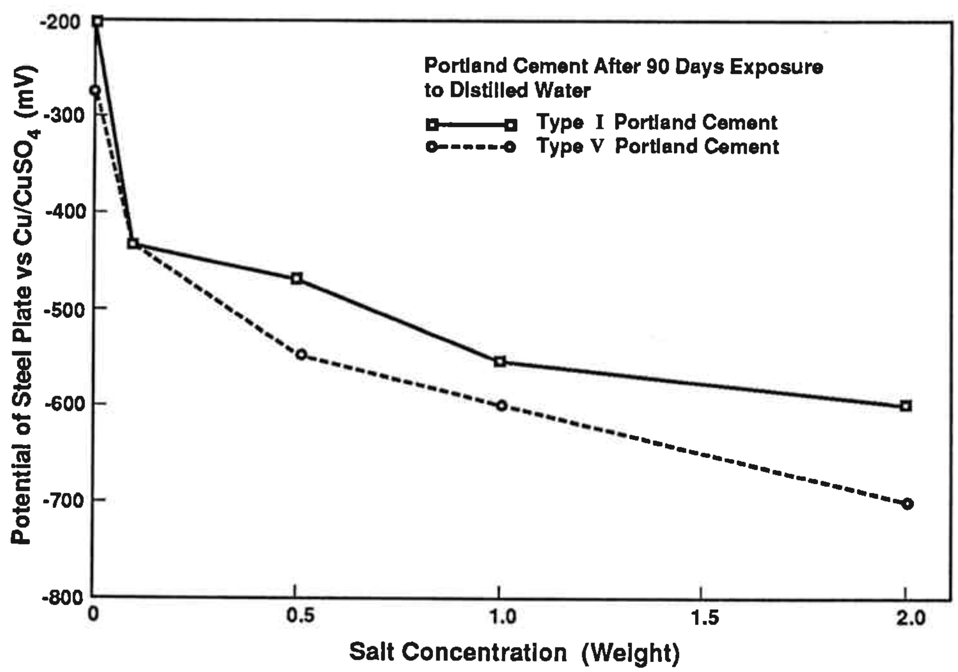

FIGURE 2 - CORROSION POTENTIAL OF STEEL AS A FUNCTION OF SALT CONTENT IN TYPES I AND V PORTLAND CEMENT CONCRETE[7]

The reinforcing steel is now freely corroding and situated at point 'C' in the corrosion zone on Figure 1. By applying cathodic protection, the steel potential can be shifted into the immunity zone denoted by point 'I'.

The transition from the corrosion zone to the immunity zone is not sudden but gradual as indicated in Figure 3. Here it can be seen that the iron becomes progressively less soluble as the

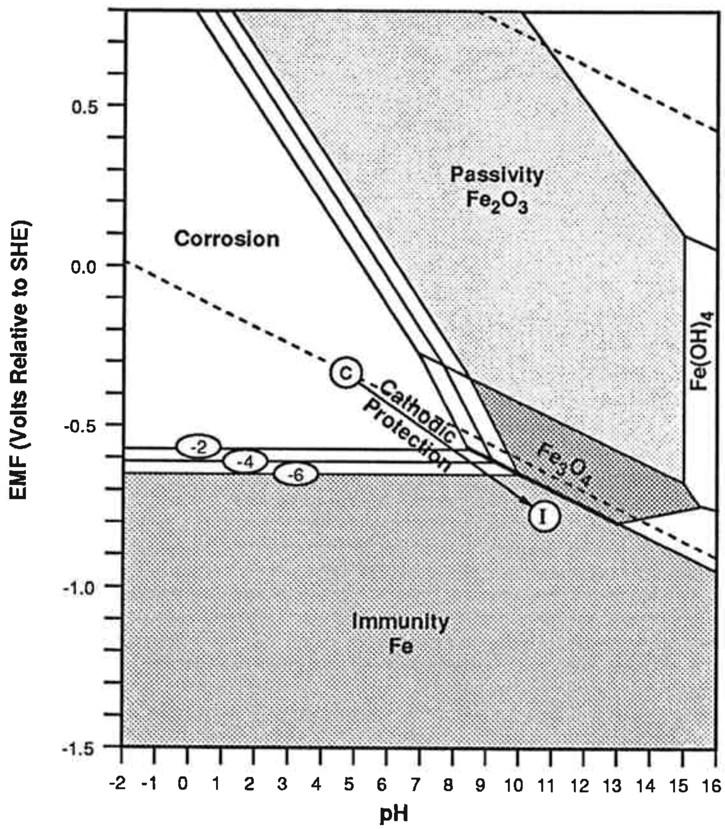

FIGURE 3 - EMF-pH DIAGRAM SHOWING STABILITY CONDITIONS BETWEEN CORROSION AND IMMUNITY ZONES AT ION ACTIVITIES OF 10^{-2}, 10^{-4} and 10^{-6} MOLES PER LITRE.

potential becomes more electronegative. The relationship between potential (E) and the solubility of iron is given by the following equation

$$Eo = -0.440 + 0.0295 \log [Fe^{++}]$$

which indicates that for every change of a magnitude of 10 in the iron ion concentration in moles per litre, the potential will change by 29.5 mV. Conversely, if the potential is changed by polarization by 29.5 mV in the electronegative direction, it is theoretically assumed that the corrosion rate can be reduced by a factor of 10. These thermodynamic considerations do not however take into account kinetic factors.

Kinetic Considerations

When reinforcing steel corrodes, it does so in the context of a corrosion cell where only areas of high negative corrosion potential corrode (anode sites) and other locations of lower electrical potential do not corrode (cathode sites). The difference in electrical potential energy between these sites causes a corrosion current (i_c) to flow within the reinforcing steel and the concrete electrolyte as shown in Figure 4.

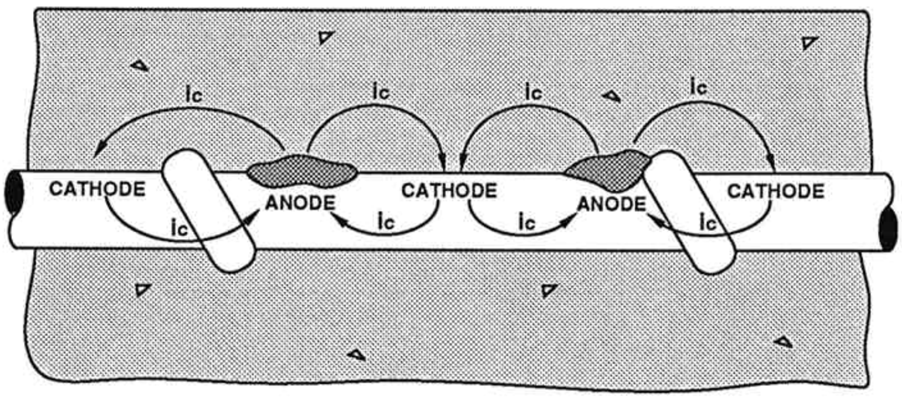

FIGURE 4 - CORROSION CELLS ON REINFORCING STEEL SURFACE

If one could measure the electrical potential with a small probe placed close to the surface of the steel as shown in Figure 5 then a corrosion potential profile would be found as illustrated in Figure 6.

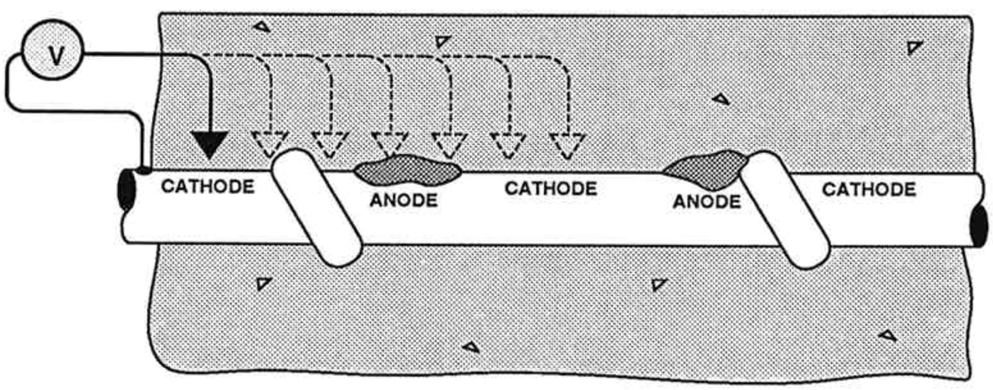

FIGURE 5 - MEASURING CORROSION POTENTIAL OF CORRODING REINFORCING STEEL

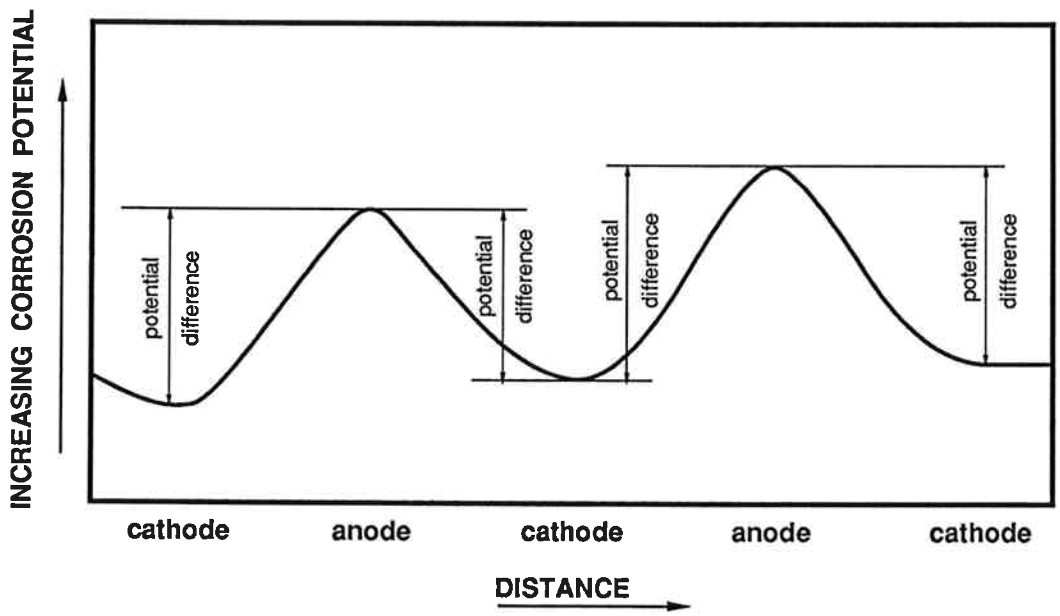

FIGURE 6 - CORROSION ENERGY AS INDICATED BY MAGNITUDE OF ELECTRICAL POTENTIAL

The peaks of this figure represent the anode sites and the valleys are the cathode sites. The difference in height between the peaks and valleys are the EMF's of the various corrosion cells. The greater the EMF (potential difference) the greater will be the corrosion current as long as all other factors remain constant. The corrosion current relates to material loss by Faraday's Law.

If the potential difference between the peaks and valleys can be decreased then the corrosion rate can be correspondingly reduced. Cathodic protection can produce such an effect on a corrosion cell by polarization.

Polarization

Cathodic protection is an electrochemical method of preventing corrosion on metallic objects exposed to an aqueous environment such as reinforcing steel in moist chloride contaminated concrete. Typically a direct current (Icp), as supplied by an external source, is caused to flow through the electrolyte (concrete) as illustrated in Figure 7.

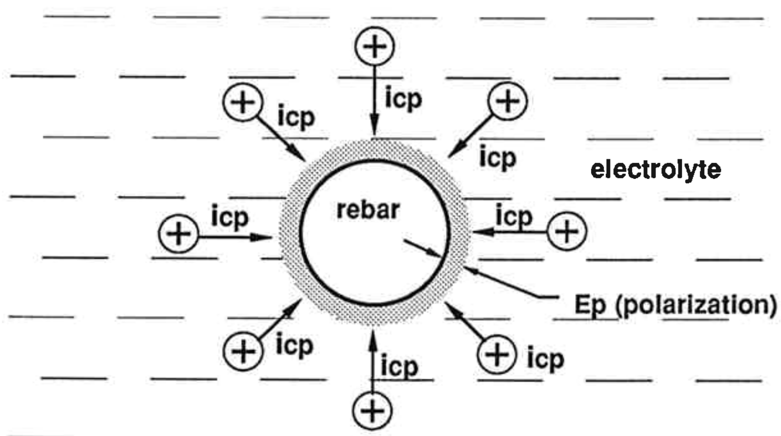

FIGURE 7 - CATHODIC PROTECTION INVOLVES THE SUPPLY OF A DIRECT CURRENT THROUGH THE CONCRETE TO THE REINFORCING STEEL TO CHANGE THE ELECTRICAL POTENTIAL OF THE STEEL BY POLARIZATION.

The slow transfer of charge across the rebar/concrete interface results in a change in the electrical potential (ΔE_p) across the interface. This potential change is called polarization. When cathode sites become increasingly polarized, the corrosion current is reduced proportionately because the potential difference is reduced. This can be illustrated on Figure 8 where the valley potentials are increasingly polarized towards the anodic peaks.

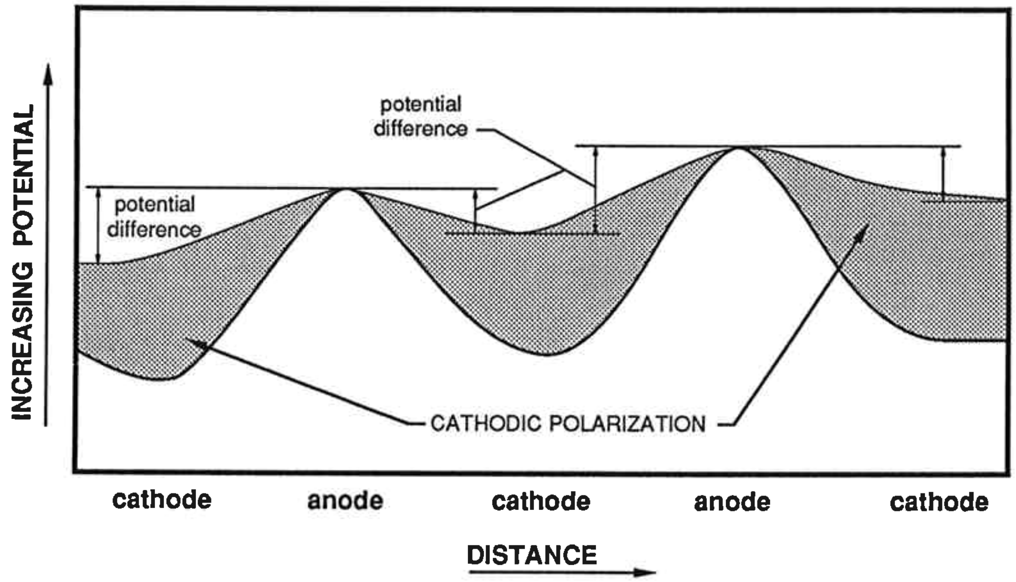

FIGURE 8 - CORROSION POTENTIAL DIFFERENCE IS DECREASED BY CATHODIC POLARIZATION

This figure can also be used to illustrate the Mears and Brown[8] definition of cathodic protection which states that, for complete corrosion protection, all cathodes (valleys) must be polarized to equal the most electronegative anode site (highest peak). Obviously when all the cathodic sites are of equal electrical potential at a value of the most electronegative anode site, there would be no difference in potential and hence there would be no corrosion current.

The amount of polarization shift required however to achieve satisfactory corrosion control on reinforcing steel remains ill-defined. One standard published by the National Association of Corrosion Engineers (NACE)[9] recommends a minimum polarized potential shift of 100mV although this was an arbitrarily selected number borrowed from a pipeline standard. Some investigators [10] have concluded that for complete protection polarization shifts greater than 200mV may be required. Preliminary results however, from a recent study[11] seem to indicate that effective corrosion control can be achieved at much lower cathodic polarization potential shifts and at current densities lower than 10mA/m^2. The National Reinforced Concrete Cathodic Protection Association (NRCCPA) has adopted multi-staged criteria shown in Table 1 based on the probability of corrosion activity if the reinforcing steel potential resides within certain potential ranges.

Instant 'OFF' Potential w.r.t. $Cu/CuSO_4$	Minimum Polarization Decay
more electronegative than -350mV	50mV
more electronegative than -200mV and less electronegative than -350mV	1mV
less electronegative than -200mV	N/A

TABLE 1 - CATHODIC PROTECTION CRITERIA

The three potential ranges are referred to in ASTM STD 876-87[12] and relate in descending order to a greater than 90% probability of corrosion, corrosion uncertainty and less than 10% probability of corrosion. Hence the polarization requirements are greatest for the 90% probability range.

Polarization Measurement

The most practical method for determining the amount of polarization is by the following polarization decay technique. Using a high input resistance voltmeter and a suitable reference such as a saturated copper-copper sulfate electrode placed on the top surface of the concrete, a potential measurement is recorded as the 'ON' reinforcing steel potential. The cathodic protection current is then interrupted and within 1 to 2 seconds of interruption, the potential is again recorded as the instant 'OFF' potential. While the current remains off the potential continues to decay with time as illustrated in Figure 9 until the change in potential with time approaches zero ($\Delta E/\Delta T \rightarrow 0$). The difference between the 'instant OFF' potential and the decayed 'OFF' potential is the level of polarization which had been established on the reinforcing steel by the cathodic protection system.

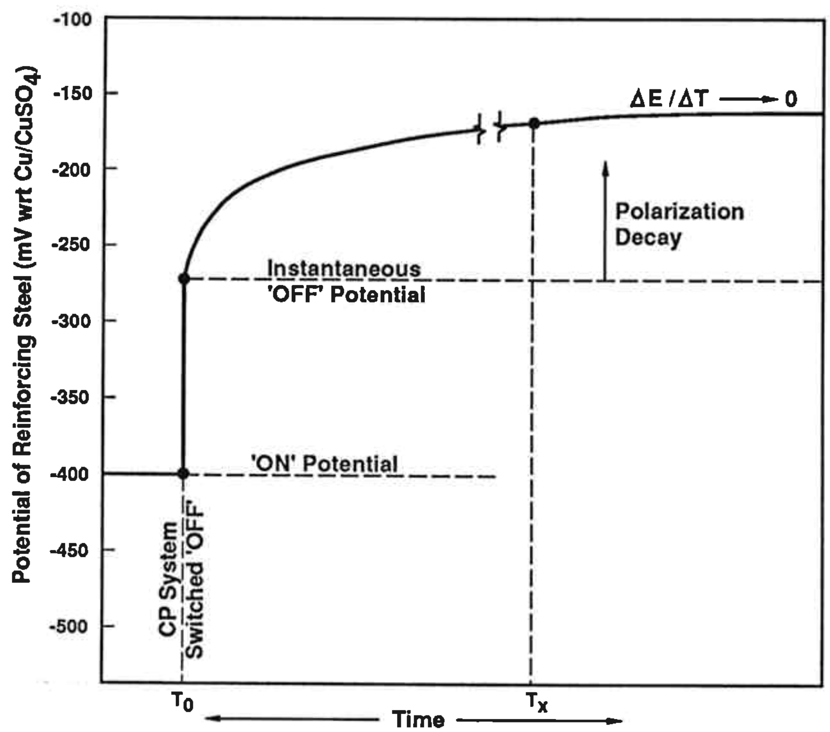

FIGURE 9 - DETERMINATION OF LEVEL OF POLARIZATION BY DECAY METHOD

The most practical objective when operating a cathodic protection system on an existing deck is to reduce the corrosion rate to an acceptable level rather than attempting to halt corrosion activity entirely. In this regard, a reduction in the corrosion rate by a factor of 5 or 10 would substantially extend the life of most chloride contaminated parking structures.

Other Considerations

Besides providing a polarization shift at the reinforcing steel to reduce corrosion by reducing the electrical potential differences between naturally occurring anode and cathode sites, cathodic protection systems also produce other benefits as illustrated in Figure 10.

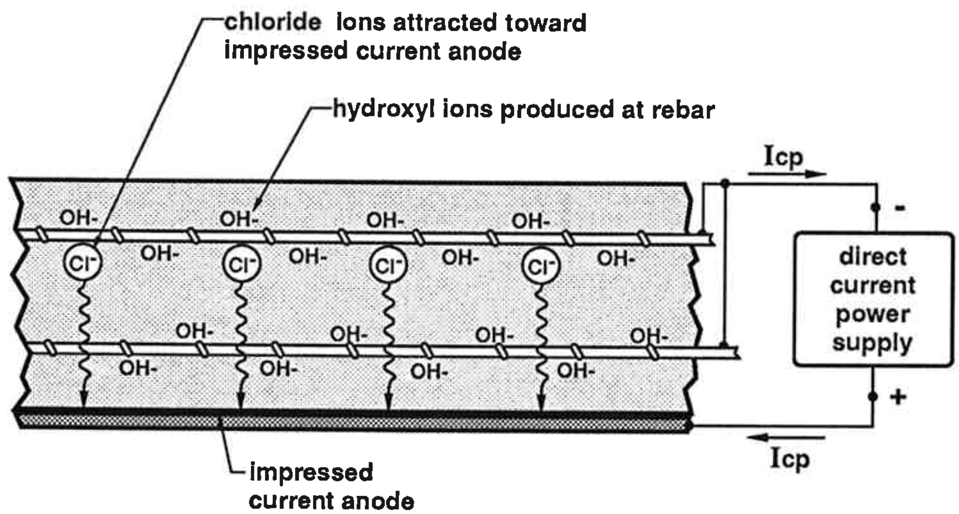

FIGURE 10 - OTHER BENEFICIAL EFFECTS OF CATHODIC PROTECTION INCLUDE Cl^- REMOVAL AND OH^- PRODUCTION AT REINFORCING STEEL SURFACE

Firstly, the charge transfer reactions at the reinforcing steel produce excess hydroxyl ions (OH^-) which increase the local pH at the reinforcing steel thereby restoring a very alkaline environment and allowing the passive film to reform. The predominant charge transfer reaction at the surface of reinforcing steel in concrete decks is as follows:

$$2H_20 + 0_2 + 4e^- \rightarrow 4OH^-$$

It has been observed that reinforcing steel potentials can decay to very electropositive rest potentials indicating that passivity has been re-established on the reinforcing steel surface. This would correspond to a return to point 'P' in Figure 1.

Secondly, the impressed current anode, being electro-positive with respect to the reinforcing steel, attracts chloride ions (Cl^-) away from the reinforcing steel. This effect is illustrated in Figure 11 which indicates that it is current density dependent.

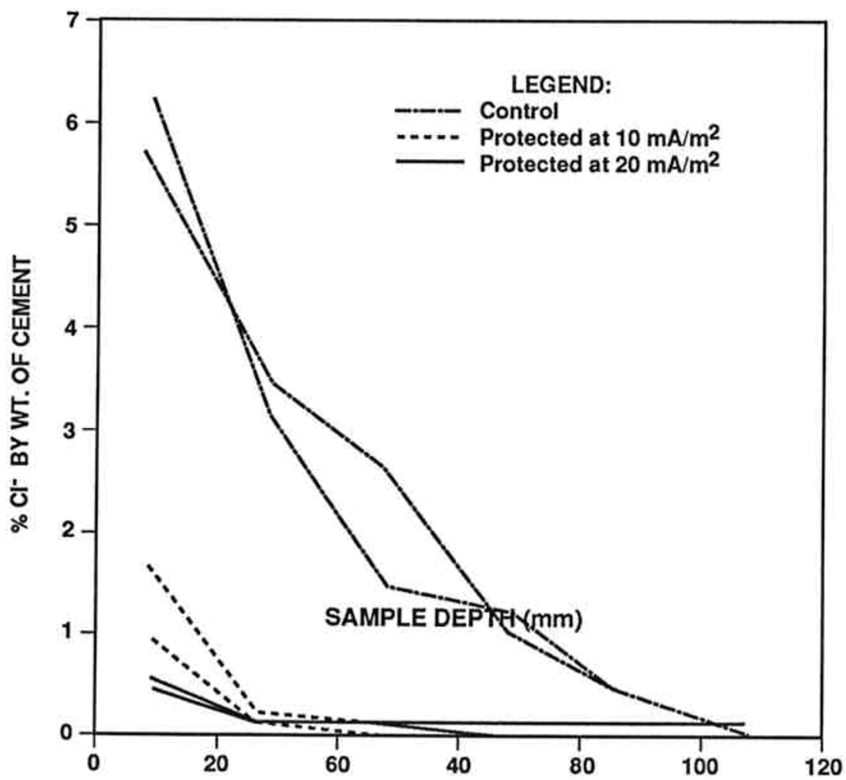

FIGURE 11 - EFFECT OF CATHODIC PROTECTION ON THE PENETRATION OF CHLORIDE IONS INTO CONCRETE[13]

In summary, a cathodic protection system protects reinforcing steel in chloride contaminated concrete in three distinct ways:

(i) by polarizing the steel electronegatively;

(ii) by causing the Cl^- ions to migrate away from the reinforcing steel; and

(iii) by increasing the pH at the surface of the steel.

System Description

The conductive coating cathodic protection system applied to the soffit of a reinforced concrete slab is illustrated in Figure 12. It is composed of a carbon pigmented solvent based or water based resin applied to the concrete surface with platinum clad, copper cored, niobium wires embedded in the coating to provide primary current distribution from a DC power supply. The conductive coating functions as a secondary anode, distributing the cathodic protection current throughout the reinforced concrete structure.

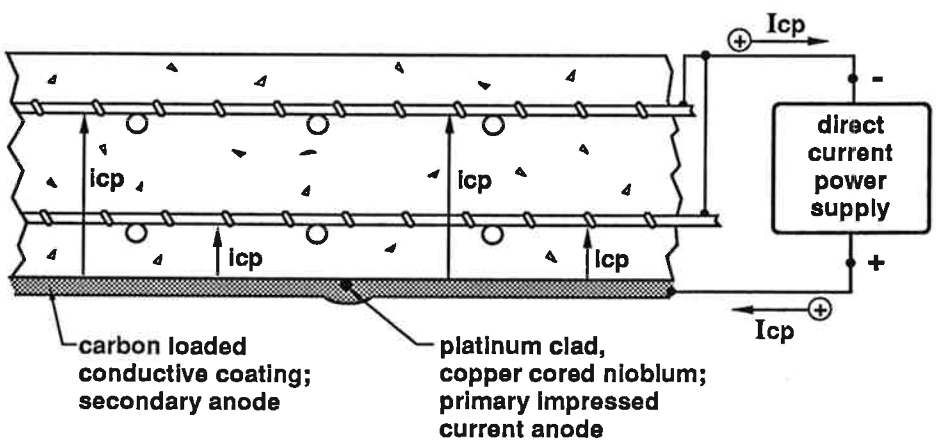

FIGURE 12 – THE MOST WIDELY USED SYSTEM FOR PARKING STRUCTURES CONSISTS OF A CONDUCTIVE COATING SECONDARY ANODE APPLIED TO THE SOFFIT OF THE REINFORCED CONCRETE SLAB.

Advantages

A soffit system has several advantages over other types of cathodic protection systems applied on the top side of the structural slab as follows:

- Material costs are lowest.
- There is usually significantly fewer concrete delaminations on the soffit than on the top-side and therefore preparation of the surface is less costly than for top-side systems.

- The conductive coating when applied to the soffit does not require a surface wear coarse which is required on top-side systems.

- Conductive coatings are lightweight whereas some top-side systems require relatively thick cementitious overlays which can diminish the load capacity of the slab as well as reduce the headroom.

- Since the bottom rebar is usually cathodic to the top rebar the soffit applied conductive coating polarizes the bottom rebar preferentially thus eliminating this macro cell activity.

A soffit system also has a few disadvantages as follows:

- On very thick slabs, it is more difficult to eliminate the micro-corrosion cells existing on the top rebar.

- Because of the preponderance of tramp metal that collects on the bottom of the forms during structural slab construction, numerous tramp metal delaminations can result when these metal pieces contact the conductive coating as illustrated in Figure 13.

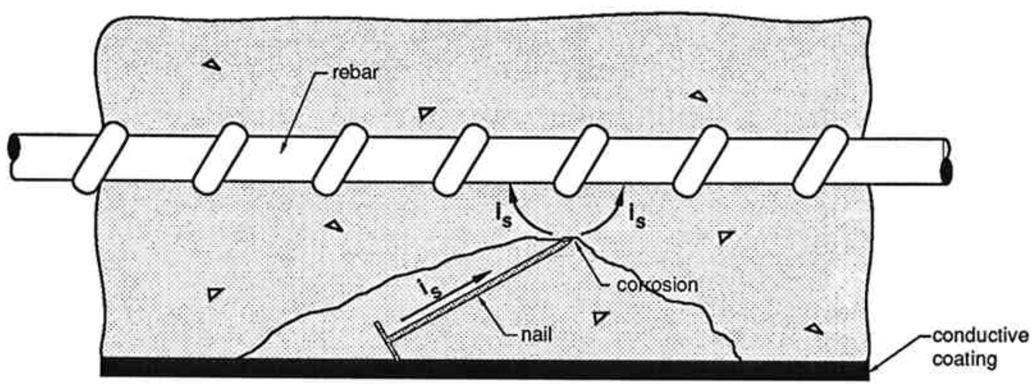

FIGURE 13 - NAIL CONTACTING CONDUCTIVE COATING CONDUCTS CURRENT TO END WHERE CURRENT DISCHARGES CAUSING CORROSION AT END OF NAIL AND SUBSEQUENT TRAMP METAL DELAMINATION.

- There is a greater likelihood of a short circuit between the rebar and conductive coating than for the topside system and additional tasks such as testing, locating, and eliminating short circuits is very labour intensive.

Case Histories

General

Owing to the lack of agreement on a single potential criterion in the cathodic protection industry and coupled with the aversion of the restoration industry to embrace the concept of potential measurement as a performance indicator, it was decided in 1989 to assess the effectiveness of cathodic protection, by engaging several civil and structural engineering consultants to conduct delamination surveys on a number of soffit applied cathodic protection systems over a period of time. Generally, these surveys were done only on a portion of the entire protected area and the surveys were repeated at about 6 month intervals. The consultants were free to choose the size and location of the test area. In all cases, the systems had been installed by Corrosion Service personnel in accordance with the general provisions of NRCCPA Guideline Specification even though this specification was not published until 1990 and many of the systems predate this document.

Case History #1

The first large scale soffit cathodic protection system installed by Corrosion Service was on a 10,000m^2 condominium garage during the fall of 1986. The system, consisting of 21 zones, was energized in February 1987 at an average current density of 10mA/m^2.

Simultaneous with the cathodic protection system installation, minor restoration involving repair of spalled concrete, crack sealing and reconstruction of the expansion joints was completed. The parking garage originally constructed in 1972 does not have a sealer or membrane.

Delamination surveys were commenced in 1989 on a 330m^2 area representing about 80% of one discrete control zone, and have continued on six month nominal intervals. The same consultant has conducted each survey, the results of which are shown in Figure 14.

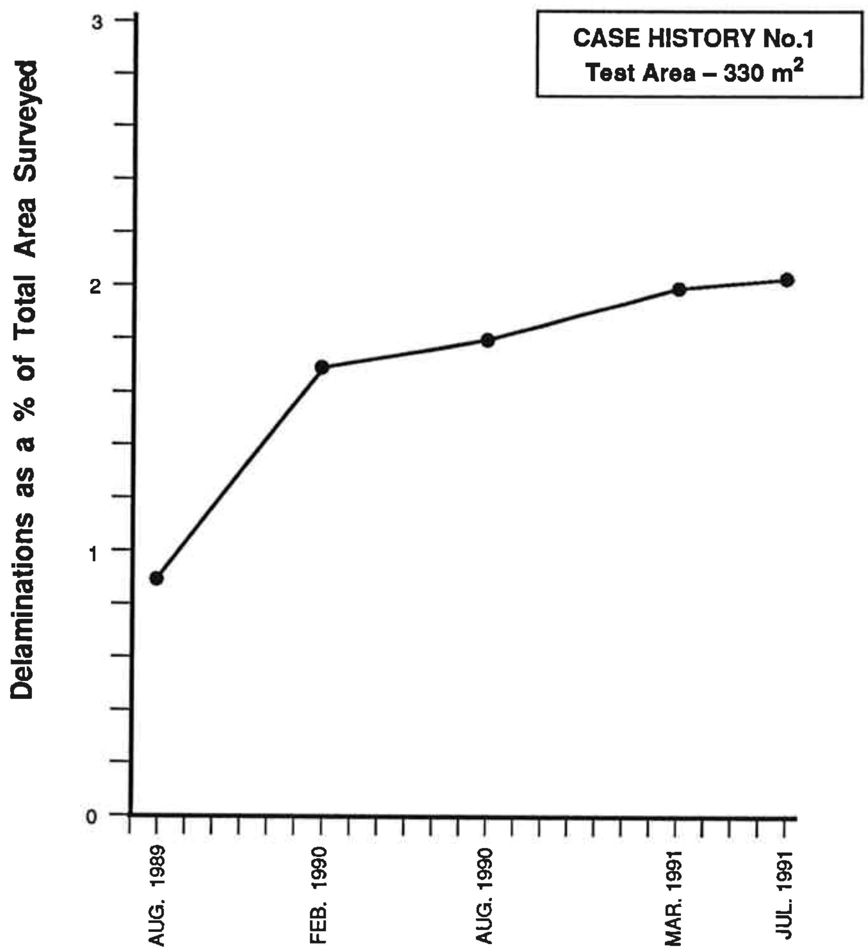

FIGURE 14 - DELAMINATION SURVEY RESULTS WITH TIME

From February 1990 to July 1991, a period of seventeen months, the delamination growth is very small averaging 0.26% annually. It should be noted that some work was done in this section in June 1990 which improved the current distribution.

Typical system voltage and current output characteristics are shown on Figure 15. Output voltage is constant and limited at about 13 volts and the current output varies with the humidity around an average of 400mA which is an average operating current density of 0.8mA/m^2. This

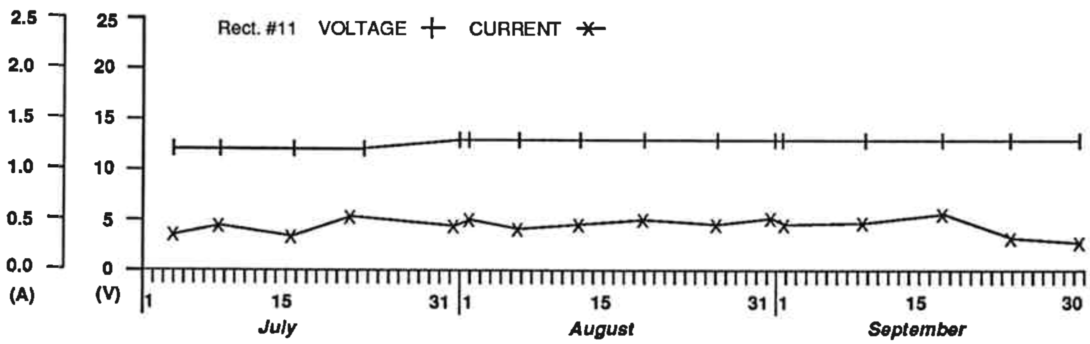

FIGURE 15 - TYPICAL CP SYSTEM OPERATING DATA FOR SECTION #11

current density will be maintained as long as the delamination rate does not increase. The next delamination survey in March 1992 will be at the 5 year anniversary of system energization. Potential survey data recorded as Table 2 indicates that there is 100% compliance with respect to NRCCPA criteria. In fact, it is apparent that the cathodic protection current could be reduced from the present operating level.

Y Direction (feet) \ X Direction (feet)	0	10	20	30	40
70	-390 -150 240	-408 -166 242	-435 -192 243	-399 -164 235	-420 -176 244
60	-520 -261 259	-540 -260 280	-445 -216 229	-445 -123 322	-402 -175 227
50	-501 -265 236	-535 -263 272	-490 -193 297	-463 -136 327	-422 -164 258
40	-510 -245 265	-532 -138 394	-420 -142 278	-429 -137 292	-439 -166 273
30	-555 -297 258	-559 -296 263	-483 -295 188	-484 -228 256	-463 -190 273
20	-445 -234 211	-465 -290 175	-485 -320 165	-446 -212 234	-432 -261 171
10	-460 -218 242	-500 -265 235	-582 -405 177	-350 -126 224	-454 -247 207
0	-302 -225 77	-354 -272 82	-169 -134 35	-307 -217 90	-444 -323 121

LEGEND
Top - Instant 'Off' Potential Middle - Decayed 'Off' Potential Bottom - Polarization

TABLE 2 - REINFORCING STEEL POTENTIAL (mV/CSE) DATA

Case History #2

A soffit cathodic protection system was installed in the late fall of 1987 on about 8,000 m^2 of a condominium parking garage which had been constructed in 1974. Delamination repairs to 13% of the surface were completed in 1987, and a sealer was applied. The cathodic protection system was energized in February 1988 and final short clearing was completed by the end of June 1988.

At this site the entire surface was surveyed for delaminations in June 1989 and again in October 1990. After 2-1/2 years following energization of the cathodic protection system and 3 years after completion of delamination repairs the total amount of delamination is less than 0.65% as indicated in Figure 16. The growth rate between the June '89 and October '90 survey was calculated to be 0.06% annually.

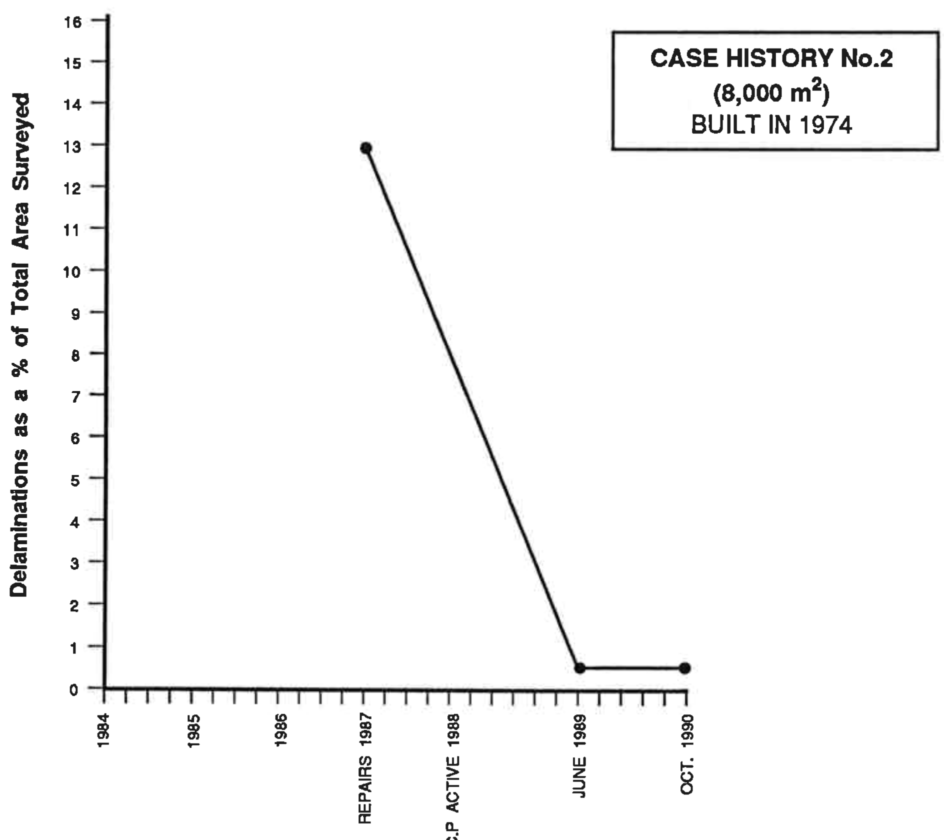

FIGURE 16 - DELAMINATION SURVEY RESULTS FOR CASE HISTORY #2

Initial current densities averaged between 2 and 3 mA/m^2 on most of the 16 zones and after approximately 3-1/2 years, the system is presently operating at an average current density of 1 mA/m^2 with the driving voltage limited at 12 volts. Another delamination survey is expected to done before the end of 1991.

Case History #3

During the fall of 1988, a soffit cathodic protection system was installed on 3500 m^2 of a condominium parking garage and subsequently energized in February 1989 with all short clearing having been completed. The system consisted of 7 zones and was energized at an average current density of 2.5 mA/m^2.

Delamination repairs were made and a membrane put down two years prior to the installation of the cathodic protection system. Delamination surveys were initiated in August 1989 on three areas using chain drag and hammer testing techniques to identify 'hollow' sounding areas. These results and subsequent survey data are shown on Figure 17.

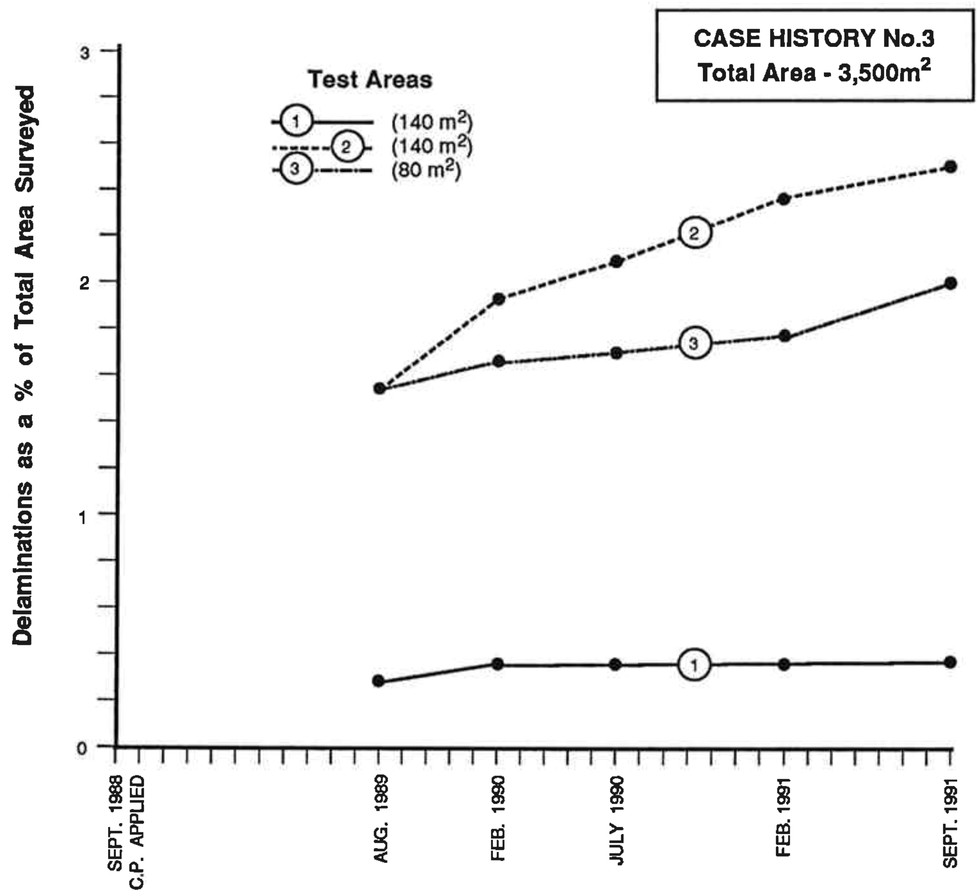

FIGURE 17 - DELAMINATION SURVEY RESULTS FOR CASE HISTORY #3

Because there was a question as to whether or not the hollow sound in areas 2 and 3 were concrete or membrane delaminations, the consultant carried out an additional test to investigate two locations within each area. In every instance, the hollow sound was found to be due to membrane or concrete scaling as opposed to concrete delamination at the reinforcing steel level.

The worst case combined concrete and membrane delamination growth in this structure is less than 0.25% per year.

Case History #4

A total of 5600 m^2 of condominium parking garage was protected with a soffit cathodic protection system installed and energized in mid 1989 following delamination repairs to 35% of the garage and the application of a sealer to the entire garage. The system was energized at an average current density of 2.5 mA/m^2 and is presently operating at this level.

Delamination surveys on the entire area commenced in February 1990 on the entire area and have been continued at approximately six month intervals. Survey data is shown in Figure 18.

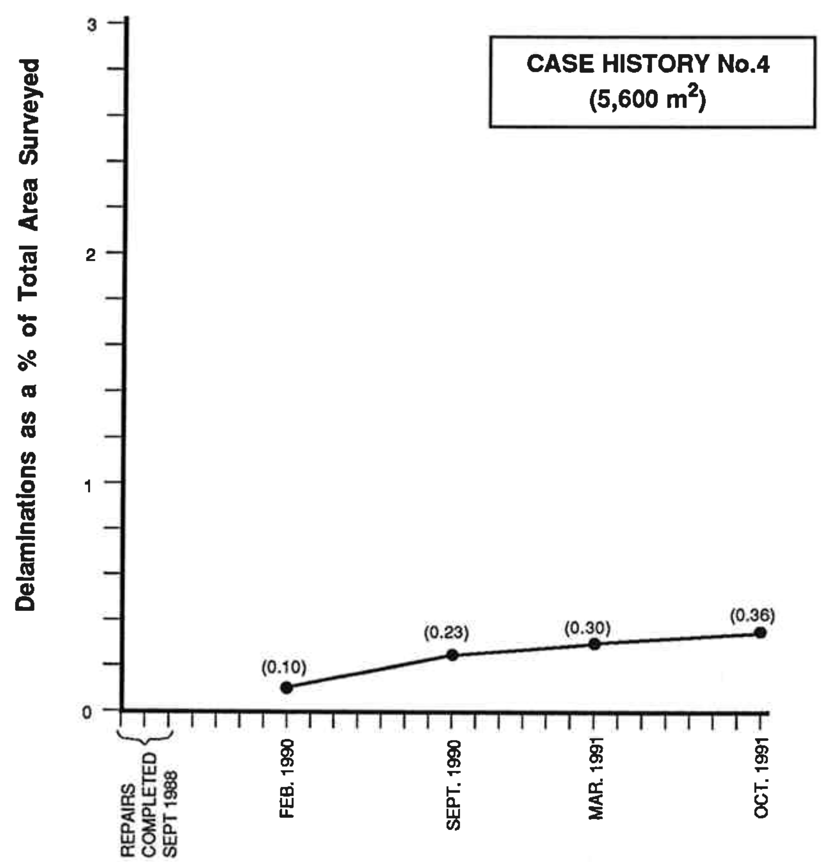

FIGURE 18 - DELAMINATION SURVEY RESULTS FOR CASE HISTORY #4

For the initial 20 month testing period, the average annual delamination rate is 0.16% based on the total area surveyed.

Case History #5

In 1987, a cathodic protection system was installed on a 7200 m^2 area of a condominium parking garage. The system was finally short cleared and commissioned in June 1988. There has never been any delamination or crack repairs in this garage nor any other means of protection applied.

In August 1989, a detailed delamination survey was conducted on a 40 m^2 test section. About 24% of the test section was found to be delaminated initially and this had grown to 34% by September 1991 as shown in Figure 19. Initially, the growth seems to be between nearby

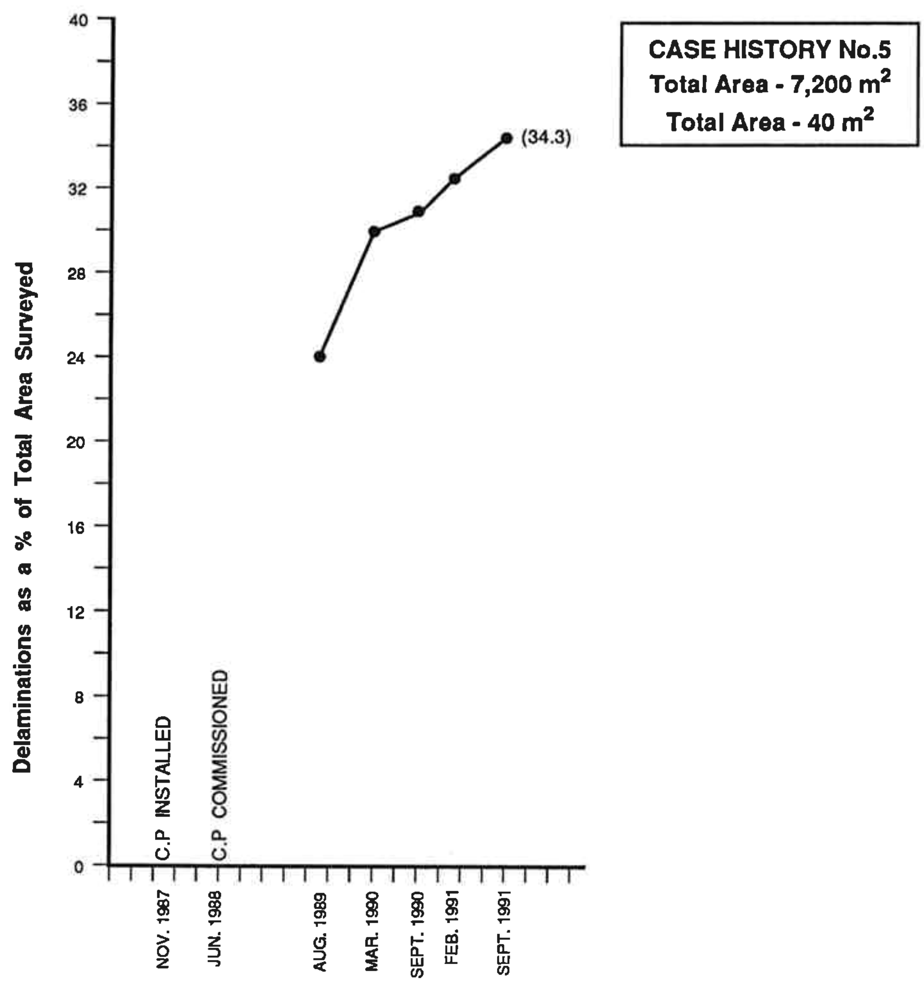

FIGURE 19 - DELAMINATION SURVEY RESULTS FOR CASE HISTORY #5

delaminations giving the appearance of 'webbing' between delaminated fingers, and therefore considered to be caused more by mechanical action from cyclic loading than corrosion activity. The relatively modest growth between the March 1990 and September 1990 survey seemed to justify this assumption. Since then however the delamination growth rate, still predominantly between adjacent delaminated areas has increased at a rate of approximately 3.0% per year.

A cathodic protection analysis indicates that the protection current density in the test area is only 0.20 mA/m^2 which is substantially less than the average of 1.1 mA/m^2 in the rest of the garage. Furthermore a polarization decay test indicated that there was only 33% compliance with the NRCCPA criteria. It was decided to increase the cathodic protection current output for this section.

Case History #6

In 1986, a potential survey was conducted in accordance with ASTM 876 standard in a condominium parking garage. In one area, having a surface area of approximately 1000m^2, over 95% of the corrosion potentials were found to be more electronegative than -0.200V/CSE. A second and third area contained corrosion potentials more electronegative than -0.200V/CSE in about 40% and 60% of the test locations respectively.

It was decided to apply a soffit conductive coating cathodic protection system to the first area and a sealer after minimal repairs. The system was installed and energized during the fall of 1987 and was finally short-cleared by June 1988. The first delamination survey undertaken in March 1989 covered the entire garage, the results of which are shown on Figure 20.

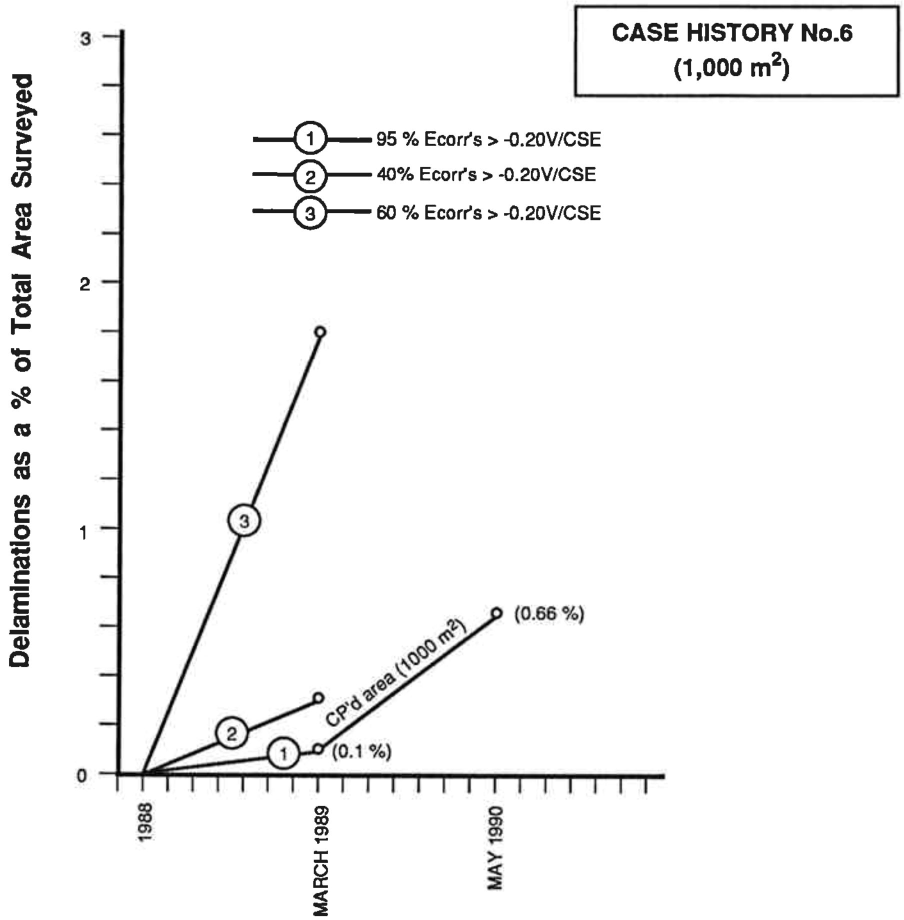

FIGURE 20 - DELAMINATION SURVEY RESULTS FOR CASE HISTORY #6

Here it can be seen that the delaminations in the cathodically protected area (the worst area identified by corrosion potentials) was less than either of the two other areas.

The cathodic protection system was originally energized at an average current density of 10mA/ m^2 but this was reduced to approximately 3mA/m^2 in April 1988 after some conductive coating disbondment was observed near some leaking cracks. A delamination survey in May 1990 indicated that the delaminations had grown to 0.66% of the total area from 0.1% 14 months earlier. The cathodic protection system was off for approximately 2 months during this period. The remaining areas were not surveyed for delaminations since a membrane had been installed.

COST EFFECTIVENESS

As cathodic protection is a specific method of reducing corrosion which requires a significant capital outlay as well as yearly expenses for monitoring and maintenance, the most economically advantageous time to install a system is immediately after corrosion activity has started. The extent of corrosion activity can be determined either by completing a potential survey in accordance with ASTM 876-87[12] or by conducting a delamination survey. Corrosion caused delaminations generally show a logarithmic growth with time as shown in Figure 21.

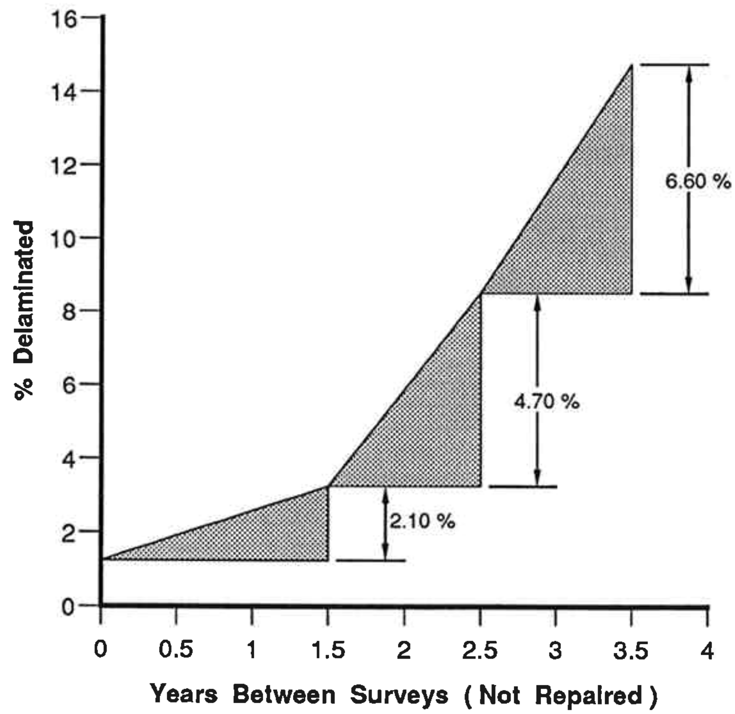

FIGURE 21 - TYPICAL DELAMINATION GROWTH WITH TIME WITHOUT PROTECTION

Substantial savings can be realized therefore if cathodic protection can be applied at a time corresponding to the toe of the delamination curve. The application of cathodic protection should result in delamination growth similar to that shown in Figure 22.

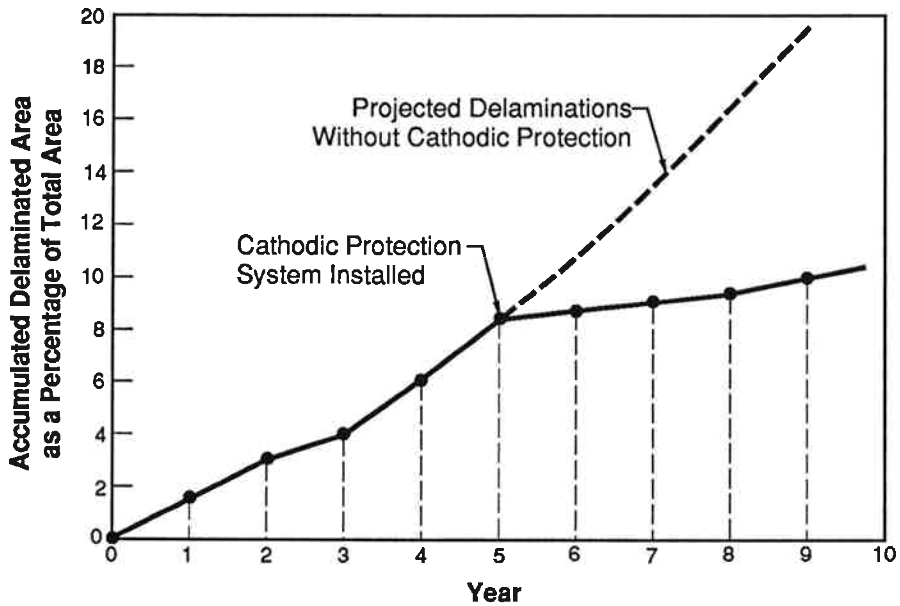

FIGURE 22 - TYPICAL EFFECT OF CATHODIC PROTECTION SYSTEM ON CONCRETE DELAMINATION GROWTH

To determine the cost effectiveness of applying cathodic protection especially in comparison with the more conventional repair techniques and where the alternatives have different anticipated service lives, an economical analysis should be done on an equivalent annual cost basis. This method determines the equivalent annual cost (EAC) of an option such that the chosen alternative would be funded in perpetuity. The analysis ignores the impact of inflation and the equivalent annual cost is determined from the following relationships:

EAC = Present Worth (PW) x Capital Recovery Factor

where any future expenditure must be reduced to present worth

PW = Future Worth (FW) x Single Payment Factor

Case Study

General Description

A 10,000 m^2 parking garage has a total of 10% (1,000 m^2) of delaminations and a current delamination growth rate of 3%. Repair costs are \$200/m^2, membrane costs \$25/m^2, cathodic protection costs are \$45/m^2, annual monitoring, maintenance and operating costs for cathodic protection are \$0.50/m^2 and interest rates are 10%.

Proposal A - Repair and Apply Membrane

- Repair 1,000 m^2 @ \$200/m^2 with a repair life of 50 years
- Apply a membrane to 10,000 m^2 @ \$25/m^2 having a service life of 15 years
- Repair concrete and membrane every 5 years to 5 x 3% yr. = 15% of area or 1500 m^2 at a cost of \$200/m^2 for concrete repair and \$25/m^2 for membrane repair

Future repairs to 15% of area = 1500m^2 x \$200/m^2 + 1500m^2 x \$25/m^2

= \$300,000 + 37,500 = **\$337,500**

PW of future repairs = \$337,500 x 0.62092 = \$209,562

EAC of future repairs	=	\$209,562 x .26393	=	\$55,310
EAC of present repairs	=	\$200,000 x .10086	=	20,172
EAC of membrane	=	\$250,000 x .131474	=	32,868
CAPITAL COST = \$450,000 EAC Total			=	\$108,350

Proposal B - Extensive repairs to remove all chloride contaminated concrete and apply membrane

- Repair 35% of 10,000 m^2 @ \$200/m^2 with a repair life of 50 years
- Apply membrane having a service life of 15 years to 10,000 m^2 @ \$25/m^2

EAC of present repairs	=	\$700,000 x .10086	=	\$70,602
EAC of membrane	=	\$250,000 x .131474	=	32,868

CAPITAL COST = \$950,000 EAC Total = \$103,470

Proposal C - Apply cathodic protection system having a 20 year life to entire garage and repair only those delaminations that affect structural integrity and repair spalls to prevent personal injury. The system will reduce delamination growth to 0.3% per year from 3.0% per year.

- Repair 250 m^2 @ \$200/m^2 with a repair life of 50 years
- Install cathodic protection system on 10,000 m^2 @ \$45/m^2 = \$450,000
- annual CP power and maintenance is \$0.50/m^2 x 10,000 = \$5,000
- repair spalls & delaminations which threaten structural integrity 250m^2 every 10 years @ \$200/m^2

PW of future repairs = \$50,000 x .38555 = \$19,277

EAC of future repairs	=	\$19,277 x .16274	=	3,137
EAC of cathodic protection	=	\$450,000 x .11745	=	52,852
EAC of pwr, monitoring & mtce			=	5,000
EAC of present repairs	=	\$50,000 x .10086	=	5,043

CAPITAL COST = \$500,000 EAC Total = \$66,032

The total equivalent annual cost and capital cost of various restoration scenarios are compared on Figure 23 and shows that cathodic protection can produce a $40,000 annual savings over conventional repairs or the more extensive restoration strategy.

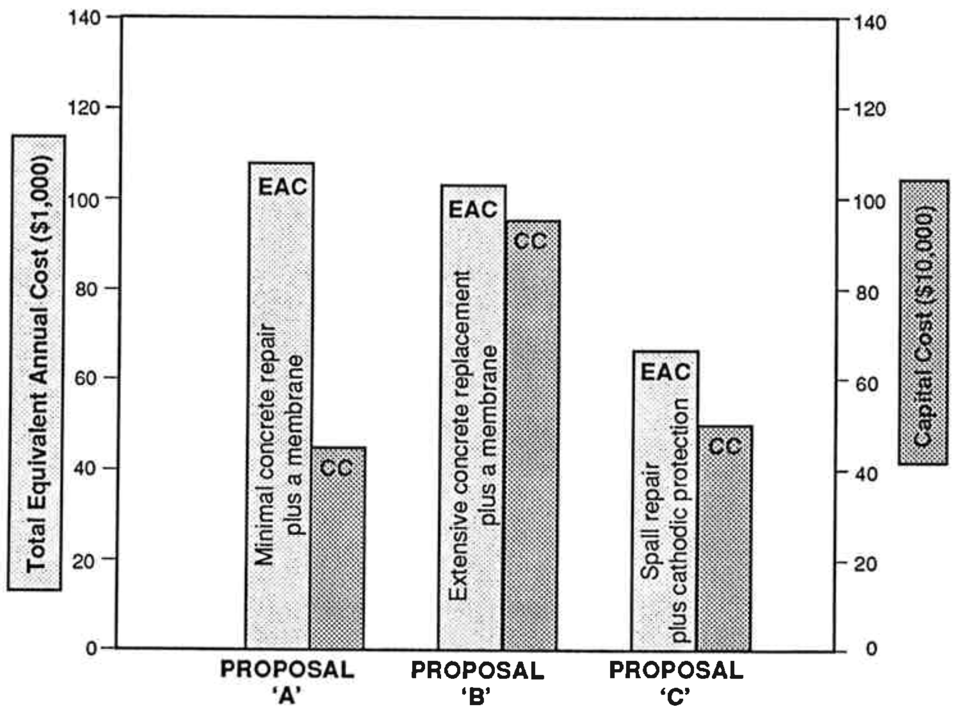

FIGURE 23 - COST COMPARISON FOR VARIOUS REPAIR ALTERNATIVES ON A 10,000 m^2 PARKING GARAGE

CONCLUSIONS

It is clear from the case histories reported herein that a cathodic protection system when installed and operated according to existing standards can maintain low delamination growth rates and therefore has a significant economic advantage over many other presently popular repair strategies. The delamination survey case histories also provide confidence that cathodic protection of reinforcing steel in parking garages using conductive coatings applied to the soffit can be as effective as the cathodic protection systems installed on bridges over the last 15 years. Furthermore, the durability of conductive coating systems is now less doubtful since many of these systems have been operating reliably for several years.

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