

portable exploring reference electrode ( $\text{Cu-CuSO}_4$ ) on the concrete surface. Values of -250 millivolts or less negative values are indicative of little or no corrosion (cathodic sites). Where the potential of steel rebar to a  $\text{Cu-CuSO}_4$  reference electrode is -350 millivolts or more negative, corrosion is suspect (anodic sites). Where carbonation of concrete is prevalent, these corroding and non-corroding potentials may shift electronegatively as much as 100 millivolts. Moreover, a difference of 200 millivolts, or more, between sites in close proximity (within 6 to 12 inches) could be indicative of active corrosion. As chloride concentration increases and oxygen supply is abundant, the corrosion activity becomes more intense and widespread.

### Corrosion Control

Salt contamination is the primary source of corrosion on steel reinforcing within concrete. Chlorides are introduced to concrete structures in many ways:

- De-icing Salts
- Bleaching Operations
- Marine Environments
- Spillage
- Contaminated Aggregate

Naturally, corrosion can be eliminated by preventing salts from ever entering concrete or coming in contact with the rebar. On new structures this can be accomplished by using protective coatings, sealants, penetrants, inhibitors, barriers and the like. However, on existing structures where chlorides have already accumulated in the concrete, such measures are useless. Once concrete is contaminated with chlorides, surface coating treatment is no longer effective. Indeed after extensive research and testing, the Federal Highway Administration (FHWA) issued the following policy statement (Barnhart 1982):

"Rehabilitation techniques such as overlays, sealers and waterproof membranes have been evaluated in both the laboratory and the field in an effort to protect the reinforcing steel from the corrosive effects of salt.

The only rehabilitation technique that has proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of the concrete is cathodic protection." (Emphasis added.)

Since this statement was published in 1982, significant technological breakthroughs have been achieved. Today cathodic protection is the most cost effective means of controlling corrosion of reinforcing steel in chloride-contaminated concrete.

Cathodic Protection

Cathodic protection has a long history dating back to 1824 when Sir Humphrey Davy and Michael Faraday designed and installed the first system (about the time that Joseph Aspdin of England produced the first portland cement). Since this early application, cathodic protection has been employed to control corrosion on many different structures (e.g. pipelines; ship hulls; storage tanks; offshore platforms; docks and marine terminals; and various appurtenances throughout power plants, refineries, pulp and paper mills, food and chemical process plants, and utilities). Indeed, cathodic protection has been characterized as "a most unique and complete form of corrosion control ... using the corrosion process, itself, to combat corrosion".

The principals of cathodic protection are simple. Corrosion is an electrochemical process that involves the flow of electrical current through an electrolyte (such as soil, water, various solutions, or concrete). The current flows between sites of different voltage on a metal surface. The differences in voltage (or potential differences) are caused by a variety of environmental and metallurgical characteristics including salt concentration, oxygen variations, temperature, metal grain structure, solution velocity, and alloying. But whatever the cause, corrosion always follows the same electrochemical process: current flows from an anodic site, through the electrolyte, and is collected on cathodic sites. Corrosion occurs at the anodes where current leaves the metal surface. No corrosion occurs at the cathodes where current is collected from the electrolyte.

When an external electric current is applied to corrosion cells, the electrical potential (voltage) of the anodes and cathodes changes. If we change the system so that the potential difference between anodes and cathodes is zero no current will flow -- and corrosion stops. Indeed, the definition of cathodic protection is:

"Polarizing (changing) the potential of cathodes to the potential of the anodes".

Cathodic protection functions by extinguishing the potential difference between anodic and cathodic surfaces through the application of electric current. When the potential (voltage) difference between anodes and cathodes is zero, no current can flow and corrosion is stopped.

In concrete structures, the potential difference between anodes and cathodes (on steel rebars) usually ranges between 20 and 500 mv, depending on chloride and oxygen concentration and the chemistry of the mixture.

The electric current needed to achieve and maintain cathodic protection is quite small -- usually a fraction of a milliamperere

per square foot of concrete surface. Typically, the power used to protect 10,000 sq. ft. of concrete is about equivalent to that used by a 150 w bulb.

The first use of cathodic protection to control corrosion of steel in concrete was made sometime in the period 1945-55 on buried concrete pipelines. In 1959 Stratfull reported on the first system designed to protect reinforced concrete beams on a highway bridge; he also reported on the first experimental bridge deck system (Stratfull 1974). Throughout the 1970s a variety of bridge deck cathodic protection designs were initiated involving many different techniques. These included disc anodes with overlayers, conductive coke-asphalt overlayers, rod anodes with concrete or conductive grout, and platinum wire or graphite fiber anodes on the concrete surface or in slots surrounded by conductive polymer materials. During the early 1980s systems using anodes that covered the entire concrete surface were first introduced (Ellis and Colson 1980, Jackson 1982, Schell and Manning 1985, and Turgeon 1984). R. P. Brown was the first to employ conductive coatings for cathodic protection of concrete structures (Florida DOT) in 1980-81. Previously Brown developed conductive concrete (1974) as an anode material. Many different systems were developed using metalizing, paint-on conductive coatings, or mesh or a network of conductive polymer cable. All had various claims and different degrees of success and cost effectiveness. However, all the cathodic protection systems were effective in controlling rebar corrosion. (See Brown and Kessler 1981 and 1983, Brown and Powers 1985, and Apostolos 1984.)

Present-day systems can be characterized as:

(1) Non-Overlay Slotted System:

This system (Fig. 2) employs a platinum wire (0.031 in. diameter) or carbon fiber anode installed in a small slot cut in the concrete surface. The slot is usually 3/4 in. deep by 1/2 or 1/4 in. wide. The slots are cut parallel on 10 or 12 in. centers. After the anode is placed in the slot, it is backfilled with a special conductive polymer grout.

(2) Strip System with Conventional Overlay:

Same as (1) above, except the parallel anodes are placed directly on the cleaned concrete surface (i.e., no slots cut), covered with a conductive polymer "bead" or mound and followed by a concrete overlay.

(3) Conductive Polymer Concrete Overlay:

Same as (2) above, except the anode wire or fiber filaments are spaced farther apart and the concrete overlay is made of a conductive polymer.

(4) Conductive Polymer Wire Mesh System:

These systems are quite similar to the conductive coating techniques; they employ an anode covering large concrete areas. Consequently, the technical benefits are also similar. The wire-like mesh made of conductive polymer is a complete anode unit in itself. This particular anode system consists of a mesh of wire-like anodes which are made of a flexible, conductive polymer electrode material coated onto copper conductors. The conductive polymer not only serves as an active anode material, but also shields the copper conductors from chemical attack. The individual anodes are designed and spaced to provide up to 2 mA of protective current per square foot of concrete surface, uniformly over the structure. With ideal current distribution, protective potentials (150 to 200 mV negative shift) can usually be maintained at 1.0 to 1.5 mA/ft.<sup>2</sup> using constant current controls. It is applicable to both bridge decks and substructures as well as a variety of marine and industrial concrete facilities. Installing it entails simply attaching the lightweight plastic mesh to the concrete surface and then covering it with a thin (1-1/2 to 2 in.) concrete overlay, which can be shotcrete.

A variation of the polymer wire mesh is a newly developed titanium oxide metal wire system. This anode resembles "chicken wire" and is particularly adaptable to a variety of concrete surfaces. The metal wire mesh anode is installed much the same way as the polymer wire mesh system.

(5) Conductive Coating Systems:

Conductive coatings, which act as continuous distributive anode (diagrammed in Figs. 3 and 4), require the installation of a platinum wire to introduce the protective current to the coating (anode). The platinum wire (0.031 in. diameter, copper core, niobium jacket) is embedded in the base coating (approximately 15 mils dry film thickness). The embedded wire is then covered with a 2-6 in. wide strip of fine glass fiber screening. The screen is then covered with a second application of conductive coating (only in the wire/screen area). Because of the low resistance of the conductive coating, the platinum wire is needed only every 10 to 20 ft., depending on the particular coating employed and the geometry of the structure being protected.

In general, these coatings require a design current density of 2.0 to 4.0 mA/ft.<sup>2</sup> and operate (after polarization) at 0.5 to 1.25 mA/ft.<sup>2</sup>. It is ideal to divide the system into manageable segments, usually 8 to 12 A each. Such systems require a rectifier unit with a maximum output voltage rating of 12 to 22 v., depending on circuit resistance, cable voltage drop and the particular conductive coating employed.

Under some conditions, the circuit resistance may progressively increase. This is particularly noticeable when chlorides are minimal or very heterogeneous. This increase in circuit resistance is thought to be associated with chloride ion migration away from rebar. The migration is the result of cathodic protection current flow. As the chloride ions move away from the rebar, the electrical contact resistance of the rebar to concrete increases. This movement of ions is beneficial to corrosion control, but may lead to difficulty in defining cathodic protection electrochemical criteria. An increase in the maximum output voltage rating for rectifiers may be needed where this condition is suspect.

As most conductive coatings are black, compatible cosmetic cover coatings have been developed in many colors (primarily to match the existing concrete). These cosmetic coatings also provide some inexpensive protection to the conductive coating.

Masking metal appurtenances to avoid contact with the conductive coatings is vitally important. If the conductive coating comes in contact with any metal (connected to the rebars) a short circuit on the rectifier is created. Care must be taken to grout over any exposed rebar, wires, chairs, stirrups, etc. before applying conductive coatings. Also, it is advisable to provide masked areas (approximately 2 x 2 in.) to accommodate portable reference electrodes for future system testing.

### Conductive Coating Cathodic Protection

The systems described above have gone through periods of testing and evolution in which polymer formulation, installing techniques, electrical controls, and hardware have been refined. Such refinements have resulted in constantly improved effectiveness. Indeed, the most recently developed method, conductive coatings, was specifically designed to overcome previously encountered problems common in other systems. Some of the more important advantages associated with conductive coating systems include:

-- Ease of Installation. The coatings can be sprayed, brushed, or rolled directly onto the concrete surface with very little surface preparation. The installation work is not labor intensive. Installation costs are minimum.

-- It Goes Anywhere. Conductive coatings (with embedded platinum wire anodes) can readily be applied to underdecking, vertical walls, columns, piers, piles, beams, bulkheads, railings, etc. With this system there is virtually no limitation to the geometry. Bridge decks can be protected from beneath, avoiding the necessity to cut into concrete wear surfaces; traffic is not

interrupted and the system is not affected by wear or weather. Figs. 5-8 illustrate some uses of cathodic protection systems employing conductive coatings.

-- Even Current Distribution. Cathodic protection is most efficient if the protective current is provided evenly over the structure. With conductive coatings applied over the entire concrete surface, ultimate efficiency is achieved. This means minimum electric power, no complex electrical controls, no concrete deterioration due to anodic chloride concentration, simplified and reliable operation, and ideal protection.

-- Low Operating Voltage. Because of the large anode area (conductive coating), the electrical resistance of the anode to the concrete is very low. This means that systems operate at relatively low voltage (less power needed) and adverse cathodic protection interference effects are avoided.

-- No "Shielding" Effects. Due to low operating voltage and low anode current density through the conductive coating/concrete interface, the protective current is distributed throughout the reinforcing network. There are no "shadow areas" or metal surfaces shielded from protection. The voltage gradient throughout structures is even and protection is complete.

-- Longevity. Most conductive coatings are formulated with materials already proven for long reliable life when applied to concrete. Moreover, the bond of these coatings to concrete is usually stronger than the concrete itself. Formulations have been developed and tested to demonstrate absolute resistance to freeze-thaw cycles, high ambient temperatures, marine environments and maximum expansion and contraction cycles of concrete.

Indeed, the development of conductive coatings for use in concrete cathodic protection systems is an extraordinary breakthrough. Clearly, these new systems offer outstanding characteristics and benefits proven by both laboratory and field tests. There is no question that leading consultants, highway engineers, and concrete rehabilitation specialists are looking to conductive coatings as a means of providing cost effective corrosion protection for the future.

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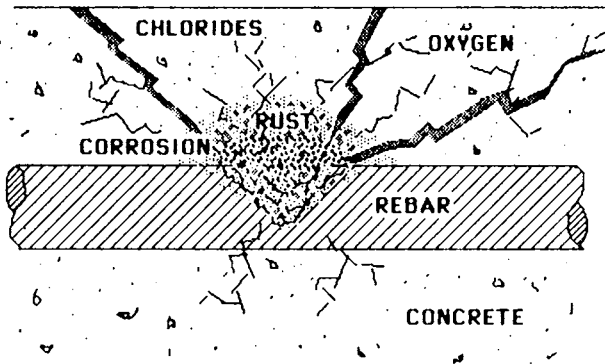


Fig. 1--Rust on rebar occupies more volume than steel — the resulting pressure cracks the concrete

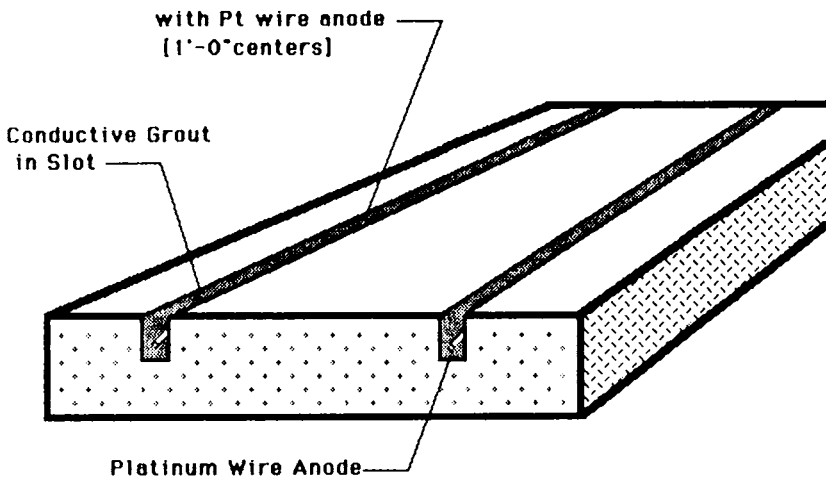


Fig. 2--Bridge deck protected by platinum wires grouted into slots in deck

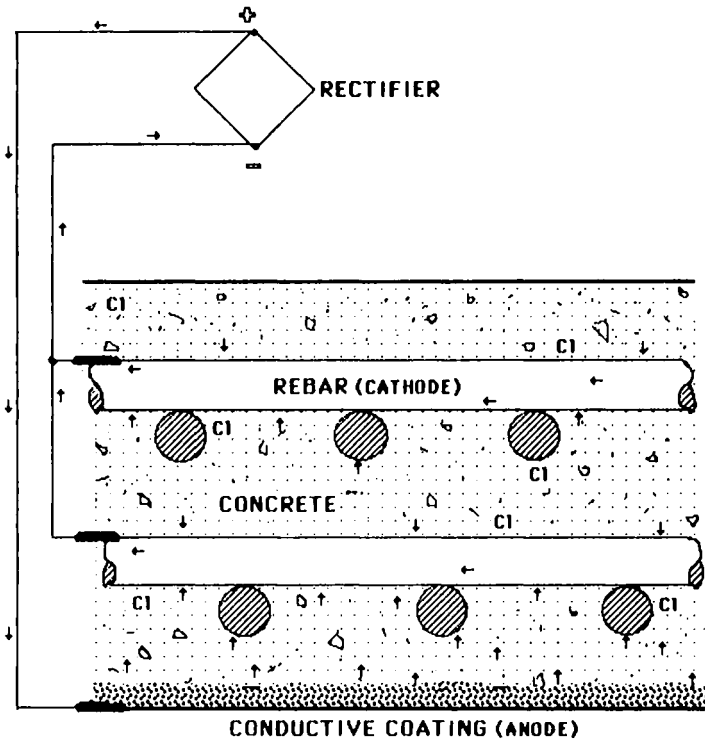


Fig. 3--Principle of cathodic protection of rebars in concrete using conductive coating as the anode

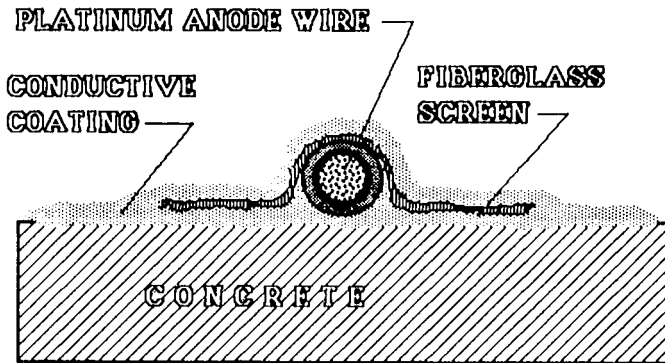


Fig. 4--Wire anode is placed on top of initial coating and covered with strip of glass fiber screen, then wire and screen receive second coating of conductive material — wire is platinum over niobium and copper