

# NONDESTRUCTIVE TECHNIQUES TO INVESTIGATE CORROSION STATUS IN CONCRETE STRUCTURES

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**ABSTRACT:** A critical step in selecting the most appropriate repair strategy for a distressed concrete structure is to determine the corrosion status of reinforcing bars. Because of the complexity of the corrosion process, it is prudent to involve personnel who are experienced in the corrosion of steel in concrete. The corrosion engineer may employ a variety of tools to help make an assessment of the corrosion conditions. This paper provides an overview of the corrosion of steel in concrete and presents some nondestructive electrochemical tools that are commonly used in corrosion investigations. The objective is to provide the repair specialist with basic information to allow effective communication with the corrosion engineer. Electrochemical principles involved in the corrosion of steel in concrete are reviewed. Subsequently, the half-cell potential method, the concrete resistivity test, and the linear polarization method are discussed. The principles of operation and the inherent limitations of these methods are emphasized.

## INTRODUCTION

The corrosion of ordinary steel is inevitable. This is because, under atmospheric conditions, the iron in the steel is unstable and there is a natural tendency for it to revert to a more stable state, which is iron oxide (Smith 1977). To understand why there is this tendency, consider how steel is produced. First, the iron ore, which contains iron oxide, is mined. The ore is processed by using a large amount of energy to remove the iron from the ore. The energy used to produce steel results in a material that is in a higher energy state at room temperature than the ore from which it came. The laws of thermodynamics dictate that materials have a tendency to revert to the lowest energy state that is in equilibrium with the environment. For iron at ordinary atmospheric conditions, the lowest energy state is as an oxide, that is, a type of rust. The presence of atmospheric oxygen provides the necessary ingredient to form the iron oxide. At ordinary temperatures, the transformation is very slow; but if water is also present, the transformation proceeds rapidly, and the iron turns to rust. This simplified explanation is intended to show that it is not surprising that steel corrosion is a widespread problem. Fortunately, in reinforced concrete, a passive oxide coating forms because of the alkaline conditions (high pH, normally about 12.5) in the pores of the cement paste (Tutti 1980; Rosenberg et al. 1989). There are two major factors that cause the passive oxide coating to break down: (1) Carbonation; and (2) the presence of chloride ions.

Carbonation refers to reactions between carbon dioxide and alkalis in the pore solution of the cement paste (Tutti 1980; Rosenberg et al. 1989). As a result of these reactions, hydroxyl ions are consumed and the pH of the pore solution decreases (even below a value of pH 9). Thus conditions are no longer favorable for maintaining the passive coating on the reinforcing steel. The steel becomes susceptible to corrosion. The penetration of the "carbonation front" depends on the quality of the cover concrete (water-cement ratio and degree of hydration) and the degree of saturation of the pores in the cement paste. The penetration rate is low for dry concrete and for saturated concrete, and it is a maximum when the concrete is

in equilibrium with ambient relative humidities between about 40 and 80% (Rosenberg et al. 1989).

The presence of chloride ions also breaks down the passive coating. The exact mechanism for this breakdown is not known with certainty (Hime 1993), but it is known that it happens when the chloride ion content reaches a "threshold value." As pointed out by Rosenberg et al. (1989), there are many factors that affect the threshold chloride ion concentration. For this reason, there is no single minimum value of chloride ion concentration that will break down the passive film. In the United States, the general guideline is 0.2% of acid-soluble chloride by mass of cement [ACI 222R ("Corrosion" 1989)], but others suggest a higher level of 0.4% (Browne 1980). The term "acid soluble" refers to the chloride ion content measured when the sample is prepared by acid dissolution. There is controversy over whether the threshold value should be based on acid-soluble or "water-soluble" chlorides.

Electrochemical methods are used to evaluate corrosion activity of steel reinforcement. As is the case with other non-destructive test methods, an understanding of their underlying principles and inherent limitations is needed to obtain meaningful results. In addition, an understanding of the factors involved in the corrosion of steel in concrete is essential for reliable interpretation of data from this type of testing. This paper provides basic information about three commonly used methods: (1) Half-cell potential; (2) concrete resistivity; and (3) polarization resistance.

Corrosion science is complex, and unfortunately, it is not covered in the typical civil engineering curriculum. As a result, practicing engineers involved in structural evaluations may lack the basic knowledge for understanding the underlying principles of nondestructive test methods used to assess corrosion activity in concrete. Therefore, the paper begins with a simplified discussion of the basic principles of corrosion. Interested readers should consult additional references on the electrochemistry of corrosion and the factors affecting corrosion of steel in concrete (Evans 1960; Uhlig 1971; West 1986; Fontana 1986; "Corrosion" 1989; Rosenberg et al. 1989).

## PRINCIPLES OF CORROSION

### Electrolytic Cell

Corrosion is an electrochemical process, which means that it involves chemical reactions (gain and loss of electrons) and electrical current (flow of charges through a conductor). The classic approach for understanding the mechanism of corrosion is to consider the operation of an electrolytic, or galvanic, cell (Brown and LeMay 1988). An electrolytic cell is a system

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involving two electrodes and two types of chemical reactions, one of which supplies electrons and the other that consumes electrons. To maintain electrical neutrality and sustain the chemical reactions, electrical charge transfer occurs through external and internal pathways connecting the two electrodes where these reactions take place. Electrons flow through the external connection and ions flow between the two solutions surrounding the electrodes.

Fig. 1 illustrates the basic components of an electrolytic cell. One metal electrode is immersed in an ionic solution containing the positive ions of the metal. The other electrode is made of a different metal immersed in an ionic solution containing the positive ions of that metal. The electrodes are connected externally by an electrical conductor. There is also an internal connection (salt bridge) that permits movement of ions between the two solutions. One electrode is the anode where a half-cell oxidation reaction occurs. At the anode, the electrode dissolves and goes into solution as positive ions leaving behind electrons. This anodic reaction can be written as follows:



where  $A$  represents an atom;  $A^{n+}$  = positively charged ion; and  $e$  represents an electron. Each atom of material  $A$  loses  $n$  electrons as it goes into a solution as a positively charged ion. This is the corrosion reaction for the cell.

The other electrode is the cathode and a half-cell reduction reaction occurs on its surface. The cathodic reaction involves the combination of electrons with positive ions in the solution to produce an atom that deposits on the electrode. The cathodic reaction can be represented as follows:



As a result of these two reactions, there is an increase in positive ions in the solution containing the anode and a depletion of positive ions in the solution containing the cathode. To sustain the half-cell reactions, there must be a connection between the two solutions so that electrical neutrality is maintained. In this case there would be a flow of positive ions from the anodic half-cell to the cathodic half-cell.

If an electrical conductor does not connect the electrodes, there is no net corrosion of the cathode and no net deposition at the cathode. The word "net" is used, because at both electrodes some atoms go into solution and some are deposited,

but the rates are equal and there is no net change at the electrodes. The rate at which atoms are dissolved and deposited on the electrode surface defines the equilibrium exchange current, which is a misnomer because the net current is actually zero (Fontana 1986).

In summary, an electrolytic cell can be two electrodes of dissimilar metals immersed in ionic solutions (electrolytes). The electrodes are connected externally by an electrical conductor and there is a means for ionic transfer between the electrolytes. The anode is consumed (corrodes) and reaction products are deposited on the cathode.

### Electrical Potential

The ease with which the half-cell reactions occur is governed by their half-cell potentials that are measured in volts. These potentials affect how vigorously the anode corrodes when the external circuit is completed. Half-cell potentials are usually expressed for the oxidation reaction, that is, they represent the ease with which atoms will give up electrons and go into solution as positive ions. A half-cell potential cannot be measured for a single electrode, therefore, it is referenced to the potential of a standard reduction reaction in which hydrogen ions gain electrons to form hydrogen gas (Guy 1976). The half-cell potential depends on the ionic concentration and temperature of the solution in which the electrode is immersed. Standard half-cell potentials are measured for unit concentrations of the solutions at a standard temperature. The more negative the value of the standard half-cell potential, the greater the tendency of the metal to lose its electrons, that is, to corrode.

Suppose that the external circuit in Fig. 1 is replaced with a high-impedance voltmeter, which means that there is no current in the external circuit. This is referred to as the open-circuit condition. The voltmeter reads a voltage that equals the difference between the half-cell potentials of the anodic and cathodic reactions (Brown and LeMay 1988). For example, suppose one electrode is iron in a standard solution of iron ions and the other electrode is zinc in a standard solution of zinc ions. The standard half-cell potential for the oxidation of iron is  $-0.44$  V, and the standard half-cell potential for the oxidation of zinc is  $-0.76$  V (Fontana 1986). The greater negative potential for the zinc electrode means that it tends to give up its electrons more readily than iron. If the positive terminal of the voltmeter is connected to the zinc electrode, the voltmeter would read  $-0.32$  V, which is the difference between  $-0.76$  V and  $-0.44$  V. If the positive terminal of the voltmeter had been connected to the iron electrode, the reading would be  $+0.32$  V. The zinc electrode is the anode and the iron is the cathode. If a conductor replaces the voltmeter, electrons would flow from the zinc to the iron. The zinc electrode would dissolve and iron atoms would deposit on the iron electrode.

### Polarization

The next discussion deals with the magnitude of the current when the external circuit of an electrolytic cell is completed. This establishes the corrosion rate of the anode. Fig. 2(a) shows an electrolytic cell with the electrodes connected to a high-impedance voltmeter. As explained above, the voltmeter reads a voltage equal to the difference of the half-cell potentials for the electrode reactions. This is the equilibrium or open-circuit potential (Fontana 1986). When the electrodes are connected with a conductor, they must be at the same potential. The potential of the electrodes can be measured by introducing a reference electrode and measuring the potential with a voltmeter as shown in Fig. 2(b). The measured potential will

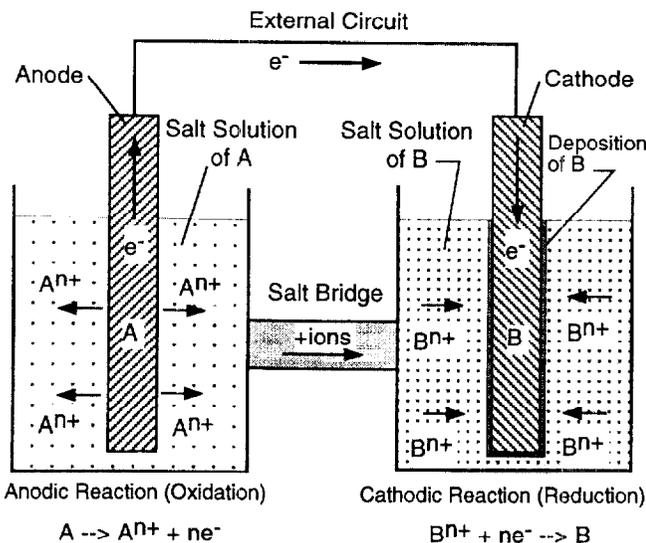


FIG. 1. Example of Electrolytic Cell; Oxidation Occurs at Anode and Reduction Occurs at Cathode (Adapted from Brown and LeMay 1988)

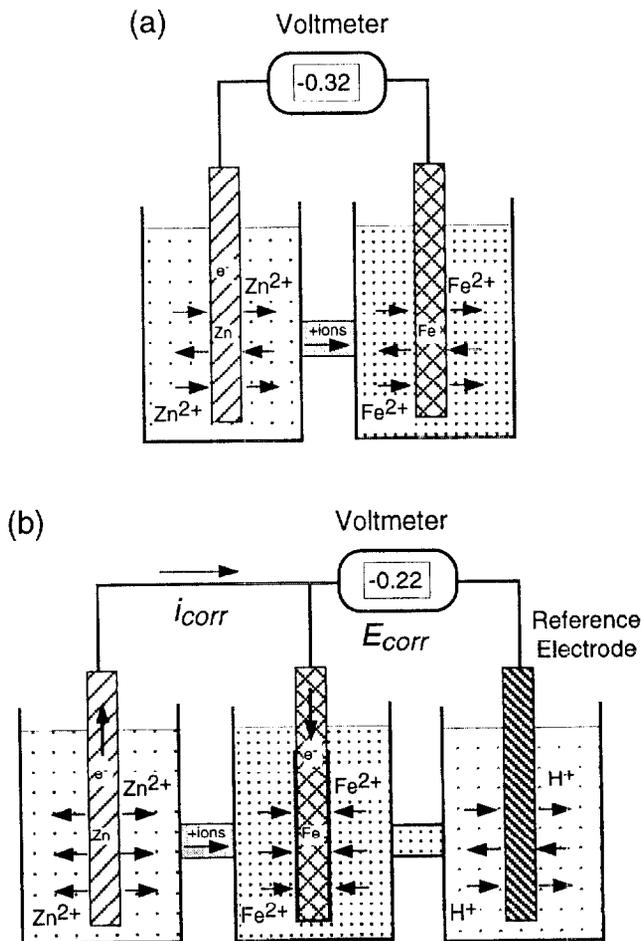


FIG. 2. Electrolytic cell: (a) with No External Current, Voltmeter Reads Equilibrium Voltage; (b) Short-Circuited Cell with Electrodes at Same Potential

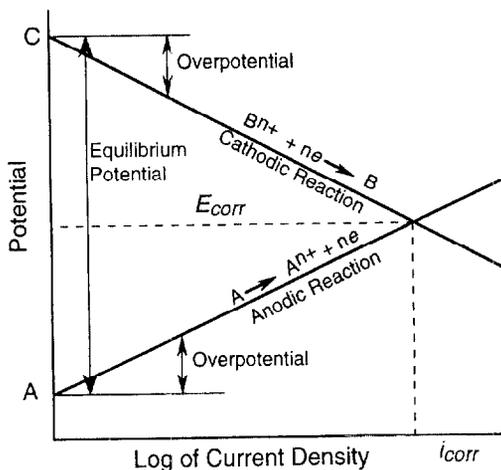


FIG. 3. Polarization Curves for Short-Circuited Electrolytic Cell Showing Stable Cell Potential and Corrosion Current (Adapted from Rosenberg et al. 1989)

be between the half-cell potentials of the electrodes. The anode is, therefore, at a more positive potential than its half-cell potential, and the cathode is at a more negative potential than its half-cell potential. Thus, the current between the electrodes leads to a change from the equilibrium half-cell potential of each electrode. This potential change is called polarization (Fontana 1986; "Terminology" 1997). The difference between the equilibrium half-cell potential and the electrode potential with current is the overpotential.

Every half-cell possesses a characteristic polarization curve

that represents the relationship between overpotential and the net current into or out of the electrode. Fig. 3 shows idealized (and simplified) polarization curves for the anode and cathode of an electrolytic cell (Uhlir 1971; Fontana 1986; West 1986; Rosenberg et al. 1989). The horizontal axis is a log scale, so that the relationship is nonlinear in terms of actual current. In addition, the current is usually expressed as a current density, which is the net electrode current per unit surface area of the electrode. Points A and C in Fig. 3 correspond to the half-cell equilibrium conditions with no net current at the electrodes, and the difference between the potential values is the equilibrium (or open-circuit) potential of the cell. The curves show that the net current out of the anode increases as its potential becomes more positive, and the net current into the cathode increases as its potential becomes more negative. These polarization curves permit determination of the corrosion current density and the corrosion potential of the short-circuited electrolytic cell. When the cell is in a stable condition, the net current out of the anode must equal the net current into the cathode. Thus, the intersection of the polarization curves defines the corrosion potential  $E_{corr}$  and corrosion current density  $i_{corr}$  of the electrolytic cell. Faraday's law allows one to convert the corrosion current density to the rate of loss of the electrode (Evans 1960; Andrade 1996; "Practice" 1997a). Fig. 3 shows both curves with equal current density at the half-cell equilibrium conditions (Points A and C). In reality, the current densities at Points A and C are the equilibrium exchange currents for the half-cells and would not necessarily be equal (Fontana 1986).

In summary, when a conductor connects the anode and cathode of an electrolytic cell, corrosion occurs at the anode. The polarization curves of the anodic and cathodic half-cell reactions are the key for understanding the corrosion rate of the cell. There are several ASTM standards that should be consulted for additional information on terminology and procedures for developing these polarization curves [ASTM G 102 ("Practice" 1997a); ASTM G 59 ("Practice" 1997b); ASTM G 3 ("Practice" 1997c); ASTM G 15 ("Terminology" 1997)].

## CORROSION OF STEEL IN CONCRETE

Attention can now be turned to a reinforcing bar embedded in moist concrete, as shown in Fig. 4. The water in the pores of the paste contains various dissolved ions and serves as the electrolyte. If the passive coating on the steel is destroyed, due to carbonation or to the presence of chloride ions above the critical concentration, conditions are favorable for corrosion. Heterogeneities in the surface of the steel, such as differences in grain structure and composition, and local differences in the electrolyte, due to the heterogeneous nature of concrete, cause a region of the bar to act as an anode and another region to act as a cathode. Because the anode and cathode are on the same bar, there is an electrical connection between the two. Thus, there is a short-circuited electrolytic cell, analogous to Fig. 2(b).

At the anode, iron atoms lose electrons and move into the

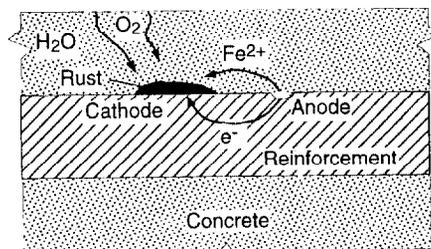


FIG. 4. Localized Corrosion of Steel Bar Embedded in Concrete; Iron Is Dissolved at Anode and Rust Forms at Cathode

surrounding concrete as ferrous ions ( $\text{Fe}^{2+}$ ). The electrons flow through the bar to cathodic sites, where they combine with water and oxygen in the concrete to form hydroxyl ions ( $\text{OH}^-$ ). To maintain electrical neutrality, the ferrous ions migrate through the pores of the paste to the cathode where they combine with the  $\text{OH}^-$  ions to form hydrated iron oxide, or rust. Thus, when the bar is corroding, there is a flow of electrons through the bar and a flow of ions through the concrete.

From the above discussion, it can be concluded that corrosion of embedded steel in concrete requires the following conditions: (1) Loss of passivation; (2) presence of moisture; and (3) presence of oxygen. If any of these are absent, there is no corrosion. If there is a limited amount of water or oxygen, corrosion proceeds at a slow rate. These factors are discussed further because they are important in understanding the corrosion process.

The short-circuited electrolytic cell in Fig. 2 has a bridge

that allows the unrestricted flow of ions between the cell solutions to maintain electrical neutrality. For the bar embedded in concrete, the concrete provides the bridge between the anode and cathode to allow the movement of ions. The pore structure of the paste and the degree of saturation of the capillary pores control the ease with which ions can move through the concrete. In short, the mobility of the ions is related to the electrical conductance of the paste. Fig. 5 shows an electrolytic cell in which the bridge between the solutions is replaced by a resistor that restricts the flow of charge between the cells. This, in turn, reduces the corrosion current compared with the electrolytic cell in Fig. 2(b). The polarization curves in Fig. 5(b) help explain why the corrosion current is reduced. The driving voltage due to the difference between the half-cell equilibrium potentials of the cathode and anode ( $E_c - E_a$ ) is dissipated in polarizing the electrodes and overcoming the electrolytic resistance of the concrete (West 1986)

$$E_c - E_a = \eta_a + |\eta_c| + I_{corr}R \quad (3)$$

where  $\eta_a$  and  $\eta_c$  = overpotentials of the electrodes;  $R$  = electrolytic resistance; and  $I_{corr}$  = corrosion current. The corrosion current is lower than the case where the resistance is zero (Figs. 2 and 3). Fig. 5(c) shows an equivalent circuit of the corroding bar (West 1986). The polarized electrodes are shown as resistors, which are usually referred to as "reaction resistances" (Elsener et al. 1990). If the electrolytic resistance is reduced from  $R_1$  to  $R_2$ , less of the cell potential is required to overcome the electrolytic resistance, the overpotentials increase, and the corrosion current increases.

If the amount of oxygen in the concrete is less than needed for the cathodic reaction, a condition known as concentration polarization occurs, and the corrosion current is reduced (Uhlig 1971; Fontana 1986; West 1986). This is illustrated in Fig. 6. Because of the limited amount of oxygen for the cathodic reaction, the cathodic polarization curve is no longer a linear function of the logarithm of the current density. Instead, there is a limiting value of the cathodic current density and the polarization curve is asymptotic as shown in Fig. 6. The limiting current density depends on the concentration of oxygen in the paste, the diffusion coefficient of oxygen through the paste, and other factors (Uhlig 1971). As shown in Fig. 6, concentration polarization at the cathode reduces the corrosion current. This explains why the corrosion rate of steel in submerged concrete is very low. Note that the corrosion potential shifts to a more negative value, but the corrosion current is reduced compared with the conditions represented by Fig. 2. This is important in the interpretation of half-cell potential, as discussed in the next section.

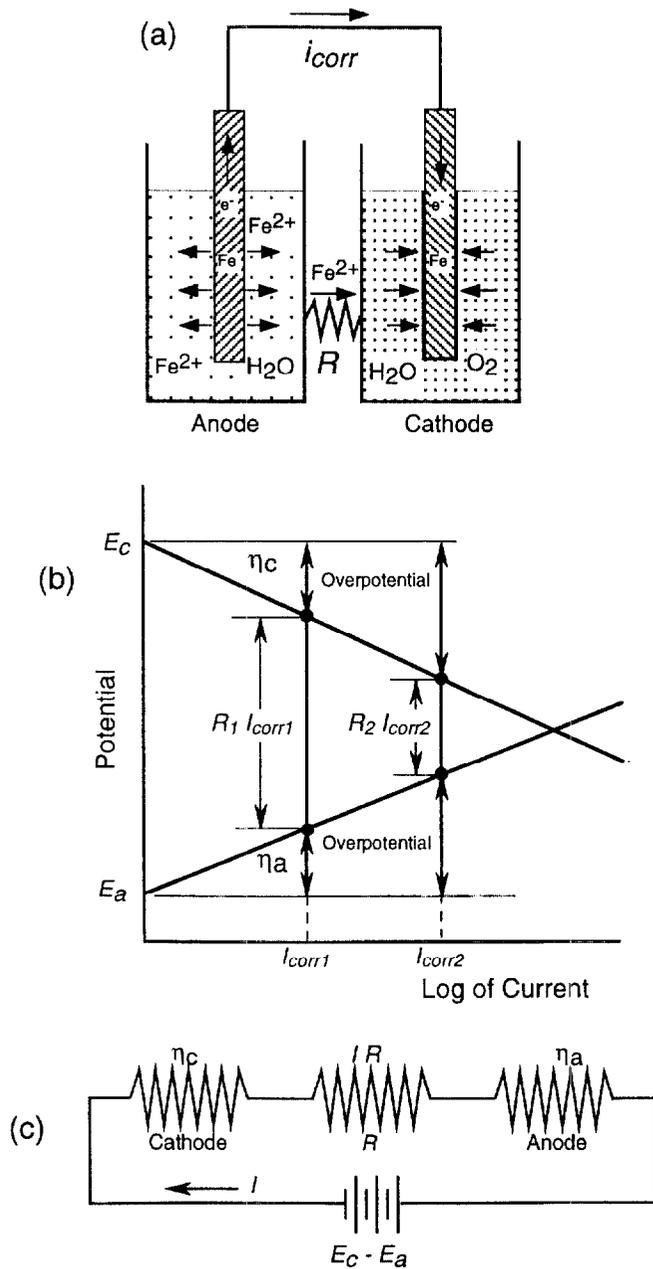


FIG. 5. (a) Electrolytic Cell Analogy of Corroding Steel Bar in Concrete; (b) Polarization Curves Showing Effect of Concrete Resistance (Ohmic Polarization); (c) Equivalent Electric Circuit of Corroding Bar (Adapted from West 1986)

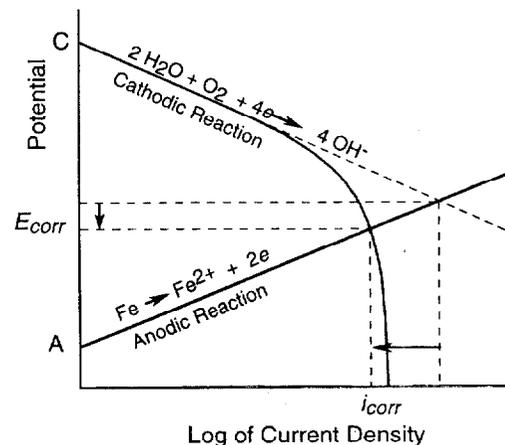


FIG. 6. Polarization Curves to Illustrate Concentration Polarization; Corrosion Current Is Limited by Rate of Cathodic Reaction

In summary, when steel in concrete loses its passive layer, corrosion is possible due to naturally occurring anodic and cathodic sites. However, the rate of corrosion depends on the electrical resistance of the concrete surrounding the anodic and cathodic sites and on the availability of oxygen. If the paste has low porosity, the resistance will be high, the oxygen diffusion coefficient will be low, and the corrosion rate will be low.

Tutti (1980) provided a conceptual model to represent the service life of a reinforced concrete structure that is susceptible to steel corrosion. Fig. 7 shows the degree of corrosion as a function of time. During the initiation period, there is no corrosion, but chloride ions or the carbonation front penetrate from the surface to the reinforcement. When the steel loses its passive layer, the propagation phase begins, and the degree of corrosion increases rapidly with time. The rate of corrosion during the propagation phase is affected by the factors listed in the previous paragraph. The service life is denoted by the time when the degree of corrosion has reached a level where the strength or serviceability of the structure is reduced below a critical level. The dashed line in Fig. 7 represents a structure with a longer service life because of a longer initiation period and reduced rate of corrosion during the propagation phase. With this simple model, it is easy to explain why increasing the concrete cover and using a low water-cement ratio concrete are effective in increasing service life.

## HALF-CELL POTENTIAL METHOD

### Principle

Having reviewed some of the basic principles underlying the corrosion of steel in concrete, our attention can be turned to methods for assessing corrosion conditions in a reinforced concrete structure. When there is active corrosion, current flow (ion migration) through the concrete between anodic and cathodic sites is accompanied by an electric potential field surrounding the corroding bar (Fig. 8). The equipotential lines intersect the surface of the concrete and the potential at any point can be measured using the half-cell potential method. By mapping equipotential contours on the surface, those portions of the structure where there is a high likelihood of corrosion activity are identified by their high negative potentials (Browne et al. 1983; Elsener and Böhni 1990; Elsener et al. 1990).

The standard test method is given in ASTM C 876 ("Test" 1997b) and is illustrated in Fig. 8. The apparatus includes a copper-copper sulfate half-cell, connecting wires, and a high-impedance voltmeter. The measured voltage depends on the type of half-cell, and conversion factors are available to convert readings obtained with half-cells other than copper-copper sulfate. The positive terminal of the voltmeter is attached to

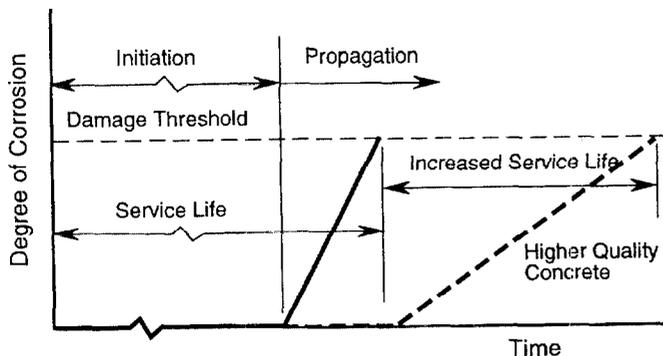


FIG. 7. Model Proposed by Tutti (1980) to Represent Corrosion Process of Steel in Concrete

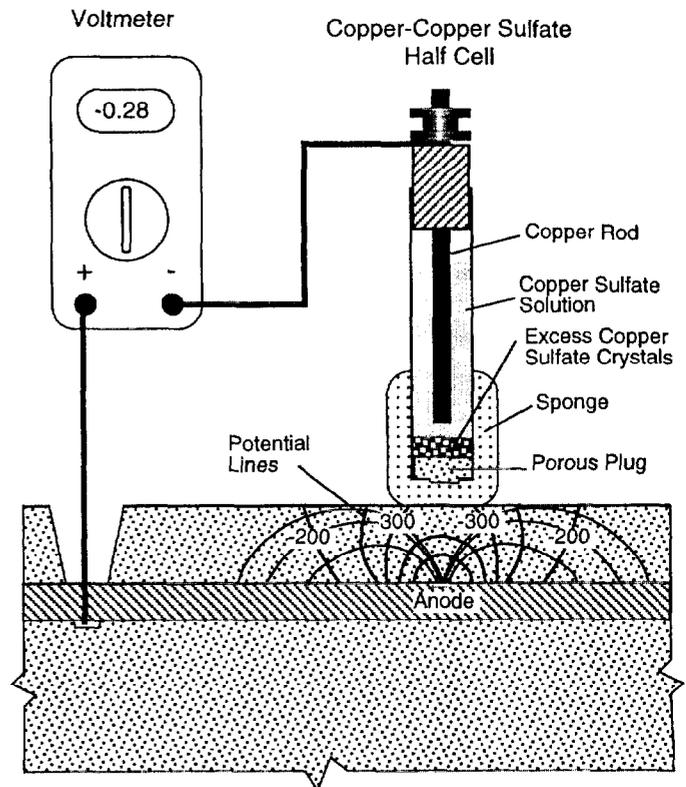


FIG. 8. Apparatus for Half-Cell Potential Method Described in ASTM C 876 to Measure Surface Potential Associated with Corrosion Current

the reinforcement and the negative terminal is attached to the half-cell. A high-impedance voltmeter (normally  $>10\text{ M}\Omega$ ) is used so that there is very little current through the circuit. The half-cell makes electrical contact with the concrete by means of a porous plug and a sponge moistened with a wetting solution (such as liquid detergent).

If the bar were corroding, the excess electrons in the bar would tend to flow from the bar to the half-cell. Because of the way the terminals of the voltmeter are connected in the electrical circuit shown in Fig. 8, the voltmeter indicates a negative voltage (see ASTM G 3 for standard conventions related to electrochemical measurements). The measured half-cell potential is the open-circuit potential, because it is measured with no current in the measuring circuit [ASTM G 15 ("Terminology" 1997)]. A more negative voltage reading is interpreted to mean that the embedded bar has more excess electrons, and there is, therefore, a higher likelihood that the bar is corroding.

The half-cell potential readings are indicative of the probability of corrosion activity of the reinforcing steel located beneath the copper-copper sulfate reference cell (Van Daveer 1975). However, this is true only if that reinforcing steel is electrically connected to the bar attached to the voltmeter. To assure that this connection exists, electrical resistance measurements between widely separated reinforcing bars should be carried out (ASTM C 876). This means that access to the reinforcement must be provided. The half-cell potential method cannot be applied to concrete with epoxy-coated reinforcement or to concrete with coated surfaces. Refer to ACI 228.2R ("Nondestructive" 1998) for additional limitations in the use of this method.

A key aspect when doing half-cell potential surveys is to assure that the concrete is sufficiently moist to complete the circuit necessary for a valid measurement. If the measured value of the half-cell potential varies with time, prewetting of the concrete is required and ASTM C 876 provides two ap-

proaches for doing this. The concrete is sufficiently moist if the measured potential at a test point does not change by more than  $\pm 20$  mV within a 5-min period (ASTM C 876). If stability cannot be achieved by prewetting, there may be stray electrical currents or excessive electrical resistance in the circuit. In either case, the half-cell potential method should not be used.

### Data Interpretation

According to ASTM C 876, data from a half-cell potential survey can be presented in two ways: (1) As an equipotential contour map; or (2) as a cumulative frequency diagram. The equipotential contour map is created by locating the test points on a scaled plan view of the test area. The half-cell voltage readings at each point are marked on the plan, and contours of equal voltage values are sketched. Computer-based test equipment is available to generate these contour maps. The cumulative frequency diagram is obtained by plotting the potential readings on normal probability paper, and drawing a best-fit straight line to the points. The diagram is used to determine the percentage of half-cell potential readings that are more negative than a certain value, and can be used to identify those potential values associated with different levels of corrosion activity (Elsener et al. 1990). Irrespective of the presentation method, reports of potential surveys must indicate the reference electrode that was used.

According to ASTM C 876, two techniques can be used to evaluate the results: (1) The numeric technique; or (2) the potential difference technique. In the numeric technique, the value of the potential is used as an indicator of the likelihood of corrosion activity. The Appendix of ASTM C 876 provides guidelines on interpreting half-cell potential readings. However, it is stated that, unless there is positive evidence to suggest their applicability, the numeric criteria should not be used under the following conditions: (1) If carbonation extends to the level of the reinforcement; (2) to evaluate indoor concrete that has not been subjected to frequent wetting; (3) to compare corrosion activity in outdoor concrete with highly variable moisture or oxygen content; and (4) to formulate conclusions about changes in corrosion activity due to repairs that changed the moisture or oxygen content at the level of the steel.

These precautions are necessary because there are many factors that can affect the magnitude of the potentials so that they are not indicative of the true corrosion conditions (Browne et al. 1983; Elsener and Böhni 1990; Elsener et al. 1990). For example, a surface layer with high resistance results in less negative surface potentials; this can mask underlying corrosion activity. On the other hand, cathodic polarization due to the lack of oxygen results in more negative potentials (Fig. 6), whereas the actual corrosion rate is reduced. Increasing cover tends to result in similar surface potential readings irrespective of the underlying differences in corrosion activity. Fig. 9 illustrates the generally poor correlation between half-cell potential and corrosion current density as measured by the polarization resistance method to be described (Feliú et al. 1996). As will be discussed, a corrosion current density  $< 0.1 \mu\text{A}/\text{cm}^2$  has been suggested as indicative of negligible corrosion and a value  $> 1 \mu\text{A}/\text{cm}^2$  as indicative of high corrosion. Fig. 9 shows that strict application of the limits suggested in ASTM C 876 (more positive than  $-200$  mV indicates a low likelihood of corrosion, and more negative than  $-350$  mV indicates a high likelihood of corrosion) can lead to incorrect inferences about the true corrosion activity.

In the potential difference technique, the areas of active corrosion are identified on the basis of the potential gradients. In the equipotential contour plot, close spacing of the voltage

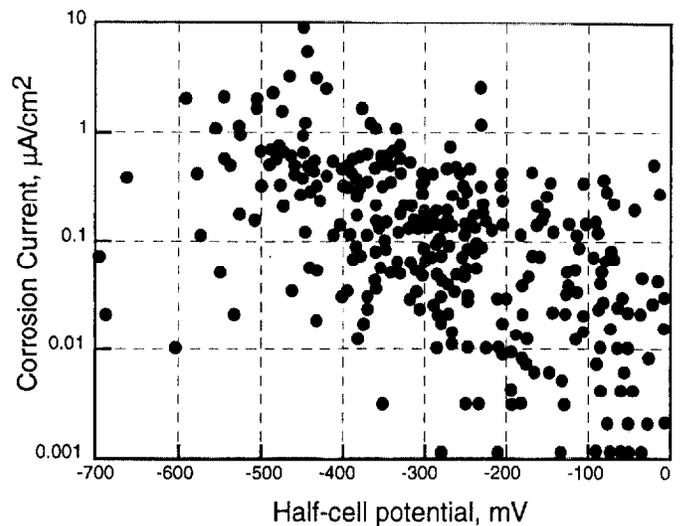


FIG. 9. Comparison of Corrosion Current with Half-Cell Potential (Adapted from Feliú et al. 1996)

contours indicates regions of high gradients. Some practitioners use the change in potential over a given surface area as an indicator of active corrosion, such as a change  $> 100$  mV over  $5 \text{ m}^2$ . It is generally accepted that the potential difference technique is more reliable for identifying regions of active corrosion than is the use of numerical limits (Elsener and Böhni 1990; Elsener et al. 1990; Dawson et al. 1990; Naish et al. 1990; Takewaka et al. 1992).

## CONCRETE RESISTIVITY

### Principle

The half-cell potential method provides an indication of the likelihood of corrosion activity at the time of measurement. It does not, however, furnish direct information on the rate of corrosion of the reinforcement. As has been discussed, after a bar loses its passivity, the corrosion rate depends on the availability of oxygen for the cathodic reaction. It also depends on the electrical resistance of the concrete, which controls the ease with which ions migrate through the concrete between anodic and cathodic sites. Electrical resistance, in turn, depends on the microstructure of the paste and the moisture content of the concrete. Thus, measurement of the resistivity of the concrete is useful in conjunction with a half-cell potential survey. The resistivity is numerically equal to the electrical resistance of a unit cube of a material and has units of resistance (in ohms) times length (Millard et al. 1989).

There is no ASTM test method for measuring the in-place resistivity of concrete. One technique that has been used successfully is shown in Fig. 10 (Bungey 1989; Millard et al. 1989, 1990). This is based on the classical four-electrode system described by Wenner (1915), which has been incorporated into a standard test method for measuring soil resistivity [ASTM G 57 ("Test" 1997a)]. The four, equally spaced electrodes are electrically connected to the concrete surface by using, for example, a conducting cream (Millard et al. 1990). The outer electrodes are connected to a source of alternating current, and the inner electrodes are connected to a voltmeter. The apparent resistivity  $\rho$  is given by the following expression (Wenner 1915; Millard et al. 1990):

$$\rho = \frac{2\pi sV}{I} \quad (4)$$

where  $s$  = probe spacing;  $V$  = measured voltage between the inner electrodes; and  $I$  = current between the outer electrodes.

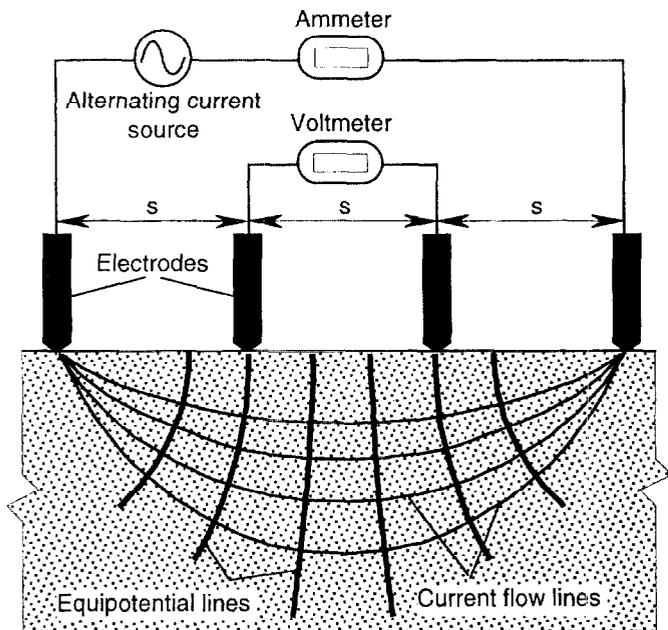


FIG. 10. Four-Probe Resistivity Test (Adapted from Bungey 1989)

The word “apparent” is used because Wenner derived (4) under the assumption that the material is semi-infinite and homogeneous. Thus, the relationship gives the correct measure of resistivity when these assumptions are satisfied. Deviations from Wenner’s assumptions lead to differences between the calculated apparent resistivity and the true resistivity of the material (Millard et al. 1990).

### Data Interpretation

Millard et al. (1990) carried out experimental and analytical studies to establish the magnitudes of the errors between the apparent and true resistivities when (4) is applied to a finite-sized concrete member. Because concrete is made of paste and aggregates, which have different resistivities, the spacing should be large enough so that a representative average resistivity of concrete is measured. The spacing also determines the depth of the material that affects the measurements. The greater the spacing, the greater the depth of concrete that contributes to the measurement. If the member is too shallow relative to the electrode spacing, there are boundary effects and the Wenner relationship is not valid. Millard et al. (1990) recommend an electrode spacing of 50 mm as sufficient for typical concrete mixtures, and the width and depth of the member should be at least four times the electrode spacing. In addition, the edge distance should not be less than twice the electrode spacing. When these minimum dimensions are not satisfied, the apparent resistivity calculated by (4) will exceed the true resistivity.

Other factors that affect the calculated resistivity are the presence of a thin surface layer of low-resistivity concrete and the presence of reinforcing bars. Both of these conditions result in an apparent resistivity that is lower than the true value. The effect of reinforcing bars is related strongly to the depth of cover and less so to the bar diameter. If possible, resistivity measurements should be conducted midway between two bars. When the depth of cover is low and the bar spacing is small, it may be possible to apply a correction factor if the diameter and location of the reinforcement is known (Millard et al. 1990).

Another technique for measuring resistivity is incorporated into one of the linear polarization devices to be described in

the next section (Broomfield 1996). A special probe is used to measure ambient temperature, ambient relative humidity, and concrete resistivity in conjunction with the measurement of polarization resistance. In this case, the resistance measurement is affected by the concrete between the reinforcing bar and the point on the surface where the probe is located. The writer is not aware of published comparisons of the resistivities measured by the four-electrode device and the single-probe device. The developers of the single-probe device offer the recommendations shown in the upper half of Table 1 for relating concrete resistivity to the risk of corrosion (Feliú et al. 1996). On the other hand, Bungey (1989) quotes the guidelines shown in the lower half of Table 1. The dissimilarity of the relationship between concrete resistivity and corrosion risk when reinforcement has lost its passivity.

Fig. 11 shows the relationship between the concrete corrosion rate (measured as explained in the next section) and concrete resistivity (Feliú et al. 1996). In comparison with Fig. 9, it is evident that, when steel loses its passivity, concrete resistivity correlates with corrosion rate better than does a half-cell potential.

In summary, the measurement of concrete resistivity provides additional information to assist in assessing the likelihood of different levels of corrosion activity. It is a useful supplement to a half-cell potential survey. A high resistivity indicates that, even though the steel is actively corroding as determined from the potential survey, the corrosion rate may be low. As mentioned, the resistivity of concrete is related to the ease with which ions can migrate through the concrete under the action of the potential field surrounding anodes and

TABLE 1. Comparison of Relationships between Concrete Resistivity and Corrosion Risk

Resistivity (kΩ · cm) (1)	Corrosion risk (2)
(a) Feliú et al. 1996	
>100–200	Negligible corrosion; concrete is too dry
50–100	Low corrosion rate
10–50	Moderate to high corrosion rate when steel is active
<10	Resistivity does not control corrosion rate
(b) Bungey 1989 (nonsaturated concrete)	
>20	Low
10–20	Low/moderate
5–10	High
<5	Very high

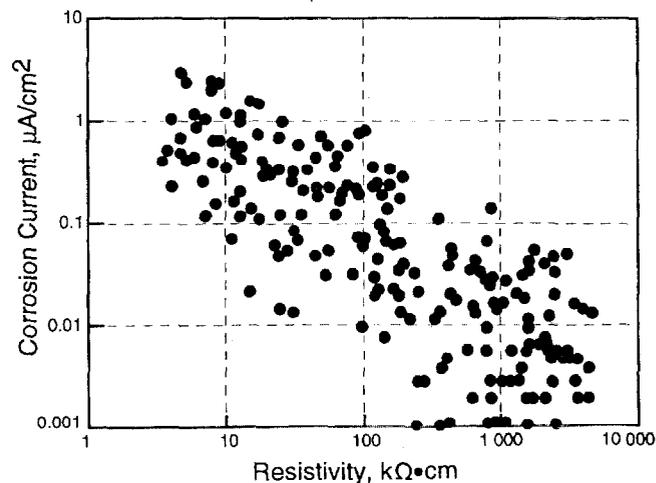


FIG. 11. Comparison of Corrosion Current and Resistivity from Field Measurements (Adapted from Feliú et al. 1996)

cathodes. The resistivity increases as the capillary pore space in the paste is reduced. This explains why high-quality concrete is of such critical importance for long service life under corrosion-inducing conditions.

## POLARIZATION RESISTANCE

To overcome a major drawback of the half-cell potential method, several approaches have been investigated for measuring the in-place corrosion rate (Rodríguez et al. 1994). Among these methods, the linear polarization resistance method appears to be gaining the most acceptance (Cady and Gannon 1992; Flis et al. 1992).

### Principle

The polarization resistance technique is a well-established method for determining corrosion rate by using electrolytic test cells (ASTM G 59). The technique basically involves measuring the change in the open-circuit potential of the short-circuited electrolytic cell when an external current is applied to the cell. For a small perturbation about the open-circuit potential, there is a linear relationship between the change in voltage  $\Delta E$  and the change in applied current per unit area of electrode  $\Delta i$ . The ratio  $\Delta E/\Delta i$  is called the polarization resistance  $R_p$ . Because the current is expressed per unit area of an electrode that is polarized, the units of  $R_p$  are ohms times area. It has been pointed out that  $R_p$  is not a true resistance in the usual sense of the word (Stern and Roth 1957), but the term is widely used (ASTM G 15).

Stern and Geary (1957) established the underlying relationships between the corrosion rate of the anode and the polarization resistance. No attempt is made to explain these relationships other than to state that they are derived from the slopes of the anodic and cathodic polarization curves (Fig. 3). The corrosion rate (expressed as the corrosion current density) is inversely related to the polarization resistance (ASTM G 59).

$$i_{corr} = \frac{B}{R_p} \quad (5)$$

where  $i_{corr}$  = corrosion current density in A/cm<sup>2</sup>;  $B$  = a constant in V; and  $R_p$  = polarization resistance in  $\Omega \cdot \text{cm}^2$ . The constant  $B$  is a characteristic of the polarization curves, and a value of 26 mV is commonly used for steel that is actively corroding in concrete (Feliú et al. 1989).

### Instrumentation

Basic apparatus for measuring the polarization resistance of reinforcing bars in concrete is the system shown in Fig. 12 (Clear 1989; Escalante 1989). This basic configuration is often referred to as a "3LP" device, because it involves three electrodes. One electrode is a reference half-cell, and the reinforcement is a second electrode called the working electrode. The third electrode is called the counter electrode, and it supplies the polarization current to the bar. Supplementary instrumentation measures the voltages and currents during different stages of the test.

The main steps for using the 3LP device to measure polarization resistance are as follows (Cady and Gannon 1992):

- Measure the open-circuit potential  $E_o$  of the reinforcement relative to the reference electrode, i.e., measure the half-cell potential [Fig. 12(a)].
- Measure the current from the counter electrode to the working electrode that is necessary to produce a small change in the potential of the working electrode [Fig. 12(b)].

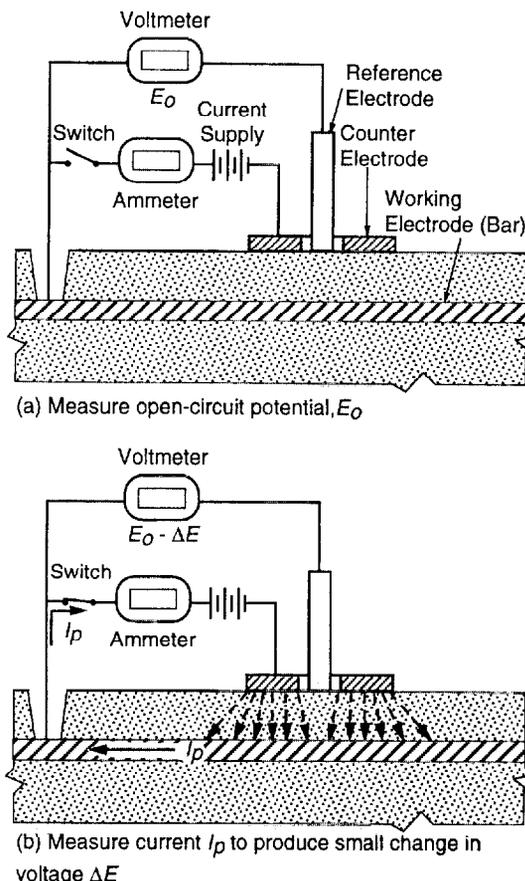
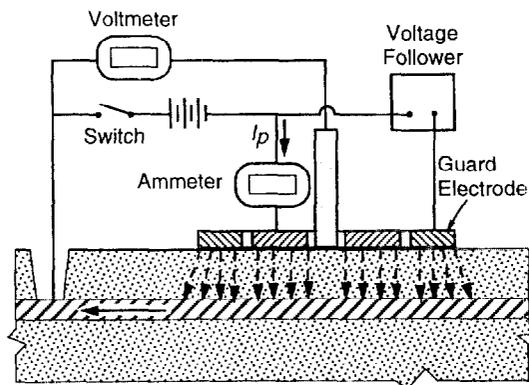


FIG. 12. Three-Electrode, Linear Polarization Method to Measure Corrosion Current

- Repeat the previous step for other small changes in potential beyond the corrosion potential.
- Plot the potential versus the current per unit area of the bar affected by the measurement and determine the slope of the best-fit straight line. This is the polarization resistance.

A major source uncertainty in the above procedure is the area of the steel bar that is affected by the current from the counter electrode. In the application of the 3LP device, it is assumed that current flows in straight lines perpendicular to the bar (working electrode) and the counter electrode. Thus, the affected bar area is taken as the bar circumference multiplied by the length of the bar below the counter electrode. Numerical simulations of current flow, however, show that the above assumption is incorrect and that the current lines are not confined to the region directly below the counter electrode (Feliú et al. 1989; Flis et al. 1992). In an effort to better control the current path from the counter electrode to the bar, a device has been developed that includes a fourth electrode, called a guard or auxiliary electrode, that surrounds the counter electrode (Feliú et al. 1990a,b, 1996). Fig. 13 is a schematic of this type of device. The guard electrode is maintained at the same potential as the counter electrode. As a result, the current flowing from the counter electrode to the working electrode is confined to the region below the counter electrode, and the nonuniform lateral spreading of the current is reduced.

A comparative study, involving laboratory and field tests, was conducted of three commercially available corrosion rate devices (Flis et al. 1992). One of the devices was the 3LP type and the other two used guard electrodes. From laboratory measurements on slabs it was concluded that the device with a guard electrode developed in Spain (Feliú et al. 1990a,b) gave



**FIG. 13. Linear Polarization Technique Using Guard Electrode to Confine Current from Counter Electrode to Reinforcement (Adapted from Feliú et al. 1990a)**

**TABLE 2. Relationship between Corrosion Current Density Measured with Guard-Ring Device and Corrosion Risk\***

Corrosion current density ( $\mu\text{A}/\text{cm}^2$ ) (1)	Corrosion risk (2)
<0.1	Negligible
0.1–0.5	Low
0.5–1	Moderate
>1	High

\*Feliú et al. 1996; Andrade and Alonso 1996.

corrosion rates closest to the true corrosion currents measured independently by standard polarization resistance techniques. In the field tests it was found that the 3LP device gave higher values of corrosion current. Each device, however, was capable of distinguishing between passive and active sites, and there were well-defined relationships between the corrosion currents measured by the different devices. It was concluded that each device could be used to estimate the corrosion rate in a structure.

### Data Interpretation

The corrosion rate measured using polarization resistance represents the rate at the time of the test. The corrosion rate at a particular point in a structure will depend on several factors, such as the moisture content of the concrete, the availability of oxygen, and the temperature. Thus, the corrosion rate at any point in an exposed structure would be expected to have seasonal variations. Such variations were observed during multiple measurements that extended over a period of more than 1 year (Clemeña et al. 1992). To project the amount of corrosion that would occur after an extended period, it is necessary to repeat the corrosion rate measurements at different times of the year. Clemeña et al. (1992) suggest several alternatives to predict the remaining life of the reinforcement.

The corrosion rate is calculated from the polarization resistance by the use of the constant  $B$ , which is typically assumed equal to 26 mV. This constant, however, is related to the anodic and cathodic activity (Broomfield 1996). Feliú et al. (1996) have pointed out that a value of 26 mV is reasonable for actively corroding bars, but a value twice as large is applicable under less active conditions. Thus, there is an inherent uncertainty in the calculated corrosion rate that can be as high as a factor of 2.

At this time, there is no ASTM standard for interpreting corrosion rate measurements obtained with different devices. As mentioned, different devices result in different corrosion rate values at the same test site. Published guidelines are for

specific test devices (Clear 1989; "Nondestructive" 1998). For example, based on years of experience from laboratory and field testing, the guidelines shown in Table 2 have been developed for interpreting corrosion rate measurements using the guard ring device (Andrade and Alonso 1996; Feliú et al. 1996).

As mentioned, corrosion current densities can be converted to metal loss by using Faraday's law (ASTM G 102). For example,  $1 \mu\text{A}/\text{cm}^2$  corresponds to  $\sim 0.012 \text{ mm}/\text{year}$  of section loss (Broomfield 1996). This assumes that corrosion is occurring uniformly on the bar, which is the typical condition with carbonation-induced corrosion. Chloride-induced corrosion, however, is associated with localized corrosion, or pitting. It has been reported that the depth of local pitting may be four to eight times the average depth of corrosion (Feliú et al. 1996). This factor should be considered if the effect of section loss on structural capacity is a concern. Other limitations that should be considered when planning corrosion rate testing have been presented (Cady and Gannon 1992; "Nondestructive" 1998).

In summary, testing instruments based on linear polarization resistance have been developed for estimating the instantaneous corrosion rates. These are based on measuring the change in open-circuit potential when a small current is applied to the reinforcing bar. The calculations make certain assumptions about how much of the underlying bar is polarized during the test. As a result, different devices will give different corrosion rates if testing were done at the same point. It is important to understand that a corrosion rate measurement represents the conditions at the time of the test. Changes in the factors that affect corrosion rate, such as temperature, concrete resistivity, and oxygen availability, will change the corrosion rate. Thus, it is difficult to extrapolate service life based on one measurement. Measurements need to be repeated under different seasonal conditions to have an understanding of the average corrosion rate over an extended time period.

### SUMMARY

The basics of the corrosion process have been reviewed by presenting the behavior of electrolytic cells. The key to understanding corrosion phenomena is the polarization curve, which summarizes the net electrode current as a function of the electrode potential. Simplified polarization curves have been used to explain concepts such as the corrosion potential, cathodic polarization, and resistance effects. These basic concepts were used to explain the corrosion behavior when a bar embedded in concrete loses its protective passive film.

A review has been presented of three nondestructive techniques to investigate the status of corrosion in reinforced concrete members. These techniques are half-cell potential, concrete resistivity, and polarization resistance. Each provides distinct information related to the corrosion status. The half-cell potential provides an assessment of the likelihood that there is active corrosion in the structure. It does not, by itself, provide information on the corrosion rate. One of the controlling factors for corrosion rate is the concrete resistivity, and measurement of concrete resistivity is a useful complement to the half-cell potential survey. The polarization resistance technique allows measurement of half-cell potential along with the actual corrosion current. The latter can be used to estimate the rate of section loss of the bar. It is emphasized that any of these measurements represent the conditions at the time of testing. Care must be exercised in extrapolating "one-time" measurements to estimate long-term corrosion.

Any assessment of the status of corrosion should include two additional determinations: (1) Depth of carbonation; and (2) chloride ion profiles. The former is a relatively simple measurement. The measurement of chloride profiles is a more in-

involved process, and there is still debate over whether water soluble or total chlorides is the key parameter.

Finally, the corrosion of steel in concrete is a complex and not completely understood process. Experienced individuals should be involved in the assessment of corrosion.

## ACKNOWLEDGMENTS

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## APPENDIX II. NOTATION

The following symbols are used in this paper:

$B$  = constant (V);  
 $E_a$  = equilibrium half-cell potential of anode (V);  
 $E_c$  = equilibrium half-cell potential of cathode (V);  
 $E_{corr}$  = corrosion potential (V);  
 $E_o$  = open-circuit potential of reinforcement (V);  
 $I$  = current (A);  
 $I_{corr}$  = corrosion current (A);

$i_{corr}$  = corrosion current density (A/cm<sup>2</sup>);  
 $R$  = resistance ( $\Omega$ );  
 $R_p$  = polarization resistance ( $\Omega \cdot \text{cm}^2$ );  
 $s$  = electrode spacing (mm);  
 $\Delta E$  = change in voltage (V);  
 $\Delta i$  = change in current per unit area of polarized electrode (A/cm<sup>2</sup>);  
 $\eta_a$  = overpotential of anode (V);  
 $\eta_c$  = overpotential of cathode (V); and  
 $\rho$  = resistivity ( $\Omega \cdot \text{cm}$ ).