Evaluation Of Half-cell Corrosion Detection Test For Concrete Bridge Decks

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16. Abstract

This report includes three chapters. The first chapter discusses the corrosion of steel in concrete and provides information on the half-cell corrosion detection technique. In the second chapter, WSDOT's use of the test is reviewed, its concerns with the test are discussed, and the reliability of data collected is determined based on the field tests conducted. In the third chapter, a systematic procedure is developed with which to incorporate half-cell data into the WSDOT's bridge deck repair priority and protective system selection program.

The findings of this work support the use of the half-cell test on bridge decks for classifying their overall condition. The use of half-cell data for designating specific bridge deck areas needing repair, however, is not recommended. The criteria presented in ASTM for evaluating the significance of half-cell potentials can be used for interpretation of data at this time. However, the empirical criteria may be modified in the presence of more data.

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FOREWORD

WSDOT has started a comprehensive bridge deck condition survey program in which it is testing bare concrete decks employing different evaluation techniques, including the half-cell corrosion detection test. The data obtained through the bridge condition survey program are being incorporated into WSDOT's bridge deck repair priority program. At present, the bridge deck repair priority program does not use half-cell data since WSDOT is concerned about the reliability of half-cell data, and a method has not been established for combining half-cell data with traditional bridge deck data (i.e., data on concrete deterioration and chloride contamination).

This report includes three chapters. The first chapter discusses steel corrosion in concrete and half-cell corrosion detection technique. The second chapter reviews WSDOT's use of the test, discusses WSDOT's concerns about the test, and determines the reliability of half-cell data based on field tests conducted during this research. In the third chapter, a systematic procedure is developed to incorporate half-cell data into the WSDOT's bridge deck repair priority and protective system selection program.

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EXECUTIVE SUMMARY

Rebar corrosion has been blamed for a large portion of the problems associated with deterioration of concrete bridge decks. Presently the half-cell corrosion test is the only simple, non-destructive, and practical test which can be employed to obtain large amounts of data regarding the corrosion activity of bridge decks. The test measures electrical potential between a copper electrode immersed in copper sulfate solution (half-cell) and steel embedded in concrete (half-cell). The magnitude of the potential determines the state of corrosion activity of the steel.

WSDOT has started a comprehensive bridge deck condition survey program which encompasses all of its six districts. In the course of this program, concrete decks are tested employing different condition determination techniques, including a half-cell potential survey, chloride content determination, deterioration detection, and a rebar depth survey. Presently chloride content results and data on concrete deterioration are incorporated into WSDOT's bridge deck repair priority and protective system selection program in conjunction with data on traffic volumes. However, the WSDOT bridge deck rehabilitation/protection program does not employ half-cell data since WSDOT is concerned about the reliability of the half-cell data, and a method has not been established for combining half-cell data with traditional bridge deck data (i.e., data on concrete deterioration and chloride contamination).

THE RELIABILITY OF HALF-CELL DATA

The reliability of half-cell data was evident from the many field surveys conducted and recorded by WSDOT in which concrete deterioration and active half-cell potentials (potentials more negative than -0.350 V CSE, measured by copper-copper sulfate half-cell), coincided. However, not all active corrosion is extensive enough to cause concrete deterioration and not every corrosion activity constitutes red rust, the final product of corrosion.

THE RELIABILITY OF POSITIVE HALF-CELL POTENTIALS

Half-cell potentials with positive sign generally indicate a lack of rebar corrosion activity when the half-cell test is conducted correctly. However, field tests conducted during this project implied that positive half-cell potentials can be obtained as a result of interference from electrical conduits embedded in bridge decks. Future research should interpret the significance of those potentials and clarify the nature of the interference. Positive half-cell potentials can also be obtained when the test is not conducted properly, such as when the concrete surface is dry, the copper sulfate solutions are diluted, or the polarity is reversed (the connection to the voltmeter jacks is reversed). Recommendations are made in this work to prevent the collection of incorrect data and to help personnel distinguish reliable half-cell data from unreliable data.

THE SENSITIVITY OF HALF-CELL POTENTIAL SURVEYS

Field investigations conducted in this work indicated that

1. normal differences in the condition of half-cell equipment should not result in serious differences in half-cell potential surveys;
2. in the presence of rebar electrical continuity, ground location should not cause serious differences in half-cell potential surveys; and
3. generally, active half-cell potentials (potentials more negative than -0.350 V CSE) read in summer are read in fall; however, passive and questionable half-cell potentials (potentials less negative than -0.350 V CSE) may shift slightly toward less negative half-cell potentials in fall surveys, possibly due to a decrease in corrosion activity as a result of decreases in temperature and the relative instability of the half-cell potential in these regions.

USE OF THE HALF-CELL DATA

The half-cell data obtained on bridge decks can be used for planning and decision making regarding bridge deck rehabilitation/protection. For example, the data may be incorporated into the WSDOT bridge deck repair priority and protective system selection program by employing a systematic procedure developed in this work.

Half-cell surveys can be used to monitor the effectiveness of concrete overlay protective systems in halting rebar corrosion activity. Half-cell cumulative-frequency distribution curves are the best way to monitor the size of areas affected by corrosion activity. Also, half-cell surveys can be employed to select candidate sites for cathodic protection.

The author does not recommend use of half-cell data for designating specific bridge deck areas to be rehabiliated, since bridge deck repair activities are very expensive and half-cell potentials are interpreted based on probabilities. The interpretation is more meaningful when applied to an overall survey and a large number of readings rather than a local area.

SUMMARY OF FINDINGS

REVIEW AND ANALYSIS OF THE PUBLISHED DATA

The Reference Cell's Sensitivity to Electrolyte Concentration and Temperature

Diluted copper sulfate and low temperatures both tend to make the copper-copper sulfate half-cell device less cathodic. This means that under these circumstances less negative half-cell potential values are obtained for the rebar than when the test is conducted under standard conditions (i.e., saturated copper sulfate electrolyte and a temperature of 72°F or 22°C). Potentials surveyed with the half-cell device can be adjusted so that their electrolyte concentrations and temperatures are similar to standard conditions. However, under practical conditions, these changes may not be necessary due to their small magnitude.

Polarization of the Reference Cell

In measuring the potential difference between the copper-copper sulfate half-cell device and the steel in the concrete, polarization of the copper electrode and the steel electrode is possible due to current flowing in the circuit caused by their electromotive force. This may result in recording less negative half-cell potential values for the steel. To eliminate this problem, a high internal impedance voltmeter should be used in the circuit.

The Significance of Copper-Copper Sulfate Half-Cell Potentials

As recognized by the American Society for Testing and Materials (ASTM), laboratory tests and field tests show that in rebar in concrete, copper-copper sulfate half-cell potentials less negative than -0.200 V correspond to a 10 percent probability of corrosion; potentials between -0.200 V and -0.350 V correspond to a 50 percent probability of corrosion; and potentials more negative than -0.350 V correspond to a 90 percent probability of corrosion. A recent WSDOT investigation conducted to determine the conditions of five bridge decks covered with asphalt/membrane systems found the significance of the half-cell potentials by coring through asphalt and membranes at 63 locations and determining the half-cell potentials and condition of the concrete (19). The results indicated that 11 percent of the potentials less negative than -0.200 V, 36 percent of the potentials between -0.200 V and -0.350 V, and 80 percent of the potentials more negative than -0.350 V were associated with deteriorated concrete. These results support those presented by ASTM. Note that the half-cell potential interpretation criteria are empirical and that it is possible that the criteria may be improved based on further experience gained in this field.

The Stability of Half-Cell Potentials with Regard to Corrosion Current

An analysis, by this author, of the results of previous laboratory research (9) indicated that in bridge decks in which the rebar is actively corroding (potentials more negative than -0.350 V CSE), half-cell potentials are generally independent of the corrosion current and do not necessarily increase as the corrosion current increases. This emphasizes the point that half-cell potentials more negative than -0.350 V CSE do not represent the rate of corrosion but only indicate corrosion activity. However, potentials indicating a transition from a passive state (potentials less negative than -0.200 V CSE) to an active state increase sharply with a small increase in corrosion current.

The Presence of Half-Cell Potentials Indicating Corrosion Activity and Corrosion Current in Low Temperatures

Concrete electrical resistance increases with a decrease in temperature when a concrete's moisture content remains constant. This may reduce the intensity of the rebar corrosion or corrosion current. Half-cell potentials indicating corrosion activity and their corresponding corrosion currents have been detected at concrete temperatures as low as 36°F (2.2°C) and 33°F (0.8°C) (9). However, the half-cell test may not be performed when concrete is frozen because the high electrical resistance of ice prevents the completion of the circuit (10).

Recent Developments in Half-Cell Testing

A recent investigation carried out by the Transportation and Road Research Laboratory (TRRL), England, described a multiple half-cell array controlled by a microprocessor (34). The multiple array consisted of eight half-cells mounted on a beam, 100 mm (4 inches) apart. The technique provided a fine resolution which could not be obtained by using the size of grid normally used on bridge decks. As a result, data were collected and printed out instantly, providing more accurate half-cell potential contour maps.

EVALUATION OF WSDOT'S USE OF THE HALF-CELL TEST

The Reliability of Half-Cell Data

The reliability of half-cell data is evident from the many field surveys conducted and recorded by WSDOT in which concrete deterioration and numerically high potential values (generally more negative than -0.350 V CSE) coincided. However, not all corrosion is extensive enough to cause concrete deterioration and not every corrosion activity results in red rust, the final product of corrosion. When half-cell data are used for planning and decision making regarding the rehabilitation and protection of bridge decks, the ASTM criteria determining the significance of half-cell potentials can be employed reliably. However, using half-cell data to designate specific concrete repair areas is not justified, since the criteria are based on probabilities, and furthermore, the trend of corrosion activity may change after the application of a protective system.

Positive Potentials of Small Magnitude

Positive half-cell potentials of small magnitude (generally less positive than +100 mV) may result from large resistance in the circuit (dry concrete or the absence of electrical continuity) or the absence of corrosion activity. Positive potentials as high as +30 mV CSE from concrete dryness and +70 mV CSE from the absence of corrosion activity have been detected (12, 9). In the case of high resistance in the circuit, the overall potentials were shifted toward less negative values (12, 22). Shifted potentials may be negative or positive values depending on their original value. In the case of absence of corrosion, positive potentials were obtained together with small negative (passive) potentials.

Diluted copper-copper sulfate solutions and low temperatures can also shift the potentials toward less negative values. However, this shift is generally very small and positive potentials obtained as a result of diluted solutions and low temperatures represent a passive state or an absence of corrosion activity.

Positive Potentials of Small and Large Magnitude

Field investigations conducted in the course of this work indicated that some positive half-cell potentials detected on Washington bridge decks result from reversed polarity or interference with electrical facilities.

In the case of reversed polarity (reversed connection to the voltmeter jacks), the digital voltmeter displays the negative potentials with a positive sign. Therefore, the magnitude of the potentials can vary from very small to very large values as the magnitude of negative potentials would. Positive potentials of this nature usually cover the entire bridge deck and potentials more positive than +0.350 V CSE are usually concentrated in deteriorated areas.

Electrical conduits running along bridges and buried near curb lines or under traffic barriers may cause positive potentials through electrical leakage or electromagnetic interference. Positive half-cell potentials of up to +0.490 V CSE, attributed to interference with an electrical conduit buried in the concrete deck, were obtained in a field test. The highest positive potentials were detected along and near the conduit. As the survey moved toward the centerline, the positive potentials decayed and became small positive or negative values. Finally, at a survey line of 20 feet (6 meters) from the conduit the interference totally decayed and negative potentials indicating active corrosion coincided with concrete deterioration.

The Sensitivity of Half-Cell Potentials to Equipment Condition

During this study, in an experiment conducted on a bridge deck utilizing two different half-cell instruments and voltmeters but sharing the same ground, the mean value of the difference in potential for 51 test locations was 11 mV with a standard deviation of 7 mV. The conclusion based on this experiment is that normal differences in the condition of half-cell equipment should not result in serious differences in half-cell potential surveys.

The Sensitivity of Half-Cell Potentials to Ground Location

During this study, in an experiment conducted on a bridge deck using two different rebar ground locations but using the same half-cell equipment, the mean value of the difference in potential for 51 test locations was 10 mV with a standard deviation of 7 mV. The conclusion based on this experiment is that in the presence of rebar electrical continuity, ground location should not cause severe differences in half-cell potential surveys.

The Sensitivity of Half-Cell Potentials to Seasonal Surveys

A comparison of fall half-cell surveys conducted on two bridge decks in this study with summer surveys of the same bridge decks indicated that the seasonal surveys both found almost the same half-cell potentials indicating active corrosion (more negative than -0.350 V CSE). For the half-cell potentials that indicated no corrosion or questionable corrosion (less negative than -0.350 V CSE), the fall surveys showed a small shift toward less negative potentials, possibly due to a decrease in corrosion activity as a result of the decrease in temperature and the relative instability of the potentials in these regions. However, a portion of this shift was related to the effects of temperature on the reference cell itself and could be adjusted. These results are encouraging, mainly because half-cell surveys are generally judged based on the percentage of their potentials which represent active corrosion and also because the shift of the potentials which represent passive and questionable corrosion was not significant.

DEVELOPMENT OF A PROCEDURE TO USE HALF-CELL DATA FOR REHABILITATION/PROTECTION PLANNING

Using the calculations methods presented in this work, a step-by-step systematic procedure was developed to incorporate the half-cell data, in conjunction with chloride and depth of rebar data, into WSDOT's bridge deck repair priority and protective system selection program. A case study was included as an example to illustrate using the systematic procedure.

RECOMMENDATIONS

USE OF THE HALF-CELL TEST

- The findings of this work support the use of the half-cell test on bridge decks for evaluating the decks' overall condition and its variation over time. At this time, the criteria presented in ASTM for the significance of half-cell potentials should be used to interpret half-cell data obtained on bridge decks when the test is conducted correctly. However, the criteria may be modified in the presence of more data. Also, there may be situations in which the potentials obtained are affected by interference with nearby electrical facilities. These situations should be distinguished from ordinary cases and further interpretation of their potential values may be required.
- The half-cell potential data obtained on bridge decks can be used for planning and making decisions regarding bridge deck rehabilitation. For example, the data may be incorporated into the WSDOT bridge deck repair priority and protective system selection program employing the systematic procedure developed in this work. The author does not recommend use of half-cell data for designating specific bridge deck areas to be repaired, since bridge deck repair activities are very expensive and the potentials are interpreted based on probabilities. The interpretation is more meaningful when applied to the overall survey and a large number of readings rather than a local area. Furthermore, corrosion activity does not necessarily accompany deterioration and corrosion may be alleviated by applying a protective system.
- Half-cell surveys can be employed to monitor the effectiveness of concrete overlay protective systems in halting rebar corrosion activity. Half-cell cumulative-frequency distribution curves are the best way to monitor the size of areas affected by corrosion activity. Shifting of these curves over time will indicate decreases or increases in the size of areas actively corroding, passive areas, and those areas in the transition state. The preferred procedure is to take the potential readings on the selected sites once a year in the same season, at the same locations, and utilizing the same ground.
- The half-cell test can be used to select candidate sites for cathodic protection. The Ontario Ministry of Transportation's criteria (21) (i.e., corrosion potentials more negative than 350 mV over 20 percent of deck area) may be applied at this time. In the field of cathodic protection, the half-cell technique will be required

to determine the magnitude of cathodic current density in conjunction with E-log-I technique and to monitor the polarized potentials periodically.

THE CONDITION OF HALF-CELL EQUIPMENT

- The copper sulfate solution should be saturated to yield a standard potential. In a saturated solution an excess of undissolved crystals lies at the bottom of the solution.
- The copper electrode should be cleaned and the copper sulfate solution should be renewed when deemed necessary, since after each use some of the copper in the solution plates out on the copper electrode (see ASTM C876 for details of the cleaning procedure).
- An electrical junction device (a wetted sponge folded around the tip of the half-cell device) should be used when measuring half-cell potentials to reduce the electrical resistance between the surface of the concrete and the half-cell device. Care should also be taken to prevent the porous plug of the half-cell device from drying when not in use. During drying the crystalline copper sulfate can block the pores, causing large resistance in the circuit.
- The voltmeter should have high input resistance to avoid polarization of the electrodes (see ASTM C876 for the magnitude of voltmeter resistance).

THE TEST PROCEDURE -- GENERAL

- The exact location of the ground (station and offset), type of ground (method of connection to the rebar), and electrical resistance of the ground joint should be recorded on a data form.
- The type of voltmeter (digital or regular) and its connection terminal (positive or negative) to the half-cell device should be recorded on a data form.
- The voltmeter's battery should be checked at the beginning of the test and its satisfactory condition should be recorded on a data form.
- At least five half-cell readings should be checked at the beginning and the end of the test while their test location has been kept wet during the survey period. The duplicate average potentials should not differ more than 25 mV. If larger differences are obtained, the test should be repeated on the whole bridge with emphasis on prewetting the concrete.

THE TEST PROCEDURE -- POSITIVE POTENTIALS

When positive half-cell potentials are detected, the following measures should be taken successively before reporting the positive potentials:

1. The electrical connection of the voltmeter to the half-cell device should be checked for the possibility of reversed polarity. Reversed polarity may be the sole cause of the positive potentials.
2. The saturation of the copper/copper sulfate solution should be verified and the potentials should be adjusted for the temperature. This can eliminate positive potentials if they are caused by diluted solutions and/or ambient temperatures below 70°F (21°C).
3. At least five, positive half-cell potentials should be monitored over time while their test locations have been kept wet. If the potentials tend to be less positive with time, consider a wetting period for the amount of time needed to stabilize the potential readings for at least five minutes. If the positive potentials are caused by concrete dryness, the above procedure may eliminate the problem.
4. If none of the above measures eliminates the positive potentials, the positive potentials should be recorded as they are detected and a specialized crew should check the bridge deck condition data for a lack of corrosion activity or examine the bridge deck for possible interference with electrical facilities, depending on the nature and magnitude of the potentials obtained.

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CHAPTER ONE

REVIEW OF CORROSION AND CORROSION DETECTION OF STEEL IN CONCRETE

Knowledge of the factors that cause and control the corrosion of steel in concrete is important for bridge and materials engineers who evaluate the condition of reinforced concrete structures utilizing the half-cell corrosion detection test. This chapter discusses the principles of steel corrosion in concrete, analyzes the factors influencing this corrosion, and provides information about half-cell corrosion detection methods. Also included in this chapter are descriptions of practical experience gained in this area as well as selected highway agencies' current policies concerning the half-cell test method.

THE ELECTROCHEMICAL PRINCIPLES OF METALLIC CORROSION

Metallic corrosion is an electrochemical process which involves the transfer of electrons, or flow of electrical current, from one metal to another metal. If two metals of a different nature are immersed in an electrolyte (aqueous environment), depending on their natural electromotive force, one will have the potential to release electrons which will be received by the other metal. If the two metals or electrodes are connected by a metallic conductor, there will be an electrical current, or flow of electrons, from one metal to the other one through the metallic path and the electrolyte. This condition establishes a corrosion cell.

Under the above condition, the electrode which releases the electrons is called the "anode" and the electrode which receives the electrons is called the "cathode." The anode metal in this process goes into the electrolyte solution around the anode in the form of ionic metal since it has lost electrons. The consumption of the electrons in the cathode involves an ionic reaction which is called reduction. Within the electrolyte, current is carried by the ions from the cathode to the anode. As a result, chemical oxidation, or the formation of corrosion products, occurs in the anode. A basic corrosion cell is illustrated in Figure 1.

Types of Corrosion Cell

The corrosion cell discussed earlier has electrodes of a dissimilar nature. A cell of this type is called a "galvanic cell." However, galvanic corrosion cells can occur on the surface of the same metal because most metals are not homogeneous. Impurities in metals can establish local electrodes (1). Stress in metals can also cause a

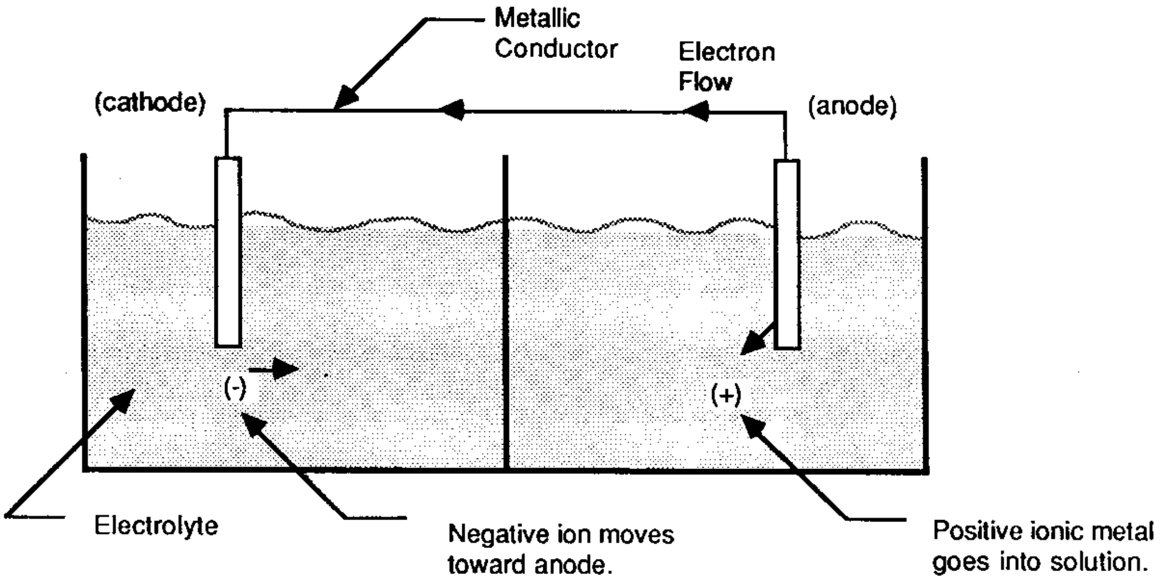


Figure 1. Basic Corrosion Cell.

condition similar to non-homogeneity because unstressed areas are cathodic to stressed areas on the same metal (2). However, stress has been reported to have little influence on the corrosion of steel in concrete (8).

In addition to "galvanic cells," there are two other types of corrosion cells: the "concentration cell" and the "differential temperature cell" (6). Concentration cells can form when two identical electrodes are each in contact with electrolytes of different concentration. For example, a copper electrode in a concentrated copper sulfate solution is cathodic to the one in a diluted copper sulfate solution (1). Concentration cells are also caused by a difference in oxygen concentration around the electrodes. For example, if two similar electrodes are placed in an electrolyte and the electrolyte around one electrode is aerated but the other is not, the difference in oxygen concentration makes the de-aerated electrode anodic and it corrodes. This type of corrosion accounts for pitting under rust (6).

Differential temperature cells constitute similar electrodes each at a different temperature placed in the same electrolyte. An example is the current produced in a copper sulfate solution between two copper electrodes having different temperatures. In this case the electrode at the higher temperature is cathodic and the one at the lower temperature is anodic (1).

Electromotive Force Series

The electrical current between two electrodes in a corrosion cell is the result of the difference in voltage or electromotive force (EMF) between the two electrodes. This may be written as $\Delta V = V_{cathode} - V_{anode}$. The difference in voltage can actually be measured by placing a high impedance voltmeter in the circuit. If the voltage of one of the electrodes is arbitrarily assigned zero, then the measured potential will be the voltage or EMF of the other electrode. The standard electrode selected for this purpose is the hydrogen electrode. Table 1 gives the electromotive force (EMF) series in an orderly arrangement for different electrode reactions relative to a standard hydrogen electrode (SHE) (2). Note that each electrode reaction in the table is anodic to the ones above it. Each electrode and its electrolyte is referred to as a half-cell because it comprises half of the total corrosion cell, the hydrogen electrode being the standard reference cell. As mentioned earlier, concentration of electrolytes and temperature influence the current flow. Thus the electrolyte of each half-cell in the table has a standard 1 mole per liter concentration of ionic species at 25°C (3).

The EMF series in Table 1 can be used to determine the corrosion driving voltage between any two electrodes as long as they are placed in their standard concentration electrolytes. For example, if iron in an

Table 1. Electromotive Force Series (2).

$Au = Au^{+3} + 3e$	+ 1.498
$O_2 + 4H + 4e = 2H_2O$	+ 1.229
$Pt = Pt^{+2} + 2e$	+ 1.2
$Pd = Pd^{++} + 2e$	+ 0.987
$Ag = Ag^{+} + e$	+ 0.799
$2Hg = Hg_2^{++} + 2e$	+ 0.788
$Fe^{+3} + e = Fe^{+2}$	+ 0.771
$O_2 + 2H_2O + 4e = 4\ OH$	+ 0.401
$Cu = Cu^{+2} + 2e$	+ 0.337
$Sn^{+4} + 2e = Sn^{+2}$	+ 0.15
$2H^{+} + 2e = H_2$	0.000
$Pb = Pb^{+2} + 2e$	- 0.126
$Sn = Sn^{+2} + 2e$	- 0.136
$Ni = Ni^{+2} + 2e$	- 0.250
$Co = Co^{+2} + 2e$	- 0.277
$Cd = Cd^{+2} + 2e$	- 0.403
$Fe = Fe^{+2} + 2e$	- 0.440
$Cr = Cr^{+3} + 3e$	- 0.744
$Zn = Zn^{+2} + 2e$	- 0.763
$Al = Al^{+3} + 3e$	- 1.662
$Mg = Mg^{+2} + 2e$	- 2.363
$Na = Na^{+} + e$	- 2.714
$K = K^{+} + e$	- 2.925

electrolyte having an activity of 1 mole/liter of Fe^{++} is coupled with copper in an electrolyte having an activity of 1 mole/liter of Cu^{++}, then the corrosion current driving voltage can be calculated as $\Delta V = V_{cathode} - V_{anode} = 0.337 - (-0.440) = +0.770$ V. This voltage can actually be measured using a high impedance voltmeter as shown in Figure 2 (2). Fe^o in this process is anodic and releases electrons and enters into the solution as Fe^{++} and subsequently corrodes. The electrons are consumed by the cathode and as a result Cu^{++} plates out on the copper electrode.

The Effects of Electrolyte Concentration and Temperature on Half-Cell Potentials

If the standard hydrogen electrode (SHE) is coupled with an electrode having different electrolyte ionic activities and temperature than the standard one, the half-cell potentials may be calculated using the Nernst equation. Assuming a symbolic electrode reaction to be

$$M^{b+} + be^- \dashrightarrow M,$$

the Nernst equation can be written as

$$E = E° - \frac{RT}{bF} \ln \left(\frac{a_m}{a_{m^{b+}}}\right)$$

In this equation,

E = the half-cell potential (SHE)

E^o = the standard half-cell potential (SHE) as listed in Table 1,

R = gas law constant,

T = absolute temperature (273.2+°C),

F = Faraday number (96,500 coloumbs/equivalent),

a_m and $a_{m^{b+}}$ are the activities (molality x activity coefficient) of the substances taking part in the electrode reaction (3).

By definition, the activity of a pure metal, solids, and water are set equal to one (1, 3), and the activity of a gas is its partial pressure and is approximated at ordinary pressures by the pressure in the atmosphere (1). After substituting the values of different constants in the Nernst equation, it can be written as

$$E = E° - \frac{0.0001985T}{b} \log \left(\frac{a_m}{a_{m^{b+}}}\right)$$

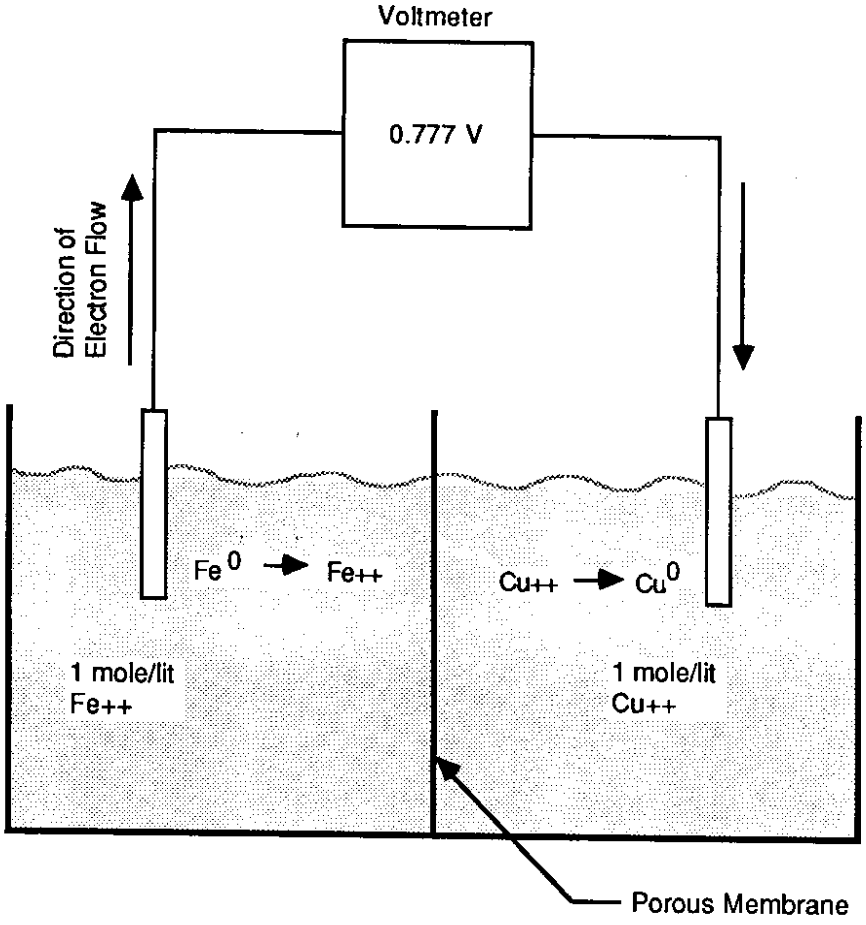


Figure 2. Corrosion Cell of Standard Half-Cell of $Cu^0 \rightarrow Cu^{++}$ and $Fe^0 \rightarrow Fe^{++}$ (2).

For 25°C the equation will be

$$E = E^\circ - \frac{0.0592}{b} \log \left(\frac{a_m}{a_{m^{b+}}}\right)$$

Note that in this equation the values of E and E^o are in terms of volts.

The Nernst equation can be used to calculate the difference in voltage between any two half-cell or electrode reactions. This may be done by writing the equation for each electrode and subtracting one from the other. If the result is positive voltage, the first electrode will be cathodic and the second one anodic. In case of a negative result the reverse will be true.

Polarization of Half-Cells

The half-cell potentials discussed previously are created by the equilibrium state of the electrodes or their reversible reactions. These potentials, such as those listed in the EMF series of Table 1, only indicate the basis for corrosion tendency. Their magnitude depends on the ionic activities taking place and temperature (4, 1).

When two electrodes are connected through a conductor and electrons flow from the anode to the cathode, the measured half-cell potentials shift from the reversible potentials. This shift is called polarization (4). As a result of this shift the anode potential becomes more positive and the cathode potential becomes more negative. This phenomenon reduces the potential difference between the anode and the cathode, opposes the flow of current, and determines the actual corrosion driving current. Figure 3 illustrates the mechanism of polarization for the electrodes of a corrosion cell. As shown in the figure the corrosion driving current depends on the difference between the polarized anodic and cathodic potentials as well as the resistance of the circuit according to Ohm's law. This will be further discussed in "The Corrosion of Steel in Concrete." The resistance of the circuit is generally that of the electrolyte (concrete) only, since resistance of the metallic conductor is usually negligible.

Polarization of half-cells is controlled either cathodically or anodically. In cathodic control of polarization, the cathode potentials shift significantly toward the anode potentials, whereas the anode potentials shift only slightly toward the cathode potentials. In anodic control of polarization, the anode potentials shift significantly toward the cathode potentials and the cathode potentials shift slightly toward the anode potentials.

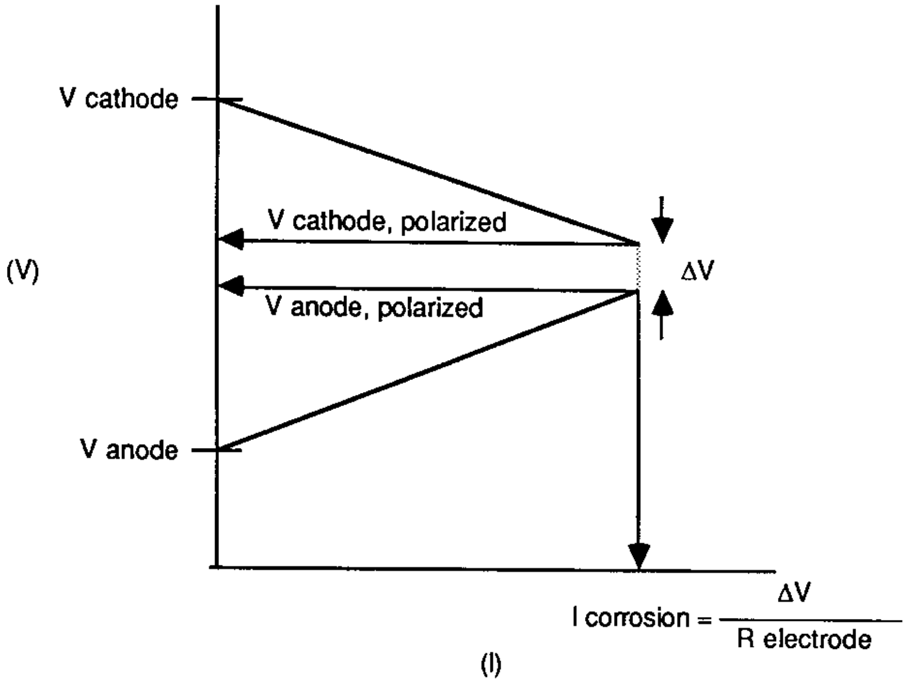


Figure 3. Polarization of Half-cells.

Two types of polarization are concentration polarization and activation polarization.

1. **Concentration Polarization**. After the current flows, the concentration of electrolyte changes near the electrodes as a result of oxidation or reduction activities. Based on the Nernst equation, changes in concentration create changes in half-cell potentials. An example is a depletion of the oxygen concentration in the cathodic steel in concrete, which results in cathodically controlled polarization (4).

2. **Activation Polarization**. This type of polarization is the result of current flowing through the system. Activation polarization increases with increases in current density according to Tafel's equation:

   $$\eta = a + b \log i$$

   In this equation, activation polarization (η) is proportional to the logarithm of current density (i) for large currents (4). Activation polarization usually decays at a measurable rate when the current is shut off. Half-cell potentials measured on bridge decks can be influenced by activation polarization when corrosion is in process. Activation polarization can be caused by an impressed current as well. An example is impressed current cathodic protection. By employing this latter technique, the potential of non-corroding cathodic steel is polarized and brought to the level of the potential of anodic steel. Under this condition corrosion will halt, since the difference between the cathodic and anodic potentials becomes negligible.

The Rate of Corrosion

The rate of corrosion of metals is expressed in terms of IPY, or inch penetration of corrosion per year, which represents a uniform corrosion. This rate of corrosion unit (IPY) can be converted to weight loss of metal per unit area of metal per year by knowing its unit weight. Rate of corrosion is a function of corrosion current density, and can be expressed in terms of current per unit area (A/in^2 or A/cm^2). For reaction of $Fe \rightarrow Fe^{++} + 2e$, a current density of 6.42×10^{-5} A/in^2 (1×10^{-5} A/cm^2) will result in 0.005 IPY of steel corrosion, which is equal to the rate of corrosion of steel in seawater (1).

The above discussion indicates that rate of corrosion is a function of corrosion current. Corrosion current, on the other hand, can be a function of polarized half-cell potentials ΔV and the electrolyte resistivity according to

Ohm's law. ΔV in turn depends on other factors, including the ratio of anodic areas to cathodic areas and the oxygen diffusivity of the cathode.

THE CORROSION OF STEEL IN CONCRETE

Concrete, due to its high alkalinity, provides a non-corrosive environment for steel and maintains the steel's passivity (4, 6). Iron is in a passive state at a pH level of 8 to 13 (4). Concrete has a pH of about 12.5, which maintains the passivity of steel. Voids between steel and concrete have been reported to be corrosion sites (6), which implies that continuous contact between steel and the alkaline environment is required for maximum protection.

The passivity of steel in an alkaline environment of concrete can be destroyed by the penetration of chlorides into the matrix. This in turn increases the ease with which metal ions enter into the solution. Concrete passivity can also be destroyed by the carbonation of concrete, which reduces the concrete's pH. Carbonation occurs when carbon dioxide in the atmosphere reacts with concrete's $Ca(OH)_2$ and reduces the concrete's alkalinity (6). Carbonation mainly appears in cracked or low quality concrete and it can harm a concrete with a thin rebar cover (4).

Concrete as an Electrolyte

The existence of an electrolyte is necessary for the corrosion of a metal to occur. A totally dry concrete is neither an environment for ions to react nor is it sufficiently conductive to allow corrosion current to flow. In the presence of moisture, however, the electrical resistivity of concrete drops significantly. Resistivity values of $6{,}000 \times 10^3$ ohm-cm have been reported for dry concrete and 7×10^3 ohm-cm for saturated concrete (4). The presence of salt in concrete also lowers its resistivity. Field observations have shown that a concrete resistivity of $50\text{-}70 \times 10^3$ ohm-cm is the level above which corrosion is negligible (4). The water content of concrete, corresponding to the threshold resistivity, varies and depends on the mix characteristics. To the writer's knowledge, no definite values have yet been established.

The Nature of the Half-Cells of a Corrosion-Cell in Reinforced Concrete

The nature of the half-cells of a corrosion cell in concrete is stated as follows (10):

Steel ions enter into the solution and thereby liberate electrons at the anode:

1. $Fe^{\circ} \dashrightarrow Fe^{++} + 2e^{-}$ (anodic half-cell reaction)

The electrons move from anodic areas to cathodic areas and cause the formation of hydroxyl ions in the presence of moisture and oxygen:

2. $1/2\ O_2 + H_2O + 2e^- \text{-->} 2o^-H$ (cathodic half-cell reaction)

The Nernst equation can be used to obtain the half-cell potentials for these two reactions at 25°C (77°F) relative to the SHE but disregarding the effects of polarization.

1. $$E_1 = -0.440 - \frac{0.0592}{2} \log \frac{1}{(a_{Fe^{++}})} \quad \text{(Anodic half-cell)}$$

2. $$E_2 = -0.401 - \frac{0.0592}{2} \log \frac{(a_{OH^-})^2}{(P_{O2})^{1/2}} \quad \text{(Cathodic Half-cell)}$$

The potential or EMF of the corrosion cell can be obtained by subtracting equation 2 from equation 1:

$$EMF = E_2 - E_1.$$

Laboratory research has shown that pH measurements at the cathodic sites in reinforced concrete beams and slabs range from 11.5 to 13.0 regardless of the chloride content of the concrete (7). If a pH value of 12 is assumed, a_{o^-H} will be 10^{pH-14} or 10^{-2} for 25°C (77°F). The value of ferrous iron activity at the anode ($a_{Fe^{++}}$) is assumed to be 0.1 and the partial pressure of oxygen at the cathode (P_{O2}) is assumed to be 0.2 atm (1).

The EMF of the corresponding corrosion cell thus will be

$$E_2 - E_1 = (0.509) - (-0.470) = 0.979 \text{ V}.$$

This is a considerable potential difference considering that reinforced concrete undergoing corrosion has been reported to have a potential difference of 0.200 V (4). However, the latter value, generally documented on bridge decks, can include the effects of high degrees of polarization mainly due to oxygen depletion in the cathode (concentration polarization). As a result of polarization the potential difference is reduced.

The Nature of Anodic and Cathodic Steel

Anodic and cathodic areas on embedded steel can develop because of different salt concentrations, impurities in the steel, different oxygen concentrations or stress levels. The rebar itself short circuits the anodic and cathodic areas and permits the flow of corrosion current. Anodic and cathodic areas on the rebar can vary from 1 inch (2.54 cm) to 20 feet (6 meters) (10). When large anodic and cathodic areas are separated the type of corrosion is called macrocell (8).

Research at the Federal Highway Administration has demonstrated the effects of macrocell corrosion on embedded steel in bridge decks (7, 9). In bridge decks, the bottom mat rebar, located in chloride-free concrete, acts as the major cathode and areas of top mat rebar in chloride contaminated concrete act as the anode. Since the top and bottom mats are connected by different metallic elements, corrosion current can flow. The large-cathode/small-anode ratio existing in this case can increase the rate of corrosion. Under this condition the corrosion rate of the embedded steel may reach its upper limit, which is proportional to the maximum difference in cathodic and anodic half-cell potentials and to the inverse of the concrete's electrical resistance; as more anodic areas develop, the ratio of cathodic to anodic areas decreases, but the corrosion rate also depends on other factors, including the oxygen diffusivity at the cathode (35).

In addition to macrocell corrosion, corrosion of the embedded steel in chloride contaminated concrete can be "microcell," which is self-corrosion of a small section of steel with relatively low corrosion rates (4).

THE HALF-CELL TECHNIQUE OF CORROSION DETECTION IN BRIDGE DECKS

The concept behind the half-cell technique is to detect corrosion by delineating the cathodic and anodic areas on a structure by measuring their half-cell potentials using a reference electrode. The fact that cathodic and anodic areas exist in a structure indicates the existence of corrosion activity. However, the half-cell technique does not measure the rate of corrosion, since that depends not only on the difference between the cathodic and anodic potentials but also the electrical resistance of the concrete spanning between the cathodes and anodes. The rate of corrosion in bridge decks can vary sharply due to significant changes in the resistivity of the concrete (moisture and temperature effects). However, this change may not necessarily affect the half-cell potentials of the actively corroding steel. This will be discussed later. A brief description of the methods for measuring the rate of corrosion of steel in bridge decks is provided at the end of this section.

Half-cell corrosion detection in bridge decks was pioneered by Stratfull at the California Department of Transportation. Due to its practicality and simplicity, it is now used on various types of reinforced concrete structures susceptible to corrosion, in addition to bridge decks. Because of its extensive use, the technique is covered in ASTM Test Method C876. The results of many field experiments show that copper-copper sulfate half-cell potentials more negative than -0.35 V indicate a 90 percent possibility of corrosion and those less negative than

– 0.20 V indicate a 90 percent possibility of passivity. The values between these two limits represent an uncertain condition.

Many highway agencies in the United States employ the half-cell method for assessing bridge deck condition in conjunction with other bridge evaluation techniques. The Washington State Department of Transportation has adopted the half-cell technique in conjunction with four other condition evaluation techniques to assess and monitor the condition of the state's bridge decks. The Ontario Ministry of Transportation has included the half-cell test as an element of its bridge deck condition survey in its bridge deck rehabilitation manual (21). The manual was prepared to help engineers evaluate the condition of Ontario's bridge decks and select the most appropriate rehabilitation technique prior to preparing contract documents.

The Copper-Copper Sulfate Reference Half-Cell Device and its Sensitivity

The standard hydrogen electrode (SHE) reference half-cell is not practical to use on reinforced concrete structures. A saturated copper-copper sulfate (CSE) half-cell is normally used instead. A CSE consists of a copper rod immersed in a saturated copper sulfate solution, as shown in Figure 4. The electrode reaction for this half-cell is

$Cu^{++} + 2e \dashrightarrow cu^{0}$.

The potential of the half\-cell relative to the SHE at 25°C (77°F) can be obtained using the Nernst equation:

$$E_1 = +0.337 - \frac{0.0592}{2} \log \left(\frac{a_{CU^0} = 1}{(a_{Cu^{++}})} \right)$$

The potentials of the cell relative to the SHE for different electrolyte concentrations have been calculated by this writer based on the above relationship and are given in Table 2.

The calculated potentials indicate that the cell becomes cathodic as its electrolyte concentration is increased. This is in agreement with the discussion presented earlier. They also indicate the error that can result by using diluted copper sulfate solutions. The error will be 0.018 V for a 1 mole/lit solution, 0.022 V for a 0.5 mole/lit solution, 0.030 V for a 0.1 mole/lit solution, and 0.050 V for a 0.01 mole/lit solution. The theoretical values, however, may not necessarily apply to the extremely diluted solutions.

The potential of the CSE is also temperature dependent. ASTM C876 has reported the temperature coefficient of the cell to be about 0.0005 V/°F (0.0009 V/°C). Assuming low and high ambient temperatures of 40°F (4°C) and 110°F (43°C), which may be encountered while field testing bridge decks, the difference in potential

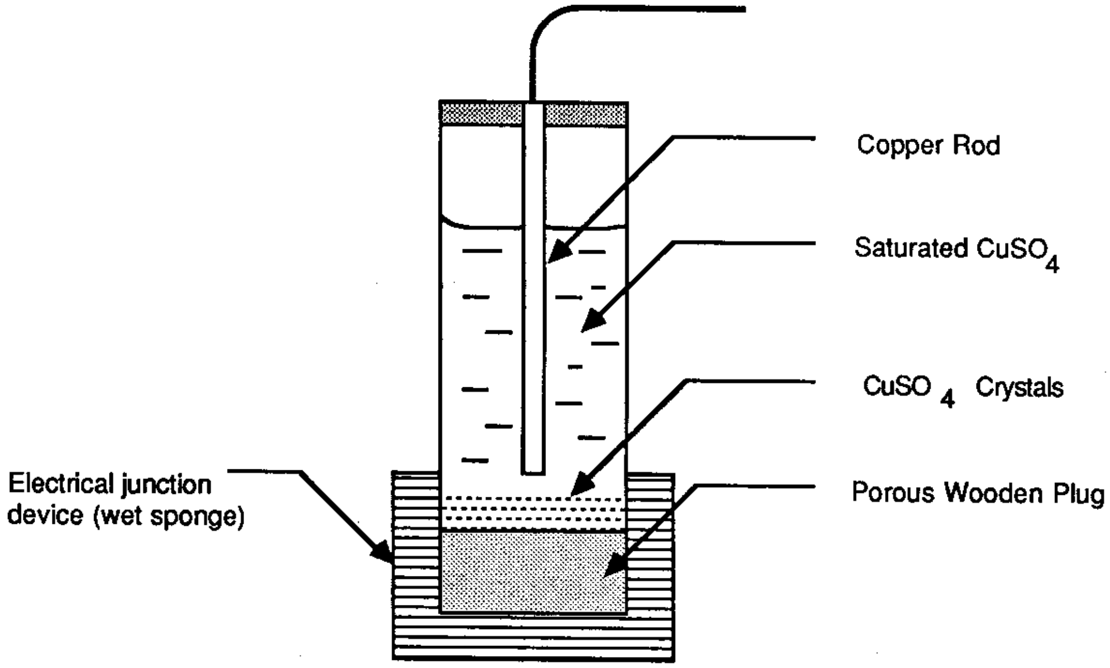


Figure 4. Copper - Copper Sulfate Reference Electrode.

Table 2. Copper - Copper Sulfate Half-cell Potentials (SHE) Calculated for Different Copper-Sulfate Concentrations.

Concentration		Coeff. (1) of Activity (g)	Activity, a_{cu++} (Cu++) x (g)	Half-cell Potential SHE (V)	Diff. from Potential of Saturated Cell (V)
Mole/lit (Cu++)	g/lit. water ($CuSO_4$)				
0.01	1.6	0.41	0.0041	0.266	0.050
0.10	16	0.16	0.016	0.284	0.032
0.50	80	0.068	0.034	0.294	0.022
1	160	0.047	0.047	0.298	0.018
2 (saturated)	320	——	——	0.316 (2)	0

(1) Reported in Ref. 1
(2) Reported in ASTM C876

from that of the standard temperature (25°C or 77°F) will be (40°-77°)(0.0005) = -0.019 V and (110°-77°)(0.0005) = 0.020 V, respectively. Higher temperatures tend to make the cell more cathodic as shown from this calculation and as discussed previously.

The Measurement of Copper-Copper Sulfate Half-Cell Potentials

The potential difference between any two electrodes can be measured using a simplified circuit with a voltmeter (potentiometer) as shown in Figure 5. To measure the potential of the cell, the calibrated variable resistance in the voltmeter is changed until the potential of the cell is balanced with that of the voltmeter, which includes a battery. Under the balanced condition the potential of the cell can be read directly according to the calibration of the voltmeter.

If a CSE is placed in the circuit as one of the electrodes, its electrolyte of copper sulfate solution should be in contact with the other electrode's electrolyte so that there will be electrical continuity in the circuit. When steel embedded in the concrete is the other electrode, continuity is achieved by contacting the porous plug of CSE, with an electrical junction device (wet sponge) folded around it, with the wetted concrete, which acts as the electrolyte of the steel electrode. To achieve a balanced condition, the positive jack of the voltmeter is connected to the copper electrode, which is generally cathodic to an iron electrode (see the electromotive force series in Table 1), and the negative jack is connected to the steel. The potential measured using this procedure is always positive, which indicates $V_{cathode}$-V_{anode}; negative values cannot be measured.

However, when the half-cell potential of steel to CSE is measured, convention dictates that the potential be recorded negatively, since steel is active to copper in the electromotive force series (see Table 1) and more active elements are conventionally labeled with a negative sign. When a digital voltmeter is used in the circuit, both positive and negative potential values can be recorded. The change in sign in this case indicates the reversed connection of the poles of the cell to those of the voltmeter. When recording the CSE half-cell potentials of steel embedded in concrete using a digital voltmeter, usually the positive jack of the voltmeter is connected to the steel, which is generally anodic to copper, in order to directly record negative values and satisfy the convention.

In measuring the potential difference between the CSE and the rebar in concrete, polarization between the copper and steel electrodes is possible, as described earlier, due to current flowing in the circuit. Thus the difference between the polarized potentials may be measured rather than between the static potentials. To eliminate this

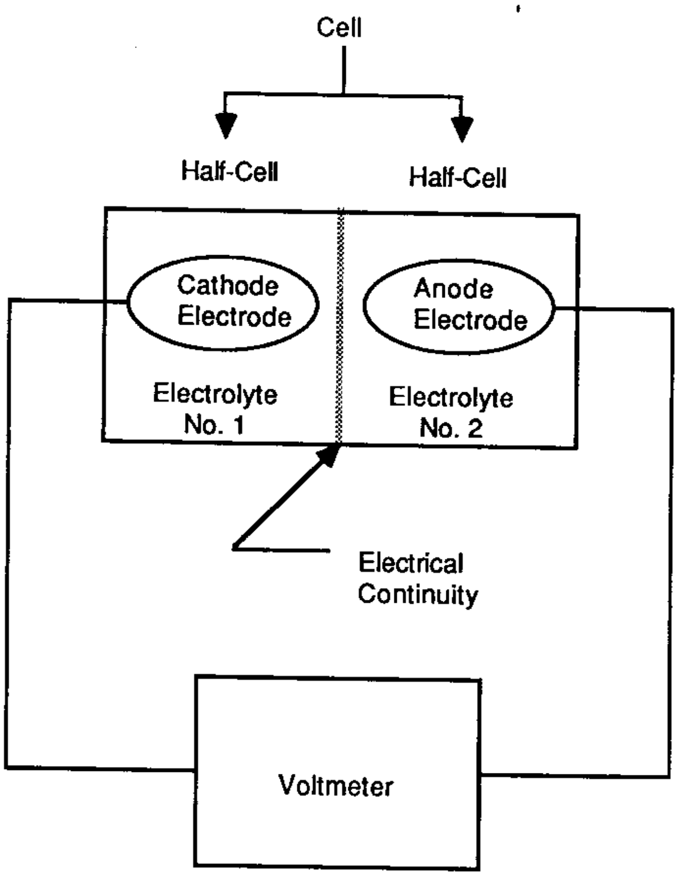


Figure 5. Schematic Diagram of Measuring Potential of a Cell.

problem, a high internal impedance voltmeter is used in the circuit to reduce the current flowing between the two electrodes and the polarization as well. ASTM C876 designates that the input impedance should not be less than 10 million ohms when operated at a full scale of 100 mV.

The Rate of Corrosion Measurement

A second technique for detecting corrosion is measuring the rate of corrosion, which generally includes the electrical resistance method and the polarization resistance method (linear polarization). The concept behind these test methods is to determine the rate of corrosion of steel in terms of loss of metal per year. In the electrical resistance method, probes are buried in the deck and connected to the rebar mat. When the probes start corroding, corrosion reduces their section and affects their electrical resistance, since the latter is inversely proportional to the sectional area. By measuring the changes in the electrical resistance of the probes, one can find the rate of corrosion.

In the polarization resistance method, probes are again buried in the concrete and connected to the rebar mat, or sections of the rebar mat are prepared to function as probes. A small amount of current is then applied to the rebar mat (using a procedure similar to that of impressed current cathodic protection) and changes in the polarized potential of the probes are recorded. The Stern-Geary equation makes the corrosion current (or rate of corrosion) proportional to di/dE, in which di indicates the increment of applied current in amperes and dE indicates the corresponding change in the potential of the probe in volts as measured by a reference half-cell.

The E-log-I technique, basically used to determine the level of protective current for cathodic protection, can also be used to find the corrosion current, or rate of corrosion. The technique applies small increments of cathodic current to a selected site in the deck and monitors its polarized half-cell potential. Half-cell potentials (E) are then plotted against a logarithm of applied current (logI). The straight line (Tafel slope) portion of the curve is extended to intersect with the original static half-cell potential line. From the point of intersection, the original corrosion current can be read on the logI axis. The minimum cathodic protection current can be read on the logI axis from the point on the curve where the Tafel slope starts.

Using the rate of corrosion figures, one can actually determine the magnitude of the corrosion distress that the structure is undergoing. However, using the rate of corrosion figures to predict the rebar's condition may not be easy, since the rate of corrosion in bridge decks is dynamic and its value can sharply change due to changes in the resistivity of the concrete as a result of moisture and temperature. Rate of corrosion measurement techniques on bridge decks have not been used as widely as the half-cell technique. Their use has been limited to experimental projects to learn more about their interpretation and the accuracy of their results.

THE THEORETICAL AND EXPERIMENTAL RANGE OF CSE HALF-CELL POTENTIAL VALUES ON BRIDGE DECKS

The standard saturated CSE has a potential of 0.316 V relative to a hydrogen electrode. CSE half-cell potentials of anodic and cathodic steel may be found based on the assumptions and calculations presented previously in this report (see "The Corrosion of Steel in Concrete") as follows:

For Anodic Steel: CSE potential = (0.316)-(-0.470) = 0.786, or conventionally recorded -0.786 V

For Cathodic Steel: CSE potential = (0.316)-(0.509) = -0.193, or conventionally recorded +0.193 V

However, with cathodic control polarization of the cathodic steel (oxygen electrode), measured half-cell potentials of the cathodic steel can be values more negative than the one calculated above and can actually be a negative potential.

Some positive potential readings have been reported in a few field and laboratory tests. A study conducted in Ontario reported positive readings of 0.030 V along with mostly negative readings (12). In this case the dryness of the concrete (electrolyte) was determined as the cause of the positive values. Although ASTM C876 regards positive readings caused by concrete dryness to be invalid, the Ontario work considered the entire range of readings, both positive and negative, as the corrosion driving voltage.

A few small positive potential readings were detected in one FHWA laboratory study (9). In this case the half-cell potentials were measured on both the top and bottom mat rebars of the test slabs. Positive potentials as high as +0.070 V were obtained when there was no chloride contamination or the contamination was not enough to induce corrosion. The negative readings detected in this case were also small and generally limited to -0.050 V. Since the values of electrical resistance reported for the concrete in this work were relatively small, the cause of the small positive readings does not seem to be the dryness of the concrete. Furthermore, their presence does not coincide with the existence of corrosion in the bridge deck specimens, detected by measuring corrosion current. Thus, the cause of positive readings in this case is most likely the presence of cathodic steel.

In half-cell surveys of bridge decks in Washington state, negative readings as high as -0.700 V have been obtained. In these surveys, positive potential values have also occasionally been reported. These positive readings have been generally small (i.e., < +0.100 V) and have indicated the absence of corrosion or perhaps concrete dryness during the test. In some cases positive readings with values as high as +0.400 V have been detected. An analysis of the causes of positive readings and their interpretation is included in "Chapter Two, Evaluation of WSDOT's Practice with Half-Cell Corrosion Detection."

The Effect of the Variation in the Rate of Corrosion on the Stability of Half-Cell Potentials

As stated earlier, corrosion in bridge decks is dynamic and the rate of corrosion, which is directly related to corrosion current, can increase sharply when concrete becomes wet. It can also increase with increases in temperature. Moisture and temperature both decrease the electrical resistance of concrete and facilitate corrosion. This raises the question of how much the variation in corrosion current affects the half-cell potentials.

Research conducted in FHWA laboratories measured the corrosion current between the top and the bottom mats of test bridge deck slabs containing uncoated steel and subject to chlorides (9). The specimens were exposed to an outdoor environment for about one year. The research recorded the half-cell potentials of the top mat rebar at different locations and different times.

This author has analyzed the performance of six of the FHWA test slabs subject to different chloride conditions. The analysis is plotted and shown in Figure 6. As indicated in the figure, when the slabs were actively corroding the half-cell potentials were independent of the corrosion current and did not necessarily increase as the corrosion current increased. This emphasizes the point that half-cell potentials representing corrosion activity do not represent the rate of corrosion but are only indicative of the presence of corrosion. Therefore, a high active half-cell reading can coincide with a small rate of corrosion or vice versa. However, half-cell potentials indicating a passive state to an active state, tend to increase sharply with a small increase in corrosion current, as may be noted in Figure 6. Other laboratory research has also shown that the potential of steel in its transition from a passive state into an active state can sharply increase (22, 23). Another point of interest in Figure 6 is that half-cell readings representing active corrosion can be obtained in concrete temperatures as low as 36°F (2.2°C) and 33°F (0.8°C). The test, however, may not be performed when concrete is frozen because of the high electrical resistance of ice, which prevents the completion of the circuit (10).

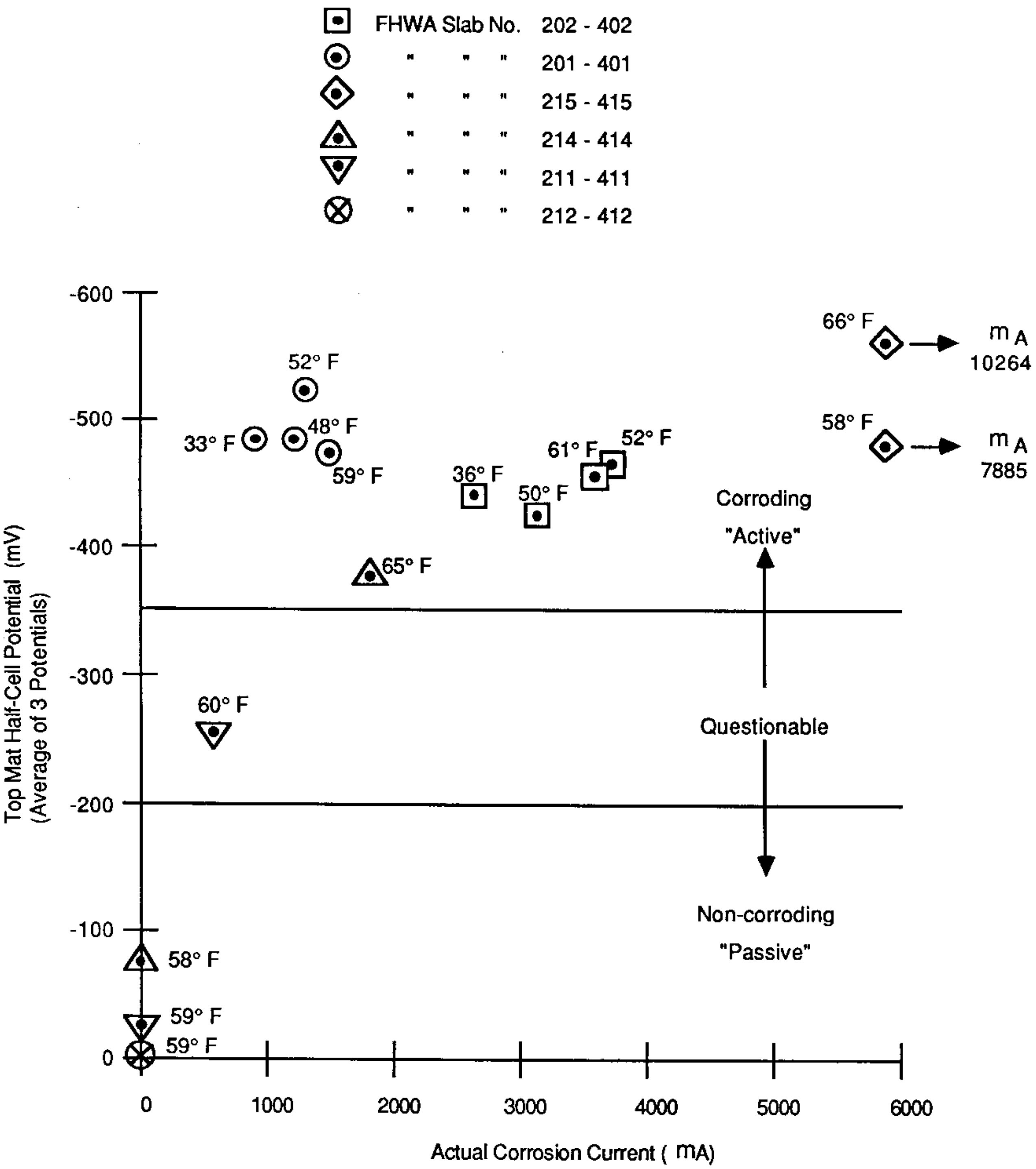


Figure 6. Relation between Half-cell Potentials and Corosion Current
(Analysis of data introduced in appendix of Ref. 9).

HIGHWAY AGENCIES' EXPERIENCE WITH THE HALF-CELL TEST METHOD

Kansas. A bridge condition survey in Kansas showed that generally older decks have somewhat higher potential values than younger ones (14). In one case, half-cell measurements showed potentials numerically greater than 0.35 V (CSE) when there was no sign of concrete deterioration. About a year later deterioration was detected in that area (14). Presently, the Kansas Department of Transportation includes half-cell tests in conjunction with chloride tests and delamination detection when evaluating the condition of a bridge deck (27). The test is also conducted on experimental projects to determine if corrosion can be arrested by applying a protective system, and to compare different protective measures (27).

Alaska. A bridge deck research study in Alaska found half-cell testing simple, inexpensive, and straightforward (28). However, the study recognized that the simplicity of the half-cell survey was somewhat deceiving because of the possibility for error from sources such as the dryness of the concrete around the rebar, the ground connections made to the galvanized metal embedded in the concrete, tellaric currents induced by auroral activities, and stray current leaking from dc sources (such as arc welders and telephone lines). Therefore, the need for inspection personnel to have some knowledge and experience and for survey data from other tests was emphasized. Currently the Alaska Department of Transportation uses the half-cell test in combination with chloride and delamination tests when evaluating the condition of a bridge deck (29).

Ohio. A study conducted in Ohio found that on bridges rehabilitated and overlaid with latex modified concrete it became harder to detect areas of active corrosion or half-cell potential values numerically greater than -0.35 V (CSE) over time (15). The survey also showed that when measured at crack locations, active potentials could still be obtained. The investigation concluded that the cumulative frequency distribution curves clearly represented half-cell potential values and their evolution over time on the bridge decks.

Minnesota. The half-cell corrosion detection test has been used in Minnesota in conjunction with other test methods to determine the effectiveness of selected installations of protective systems, especially concrete overlays, by monitoring the evolution of the rebar's potential. To do this, the Minnesota Department of Transportation has used cumulative frequency distribution curves to represent half-cell test results for each survey (30). The Minnesota Department of Transportation is presently continuing the monitoring program (31). On bare decks, the department employs the test in combination with a chloride test, delamination detection, and visual inspection to evaluate a bridge deck when necessary (31).

Ontario. The Ontario Ministry of Transportation has employed the half-cell test to monitor the effectiveness of bridge deck protective strategies (16). In one case, after a deck had been repaired and waterproofed with asphalt and a membrane, five cores were taken at those locations where the potential was -0.50 (CSE) or numerically greater. Three of the cores were found to be delaminated. Ontario has also incorporated half-cell data into its decision matrix for the selection of bridge deck protection methods. When corrosion potentials are more negative than -0.35 V (CSE) over more than 20 percent of the deck area, the matrix suggests cathodic protection or a concrete overlay (21).

California. A half-cell survey of bridge decks in California confirmed that half-cell testing could usually be trusted to report active rebar corrosion when the potential values were numerically greater than 0.35 V (CSE) (13). The study indicated that for potentials numerically less than 0.35 V (CSE) additional information, such as plotted equipotential contours that could delineate anodic or cathodic areas, was needed. At present the California Department of Transportation employs half-cell testing mainly for research activities due to the different factors that may influence the test results (23). One area in which CalTrans applies half-cell testing is cathodic protection (23). The test is used to determine the effectiveness of cathodic protection by detecting the shift of polarized rebar potentials when the cathodic protection system is turned off.

Iowa. The Iowa Department of Transportation currently employs the half-cell test together with chloride and delamination detection when evaluation of a bridge deck is required (32). The test is also used for monitoring the effectiveness of different protective systems. Sites in the past have been selected for this purpose and monitoring using the half-cell test is continuing (32).

Washington. The Washington State Department of Transportation is using the half-cell test in conjunction with chloride content determination, delamination detection, depth of rebar cover detection, and visual inspection to evaluate the conditions of state bridge decks. The department has also used the half-cell test in combination with the other bridge deck evaluation techniques on different research projects (17, 18). A more recent WSDOT research project, conducted to determine the conditions of five bridge decks covered with an asphalt/membrane system, attempted to determine the correlation between half-cell potentials and concrete deterioration (19). The results are presented in Table 3. In this investigation, the potentials were taken in 63 core locations drilled to the surface of the concrete, and concrete deterioration was detected by sounding the concrete with a hammer or further coring through the concrete. As indicated in Table 3, 11 percent of the potentials less negative than -0.20 V (CSE), 35 percent of potentials between -0.20 and -0.35 V (CSE), and 80 percent of potentials more negative than -0.35 V (CSE) were associated with deteriorated concrete.. The average moisture content of the decks at a depth of 1/4 inch (0.6 cm) to 1-1/2 inch (3.8 cm) was 3 percent of the dry concrete by weight, although some moisture was lost due to the nature of the sampling technique. This was believed to be a reason for the continuing corrosion activity in the chloride contaminated decks under the asphalt/membrane system. WSDOT's current use of the half-cell test will be discussed in detail in Chapter Two.

Transport and Road Research Laboratory (TRRL) Department of Transport (England). A 1985 half-cell research study carried out in the Highway and Structures Department of TRRL described the half-cell technique as a well defined technique and the only direct, non-destructive test available to assess the risk of corrosion in reinforced concrete (34). Since using a 0.5 meter by 0.5 meter (1.6 feet by 1.6 feet) grid in order to produce half-cell contour maps was time consuming and did not give fine resolution, the study used a multiple half-cell array controlled by a microprocessor. The multiple array consisted of eight half-cells mounted on a beam with 100 mm (4 inch) centers. The technique provided a fine resolution and data were collected and printed out instantly. The data were interpreted using criteria similar to those presented in ASTM C876. The multiple half-cell monitor is now being commercially manufactured.

Table 3. Overall Correlation of Ranked Half-cell Readings with Delaminations, Washington Experience.

		Ranked Half-cell Readings[1] V																											Delams. % of Readings
Range[2] V	< |.20|	.058	.083	.083	.107	.109	.112	.120	.126	.128	.133	.141	.145	.148	.148	.152	.154	.154	.155	.169	.170	.172	.177	.184	.187	.190	.190	.195	11%
Delam.[3]																							D			D	D		
Range V	|.20| - |.35|	.200	.202	.205	.206	.212	.217	.233	.235	.238	.244	.248	.251	.256	.267	.268	.272	.273	.278	.281	.284	.305	.314	.320	.328	.346			36%
Delam.											D	D						D			D	D	D	D	D	D			
Range V	> |.35|	.353	.369	.375	.389	.397	.409	.419	.429	.431	.454																		80%
Delam.			D		D	D	D	D	D	D																			

1 All readings are negative
2 Negative sign is eliminated
3 "D" indicates delamination

CHAPTER TWO

EVALUATION OF WSDOT'S USE OF THE HALF-CELL CORROSION DETECTION TEST METHOD

WSDOT has started a comprehensive bridge deck condition survey program which encompasses all of its six districts. Bare concrete decks are tested in the course of this program employing different condition determination techniques, including the half-cell potential survey, chloride content determination, deterioration detection, and the rebar depth survey. Presently, chloride content results and data on concrete deterioration are incorporated into WSDOT's bridge deck repair priority program in conjunction with data on traffic volumes. At this time, the WSDOT bridge deck repair priority program does not employ half-cell data for two reasons:

- first, the department has concerns about the reliability of half-cell data, and
- second, presently a method has not been established for combining half-cell data with concrete deterioration data and chloride contamination data.

In this chapter, WSDOT's use of the half-cell test is reviewed, WSDOT's concerns with the test are discussed, and the reliability of the data collected is determined. Based on the information generated in this chapter, recommendations are made for modifying the test method in order to collect more accurate data. (Chapter Three of the report will deal with development of a method to incorporate half-cell data into the WSDOT bridge deck repair priority program.)

REVIEW OF WSDOT'S USE OF THE HALF-CELL TEST

A telephone survey of the six WSDOT districts was conducted to determine their half-cell testing procedures. The districts' testing procedures were generally the same and followed the ASTM procedure. The following is a brief description of the districts' use of the half-cell test.

For every separated span or panel on the deck, one ground to the rebar is located. The ground is provided by exposing the rebar in the deck completely and attaching a compression type clamp to the rebar, or exposing the rebar partially and inserting a self-tapping screw attached to a compression type clamp. Five districts use a digital voltmeter and one uses a regular voltmeter. The length of electrical wire connecting the voltmeter to the ground varies from 250 to 500 feet (76 to 152 m) and dictates the location of the ground if separated spans are large. After the ground is connected to the rebar, the resistance of the ground joint is measured for a satisfactory connection. Ground resistances as high as 1 ohm, which is considered negligible, have been reported. Observations of routine bridge deck half-cell testing showed that the copper sulfate was not necessarily saturated, and in one case the electrical junction device of the half-cell was missing. A 5-foot by 5-foot (1.5-m by 1.5-m) grid is used for the survey with a minimum distance of 1.5 feet (45 cm) from the curb line. Test locations are prewetted with a solution composed of water and detergent in order to standardize the potential drop through the concrete portion.

WSDOT's half-cell data log provides space for ambient temperature, type of voltmeter, and location (only station) and type of ground. However, the location and type of ground have not been recorded in some half-cell survey logs. The sign of the potential values are not recorded in the data log. However, when positive readings are obtained, they are circled to indicate the sign.

THE RELIABILITY OF HALF-CELL DATA

The excellent correlation between high half-cell potentials and concrete deterioration obtained in one WSDOT research project conducted on five bridge decks indicated the reliability of the half-cell test method (see Table 3, Chapter One, for the correlation) (19). The significance of the numerical values of the potentials supported the criteria for interpretation presented in ASTM C876. These results show that when corrosion is present, it can be detected using the test. In this case the evidence of deterioration in the concrete and rust on the rebar confirmed the presence of corrosion activity. However, not all corrosion is destructive enough to cause concrete deterioration and not every corrosion activity constitutes hydrated red rust ($Fe(OH)_3$), the final product of corrosion.

The significance of the half-cell potentials has also been evident in many other field surveys conducted and recorded by WSDOT, including one field survey conducted in the course of this investigation. The selected site (Bridge 2/516) was a three-span, continuous, concrete box girder located west of Spokane. The bridge deck was extensively cracked and patched. The results of the half-cell and delamination survey conducted on one lane of the bridge (westbound) are plotted and given in Figure 7. The significance of the potential values is evident by the coincidence of deterioration and numerically high potential values. In this case, 80 percent of the samples tested had chloride content greater than 2 lb/cubic yard (1.18 kg/m^3).

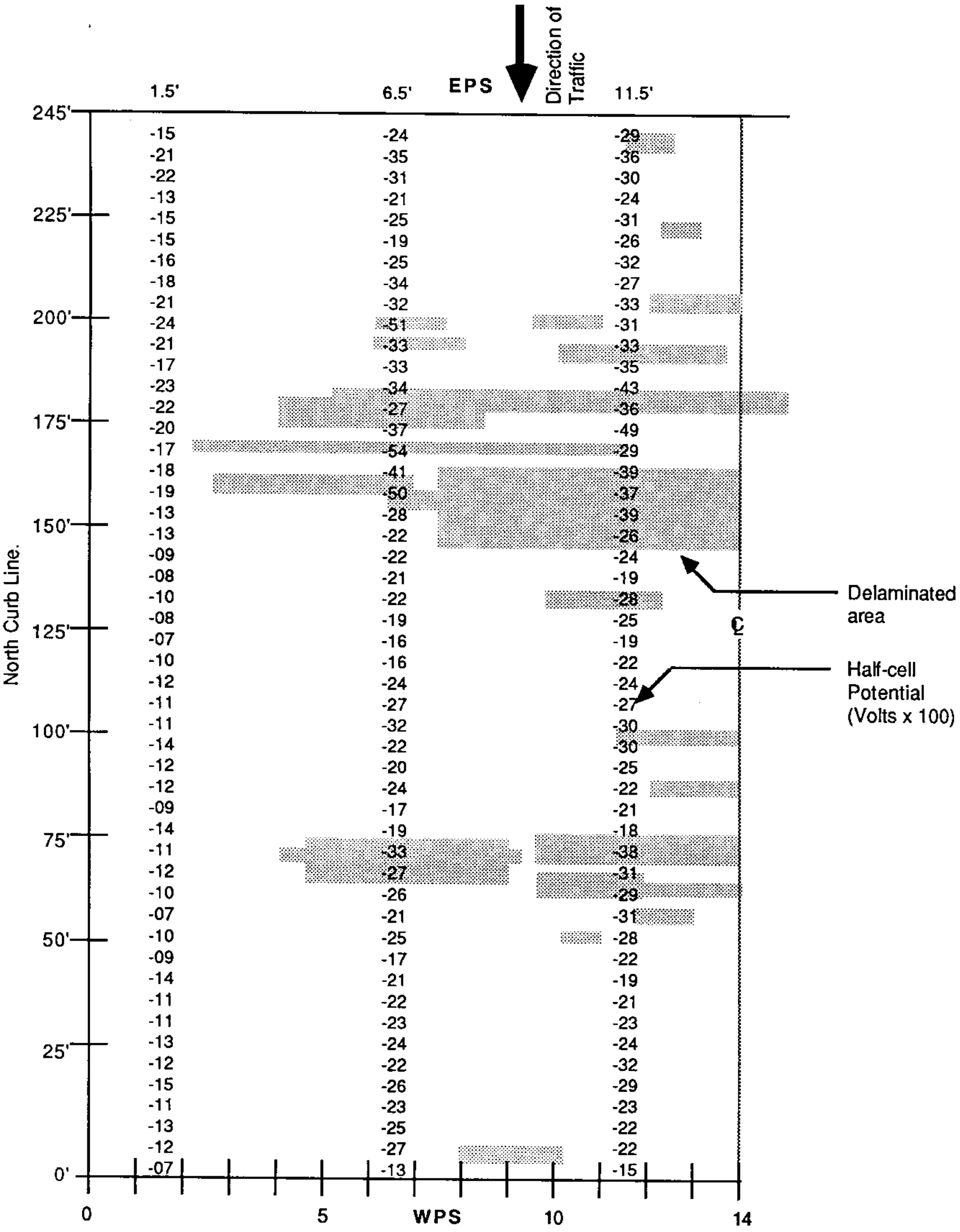


Figure 7. Correlation of Half-cell Potentials and Concrete Delamination of Bridge 2/516.

However, in WSDOT's half-cell survey of bridge decks, concerns were expressed over the positive potentials detected, the sensitivity of the data to the equipment, the location of the ground, and environmental conditions. The following material discusses the results of this study's efforts to clarify these conditions.

Positive Potential Values of Small Magnitude

Positive half-cell potentials of a magnitude generally smaller than 100 mV may be obtained when the following conditions are present:

- dry concrete,
- the absence of electrical continuity,
- the absence of corrosion,
- diluted copper/copper sulfate solution and/or low temperatures,
- reversed polarity, or
- interference from electrical facilities.

Dry Concrete. The dryness of the surface concrete causes higher electrical resistance in the circuit and shifts the potential value toward a more positive value. Depending on the magnitude of the shift, some originally negative potentials may become small positive potentials. Positive potentials as high as 30 mV attributed to concrete dryness have been reported (12). This condition may be overcome by wetting the concrete for the amount of time necessary to stabilize the potential reading for at least 5 minutes. However, if the dryness extends deep into the concrete to the level of the rebar, the wetting may not be able to shift positive potentials. Naturally, in the latter case there would not be an environment suitable for corrosion to occur and the positive potential would imply the absence of corrosion.

The Absence of Electrical Continuity. The absence of electrical continuity between the ground and the test location, which provides higher resistance in the circuit, may shift the potential value toward a more positive value. This condition was documented in an experiment conducted by Stratfull in which the half-cell was first grounded to all reinforcing steel and then to an isolated probe (22). Although the pattern of the half-cell equipotential contours was the same, there was a shift from a potential range of (-480)-(-280) mV to a potential range of (-182)-(-18) mV.

In the current study, an examination of a section of bridge deck which was electrically isolated from the rest of the deck by means of an expansion joint (a closed on-ramp on the eastbound Bridge 520/8, Evergreen Point Floating Bridge) indicated that positive values very small in magnitude (one digit) could be detected when the ground was placed in one section and the other section was surveyed. The nature of the positive readings caused by the lack of electrical continuity is probably the same as that caused by dry concrete, since both are the result of high electrical resistance in the circuit. However, in bridge decks there is a strong possibility that all of the rebar not across expansion joints is interconnected. Thus, providing a satisfactory ground can eliminate the possibility of positive potentials being caused by the absence of electrical continuity.

Absence of A Corrosive Environment. Positive readings may be obtained in some instances in which there is an absence of a corrosive environment. As mentioned earlier in this report, positive potentials as high as 70 mV were detected in one FHWA laboratory experiment in which there was no chloride contamination or the contamination was not sufficient to induce corrosion (9). The measured resistance of the concrete in this case indicates that high resistance (dry concrete) is not the cause of the positive readings. The measured corrosion current confirms the absence of corrosion activity.

Diluted Copper/Copper Sulfate Solutions and/or Low Temperatures. Diluted copper/copper sulfate solutions and/or low temperatures slightly shift the potential values toward more positive values. A shift of 18 mV can be theoretically expected when the solution is diluted to one-half of the saturated solution (see Table 2) and 19 mV when the ambient temperature is 40°F (4°C) (see page 16). Obviously this shift is very small and it can only cause positive potentials when the original potentials are less negative than -19 mV. Thus, positive potentials, if caused by diluted solutions normally encountered in practice and/or low temperatures, only indicate the absence of corrosion activity.

Reversed Polarity and Interference from Electrical Facilities. These two subjects are discussed in the following section, since the magnitude of positive potentials caused by them may not necessarily be small and limited to 100 mV.

Positive Potential Values of Large Magnitude

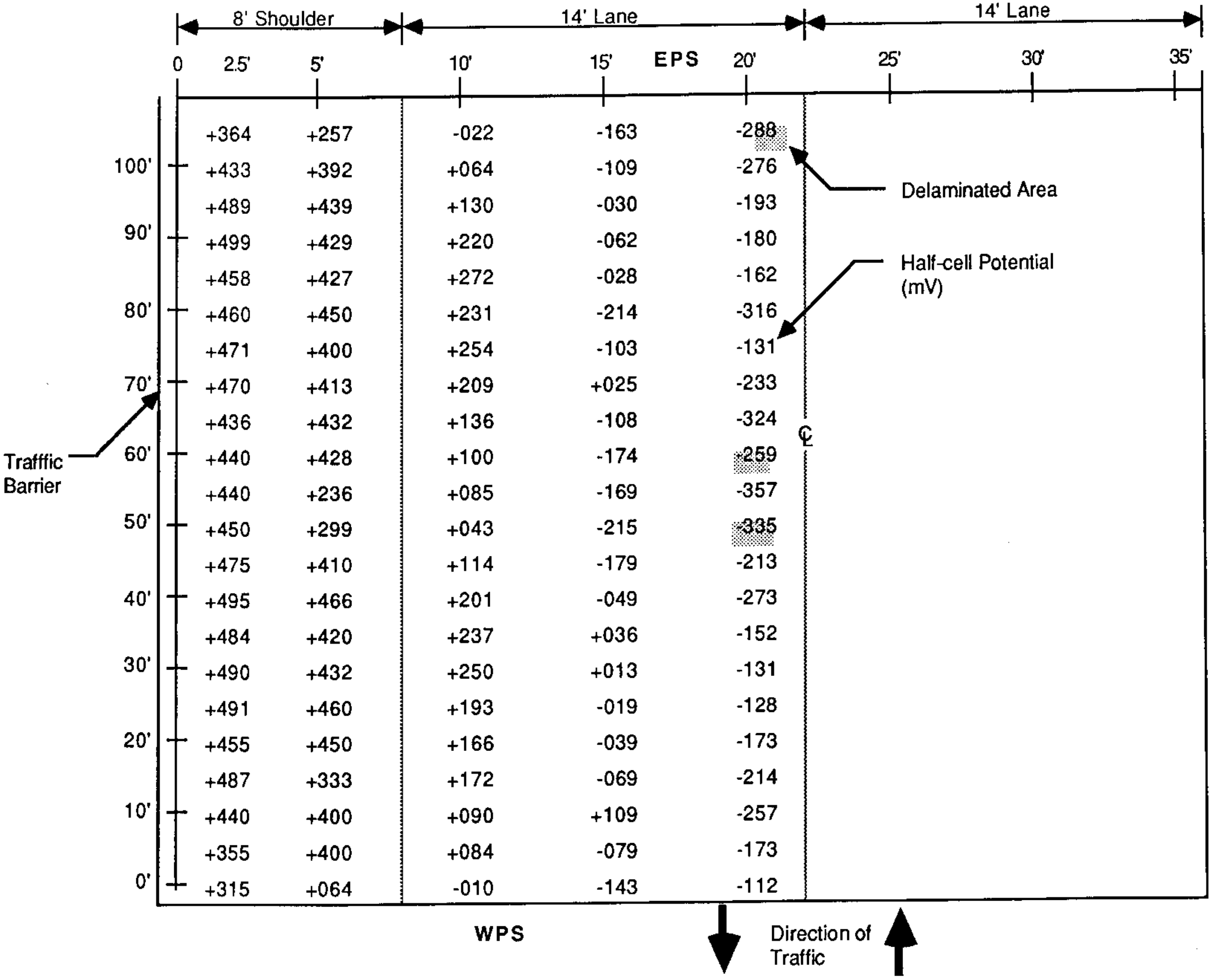
Positive half-cell potentials of a magnitude generally larger than 100 mV have been reported during bridge deck surveys in Washington. Investigations conducted in the course of this study have found the causes of this condition to be

- reversed polarity, and
- interference from electrical facilities.

Reversed Polarity. When using a digital voltmeter, if the plus terminal of the voltmeter is connected to the steel and the negative terminal to the half-cell, the displayed sign of potential is the one accepted conventionally. In the case of a reversed connection, however, the displayed sign will be the opposite of the conventional sign. Positive potentials obtained in this way are actually negative and can be either smaller or larger than 100 mV as the negative half-cell potentials would be. During this study, the results from the retesting of a bridge deck with recorded positive half-cell potentials indicated that reversed polarity was actually the reason for the positive readings.

Positive half-cell potentials obtained by reversed polarity generally have their own characteristics. They usually cover the entire bridge deck or they may be mixed with small number of negative potentials of small magnitude (generally smaller than 100 mV). When there is deterioration in the concrete, potentials more positive than +350 mV will be possibly concentrated in the deteriorated areas. Mapping deteriorated areas and equipotential contours can give clues regarding reversed polarity. Upon confirmation of reversed polarity the sign of potentials should be changed and they should be treated as negative potentials.

Interference from Electrical Facilities. The presence of positive half-cell potentials as high as +495 mV was documented on Bridge 405/28 (a continuous two-span concrete slab located over SR-405 and widened five feet in the westbound lane) during the current investigation. The half-cell potentials surveyed on the deck by the research team in September 1985 are illustrated in Figure 8. The temperature at the time the test was conducted was 70°F (21°C) and it had rained the night before and early in the morning. As can be seen in the figure, very high positive potentials were detected along the traffic barrier and 2.5 and 5 feet (76 and 152 cm) from it. As the survey moved toward the center of the bridge deck, the positive potentials decayed and became more negative. At a survey line 15 feet (4.5 m) from the traffic barrier the potentials were generally small negative values and at 20 feet (6.1 m) from the barrier potentials as negative as -0.357 mV were found. In the latter region some delaminations



	2.5'	5'	10'	15'	20'	25'	30'	35'
	+364	+257	-022	-163	-288			
100'	+433	+392	+064	-109	-276			
	+489	+439	+130	-030	-193			
90'	+499	+429	+220	-062	-180			
	+458	+427	+272	-028	-162			
80'	+460	+450	+231	-214	-316			
	+471	+400	+254	-103	-131			
70'	+470	+413	+209	+025	-233			
	+436	+432	+136	-108	-324			
60'	+440	+428	+100	-174	-259			
	+440	+236	+085	-169	-357			
50'	+450	+299	+043	-215	-335			
	+475	+410	+114	-179	-213			
40'	+495	+466	+201	-049	-273			
	+484	+420	+237	+036	-152			
30'	+490	+432	+250	+013	-131			
	+491	+460	+193	-019	-128			
20'	+455	+450	+166	-039	-173			
	+487	+333	+172	-069	-214			
10'	+440	+400	+090	+109	-257			
	+355	+400	+084	-079	-173			
0'	+315	+064	-010	-143	-112			

Figure 8. Half-cell Potential Survey on Bridge 405/28, Pleasure Point U/C.

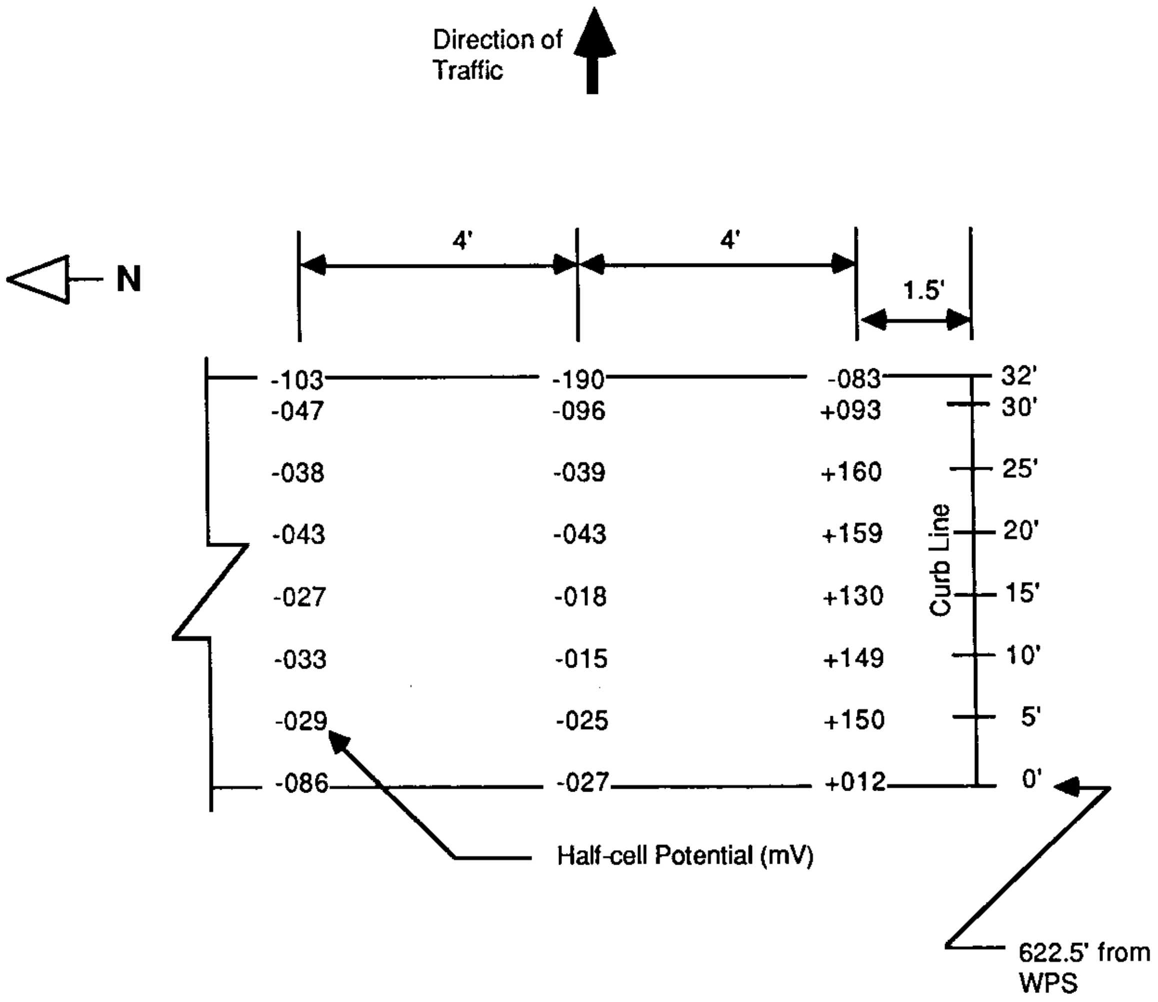
coincided with high negative potential values. Interestingly, the nature of some of the potentials detected differed from the norm. The last digit of some of the readings in the areas closer to the traffic barrier did not quite stabilize while recording. This condition differs from the normal condition in which readings stabilize in at most a few minutes after placing the half-cell on a fairly wet concrete.

The half-cell potential pattern of Bridge 405/28 implied that the potentials obtained were not typical of potentials for a concrete slab rebar and might have been distorted by some kind of interfering system. Later, a review of the bridge plans revealed the presence of a 2 inch (5 cm) electrical conduit inside the traffic barrier and about 2 inches (5 cm) above the top of the bridge deck. The conduit was placed along the deck and was in contact with the rebar in the traffic barrier. It is possible that some potential had built up on the deck rebar (especially in the areas close to the conduit) because of an electricity leak in the conduit, perhaps caused by dc current found in telephone lines. Theoretically, ac current is not able to cause this condition. However, actually every cycle of ac current may function in the same way to some extent (23). Another explanation for the existence of the unusual half-cell potentials may be that electromagnetic interference emanated from the conduit. Although unlikely, the newer concrete and steel in the widened section of the deck might also have played a part in the occurrence of the positive potentials.

A similar case was recorded during a WSDOT research project conducted on the Columbia River Bridge in Wenatchee in 1983 (18). The half-cell test results obtained on test section 3 of this bridge included positive readings along and in the vicinity of the curb line, as illustrated in Figure 9. The occurrence of positive half-cell potentials along curb lines were also noticed on a few bridge decks located in WSDOT districts 5 and 6 (25, 26). Electrical interference, however, may not necessarily have been the cause of the latter cases of positive potentials; rather, cathodic steel may have been the cause.

Sensitivity to Equipment Condition

Concerns have been expressed over the effects of types of half-cell instruments and their condition on half-cell potentials. An experiment was conducted on a section of Bridge 2/516 with active half-cell potentials. The experiment included two half-cell surveys (Survey A and Survey B), each utilizing a different half-cell instrument and voltmeter but sharing the same ground.



-103	-190	-083	32'
-047	-096	+093	30'
-038	-039	+160	25'
-043	-043	+159	20'
-027	-018	+130	15'
-033	-015	+149	10'
-029	-025	+150	5'
-086	-027	+012	0'

Figure 9. Half-cell Test Results on Exposed Concrete (Columbia River Bridge Deck, Test Section 3).

The results from Surveys A and B are given in Table 4. Also included in the table is the difference in potential between the two surveys for each test location. The mean value of the difference in potential for 51 test locations is 11 mV, with a standard deviation of 7 mV and maximum and minimum values of 29 and 0 mV, respectively. A comparison of the distribution of the potentials obtained in the two surveys is illustrated in Figure 10. As shown in the figure, the two surveys are in close agreement. This experiment shows that normal differences in the condition of half-cell equipment should not result in serious differences in half-cell potential surveys.

Sensitivity to Ground Location

In order to find the influence of the rebar ground location on half-cell potentials, a section of Bridge 2/516 was surveyed twice using the same half-cell equipment but two different ground locations. The first survey (Survey A) used a ground to a rebar located 109 feet (33 m) from the west pavement seat and 12 feet (3.7 m) from the north curb line. The second survey's (Survey C) ground was located 230 feet (70 m) from the west pavement seat and 11.5 feet (3.5 m) from the north curb line. The electrical resistance measured between the two grounds was 1.8 ohms, indicating electrical continuity between the two rebar locations.

The results of Surveys A and C are given in Table 5. Table 5 also presents the difference in potential between the two surveys for each test location. The mean value of the difference in potential for the 51 test locations was 10 mV, with a standard deviation of 7 mV and maximum and minimum values of 34 and 0 mV, respectively. In Figure 11, the distribution of the half-cell potentials obtained in each survey is plotted and compared. As shown in the figure, the two surveys are in close agreement. This experiment shows that if there is electrical continuity in the rebar, differences in ground location do not cause severe differences in half-cell potential surveys.

Sensitivity to Seasonal Surveys

The WSDOT bridge deck condition survey program usually conducts half-cell tests on bridge decks during the summer. Climatic conditions, however, may change even during the summer months, which may affect the surveyed half-cell potentials. In order to find the extent of the effects of seasonal changes, two bridge decks representing two different half-cell potential conditions were selected for examination. Half-cell potentials from the first bridge (2/516), obtained by a WSDOT survey in the summer of 1985, showed that relatively large areas of the

Table 4. Comparison of Two Half-cell Surveys Employing Two Different Types of Equipment, Bridge 2/516.

	Potential Survey "A" (mV)			Potential Survey "B" (mV)			"A" - "B" (mV)		
	Offset from North Curb Line (ft)								
Station from WPS (ft)	1.5'	6.5'	11.5'	1.5'	6.5'	11.5'	1.5'	6.5'	11.5'
165'	178	407	388	165	419	386	13	-12	2
170'	170	535	288	161	515	337	9	20	-29
175'	199	368	491	201	374	507	-2	-6	-16
180'	221	270	356	223	266	347	2	4	9
185'	226	342	431	227	320	447	-1	22	-16
190'	172	326	347	197	337	352	-25	-11	-5
195'	214	334	327	231	344	336	-17	-10	-9
200'	237	509	309	260	491	318	-23	18	-9
205'	209	322	333	210	344	324	-1	-22	-9
210'	178	339	272	187	363	291	9	-24	-19
215'	158	245	323	171	267	319	13	-22	4
220'	146	188	255	154	210	267	-8	-22	12
225'	158	250	305	180	243	298	-22	7	7
230'	150	210	242	140	210	249	10	0	7
235'	219	314	300	226	317	297	-7	-3	3
240'	205	353	361	217	347	352	-12	6	9
245'	146	243	285	166	233	292	-20	10	-7
							mean = |11| mV d = |7| mV max. = |29| mV min. = |0| mV		

All potentials are negative

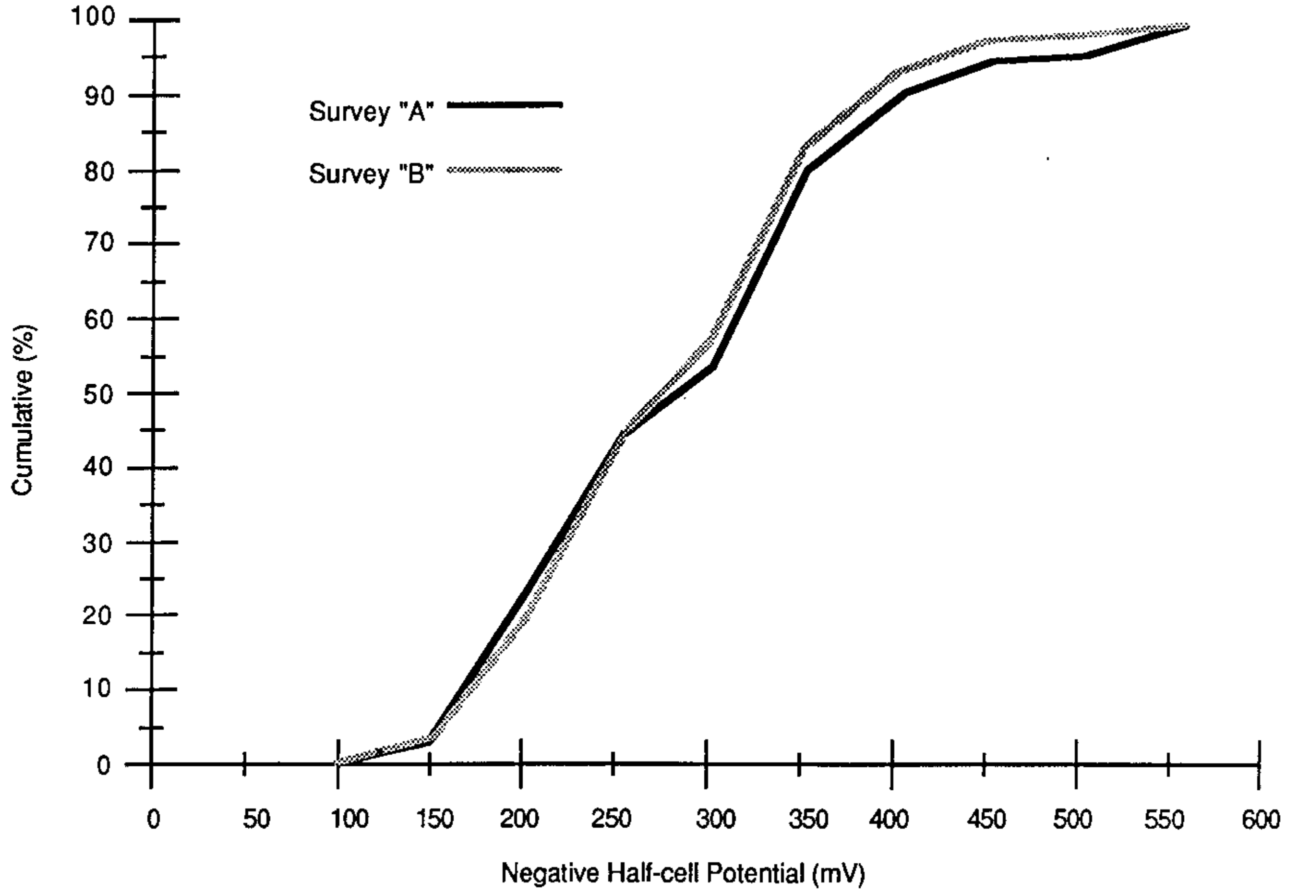


Figure 10. Distribution of Half-cell Potentials for Two Surveys Employing Two Different Types of Equipment, Bridge 2/516.

Table 5. Comparison of Two Half-cell Surveys Employing Two Different Grounds, Bridge 2/516.

		Potential Survey "A" (mV)			Potential Survey "C" (mV)			"A" - "C" (mV)		
		Offset from North Curb Line (ft)								
		1.5'	6.5'	11.5'	1.5'	6.5'	11.5'	1.5'	6.5'	11.5'
Station from WPS (ft)	165'	178	407	388	182	402	377	-4	5	11
	170'	170	535	288	166	528	270	4	7	18
	175'	199	368	491	199	377	490	0	-9	1
	180'	221	270	356	231	275	352	-10	-5	4
	185'	226	342	431	229	326	425	-3	16	6
	190'	172	326	347	193	333	349	-21	7	-2
	195'	214	334	327	233	364	335	-19	-30	-8
	200'	237	509	309	251	512	322	-14	-3	-13
	205'	209	322	333	218	327	326	-9	-5	7
	210'	178	339	272	192	345	285	-14	-6	-13
	215'	158	245	323	170	258	322	-12	-13	-1
	220'	146	188	255	149	215	266	-3	-27	-11
	225'	158	250	305	172	264	339	-14	-14	-34
	230'	150	210	242	172	212	246	-22	-2	-4
	235'	219	314	300	226	299	289	-7	15	11
	240'	205	353	361	216	352	347	-11	1	14
	245'	146	243	285	161	239	292	-15	4	-7
								mean = |10| mV d = |7| mV max. = |34| mV min. = |0| mV		

All potentials are negative

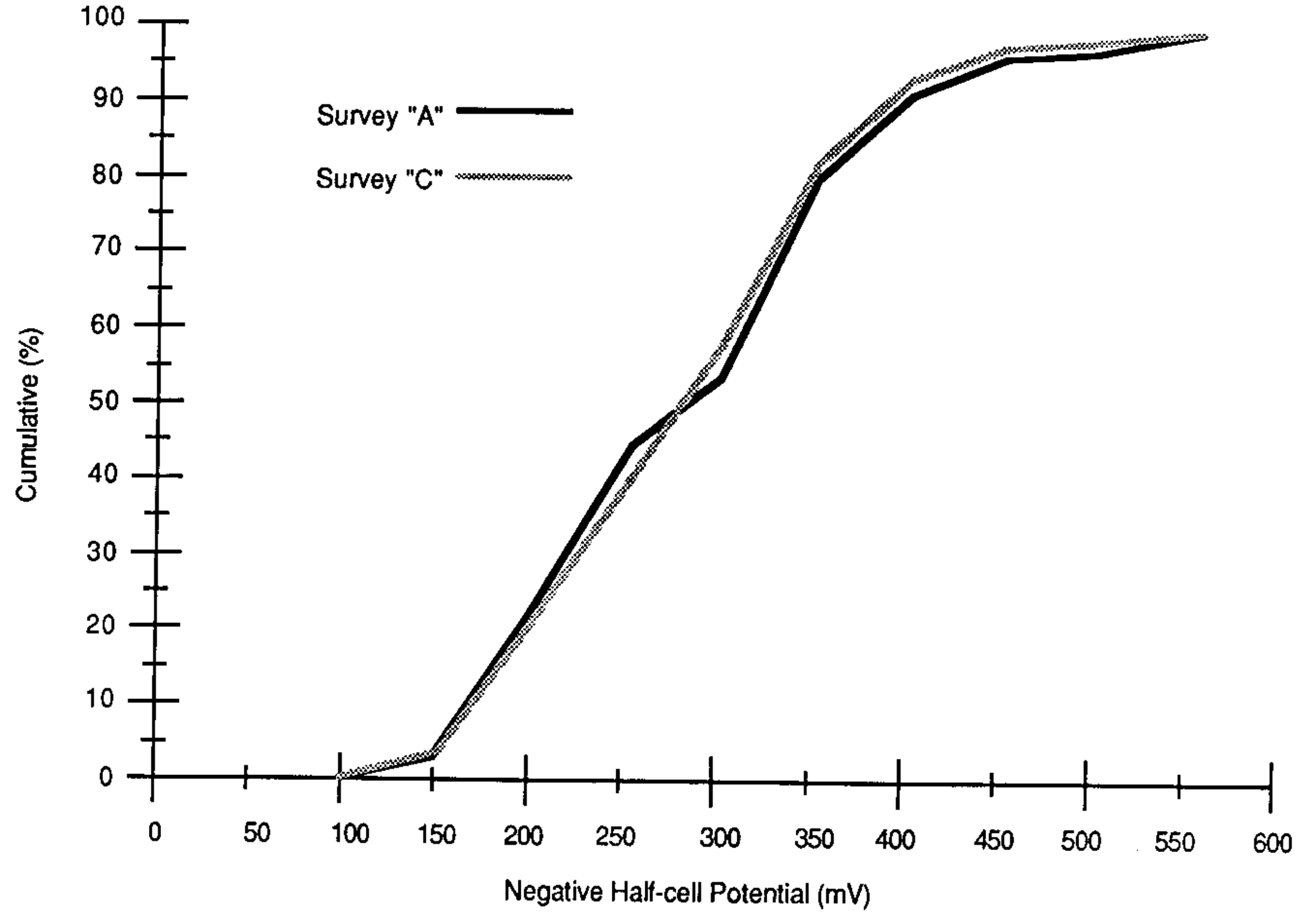


Figure 11. Distribution of Half-cell Potentials for Two Surveys Employing Two Different Grounds, Bridge 2/516.

deck were actively corroding (i.e., the potentials were more negative than -0.350 V). The half-cell potentials from the second bridge (90/90 N), on the other hand, showed the bridge to be in a passive state (i.e., the potentials were less negative than -0.200 V), as documented by a WSDOT survey in the summer of 1985.

- **Bridge 2/516**. This WSDOT half-cell survey was conducted on August 1, 1985, at 82°F (28°C). The research team again surveyed a portion of the deck on September 26, 1985, at 61°F (16°C) using the same grid. The results of both surveys are given in Table 6 and plots of their distribution are presented in Figure 12. As shown in the figure, in the active potential region the surveys are very close to each other, both indicating that 21 percent of the area surveyed was corroding. This correlates well with the level of concrete deterioration, which is 15 percent of the area surveyed. In the questionable and passive regions the fall survey indicates somewhat less negative potentials by slightly shifting toward the left. This shift is probably due to the 21°F (12°C) decrease in temperature for the fall survey, which may have influenced the relatively instable potentials in that region. A portion of the shift, however, is due to the sensitivity of the reference cell to the changes in temperature. This portion is equal to (21°F)(0.5 mV/F) = 11 mV. Comparison of the two half-cell surveys in Figure 12 implies that the active potentials were not affected by the seasonal changes, although they may have increased naturally in time. Those in the questionable and passive regions, however, were slightly sensitive to climatic conditions, although not considerably. These results are encouraging, since half-cell surveys are generally judged based on the percentage of their active potentials.
- **Bridge 90/90 N**. This WSDOT half-cell survey was conducted on July 16, 1985, at 75°F (24°C). The research team again surveyed one lane of the deck on November 8, 1985, at 41°F (5°C) using the same grid. The results of both surveys are shown in Table 7 and plots of their distribution are given in Figure 13. As illustrated in Figure 13, both surveys follow the same pattern and do not exceed the passive region. The fall survey, however, is slightly shifted toward the left, indicating somewhat less negative potentials. As discussed earlier for Bridge 2/516, this is probably due to the 34°F (19°C) decrease in temperature for the latter survey. The portion of the shift caused by the sensitivity of the reference cell to the changes in temperature is

Table 6. Comparison of Two Half-cell Surveys Conducted in Summer and Fall of 1985, Bridge 2/516.

		Summer Potential Survey (mV)				Fall Potential Survey (mV)		
		Offset from North Curb Line (ft.)						
		1.5'	6.5'	11.5'		1.5'	6.5'	11.5'
Station from WPS (ft.)	165'	282	384	384		165	419	386
	170'	191	331	292		161	515	337
	175'	234	472	446		201	374	507
	180'	269	335	416		223	266	347
	185'	293	433	452		227	320	447
	190	226	339	334		197	337	352
	195'	281	385	368		231	344	336
	200'	225	379	304		260	491	318
	205'	214	345	342		210	344	324
	210'	213	315	325		187	363	291
	215'	193	338	321		171	267	319
	220	171	225	306		154	210	267
	225'	178	305	314		180	243	298
	230'	203	271	272		140	210	249
	235'	278	335	336		226	317	297
	240'	221	348	343		217	347	352

All potentials are recorded negative.

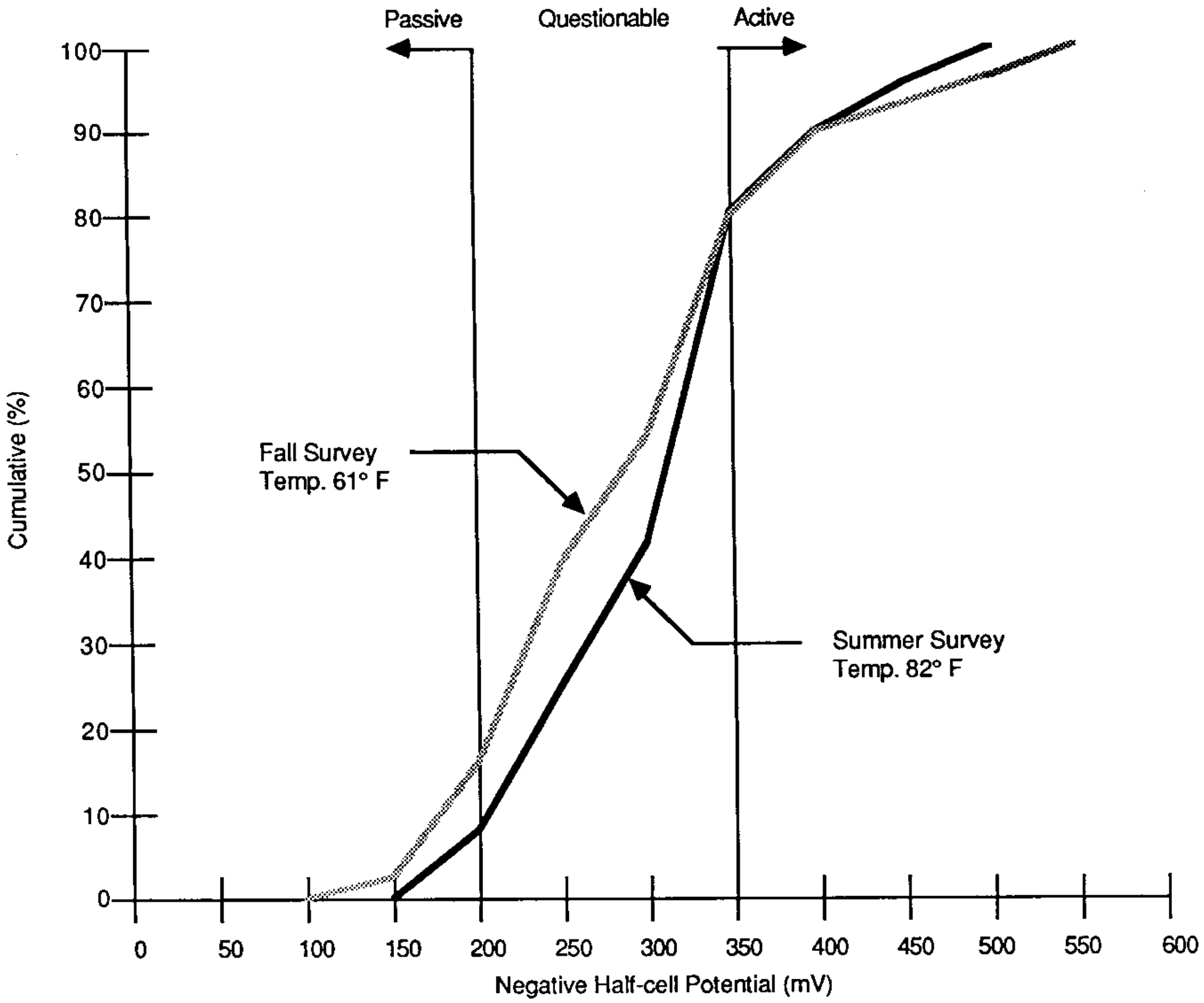


Figure 12. Distribution of Half-cell Potentials for Two Surveys Conducted in Summer and Fall, 1985, Bridge 2/516.

Table 7. Comparison of Two Half-cell Surveys Conducted in Summer and Fall of 1985, Bridge 90/90N.

Station from EPS (ft)	Summer Potential Survey (mV)					Fall Potential Survey (mV)				
	Offset from South Curbline (ft)									
	31'	36'	41'	46'	51'	31'	36'	41'	46'	51'
-015	----	077	058	034	022	---	065	071	066	042
-010	082	064	070	032	015	096	079	048	048	055
-005	030	054	045	045	079	040	060	048	049	040
000	004	067	071	070	069	047	050	023	046	035
005	004	070	068	184	057	055	079	064	037	026
010	004	052	065	121	058	051	087	042	036	020
015	000	075	063	077	077	033	052	052	034	025
020	009	016	061	090	084	036	063	026	040	025
025	012	075	064	098	071	047	048	033	066	030
030	089	098	066	050	058	061	049	049	046	041
035	092	102	061	052	048	052	054	043	047	030
040	098	109	083	078	040	061	075	052	042	042
045	104	098	078	077	039	067	082	051	040	053
050	114	131	104	085	052	111	099	060	031	036
055	098	101	099	077	047	080	065	083	058	059
060	119	154	118	086	032	098	084	080	055	069
065	129	116	099	064	029	082	092	048	043	031
070	107	126	104	070	017	054	081	076	057	031
075	087	107	059	078	042	077	084	058	045	045
080	091	095	137	047	021	056	068	065	094	042
085	092	093	069	061	038	061	065	029	027	029
090	094	095	073	058	028	044	072	058	034	028
095	084	087	061	059	040	065	070	104	023	043
100	104	102	093	088	024	092	102	077	031	017
105	090	100	094	054	032	070	082	075	045	042
110	116	134	087	045	001	106	087	059	035	037

Table 7. (cont.)

		Summer Potential Survey (mV)					Fall Potential Survey (mV)				
		Offset from South Curbline (ft)									
		31'	36'	41'	46'	51'	31'	36'	41'	46'	51'
Station from EPS (ft)	115	100	100	086	042	018	110	106	0064	054	035
	120	148	145	181	095	165	103	108	108	074	059
	125	143	193	131	120	157	122	145	102	106	050
	130	179	162	112	102	022	125	124	115	088	047
	135	190	161	136	095	065	170	148	137	087	061
	140	177	200	192	188	065	181	171	116	095	053
	145	165	198	142	121	051	158	151	124	088	036
	150	154	135	176	091	044	150	124	137	086	022
	155	146	160	080	053	018	124	131	083	057	037
	160	153	138	086	040	024	127	122	067	058	030
	165	141	155	108	068	024	109	116	087	059	039
	170	169	145	098	072	030	154	105	080	070	032
	175	177	157	076	074	020	126	099	082	056	042
	180	120	133	078	068	022	102	135	084	055	036
	185	146	165	093	080	028	123	104	089	065	038
	190	136	163	135	083	055	105	113	102	073	042
	195	000	152	112	088	089	081	115	071	074	078
	200	087	102	080	076	064	074	078	080	071	058
	205	111	116	102	131	133	082	082	111	105	084
	210	130	148	----	----	----	062	093	----	----	----

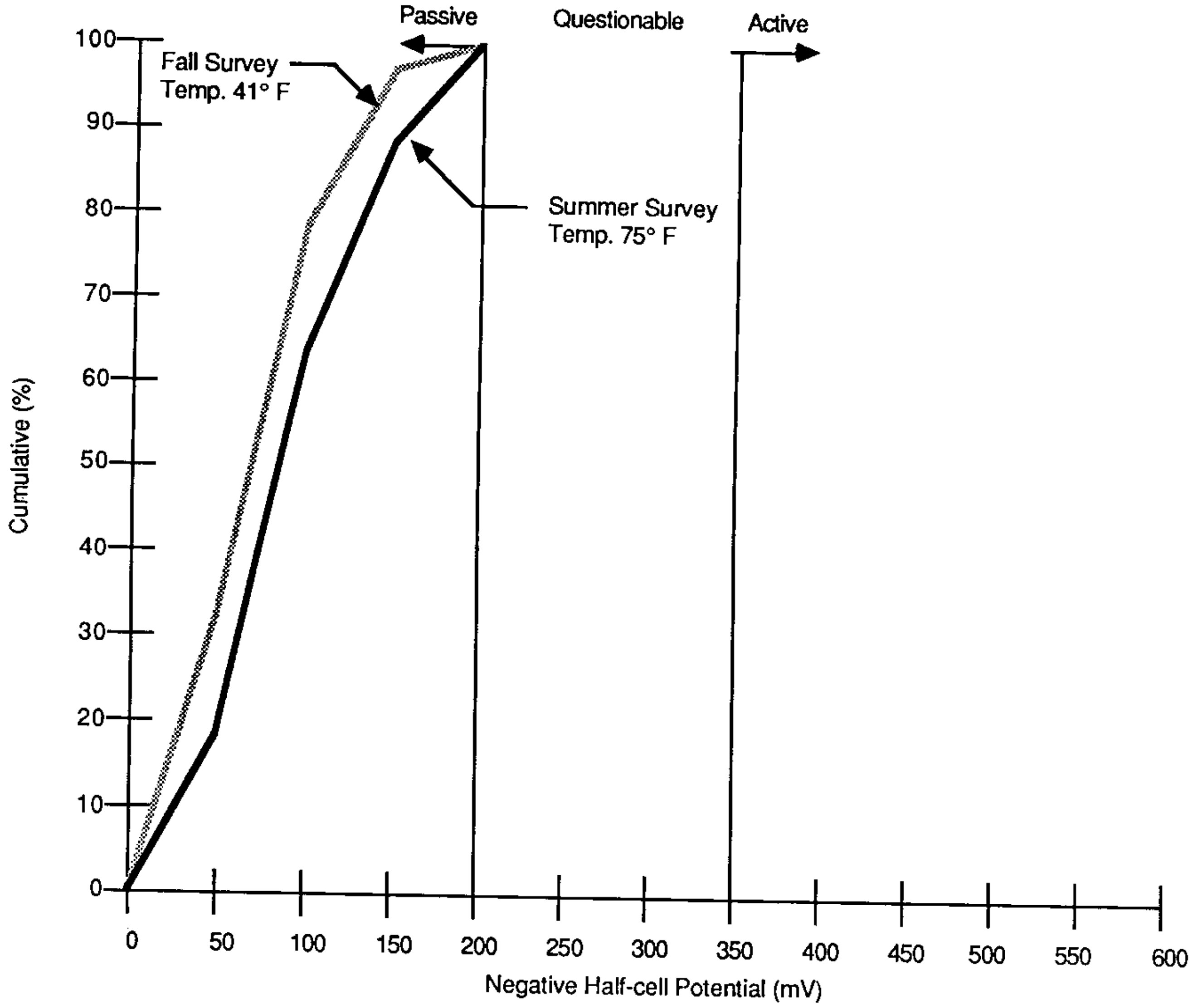


Figure 13. Distribution of Half-cell Potentials for Two Surveys Conducted in Summer and Fall, 1985, Bridge 90/90N.

(34°F)(0.5 mV/F) = 17 mV, which constitutes a large portion. Both half-cell surveys correlate well with the level of concrete deterioration, which is 0.06 percent of the lane surveyed. Note that a reason for selecting this site was that despite its high chloride contamination (i.e., 87 percent of samples had more than 2 lb/cubic yard, or 1.18 kg/cm^3, of chloride) the summer survey showed only passive potentials. This might have been the result of a dry deck during the summer testing. The fall survey, however, was conducted when the deck was wet from the heavy seasonal rainfall. The results of the fall survey were in agreement with the summer survey, indicating the validity of both surveys. The lower temperature associated with the fall survey could not have prevented the occurrence of active potentials, if they had existed. The latter statement is supported by the results of an FHWA laboratory study (9) (see Figure 6) which documented that active half-cell potentials can be obtained at 33°F (1°C) (9). An explanation for the coincidence of passive potentials with a high level of chloride contamination is that the bridge is relatively new and chlorides may need more time to induce corrosion.

Repeatability of Half-Cell Surveys

The nature of the sensitivity of half-cell readings to equipment condition and ground location and the similarity between them suggests that the difference in the readings between two surveys may be mainly the repeatability of the test rather than the effects of equipment condition or ground location. In other words, the small difference of 10 mV may also be obtained between two surveys sharing the same equipment and ground as a result of the following factors not necessarily being exactly the same in each survey:

- moisture content of surface concrete,
- moisture content of the electrical junction device, and
- the half-cell/concrete contact location.

Sensitivity of the half-cell readings to seasonal survey, on the other hand, can be minimized by adjusting the results to standard temperature for reasonable comparison.

CHAPTER THREE

DEVELOPMENT OF A PROCEDURE FOR INCORPORATING HALF-CELL DATA INTO WSDOT'S BRIDGE DECK REPAIR PRIORITY AND PROTECTIVE SYSTEM SELECTION PROGRAM

WSDOT'S bridge deck repair priority and protective system selection program, patterned after Minnesota's, classifies bridge decks based on their condition and their traffic use. WSDOT's decision-making matrix for bridge deck rehabilitation/protection is given in Table 8. As indicated in the table, three groups of deck conditions based on chloride contamination or concrete deterioration and three categories for traffic use are identified. The repair priority or the type of protection is then selected in the matrix based on the bridge deck condition and level of traffic use. The objective of this chapter is to incorporate half-cell potential data usually obtained during the bridge testing program into the WSDOT's decision-making matrix.

The author believes that the way to accomplish this is to quantitatively determine how much corrosion activity contributes to deterioraton. The deterioration found during rehabilitation can be much larger than the deterioration detected at the time of the initial survey. This is mainly due to the continuing corrosion of the rebar at sound concrete areas, which eventually causes internal cracking in the concrete. The sound but corroding areas on the deck can be detected through chain dragging and half-cell testing. Thus, in order to find out how much corrosion contributes to deterioration, one needs to know how much sound concrete will deteriorate during the period between the initial survey and the beginning of rehabilitation.

Therefore, the deterioration which should be used in the decision-making matrix is the deterioration detected by the survey plus the deterioration caused by rebar corrosion estimated to occur before rehabilitation. In the following sections a method to quantitatively determine the contribution of corrosion to deterioration is developed, and a step-by-step procedure for integrating the method into the WSDOT's bridge deck repair priority and protective system selection program is suggested.

AMOUNT OF TIME BEFORE CRACKING OCCURS IN CONCRETE

According to Bazant (35) cracking in concrete due to the expansion of corrosion products may occur basically in two different modes. When spacing (S) of the rebar is much larger than rebar diameter (D), such as

Table 8. WSDOT's Bridge Deck Repair Priority and Protection System Selection Matrix.

					Traffic Category (ADT)		
Group	Rating	Code	cl>2#/cy [1]	Deterioration [2]	>10,000 (priority)	2,000 - 10,000 (priority)	<2,000 (priority)
1	slight	8	none	<2%	3(LMC)[3]	4(LMC-AC)[4]	8(LMC-AC)
		7	none	<2%			
2	moderate	6	<20%	2-5%	6(LMC)	7(LMC-AC)	9(LMC-AC)
		5	20-40%	2-5%			
3	severe	4	40-60%	>5%	1(LMC)	2(LMC)	5(LMC)
		3	>60%	>5%			

1. Percent of chloride samples exceeding 2#/c.y.
2. Deterioration is defined as the percent of the total deck area that has spalls and/or delaminations.
3. Protection method: latex modified concrete overlay.
4. Protection method: latex modified concrete overlay or asphalt concrete and waterproofing membrane.

S > 6D, the failure occurs as two planar cracks of a 45° inclination emanating from the corroding surface (see Figure 14). For this type of failure, the increase in bar diameter (ΔD) which causes the failure is expressed in inches as

$$\Delta D = 2 f'_t \frac{L}{D} \delta pp \qquad \text{(inclined cracks) (1)}$$

in which f'_t = tensile strength of concrete in psi, L = depth of cover in inches, and δpp = bar hole flexibility in inches/psi. Bar hole flexibilityz can be expressed by (36)

$$\delta pp = [\frac{D(1 + \phi_{cr})}{E}] \quad \{ (1 + v) + D^2 [\frac{2}{S^2} + \frac{1}{4L(L + D)}]\} \qquad (2)$$

in which E = modulus of elasticity of concrete in psi, ϕ_{cr} = creep coefficient of concrete, and v = Poisson's ratio of concrete.

The failure mode discussed above applies well to the bridge deck slabs since in bridge decks rebar spacing is generally much greater than the rebar diameter. The second mode of failure, according to Bazant (35), prevails whenever

$$L > \frac{(S - D)}{2}$$

This type of failure consists of a crack which is parallel to the surface (see Figure 14). For this mode of failure the increase in bar diameter causing the cracking in the concrete is expressed as

$$\Delta D = f'_t (\frac{S}{D} - 1) \ \delta pp \qquad \text{(cracks parallel to surface) (3)}$$

The possibility of this type of failure, however, is not high for bare bridge decks designed with older specifications because of the relatively shallow depths of their cover.

The amount of time between the beginning of the corrosion activity and the development of cracking in concrete (35) is expressed as

$$T_{cr} = P_{cor} \ \frac{D \Delta D}{S \ j_r} \qquad (4)$$

in which T_{cr} = time to cracking due to rebar corrosion in years, P_{cor} = a factor determined by mass densities of steel and final conversion products, $Fe(OH)_3$, approximated at 0.130 lb/in^3; and j_r = rate of rust production per unit area of concrete in lb/in^2/year.

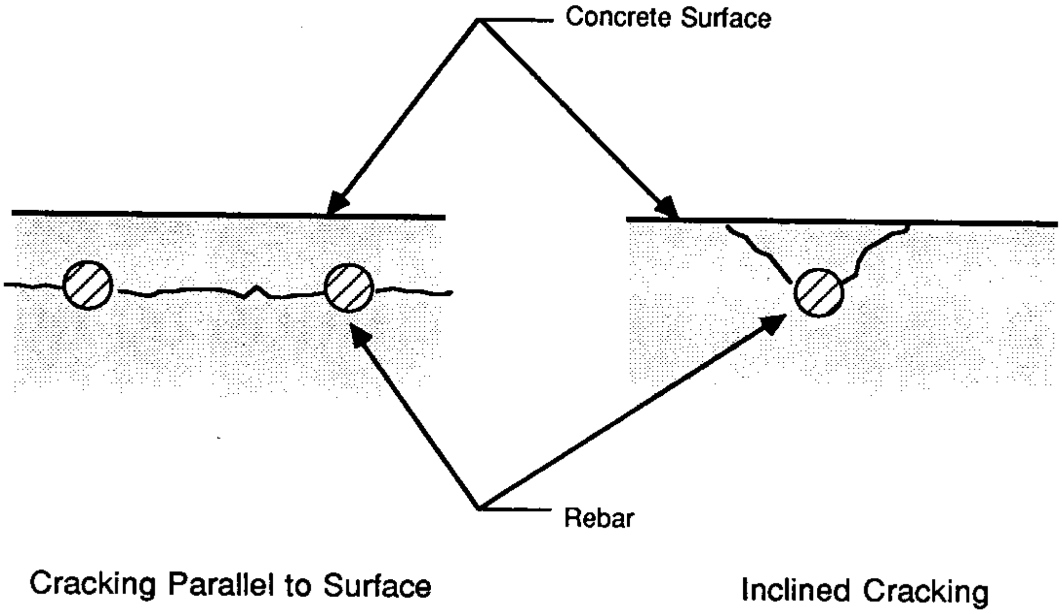


Figure 14. Modes of Concrete Cracking Due to Rebar Expansion.

T_{cr} found by Equation 4 represents time to spalling of concrete when corrosion products form quickly. However, in reality, the formation of rust and thereby ΔD is gradual. This allows evolution of the cracks and the creep behavior and buys more time to spalling than the T_{cr}. Therefore, T_{cr} found by Equation 4 will likely represent delaminations rather than spalling.

SIGNIFICANCE OF FACTORS INFLUENCING THE AMOUNT OF TIME BEFORE CRACKING BEGINS

Finding the amount of time before cracking begins in concrete can be solved from Equation (4) by estimating ΔD from Equation (1):

$$T_{cr} = 2\, P_{cor} \frac{f'_t \; L}{S \; j_r} \; \delta pp \qquad (5)$$

From Equation (5), the amount of time before cracking begins (T_{cr}) increases when

- the tensile strength of concrete (f't) is increased,
- the depth of cover (L) is increased,
- the rate of rust production per unit length of rebar (Sj_r) is decreased, and
- the bar hole flexibility (δ_{pp}) is increased.

The bar hole flexibility in turn, according to Equation (2), increases when

- the creep coefficient of concrete (ϕ_{cr}) is increased,
- the modulus of elasticity of concrete (E) is decreased,
- the Poisson's ratio of concrete is increased, and
- the rebar diameter is increased (increasing rebar diameter, however, can increase the rate of rust production as well and decrease the amount of time before cracking begins).

For a typical concrete bridge deck supported by longitudinal girders, the following assumptions may be made (36):

f't = 500 psi (3.45 Mpa)

E = 3×10^6 psi (2.07×10^4 Mpa)

S = 6 inches (15 cm.)

D = #5 rebar, 5/8 inch (1.59 cm.)

ϕ_{cr} = 2

v = 0.18

P_{cor} = 0.130 lb/in^3 (3.6 g/cm^3)

Using the above data, δpp and T_{cr} can be solved from equations 2 and 5, respectively.

$$\delta pp = [\, 0.751 + \frac{0.098}{L\,(L + 0.625)} \,] \times 10^{-6} \tag{6}$$

The second term in the bracket of Equation 6 is relatively small for normal values for bridge deck rebar depth of cover (L). δpp for L = 1.5 inches (3.81 cm), the average rebar depth of cover for most of the existing decks, is 0.782 x 10^{-6} inches/psi (2.89 x 10^{-4} cm/Mpa). Substituting this value of δpp and the other data in Equation 5 gives

$$T_{cr} = 0.169 \times 10^{-4} \; \frac{L}{j_r} \tag{7}$$

Equation 7 is valid when the contribution to deterioration, from a concentration of wheel load stresses at the evolving cracks, is ignored. Research in the past has not covered the impact of traffic on the progression of deterioration in bridge decks. Also, the propagation of cracks around the rebar and in the concrete can greatly accelerate the corrosion activity by intensifying the penetration of oxygen, chlorides, or moisture into the concrete. A finite element modeling technique in the concrete may be employed to reveal the impact of traffic on concrete deterioration. Note that the modeling of concrete cracking due to rebar expansion discussed here is based on the elastic behavior of corrosion products. However, an inelastic behavior can result in a larger amount of time until cracking begins (T_{cr}) than that obtained from Equation 5 or 7. Thus, the modeling presented may compensate for the impact of traffic flow.

DETERMINATION OF THE AMOUNT OF TIME BEFORE CRACKING BEGINS

There is little information in the literature regarding the rate of corrosion of steel in concrete bridge decks. The value of the rate of rust production in chloride contaminated concrete was assumed to be 0.017 x 10^{-3} lb/inch^2 per year (1.2 x 10^{-3} g/cm^2/year) in one study (36). The rate of corrosion of steel in concrete, however, can vary with variations in a concrete's chloride content. This is evident from the data obtained in an experiment by FHWA, discussed below.

Research conducted in FHWA laboratories (9) measured the average corrosion content in slabs 2 feet by 5 feet (61 cm. by 152 cm.) containing two mats of reinforcing steel (uncoated) with a clear concrete thickness of 3/4 inch (1.9 cm.) and 1-3/8 inches (3.5 cm.) over the top mat rebar and between the two mats, respectively. Concrete surrounding the top mat contained specific amount of chlorides, in the range of 0 to 35 lb/c.y. (0 to 21 kg/m^3), dissolved in the mix water. To ensure that a highly corrosive environment existed the slabs were continuously ponded with a 3 percent sodium chloride solution for 46 days, the time needed to initiate corrosion in a control slab with no original chloride content. The slabs were exposed to an outdoor environment for about one year. The corrosion current between the top and bottom mat rebar was measured periodically and was adjusted for 70°F (21°C) concrete resistivity. The FHWA study obtained the following equation for the average weighted 70°F (21°C) corrosion current of a slab and its chloride content.

$$\text{Corrosion Current } (\mu\text{A}) = 473\ (\bar{\text{cl}}\ (\text{lb/c.y.}) - 1.8) \tag{8}$$

This author has converted the corrosion current in Equation 8 into rate of rust production per an FHWA slab unit area (in^2) per year by knowing that 1.0 amp of corrosion current consumes 2.29 x 10^{-3} lb (1.04 g) of iron every hour (9) and that the mass of steel consumed is 0.523 times the mass of rust produced (35).

$$\text{Rate of rust production } (\text{lb/in}^2\text{/yr}) = 12.599 \times 10^{-6}\ (\bar{\text{cl}}\ (\text{lb/c.y.}) - 1.8) \tag{9}$$

A plot of Equation 9 is given in Figure 15. As may be seen in the figure, the rate of rust production per unit area of slab per year for the experimental slabs increases linearly with an increase in chloride content.

The rate of rust production given in Equation 9 corresponds to the top mat rebar, which includes rebar in both directions. However, j_r (see Equation 7) corresponds only to the uppermost rebar. In the FHWA slabs the ratio of uppermost rebar to the top mat rebar was about 0.80. Thus, the rate of rust production corresponding to the upper most rebar (j_r), in the FHWA slabs is

$$j_r = (0.80) \times [12.599 \times 10^{-6}\ (\bar{\text{cl}}\ (\text{lb/c.y.}) - 1.8)] \tag{10}$$

The j_r = 0.017 x 10^{-3} lb/in^2/year (1.2 x 10^{-3} g/cm^2/yr) suggested for bridge decks in the literature (36), corresponds to a 3.50 lb/c.y. (2.06 kg/m^3) chloride content, according to Equation 10, which is reasonable.

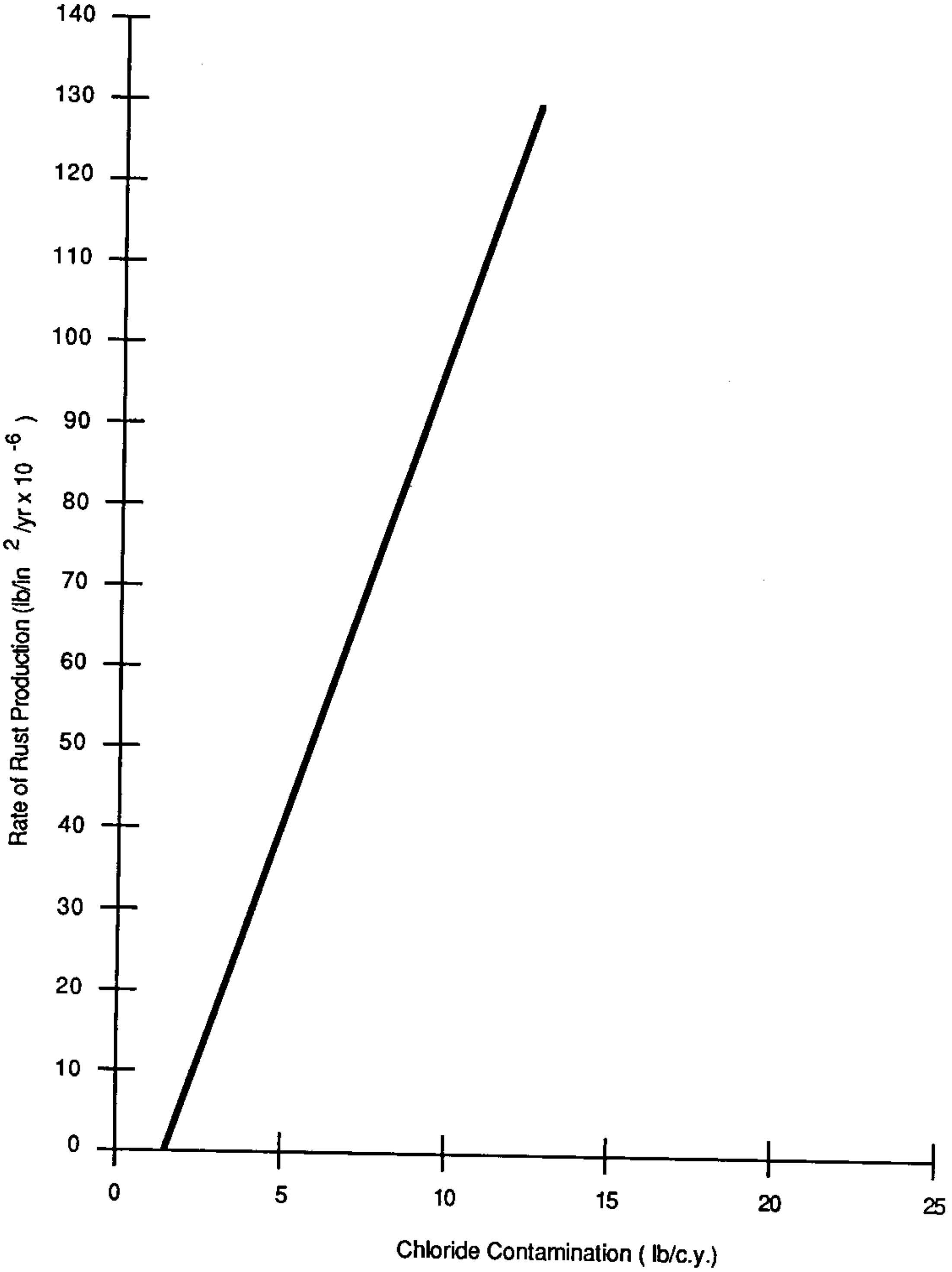


Figure 15. Relation between Chloride Content and Metal Consumed by Corrosion (Adapted from Ref. 9).

By using the values of j_r determined from Equation 10 in Equation 7, the amount of time before cracking (T_{cr}) can be obtained for the depth of cover (L):

$$T_{cr} = \frac{1.68\ L}{(\overline{cl} - 1.8)} \tag{11}$$

in which T_{cr} is in years, $\overline{cl}$ is in lb/c.y., and L is in inches.

PREDICTION OF THE AMOUNT OF CRACKING IN CONCRETE THAT WILL OCCUR BEFORE REHABILITATION

Solving Equation 11 for depth of cover will give

$$L = \frac{(\overline{cl} - 1.8)}{1.68} T_{cr} \tag{12}$$

If the period of time between the initial survey and the bridge deck rehabilitation (T_{reh}) is known, one can find from Equation 12 the depth of cover which may allow concrete cracking due to corrosion before rehabilitation takes place. This value for the depth of cover will be the maximum depth of cover (L_{max}) which may result in cracking. In other words, any concrete associated with a depth of cover smaller than or equal to L_{max} may possibly crack before rehabilitation because of corrosion. L_{max} is determined as follows:

$$L_{max} = \frac{(\overline{cl} - 1.8)}{1.68} T_{reh} \tag{13}$$

in which L_{max} is in inches, $\overline{cl}$ is in lb/c.y., and T_{reh} is in years. If the value of L_{max} exceeds

$$\frac{S - D}{2} = 2.69 \text{ inches (6.83 cm.)}$$

(see the assumption on page 51), the type of cracking in a concrete with L > 2.69 inches (6.83 cm.) will be parallel to the surface (see Figure 14) and the amount of time before cracking occurs will no longer depend on the depth of the cover thickness (see Equations 3 and 4). In this case, usually T_{reh} exceeds T_{cr} for the type of parallel cracking obtained from Equation 4. Therefore, when L_{max} from Equation 13 is larger than 2.69 inches (6.83 cm.), all of the concrete in the corroding area may crack by the time rehabilitation begins, regardless of the thickness of the rebar cover. This provision will mainly be of use for decks built with cover depths > 2.69 inches (6.83 cm.). However, in Washington the older specifications required a 1.5-inch (3.81 cm.) clear depth of cover in bridge decks, and the possibility of a depth of cover larger than 2.69 inches (6.83 cm.) in any section of these bridge decks is almost nonexistent.

WSDOT's bridge deck survey program includes detection of

1. the half-cell potential, detected at grid points,
2. the depth of cover, detected at grid points,
3. deteriorated concrete areas, through chain dragging and mapping, and
4. the chloride content at the rebar level, with one sample per 750 square feet (70 m^2) of deck area.

Thus, the corroding but sound areas in a bridge deck and their corresponding cover depth are detected when surveying the deck. Any corroding but sound area with a rebar depth smaller than or equal to L_{max} may possibly crack within the period of time between the survey and the rehabilitation (T_{reh}). L_{max} can be found for decks supported on longitudinal girders from Equation 13 by using the average rebar level chloride content of the bridge deck (or preferably the average rebar level chloride content of the corroding areas of the bridge deck).

However, some areas with cover depth larger than L_{max} might have been corroding prior to the survey and, therefore, may crack before rehabilitation occurs, adding to the estimation of cracked concrete before rehabilitation. In order to account for the latter, the corroding but sound areas can be divided into two groups as follows:

1. presently corroding areas which did not show corrosion in the previous survey, and
2. presently corroding areas which did show corrosion in the previous survey.

Each group can be treated separately to determine L_{max}. For the first group, T_{reh} will be the amount of time between the survey and rehabilitation. For the second group, T_{reh} will be the amount of time between the previous survey and rehabilitation.

A STEP-BY-STEP PROCEDURE FOR INCORPORATING HALF-CELL DATA INTO WSDOT'S BRIDGE DECK REPAIR PRIORITY PROGRAM

Using the methods developed and presented in this work, the author suggests the following step-by-step procedure for incorporating the half-cell data into the WSDOT's repair priority and protective system selection program.

Step 1 Determine T_{reh}, the period of time between the most recent bridge deck survey and the projected rehabilitation for the bridge deck.

Step 2 Determine T_s, the amount of time between the most recent bridge deck survey and the survey prior to that, if a previous survey existed.

Step 3 Determine A_{cor}, the sound concrete areas in the bridge deck with half-cell potentials more negative than -0.350 V which had half-cell potentials less negative than -0.350 V in the previous survey. A_{cor} is a percentage of total deck area. If a previous survey did not exist, assume that all of the previous potentials were less negative than -0.350 V for the presently sound concrete. This will make A_{cor} equal to the percentage of all of the sound but presently corroding areas. Note also that the threshold corrosion potential of -0.350 V may be modified in the presence of more information.

Step 4 Determine A'_{cor}, the sound concrete areas on the bridge deck with half-cell potentials more negative than -0.350 V which also had half-cell potentials more negative than -0.350 V in the previous survey. A'_{cor} is a percentage of total deck area. If a previous survey did not exist, assume that all of the previous potentials were less negative than -0.350 V for the presently sound concrete. This will make A'_{cor} equal to 0 percent.

Step 5 Determine L_{max} and L'_{max} (the maximum depth of cover that is subject to cracking before rehabilitation) corresponding to A_{cor} and A'_{cor}, respectively, as follows:

$$L_{max} = \frac{(\overline{cl} - 1.8)}{1.68} T_{reh}$$

$$L'_{max} = \frac{(\overline{cl} - 1.8)}{1.68} (T_{reh} + T_s)$$

in which L_{max} and L'_{max} are in terms of inches and T_{reh} and T_s are in term of years. cl is the average rebar level chloride content of the bridge deck (or preferably the average rebar level chloride content of the corroding areas of the bridge deck) found by the most recent survey. If a previous survey did not exist, determine only L_{max}.

If the deck is not a typical structure supported by longitudinal girders, such as a concrete slab bridge, Equations 1, 2, 3, 4, and 10 may be used for determining L_{max} and L'_{max} more accurately.

Step 6 Determine P and/or P', the percentage of area with a depth of cover smaller than or equal to L_{max} and L'_{max} and corresponding to A_{cor} and A'_{cor}, respectively. If L_{max} and/or L'_{max} is greater than 2.69 inches, P and/or P' will be 100 percent. If a previous survey did not exist, P' does not need to be determined.

Step 7 Determine A_{det}, the additional deterioration which may occur before rehabilitation, based on the percentage of deck area as follows:

$$A_{det} = P\,(A_{cor}) + P'\,(A'_{cor})$$

Step 8 Add A_{det} to the percentage of deterioration detected by the most recent bridge deck survey and use it as bridge deck deterioration in the WSDOT's bridge deck repair priority and protective system selection matrix (see Table 8 for the matrix).

Step 9 Determine the priority for the rehabilitation and the type of protection from the matrix, based on the extent of chloride contamination, deterioration and average daily traffic.

CASE STUDY

Assume that a typical concrete bridge deck supported by longitudinal girders was surveyed twice, in April 1983 and April 1985. The rehabilitation is projected to occur in July 1986. The ADT on this bridge is 7000.

Step 1 $T_{reh} = \dfrac{15 \text{ mos.}}{12} = 1.25 \text{ yrs.}$

Step 2 $T_s = \dfrac{24 \text{ mos.}}{12} = 2 \text{ yrs.}$

The 1985 survey shows that the sound areas of the deck with half-cell potentials more negative than -0.350 V comprise 5 percent of the deck area. The 1983 survey shows that one-third of the 1985 corroding but sound areas had potentials more negative than -0.350 V in that survey.

Steps 3 and 4

$A_{cor} = (5\%) - 1/3(5\%) = 3.33\%$ of deck area

$A'_{cor} = 1/3(5\%) = 1.67\%$ of deck area

The 1985 survey also indicates that the average rebar level chloride content of the deck is 3.5 lb/c.y. The percent of chloride samples exceeding 2 lb/c.y. is 30 percent.

Step 5

$$L_{max} = \frac{(\overline{cl} - 1.8)}{1.68} T_{reh}$$

$$= \frac{(3.5 - 1.8)}{1.68} \text{ x } 1.25 = 1.26 \text{ in.}$$

$$L'_{max} = \frac{(\overline{cl} - 1.8)}{1.68} (T_{reh} + T_s)$$

$$= \frac{(3.5 - 1.8)}{1.68} \text{ x } (1.25 + 2) = 3.29 \text{ in.}$$

Step 6

$L'_{max} = 3.29$ inches > 2.69 inches $\Rightarrow$ $P' = 100\%$

$L_{max} = 1.26$ inches < 2.69 inches

The depth of cover survey corresponding to A_{cor} shows that 35 percent of depth of cover in that area is $\leq L_{max} = 1.26$ inches. Therefore, $P = 35$ percent.

Step 7

$$A_{det} = P\,(A_{cor}) + P'\,(A'_{cor})$$

$$= 35\ \%\ (3.33\%) + 100\%\ (1.67\%)$$

$$= 1.17\% + 1.67\% = 2.84\% \approx 3\% \text{ of deck area}$$

The 1985 survey shows that the deteriorated areas in the deck comprise 4 percent of the deck area.

Step 8 The estimate of deterioration before rehabilitation takes place = 4 percent + 3 percent = 7 percent of the deck area.

Step 9 Using the deterioration of 7 percent found in Step 8 and ADT of 7000, the priority for the rehabilitation and the type of the protective system from the WSDOT bridge deck rehabilitation/protection matrix (see Table 8) will be 2 and latex-modified concrete overlay, respectively. If the half-cell potentials were not incorporated into the matrix, according to Table 8, the priority would be 7 and the type of protection would be either latex-modified concrete or water-proofing membrane.

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