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Sensitivity of Half-Cell Potential Measurements to Properties of Concrete Bridge Decks

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SENSITIVITY OF HALF-CELL POTENTIAL

MEASUREMENTS TO PROPERTIES

OF CONCRETE BRIDGE DECKS

by

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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ABSTRACT

SENSITIVITY OF HALF-CELL POTENTIAL

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Half-cell potential testing has been recommended as a non-destructive method for assessing the corrosion potential of reinforcing steel in concrete bridge decks. The technique is particularly useful because it can be utilized to evaluate the probability of corrosion before damage is evident at the surface of a bridge deck. The specific objective of this research was to quantify the effects of age, chloride concentration, concrete cover thickness, spatial position, temperature, and presence or condition of epoxy coating on half-cell potential measurements of concrete bridge decks typical of those in Utah.

The laboratory testing associated with this research followed a full-factorial experimental design. Nine rectangular concrete slab specimens were prepared, each containing three black reinforcing steel bars at three different concrete cover depths and four epoxy-coated bars each having different coating conditions. Three replicate slabs were created at each of three different chloride concentrations. Three repeated measurements were made at each of three locations along each of the seven bars in all nine of the slabs at three ages, with testing performed at three temperatures per age. In

addition, compressive strengths of the concrete cylinders were measured at 7 and 28 days. Statistical analyses of the half-cell potentials were performed using analysis of variation and Tukey's method for multiple comparisons.

Although American Society for Testing and Materials C 876 only specifies the measuring of half-cell potentials of uncoated reinforcing steel, credible half-cell potentials were also obtained for epoxy-coated rebar in this research. The results of the testing indicated that all of the factors except for cover thickness and spatial position have important impacts on half-cell potentials over the ranges of levels investigated in this research. Half-cell potential measurements became consistently less negative with increasing age and consistently more negative with increasing chloride concentrations and increasing temperature. With regard to the factor of treatment, the uncoated rebar had the most negative half-cell potential, followed by epoxy-coated rebar with rib scrapes, pliers strikes, end cuts, and full epoxy coatings, in that order. While these data indicate that a coating, even damaged, reduces the probability of corrosion when compared to uncoated rebar, the data also suggest that both the amount and distribution of the coating damage over the affected rebar influence corrosion.

Given these research findings, bridge engineers and managers should have confidence in using half-cell potential testing for assessing the corrosion probability of reinforcing steel in concrete bridge decks. In decks with properties similar to those investigated in this research, variations in age, chloride concentration, temperature, and presence or condition of epoxy coating cause variation in half-cell potential readings consistent with the effects of these factors on corrosion. Therefore, the half-cell potential technique is recommended for assessing the probability of corrosion of reinforcing steel on bridge decks.

Although the use of epoxy-coated reinforcement, even when damaged, reduces the probability of corrosion, care should still be taken to minimize any damage to the coating during shipping and field handling. Owners and contractors alike should establish appropriate inspection protocols and repair methods for epoxy-coated reinforcing steel used on bridge decks to ensure maximum service life.

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CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT

In cold regions such as Utah, the distribution of deicing salts during winter is necessary to ensure adequate skid resistance on bridge decks. However, routine applications of deicing salts inevitably lead to chloride accumulations within concrete bridge decks; the salts diffuse into the concrete over time and ultimately cause corrosion of the reinforcing steel, a primary mechanism of deck deterioration (*1*).

Bridge engineers and managers most anxious to preserve affected structures will program preventive maintenance treatments before chloride concentrations exceed the generally accepted critical value of 2 lb of chloride per cubic yard of concrete in the vicinity of the reinforcing steel. At this level, corrosion of exposed reinforcement is initiated, certain maintenance and rehabilitation treatments may no longer be effective, and the service life of the bridge deck becomes uncertain (*1*). Thus, understanding the condition of the reinforcement within the concrete is helpful to bridge engineers and managers responsible for programming deck maintenance and rehabilitation treatments.

Although frequent visual inspections of bridge decks are performed by most agencies, visual evidence of deterioration may not be manifest for several years after the onset of corrosion, therefore requiring the use of other procedures for deck evaluation. In particular, half-cell potential testing has been recommended by previous researchers for this purpose (*2*). Half-cell potential testing is a non-destructive method designed to assess the corrosion potential of reinforcing steel in concrete bridge decks and is fully described in American Society for Testing and Materials (ASTM) C 876 (Standard Test Method of Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete). The technique is particularly useful because it can be utilized to evaluate the probability of corrosion before damage is evident at the surface of a bridge deck.

The ASTM C 876 standard, however, does not address the impact of some aspects of testing, including specific deck properties, that may influence half-cell potential measurements. Furthermore, the standard does not admit the possibility of testing concrete bridge decks reinforced with epoxy-coated steel, although previous researchers have successfully employed the method on such decks (*2*). Therefore, additional research on the sensitivity of half-cell potential measurements was needed. The specific objective of this research was to quantify the effects of age, chloride concentration, concrete cover thickness, spatial position, temperature, and presence or condition of epoxy coating on half-cell potential measurements of concrete bridge decks typical of those in Utah.

1.2 SCOPE

This research consisted primarily of laboratory testing. Nine slab specimens, each having a thickness of 5.5 in. and side lengths of 18 in. and 22 in., were prepared and tested at the Brigham Young University (BYU) Highway Materials Laboratory. Each of the nine specimens contained three uncoated reinforcing bars, also known as black bar, cast at three different depths, as well as four epoxy-coated bars each having different coating conditions. The three concrete cover depths, or thicknesses of concrete above the top of the reinforcing steel, were 2.0, 2.5, and 3.0 in., and the four coating conditions included a fully intact coating, an exposed end cut, a pliers strike, and a rib scrape. Three levels of chlorides, 0, 2, and 4 lb of chloride per cubic yard of concrete, were introduced during mixing of the concrete and were cast in place. Three replicate slabs were created at each chloride concentration.

Half-cell potential measurements were recorded for each slab at three different temperatures, namely, 60, 80, and 100°F, at each of three ages, including 28, 56, and 90 days from the time of placement. The effect of spatial position along each rebar was also evaluated. Finally, the 7- and 28-day compressive strengths of concrete cylinders cast during slab preparation were also measured and analyzed.

1.3 OUTLINE OF REPORT

This report contains five chapters. Chapter 1 presents the objectives and scope of the research. In Chapter 2, the results of a literature review addressing corrosion and the use of half-cell potentials for determining the probability of rebar corrosion are presented. Descriptions of the experimental plan, laboratory testing procedures, and statistical analyses are given in Chapter 3. The results from testing and the statistical analyses are explained in Chapter 4 together with a discussion of the research findings. In Chapter 5, summaries of the procedures, research findings, and recommendations are presented.

CHAPTER 2
BACKGROUND

2.1 OVERVIEW

The following sections present the findings of a literature review focused on the mechanism of steel corrosion in reinforced concrete bridge decks and the use of half-cell potentials to evaluate the probability of such corrosion.

2.2 CORROSION OF DECK REINFORCEMENT

Concrete has long been utilized in the building of bridge decks due to its workability while in its uncured state and its durability and high compressive strength (*3*). Due to its relatively low tensile strength, however, concrete must be reinforced when it is exposed to tensile forces. With the addition of reinforcing steel, the tensile capacity of concrete is greatly increased (*4*). Nonetheless, in certain environmental conditions, the reinforcing steel can begin to corrode. Corrosion is especially paramount in areas where chlorides are prevalent, primarily coastal regions and cold regions where deicing salts are used as part of regular winter roadway maintenance (*5*). As chlorides diffuse into the concrete and accumulate at levels exceeding the threshold value of 2 lb of chloride per cubic yard of concrete in the vicinity of the reinforcing steel, the formation of corrosion products generates expansive forces within the concrete that inevitably lead to concrete cracking, delamination, spalling, and other forms of distress (*6*, *7*).

In order for corrosion of the rebar to occur, both moisture and oxygen must be present. The presence of water and oxygen does not guarantee that corrosion will occur, however; the highly alkaline environment that exists in concrete, a pH greater than 13.0, facilitates the formation of a passive oxide film on the surface of the steel that prevents oxygen and moisture from reacting with the metal surface, thus preventing corrosion from occurring (*3*). However, because the passivity of the steel is destroyed in the presence of elevated concentrations of chloride ions in the concrete (*8*), other techniques, such as the use of epoxy coatings, have been employed to protect the reinforcing steel (*9*). The purposes of an epoxy coating on rebar are to interrupt the corrosion circuit by preventing current from entering or exiting the steel and to prevent chloride ions from coming in contact with the surface of the rebar (*10*). A continuous, undamaged epoxy coating applied in accordance with ASTM A 775 (Standard Specification for Epoxy-Coated Steel Reinforcing Bars) and ASTM D 3963 (Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Steel Reinforcing Bars) will therefore increase the service life of the reinforcing steel.

The protection provided by the epoxy coating is reduced, however, when the coating is damaged during shipping and/or field handling (*10*). Corrosion of the reinforcing steel can begin even before the concrete has been placed, as illustrated in Figure 2.1 showing an unrepaired end cut; this picture was taken by W. S. Guthrie during a scanning tour in Colorado (*11*). Provided by a local epoxy coating manufacturer, Figures 2.2 and 2.3 show two common forms of field damage to epoxy-coated rebar at a job site. The damage in Figure 2.2 resulted from pliers being used to strike down tie

FIGURE 2.1 End cut damage in the field.

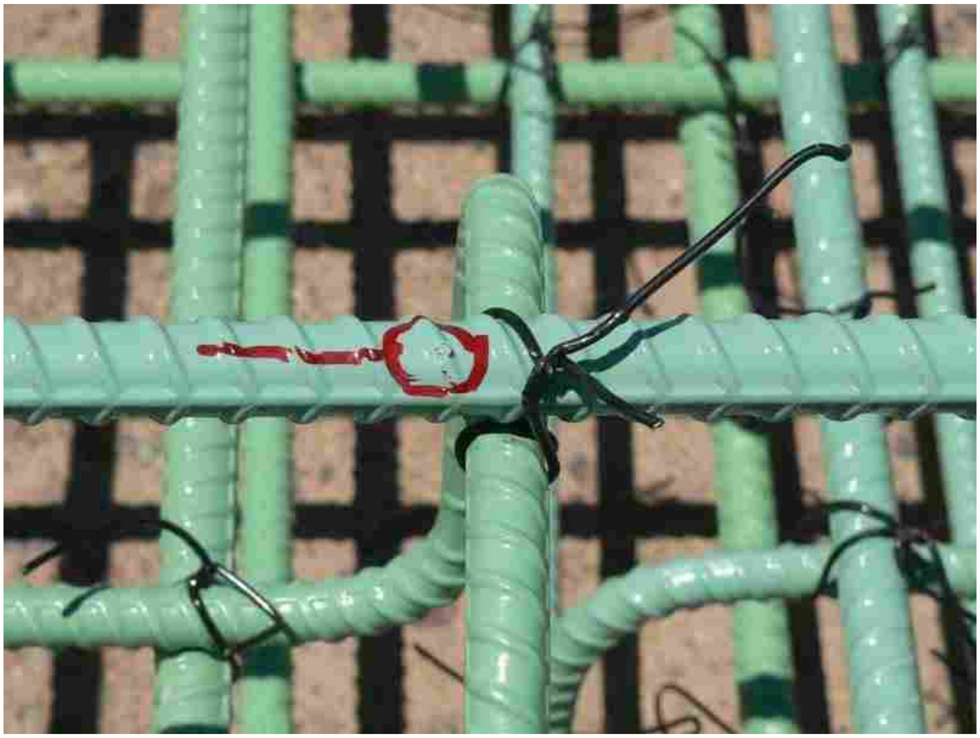


FIGURE 2.2 Pliers strike damage in the field.

FIGURE 2.3 Rib scrape damage in the field.

wires, while the damage in Figure 2.3, a rib scrape, probably resulted from improper unloading and/or other mishandling of the rebar. Although epoxy-coated rebar has proven to provide substantially improved performance compared to black bar, it does require careful handling (*6*). Locations of damage in the coating can become highly active corrosion sites (*12*).

2.3 HALF-CELL POTENTIAL TESTING OF DECK REINFORCEMENT

Confidence in using half-cell potentials as an indication of corrosion potential has developed from the success of bridge deck corrosion surveys (*13*). As a result, potential surveys are now commonly conducted on bridges, garages, water tanks, pre-cast concrete tunnel liners, and many other structures (*14*). Half-cell potential measurements provide a classification of the corrosion activity of the steel and indicate locations where the steel is potentially corroding (*8*), although potentials cannot be used to estimate the rate of corrosion of the steel or the condition of the concrete (*15*, *16*).

As shown in Figure 2.4, a half-cell potential measurement apparatus consists of a voltmeter with one lead connected to a reference electrode, normally a copper copper-sulfate ($Cu/CuSO_4$) electrode, placed on the surface of the concrete and a second lead connecting the voltmeter to the reinforcing steel (*13*). Current passes from the reference electrode to the concrete surface through a sponge soaked with an electrolytic solution (*17*). The objective of the instrumentation is to measure the voltage, or potential difference, between the rebar and the reference electrode (*17*). In the half-cell potential setup, the reference electrode behaves as the cathode, as copper is higher in the galvanic series than steel (*18*).

Through the circuit created, the potential difference is measured. With the reference electrode acting as the cathode and being connected to the positive terminal of the voltmeter, measured half-cell potentials have a negative value. A half-cell potential measurement results from the multiplication of the reinforcement corrosion potential by the ratio of the internal resistance of the voltmeter to the sum of the internal resistance of the voltmeter and the resistance of the concrete (*13*). A schematic of the test circuit is shown in Figure 2.5.

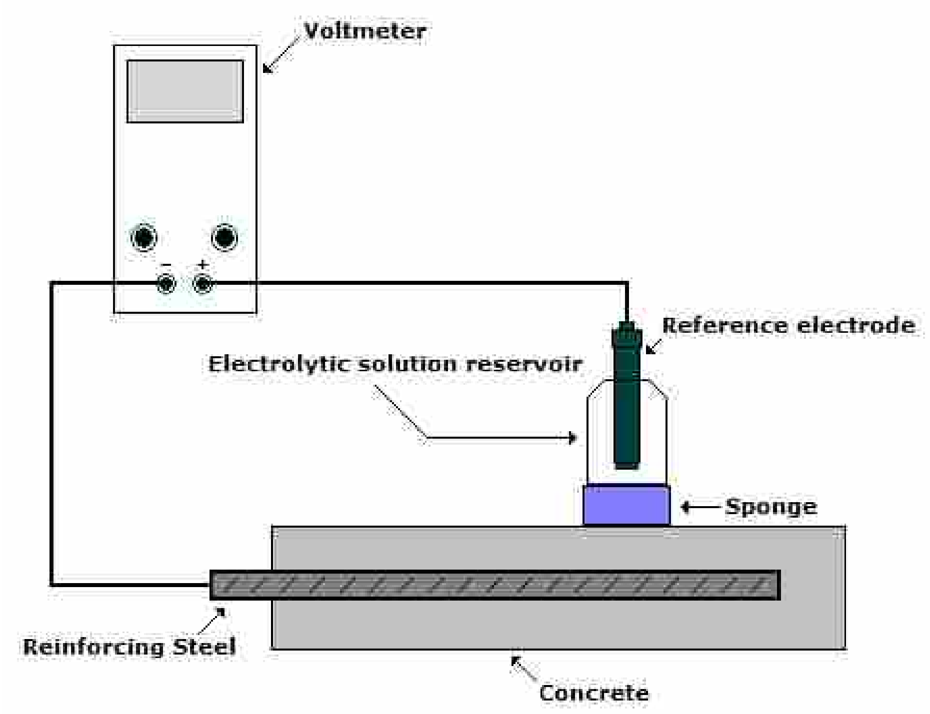


FIGURE 2.4 Half-cell potential apparatus.

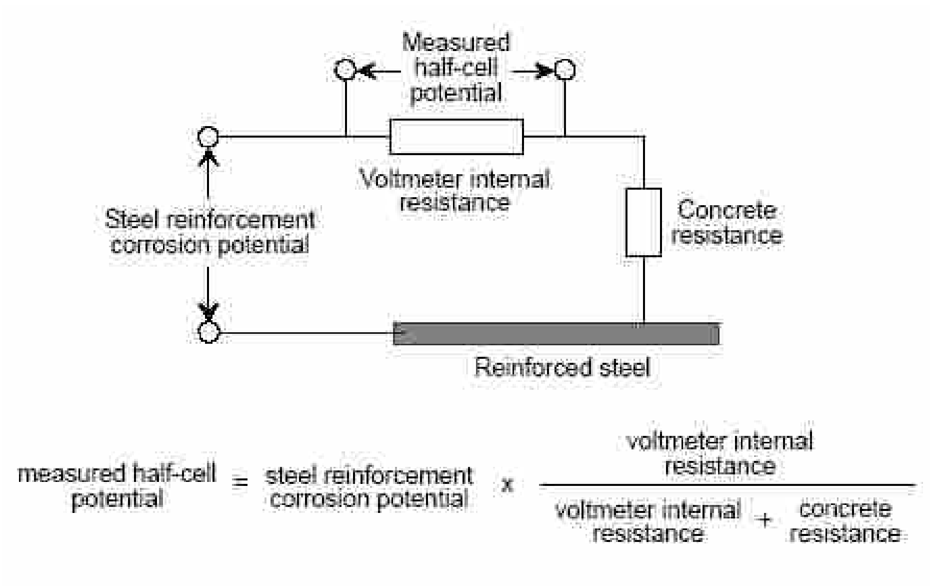


FIGURE 2.5 Schematic of the half-cell measurement circuit (*13*).

A wide range of factors influence corrosion potentials, including concrete moisture content, oxygen content, chloride concentration, concrete cover thickness, temperature, and presence or condition of epoxy coating (*19*). In order to reduce the occurrence of half-cell potentials that are erroneously low in magnitude, or incorrectly shifted toward less negative readings, the surface of the concrete should be wetted prior to testing. Wetting the concrete surface reduces the resistance of the concrete (*16*). A low oxygen concentration at the concrete-steel interface may result in a significant increase in the negativity of the half-cell potential measurement, which does not accurately reflect the actual corrosion status of the steel (*13*). As the concentration of chloride ions increases, the rate at which the reinforcing steel corrodes significantly increases, resulting in a shift toward more negative half-cell potential readings (*13*). A greater concrete cover thickness increases the potential for greater concrete resistance, thereby creating a shift toward less negative half-cell potential readings (*13*). Table 2.1 presents the relationship given in ASTM C 876 between the half-cell potential value, reported in volts, and the probability of steel corrosion.

Authentic and stable half-cell readings may not be achievable when the rebar has a continuous, undamaged epoxy coating applied in accordance with specifications because of the inability to measure current flow in the half-cell potential circuit. However, a stable reading may be obtained in situations in which the rebar is characterized by coating defects, damage, or unprotected rebar ends (*6*, *13*); in these cases, half-cell potential measurements obtained from epoxy-coated bars are just as useful for indicating areas of relative corrosion activity as those obtained from black bar (*20*). Indeed, the chloride concentration threshold for damaged epoxy-coated bars has been found to be similar to that established for black bars (*14*, *21*).

Damaged areas of the epoxy coating provide localized points of access for chloride ions, thus leading to corrosion and subsequent deterioration of the concrete/rebar bond (*10*). For this reason, recent research has brought into question the ability of epoxy coatings to provide long-term corrosion protection to the reinforcing steel in concrete

TABLE 2.1 Probability of Corrosion According to a Copper Copper-Sulfate Half-Cell

Half-Cell Potential	Corrosion Activity
Less negative than -0.20 V	90% probability of no corrosion
Between -0.20 and -0.35 V	Uncertain corrosion activity
More negative than -0.35 V	90% probability of corrosion

exposed to chlorides (*7*). This lack of protection has been attributed to the number and size of breaks or defects in the epoxy coating (*22*). When damaged coatings are identified during construction, a two-part epoxy compound is often applied as a patch to the affected areas, but this product has been found to be far less effective in adhering to and protecting the reinforcing steel than fusion-bonded epoxy coatings (*9*).

2.4 SUMMARY

Corrosion is the leading cause of service-life reductions in steel-reinforced concrete structures. Especially in coastal areas and cold regions where deicing salts are used as part of regular winter roadway maintenance, accumulation of chlorides in the vicinity of the reinforcing steel is the leading cause of corrosion. Although intact epoxy coatings can protect rebar from corrosion by eliminating potential contact with chlorides, epoxy-coated steel requires careful handling to prevent damage. The probability of steel corrosion can be evaluated using half-cell potential testing, in which the potential difference between the rebar and a reference electrode is measured non-destructively. The technique is particularly useful because it can be utilized to evaluate the probability of corrosion before damage is evident at the surface of a bridge deck. Half-cell potential measurements are influenced by concrete moisture content, oxygen content, chloride concentration, concrete cover thickness, temperature, and presence or condition of epoxy coating. Quantifying the variability in half-cell potential measurements to specific properties of concrete bridge decks was the purpose of this research.

CHAPTER 3
PROCEDURES

3.1 OVERVIEW

The sensitivity of half-cell potential measurements to properties of concrete bridge decks was investigated in this research through a full-factorial experimental design. Details associated with the experimental design, specimen preparation, testing, and data analyses are provided in the following sections.

3.2 EXPERIMENTAL DESIGN

The full-factorial experimental design utilized in this research involved several factors, including age, chloride concentration, concrete cover thickness, spatial position, temperature, and presence or condition of epoxy coating. Each of the nine specimens created for this research consisted of a rectangular concrete slab containing seven lengths of reinforcing steel.

Each specimen contained three black bars and four epoxy-coated bars. The three black bars were given individual concrete cover thicknesses of 2.0, 2.5, and 3.0 in., while all of the epoxy-coated bars were given a concrete cover thickness of 2.5 in. The first of the four epoxy-coated bars in each specimen consisted of a fully epoxy-coated bar with an end cut that had been repaired with a two-part epoxy patch; no visible defects or damage were evident in these bars. The second bar in each specimen also consisted of a fully epoxy-coated bar with an end cut; however, in this case the end was left unrepaired. Similar to the first bar, the third and fourth bars had repaired end cuts, but they were given a specific number of defects in the epoxy coating to simulate pliers strikes and rib scrapes, respectively.

Three levels of chloride concentration were specified in the research to simulate bridge decks contaminated to various degrees with deicing salts. Sodium chloride was introduced during the concrete mixing process for six of the nine specimens. The three remaining specimens did not contain any chlorides. Three of the six specimens containing chlorides had 2 lb of chloride per cubic yard of concrete, which is the threshold at which steel corrosion is expected to begin (*1*), while the other three specimens containing chlorides had 4 lb of chloride per cubic yard of concrete. Although this latter value is double the threshold value, it is still readily achieved by concrete bridge decks in Utah. Previous research has shown that decks have attained chloride concentrations in excess of 17 lb of chloride per cubic yard of concrete in the vicinity of the top mat of reinforcing steel after just 16 years of service (*2*).

Three half-cell potential measurements were recorded at three locations along each bar at temperatures of 60, 80, and 100°F for concrete ages of 28, 56, 90 days. Measurements along each bar provided for the evaluation of the effect of spatial position, or location from the connection to the steel, on half-cell potentials.

3.3 SPECIMEN PREPARATION

All bars utilized in this research were 18-in lengths of No. 5 rebar, each having a diameter of 0.625 in. and a cross-sectional area of 0.3 in^2. Epoxy coating of some of the bars, including end patching where required, was performed by Western Coating personnel in accordance with current industry standards. End patching was performed using a two-part epoxy patch material. The bars were then carefully packaged and transported to the BYU Highway Materials Laboratory for testing in this research.

An epoxy-coated bar with a repaired end cut is shown in Figure 3.1, while an epoxy-coated bar with an end cut that has not been repaired is depicted in Figure 3.2. Epoxy-coated bars subjected to pliers strikes and rib scrapes are shown in Figures 3.3 and 3.4, respectively.

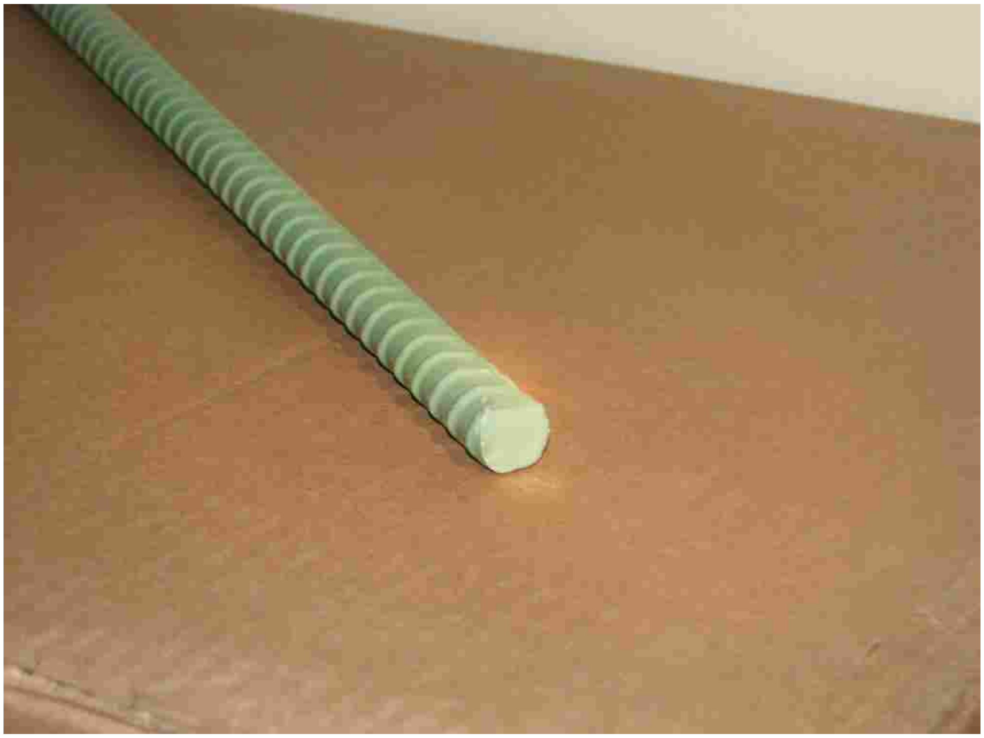


FIGURE 3.1 Epoxy-coated rebar with repaired end cut.

FIGURE 3.2 Epoxy-coated rebar with end cut not repaired.

FIGURE 3.3 Epoxy-coated rebar with damage from pliers strike.

FIGURE 3.4 Epoxy-coated rebar with damage from rib scrape.

At BYU, 18 of the epoxy-coated bars with end patches were subjected to two types of damage. Nine of the bars were struck with the tip of a pair of bull-nosed pliers in two locations spaced 12 in. apart to simulate the damage that occurs in the field when steel workers accidentally strike the epoxy coating while bending over tie wires. The other nine bars were subjected to rib scraping along a 12-in. length to simulate the damage that occurs in the field when the rebar is dragged against the side rail of a truck bed during the unloading process. In this research, removal of the epoxy coating at each of the ribs was accomplished by scraping the bar against a piece of angle iron clamped to a laboratory bench. The damaged ribs were then filed where needed to ensure uniformity between ribs and between bars.

After the epoxy-coated bars were appropriately damaged for testing, a threaded 0.75-in. polyvinyl chloride (PVC) pipe fitting was bonded as shown in Figure 3.5 to one end of each bar using a two-part PVC compound to facilitate mounting in the wooden forms prepared for concrete casting. The forms for each of the nine specimens were designed to facilitate a specimen thickness of 5.5 in. and side lengths of 18 in. and 22 in. and were constructed using structural timber having nominal cross-sectional dimensions of 2 in. by 6 in. The lengths of rebar were oriented parallel to the 18-in. side and positioned with a center-to-center spacing of 2.125 in. Each bar was affixed to the form by inserting the threaded fitting through a 1-in. hole in the front form member and then tightening a PVC cap over the exposed end. Holes through the front form member were made using a 1-in. hole saw, and recesses necessary to accommodate the caps were drilled using a 1.625-in. spade bit into the outside face of the front form member as illustrated in Figure 3.6. Pressure created from compressing the wall of the form between the cap and the unthreaded portion of the PVC fitting held the rebar in place.

FIGURE 3.5 PVC fitting bonded to a length of rebar.

FIGURE 3.6 Outside face of front form member.

To ensure that the threaded PVC fittings would be properly aligned with respect to the longitudinal axes of the bars, the bars were situated in their respective forms while the PVC compound cured, and the back member of each form, with holes drilled at the same locations as those in the front form member, was temporarily placed across the middle of the form to hold the bars in a level position.

Transportation of the slabs was facilitated by setting two segments of PVC pipe parallel to the reinforcement about 1.5 in. from the inside edges of the form. When the cured slabs were to be moved, steel rods were placed through the PVC pipes and used as handles. Spacing between the PVC pipes, reinforcing steel, and inside edges of the form met all the spacing requirements associated with the maximum size of aggregate used in the concrete mix design.

For measurement of internal slab temperatures, a thermocouple was inserted between two of the reinforcing bars in each slab and set in place with the use of fishing line prior to concrete casting. The thermocouple was mounted at mid-depth in the slab and set in a distance equal to half of the depth of the slab to achieve a temperature reading that represented the internal temperature of the slab. Plastic sheeting was then wrapped around the back member of the form to cover the holes used to hold the rebar level while the PVC compound cured, wrapped across the bottom of the form and half way up the remaining three sides of each form, and stapled in place. A completed form is shown in Figure 3.7.

Following assembly of the forms, the concrete was cast around the reinforcing bars. The concrete mix design implemented in this research complied with the Utah Department of Transportation (UDOT) specifications for concrete mixtures utilized for constructing bridge decks. Provided by a local concrete batch plant supervisor, the mix design required six bags of cement, a water-cement ratio of 0.44, a slump of 4.0 ± 1.0 in., and an entrained air content of 6.0 ± 1.0 percent. Trial batches were used to determine the amount of air-entraining agent needed to meet the specified slump and air content. The cementitious material specified in the mix design consisted of Type I/II Portland cement and Class F fly ash. The fly ash used in the mix originated from the Antelope Flats Power Plant near Paige, Arizona.

FIGURE 3.7 Completed form.

A separate concrete batch was prepared at each chloride concentration level. In addition to the concrete material needed for each of the three slabs in a batch, sufficient additional material was prepared to allow casting of seven 4-in.-diameter cylinders each 8 in. in height. The batch size was then increased by 10 percent to accommodate any loss of material during casting. The quantities of materials common to all batches are shown in Table 3.1, in which the specified amounts of both coarse aggregate (CA) and fine

TABLE 3.1 Concrete Mix Design

Ingredient	Specific Gravity	Design Weight Per Cubic Yard (lb)	Design Volume Per Cubic Yard (yd^3)	Design Weight Per Batch (lb)	Measured-Out Weight Per Batch (lb)
Free Water	1.00	280.0	0.166	53.7	59.9
Cement	3.15	519.0	0.098	99.4	99.4
CA (SSD)	2.55	1714.0	0.399	328.4	325.6*
FA (SSD)	2.60	1071.0	0.244	205.2	201.8*
Fly Ash	2.30	115.0	0.030	22.0	22.0
Air Entrainer (Amex 210)	1.00	0.5	0.000	0.087 (39.4 mL)	0.087 (39.4 mL)
Total		3699.5	0.937	708.9	708.8

* Oven-Dry Weight

aggregate (FA) are given as saturated-surface-dry (SSD) weights. The absorptions of 0.87 and 1.67 percent for the coarse and fine aggregates, respectively, were used to compute the equivalent amount of oven-dry aggregate needed for preparation of the specimens. The water weight was then increased commensurately.

Coarse and fine aggregates meeting ASTM C 33 (Standard Specification for Concrete Aggregates) were obtained from a local pit for utilization in the concrete mixture. To facilitate exact replication of aggregate gradations within each batch, the aggregate was oven-dried and separated across several sieves. For the coarse aggregate, the sieve sizes used were 0.75 in., 0.50 in., 0.375 in., No. 4, and No. 8. For the fine aggregate, the sieve sizes used were No. 16, No. 30, No. 50, No. 100, and pan. The aggregate weights used in all batches are shown in Table 3.2.

The amount of sodium chloride added to each batch is shown in Table 3.3. In each case, the sodium chloride for a given batch was dissolved completely in a portion of the mixing water prepared for the batch and then added to the mix. Batch 1 was used to prepare slabs 1 to 3, batch 2 was used to prepare slabs 4 to 6, and batch 3 was used to prepare slabs 7 to 9.

TABLE 3.2 Design Aggregate Batch Weights

Sieve Size	Oven-Dry Weight (lb)
1 in.	0.0
3/4 in.	16.3
1/2 in.	93.6
3/8 in.	93.6
No. 4	110.9
No. 8	31.4
No. 16	45.4
No. 30	50.5
No. 50	50.5
No. 100	25.3
Pan	10.1
Total	527.4

TABLE 3.3 Sodium Chloride Batch Quantities

Sodium Chloride (NaCl)	Batch		
	1	2	3
Concentration (lb Cl^-/yd³ Concrete)	4	2	0
Weight (lb)	1.263	0.632	0.000

Trial batches were prepared in a large-capacity drum mixer to determine the order in which materials were combined and the lengths of successive mixing times. The resulting procedure developed for this research is described in the following 10 steps:

Step 1. Before any material was added to the drum mixer, the inside surface of the mixer was sprayed with water. The walls of the mixer were moistened before each batch to prevent the mixer from absorbing a portion of the free water in the concrete mix. Excess water was then poured out of the mixer.

Step 2. Once the walls of the concrete mixer were sufficiently moistened, the first 75 percent of the total water needed was placed into the mixer. From trial batches, the conclusion was made that the water needed to be added to the mixer prior to any aggregates to ensure adequate dispersion of water among the aggregate particles. The sodium chloride was also added to the mix with the water during this step if chlorides were specified for the given batch.

Step 3. Once the initial allotment of water was added, all of the aggregates for the mix were then added. The mixer was allowed to rotate while the aggregates were being added.

Step 4. After all of the aggregates were added, the aggregates and water were allowed to mix together for one additional minute.

Step 5. In order for the oven-dried aggregates to approach the SSD condition, the mixer was stopped, and the mixture of aggregates and water was allowed to sit for 15 minutes. To prevent any loss of water through evaporation, the opening of the mixer was covered with a piece of plastic during this period.

Step 6. After the aggregate and water mixture equilibrated for 15 minutes, 39.4 mL of Amex 210 was then added with 2 lb of water. The mixer was allowed to rotate while the solution of air entrainer and water was added.

Step 7. The mixer was allowed to rotate for one additional minute after the air entrainer was added.

Step 8. The cement, fly ash, and all remaining water were then added to the mix. To facilitate adequate mixing of the cement and fly ash with the aggregate, the mixer was allowed to rotate while the cement, fly ash, and water were added.

Step 9. After all the materials for the mix were added, final mixing was performed. The mixer was run for three minutes, stopped to let the mix sit covered for three minutes, and then run for one additional minute. The waiting period was provided to allow the absorption of water by the cement and fly ash.

Step 10. Finally, after mixing was complete, tests were performed to check for the appropriate slump and air entrainment. Slump was tested in accordance with ASTM C 143 (Standard Test Method of Slump for Hydraulic Cement Concrete), and entrained air was tested in accordance with ASTM C 231 (Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method). If the slump failed to be within the specified range of 4.0 ± 1.0 in., the concrete sample was returned to the mixer, the entire batch was mixed for an additional two minutes, and the concrete mix was again tested for slump. When the required slump was met, the concrete mix was then tested for the percent of entrained air. If the concrete failed to meet the required level of air, the sample was discarded, the remaining concrete was mixed for an additional two minutes, and the slump and entrained air tests were again performed.

When the concrete satisfied the project specifications, casting and curing were performed following a modified version of ASTM C 192 (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). The concrete was distributed by wheelbarrow to the prepared specimen molds, and consolidation of the concrete in each form was performed by carefully rodding the concrete with a 0.375-in.-diameter steel rod. Care was taken not to strike the reinforcing steel, as this could potentially damage the epoxy coating, where present. A concrete stinger was also held against the exterior of the forms in order to facilitate consolidation; since the diameter of the stinger's vibrating head was larger than the spacing between bars in the form, the stinger could not be used for internal consolidation. After the concrete was sufficiently consolidated, the surface was screeded using a straight timber. The concrete slabs were then allowed to sit uncovered while the bleed water evaporated from the specimen surfaces. Once the bleed water had evaporated and the concrete had begun to stiffen, a number was etched into each of the slabs for identification purposes. Finally, each slab was edged and broomed as exemplified in Figure 3.8.

Each of the three concrete batches was prepared and cast separately since the same mixer was used for all three batches. While one batch was setting up, another batch was being mixed for subsequent placement in the next set of forms. Figure 3.9 shows the layout of the specimens during casting in the laboratory; the three slabs on the left have been finished, while the three slabs on the right have been consolidated and screeded and are waiting for the bleed water to evaporate.

Once the concrete had reached initial set, it was covered with plastic for a period of 7 days to minimize moisture loss during curing. The ambient temperature at which the

FIGURE 3.8 Completed slab.

FIGURE 3.9 Slab casting layout.

slabs were cured ranged from 70 to 75°F. The forms were removed from the specimens 10 days after the slabs were cast. In order to remove the forms from the slabs, the caps on each length of rebar were unscrewed. Once the forms had been removed, the exposed rebar ends were then coated with petroleum jelly and recapped. Capping the exposed end of each rebar minimized any potential effects of direct exposure of the bars to air. The slabs were then allowed to continue curing in the laboratory for the duration of the experiment.

At the same time the slabs were cast, seven concrete test cylinders were also cast from each batch in accordance with ASTM C 192. Cylinders were stripped of their molds after 24 hours of curing in the laboratory and were then placed in a fog room for continued curing.

3.4 SPECIMEN TESTING

At curing periods of 28, 56 and 90 days, all of the specimens were subjected to half-cell potential testing in accordance with ASTM C 876 as described previously. An environmental chamber was used to either heat or cool the test specimens to the desired temperature for testing while maintaining a relative humidity of 50 percent. To ensure more rapid equilibration of the slab temperature with the surrounding air, specimens were elevated in the environmental chamber on timber blocks. During environmental conditioning, the internal temperatures of the slabs were monitored using the thermocouples embedded into the concrete during the casting process. An equilibration period of 24 hours was adequate for the slabs to reach thermal equilibrium at each testing temperature. The interior of the environmental chamber used for the research experiment is shown in Figure 3.10.

When the internal temperature stabilized, the slabs were assumed to be in thermal equilibrium with the surrounding air, and the actual slab temperatures were recorded to the nearest 0.1°F. The PVC caps were then removed from the PVC fittings bonded to the reinforcing bars in each slab to provide a convenient point of electrical contact for testing. Two wire leads were used to connect the rebar and the reference electrode to the voltmeter utilized for measuring half-cell potentials. The negative lead of the voltmeter was attached to the end of the rebar protruding out of the concrete slab, as shown in

FIGURE 3.10 Slabs inside environmental chamber.

Figure 3.11, while the positive lead from the voltmeter was attached to the copper copper-sulfate reference electrode. As needed, the epoxy coating covering the ends of the bars was removed by filing to ensure a good electrical connection.

During testing, care was taken to ensure that the reservoir surrounding the reference electrode always contained sufficient electrolytic solution. Containers of electrolytic solution used to maintain the level within the reservoir were stored in the laboratory outside the environmental chamber at a temperature between 70 and 75°F. Because the reservoir was necessarily refilled after testing of every one to two slabs, on average, the reference electrode maintained a temperature within the range prescribed in ASTM C 876, eliminating the need for temperature calibrations of the half-cell. Figure 3.12 shows the reservoir of the half-cell potential apparatus containing the reference electrode and an electrolytic solution.

The voltmeter used for measuring half-cell potentials included a digital display that provided the value within seconds after connection of the negative lead to the rebar and seating of the sponge on the surface of the slab. The complete half-cell potential

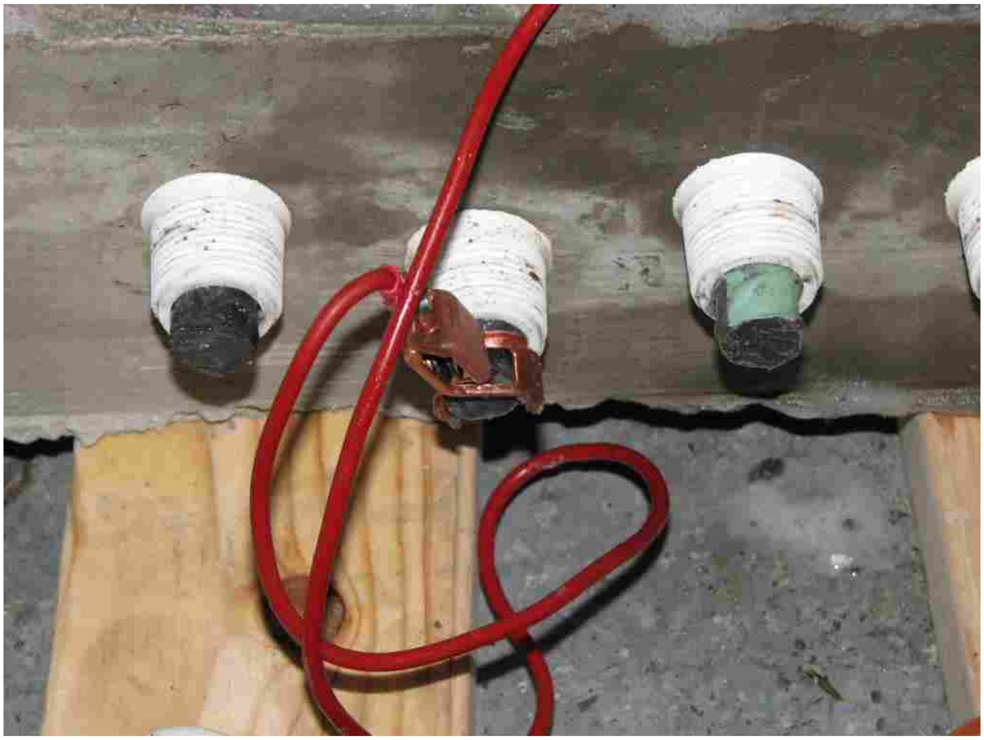


FIGURE 3.11 Electrical connection to rebar.

FIGURE 3.12 Reservoir and reference electrode.

apparatus and the digital thermometer utilized for measuring slab temperatures are shown together in Figure 3.13.

Three repeated measurements were made at each of three locations along each of the seven bars in all nine of the slabs at three ages, with testing performed at three temperatures per age. Thus, nine half-cell potential readings per bar were collected in

FIGURE 3.13 Half-cell potential testing.

each condition, corresponding to 567 readings per slab. In total, 5103 half-cell potential measurements were collected in the experiment. The order of testing along each bar is shown in Figure 3.14. The copper-sulfate crystals in the reference electrode were replaced prior to testing of the slabs at each of the three curing times, eliminating any possible error that may have otherwise arisen from an expired copper-sulfate solution, and the exposed ends of the reinforcing bars were coated with petroleum jelly and capped when not in use.

Seven- and 28-day concrete compressive strengths for each batch were obtained by testing at least three concrete cylinders after the appropriate curing time. Compressive strength tests were performed in accordance with ASTM C 39 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens). The specimens were capped with sulfur to ensure uniform distribution of load across the specimen ends in each case and loaded at a constant strain rate of 0.05 in. per minute on a floating base. The loading configuration is displayed in Figure 3.15.

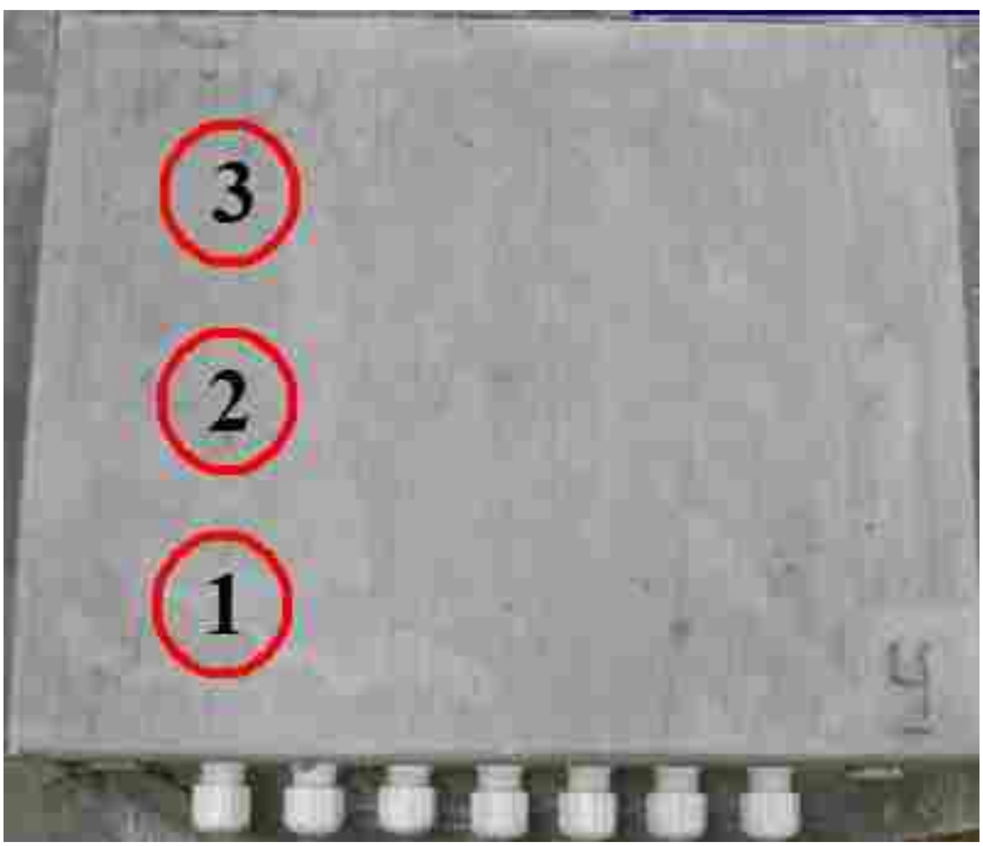


FIGURE 3.14 Locations of half-cell potential testing along each bar.

FIGURE 3.15 Compressive strength testing.

3.5 STATISTICAL ANALYSES

An analysis of variance (ANOVA) was used to evaluate the recorded half-cell potentials. This method allows for comparison of multiple factors simultaneously while controlling the probability of making a Type I error. A Type I error is defined as the acceptance of a false alternative hypothesis, or rejection of a true null hypothesis (*23*). The probability of committing a Type I error is established by the selection of α, also known as the confidence level or the acceptable level of error for the experiment. For this experiment a confidence level of 95 percent was used by selecting the standard value of 0.05 for α. The null hypothesis is defined as the assumption that no difference exists between the populations being evaluated. The alternative hypothesis is the assumption that a difference does exist between the populations being evaluated. In this research, each level of each factor represented a different population. The difference referred to in the alternative hypothesis is determined by comparison of the within-sample variability to the between-sample variability among different populations, or levels of a factor, in the ANOVA. The results of the ANOVA include a *p*-value for each factor of interest in the experiment. A *p*-value is defined as a measurement of the level of significance of a given factor for comparison to the selected α-value. When the *p*-value is less than α, the null hypothesis may be rejected, and the factor is said to be statistically significant.

In addition to the ANOVA performed on the measured half-cell potentials, Tukey's method for multiple comparisons was also used. While the ANOVA is particularly useful in determining whether or not a difference exists between the levels of a given factor, it does not identify which levels of a factor are different from each other. Once the statistically significant factors were identified in this research through the ANOVA, a comparison of these factors was therefore accomplished using Tukey's method.

A mixed effects model was used in analyzing the test results. A mixed effects model is one that incorporates both fixed and random effects models. A fixed effects model is one in which all factors or treatments have a predetermined set of levels. A random effects model is a model in which the levels of treatments are randomly selected (*24*). In this experiment, the fixed effects were age, chloride concentration, concrete cover thickness, spatial position, temperature, and the condition or presence of epoxy coating. Each of the fixed effects had specific levels of treatments for testing. The random effect in this experiment was the slab effect. Since the individual slabs represented a sample of some but not all of the possible slabs that could theoretically be constructed for testing, the slabs must be defined as a random effect. Although the random slab effect was an integral part of the analysis, comparing the performance of one slab to another was not an objective of this research. Instead, the variability between slabs was used to test for differences in fixed effects. The focus of this research was how the fixed effects affected the half-cell measurements.

For the purpose of this research, two sets of ANOVAs and Tukey's analyses were performed. The first set of analyses evaluated the effects of age, chloride concentration, concrete cover thickness, spatial position, temperature, and slab on half-cell potentials of black bar. The second set of analyses evaluated the effects of age, chloride concentration, spatial position, temperature, condition or presence of epoxy coating, and slab on half-cell potentials. The first analyses only considered the half-cell potential measurements obtained from the black bars, while the second set of analyses only considered the half-cell potentials obtained from the epoxy-coated rebar specimens and the black bar specimens with the same concrete cover thickness of 2.5 in. In each set of analyses, a full model was initially created using all factors and their interactions. A reduced model was then created using a Type I error rate of 0.15 commonly specified for this purpose; only factors with *p*-values less than 0.15 were included in the reduced model. When the ANOVA indicated that a main effect was significant, as indicated by a *p*-value less than 0.05, Tukey's method was used to identify the differences.

3.6 SUMMARY

The full-factorial experimental design utilized in this research involved several factors, including age, chloride concentration, concrete cover thickness, spatial position, temperature, and presence or condition of epoxy coating. Each of the nine specimens created for this research consisted of a rectangular concrete slab containing three black reinforcing steel bars at three different concrete cover depths and four epoxy-coated reinforcing steel bars with four different coating conditions. Three batches of concrete were prepared at three different chloride concentrations. Sufficient material was prepared in each batch to allow casting of three slab specimens and seven concrete cylinders. The concrete mixing and casting process was uniform for all three batches to ensure consistency in the research. Three repeated measurements were made at each of three locations along each of the seven bars in all nine of the slabs at three ages, with testing performed at three temperatures per age. In addition, compressive strengths of the concrete cylinders were measured at 7 and 28 days. Statistical analyses of the half-cell potentials were performed using ANOVAs and Tukey's method for multiple comparisons.

CHAPTER 4

RESULTS

4.1 OVERVIEW

The properties of each concrete mix prepared for this experimentation, as well as discussion of the test results and statistical analyses completed in this research, are presented in the following sections.

4.2 CONCRETE PROPERTIES

The slump, percent of entrained air, mean compressive strengths, and standard deviations of the compressive strengths for each concrete mix prepared for this experimentation are shown in Table 4.1. For all three mixes, both the slump and entrained air were within the specifications outlined by UDOT. Each of the mix designs also exhibited acceptable compressive strengths.

Three of the seven cylinders per batch were tested for 7-day compressive strength for batches 1 and 3, while the remaining four cylinders per batch were tested for 28-day compressive strength. For batch 2, four cylinders were tested for 7-day compressive strength, with the remaining three cylinders tested for 28-day compressive strength. The testing of the additional cylinder in batch 2 for 7-day compressive strength was performed since one of the initial three cylinders exhibited a compressive strength substantially higher than the other two tested.

TABLE 4.1 Concrete Mix Properties

Mix	Slump (in.)	Entrained Air (%)	Compressive Strength (psi)			
			7-day		28-day	
			Mean	Std. Dev.	Mean	Std. Dev.
1	3.75	5.5	4577	271	6112	366
2	4.50	5.5	3231	692	5074	565
3	4.50	6.0	3787	152	4973	554

4.3 TEST RESULTS AND ANALYSES

Analyses of half-cell potential measurements obtained from the black bars, as well as analyses of half-cell potential measurements obtained from the epoxy-coated rebar specimens and the black bar specimens with the same concrete cover thickness of 2.5 in., are presented in the following sections.

4.3.1 Evaluation of Black Bars

The factors in the experimentation on black bars included age, chloride concentration, concrete cover thickness, spatial position, and temperature. Table 4.2 shows the main effects and interactions included in the reduced ANOVA model associated with experimentation on black bars. Asterisks in the table indicate interactions. As described in Chapter 3, only those factors having *p*-values less than 0.15 are included in the reduced model. The main effects and interactions are discussed in detail in the following sections.

TABLE 4.2 ANOVA Results for Experimentation on Black Bar

Factor	*p* -value
Age	<0.0001
Chlorides	<0.0001
Cover	<0.0001
Position	<0.0001
Temperature	<0.0001
Age*Chlorides	<0.0001
Age*Cover	0.0108
Age*Temperature	<0.0001
Chlorides*Cover	0.0812
Chlorides*Temperature	<0.0001
Age*Chlorides*Cover	<0.0001
Age*Chlorides*Temperature	<0.0001

4.3.1.1 Main Effects

As described in Chapter 3, factors having *p*-values less than 0.05 in the ANOVA are considered significant. Because the *p*-values of all of the main effects are less than 0.05, sufficient evidence exists to reject the null hypothesis that no difference exists between the levels of each factor and accept the alternative hypothesis that variation in each of the factors has a significant impact on half-cell potentials over the ranges of levels investigated in this research. That is, the half-cell potentials corresponding to one level of a given factor are significantly different from those corresponding to at least one other level of the same factor in each case.

The least square mean half-cell potentials calculated in the ANOVA for each of the statistically significant main effects are shown in Table 4.3. Based on the data given previously in Table 2.1, the probability of corrosion of the reinforcing steel is also given for each level of each factor in Table 4.3. The probability of corrosion was less than 90 percent in four cases and was uncertain in the remaining 11 cases. In no cases was the probability of corrosion determined to be greater than 90 percent.

TABLE 4.3 Least Square Mean Half-Cell Potential Values for Main Effects Associated with Experimentation on Black Bar

Factor	Level	Half-Cell Potential (V)	Corrosion Classification
Age (days)	28	-0.275	Uncertain
	56	-0.201	Uncertain
	90	-0.160	Improbable
Chlorides (lb Cl^-/yd^3 Concrete)	0	-0.134	Improbable
	2	-0.190	Improbable
	4	-0.311	Uncertain
Cover (in.)	2.0	-0.208	Uncertain
	2.5	-0.217	Uncertain
	3.0	-0.210	Uncertain
Position	1	-0.208	Uncertain
	2	-0.211	Uncertain
	3	-0.216	Uncertain
Temperature (°F)	60	-0.184	Improbable
	80	-0.217	Uncertain
	100	-0.234	Uncertain

For the purpose of determining whether statistically significant differences identified in the ANOVA were of practical engineering importance in this research, the magnitude of the range of least square mean half-cell potentials for each of the factors listed in Table 4.3 was compared against the value of 0.05 V. The magnitude of the range for a factor was determined as the difference between the highest and lowest half-cell potentials listed in Table 4.3 for that factor. The value of 0.05 V, which is one-third of the magnitude of the uncertain range listed in Table 2.1, was selected as a reasonable basis for comparison using engineering judgment. Statistically significant factors having half-cell potential ranges with magnitudes less then 0.05 were thus defined as having no practical importance.

As shown in Table 4.3, half-cell potential measurements became consistently less negative with increasing age for all nine specimens. The change in potentials may be attributable to reductions in concrete permeability due to both the loss of moisture and the continuing formation of hydration products. Although outside the scope of the current project, long-term analysis of the slabs may provide further insight into the mechanisms associated with this observation. Previous research conducted on bridge decks having ages between 2 and 21 years indicated that the relationship between age and half-cell potential was in fact not significant (*25*). With a range in half-cell potential of 0.115, the factor of age was determined to be of practical importance.

With increasing chloride concentrations in this research, half-cell potentials became more negative, consistent with the role of chlorides in the corrosion process. With a range in half-cell potential of 0.117, the factor of chloride was also determined to be of practical importance.

Half-cell potentials became less negative as the cover thickness changed from 2.5 in. to either 2.0 or 3.0 in. With a range in half-cell potential of 0.009, however, the factor of cover was determined to be of no practical importance.

The half-cell potential values for position became more negative in this research with increasing distance from the connection to the reinforcing steel. However, having a range in half-cell potential of only 0.008, the factor of position was determined to be of no practical importance, just as with cover.

Half-cell potentials became more negative with increasing temperature, corresponding with the fact that higher temperatures accelerate electrolytic current flow. Having a range in half-cell potential of 0.050, the factor of temperature was determined to be of practical importance.

Through the use of Tukey's method for multiple comparisons, the levels of each statistically significant factor were compared in a pair-wise fashion to identify which levels were significantly different from each other. Comparisons of the levels of each factor were facilitated by organizing the *p*-values generated by the Tukey's analysis into Table 4.4. A *p*-value less than 0.05 indicates that the difference in half cell-potentials associated with the levels of the given factor is statistically significant.

In all except one of the two-way comparisons shown in Table 4.4, the levels of the factors were significantly different from each other as indicated by *p*-values less than 0.05. That is, every level of the age, chlorides, position, and temperature factors corresponds to a half-cell potential value significantly different than that associated with

TABLE 4.4 Tukey's Mean Separation Results for Main Effects Associated with Experimentation on Black Bar

Age (days)		
	28	56
56	<0.0001	
90	<0.0001	<0.0001
Chlorides (lb Cl^-/yd^3 Concrete)		
	0	2
2	<0.0001	
4	<0.0001	<0.0001
Cover (in.)		
	2.0	2.5
2.5	<0.0001	
3.0	0.304	0.0003
Position		
	1	2
2	0.0457	
3	<0.0001	0.0108
Temperature (°F)		
	60	80
80	<0.0001	
100	<0.0001	<0.0001

every other level of the same factor. Only the comparison between 2.0- and 3.0-in. cover thicknesses yielded a *p*-value exceeding this threshold, indicating that insufficient evidence is available to conclude that half-cell potential measurements associated with those two levels are significantly different.

4.3.1.2 Interactions

Calculated *p*-values for two- and three-way interactions between the individual factors are shown in Table 4.2 for the reduced model. Significant two-way interactions included age by chlorides, age by cover, age by temperature, and chlorides by temperature. In addition to the two-way interactions, two significant three-way interactions also existed between age, chlorides, cover, and temperature. The corresponding least square mean half-cell potential values for each significant two-way interaction are shown in Table 4.5 and plotted in Figures 4.1 to 4.4.

TABLE 4.5 Least Square Mean Half-Cell Potential Values for Interactions Associated with Experimentation on Black Bar

Age (days)	Chlorides (lb Cl^-/yd^3 Concrete)		
	0	2	4
28	-0.179	-0.268	-0.377
56	-0.127	-0.178	-0.296
90	-0.096	-0.124	-0.259
Age (days)	Cover (in.)		
	2.0	2.5	3.0
28	-0.273	-0.277	-0.274
56	-0.195	-0.204	-0.202
90	-0.156	-0.168	-0.155
Age (days)	Temperature (ºF)		
	60	80	100
28	-0.240	-0.277	-0.307
56	-0.178	-0.209	-0.215
90	-0.134	-0.164	-0.180
Chlorides	Temperature (ºF)		
(lb Cl^-/yd^3 Concrete)	60	80	100
0	-0.109	-0.139	-0.155
2	-0.155	-0.204	-0.211
4	-0.288	-0.307	-0.336

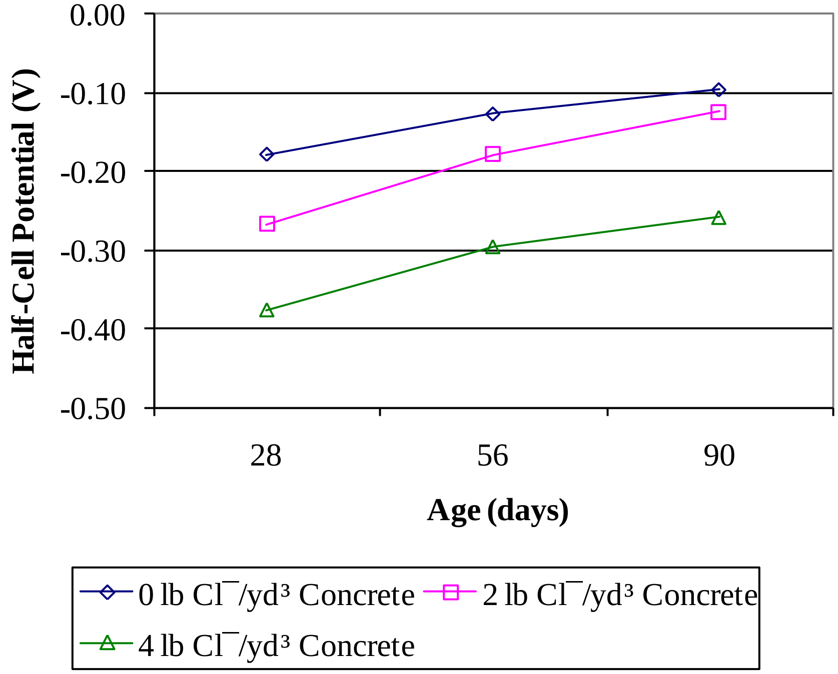


FIGURE 4.1 Two-way interaction between age and chlorides from experimentation on black bar.

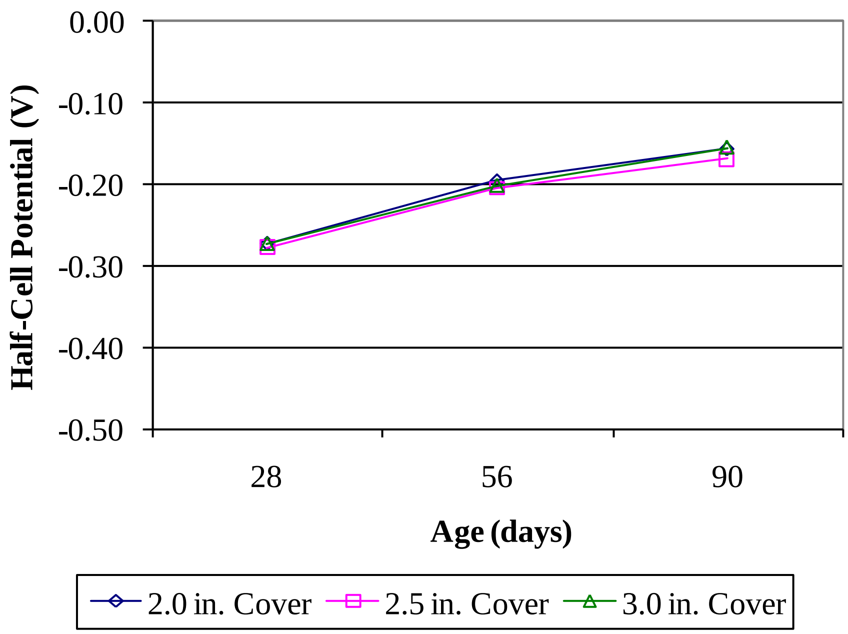


FIGURE 4.2 Two-way interaction between age and cover from experimentation on black bar.

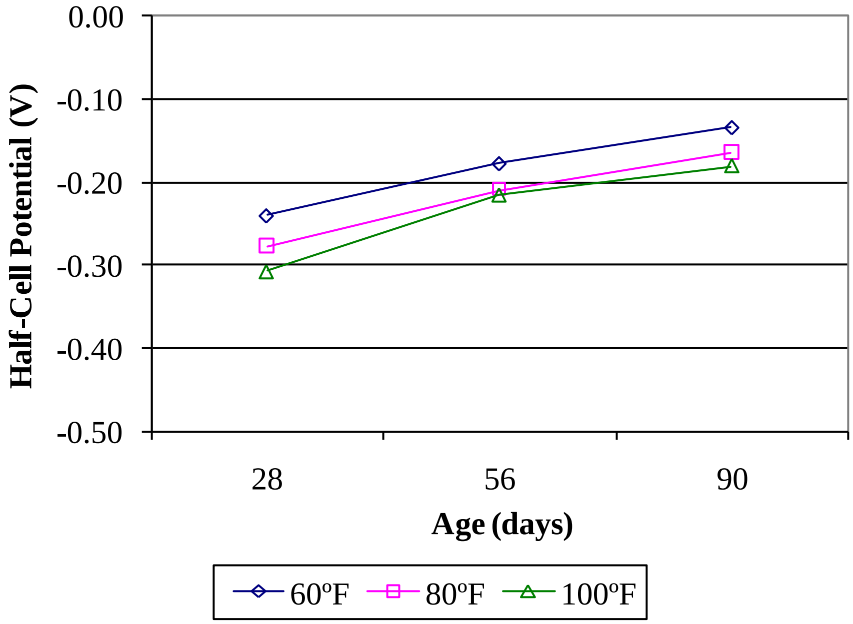


FIGURE 4.3 Two-way interaction between age and temperature from experimentation on black bar.

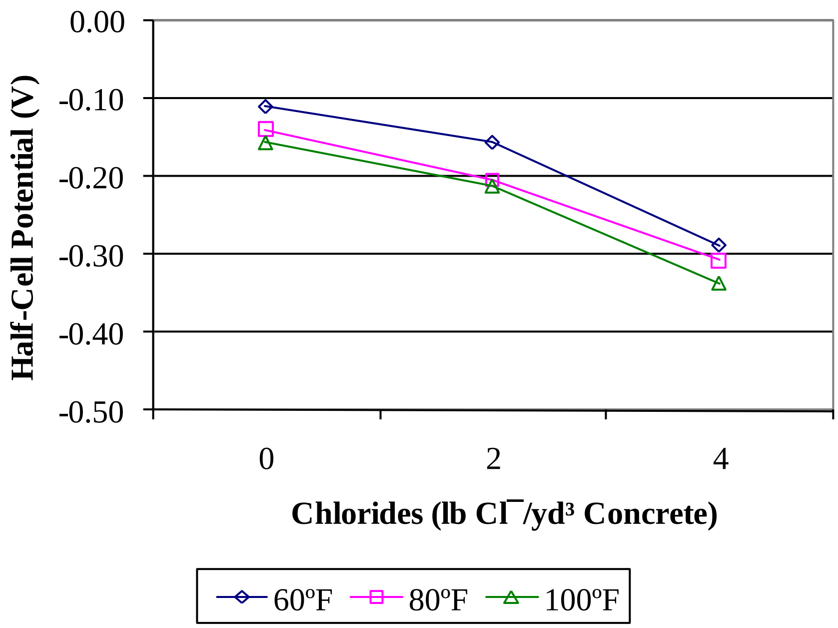
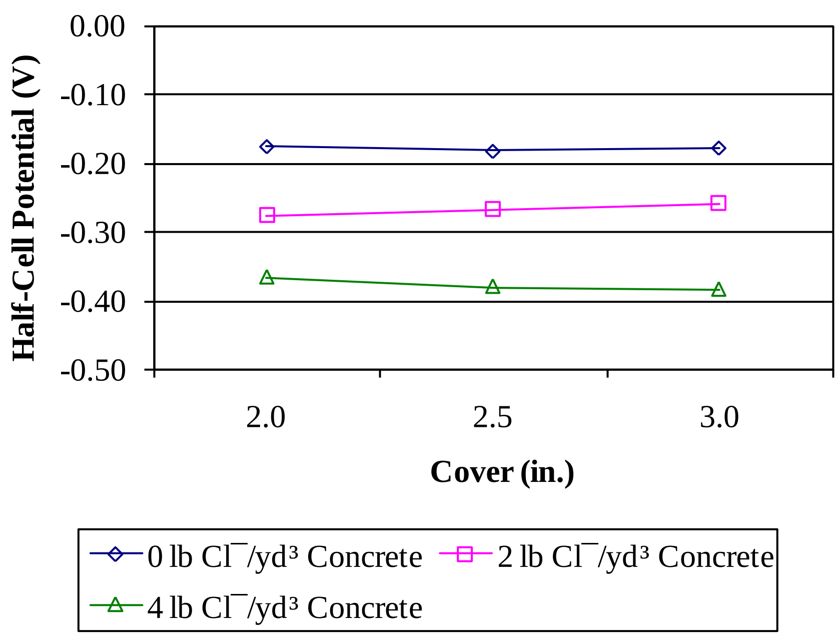


FIGURE 4.4 Two-way interaction between chlorides and temperature from experimentation on black bar.

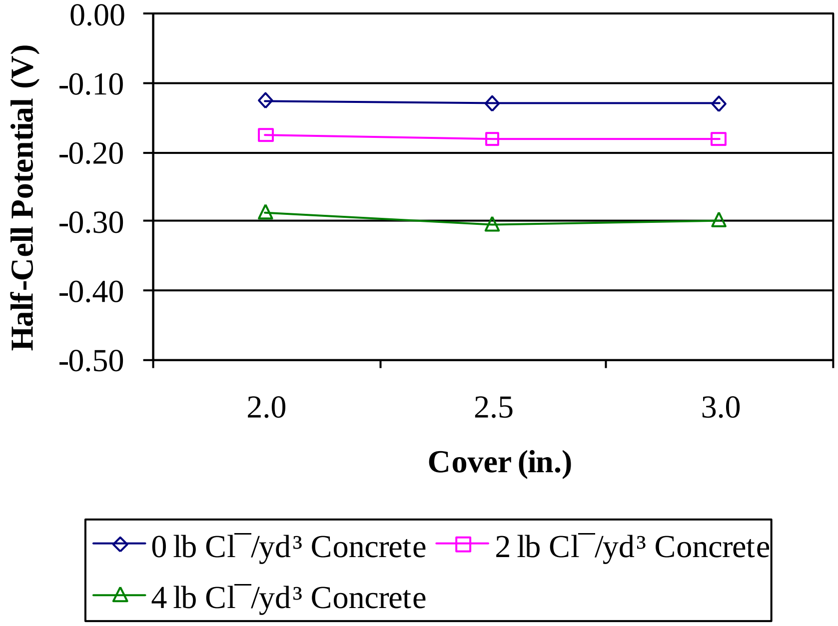
Each line of data in these figures illustrating two-way interactions has a noticeable slope. In the interactions involving age, the slopes of the lines relative to each other do not appreciably change as a function of age and are therefore not considered as having any practical importance in this research. That is, while the interactions of age by chlorides, age by cover, and age by temperature are statistically significant, the interactions are of no engineering value. The same conclusion applies to the interaction of chlorides by temperature. While the effect of chlorides on half-cell potential was determined in the ANOVA to be statistically dependent upon the temperature, the variation in half-cell potential across all the levels of temperature at any given chloride concentration is of no practical importance.

Illustrating each of the two three-way interactions required preparation of three plots. Figure 4.5 illustrates the first three-way interaction involving age, chlorides, and cover, while Figure 4.6 illustrates the second three-way interaction involving age, chlorides, and temperature.

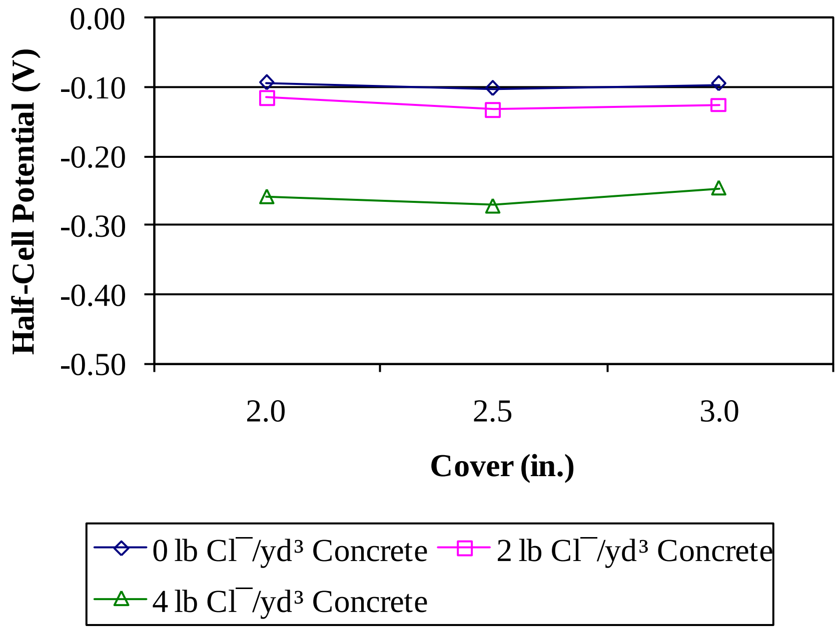


(a) Age of 28 days.

FIGURE 4.5 Three-way interaction between age, chlorides, and cover from experimentation on black bar.

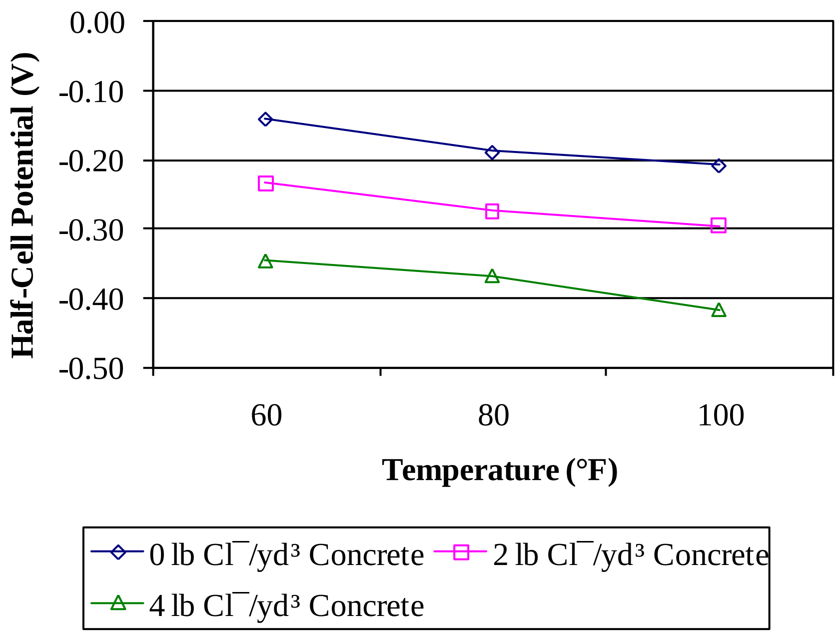


(b) Age of 56 days.

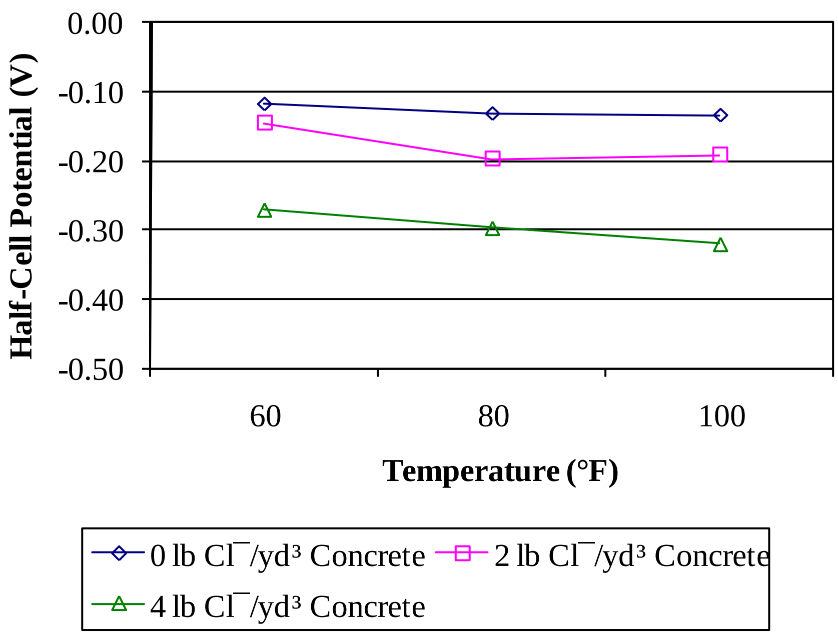


(c) Age of 90 days.

FIGURE 4.5 (Continued).

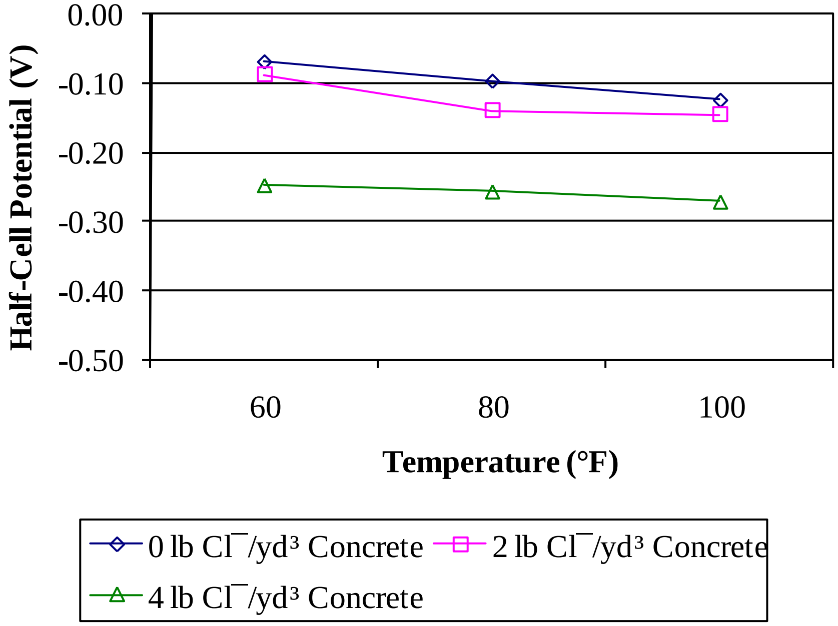


(a) Age of 28 days.



(b) Age of 56 days.

FIGURE 4.6 Three-way interaction between age, chlorides, and temperature from experimentation on black bar.



(c) Age of 90 days.

FIGURE 4.6 (Continued).

As with the two-way interactions, neither of the three-way interactions exhibited appreciable changes in the magnitudes of the differences in half-cell potential between the levels of one factor across the values of any other factor. Therefore, these interactions are also of no practical importance in this research.

4.3.2 Evaluation of Epoxy-Coated Bars

The factors in the experimentation on epoxy-coated bars included age, chloride concentration, temperature, spatial position, and treatment. Table 4.6 shows the main effects and interactions included in the reduced ANOVA model associated with experimentation on epoxy-coated bars. The main effects and interactions are discussed in detail in the following sections.

TABLE 4.6 ANOVA Results for Experimentation on Epoxy-Coated Bar

Factor	p -value
Age	<0.0001
Chlorides	<0.0001
Temperature	<0.0001
Treatment	<0.0001
Age*Chlorides	<0.0001
Age*Treatment	0.0254
Chlorides*Treatment	<0.0001

4.3.2.1. Main Effects

The least square mean half-cell potentials calculated in the ANOVA for each of the statistically significant main effects are shown in Table 4.7. Based on the data given previously in Table 2.1, the probability of corrosion of the reinforcing steel is also given for each level of each factor in Table 4.7. The probability of corrosion was less than 90

TABLE 4.7 Least Square Mean Half-Cell Potential Values for Main Effects Associated with Experimentation on Epoxy-Coated Bar

Factor	Level	Half-Cell Potential (V)	Corrosion Classification
Age (days)	28	-0.214	Uncertain
	56	-0.156	Improbable
	90	-0.114	Improbable
Chloride (lb Cl^-/yd^3 Concrete)	0	-0.127	Improbable
	2	-0.156	Improbable
	4	-0.221	Uncertain
Temperature (°F)	60	-0.142	Improbable
	80	-0.172	Improbable
	100	-0.188	Improbable
Treatment	Black Bar	-0.216	Uncertain
	Full Epoxy	-0.130	Improbable
	End Cut	-0.142	Improbable
	Pliers Strike	-0.159	Improbable
	Rib Scrape	-0.189	Improbable

percent in 11 cases and was uncertain in the remaining three cases. In no cases was the probability of corrosion determined to be greater than 90 percent.

The factor of position is not listed as a main effect in Table 4.6 since the factor had a *p*-value exceeding 0.15. Because the *p*-values of all of the other main effects are less than 0.05, sufficient evidence exists to conclude that variation in each of those factors has a significant impact on half-cell potentials over the ranges of levels investigated. As stated previously, for the purpose of interpreting the data collected from this research, the practical importance of each statistically significant main effect was determined by comparing the magnitude of the range of least squared mean half-cell potentials for each factor against the value of 0.05 V.

As shown in Table 4.7, half-cell potential measurements became consistently less negative with increasing age for all nine specimens. As stated previously, the change in potentials may be attributable to reductions in concrete permeability due to both the loss of moisture and the continuing formation of hydration products. With a range in half-cell potential of 0.100, the factor of age was determined to be of practical importance. As discussed in the results of experimentation on black bar, the factor of age may not be of practical importance in the long term, however.

Just as in the experimentation on black bar, half-cell potentials became more negative with increasing chloride concentrations. With a range in half-cell potential of 0.094, the factor of chloride was also determined to be of practical importance.

Once again, half-cell potentials became more negative with increasing temperature. Having a range in half-cell potential of 0.061, the factor of temperature was determined to be of practical importance.

With regard to the factor of treatment, the uncoated rebar had the most negative half-cell potential, followed by epoxy-coated rebar with rib scrapes, pliers strikes, end cuts, and full epoxy coatings, in that order. While these data indicate that a coating, even damaged, reduces the probability of corrosion when compared to uncoated rebar, the data also suggest that both the amount and distribution of the coating damage over the affected rebar influence corrosion. For example, even though the end cut exposed more surface area than the pliers strikes, the former exhibited less negative half-cell potentials than the latter. With a range in half-cell potential of 0.086, the factor of treatment was also determined to be of practical importance.

Through the use of Tukey's method for multiple comparisons, the levels of each statistically significant factor were again compared in a pair-wise fashion to identify which levels were significantly different from each other. Comparisons of the levels of each factor were facilitated by organizing the *p*-values generated by the Tukey's analysis into Tables 4.8 and 4.9. Again, a *p*-value less than 0.05 indicates that the difference in half cell-potentials associated with the levels of the given factor is statistically significant.

In all except one of the two-way comparisons shown in Tables 4.8 and 4.9, the levels of the factors were significantly different from each other as indicated by *p*-values less than 0.05. That is, every level of the age, chlorides, temperature, and treatment factors corresponds to a half-cell potential value significantly different than that

TABLE 4.8 Tukey's Mean Separation Results for Main Effects of Age, Chlorides, and Temperature Associated with Experimentation on Epoxy-Coated Bar

Age (days)		
	28	56
56	<0.0001	-
90	<0.0001	<0.0001
Chlorides (lb Cl^-/yd^3 Concrete)		
	0	2
2	<0.0001	-
4	<0.0001	<0.0001
Temperature (°F)		
	60	80
80	<0.0001	-
100	<0.0001	0.0002

TABLE 4.9 Tukey's Mean Separation Results for Main Effect of Treatment Associated with Experimentation on Epoxy-Coated Bar

Treatment				
	Black Bar	Full Epoxy	End Cut	Pliers Strike
Full Epoxy	<0.0001	-	-	-
End Cut	<0.0001	0.1317	-	-
Pliers Strike	<0.0001	<0.0001	0.0097	-
Rib Scrape	<0.0001	<0.0001	<0.0001	<0.0001

associated with every other level of the same factor. Only the comparison between the full epoxy and the end cut yielded a *p*-value exceeding this threshold, indicating that insufficient evidence is available to conclude that half-cell potential measurements associated with those two levels are significantly different. Since the half-cell potential of the fully-coated epoxy bar was similar to that of the rebar with an exposed end cut, the efficacy of the two-part epoxy patch compound comes in question.

4.3.2.2 Interactions

Calculated *p*-values for interactions between the individual factors are shown in Table 4.6 for the reduced model. Significant two-way interactions included age by chlorides, age by temperature, and chlorides by treatment. None of the other two-way interactions, nor any of the three-way interactions, were significant. The corresponding least square mean half-cell potentials for each significant two-way interaction are shown in Tables 4.10 and 4.11 and are plotted in Figures 4.7 to 4.9.

For the same reasons given in the previous analysis, the interactions involving age are not considered as having any practical importance. That is, while the interactions of age by chlorides and age by temperature are statistically significant, the interactions are of no engineering value. However, the plot illustrating the interaction of chlorides by treatment does show important changes in the slopes of the lines relative to each other. These data clearly show that the effect of the type of epoxy coating damage depends upon the chloride concentration. For example, at a chloride concentration of 2 lb of chloride per cubic yard of concrete, the rebar with the rib scrape exhibited the most negative half-cell potential; however, at a chloride concentration of 4 lb of chloride per cubic yard of concrete, the black bar exhibited the most negative half-cell potential. No

TABLE 4.10 Least Square Mean Half-Cell Potential Values for Interaction between Age and Chlorides Associated with Experimentation on Epoxy-Coated Bar

Age (days)	Chlorides (lb Cl^-/yd^3 Concrete)		
	0	2	4
28	-0.186	-0.239	-0.270
56	-0.113	-0.137	-0.218
90	-0.077	-0.090	-0.174

TABLE 4.11 Least Square Mean Half-Cell Potential Values for Interactions between Age and Treatment and Chlorides and Treatment Associated with Experimentation on Epoxy-Coated Bar

Age (days)	Treatment				
	Black Bar	Epoxy-Coated Bar			
		Full Epoxy	End Cut	Pliers Strike	Rib Scrape
28	-0.277	-0.195	-0.192	-0.233	-0.263
56	-0.204	-0.116	-0.141	-0.148	-0.172
90	-0.168	-0.079	-0.093	-0.097	-0.131
Chlorides (lb Cl^-/yd^3 Concrete)	Treatment				
	Black Bar	Epoxy-Coated Bar			
		Full Epoxy	End Cut	Pliers Strike	Rib Scrape
0	-0.138	-0.106	-0.097	-0.127	-0.161
2	-0.194	-0.109	-0.116	-0.150	-0.209
4	-0.319	-0.174	-0.213	-0.200	-0.197

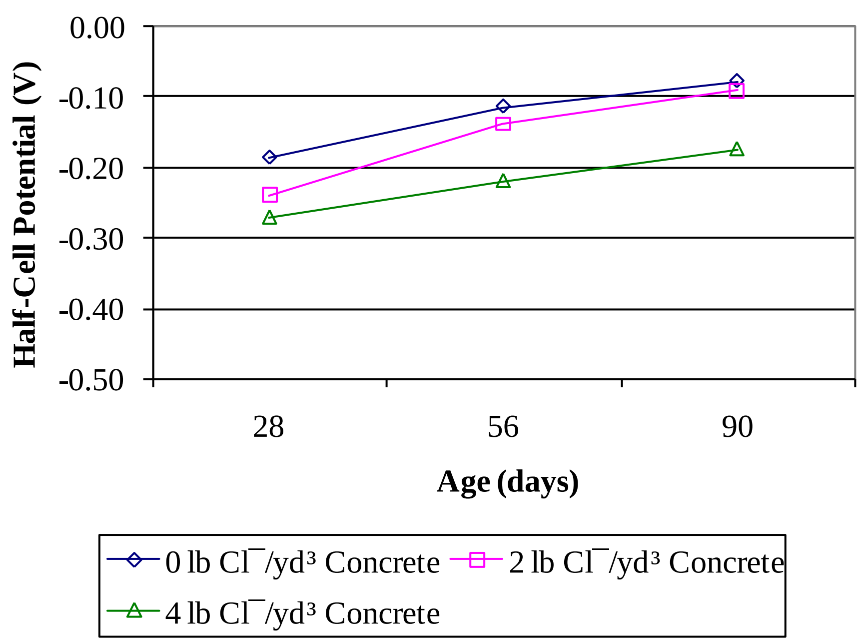


FIGURE 4.7 Two-way interaction between age and chlorides from experimentation on epoxy-coated bar.

FIGURE 4.8 Two-way interaction between age and treatment from experimentation on epoxy-coated bar.

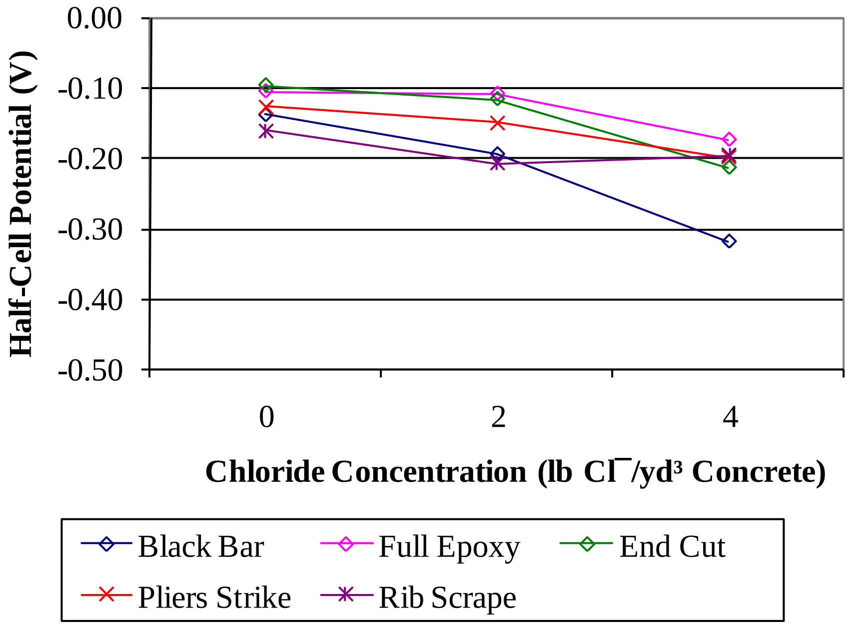


FIGURE 4.9 Two-way interaction between chlorides and treatment from experimentation on epoxy-coated bar.

explanation for the positive slope of the line representing the rib scrape between chloride concentrations of 2 and 4 lb of chloride per cubic yard of concrete has been developed in this research. Long-term monitoring may ultimately reveal the reason for this behavior.

The least square mean half-cell potentials listed in Table 4.11 for the interaction of chlorides by treatment were ordered to facilitate ranking of the treatments by degree of negativity. A scale from one to five was used, with a five given to the potential that was the most negative and a one given to the potential that was the least negative. The ranking was performed for each level of chlorides. The rank values for each treatment were then summed, and the treatment with the highest total was defined as the treatment having the highest probability of corrosion. Likewise, the treatment with the lowest total was then defined as the treatment with the lowest probability of corrosion. The rankings are shown in Table 4.12.

The fully epoxy-coated rebar with the end patch performed the best overall against chloride-induced corrosion, while the black bar performed the worst overall. The rib scrape bar actually ranked lower than the black bar at two of the three chloride concentrations. The better performance of the black bar over the rib scrape bar emphasizes the need for careful handling of epoxy-coated rebar.

TABLE 4.12 Ranking of Treatments Associated with Experimentation on Epoxy-Coated Bar

Chlorides (lb Cl^-/yd^3 Concrete)	Treatment				
	Black Bar	Epoxy-Coated Bar			
		Full Epoxy	End Cut	Pliers Strike	Rib Scrape
0	4	2	1	3	5
2	4	1	2	3	5
4	5	1	4	3	2
Total	13	4	7	9	12
Rank	5	1	2	3	4

4.4 SUMMARY

Although ASTM C 876 only specifies the measuring of half-cell potentials of uncoated reinforcing steel, credible half-cell potentials were also obtained for epoxy-coated rebar in this research. Summaries of the research findings are provided in the following sections.

4.4.1 Evaluation of Black Bars

The factors in the experimentation on black bars included age, chloride concentration, concrete cover thickness, spatial position, and temperature. Because the *p*-values of all of the main effects are less than 0.05 in the ANOVA, sufficient evidence exists to conclude that variation in each of the factors has a statistically significant impact on half-cell potentials over the ranges of levels investigated in this research. However, the effects of variation in cover thickness and spatial position on half-cell potential readings were determined to be of no practical importance.

Half-cell potential measurements became consistently less negative with increasing age for all nine specimens; the change in potentials may be attributable to reductions in concrete permeability due to both the loss of moisture and the continuing formation of hydration products. With increasing chloride concentrations in this research, half-cell potentials became more negative, consistent with the role of chlorides in the corrosion process. Half-cell potentials also became more negative with increasing temperature, corresponding with the fact that higher temperatures accelerate electrolytic current flow. In all except one of the two-way comparisons evaluated using Tukey's method, the levels of the factors were significantly different from each other as indicated by *p*-values less than 0.05. Only the comparison between 2.0- and 3.0-in. cover thicknesses yielded a *p*-value exceeding this threshold, indicating that insufficient evidence is available to conclude that half-cell potential measurements associated with those two levels are significantly different.

Four two-way interactions and two three-way interactions were determined to be statistically significant in the experimentation on black bar, but none of the interactions were of practical importance.

4.4.2 Evaluation of Epoxy-Coated Bars

The factors in the experimentation on epoxy-coated bars included age, chloride concentration, temperature, spatial position, and treatment. Except for position, all of the factors had *p*-values less than 0.05, indicating that variation in each of these factors has a statistically significant impact on half-cell potentials over the ranges of levels investigated in this research. Furthermore, all of the statistically significant factors were also determined in the research to be of practical importance.

Half-cell potential measurements became consistently less negative with increasing age for all nine specimens. Just as in the experimentation on black bar, half-cell potentials became more negative with increasing chloride concentrations and with increasing temperature. With regard to the factor of treatment, the uncoated rebar had the most negative half-cell potential, followed by epoxy-coated rebar with rib scrapes, pliers strikes, end cuts, and full epoxy coatings, in that order. While these data indicate that a coating, even damaged, reduces the probability of corrosion when compared to uncoated rebar, the data also suggest that both the amount and distribution of the coating damage over the affected rebar influence corrosion. In all except one of the two-way comparisons evaluated using Tukey's method, the levels of the factors were significantly different from each other as indicated by *p*-values less than 0.05. Only the comparison between the full epoxy and the end cut yielded a *p*-value exceeding this threshold, indicating that insufficient evidence is available to conclude that half-cell potential measurements associated with those two levels are significantly different. Since the half-cell potential of the fully-coated epoxy bar was similar to that of the rebar with an exposed end cut, the efficacy of the two-part epoxy patch compound comes in question.

Three two-way interactions were determined to be statistically significant in the experimentation on black bar, but only the interaction of chlorides by treatment was of practical importance. These data clearly show that the effect of the type of epoxy coating damage depends upon the chloride concentration. For example, at a chloride concentration of 2 lb of chloride per cubic yard of concrete, the rebar with the rib scrape exhibited the most negative half-cell potential; however, at a chloride concentration of 4 lb of chloride per cubic yard of concrete, the black bar exhibited the most negative half-cell potential. Overall, the fully epoxy-coated rebar with the end patch performed the best against chloride-induced corrosion, while the black bar performed the worst overall. The rib scrape bar actually ranked lower than the black bar at two of the three chloride concentrations. The better performance of the black bar over the rib scrape bar emphasizes the need for careful handling of epoxy-coated rebar.

CHAPTER 5
CONCLUSION

5.1 SUMMARY

Half-cell potential testing has been recommended as a non-destructive method for assessing the corrosion potential of reinforcing steel in concrete bridge decks. The technique is particularly useful because it can be utilized to evaluate the probability of corrosion before damage is evident at the surface of a bridge deck. The specific objective of this research was to quantify the effects of age, chloride concentration, concrete cover thickness, spatial position, temperature, and presence or condition of epoxy coating on half-cell potential measurements of concrete bridge decks typical of those in Utah.

The laboratory testing associated with this research followed a full-factorial experimental design. Nine rectangular concrete slab specimens were prepared, each containing three black reinforcing steel bars at three different concrete cover depths and four epoxy-coated bars each having different coating conditions. Three batches of concrete were prepared at three different chloride concentrations. Sufficient material was prepared in each batch to allow casting of three slab specimens and seven concrete cylinders. The concrete mixing and casting process was uniform for all three batches to ensure consistency in the research. Three repeated measurements were made at each of three locations along each of the seven bars in all nine of the slabs at three ages, with testing performed at three temperatures per age. In addition, compressive strengths of the concrete cylinders were measured at 7 and 28 days. Statistical analyses of the half-cell potentials were performed using ANOVAs and Tukey's method for multiple comparisons.

5.2 FINDINGS

The factors in the experimentation on black bars included age, chloride concentration, concrete cover thickness, spatial position, and temperature. The results of the ANOVA indicated that variation in each of the factors has a statistically significant impact on half-cell potentials over the ranges of levels investigated in this research. However, the effects of variation in cover thickness and spatial position on half-cell potential readings were determined to be of no practical importance. Half-cell potential measurements became consistently less negative with increasing age and consistently more negative with increasing chloride concentrations and increasing temperature. In all except one of the two-way comparisons evaluated using Tukey's method, the levels of the factors were significantly different from each other. Only the comparison between 2.0- and 3.0-in. cover thicknesses yielded a *p*-value above the threshold, indicating that insufficient evidence is available to conclude that half-cell potential measurements associated with those two levels are significantly different.

Although ASTM C 876 only specifies the measuring of half-cell potentials of uncoated reinforcing steel, credible half-cell potentials were also obtained for epoxy-coated rebar in this research. The factors in the experimentation on epoxy-coated bars included age, chloride concentration, temperature, spatial position, and treatment. The results of the ANOVA indicated that variation in all of the factors except position has a statistically significant impact on half-cell potentials over the ranges of levels investigated in this research. Furthermore, all of the statistically significant factors were also determined in the research to be of practical importance. As in the experimentation on black bar, half-cell potential measurements became consistently less negative with increasing age and more negative with increasing chloride concentrations and increasing temperature. With regard to the factor of treatment, the uncoated rebar had the most negative half-cell potential, followed by epoxy-coated rebar with rib scrapes, pliers strikes, end cuts, and full epoxy coatings, in that order. While these data indicate that a coating, even damaged, reduces the probability of corrosion when compared to uncoated rebar, the data also suggest that both the amount and distribution of the coating damage over the affected rebar influence corrosion. In all except one of the two-way comparisons evaluated using Tukey's method, the levels of the factors were significantly different from each other. Only the comparison between the full epoxy and the end cut yielded a *p*-value above the threshold, indicating that insufficient evidence is available to conclude that half-cell potential measurements associated with those two levels are significantly different. Since the half-cell potential of the fully-coated epoxy bar was similar to that of the rebar with an exposed end cut, the efficacy of the two-part epoxy patch compound comes in question.

5.3 RECOMMENDATIONS

Given these research findings, bridge engineers and managers should have confidence in using half-cell potential testing for assessing the corrosion probability of reinforcing steel in concrete bridge decks. In decks with properties similar to those investigated in this research, variations in age, chloride concentration, temperature, and presence or condition of epoxy coating are associated with practically important variations in half-cell potential readings over the ranges of levels investigated in this research. Because each of these factors plays a role in the corrosion process consistent with its effect on half-cell potential measurements, the half-cell potential technique is recommended for assessing the probability of corrosion of reinforcing steel on bridge decks. Variations in concrete cover thickness and spatial position, however, are not associated with practically important variations in half-cell potential readings over the ranges of levels investigated in this research. This finding is especially convenient since adjustments to half-cell potential readings for variation in either of these factors would require additional testing and measurement not currently required in ASTM C 876.

Although the use of epoxy-coated reinforcement, even when damaged, reduces the probability of corrosion, care should still be taken to minimize any damage to the coating during shipping and field handling. Owners and contractors alike should establish appropriate inspection protocols and repair methods for epoxy-coated reinforcing steel used on bridge decks to ensure maximum service life.

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APPENDIX

TABLE A.1 Half-Cell Potentials at 28 Days for 60°F

Slab	Temperature (^{o}F)	Position	Bar 1	2	3	4	5	6	7
1	60.4	1	-0.333	-0.360	-0.360	-0.251	-0.228	-0.234	-0.197
			-0.340	-0.356	-0.365	-0.251	-0.223	-0.233	-0.197
			-0.341	-0.359	-0.363	-0.252	-0.225	-0.229	-0.198
		2	-0.352	-0.369	-0.366	-0.248	-0.218	-0.227	-0.199
			-0.353	-0.371	-0.367	-0.250	-0.221	-0.223	-0.198
			-0.353	-0.370	-0.369	-0.250	-0.221	-0.222	-0.199
		3	-0.342	-0.366	-0.363	-0.243	-0.219	-0.213	-0.190
			-0.344	-0.366	-0.364	-0.244	-0.221	-0.213	-0.192
			-0.345	-0.365	-0.364	-0.244	-0.220	-0.210	-0.192
2	61.1	1	-0.314	-0.322	-0.328	-0.184	-0.300	-0.211	-0.242
			-0.314	-0.322	-0.330	-0.183	-0.304	-0.200	-0.242
			-0.316	-0.323	-0.332	-0.182	-0.305	-0.197	-0.244
		2	-0.325	-0.340	-0.345	-0.189	-0.310	-0.193	-0.244
			-0.325	-0.341	-0.347	-0.190	-0.313	-0.194	-0.246
			-0.331	-0.341	-0.348	-0.190	-0.312	-0.195	-0.246
		3	-0.345	-0.353	-0.354	-0.195	-0.312	-0.192	-0.247
			-0.348	-0.356	-0.357	-0.197	-0.314	-0.194	-0.248
			-0.348	-0.357	-0.355	-0.198	-0.315	-0.195	-0.248
3	60.4	1	-0.320	-0.337	-0.352	-0.162	-0.182	-0.222	-0.229
			-0.324	-0.339	-0.354	-0.156	-0.182	-0.228	-0.226
			-0.324	-0.341	-0.352	-0.153	-0.184	-0.226	-0.225
		2	-0.329	-0.342	-0.355	-0.151	-0.185	-0.226	-0.227
			-0.331	-0.345	-0.355	-0.151	-0.185	-0.226	-0.226
			-0.333	-0.347	-0.358	-0.151	-0.184	-0.226	-0.226
		3	-0.332	-0.346	-0.354	-0.148	-0.183	-0.227	-0.225
			-0.332	-0.347	-0.356	-0.146	-0.185	-0.225	-0.225
			-0.333	-0.348	-0.357	-0.149	-0.185	-0.227	-0.226

TABLE A.1 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	2	3	4	5	6	7
4	61.0	1	-0.220	-0.210	-0.213	-0.131	-0.125	-0.188	-0.212
			-0.221	-0.209	-0.211	-0.130	-0.128	-0.183	-0.211
			-0.221	-0.208	-0.211	-0.127	-0.128	-0.179	-0.211
		2	-0.201	-0.201	-0.200	-0.123	-0.122	-0.171	-0.206
			-0.201	-0.201	-0.199	-0.121	-0.121	-0.170	-0.206
			-0.201	-0.200	-0.200	-0.120	-0.122	-0.170	-0.205
		3	-0.205	-0.208	-0.204	-0.118	-0.125	-0.177	-0.212
			-0.205	-0.209	-0.204	-0.117	-0.125	-0.176	-0.210
			-0.208	-0.211	-0.204	-0.117	-0.123	-0.176	-0.210
5	60.3	1	-0.285	-0.250	-0.212	-0.231	-0.138	-0.269	-0.360
			-0.285	-0.250	-0.213	-0.229	-0.138	-0.269	-0.360
			-0.285	-0.250	-0.215	-0.229	-0.136	-0.271	-0.361
		2	-0.255	-0.239	-0.197	-0.216	-0.131	-0.273	-0.362
			-0.255	-0.238	-0.200	-0.217	-0.133	-0.269	-0.361
			-0.254	-0.239	-0.198	-0.215	-0.132	-0.269	-0.360
		3	-0.278	-0.253	-0.210	-0.226	-0.136	0.270	-0.359
			-0.277	-0.254	-0.204	-0.215	-0.136	-0.274	-0.365
			-0.279	-0.255	-0.206	-0.217	-0.136	-0.272	-0.357
6	60.5	1	-0.253	-0.250	-0.264	-0.013	-0.178	-0.279	-0.326
			-0.253	-0.249	-0.264	-0.011	-0.176	-0.278	-0.326
			-0.253	-0.248	-0.264	-0.011	-0.177	-0.277	-0.328
		2	-0.241	-0.240	-0.252	-0.013	-0.172	-0.277	-0.329
			-0.241	-0.239	-0.253	-0.011	-0.171	-0.274	-0.328
			-0.243	-0.240	-0.252	-0.009	-0.171	-0.272	-0.328
		3	-0.256	-0.252	-0.264	-0.008	-0.183	-0.287	-0.344
			-0.254	-0.252	-0.264	-0.008	-0.185	-0.287	-0.347
			-0.254	-0.252	-0.265	-0.008	-0.184	-0.287	-0.345

TABLE A.1 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	2	3	4	5	6	7
7	60.2	1	-0.122	-0.142	-0.131	-0.184	-0.135	-0.210	-0.225
			-0.118	-0.141	-0.130	-0.180	-0.132	-0.206	-0.222
			-0.117	-0.142	-0.130	-0.178	-0.131	-0.204	-0.221
		2	-0.117	-0.142	-0.138	-0.176	-0.128	-0.201	-0.223
			-0.119	-0.142	-0.135	-0.175	-0.128	-0.200	-0.221
			-0.119	-0.142	-0.135	-0.174	-0.128	-0.199	-0.221
		3	-0.118	-0.139	-0.135	-0.178	-0.130	-0.203	-0.223
			-0.121	-0.141	-0.133	-0.176	-0.130	-0.202	-0.220
			-0.120	-0.143	-0.133	-0.175	-0.130	-0.202	-0.220
8	61.1	1	-0.140	-0.152	-0.141	-0.105	-0.113	-0.165	-0.167
			-0.143	-0.151	-0.141	-0.100	-0.112	-0.163	-0.165
			-0.145	-0.151	-0.144	-0.097	-0.112	-0.163	-0.165
		2	-0.120	-0.141	-0.140	-0.095	-0.106	-0.159	-0.154
			-0.122	-0.141	-0.141	-0.093	-0.106	-0.160	-0.154
			-0.124	-0.141	-0.141	-0.092	-0.105	-0.159	-0.154
		3	-0.134	-0.148	-0.142	-0.091	-0.110	-0.160	-0.167
			-0.132	-0.147	-0.141	-0.091	-0.110	-0.160	-0.166
			-0.136	-0.148	-0.142	-0.091	-0.110	-0.160	-0.166
9	59.7	1	-0.154	-0.148	-0.150	-0.200	-0.104	-0.188	-0.242
			-0.154	-0.149	-0.149	-0.196	-0.104	-0.183	-0.240
			-0.155	-0.149	-0.146	-0.193	-0.103	-0.181	-0.238
		2	-0.145	-0.150	-0.146	-0.189	-0.098	-0.166	-0.229
			-0.145	-0.147	-0.146	-0.187	-0.096	-0.164	-0.226
			-0.144	-0.145	-0.143	-0.186	-0.096	-0.162	-0.226
		3	-0.148	-0.152	-0.150	-0.194	-0.105	-0.174	-0.239
			-0.148	-0.151	-0.150	-0.194	-0.105	-0.173	-0.239
			-0.148	-0.151	-0.150	-0.192	-0.104	-0.173	-0.239

TABLE A.2 Half-Cell Potentials at 28 Days for 80°F

Slab	Temperature (°F)	Position	Bar 1	Bar 2	Bar 3	Bar 4	Bar 5	Bar 6	Bar 7
1	80.3	1	-0.376	-0.384	-0.382	-0.261	-0.219	-0.295	-0.232
			-0.378	-0.384	-0.385	-0.260	-0.220	-0.288	-0.232
			-0.378	-0.384	-0.384	-0.260	-0.221	-0.286	-0.232
		2	-0.390	-0.392	-0.391	-0.262	-0.221	-0.285	-0.233
			-0.390	-0.391	-0.393	-0.264	-0.220	-0.284	-0.234
			-0.390	-0.391	-0.391	-0.264	-0.223	-0.284	-0.234
		3	-0.382	-0.387	-0.384	-0.259	-0.217	-0.277	-0.228
			-0.382	-0.386	-0.386	-0.260	-0.219	-0.279	-0.232
			-0.382	-0.388	-0.387	-0.259	0.221	-0.277	-0.230
2	80.5	1	-0.334	-0.329	-0.326	-0.219	-0.337	-0.234	-0.262
			-0.330	-0.329	-0.348	-0.217	-0.339	-0.232	-0.265
			-0.334	-0.327	-0.350	-0.216	-0.340	-0.232	-0.265
		2	-0.358	-0.352	-0.363	-0.226	-0.344	-0.231	-0.264
			-0.357	-0.354	-0.364	-0.225	-0.346	-0.230	-0.266
			-0.359	-0.357	-0.368	-0.224	-0.346	-0.232	-0.265
		3	-0.368	-0.360	-0.371	-0.220	-0.344	-0.230	-0.261
			-0.369	-0.362	-0.373	-0.221	-0.347	-0.229	-0.264
			-0.370	-0.362	-0.372	-0.220	-0.348	-0.227	-0.265
3	80.2	1	-0.349	-0.368	-0.359	-0.180	-0.197	-0.240	-0.246
			-0.350	-0.369	-0.359	-0.179	-0.198	-0.242	-0.246
			-0.351	-0.370	-0.361	-0.178	-0.198	-0.242	-0.246
		2	-0.355	-0.377	-0.361	-0.172	-0.194	-0.245	-0.247
			-0.356	-0.379	-0.362	-0.173	-0.196	-0.246	-0.248
			-0.356	-0.379	-0.363	-0.172	-0.197	-0.246	-0.249
		3	-0.356	-0.374	-0.362	-0.167	-0.189	-0.239	-0.247
			-0.357	-0.375	-0.363	-0.168	-0.190	-0.240	-0.247
			-0.357	-0.376	-0.364	-0.167	-0.190	-0.242	-0.246

TABLE A.2 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
4	79.8	1	-0.248	-0.257	-0.250	-0.174	-0.166	-0.213	-0.249
			-0.249	-0.258	-0.252	-0.171	-0.167	-0.212	-0.248
			-0.250	-0.259	-0.253	-0.174	-0.168	-0.210	-0.249
		2	-0.248	-0.255	-0.249	-0.160	-0.165	-0.211	-0.249
			-0.248	-0.256	-0.250	-0.160	-0.166	-0.210	-0.251
			-0.248	-0.256	-0.250	-0.158	-0.167	-0.211	-0.252
		3	-0.245	-0.253	-0.252	-0.154	-0.162	-0.208	-0.253
			-0.248	-0.257	-0.253	-0.158	-0.163	-0.206	-0.255
			-0.248	-0.258	-0.254	-0.155	-0.163	-0.207	-0.255
5	80.0	1	-0.310	-0.283	-0.245	-0.272	-0.178	-0.290	-0.388
			-0.310	-0.285	-0.246	-0.270	-0.178	-0.291	-0.390
			-0.310	-0.284	-0.248	-0.268	-0.177	-0.290	-0.398
		2	-0.305	-0.280	-0.244	-0.260	-0.171	-0.288	-0.390
			-0.307	-0.282	-0.247	-0.260	-0.172	-0.290	-0.390
			-0.307	-0.283	-0.248	-0.260	-0.173	-0.290	-0.391
		3	-0.305	-0.279	-0.245	-0.255	-0.168	-0.289	-0.388
			-0.305	-0.282	-0.248	-0.254	-0.173	-0.291	-0.388
			-0.307	-0.283	-0.248	-0.251	-0.173	-0.291	-0.394
6	79.8	1	-0.285	-0.279	-0.298	-0.212	-0.213	-0.305	-0.348
			-0.286	-0.280	-0.300	-0.210	-0.213	-0.307	-0.350
			-0.285	-0.280	-0.300	-0.211	-0.214	-0.307	-0.350
		2	-0.292	-0.286	-0.300	-0.206	-0.208	-0.303	-0.350
			-0.289	-0.289	-0.301	-0.208	-0.208	-0.304	-0.348
			-0.290	-0.288	-0.302	-0.207	-0.209	-0.304	-0.350
		3	-0.295	-0.291	-0.301	-0.203	-0.214	-0.308	-0.359
			-0.299	-0.293	-0.304	-0.207	-0.215	-0.309	-0.357
			-0.296	-0.294	-0.305	-0.206	-0.216	-0.309	-0.358

TABLE A.2 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	2	3	4	5	6	7
7	80.0	1	-0.173	-0.188	-0.179	-0.177	-0.169	-0.221	-0.270
			-0.174	-0.191	-0.179	-0.173	-0.167	-0.223	-0.266
			-0.173	-0.190	-0.180	-0.173	-0.167	-0.223	-0.262
		2	-0.183	-0.197	-0.188	-0.169	-0.169	-0.221	-0.262
			-0.185	-0.198	-0.189	-0.171	-0.170	-0.221	-0.262
			-0.184	-0.198	-0.188	-0.171	-0.169	-0.222	-0.260
		3	-0.187	-0.199	-0.189	-0.172	-0.171	-0.223	-0.257
			-0.187	-0.201	-0.188	-0.174	-0.174	-0.224	-0.256
			-0.187	-0.201	-0.188	-0.174	-0.173	-0.224	-0.256
8	80.0	1	-0.183	-0.190	-0.182	-0.135	-0.121	-0.183	-0.204
			-0.185	-0.191	-0.182	-0.133	-0.123	-0.184	-0.205
			-0.185	-0.190	-0.181	-0.130	-0.124	-0.184	-0.203
		2	-0.189	-0.193	-0.187	-0.126	-0.126	-0.185	-0.202
			-0.189	-0.193	-0.190	-0.126	-0.126	-0.185	-0.201
			-0.187	-0.192	-0.189	-0.126	-0.126	-0.185	-0.201
		3	-0.190	-0.198	-0.195	-0.130	-0.134	-0.192	-0.205
			-0.193	-0.199	-0.196	-0.130	-0.135	-0.193	-0.206
			-0.188	-0.199	-0.195	-0.130	-0.136	-0.193	-0.207
9	80.0	1	-0.196	-0.183	-0.181	-0.223	-0.143	-0.198	-0.250
			-0.195	-0.183	-0.182	-0.223	-0.145	-0.196	-0.250
			-0.194	-0.182	-0.181	-0.222	-0.144	-0.196	-0.250
		2	-0.196	-0.186	-0.190	-0.227	-0.154	-0.195	-0.254
			-0.196	-0.186	-0.190	-0.227	-0.155	-0.197	-0.253
			-0.196	-0.185	-0.190	-0.228	-0.155	-0.194	-0.253
		3	-0.194	-0.180	-0.185	-0.220	-0.145	-0.191	-0.255
			-0.194	-0.183	-0.185	-0.220	-0.147	-0.192	-0.257
			-0.194	-0.182	-0.185	-0.220	-0.146	-0.192	-0.257

TABLE A.3 Half-Cell Potentials at 28 Days for 100°F

Slab	Temperature (°F)	Position	Bar						
			1	2	3	4	5	6	7
1	99.4	1	-0.400	-0.444	-0.446	-0.305	-0.238	-0.300	-0.271
			-0.403	-0.448	-0.448	-0.308	-0.243	-0.304	-0.267
			-0.403	-0.448	-0.448	-0.308	-0.236	-0.305	-0.269
		2	-0.412	-0.457	-0.455	-0.314	-0.243	-0.309	-0.268
			-0.412	-0.459	-0.456	-0.315	-0.244	-0.310	-0.269
			-0.412	-0.459	-0.457	-0.315	-0.244	-0.309	-0.270
		3	-0.407	-0.452	-0.446	-0.307	-0.240	-0.300	-0.265
			-0.409	-0.452	-0.448	-0.307	-0.239	-0.303	-0.266
			-0.409	-0.454	-0.447	-0.308	-0.239	-0.302	-0.266
2	99.5	1	-0.403	-0.396	-0.427	-0.260	-0.363	-0.270	-0.321
			-0.405	-0.399	-0.431	-0.259	-0.366	-0.273	-0.322
			-0.404	-0.400	-0.429	-0.260	-0.367	-0.270	-0.322
		2	-0.435	-0.427	-0.445	-0.266	-0.374	-0.274	-0.323
			-0.437	-0.427	-0.446	-0.267	-0.377	-0.274	-0.324
			-0.435	-0.429	-0.445	-0.269	-0.378	-0.273	-0.325
		3	-0.449	-0.439	-0.454	-0.265	-0.374	-0.275	-0.322
			-0.450	-0.440	-0.455	-0.266	-0.375	-0.273	-0.323
			-0.451	-0.440	-0.455	-0.264	-0.375	-0.273	-0.325
3	99.2	1	-0.356	-0.373	-0.388	-0.230	-0.238	-0.265	-0.291
			-0.360	-0.382	-0.388	-0.231	-0.240	-0.267	-0.291
			-0.361	-0.385	-0.388	-0.230	-0.241	-0.265	-0.289
		2	-0.379	-0.397	-0.402	-0.240	-0.241	-0.270	-0.296
			-0.380	-0.398	-0.403	-0.240	-0.242	-0.270	-0.295
			-0.381	-0.400	-0.404	-0.240	-0.240	-0.269	-0.296
		3	-0.372	-0.387	-0.382	-0.217	-0.225	-0.257	-0.283
			-0.373	-0.387	-0.383	-0.217	-0.225	-0.255	0.282
			-0.373	-0.387	-0.384	-0.217	-0.224	-0.254	0.283

TABLE A.3 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
4	99.3	1	-0.278	-0.285	-0.280	-0.191	-0.190	-0.241	-0.272
			-0.277	-0.286	-0.283	-0.192	-0.191	-0.239	-0.272
			-0.279	-0.285	-0.282	-0.191	-0.192	-0.239	-0.271
		2	-0.279	-0.286	-0.281	-0.197	-0.189	-0.231	-0.273
			-0.280	-0.286	-0.282	-0.197	-0.189	-0.232	-0.273
			-0.280	-0.288	-0.284	-0.186	-0.188	-0.231	-0.273
		3	-0.281	-0.284	-0.281	-0.181	-0.186	-0.227	-0.265
			-0.282	-0.286	-0.283	-0.180	-0.186	-0.228	-0.267
			-0.281	-0.287	-0.283	-0.182	-0.187	-0.228	-0.267
5	99.2	1	-0.320	-0.296	-0.260	-0.238	-0.180	-0.285	-0.337
			-0.322	-0.296	-0.262	-0.241	-0.178	-0.286	-0.345
			-0.324	-0.297	-0.263	-0.241	-0.180	-0.288	-0.348
		2	-0.329	-0.295	-0.265	-0.242	-0.181	-0.285	-0.350
			-0.330	-0.296	-0.266	-0.242	-0.181	-0.286	-0.350
			-0.329	-0.296	-0.265	-0.238	-0.183	-0.286	-0.351
		3	-0.323	-0.294	-0.263	-0.235	-0.184	-0.283	-0.350
			-0.324	-0.295	-0.264	-0.236	-0.185	-0.284	-0.349
			-0.327	-0.295	-0.264	-0.236	-0.186	-0.286	-0.349
6	99.6	1	-0.308	-0.304	-0.307	-0.229	-0.228	-0.280	-0.344
			-0.308	-0.305	-0.311	-0.231	-0.230	-0.276	-0.346
			-0.309	-0.302	-0.312	-0.230	-0.231	-0.277	-0.347
		2	-0.314	-0.311	-0.317	-0.233	-0.231	-0.274	-0.344
			-0.314	-0.308	-0.319	-0.234	-0.232	-0.277	-0.345
			-0.316	-0.309	-0.319	-0.233	-0.233	-0.278	-0.346
		3	-0.312	-0.303	-0.313	-0.229	-0.224	-0.275	-0.346
			-0.312	-0.304	-0.314	-0.228	-0.227	-0.277	-0.347
			-0.314	-0.305	-0.315	-0.228	-0.228	-0.276	-0.347

TABLE A.3 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	2	3	4	5	6	7
7	99.8	1	-0.200	-0.222	-0.207	-0.215	-0.221	-0.238	-0.257
			-0.202	-0.223	-0.210	-0.214	-0.222	-0.242	-0.262
			-0.202	-0.222	-0.210	-0.214	-0.222	-0.241	-0.260
		2	-0.205	-0.220	-0.205	-0.209	-0.217	-0.240	-0.265
			-0.206	-0.220	-0.207	-0.209	-0.216	-0.240	-0.265
			-0.206	-0.220	-0.208	-0.209	-0.218	-0.239	-0.266
		3	-0.201	-0.219	-0.211	-0.207	-0.212	-0.236	-0.258
			-0.201	-0.219	-0.211	-0.208	-0.213	-0.237	-0.260
			-0.202	-0.220	-0.210	-0.206	-0.214	-0.236	-0.259
8	99.6	1	-0.198	-0.212	-0.206	-0.155	-0.134	-0.182	-0.221
			-0.200	-0.211	-0.206	-0.156	-0.140	-0.189	-0.226
			-0.197	-0.212	-0.205	-0.155	-0.142	-0.192	-0.226
		2	-0.202	-0.220	-0.214	-0.161	-0.137	-0.196	-0.231
			-0.203	-0.220	-0.213	-0.162	-0.143	-0.194	-0.232
			-0.205	-0.219	-0.212	-0.161	-0.145	-0.194	-0.232
		3	-0.212	-0.219	-0.212	-0.159	-0.149	-0.196	-0.228
			-0.212	-0.219	-0.211	-0.153	-0.149	-0.197	-0.228
			-0.213	-0.218	-0.205	-0.153	-0.149	-0.196	-0.230
9	99.8	1	-0.203	-0.196	-0.193	-0.220	-0.160	-0.193	-0.245
			-0.205	-0.196	-0.195	-0.221	-0.160	-0.193	-0.247
			-0.211	-0.194	-0.194	-0.221	-0.160	-0.194	-0.247
		2	-0.208	-0.200	-0.207	-0.234	-0.175	-0.208	-0.251
			-0.209	-0.200	-0.207	-0.235	-0.176	-0.208	-0.252
			-0.208	-0.199	-0.208	-0.234	-0.176	-0.208	-0.253
		3	-0.214	-0.193	-0.201	-0.221	-0.163	-0.194	-0.248
			-0.213	-0.196	-0.201	-0.222	-0.165	-0.194	-0.249
			-0.214	-0.197	-0.203	-0.222	-0.163	-0.195	-0.249

TABLE A.4 Half-Cell Potentials at 56 Days for 60°F

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
1	61.0	1	-0.244	-0.264	-0.246	-0.182	-0.222	-0.226	-0.144
			-0.247	-0.269	-0.248	-0.183	-0.224	-0.227	-0.143
			-0.251	-0.276	-0.249	-0.183	-0.225	-0.226	-0.143
		2	-0.254	-0.279	-0.252	-0.183	-0.226	-0.226	-0.137
			-0.255	-0.280	-0.252	-0.186	-0.226	-0.228	-0.138
			-0.256	-0.281	-0.253	-0.188	-0.228	-0.228	-0.139
		3	-0.249	-0.273	-0.251	-0.188	-0.223	-0.225	-0.134
			-0.251	-0.276	-0.251	-0.184	-0.223	-0.224	-0.134
			-0.251	-0.278	-0.252	-0.189	-0.223	-0.224	-0.134
2	61.6	1	-0.240	-0.269	-0.263	-0.123	-0.179	-0.115	-0.175
			-0.241	-0.271	-0.265	-0.122	-0.179	-0.118	-0.175
			-0.244	-0.272	-0.266	-0.121	-0.180	-0.117	-0.174
		2	-0.258	-0.282	-0.273	-0.130	-0.183	-0.114	-0.171
			-0.259	-0.283	-0.275	-0.127	-0.184	-0.114	-0.172
			-0.262	-0.286	-0.277	0.128	-0.186	-0.116	-0.172
		3	-0.268	-0.291	-0.276	-0.129	-0.182	0.111	-0.173
			-0.268	-0.293	-0.279	-0.127	-0.184	-0.111	-0.173
			-0.267	-0.293	-0.281	-0.126	-0.184	-0.112	-0.173
3	60.7	1	-0.255	-0.276	-0.312	-0.104	-0.192	-0.165	-0.185
			-0.257	-0.277	-0.316	-0.100	-0.194	-0.165	-0.186
			-0.259	-0.277	-0.318	-0.099	-0.193	-0.165	-0.186
		2	-0.262	-0.273	-0.314	-0.093	-0.190	-0.169	-0.184
			-0.269	-0.274	-0.315	-0.093	-0.190	-0.162	-0.186
			-0.268	-0.275	-0.315	-0.091	-0.196	-0.161	-0.186
		3	-0.269	-0.272	-0.309	-0.089	-0.188	-0.157	-0.180
			-0.269	-0.271	-0.308	-0.088	-0.191	-0.157	-0.180
			-0.270	-0.272	-0.308	-0.088	-0.192	-0.157	-0.182

TABLE A.4 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	2	3	4	5	6	7
4	60.9	1	-0.117	-0.132	-0.130	-0.059	-0.073	-0.085	-0.099
			-0.119	-0.133	-0.130	-0.058	-0.076	-0.083	-0.098
			-0.120	-0.135	-0.134	-0.057	-0.076	-0.080	-0.099
		2	-0.132	-0.148	-0.147	-0.056	-0.077	-0.079	-0.097
			-0.133	-0.150	-0.149	-0.056	-0.077	-0.080	-0.098
			-0.133	-0.151	-0.151	-0.054	-0.079	-0.078	-0.098
		3	-0.133	-0.151	-0.155	-0.053	-0.084	-0.077	-0.101
			-0.134	-0.152	-0.157	-0.053	-0.086	-0.078	-0.103
			-0.135	-0.154	-0.158	-0.053	-0.086	-0.075	-0.107
5	60.2	1	-0.150	-0.127	-0.131	-0.092	-0.076	-0.105	-0.165
			-0.154	-0.128	-0.132	-0.091	-0.077	-0.106	-0.163
			-0.162	-0.133	-0.133	-0.091	-0.079	-0.105	-0.163
		2	-0.172	-0.136	-0.136	-0.095	-0.082	-0.110	-0.166
			-0.177	-0.137	-0.137	-0.096	-0.082	-0.110	-0.166
			-0.175	-0.138	-0.137	-0.095	-0.082	-0.111	-0.166
		3	-0.155	-0.135	-0.134	-0.089	-0.078	-0.105	-0.158
			-0.153	-0.131	-0.136	-0.089	-0.077	-0.106	-0.159
			-0.157	-0.130	-0.136	-0.089	-0.078	-0.106	-0.159
6	60.8	1	-0.135	-0.151	-0.160	-0.054	-0.076	-0.141	-0.208
			-0.133	-0.154	-0.163	-0.048	-0.076	-0.133	-0.206
			-0.134	-0.154	-0.164	-0.045	-0.076	-0.130	-0.206
		2	-0.124	-0.155	-0.172	-0.045	-0.079	-0.121	-0.202
			-0.126	-0.160	-0.172	-0.043	-0.080	-0.119	-0.200
			-0.130	-0.162	-0.163	-0.043	-0.081	-0.118	-0.198
		3	-0.123	-0.158	-0.169	-0.038	-0.081	-0.111	-0.188
			-0.126	-0.160	-0.170	-0.039	-0.083	-0.111	-0.187
			-0.126	-0.160	-0.171	-0.038	-0.082	-0.110	-0.191

TABLE A.4 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
7	60.3	1	-0.079	-0.092	-0.094	-0.057	-0.052	-0.109	-0.130
			-0.079	-0.095	-0.096	-0.055	-0.052	-0.107	-0.130
			-0.082	-0.096	-0.096	-0.055	-0.054	-0.104	-0.128
		2	-0.088	-0.096	-0.105	-0.056	-0.065	-0.109	-0.132
			-0.089	-0.096	-0.104	-0.058	-0.065	-0.109	-0.130
			-0.090	-0.097	-0.104	-0.057	-0.065	-0.111	-0.131
		3	-0.082	-0.090	-0.104	-0.055	-0.058	-0.103	-0.122
			-0.083	-0.093	-0.103	-0.055	-0.060	-0.103	-0.123
			-0.083	-0.095	-0.104	-0.055	-0.061	-0.103	-0.123
8	60.4	1	-0.128	-0.131	-0.122	-0.053	-0.061	-0.102	-0.113
			-0.128	-0.131	-0.122	-0.046	-0.060	-0.102	-0.112
			-0.129	-0.130	-0.122	-0.044	-0.060	-0.101	-0.111
		2	-0.130	-0.132	-0.123	-0.044	-0.063	-0.094	-0.082
			-0.130	-0.132	-0.123	-0.043	-0.063	-0.094	-0.083
			-0.130	-0.132	-0.124	-0.043	-0.062	-0.099	-0.087
		3	-0.130	-0.133	-0.125	-0.042	-0.065	-0.097	-0.083
			-0.131	-0.134	-0.126	-0.041	-0.064	-0.098	-0.081
			-0.131	-0.134	-0.125	-0.039	-0.064	-0.101	-0.082
9	60.6	1	-0.137	-0.128	-0.122	-0.091	-0.061	-0.108	-0.158
			-0.136	-0.128	-0.123	-0.086	-0.062	-0.102	-0.154
			-0.135	-0.128	-0.122	-0.078	-0.058	-0.098	-0.153
		2	-0.134	-0.128	-0.126	-0.086	-0.076	-0.105	-0.165
			-0.134	-0.129	-0.125	-0.084	-0.076	-0.103	-0.164
			-0.134	-0.129	-0.125	-0.083	-0.076	-0.102	-0.164
		3	-0.137	-0.131	-0.124	-0.079	-0.069	-0.100	-0.162
			-0.136	-0.130	-0.124	-0.079	-0.069	-0.096	-0.162
			-0.137	-0.130	-0.123	-0.079	-0.070	-0.096	-0.161

TABLE A.5 Half-Cell Potentials at 56 Days for 80°F

Slab	Temperature (°F)	Position	Bar 1	Bar 2	Bar 3	Bar 4	Bar 5	Bar 6	Bar 7
1	80.3	1	-0.272	-0.298	-0.275	-0.221	-0.270	-0.304	-0.152
			-0.271	-0.298	-0.275	-0.221	-0.271	-0.304	-0.151
			-0.273	-0.298	-0.275	-0.221	-0.272	-0.303	-0.152
		2	-0.283	-0.302	-0.277	-0.221	-0.268	-0.307	-0.153
			-0.285	-0.306	-0.278	-0.222	-0.269	-0.307	-0.155
			-0.285	-0.307	-0.280	-0.225	-0.269	-0.308	-0.153
		3	-0.277	-0.302	-0.276	-0.219	-0.271	-0.304	-0.151
			-0.281	-0.304	-0.276	-0.223	-0.265	-0.303	-0.151
			-0.282	-0.305	-0.278	-0.223	-0.269	-0.304	-0.152
2	80.3	1	-0.274	-0.294	-0.295	-0.145	-0.195	-0.141	-0.195
			-0.274	-0.292	-0.294	-0.145	-0.196	-0.140	-0.193
			-0.273	-0.292	-0.283	-0.145	-0.196	-0.149	-0.191
		2	-0.293	-0.312	-0.307	-0.152	-0.204	-0.145	-0.190
			-0.294	-0.312	-0.309	-0.154	-0.207	-0.145	-0.192
			-0.293	-0.311	-0.309	-0.155	-0.208	-0.146	-0.192
		3	-0.303	-0.324	-0.314	-0.156	-0.207	-0.145	-0.193
			-0.308	-0.326	-0.314	-0.156	-0.206	-0.145	-0.195
			-0.308	-0.326	-0.314	-0.155	-0.205	-0.144	-0.193
3	80.3	1	-0.278	-0.300	-0.314	-0.111	-0.213	-0.178	-0.271
			-0.280	-0.301	-0.315	-0.111	-0.213	-0.179	-0.273
			-0.281	-0.304	-0.315	-0.112	-0.214	-0.181	-0.272
		2	-0.293	-0.309	-0.322	-0.112	-0.209	-0.178	-0.271
			-0.292	-0.307	-0.322	-0.111	-0.209	-0.178	-0.273
			-0.292	-0.308	-0.324	-0.112	-0.211	-0.180	-0.273
		3	-0.289	-0.303	-0.322	-0.104	-0.209	-0.172	-0.269
			-0.291	-0.304	-0.322	-0.104	-0.212	-0.174	-0.268
			-0.291	-0.305	-0.323	-0.103	-0.211	-0.174	-0.270

TABLE A.5 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
4	80.0	1	-0.175	-0.195	-0.193	-0.125	-0.109	-0.114	-0.151
			-0.178	-0.195	-0.194	-0.124	-0.110	-0.113	-0.151
			-0.180	-0.196	-0.195	-0.120	-0.110	-0.112	-0.150
		2	-0.182	-0.197	-0.193	-0.118	-0.111	-0.112	-0.147
			-0.183	-0.197	-0.194	-0.117	-0.111	-0.110	-0.147
			-0.184	-0.196	-0.193	-0.115	-0.111	-0.108	-0.147
		3	-0.187	-0.196	-0.196	-0.114	-0.112	-0.108	-0.149
			-0.187	-0.199	-0.197	-0.113	-0.112	-0.107	-0.149
			-0.188	-0.200	-0.197	-0.112	-0.113	-0.106	-0.148
5	79.6	1	-0.213	-0.184	-0.173	-0.146	-0.119	-0.148	-0.194
			-0.213	-0.185	-0.175	-0.143	-0.120	-0.147	-0.194
			-0.214	-0.185	-0.175	-0.143	-0.120	-0.148	-0.192
		2	-0.214	-0.186	-0.176	-0.142	-0.121	-0.149	-0.189
			-0.215	-0.186	-0.176	-0.142	-0.121	-0.149	-0.190
			-0.214	-0.187	-0.176	-0.142	-0.121	-0.149	-0.190
		3	-0.216	-0.188	-0.178	-0.141	-0.119	-0.148	-0.190
			-0.217	-0.189	-0.178	-0.140	-0.120	-0.148	-0.190
			-0.217	-0.189	-0.177	-0.139	-0.120	-0.147	-0.189
6	79.4	1	-0.187	-0.211	-0.219	-0.090	-0.122	-0.158	-0.229
			-0.191	-0.211	-0.219	-0.089	-0.123	-0.156	-0.229
			-0.193	-0.212	-0.219	-0.088	-0.123	-0.154	-0.229
		2	-0.190	-0.214	-0.218	-0.089	-0.123	-0.152	-0.230
			-0.189	-0.211	-0.220	-0.086	-0.124	-0.151	-0.230
			-0.192	-0.213	-0.220	-0.087	-0.124	-0.151	-0.230
		3	-0.204	-0.222	-0.227	-0.087	-0.127	-0.151	-0.228
			-0.204	-0.222	-0.227	-0.086	-0.127	-0.150	-0.229
			-0.204	-0.222	-0.228	-0.086	-0.127	-0.150	-0.229

TABLE A.5 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
7	79.8	1	-0.116	-0.143	-0.146	-0.122	-0.117	-0.164	-0.163
			-0.118	-0.144	-0.146	-0.120	-0.116	-0.164	-0.162
			-0.120	-0.145	-0.146	-0.118	-0.115	-0.164	-0.162
		2	-0.120	-0.142	-0.143	-0.113	-0.111	-0.160	-0.161
			-0.121	-0.143	-0.144	-0.112	-0.111	-0.158	-0.161
			-0.122	-0.143	-0.143	-0.110	-0.111	-0.158	-0.160
		3	-0.121	-0.143	-0.145	-0.114	-0.111	-0.159	-0.160
			-0.124	-0.144	-0.145	-0.111	-0.111	-0.158	-0.159
			-0.125	-0.145	-0.145	-0.110	-0.111	-0.158	-0.159
8	79.6	1	-0.135	-0.136	-0.133	-0.065	-0.083	-0.121	-0.157
			-0.129	-0.140	-0.133	-0.064	-0.083	-0.121	-0.157
			-0.132	-0.141	-0.133	-0.064	-0.083	-0.121	-0.156
		2	-0.132	-0.137	-0.130	-0.063	-0.084	-0.124	-0.160
			-0.131	-0.137	-0.132	-0.063	-0.085	-0.125	-0.159
			-0.131	0.140	-0.133	-0.063	-0.085	-0.125	-0.158
		3	-0.135	-0.147	-0.137	-0.060	-0.087	-0.124	-0.155
			-0.135	-0.147	-0.137	-0.058	-0.087	-0.124	-0.155
			-0.136	-0.147	-0.136	-0.057	-0.087	-0.123	-0.154
9	79.9	1	-0.120	-0.130	-0.131	-0.136	-0.094	-0.115	-0.177
			-0.124	-0.130	-0.131	-0.132	-0.095	-0.112	-0.176
			-0.126	-0.130	-0.132	-0.130	-0.095	-0.111	-0.175
		2	-0.129	-0.132	-0.136	-0.129	-0.099	-0.113	-0.172
			-0.131	-0.133	-0.135	-0.127	-0.100	-0.112	-0.172
			-0.132	-0.133	-0.135	-0.125	-0.100	-0.111	-0.172
		3	-0.137	-0.133	-0.136	-0.121	-0.097	-0.106	-0.170
			-0.137	-0.134	-0.136	-0.121	-0.098	-0.107	-0.170
			-0.137	-0.134	-0.136	-0.121	-0.099	-0.107	-0.169

TABLE A.6 Half-Cell Potentials at 56 Days for 100°F

Slab	Temperature (°F)	Position	Bar 1	Bar 2	Bar 3	Bar 4	Bar 5	Bar 6	Bar 7
1	98.6	1	-0.293	-0.314	-0.278	-0.239	-0.366	-0.365	-0.192
			-0.296	-0.315	-0.278	-0.241	-0.367	-0.367	-0.190
			-0.296	-0.313	-0.278	-0.241	-0.369	-0.366	-0.187
		2	-0.310	-0.323	-0.289	-0.250	-0.374	-0.374	-0.185
			-0.310	-0.323	-0.287	-0.250	-0.374	-0.374	-0.184
			-0.310	-0.324	-0.286	-0.252	-0.375	-0.373	-0.185
		3	-0.304	-0.324	-0.288	-0.252	-0.375	-0.367	-0.183
			-0.304	-0.321	-0.288	-0.256	-0.374	-0.367	-0.182
			-0.301	-0.323	-0.286	-0.256	-0.373	-0.370	-0.177
2	98.7	1	-0.304	-0.313	-0.311	-0.170	-0.207	-0.166	-0.210
			-0.305	-0.314	-0.311	-0.169	-0.207	-0.167	-0.211
			-0.305	-0.315	-0.312	-0.170	-0.207	-0.167	-0.209
		2	-0.322	-0.332	-0.331	-0.179	-0.216	-0.173	-0.214
			-0.323	-0.333	-0.330	-0.183	-0.216	-0.170	-0.216
			-0.323	-0.333	-0.335	-0.183	-0.213	-0.171	-0.215
		3	-0.350	-0.353	-0.344	-0.198	-0.222	-0.173	-0.217
			-0.348	-0.353	-0.344	-0.197	-0.221	-0.173	-0.218
			-0.345	-0.353	-0.344	-0.193	-0.220	-0.172	-0.217
3	98.9	1	-0.304	-0.313	-0.311	-0.170	-0.207	-0.166	-0.210
			-0.305	-0.314	-0.311	-0.169	-0.207	-0.167	-0.211
			-0.305	-0.315	-0.312	-0.170	-0.207	-0.167	-0.209
		2	-0.322	-0.332	-0.331	-0.179	-0.216	-0.173	-0.214
			-0.323	-0.333	-0.330	-0.183	-0.216	-0.170	-0.216
			-0.323	-0.333	-0.335	-0.183	-0.213	-0.171	-0.215
		3	-0.350	-0.353	-0.344	-0.198	-0.222	-0.173	-0.217
			-0.348	-0.353	-0.344	-0.197	-0.221	-0.173	-0.218
			-0.345	-0.353	-0.344	-0.193	-0.220	-0.172	-0.217

TABLE A.6 (Continued)

Slab	Temperature (°F)	Position	Bar						
			1	2	3	4	5	6	7
4	98.6	1	-0.155	-0.187	-0.190	-0.073	-0.110	-0.101	-0.157
			-0.162	-0.190	-0.194	-0.077	-0.114	-0.100	-0.158
			-0.165	-0.190	-0.194	-0.080	-0.116	-0.101	-0.156
		2	-0.173	-0.193	-0.195	-0.081	-0.117	-0.108	-0.157
			-0.175	-0.192	-0.196	-0.080	-0.118	-0.107	-0.157
			-0.178	-0.194	-0.196	-0.075	-0.117	-0.106	-0.157
		3	-0.174	-0.200	-0.200	-0.075	-0.116	-0.101	-0.152
			-0.178	-0.200	-0.200	-0.070	-0.116	-0.100	-0.153
			-0.181	-0.200	-0.200	-0.073	-0.118	-0.100	-0.153
5	98.8	1	-0.195	-0.179	-0.164	-0.139	-0.111	-0.148	-0.194
			-0.199	-0.180	-0.169	-0.142	-0.115	-0.148	-0.192
			-0.201	-0.180	-0.169	-0.141	-0.114	-0.148	-0.192
		2	-0.197	-0.173	-0.162	-0.143	-0.114	-0.151	-0.189
			-0.199	-0.174	-0.160	-0.145	-0.116	-0.152	-0.192
			-0.202	-0.176	-0.163	-0.144	-0.117	-0.152	-0.193
		3	-0.204	-0.179	-0.165	-0.146	-0.116	-0.149	-0.191
			-0.204	-0.181	-0.169	-0.144	-0.116	-0.149	-0.193
			-0.203	-0.183	-0.165	-0.144	-0.115	-0.150	-0.193
6	98.8	1	-0.171	-0.212	-0.217	-0.104	-0.127	-0.160	-0.230
			-0.178	-0.216	-0.220	-0.106	-0.127	-0.162	-0.227
			-0.180	-0.216	-0.219	-0.106	-0.127	-0.157	-0.228
		2	-0.193	-0.218	-0.207	-0.105	-0.127	-0.153	-0.232
			-0.191	-0.215	-0.213	-0.104	-0.129	-0.157	-0.232
			-0.192	-0.213	-0.214	-0.105	-0.128	-0.157	-0.231
		3	-0.200	-0.220	-0.222	-0.106	-0.129	-0.156	-0.229
			-0.200	-0.219	-0.222	-0.104	-0.131	-0.156	-0.229
			-0.200	-0.219	-0.221	-0.105	-0.130	-0.155	-0.229

TABLE A.6 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
7	99.4	1	-0.131	-0.135	-0.139	-0.107	-0.109	-0.138	-0.141
			-0.133	-0.140	-0.133	-0.106	-0.096	-0.139	-0.143
			-0.132	-0.140	-0.137	-0.105	-0.104	-0.138	-0.136
		2	-0.120	-0.138	-0.134	-0.101	-0.108	-0.138	-0.143
			-0.121	-0.142	-0.130	-0.105	-0.109	-0.133	-0.144
			-0.123	-0.141	-0.133	-0.105	-0.111	-0.133	-0.141
		3	-0.123	-0.140	-0.135	-0.106	-0.108	-0.138	-0.138
			-0.120	-0.145	-0.136	-0.106	-0.109	-0.135	-0.142
			-0.122	-0.141	-0.136	-0.106	-0.109	-0.135	-0.141
8	99.9	1	-0.126	-0.146	-0.134	-0.076	-0.083	-0.120	-0.144
			-0.130	-0.148	-0.136	-0.079	-0.083	-0.119	-0.146
			-0.133	-0.149	-0.137	-0.076	-0.084	-0.117	-0.145
		2	-0.127	-0.149	-0.136	-0.080	-0.087	-0.120	-0.146
			-0.129	-0.149	-0.138	-0.079	-0.087	-0.121	-0.146
			-0.131	-0.148	-0.139	-0.079	-0.086	-0.122	-0.146
		3	-0.131	-0.151	-0.140	-0.076	-0.087	-0.122	-0.140
			-0.136	-0.152	-0.139	-0.075	-0.088	-0.122	-0.143
			-0.135	-0.152	-0.139	-0.075	-0.088	-0.123	-0.141
9	99.6	1	-0.121	-0.127	-0.126	-0.112	-0.096	-0.101	-0.158
			-0.125	-0.129	-0.126	-0.116	-0.091	-0.099	-0.159
			-0.127	-0.127	-0.127	-0.116	-0.098	-0.100	-0.157
		2	-0.134	-0.123	-0.126	-0.120	-0.103	-0.099	-0.168
			-0.134	-0.124	-0.127	-0.119	-0.104	-0.101	-0.168
			-0.135	-0.126	-0.129	-0.119	-0.104	-0.104	-0.167
		3	-0.136	-0.127	-0.132	-0.120	-0.101	-0.106	-0.163
			-0.138	-0.131	-0.131	-0.119	-0.101	-0.106	-0.165
			-0.138	-0.130	-0.131	-0.119	-0.100	-0.106	-0.167

TABLE A.7 Half-Cell Potentials at 90 Days for 60°F

Slab	Temperature (°F)	Position	Bar						
			1	2	3	4	5	6	7
1	61.9	1	-0.191	-0.244	-0.195	-0.095	-0.111	-0.125	-0.102
			-0.195	-0.245	-0.195	-0.095	-0.112	-0.125	-0.098
			-0.196	-0.245	-0.197	-0.096	-0.113	-0.124	-0.098
		2	-0.215	-0.259	-0.196	-0.096	-0.114	-0.124	-0.092
			-0.215	-0.258	-0.198	-0.096	-0.114	-0.124	-0.091
			-0.216	-0.257	-0.199	-0.098	-0.115	-0.123	-0.093
		3	-0.211	-0.260	-0.206	-0.102	-0.117	-0.129	-0.100
			-0.213	-0.261	-0.205	-0.102	-0.119	-0.130	-0.099
			-0.215	-0.261	-0.205	-0.102	-0.117	-0.132	-0.097
2	61.6	1	-0.252	-0.262	-0.234	-0.101	-0.150	-0.120	-0.129
			-0.254	-0.261	-0.235	-0.101	-0.154	-0.120	-0.127
			-0.256	-0.263	-0.236	-0.100	-0.154	-0.119	-0.128
		2	-0.259	-0.267	-0.240	-0.103	-0.154	-0.125	-0.138
			-0.259	-0.268	-0.242	-0.102	-0.155	-0.124	-0.138
			-0.260	-0.270	-0.240	-0.102	-0.157	-0.120	-0.138
		3	-0.255	-0.265	-0.239	-0.101	-0.167	-0.125	-0.150
			-0.258	-0.263	-0.237	-0.101	-0.168	-0.125	-0.150
			-0.260	-0.264	-0.236	-0.101	-0.169	-0.124	-0.150
3	61.4	1	-0.276	-0.249	-0.272	-0.139	-0.156	-0.159	-0.197
			-0.278	-0.250	-0.273	-0.139	-0.157	-0.160	-0.198
			-0.280	-0.252	-0.273	-0.138	-0.157	-0.160	-0.199
		2	-0.281	-0.251	-0.273	-0.135	-0.160	-0.161	-0.198
			-0.283	-0.255	-0.275	-0.134	-0.158	-0.163	-0.199
			-0.282	-0.257	-0.278	-0.135	-0.159	-0.163	-0.200
		3	-0.281	-0.254	-0.274	-0.137	-0.161	-0.161	-0.184
			-0.285	-0.255	-0.275	-0.137	-0.161	-0.161	-0.186
			-0.284	-0.256	-0.274	-0.137	-0.162	-0.163	-0.187

TABLE A.7 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	Bar 2	Bar 3	Bar 4	Bar 5	Bar 6	Bar 7
4	61.0	1	-0.050	-0.084	-0.087	-0.009	-0.030	-0.021	-0.056
			-0.052	-0.085	-0.088	-0.012	-0.032	-0.027	-0.054
			-0.052	-0.087	-0.090	-0.013	-0.032	-0.027	-0.056
		2	-0.072	-0.097	-0.094	-0.006	-0.023	-0.012	-0.028
			-0.067	-0.099	-0.090	-0.009	-0.024	-0.013	-0.027
			-0.070	-0.103	-0.089	-0.012	-0.025	-0.016	-0.029
		3	-0.081	-0.113	-0.111	-0.025	-0.046	-0.038	-0.060
			-0.083	-0.114	-0.114	-0.026	-0.050	-0.037	-0.062
			-0.085	-0.116	-0.115	-0.026	-0.050	-0.036	-0.061
5	61.0	1	-0.086	-0.090	-0.085	-0.056	-0.043	-0.069	-0.106
			-0.088	-0.088	-0.084	-0.054	-0.043	-0.070	-0.106
			-0.093	-0.089	-0.083	-0.054	-0.043	-0.071	-0.106
		2	-0.082	-0.063	-0.067	-0.048	-0.030	-0.059	-0.085
			-0.084	-0.067	-0.067	-0.046	-0.031	-0.059	-0.086
			-0.085	-0.070	-0.070	-0.048	-0.034	-0.060	-0.083
		3	-0.113	-0.102	-0.100	-0.067	-0.064	-0.080	-0.100
			-0.115	-0.101	-0.101	-0.067	-0.065	-0.079	-0.108
			-0.118	-0.103	-0.101	-0.067	-0.066	-0.075	-0.104
6	61.2	1	-0.055	-0.094	-0.094	-0.012	-0.028	-0.040	-0.136
			-0.057	-0.095	-0.095	-0.010	-0.029	-0.035	-0.135
			-0.058	-0.096	-0.096	-0.010	-0.029	-0.037	-0.135
		2	-0.056	-0.092	-0.092	-0.009	-0.025	-0.033	-0.130
			-0.057	-0.094	-0.092	-0.010	-0.026	-0.034	-0.131
			-0.060	-0.094	-0.093	-0.008	-0.025	-0.035	-0.131
		3	-0.066	-0.098	-0.092	-0.007	-0.026	-0.032	-0.128
			-0.066	-0.096	-0.093	-0.007	-0.025	-0.033	-0.128
			-0.069	-0.097	-0.094	-0.008	-0.023	-0.033	-0.128

TABLE A.7 (Continued)

Slab	Temperature (°F)	Position	Bar 1	2	3	4	5	6	7
7	60.9	1	-0.031	-0.048	-0.049	-0.012	-0.027	-0.048	-0.053
			-0.032	-0.051	-0.050	-0.012	-0.031	-0.049	-0.051
			-0.032	-0.051	-0.050	-0.014	-0.029	-0.049	-0.052
		2	-0.044	-0.063	-0.069	-0.015	-0.037	-0.047	-0.064
			-0.043	-0.067	-0.068	-0.014	-0.041	-0.047	-0.065
			-0.044	-0.067	-0.070	-0.013	-0.041	-0.049	-0.067
		3	-0.071	-0.093	-0.094	-0.034	-0.069	-0.049	-0.087
			-0.070	-0.093	-0.096	-0.034	-0.069	-0.050	-0.086
			-0.069	-0.093	-0.096	-0.033	-0.070	-0.050	-0.082
8	61.1	1	-0.071	-0.063	-0.053	-0.008	-0.041	-0.075	-0.062
			-0.071	-0.065	-0.053	-0.009	-0.042	-0.076	-0.062
			-0.073	-0.067	-0.053	-0.010	-0.043	-0.077	-0.064
		2	-0.060	-0.064	-0.055	-0.019	-0.055	-0.084	-0.066
			-0.062	-0.064	-0.056	-0.020	-0.054	-0.084	-0.066
			-0.062	-0.064	-0.057	-0.022	-0.054	-0.084	-0.067
		3	-0.060	-0.064	-0.062	-0.027	-0.056	-0.084	-0.064
			-0.060	-0.065	-0.062	-0.027	-0.057	-0.083	-0.064
			-0.061	-0.065	-0.063	-0.028	-0.057	-0.083	-0.064
9	60.8	1	-0.082	-0.085	-0.086	-0.058	-0.055	-0.055	-0.116
			-0.080	-0.087	-0.087	-0.056	-0.055	-0.056	-0.116
			-0.078	-0.087	-0.086	-0.055	-0.055	-0.055	-0.116
		2	-0.074	-0.082	-0.071	-0.040	-0.048	-0.048	-0.113
			-0.071	-0.077	-0.072	-0.039	-0.042	-0.066	-0.111
			-0.071	-0.077	-0.069	-0.039	-0.042	-0.064	-0.110
		3	-0.077	-0.080	-0.085	-0.078	-0.035	-0.056	-0.107
			-0.085	-0.084	-0.085	-0.079	-0.036	-0.056	-0.107
			-0.089	-0.087	-0.087	-0.079	-0.040	-0.056	-0.109

TABLE A.8 Half-Cell Potentials at 90 Days for 80°F

Slab	Temperature (°F)	Position	Bar						
			1	2	3	4	5	6	7
1	79.8	1	-0.217	-0.275	-0.220	-0.132	-0.136	-0.151	-0.122
			-0.221	-0.276	-0.222	-0.129	-0.137	-0.152	-0.122
			-0.223	-0.278	-0.226	-0.133	-0.138	-0.152	-0.123
		2	-0.237	-0.291	-0.225	-0.137	-0.141	-0.151	-0.122
			-0.240	-0.292	-0.227	-0.138	-0.142	-0.153	-0.123
			-0.241	-0.293	-0.230	-0.139	-0.144	-0.153	-0.124
		3	-0.240	-0.293	-0.229	-0.135	-0.140	-0.151	-0.119
			-0.242	-0.296	-0.231	-0.137	-0.141	-0.153	-0.121
			-0.245	-0.298	-0.232	-0.141	-0.142	-0.152	-0.121
2	79.8	1	-0.253	-0.260	-0.232	-0.126	-0.171	-0.139	-0.159
			-0.254	-0.261	-0.234	-0.126	-0.173	-0.138	-0.159
			-0.256	-0.261	-0.232	-0.126	-0.174	-0.137	-0.160
		2	-0.271	-0.273	-0.242	-0.133	-0.179	-0.139	-0.165
			-0.272	-0.275	-0.242	-0.134	-0.180	-0.139	-0.166
			-0.271	-0.276	-0.242	-0.134	-0.181	-0.139	-0.166
		3	-0.286	-0.290	-0.254	-0.142	-0.181	-0.139	-0.163
			-0.285	-0.290	-0.255	-0.141	-0.182	-0.138	-0.163
			-0.286	-0.291	-0.256	-0.141	-0.184	-0.138	-0.165
3	79.7	1	-0.268	-0.237	-0.251	-0.138	-0.153	-0.156	-0.188
			-0.271	-0.238	-0.253	-0.138	-0.152	-0.158	-0.191
			-0.272	-0.241	-0.251	-0.138	-0.154	-0.159	-0.194
		2	-0.276	-0.243	-0.262	-0.139	-0.154	-0.161	-0.194
			-0.277	-0.246	-0.263	-0.140	-0.155	-0.162	-0.195
			-0.278	-0.246	-0.264	-0.141	-0.156	-0.163	-0.195
		3	-0.274	-0.239	-0.258	-0.137	-0.157	-0.160	-0.191
			-0.276	-0.243	-0.260	-0.137	-0.159	-0.162	-0.193
			-0.276	-0.244	-0.262	-0.141	-0.159	-0.162	-0.194

TABLE A.8 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
4	79.5	1	-0.134	-0.161	-0.140	-0.050	-0.045	-0.043	-0.090
			-0.135	-0.162	-0.141	-0.050	-0.049	-0.044	-0.090
			-0.137	-0.162	-0.141	-0.045	-0.049	-0.045	-0.091
		2	-0.141	-0.167	-0.136	-0.032	-0.040	-0.038	-0.079
			-0.142	-0.166	-0.139	-0.034	-0.049	-0.042	-0.079
			-0.143	-0.163	-0.140	-0.035	-0.056	-0.042	-0.080
		3	-0.145	-0.163	-0.140	-0.039	-0.056	-0.037	-0.075
			-0.147	-0.164	-0.134	-0.039	-0.052	-0.042	-0.078
			-0.147	-0.167	-0.140	-0.045	-0.055	-0.044	-0.080
5	79.5	1	-0.115	-0.115	-0.110	-0.075	-0.048	-0.079	-0.128
			-0.119	-0.117	-0.107	-0.070	-0.053	-0.081	-0.128
			-0.121	-0.118	-0.114	-0.072	-0.056	-0.090	-0.128
		2	-0.097	-0.097	-0.092	-0.042	-0.038	-0.071	-0.126
			-0.102	-0.096	-0.095	-0.054	-0.041	-0.076	-0.128
			-0.105	-0.097	-0.099	-0.057	-0.046	-0.078	-0.130
		3	-0.128	-0.113	-0.114	-0.071	-0.061	-0.089	-0.131
			-0.130	-0.114	-0.119	-0.076	-0.064	-0.090	-0.131
			-0.132	-0.116	-0.118	-0.076	-0.066	-0.088	-0.132
6	79.8	1	-0.141	-0.167	-0.156	-0.053	-0.087	-0.093	-0.190
			-0.140	-0.167	-0.158	-0.049	-0.088	-0.094	-0.189
			-0.142	-0.167	-0.158	-0.047	-0.089	-0.091	-0.188
		2	-0.141	-0.170	-0.156	-0.048	-0.087	-0.091	-0.193
			-0.144	-0.170	-0.158	-0.046	-0.088	-0.092	-0.193
			-0.145	-0.170	-0.160	-0.045	-0.088	-0.092	-0.192
		3	-0.156	-0.173	-0.164	-0.049	-0.094	-0.092	-0.191
			-0.156	-0.173	-0.164	-0.047	-0.094	-0.093	-0.192
			-0.157	-0.173	-0.165	-0.047	-0.094	-0.092	-0.193

TABLE A.8 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	2	3	4	5	6	7
7	79.0	1	-0.090	-0.110	-0.104	-0.052	-0.036	-0.028	-0.101
			-0.092	-0.110	-0.105	-0.054	-0.033	-0.029	-0.102
			-0.092	-0.111	-0.105	-0.053	-0.037	-0.032	-0.102
		2	-0.078	-0.098	-0.093	-0.039	-0.032	-0.023	-0.095
			-0.080	-0.100	-0.096	-0.038	-0.024	-0.026	-0.097
			-0.082	-0.101	-0.097	-0.038	-0.029	-0.028	-0.098
		3	-0.078	-0.098	-0.090	-0.046	-0.049	-0.032	-0.100
			-0.079	-0.097	-0.093	-0.043	-0.053	-0.034	-0.101
			-0.080	-0.097	-0.093	-0.046	-0.053	-0.035	-0.101
8	79.7	1	-0.097	-0.108	-0.100	-0.042	-0.044	-0.070	-0.105
			-0.098	-0.109	-0.101	-0.039	-0.046	-0.071	-0.106
			-0.099	-0.110	-0.102	-0.041	-0.049	-0.073	-0.105
		2	-0.079	-0.095	-0.087	-0.026	-0.020	-0.073	-0.107
			-0.083	-0.099	-0.086	-0.025	-0.028	-0.073	-0.107
			-0.085	-0.097	-0.086	-0.022	-0.031	-0.073	-0.106
		3	-0.091	-0.102	-0.100	-0.043	-0.045	-0.075	-0.103
			-0.092	-0.104	-0.100	-0.040	-0.046	-0.076	-0.105
			-0.093	-0.105	-0.101	-0.038	-0.047	-0.076	-0.105
9	79.4	1	-0.099	-0.102	-0.099	-0.073	-0.056	-0.060	-0.091
			-0.100	-0.102	-0.099	-0.073	-0.061	-0.065	-0.104
			-0.100	-0.102	-0.099	-0.073	-0.062	-0.064	-0.100
		2	-0.096	-0.097	-0.088	-0.061	-0.056	-0.062	-0.088
			-0.096	-0.097	-0.090	-0.064	-0.058	-0.060	-0.091
			-0.096	-0.098	-0.090	-0.064	-0.058	-0.060	-0.089
		3	-0.102	-0.105	-0.092	-0.070	-0.060	-0.064	-0.105
			-0.103	-0.106	-0.094	-0.065	-0.062	-0.064	-0.111
			-0.104	-0.106	-0.095	-0.066	-0.062	-0.065	-0.114

TABLE A.9 Half-Cell Potentials at 90 Days for 100°F

Slab	Temperature (°F)	Position	Bar 1	2	3	4	5	6	7
1	98.6	1	-0.237	-0.286	-0.230	-0.146	-0.160	-0.169	-0.135
			-0.239	-0.290	-0.233	-0.144	-0.159	-0.168	-0.137
			-0.240	-0.289	-0.235	-0.147	-0.158	-0.168	-0.138
		2	-0.255	-0.308	-0.247	-0.146	-0.159	-0.170	-0.138
			-0.258	-0.310	-0.248	-0.149	-0.160	-0.172	-0.138
			-0.261	-0.311	-0.250	-0.147	-0.160	-0.172	-0.139
		3	-0.254	-0.305	-0.255	-0.144	-0.151	-0.160	-0.126
			-0.260	-0.304	-0.254	-0.149	-0.150	-0.160	-0.128
			-0.260	-0.290	-0.251	-0.150	-0.150	-0.161	-0.130
2	98.5	1	-0.240	-0.292	-0.248	-0.143	-0.176	-0.148	-0.175
			-0.251	-0.296	-0.250	-0.142	-0.177	-0.143	-0.180
			-0.257	-0.297	-0.252	-0.142	-0.177	-0.143	-0.179
		2	-0.284	-0.311	-0.260	-0.155	-0.185	-0.150	-0.182
			-0.281	-0.310	-0.262	-0.157	-0.186	-0.146	-0.183
			-0.290	-0.310	-0.260	-0.157	-0.185	-0.146	-0.183
		3	-0.296	-0.310	-0.272	-0.160	-0.185	-0.148	-0.181
			-0.302	-0.310	-0.270	-0.162	-0.186	-0.147	-0.182
			-0.302	-0.311	-0.267	-0.156	-0.184	-0.146	-0.182
3	98.9	1	-0.262	-0.258	-0.260	-0.144	-0.150	-0.174	-0.200
			-0.263	-0.259	-0.265	-0.146	-0.158	-0.169	-0.200
			-0.266	-0.256	-0.270	-0.144	-0.158	-0.171	-0.200
		2	-0.272	-0.263	-0.270	-0.148	-0.160	-0.173	-0.201
			-0.274	-0.266	-0.276	-0.150	-0.160	-0.174	-0.201
			-0.276	-0.266	-0.277	-0.150	-0.164	-0.175	-0.202
		3	-0.278	-0.263	-0.272	-0.144	-0.166	-0.171	-0.200
			-0.278	-0.264	-0.272	-0.144	-0.165	-0.173	-0.200
			-0.278	-0.263	-0.270	-0.144	-0.167	-0.173	-0.200

TABLE A.9 (Continued)

Slab	Temperature (^oF)	Position	Bar 1	2	3	4	5	6	7
4	98.7	1	-0.120	-0.160	-0.151	-0.062	-0.093	-0.090	-0.128
			-0.120	-0.161	-0.148	-0.057	-0.089	-0.085	-0.126
			-0.123	-0.163	-0.148	-0.057	-0.088	-0.086	-0.125
		2	-0.137	-0.166	-0.150	-0.064	-0.103	-0.090	-0.130
			-0.137	-0.166	-0.150	-0.057	-0.103	-0.089	-0.132
			-0.137	-0.166	-0.151	-0.060	-0.103	-0.090	-0.132
		3	-0.146	-0.169	-0.147	-0.057	-0.102	-0.083	-0.128
			-0.147	-0.169	-0.150	-0.059	-0.100	-0.083	-0.129
			-0.148	-0.170	-0.150	-0.060	-0.099	-0.083	-0.127
5	99.1	1	-0.127	-0.127	-0.127	-0.106	-0.090	-0.103	-0.147
			-0.132	-0.126	-0.135	-0.106	-0.090	-0.110	-0.151
			-0.135	-0.125	-0.135	-0.105	-0.097	-0.111	-0.153
		2	-0.119	-0.122	-0.126	-0.109	-0.097	-0.112	-0.153
			-0.122	-0.125	-0.123	-0.108	-0.098	-0.115	-0.153
			-0.128	-0.125	-0.124	-0.106	-0.100	-0.117	-0.154
		3	-0.144	-0.135	-0.130	-0.110	-0.099	-0.116	-0.150
			-0.144	-0.140	-0.136	-0.105	-0.100	-0.117	-0.154
			-0.150	-0.135	-0.135	-0.106	-0.100	-0.118	-0.156
6	98.9	1	-0.121	-0.162	-0.160	-0.038	-0.107	-0.113	-0.192
			-0.127	-0.167	-0.156	-0.042	-0.107	-0.113	-0.197
			-0.130	-0.165	-0.160	-0.044	-0.109	-0.110	-0.198
		2	-0.128	-0.171	-0.166	-0.050	-0.107	-0.113	-0.200
			-0.129	-0.170	-0.165	-0.050	-0.107	-0.113	-0.201
			-0.131	-0.177	-0.164	-0.045	-0.102	-0.109	-0.199
		3	-0.154	-0.177	-0.165	-0.046	-0.101	-0.110	-0.200
			-0.150	-0.170	-0.165	-0.050	-0.100	-0.110	-0.200
			-0.156	-0.169	-0.165	-0.044	-0.098	-0.112	-0.199

TABLE A.9 (Continued)

Slab	Temperature (^oF)	Position	Bar						
			1	2	3	4	5	6	7
7	98.9	1	-0.120	-0.132	-0.119	-0.082	-0.062	-0.053	-0.123
			-0.121	-0.132	-0.113	-0.074	-0.064	-0.055	-0.123
			-0.122	-0.132	-0.122	-0.077	-0.066	-0.056	-0.124
		2	-0.119	-0.130	-0.117	-0.071	-0.063	-0.051	-0.124
			-0.119	-0.130	-0.119	-0.069	-0.072	-0.053	-0.124
			-0.117	-0.130	-0.119	-0.070	-0.072	-0.055	-0.123
		3	-0.116	-0.132	-0.123	-0.082	-0.099	-0.073	-0.131
			-0.118	-0.133	-0.121	-0.083	-0.099	-0.073	-0.130
			-0.119	-0.132	-0.120	-0.083	-0.099	-0.071	-0.130
8	98.7	1	-0.130	-0.131	-0.120	-0.084	-0.072	-0.109	-0.125
			-0.130	-0.132	-0.120	-0.072	-0.072	-0.112	-0.125
			-0.130	-0.133	-0.119	-0.072	-0.073	-0.109	-0.126
		2	-0.131	-0.132	-0.118	-0.066	-0.072	-0.101	-0.124
			-0.132	-0.132	-0.120	-0.061	-0.072	-0.101	-0.125
			-0.131	-0.132	-0.120	-0.060	-0.071	-0.100	-0.125
		3	-0.131	-0.131	-0.121	-0.062	-0.075	-0.106	-0.122
			-0.132	-0.133	-0.120	-0.061	-0.075	-0.105	-0.123
			-0.131	-0.132	-0.120	-0.061	-0.075	-0.105	-0.123
9	98.8	1	-0.127	-0.126	-0.116	-0.103	-0.087	-0.092	-0.145
			-0.128	-0.125	-0.116	-0.102	-0.088	-0.093	-0.144
			-0.130	-0.125	-0.116	-0.100	-0.088	-0.091	-0.145
		2	-0.120	-0.120	-0.112	-0.096	-0.090	-0.093	-0.149
			-0.122	-0.121	-0.114	-0.097	-0.091	-0.091	-0.148
			-0.121	-0.120	-0.113	-0.096	-0.091	-0.092	-0.148
		3	-0.125	-0.124	-0.120	-0.098	-0.088	-0.090	-0.142
			-0.125	-0.125	-0.121	-0.099	-0.088	-0.087	-0.144
			-0.126	-0.125	-0.122	-0.098	-0.090	-0.089	-0.144