ACCELERATED CORROSION TESTING OF STEEL REINFORCEMENT IN CONCRETE

by

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ABSTRACT

In the last few decades, there has been an increasing worldwide problem of deterioration of reinforced concrete structures, caused primarily by the corrosion of the steel reinforcement embedded within the concrete. Several factors can influence the corrosion process in different types of in-service structures. This thesis reviews the basic principles of the reinforcement corrosion. Various protection and rehabilitation schemes that can be undertaken in the repair of deteriorated concrete structures are presented. In particular, three specific types of structures in the Montreal region which have undergone rehabilitation are presented as typical case studies. Additionally, major research work done in the area of reinforcement corrosion over the last twenty years is reviewed.

This thesis reports the results of an experimental research program carried out at McGill University dealing with accelerated electrochemical corrosion testing of reinforced concrete. The main objective of this study is to determine the importance and influence of the depth of the concrete cover thickness on the rate of corrosion of steel reinforcement and thereby, on the resistance of concrete. Appropriate conclusions and recommendations regarding the construction variables affecting the corrosion process are brought forth.

These conclusions and recommendations can be summarized

ABSTRACT *(continued)*

as follows:

1. Operating potential values of reinforced concrete versus a saturated calomel reference electrode (SCE) lower than 0 mv may indicate the potential for corrosion activity.

2. An electrical current reading of 3 mA and above signifies corrosion activity at the level of the reinforcing steel.

3. A minimum cover of 1½ in. (38 mm) over the reinforcing steel should be specified in order to ensure that the concrete will offer the corrosion protection in the design requirements. Furthermore, for concrete exposed to severe chloride attack, a minimum clear cover thickness of 2 in. (51 mm) is recommended.

4. An increased concrete cover thickness is no substitute for poor quality concrete cover.

RÉSUMÉ

Durant les dernières années, la déterioration des structures en béton, dont la cause principale est la corrosion de l'acier d'armature, est devenu un probleme d'ordre mondial. Plusieurs facteurs peuvent influencer le processus de la corrosion dans différentes structures. La première partie de cette thèse révise les principes fondamentales de la corrosion de l'acier d'armature de béton. Divers méthodes de protection et de réfection, qui peuvent être utiliser pour la réparation de structures en béton, sont presentées. En particulier, trois genres de structures situé dans la région de Montréal, qui ont eté soumis à un programme de rehabilitation, sont analysées comme cas typiques. De plus, les recherches principales faites pendant les vingt dernières années à l'égard de la corrosion de l'acier d'armature sont présentées.

La deuxième partie de cette thèse présente les détails et les résultats d'un programme d'étude expérimentale faite à l'Université McGill sur la corrosion accélérée de l'acier d'armature de béton conventionnel. L'objectif principal de cette étude est de déterminer l'importance et l'influence de l'épaisseur de la couverture de béton sur le taux de corrosion de l'acier d'armature et ainsi, sur la resistance du béton. Certaines conclusions et recommandations concernant les variables de la construction en béton, qui peuvent influencer le processus de la corrosion, sont aussi présentées.

RÉSUMÉ *(suite)*

Ces conclusions et recommmandations peuvent être résumées:

1. Un potentiel électrique de l'acier d'armature de béton conventionnel, par rapport à un électrode de référence, en dessous de 0 mV indique un risque de corrosion.
2. Un courant électrique de 3 mA et plus indique la présence de corrosion au niveau de l'acier d'armature de béton.
3. Une épaisseur minimum de 1½ po. (38 mm) de la couverture de béton sur l'acier d'armature devrait être spécifiée pour que le béton offre une protection suffisante contre les effets de la corrosion. De plus, pour les bétons exposés aux attaques sévères de chlorure, une épaisseur minimum de la couverture de béton de 2 po. (51 mm) sur l'acier d'armature devrait être spécifiée.
4. Une augmentation d'épaisseur de la couverture de béton sur l'acier d'armature ne remplace pas une couverture de béton de piètre qualité.

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CHAPTER 1

INTRODUCTION

Concrete is a structural material quite different from other natural or man-made materials. It is usually manufactured from materials available locally and does not arrive "ready-made" at the construction site. When exposed to a nonaggressive environment, concrete is a strong and durable building material. Despite the important developments and advances in the area of concrete durability, there has been a growing concern around the world, in the last few decades, with the problem of deterioration of reinforced concrete structures. The major cause of this deterioration is the corrosion of the steel reinforcement, that can cause disfigurement on a small scale and yet, can lead to structural problems and occasional catastrophes on a large scale.

With respect to in-service concrete, most, if not all of the critical factors influencing the corrosion of steel are understood, along with the effect of the environment on these factors. It would appear that by utilizing this available knowledge on corrosion of steel reinforcement, concrete structures could be made more durable. However, the design of a structure, the concrete used, and the construction practices employed may be deficient, and the varying environment influencing the performance of concrete may not be as expected.[6] Therefore, it is desirable to include a greater degree of performance assurance than would be required in ideal conditions to protect the embedded reinforcement.

Other leading causes of concrete deterioration, resulting ultimately in reinforcement corrosion, include frost action in cold climates and physico-chemical effects in aggressive environments. A rise in chemical aggressivity of the environment through the increasing use of de-icing salts, and an increase in land, water, and air pollution, has also contributed to the deterioration of concrete structures.

The design principles and construction practices have not been modified sufficiently despite the rapidly escalating use of chloride based de-icing salts. The durability problem, that has emerged, was caused mainly by the shortcomings of the accepted industry standards. As a result, rehabilitation is required essentially for all existing reinforced concrete structures unless immediate steps are taken to improve their durability.[167]

More concrete structures are presently suffering from durability problems than was the case fifty years ago. Their "natural" deterioration and inadequacy has drawn the attention of engineering professionals and the various levels of government. It is well known that Canada's infrastructures, including roads, bridges, and water and sewage facilities, are in need of major repairs. The various levels of government seem to provide the major funding required from time to time, however, the responsibility of coping with this inadequate funding and keeping the infrastructure operational remains with the municipalities. A report published by the Federation of Canadian Municipalities (FCM) in June 1985 showed that the costs for the upkeep of infrastructures had almost tripled in most categories, with the major component burdens as roads (40%), water and sewage treatment (37%), and bridges (10%).[166] Similar difficulties are being encountered in all parts of the world. Table 1.1 shows a $3 billion shortfall between the expenditures allocated by the three levels of government and the actual estimated need for the maintenance and repair of the transportation infrastructure in Canada.

There is increasing deterioration of concrete structures in Canada, especially in the province of Quebec. As mentioned previously, the structures largely affected include roadways, bridges, and parking garages. In terms of road maintenance, the monetary budget in Quebec has increased from $267 million in 1977 to $473 million in 1988.[167] Nevertheless, the portion of the provincial government's budget allocated to roadways has decreased from 25% in 1965 to 2% in 1986, despite the fact that the amount of total roadway requiring repair has

	Actual Expenditures ($ billion)	Estimated Needs ($ billion)
Federal	0.15	0.20
Provincial	4.00	5.91
Municipal	4.29	5.31
Total	8.44	11.42

Table 1.1: Canadian Highway Maintenance and Repair Funding Fiscal Year 1988 - 1989[166]

increased.[167] The primary reasons for the degradation of the road network is the increased use of de-icing agents and cyclic freeze-thaw action, along with substantial increases in traffic volumes.

Parking structures are also subjected to deterioration due to corrosion of steel reinforcement. In the early 1980's, it became apparent that most parking garages were built with inadequate protection for resisting the deleterious effects of de-icing chemicals. Over the last decade, expenditures have increased in the area of repairs and improvements, whereas maintenance and cleaning costs have been reduced considerably. In order to serve as a basis for the evaluation of the various repair techniques and strategies, the Canadian industry association initiated a five year study, including a sample of 49 types of parking structures across Canada. Of the data collected thus far, a comparison between the annual repair and maintenance expenses, per square meter of parking surface, is shown in Table 1.2.[168]

In order to better protect the embedded steel

YEAR	REPAIR	CLEANING	TOTAL
1982/1983	$10,924	$21,194	$32,118
1983/1984	$19,448	$9,971	$29,419
1984/1985	$52,546	$17,772	$70 318
1985/1986	$18,259	$6,447	$24,706
1986/1987	$64,867	$4,380	$69,247
1987/1988	$24,361	$3,644	$28,005
1988/1989	$37,680		$37,680
TOTAL	**$228,085**	**$63,408**	**$291,493**

Table 1.2: Yearly Expenditures per Square Meter on Repairs and Improvements, and on Cleaning[168]

reinforcement from the onset of corrosion and thereby increase the service life of a reinforced concrete structure, additional research is required in this area of steel reinforcement corrosion, possibly allowing design principles and construction practices to be modified in order to prevent the deterioration of reinforced concrete structures.

The objectives of this research program are to examine the accelerated electrochemical corrosion process of steel reinforcement in concrete. Chapter 2 reviews the basic principles of reinforcement corrosion, including the different factors affecting the corrosion activity and the numerous types of corrosion processes. Chapter 3 presents the various protection and rehabilitation measures that can be undertaken for the repair of a reinforced concrete structure. This includes the various techniques used in a detailed survey to determine the condition of the existing structure. Chapter 4 deals with three different types of structures, namely a street bridge, an elevated highway, and a parking garage, in the Montreal area, which have undergone rehabilitation over the past few years.

The major research work done in the area of reinforcement corrosion over the last twenty years is reviewed in Chapter 5. The development of the various codes of construction practice, as well as comparisons among the available international codes, are also presented. Chapter 6 presents the details of the research program carried out at McGill University during the year 1990-91. Results of the experimental investigations, including the preliminary and the final test series, are discussed.

The main objective of the research study is to determine the importance and influence of the depth of the concrete cover thickness on the resistance of concrete, and ultimately, on the rate of corrosion of steel reinforcement. Analysis and correlation of the results obtained from the experimental study are discussed in Chapter 7. In addition, comparison of the results with previous studies of similar nature are presented. Finally, Chapter 8 contains some appropriate conclusions and recommendations regarding the construction variables affecting the corrosion process.

It is hoped that the state-of-the-art of the corrosion phenomenon and the results presented in this thesis will be useful to the construction industry in the rehabilitation of reinforced concrete structures.

CHAPTER 2

PRINCIPLES OF REINFORCEMENT CORROSION

Reinforcing steel embedded in concrete is normally protected against corrosion by the high alkaline environment provided by the surrounding concrete. The penetration of corrosion-inducing elements, such as oxygen, water, carbon dioxide, and chloride ions, is further limited by a concrete environment of low permeability. Furthermore, this low permeability retards the flow of electrochemical corrosion current due to increased electrical resistivity of the concrete.[5]

As a result of inherent protective characteristics of the concrete, reinforcement corrosion does not normally occur, provided that the surrounding concrete is of suitable quality and is properly proportioned for the intended environmental exposure. Nevertheless, corrosion can result if the above criteria are not met or if other factors are not as anticipated or have changed during the life of a structure.

In some cases, the corrosion or "rusting" of the steel permeates to the surface through cracking. This phenomenon occurs because the corrosion product, iron oxide, has a volume several times greater than that of the metallic iron from which it formed. Thus, the concrete tensile strength is exceeded by the expansive force generated, resulting in cracking. Surface distress may be a result of rust staining, cracking, and concrete debonding at the reinforcement level. Additionally, the reduced cross-section of the steel, accompanied by a reduction in its tensile capacity, may lead to possible failure.

Different mechanisms may be responsible for steel corrosion. Within reinforced concrete, electrochemical corrosion is believed to be essentially the major cause of all the corrosion distress. This is due to the indirect oxidation resulting from dissimilar or non-uniform metals or from dissimilar environments.[5]

This chapter reviews the basic principles of the electrochemical process and the different classifications of reinforcement corrosion. Factors influencing the electrochemical process are discussed, and the various protective measures that can be utilized are presented.

2.1 ELECTROCHEMICAL CORROSION PROCESS

2.1.1 Key Terms and Definitions

Some basic definitions are presented in this section to describe the corrosion process in reinforced concrete. This will enable the reader to have a better understanding of this phenomenon and be able to use this as a quick reference guide.

Activation polarization: electrochemical process that is controlled by the reaction sequence at the metal-electrolyte interface

Alkalinity: quality or condition of basicity

Alkali-aggregate reaction: chemical reaction of aggregates containing silicates with alkali (sodium and potassium) contents of cement.

Anode: electrode releasing electrons (positive polarity)

Base metals: metals having a more negative potential than the hydrogen electrode

Cathode: electrode consuming electrons (negative polarity)

Electrochemical series: standard electrode potentials of defined electrochemical reactions

Electrolysis: decomposition of a chemical compound into its ions by the passage of an electrical current

Electrolyte: aqueous medium able to conduct electricity

Electromotive force (emf): driving force producing current flow resulting from chemical reactions taking place at the anode and the cathode

Electronic current: flow of electrons from the anode to the cathode

Galvanic series: list of metals and alloys arranged according to their relative potentials in a given environment (e.g., sea water)

Half-cell potential: potential of a half-cell reaction

Half-cell reaction: chemical reaction at the anode or cathode

Ionic current: flow of ionic charges

Noble metals: metals having a more positive potential than the hydrogen electrode

Permeability: ease of diffusion of liquids or gases

pH: indicator of acidity or alkalinity (basicity)

Polarization: shift of electrode potential away from the reversible potential for a current flow.

2.1.2 Basic Corrosion Cell

The basic principles of electrochemical corrosion are analogous to the components of an electrolyte cell. In order for the corrosion process to proceed, an anode, a cathode, an electrical conductor, and an electrolyte medium must be present. The body of the metal itself provides the electrical connection, while the moist concrete is the electrolyte conductor required for the flow of ions. At the anode, iron is oxidized to ferrous ions by the following equation[30]:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \qquad (2.1)$$

The ferrous ions are subsequently transformed to iron oxides through a series of complex reactions.

At the cathode, the electrons produced at the anode are consumed, typically through oxygen reduction. The cathodic reaction is as follows[30]:

$$\tfrac{1}{2}O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \qquad (2.2)$$

Figure 2.1 depicts the corrosion cell in reinforced concrete.

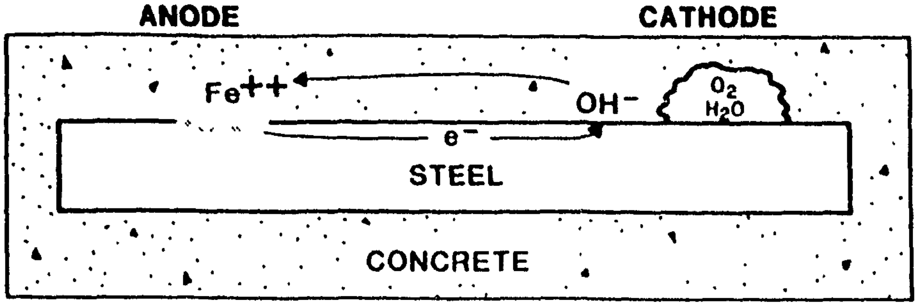


Figure 2.1: Corrosion Cell in Reinforced Concrete[10]

As the electrolyte conducts current mainly through ionic diffusion, specific minimum ion and water contents must be present to permit the flow of ions.[11] Current flows between the anode and the cathode, passing through the metal and returning through the electrolytic medium. Any non-uniformity within the electrolyte can produce a difference in potentials (emf). Examples include dissimilar metals (active and noble metals), oxygen concentrations (availability at the ion location), and temperature differentials (gradients).

The current completes the circuit back to the anode in the form of negative hydroxyl ions (OH^-). Once at the anode, the OH^- ions can combine with the Fe^{2+} cations to form a relatively soluble ferrous hydroxide as follows[11]:

$$Fe_{2+} + 2OH^- \rightarrow Fe(OH)_2 \qquad (2.3)$$

In the presence of sufficient oxygen, insoluble hydrated red rust can form. However, in the absence of cracks, oxygen usually cannot diffuse quickly enough at the anodic site to support this reaction, keeping iron in its ferrous state.

There are several important facets of the corrosion cell to consider. The anode and the cathode areas are physically separated by a certain distance. Oxygen is not involved at the corrosion site, but rather its presence at the anode can limit or prevent corrosion. Finally, "breakage" of the electrochemical cell can be accomplished by cutting the metallic conductor, preventing oxygen from reaching the cathode, or drying out the cell (i.e., removal of water) at any location between the anode and the cathode.[10]

2.1.3 Factors Affecting Corrosion Activity

Three main factors influence the activity of a corrosion cell. These include the ratio between the surface areas of the anodic and cathodic regions, polarization, and the resistivity of the electrolyte.

2.1.3.1 Area Ratio

The density of the current flow is an indication of the corrosion rate. As the ratio of anodic to cathodic area increases, the current density at the anode decreases, signifying a decrease in the corrosion rate.

2.1.3.2 Polarization

Electrochemical polarization can be classified in three main categories, which apply to both the anode and the cathode[11,30]:

1. **Concentration polarization** occurs when the concentration of the electrolyte changes in the vicinity of the electrode.

2. **Activation polarization** refer to the electrochemical processes controlled by the reaction sequence at the metal-electrolyte interface.

3. **Ohmic polarization** occurs because of the ohmic resistance of the electrolyte (i.e., moist concrete) and of any films on the electrode surface. This produces an ohmic potential drop (equal to the current times the resistance) in accordance with Ohm's Law.

The formation of a thin passive, or nonconducting, layer on the metal surface results in **passivation** of the corrosion cell, a special case of activation polarization. When the layer becomes thick enough to hinder partially or fully the current flow, corrosion activity ceases. Formation and breakdown of the passive layer depends on a number of factors, including the ionic concentrations and the pH level within the electrolyte.[11]

2.1.3.3 Electrolyte Resistance

The potential corrosion rate is inversely proportional to the resistance of the electrolyte. As the corrosion current flows through the electrolyte by ionic conduction, the resistance depends on temperature, moisture, and ionic content.

2.2 CORROSION OF STEEL REINFORCEMENT IN CONCRETE

2.2.1 Depassivation

The electrochemical corrosion process described is normally prevented by a "passivating" iron oxide film layer on the surface of the reinforcing steel. The water-soluble alkaline products formed during the hydration of the cement, along with the presence of moisture and oxygen, enable the protective layer to form. The principal soluble product is calcium hydroxide, $Ca(OH)_2$.[5] This film prevents iron cations (Fe^{2+}) from entering into the electrolyte solution and acts as a barrier to prevent oxygen anions (O^{2-}) from contacting the steel surface.

The initial concrete alkalinity is at least equal to that of saturated lime water (pH value of approximately 12.4). Additionally, small amounts of sodium and potassium oxides in the cement further increase the alkalinity.

Two general mechanisms exist that may result in the destruction of this passivating effect[11]:

1. **Neutralization** of the Portland cement paste system by leaching of alkaline substances with water or by reaction with atmospheric carbon dioxide CO_2. The latter reacts with the calcium hydroxide $Ca(OH)_2$ in the cement gel to form insoluble $CaCO_3$ and water. This results in a significant reduction in the pH value due to the removal of hydroxyl ions (OH^-) from the pore water solution.
2. **Electrochemical action** involving exposure to certain aggressive environments, especially the intrusion of chloride ions (Cl^-) in the presence of oxygen.

Since carbonation effect is not normally a concern because it proceeds at a slow rate, more emphasis is placed on the presence of chloride ions within reinforced concrete.

2.2.2 Role of Chloride in Reinforcement Corrosion

Almost all researchers agree that the chloride ion acts as an essential catalyst of the corrosion reaction.[11] Chloride ions appear to be specific and unique destroyers of the protective oxide film surrounding the reinforcing steel. The ions may be introduced in the concrete in several ways. Some are included intentionally as an accelerating admixture, some are included accidentally as contaminants within aggregates, or penetration may occur from deicing salts, sea water spray, salt brine, etc.

Despite widespread agreement on the influence of chlorides present within concrete, various concepts have been postulated as to their precise role in the corrosion reaction. There exist three modern theories to explain the electrochemical effects of chloride ions on steel corrosion.

2.2.2.1 Oxide Film Theory

This theory postulates that chloride ions penetrate the protective oxide layer through pores or defects in the film easier than other ions (e.g., sulphates). Alternatively, the chloride ions may colloidally disperse the oxide film, thus making penetration easier.[30]

2.2.2.2 Adsorption Theory

This theory presumes that as chloride ions are adsorbed on the metal surface, the hydration of the metal ions increases and dissolution of these ions is thus facilitated. The chloride ions are in competition with the dissolved oxygen or hydroxyl ions.[30]

2.2.2.3 Transitory Complex Theory

According to this concept, chloride ions compete with hydroxyl ions (OH^-) for the ferrous ions produced by the corrosion process. A soluble chemical complex of iron chloride forms and diffuses away from the anode, destroying the protective layer of $Fe(OH)_2$. Eventually, this compound breaks down, precipitating iron hydroxide and releasing the chloride ion to transport more ferrous ions from the anode.[2] It is the expansion of iron oxides, as they are transformed to higher oxidation states, that produce internal stresses, which eventually crack the concrete.[30]

2.2.3 Threshold Chloride Concentration

Usually, the tricalcium aluminate (C_3A) content in Portland cement is high enough to combine with a significant amount of chloride ions, forming an insoluble calcium chloroaluminate compound.[11] However, large quantities of chloride ions are mobilized or "free" when concrete is in a hardened state than when it is in a plastic state. Researchers agree that a threshold concentration of chloride ion exists which must be exceeded before initiation of corrosion occurs.[5] An increase beyond this "limit" results in the increased rate of corrosion up to the point where the availability of the necessary oxygen is reduced. These localized concentrations occur primarily in voids in the concrete matrix that are in direct contact with the oxide film.

The concept of the chloride threshold concentration is shown schematically in Figure 2.2. This demonstrates that increasing chloride concentrations can be tolerated provided there is a corresponding increase in the alkalinity (pH value). The threshold value increases as the alkalinity of the cement paste increases.

Based on empirical data from the previous research, a probable corrosion threshold value is at about a chloride:hydroxyl ion molar activity ratio of 0.6 in solution

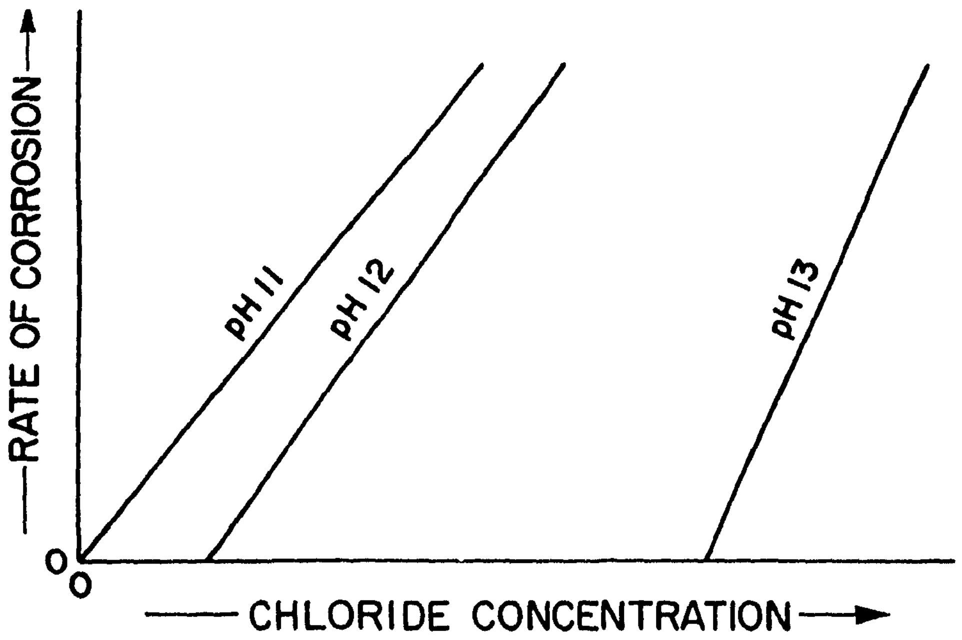


Figure 2.2: Rate of Corrosion vs Chloride Concentration[5]

at the iron-paste interface.[6] Figure 2.3 shows that the amount of chlorides required for corrosion initiation increases as the pH at the iron-liquid interface increases. Another commonly accepted value for the corrosion threshold is 0.20% total chloride ion expressed as weight of cement.[2,11] However, no widely accepted chloride threshold concentration has been established and further research is required in this area.

It is important to note that distinct differences in chemical behaviour exist between sodium and calcium chlorides. Calcium chloride increases the chloride content and reduces alkalinity due to an increase in the total ionic strength of

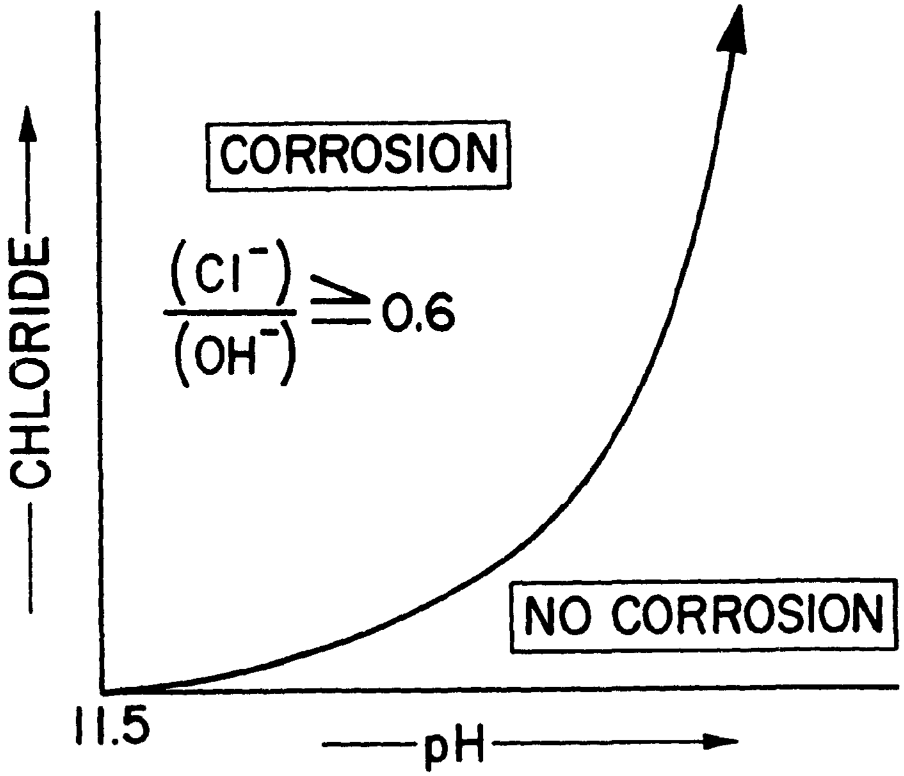


Figure 2.3: Chloride Content vs pH[6]

the resulting liquid phase. On the other hand, sodium chloride also increases the chloride content but the alkalinity of the paste liquid increases above that of the saturated calcium hydroxide.[5]

2.2.4 Types of Reinforcement Corrosion

Carbonation or chloride ingress creates conditions for corrosion of the steel reinforcement to proceed. Nevertheless, these are insufficient and additional factors must be present for corrosion to occur. These include availability of oxygen and moisture, and a low-resistivity path through the concrete. The following describe some of the common types of reinforcement corrosion that can occur.

2.2.4.1 General Corrosion

As discussed previously, this corrosion process is modeled to an electrochemical cell. The rate of corrosion is governed by the availability of oxygen at the cathodic sites and by the electrical resistance of the surrounding concrete. Under these conditions, corrosion takes place uniformly over the entire steel surface. The expansive corrosion products result in induced cracking and subsequent spalling.[3]

2.2.4.2 Pitting Corrosion

This corrosion initiates with a localized breakdown of the protective oxide layer at isolated locations. Figure 2.4 depicts pitting corrosion in a freely corroding re-bar. Metal loss at the anodic sites leads to the creation of a pit and further loss occurs from the bottom of the pit rather than around the mouth. The reduction in cross-sectional area results in failure to support the applied loading. Some time may elapse before any visual signs of distress are noticed, since the products of the pitting attack (ferric chlorides) are soluble and disperse in the concrete matrix.[3]

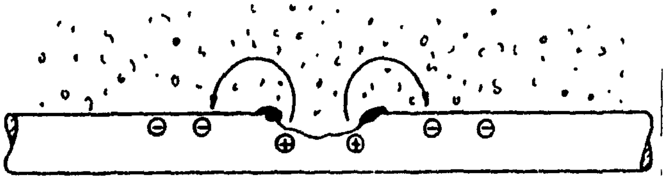


Figure 2.4: Pitting Corrosion[3]

2.2.4.3 Concentration Cells

Varying amounts of soluble ion in concrete create a potential difference between the steel in each area, permitting corrosion initiation at the anodic sites. An example of a concentration cell is shown in Figure 2.5.[3]

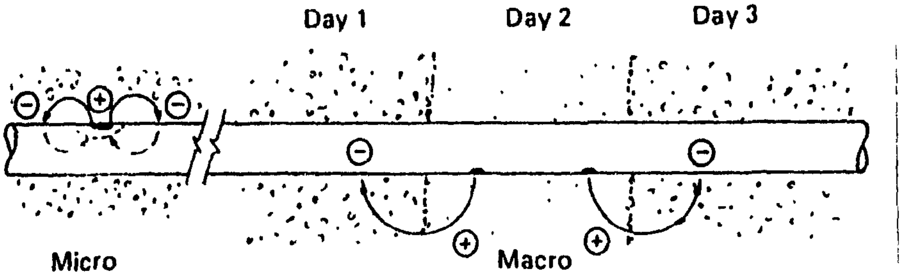


Figure 2.5: Concentration and Differential-Oxygen Cells[3]

2.2.4.4 Differential-Oxygen Cells

This type of corrosion cell arises due to the differences in the oxygen supply to the various parts of the reinforcement. The movement of oxygen is governed largely by the porosity of the cement paste. Variations in oxygen level can be introduced by localized repair work or concrete cast over an extended period (daily weather conditions). Figure 2.5 depicts both a "micro" and a "macro" differential-oxygen cell in concrete.[3]

2.2.4.5 Galvanic Cells

Galvanic cells develop when steel is in direct or incidental contact with a different metal or alloy lower in the galvanic series. The ensuing cell can force the steel to corrode in the presence of a moisture path (i.e., concrete). The electrical potential developed, along with the relative sizes of the two metals, determine the rate and the degree of steel corrosion.[3]

2.2.4.6 Stray Current

This type of corrosion applies to direct current being "picked up" in some form so as to cause certain areas of the reinforcing steel to be more anodic than others. This induced accelerated metal corrosion can be controlled in most cases.[3]

2.2.4.7 Bacterial Corrosion

In anaerobic (oxygen-less) conditions, bacteria are introduced naturally in reinforced concrete structures. The bacteria can permeate to the steel surface and create a series of iron sulphides, enabling the corrosion reaction to proceed despite the lack of oxygen. This intense reaction may lead to severe structural damage.[3]

2.3 EFFECTS OF THE CONCRETE ENVIRONMENT

2.3.1 Portland Cement

A well-hydrated Portland cement may contain 15 to 30% calcium hydroxide, $Ca(OH)_2$, by weight of the cement content, usually sufficient to maintain the concrete solution at a pH value of approximately 13. A well-proportioned, continuous grain size distribution improves the cement's resistance to chemical effects. If a greater proportion of fines exists, more mixing water will be required, thus resulting in a lower density and reduced permeability of the hardened concrete.

The chemical and physical properties of cement have a minor effect on the reinforcing steel corrosion. The properties of the tricalcium aluminate (C_3A) content have the greatest influence on the corrosion process. Increasing the C_3A content decreases the corrosion tendency, since the chloride ions react with the hydrated tricalcium sulfoaluminate in the hardened cement paste to produce an insoluble tricalcium chloroaluminate compound.[2,12] This process prevents any free chloride ions from promoting corrosion.

Nevertheless, as the presence of chlorides increases, the benefits of the C_3A complexing characteristics become less perceptible. Furthermore, increased C_3A content provides a lower resistance to sulphate attacks. Normal Type I cement is 3 to 5 times more effective in removing chloride ions than sulphate-resisting Type V cement. The C_3A contents of typical Type I and Type V cements are between 9-12% and 3-5%, respectively.[2] Research has shown that increasing the cement factor with no reductions in the water-cement ratio causes no noticeable reduction in reinforcement corrosion.[12]

2.3.2 Aggregates

Since aggregates constitute approximately 70% of the mix volume, they play a major role in determining the permeability of concrete. The permeability increases as the maximum coarse aggregate size increases, since most mineral aggregates have permeability co-efficients 10 to 1000 times greater than that of the cement paste.[2] However, the aggregates have larger pore diameters than the cement paste, and thereby they cannot compete with the paste for the available moisture on the basis of capillarity. The only role played by the aggregates in the transport process is to replenish moisture in the paste.[2]

Any aggregates supplying a source of chloride ions may have serious effects on reinforcement corrosion. These include sea dredged aggregates or porous aggregates. Additionally, the gradation of aggregates may also have significant effects if it leads to bleeding and segregation, resulting in voids.

2.3.3 Mixing Water (Moisture Content)

The water-cement ratio (i.e., moisture content) strongly influences the hydration process, the pore size distribution, and the permeability of the cement paste. The water content is the primary rate determining factor in the corrosion process and in controlling concrete strength and quality.[21] An increase in water content leads to an increase in porosity. This results ultimately in more rapid diffusion of chloride ions to the steel surface, easier ingress of oxygen, and lower concrete electrical resistivity. For high quality concrete of low permeability, the suggested water-cement ratio should be less than 0.45.[17]

2.3.4 Admixtures

Numerous chemical admixtures, both organic and inorganic, have been suggested as specific inhibitors of steel corrosion. These include water reducers, plasticizers, and air-entraining agents that reduce the water-cement ratio and are beneficial in retarding corrosion.[2] Air entrained concrete has shown improved resistance to reinforcement corrosion when subject to numerous freeze-thaw cycles.[111] With some admixtures, corrosion inhibition occurs only at addition rates sufficiently high to counteract the effects of chlorides.

Some admixtures may retard the time of setting of cement or actually be detrimental at later stages.[30] For example, use of calcium chloride ($CaCl_2$) as an accelerator in cold weather concreting operations tends to promote reinforcement corrosion.[2,79,90] The detrimental effect is limited as long as the concentration is small and concrete is sufficiently dense. Prestressed concrete has been found more susceptible to high $CaCl_2$ contents than normal reinforced concrete.[1] Non-chloride accelerators that do not lead to reinforcement corrosion are being developed.[105]

Use of pozzolans also markedly reduce concrete permeability, increase its electrical resistivity, and reduce bleeding and segregation. Pozzolans of high fineness, used as cement replacements, are effective in reducing expansion due to alkali-silica reaction and sulphate attack.[19] Different types of pozzolans, including fly ash[57,101,112], silica fume[122,131], and ground granular blast-furnace (GGBF) slag[108,122,145], have all been found to have a beneficial effect in retarding reinforcement corrosion. It is important to note that when pozzolans are used, it is more appropriate to consider the water-cementitious materials ratio rather than simply the water-cement ratio.

2.4 EFFECT OF CONSTRUCTION VARIABLES

2.4.1 Consolidation

The degree of consolidation of concrete, especially near the embedded steel, has a direct effect on reinforcement corrosion. Normally, good consolidation can be achieved by internal vibration. Insufficient consolidation provides channels of ingress for corrosion-inducing elements. A reduced consolidation effort leads to a reduction in the initial time to corrosion. If using low slump concrete, normal construction practices cannot be used for adequate consolidation.[2,21]

2.4.2 Cover Thickness

The concrete cover to steel reinforcement is the single most important design parameter influencing corrosion deterioration. A fundamental prerequisite is having concrete cover of adequate quality and thickness, consistent with good structural design, severity of the service environment, and cost expenditure. Cover also plays a significant role in the extent of cracking in fresh concrete occurring over top reinforcement due to settlement restraint of the concrete.[19,21]

The effect of cover thickness is not a simple linear relationship. The following empirical expression relates several variables influencing reinforcement corrosion:[2]

$$R_t = \frac{41*S_i^{1.22}}{K^{0.42}*(w/c)} \qquad (2.4)$$

where R_t = time to deterioration of concrete exposed continuously to saline water (years)

S_i = depth of steel below surface (cm)

K = chloride ion concentration (ppm)

w/c = water-cement ratio.

For normal diffusion of an electrolyte into a porous solid without chemical reaction, the relationship is shown in Figure 2.6. In the case of cement paste, the chloride ion diffusion is accompanied by a chemical reaction of chloride to form calcium chloroaluminate. This reduces the concentration of ions at any particular site and hence, the tendency for inward diffusion is further reduced (see Figure 2.6).[5,30] Therefore, the depth of cover is of obvious importance in protecting reinforcing steel from adverse factors promoting corrosion. Nevertheless, the amount of cover is no substitute for the quality of the cover.

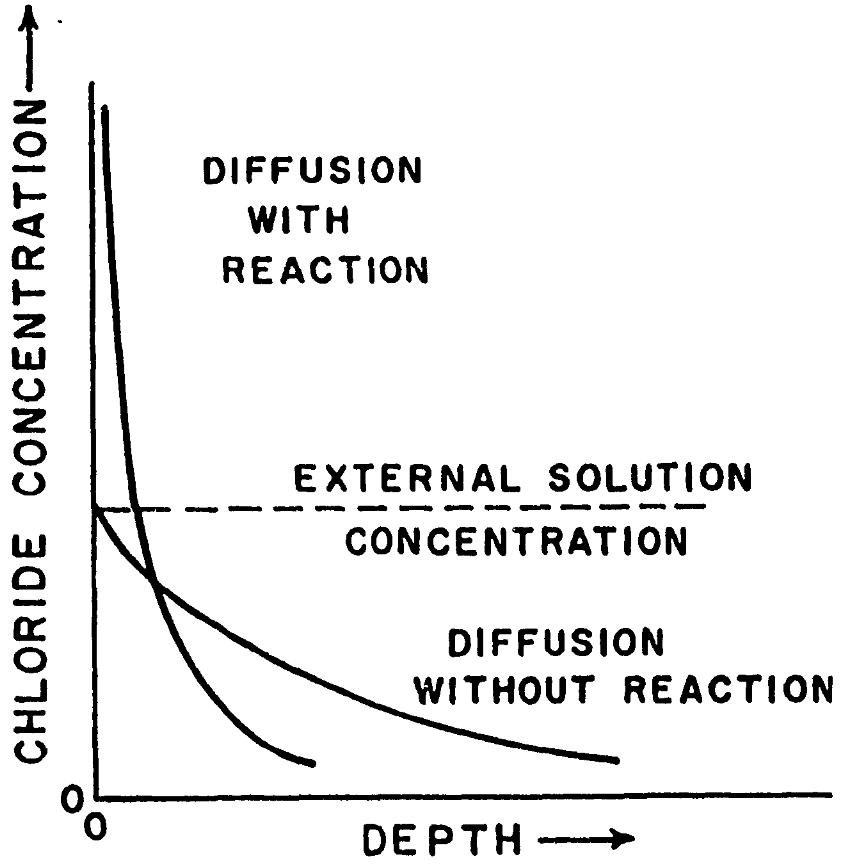


Figure 2.6: Chloride Concentration vs Depth of Cover[5]

2.4.3 Curing Time

The curing process is the final and one of the most essential elements in any concrete construction. The curing period affects the porosity of hardened concrete. A short curing period is not sufficient to allow a fully protective passive film to be formed before the ingress of chloride ions. Table 2.1 shows a significant decrease in permeability as curing time progresses.

Days of curing	Coefficient of permeability
fresh paste	1,150,000,000
1	36,300,000
2	2,050,000
3	191,000
4	23,000
5	5,900
7	1,380
12	195
24	46

Table 2.1: Effect of Curing on Permeability[5]

The effects of steam and water curing on the time to corrosion of embedded steel can be determined by the following empirical expression[2]:

$$P = a*D^{B} \qquad (2.5)$$

where P = time to active corrosion potential for partial immersion in saturated sodium chloride solution (days)

D = time of underwater curing following initial curing (days)

a = constant (6.33 for steam curing; 6.0 for water curing)

b = constant (0.66 for steam curing; 0.90 for water curing).

It can be observed that water curing provides significantly greater resistance to corrosion than steam curing. However, the effect of curing will not be as pronounced due to bleeding, degree of consolidation, aggregate permeability, and due to the fact that water will still be available in the capillary pores after curing is complete.

CHAPTER 3

REINFORCEMENT CORROSION: PROTECTION AND REHABILITATION MEASURES

3.1 CORROSION PROTECTION IN NEW CONSTRUCTION

Protective measures used in the construction of new reinforced concrete structures can be grouped into two functional classes: (i) those that must be introduced when concrete is cast and placed, and (ii) those that may be applied after concrete has hardened and cured. These measures can also be divided into three categories:[30]

(i) design and construction practices;

(ii) concrete surface treatments; and

(iii) techniques preventing corrosion directly.

These are briefly discussed in the following sections.

3.1.1 Design and Construction Practices

Careful design and good construction practices can maximize the protection provided by the Portland cement concrete. Normally, proper detailing of steel reinforcement can ensure an extended service life of a reinforced concrete structure.

For those members exposed to chlorides and subject to intermittent wetting, the first line of defense is ensuring an adequate depth of cover to the reinforcing steel, a high quality high cement content, and low permeability concrete (i.e., low water-cement ratio). For those members continuously submerged, the corrosion rate is controlled by the rate of oxygen diffusion and to a lesser degree by the concrete quality or the concrete cover thickness.

The designer has little control over the change in the use of a structure or the service environment. Nevertheless, the chloride content added to the concrete mix ingredients can be controlled. When the chloride concentration exceeds the threshold limit, unacceptable corrosion may occur provided that the other necessary conditions, namely moisture and oxygen, exist to support the chemical reactions. Worldwide investigations have brought forth various limits as to the total chloride content permissible in concrete. These limits vary depending on the environment of the service exposure conditions and on the type of reinforced concrete construction (conventional versus prestressed). Furthermore, a distinction is made as to whether the chloride content determined analytically is acid-soluble or water-soluble.[30] Section 5.3 compares the design codes of practice from various parts of the world for chloride threshold limits.

When exposed to chlorides, the concrete should be made with the lowest water-cement ratio consistent with achieving maximum consolidation and density. Figures 3.1 and 3.2 demonstrate the effects of water-cement ratio and degree of consolidation on the rate of ingress of chloride ions. As is shown, a low water-cement ratio is not necessarily sufficient to ensure a low concrete permeability.

Adequate depth of cover thickness of proper quality must also be present for concrete components exposed to chlorides

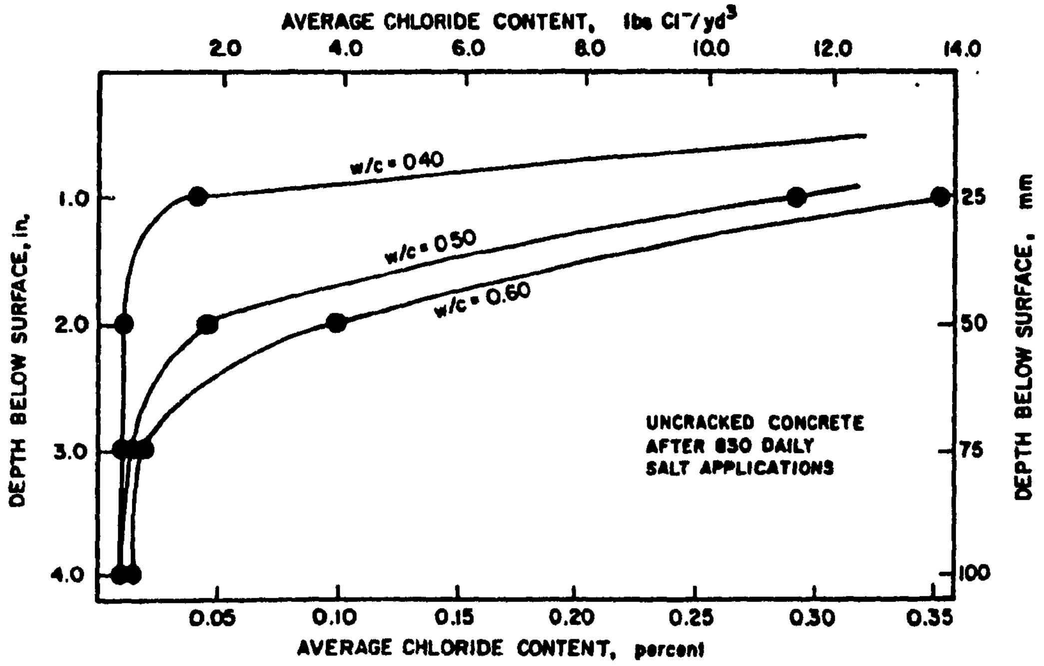


Figure 3.1: Effect of Water-Cement Ratio[30]

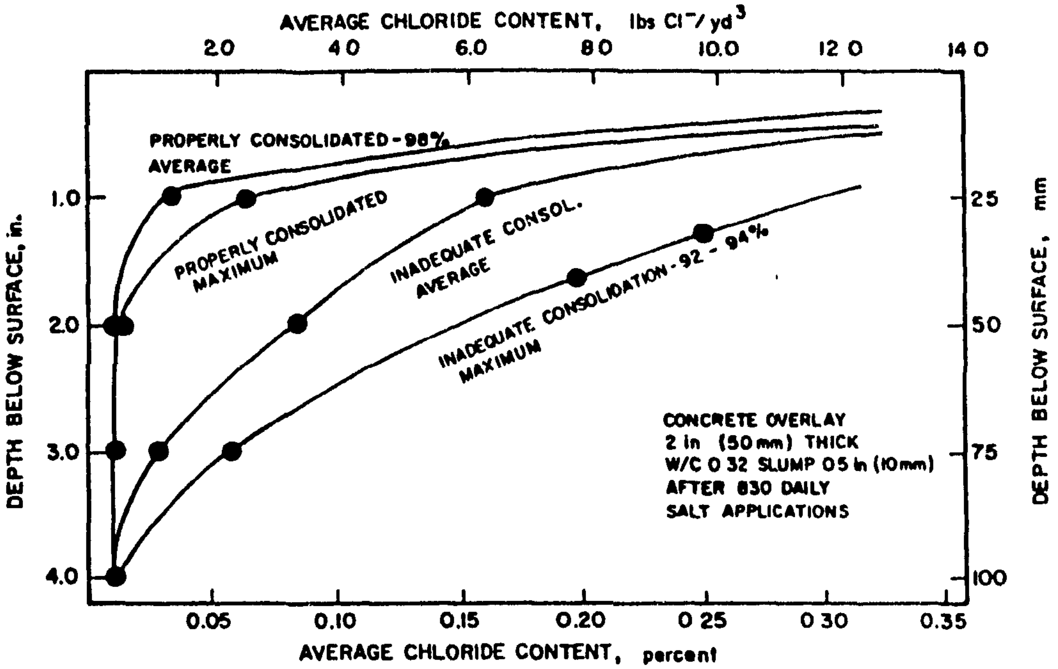


Figure 3.2: Effect of Consolidation[30]

and intermittent wetting and drying.[30] In determining the specified concrete cover thickness, tolerances of reinforcement placing, method of construction, and level of inspection should be considered. Construction practices must ensure that the specified cover is achieved. To obtain the actual minimum cover 90% of the time, the specified cover must be increased by ½ in to ⅝ in, (12.7 mm to 15.9 mm).[19]

3.1.2 Concrete Surface Sealants

There are basically two types of concrete sealants: those providing a barrier at the outer surface, retarding the penetration of corrosion-forming products to the interior, and those penetrating and sealing the capillary pore system of concrete, preventing the ingress of corrosion elements and immobilizing any that may already be present.[2]

Waterproof membranes are used quite extensively and they are usually protected by asphalt concrete wearing surfaces. There are two basic types of waterproof membranes: pre-formes sheet-type and liquid-applied systems. The most important acceptance criterion in field evaluation is permeability of the membranes. Two common problems are encountered: installation for proper sealing (entrapped gases causing blistering) and limited serviceability life due to wearing of the asphalt course.[2,30]

Other techniques can be applied to the concrete surface. One of these is **polymer impregnation**. This consists of filling some of the voids in the hardened concrete with a monomer and in-situ polymerization. Despite the fact that polymer-impregnated concrete is strong, durable, and almost impermeable, the processing is lengthy, monomers are costly, and the concrete has a tendency to crack during heat treatment.[7,30,120] Alternatively, thick overlays of impervious concrete can be used as sealants. These include:[7,30]

1. **Low-slump concrete overlays** that depend solely on the use of conventional materials and good quality workmanship (low water-cement ratio, air-entrainment, water-reducing admixture, proper consolidation, and adequate curing).
2. **Latex-modified concrete overlays**, consisting of a polymeric latex emulsion added to conventional Portland cement concrete.

The concrete produced has a low water-cement ratio, good durability, good bonding characteristics, and a high degree of penetration resistance to chlorides. **Styrene-butadiene** latexes are used most widely. The most serious deficiency with these overlays is the occurrence of shrinkage cracking in the overlay.

3. **Polymer concrete overlays**, consisting of aggregate in a polymer binder. The main problem in the application has been the occurrence of blistering, as in waterproof membranes.

3.1.3 Reinforcing Steel Protection

To prevent corrosion of the reinforcing steel in a corrosive environment, either noncorrosive steel must be used or a barrier coating must be applied on the surface of the steel. **Noncorrosive steels** include stainless steel reinforcement and stainless steel-clad bars, yet these are too expensive and do not actually prevent corrosion-inducing elements from reacting with the reinforcing steel.[30,96]

On the other hand, **barrier coatings** interfere by preventing corrosive materials from coming in contact with the steel. There are two categories of **metallic** coatings: **sacrificial**, having a more negative potential than steel (zinc and cadmium), and **noble**, having a more positive potential than steel (copper and nickel). In general, it appears that metallic coatings provide only a slight increase in service life. The most widely used and commercially available **nonmetallic coating** is **fusion-bonded epoxy powder**. The process consists of electrostatically applying finely divided epoxy powder to thoroughly cleaned and heated bars. The main difficulty in using epoxy-coated bars has been in preventing damage to the coating during transportation and handling.[2,8,9,30]

Cathodic protection (CP) is another method of steel protection, although most installations have been in existing structures. It consists primarily of supplying a current flow, either by applying direct electrical current or by using sacrificial anodes, to suppress the galvanic corrosion cell through polarization of the steel surface.[2,3] Problems arising with cathodic protection include installation of durable permanent anodes in electrical contact with the steel surface, and designing a system capable of overcoming large variations. Recently, cathodic protection has been used increasingly to protect concrete structures in several parts of the world.[4,80,118]

3.2 ASSESSMENT OF CORROSION DAMAGED CONCRETE

The previous section described some of the precautions that may be undertaken to prevent corrosion of the reinforcement steel. Nevertheless, on numerous occasions, the start and progress of the corrosion process can lead to damage and deterioration of the concrete. In these cases, a careful examination of the concrete structure must be undertaken. This would involve various methods of identifying the exact cause and extent of the active corrosion and concrete deterioration. This would enable some predictions to be made about the remaining service life of the structure. The various means of assessing corrosion damaged concrete are presented in the following sections.

3.2.1 Initial Condition Survey

The first stage in inspecting and testing consists of an initial condition survey. This makes use of simple methods to establish whether or not there is a need for repair and rehabilitation of the structure. The first step is a **visual survey** of the structure and of the service environment. Visual examinations can range from a simple inspection to a very detailed investigation, where all cracks and other evidences of physical deterioration (rust staining, efflorescence, surface "pop-out", etc.) are recorded on scaled diagrams. Photographs may also be taken of any particular details.

To delineate hollow areas or delaminations caused by corrosion, practically any sounding device can be used for this purpose. These devices range from lightweight$hammers or simple **chain-drags** for slab surfaces to more sophisticated apparatus, such as the automated **Delamtect** for surveying large surface areas.[13,30]

Testing the concrete to discover where loss of alkalinity has occurred can be useful in determining the exact locations of reinforcement corrosion. By breaking the testing surface and spraying it immediately with a pH indicator solution (**phenolphthalein** in dilute alcohol), immediate visual indication of the depassivation front relative to the steel can be obtained. The indicator solution has a very strong pink colour that is visible on concrete having retained its alkalinity (pH value of approximately 13), yet remains colourless on the carbonated portions. The maximum, the minimum, and the apparent average depths of **carbonation** can be recorded.[4,20]

The **chloride determination** is a very important aspect of the initial condition survey. For this purpose, samples must be obtained by breaking off pieces of concrete or by drilling holes and collecting the dust produced (see Figure 3.3). Obtaining samples by drilling is a quick and simple procedure, allowing many samples to be taken so as to obtain representative results. The concrete samples are then treated with acid to dissolve the cement, and the chloride content is

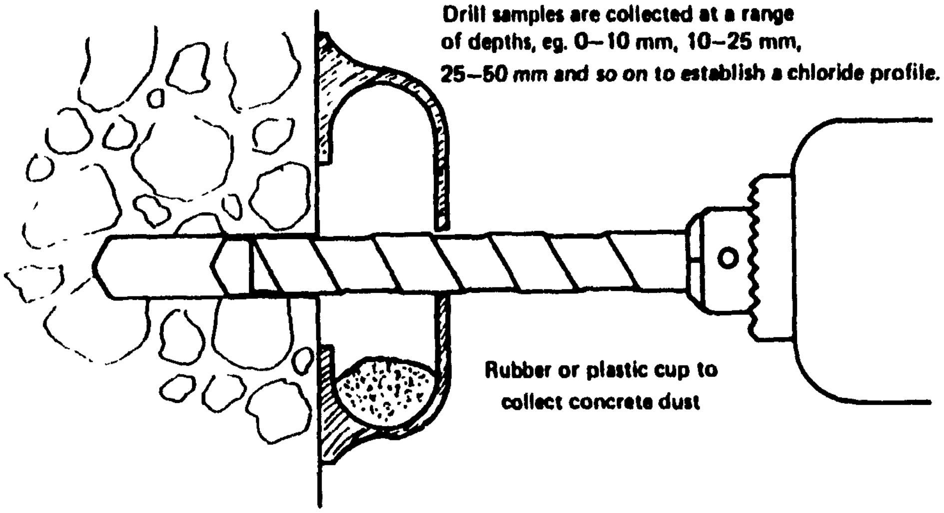


Figure 3.3: Concrete Surface Drilling[4]

determined by titration against silver nitrate.[28] Chloride ion meters and rapid field test methods for in-situ analysis may also be used.[2,4]

3.2.2 Detailed Condition Survey

After the results of the initial examination indicate the likelihood of repair, a thorough survey and testing of the representative parts of a structure must be performed. This is to allow a repair scheme to be designed and its cost to be estimated. The extent of this detailed inspection depends largely on the required degree of sophistication as well as on the cost allocated to performing the examination. More specialized equipment and instrumentation, along with a correct understanding of their utilization, are required to assess properly the damage resulting from corrosion.

The following tests are normally included in a detailed condition survey:

1. Mapping the **half-cell potential** of the concrete surface relative to the reinforcement. This is carried out by using a copper-copper sulfate half-cell (CSE), a high-impedance voltmeter, and lead wires to connect the half-cell and the reinforcing steel to the voltmeter (see Figure 3.4).

The potential values obtained provide information only on the presence or absence of corrosion and <u>not</u> on the corrosion rate. Table 3.1 summarizes the significance of the results obtained, according to ASTM Standard C876. The potential values in volts (V) are measured versus a copper-copper

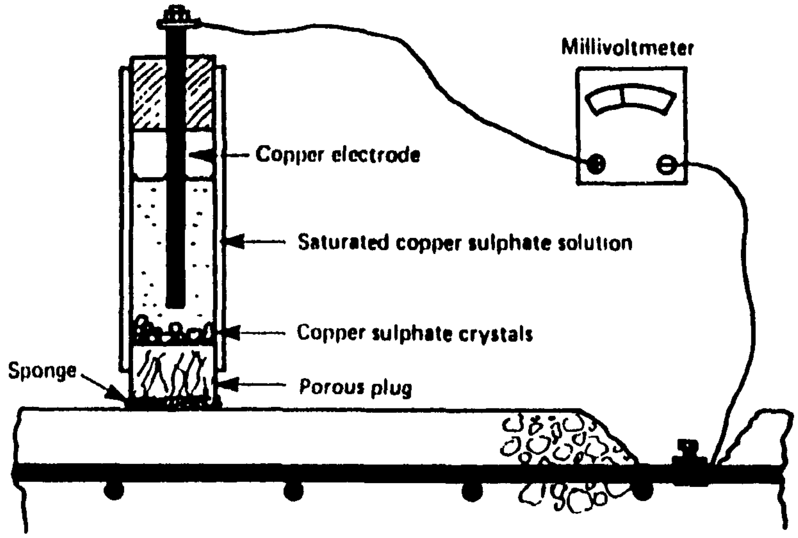


Figure 3.4: Copper-Copper Sulfate Half-Cell[4]

sulfate half cell (CSE). Isopotential contour maps of the entire concrete surface can be plotted. Large potential differences generally indicate high corrosion rates.[2,3,20,30]

POTENTIAL (V vs CSE)	**PROBABILITY OF CORROSION**
> -0.20	< 5%
< -0.20 but > -0.35	approximately 50%
< -0.35	> 95%

Table 3.1: Interpretation of Half-Cell Measurements

2. Measuring the **electrical resistivity** of the concrete. This gives a measure of how easily the corrosion current can flow as a result of the potential differences caused by the corrosion conditions. This can help in the interpretation of the electrode potential results. The resistivity of concrete

is usually measured by the four-probe method (see Figure 3.5).

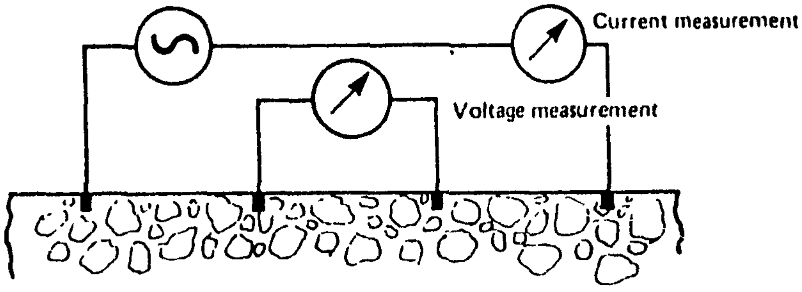


Figure 3.5: Resistivity Measurement With Four-Probe Method[4]

An electric current is passed between the outer probes and the measured potential difference between the inner probes can be used to determine the resistivity in a local area.[3,4,20]

3. Locating areas of delamination and voids by measuring the **ultrasonic pulse-velocity (UPV)** through the concrete. Pulses are sent from a transmitting probe on one side to a receiving probe on the other side (see Figure 3.6). Any air gap within the concrete greatly increases the transmission time.[4]

4. Locating the exact position of the reinforcement embedded in concrete and determining the thickness of the cover over the steel. This is performed with a **pachometer**, with automatic data recording equipment to facilitate the speed of conducting the survey. This information is essential if it is desired to extract concrete samples and is useful in determining the

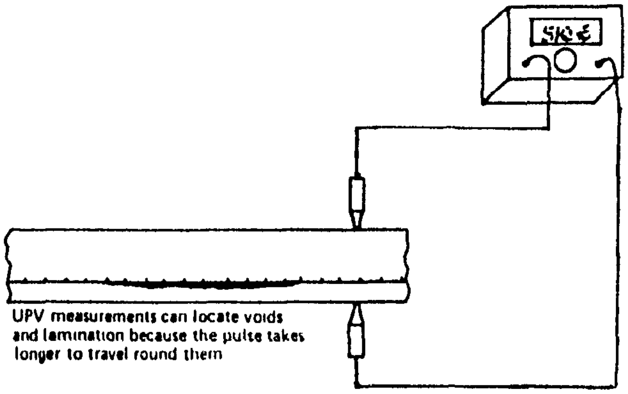


Figure 3.6: Ultrasonic Pulse-Velocity Test[4]

corrosion potential.

5. Testing **core samples** for concrete strength, permeability, contamination, composition, and density. The samples can also be examined petrographically and analyzed chemically to determine the cement content and type, chloride content, water-cement ratio, aggregate type, and grading.[4,20]

6. Measuring the **surface water absorption** of in-situ concrete. The results give an indication of the danger that chlorides or carbon dioxide will penetrate to the reinforcement and of how freely oxygen can pass through the concrete to sustain the corrosive reactions.[4]

Various other concrete properties can be determined as part of the detailed condition survey. These include original concrete mix constituents, ultimate load-bearing capacity, abrasion resistance, surface hardness, penetration resistance, sulphate content, and structural integrity. These can be obtained using both destructive and non-destructive testing methods.[13,20]

3.3 REMEDIAL MEASURES

The remedial measures undertaken are based upon the complete assessment of the concrete conditions and their interaction with the structural system, along with the type of facility to be repaired. Any repair made to a structure should fulfill three basic requirements:[32]

1. Arresting deterioration by preventing further corrosion of the reinforcing steel (i.e., ingress of oxygen, water, and chloride ions must be averted);
2. Restoring structural integrity (e.g., concrete properties); and
3. Providing an aesthetically acceptable finish (i.e., uniform appearance).

Repair techniques must be selected according to the degree of damage and the level of repair to be accomplished. These can be classified into two types: (i) where damage is limited to moderate cracking; and (ii) where damage involves extensive cracking and spalling of concrete bonded to the reinforcing steel.[38]

3.3.1 Crack Repair

The first step in repairing cracks is the removal of laitance by an abrasive blasting method. Afterwards, having identified previously the type and nature of the cracking, a suitable repair method can be selected.

Plastic shrinkage cracks occur during or very soon after construction and should be sealed with polymer-modified grout. In the case of **shear and transverse** cracking, the simplest of repairing is by pressure-injection of epoxy resins. The epoxy resin and hardener are usually premixed and fed into the crack under gravity or applied pressure. Resin injection is a highly skilled process depending largely on the experience of the operator.[4,38,39,43]

In some instances, cracks are "active" (moving) and must be widened at the surface and sealed. The sealing groove must follow the line of the crack and the sealant must be prevented from "sticking" to the groove bottom (see Figure 3.7). Cracks that have been caused by the build-up of rust forming on the reinforcement cannot be repaired without removing and replacing the concrete cover.[4]

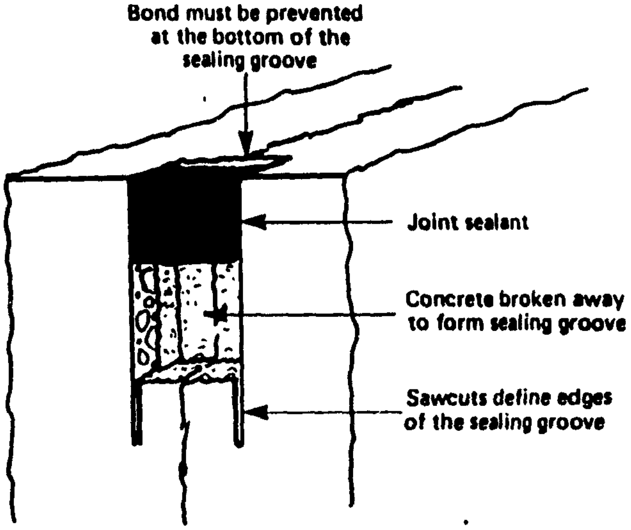


Figure 3.7: Joint Sealing of Cracks[4]

3.3.2 Patch Repairs

3.3.2.1 Concrete Removal

The first step in repairing larger distressed areas is the removal of all contaminated concrete surrounding the reinforcing steel. Several techniques can be used to achieve this goal. High pressure **water blasting**, or **hydrodemolition**, is the quickest way of removing large areas of concrete and helps in removing the concrete behind the reinforcement. Water blasting usually removes the weaker concrete, leaving the remaining aggregate intact.[45,46]

Another frequently used and less expensive method is the use of **pneumatic hammers** or **mechanical chippers**. Since these mechanical devices are not very precise in removing the required thickness and tend to shatter the aggregate that is not removed, it is advised to make a perpendicular saw-cut of at least 15 mm (0.59 in) all around the area to be removed. This will also ensure that the replacement material is properly contained by the surroundings and does not come to a "feathered" edge.[4,46]

There is usually some doubt as to the exact extent and depth of concrete removal. It is obvious that concrete must be removed to a depth that includes all of the affected reinforcement and some room for replacement behind it. If the concrete removed is carbonated only and the reinforcement is surrounded by new uncarbonated concrete providing an adequate cover thickness, no additional portions need to be removed. However, if chloride contamination is the cause of distress, the chloride ions can spread from the contaminated to the new concrete. Therefore, it will often be necessary to remove contaminated concrete in areas where there is no apparent rusting of the reinforcement to repair presently rusted areas.[4] Figure 3.8 depicts concrete removal in a zone of carbonation.

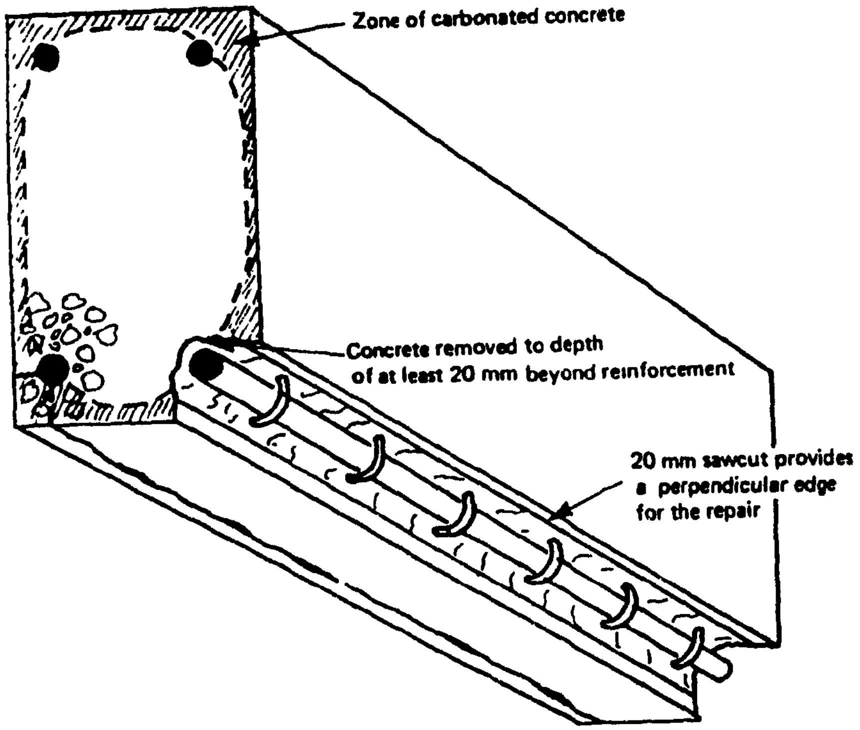


Figure 3.8: Concrete Patch Repair in Carbonated Zone[4]

3.3.2.2 Surface and Reinforcement Preparation

The single most important aspect of any patching or overlayment of concrete depends upon the preparation of the substrate surface. Removal of any laitance or debris is necessary, and the remaining concrete must be sound and clean. The most economical methods of removing surface weaknesses are sand or high pressure water blasting.[39,40]

The reinforcing steel exposed must be inspected. It is essential to remove all rust from the surface. **Water-abrasive blasting** (abrasives entrained in water jet) should be used to remove any rust. This combination of abrasives to remove solid contamination and water to dissolve chlorides is one of the best ways to ensure a chloride-free steel surface. Nevertheless, a thorough visual inspection must be carried out to ensure removal of rust from the "blind" side of the reinforcement.[4,40,46]

If rusting has reduced the cross-sectional area of the reinforcement by more than 20% additional reinforcement may have to be lap spliced to the weakened bars. The additional bars can be bonded with **epoxy resin** in holes drilled into the concrete.

The exposed reinforcement is subsequently coated to further protect the steel surface from the intrusion of corrosion-inducing elements. The coatings that could be used can be broadly classified as follows: **cement slurry; cement slurry modified with polymer or latex emulsion; epoxy resin** (with or without alkaline admixture); **inhibitive primer;** and

zinc-rich sacrificial primer. The most commonly used coating is an electrostatically-applied or liquid-applied **epoxy coating**, especially in very aggressive environments. Where there is a risk of damage to the coating, it is important that no uncoated reinforcement is nearby. Intense local corrosion at the anodic "breaks" in the coating may be produced by the corrosion current generated by the uncoated reinforcement.[4] Additionally, it is important to remember that a coating is no substitute for removing chloride contamination nor will it prevent corrosion by chlorides already present on the surface of the reinforcing steel.[46]

3.3.2.3 Material Replacement

The concrete surface must be replaced with an adequate material to provide the necessary protection of the reinforcing steel. An evaluation of the repair materials should be made before final selection. For this purpose, the following phenomena can be explained[32]:

- adhesion/bond strength;
- shrinkage, thermal movement, and cracking;
- permeability;
- chemical passivation of reinforcing steel;
- mechanical strength;
- ease of application;
- freeze-thaw resistance;
- chemical resistance; and
- overall performance (long-term exposure testing).

Monetary considerations for the overall expenditure would include the labour and the "down time" costs, in addition to the actual material costs.

There are five basic methods of restoring concrete to a sound condition. These include:[4]

1. Recasting using **conventional Portland cement concrete.** The old concrete surface must be saturated prior to casting. In some cases, it is necessary to apply a bonding coat (cement grout, polymer-modified bonding grout, or water-compatible epoxy resin). The repair mix should be made with the same aggregate type as the in-place concrete, and have a high cement paste content and a low water-cement ratio. The most practical means of achieving good compaction is by placing the concrete in small amounts and vibrating it as the work proceeds.[4,40]

2. Patching with **trowel-applied cementitious mortar.** Use of a bonding coat creates no special problems since there is no formwork to adjust. The mortar can be applied immediately after the application of the bonding coat, especially in hot dry weather. The mortar can contain polymer admixtures to increase adhesion and tensile strength.[40]

3. **Spraying-on new concrete ("shotcreting").** This simple technique is widely used in high volume repair work. It involves pneumatically applied concrete at high pressures through a hose and nozzle system. There are two distinct ways of shotcreting: the **dry process**, whereby water is supplied at the nozzle head to a dry mix, and the **wet process**, whereby air is supplied at the nozzle to a prewet mix. Shotcreting depends highly on the expertise and experience of the nozzle operator. Latex additives or silica fumes can be combined to increase permeability.[40,46]

4. **Prepacking dry aggregates**, which are subsequently grouted to fill the spaces between the aggregates.[4,40]

5. Patching with **trowel-applied resin-based mortar.** Epoxy resins are the most commonly used and are the only resins capable of making mortars with structural properties suitable for load-bearing applications. All resins require either a reactive hardener or a catalyst for proper application. The final properties are influenced by the large variety of resins and hardeners commercially available.[4]

All types of cementitious repair materials need thorough and continuous curing for at least **3 days** in a temperate climate or **7 days** under hot drying conditions. This is essential to develop the impermeability of the repair material and to minimize drying shrinkage stresses while bond strength is developing.[4]

3.3.3 Surface Treatments

The final protective system is the treatment of the concrete surface that will provide the necessary waterproofing, abrasive, and corrosion protection. Selection of the appropriate treatment should include the following considerations[39]:

- resistance to corrosion-inducing elements;
- estimated service life;
- content of the solids;
- thickness of the protective system;
- temperature condition of the application;
- ease of application;
- ease of repairing damaged areas;
- total applied cost; and
- unit cost ($\$/m^2$ or ft^2) per year of service.

The above list will serve as a guide in the final selection amongst the many commercially available surface protective systems. These include:[4]

1. **Hot-applied mastic asphalt tanking** (bituminous layer);
2. **Preformed sheet materials** (bituminous base or pvc polyurethane fabric);
3. **Building paper** (bitumen on organic paper);
4. **Polyethylene sheets;**
5. **Liquid surface coatings** (coal-tar epoxy; epoxy resin; solvent-based acrylic; methacrylate; emulsion-based acrylic; styrene-butadiene polymers); and
6. **Water-repellent treatments** (silicone, silane).

Complete instructions for repairs and material properties of the selected surface treatment must be obtained directly from the manufacturer. Moreover, there will be an unavoidable maintenance expense as the surface treatment will have to be recoated or reapplied periodically during the expected service life of the structure.

CHAPTER 4

CASE STUDIES

The basic principles and mechanisms of corrosion of reinforcing steel embedded in concrete were presented in the previous chapters. Assessment techniques of corrosion damaged concrete and the importance of proper repair procedures were also discussed. This section examines three cases of rehabilitation of concrete structures in the Montreal region. These include a downtown bridge, an elevated six lane autoroute, and a parking structure.

4.1 DORCHESTER STREET BRIDGE

The Dorchester Street Bridge in Downtown Montreal is a familiar sight to many Canadians, despite the fact that few realize it is actually a bridge. The development of the

Downtown area in the 1960's made the bridge appear as an ordinary city thoroughfare. The asphalt-surfaced roadway was enlarged to a width of 80 ft. (24.4 m) to carry six traffic lanes, with 12 ft. (3.7 m) wide sidewalks on either side. Figure 4.1 shows the general location of the Dorchester Street Bridge. At this time, lower levels of the bridge were transformed into boutiques and a parking garage.

In 1980, the underneath of the bridge deck showed evidence of concrete spalling and corrosion of embedded reinforcing steel. Damage to the parking areas and boutiques resulted from a water leakage. The increased use of salt as a

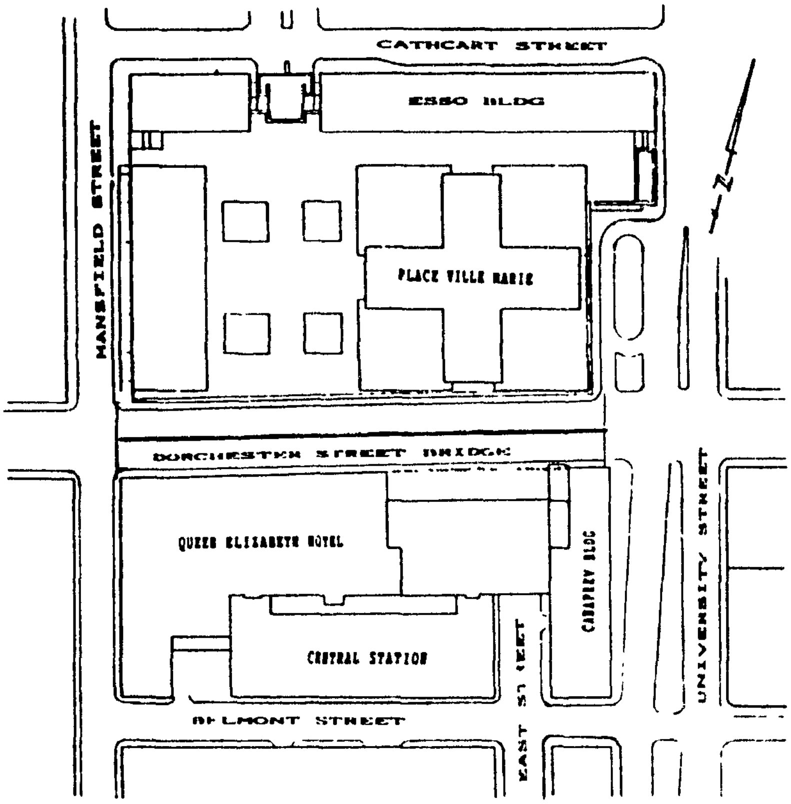


Figure 4.1: Location of Dorchester Street Bridge[48]

de-icing agent was perceived as the main cause of distress. In 1985, hotel reconstruction work nearby indicated that the underlying concrete was in a deteriorated state. It appeared that water was infiltrating through the sidewalk curb.

In 1986, a complete field investigation was carried out to properly assess the existing conditions of the bridge deck. Results of the study were as follows:[48]

- The chloride ion content was found to be 5 to 15 times the threshold value to initiate corrosion.
- Evidence of concrete spalling, delamination, and corroded reinforcing steel was noted at various areas.
- The inside faces of the abutments were always wet and showed signs of rust staining and efflorescence.
- The steel beams and columns carrying the deck loading, as a result of surface run-off leakage, were heavily corroded (see Figure 4.2).
- At one location, no core sample could be extracted because of the presence of loose granular material. At another location, the core split at a depth characterized by severe honeycombing.

A second investigation was carried in June, 1988 and similar results indicated an advanced state of deterioration of the bridge deck. In addition, a structural evaluation revealed that the load carrying capacity of the deteriorated bridge deck had decreased by approximately 40%. At this time, the city of Montreal, as an immediate safety measure to protect the public using the structure, posted a weight restriction for vehicular traffic. Plans were undertaken to design a new bridge deck.

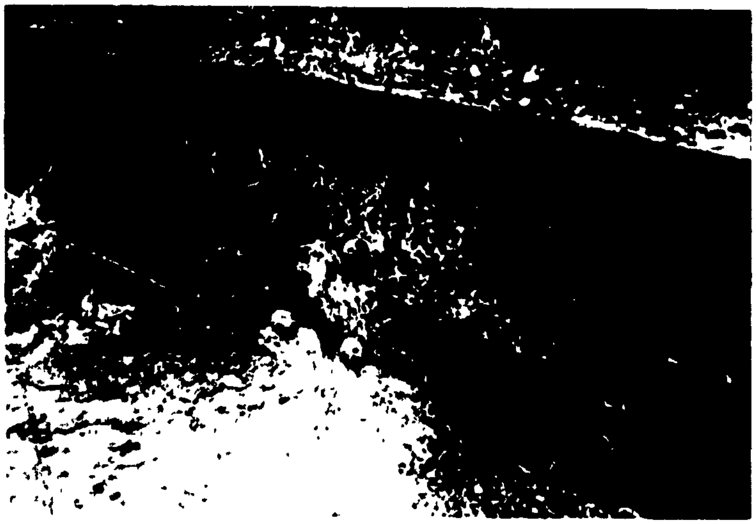


Figure 4.2: Corroded Steel Beam[48]

The major steps for the rehabilitation phase were as follows:[48]

- Construction of temporary shelters at the underground parking level to ensure normal parking operations.
- Removal of the suspended ceiling, lighting, and ventilation systems underneath the bridge deck.
- Deviation of traffic flow and installation of new street signals.
- Demolition of the bridge deck. Special care was taken during demolition to avoid debris from falling on the level below. Further precautions had to be taken due to the presence of major telephone and power lines under the sidewalks. Figure 4.3 shows the demolition of the concrete bridge deck.
- Installation of eight neoprene pad bearings, four intermediate transverse joints, and two longitudinal joints.
- Sandblasting and repairing or replacing of the steel beams and columns supporting the deck.
- Installation of formwork and reinforcing steel and casting concrete for the new deck. The new reinforced deck is 7-½ in. (190.5 mm) thick of 30 MPa (4350 psi) concrete. Epoxy coated reinforcing bars were used. A special depression within the bridge deck was provided to serve as a future floral median.

Figure 4.3: Demolition of Concrete Deck[48]

- Application of the waterproofing membrane and wearing surface. The membrane consisted of a composite of rubberized asphalt and woven polypropylene mesh, followed by a 3 in. (76 mm) thick asphalt wearing surface.

The construction work was carried out in two phases, with the major consideration that traffic was to be maintained at all times by keeping two lanes open in each direction. Figure 4.4 shows work during the first phase of construction. After completion, traffic was rerouted over the newly finished portion of the bridge and the second phase was completed in a similar fashion. The construction work started in May 1989 and the traffic was re-established completely in November 1989.[48]

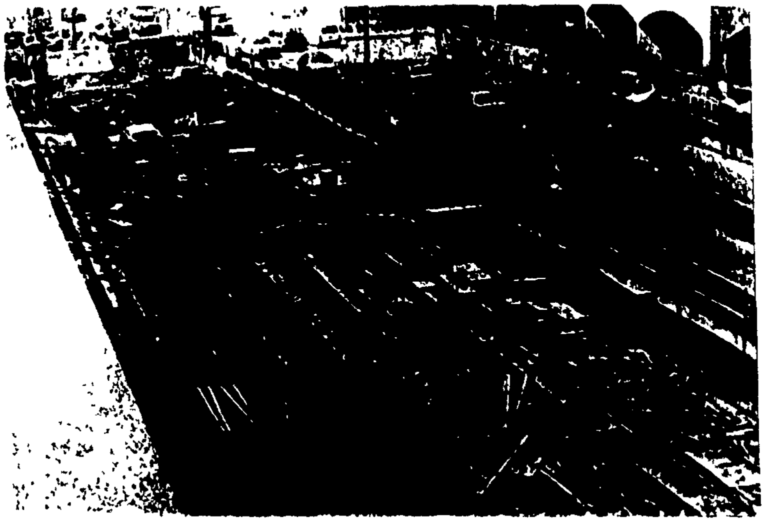


Figure 4.4: First Phase of Construction[48]

4.2 METROPOLITAN BLVD. (AUTOROUTE 40)

One of the first urban expressways built in Canada was the Metropolitan Boulevard (Autoroute 40). Its construction was first conceived in the early 1950's and was completed towards the end of that decade. It forms a link in the Trans-Canada Highway and runs across the northern part of the Island of Montreal, following an approximate east-west direction (see Figure 4.5). The autoroute provides three express lanes in each direction and has a two to four lane service road on either side. Much of the expressway is elevated well above grade on a reinforced concrete structure, thus facilitating north-south traffic mobility on cross-streets of surrounding neighbourhoods (see Figure 4.6).

Over this period of thirty years, lack of adequate

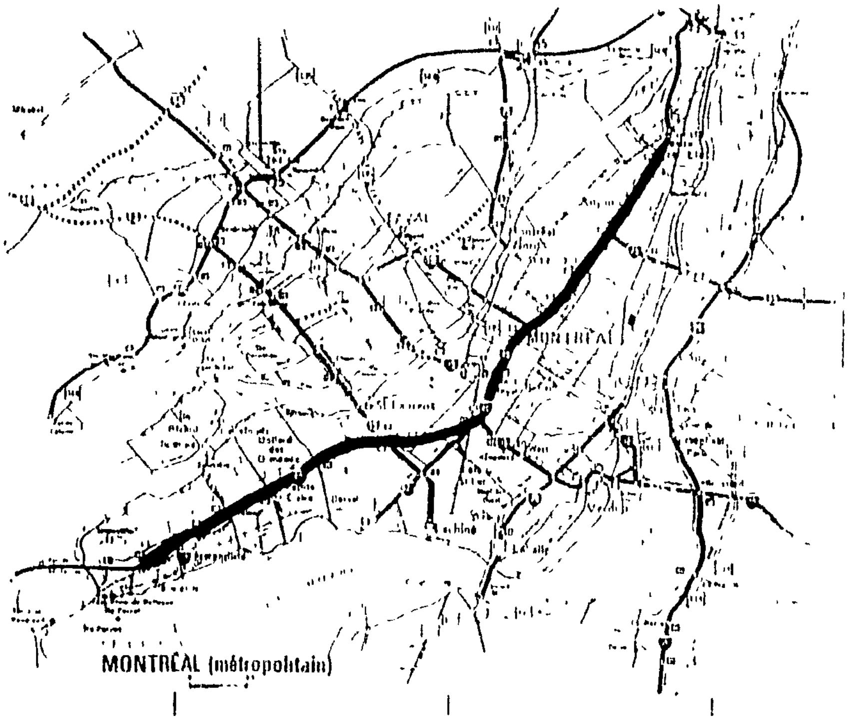


Figure 4.5: Metropolitan Blvd. (Autoroute 40)[163]

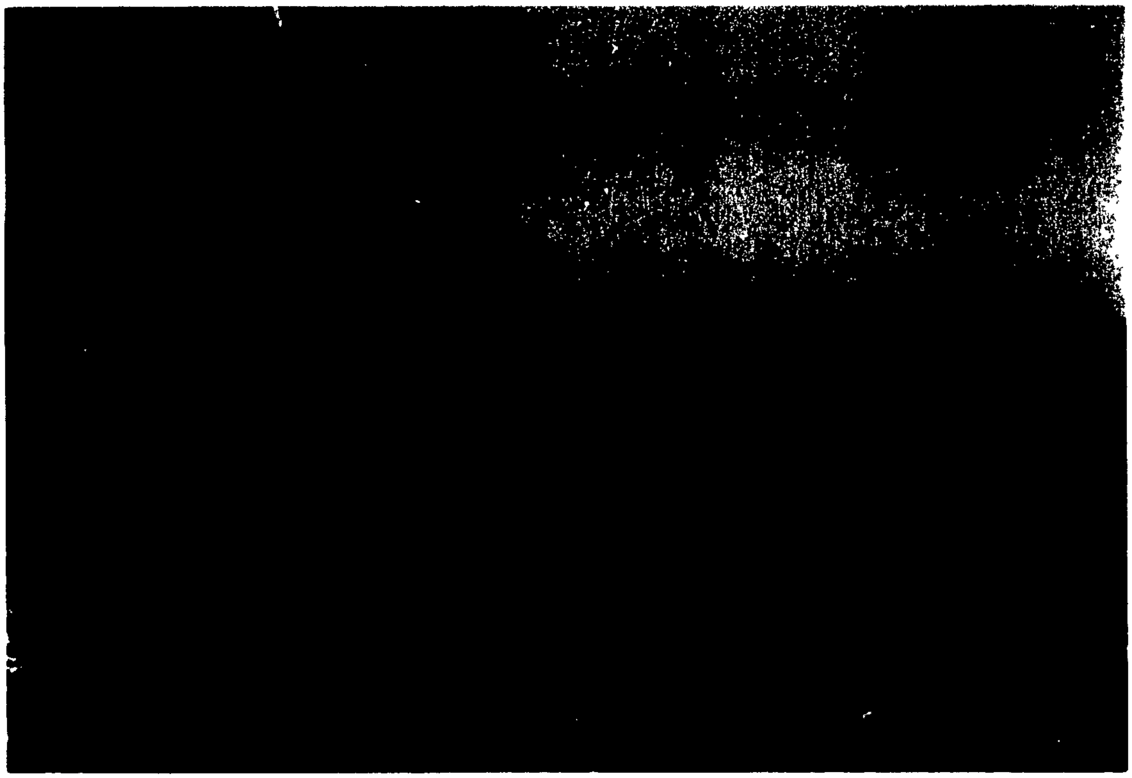


Figure 4.6: Traffic Flow on Metropolitan Blvd.[164]

maintenance has led to damage and deterioration of the road surface and the supporting concrete structure. This is particularly noticeable on the elevated sections of the expressway. The main cause of deterioration has been the corrosion of the reinforcing steel due to the intrusion of chemicals and moisture. As a result of Canada's prevailing climatic conditions, the concrete deck is continually exposed to snow and rain. The increase in traffic volume has led to greater use of de-icing chemicals, further contributing to the problem. According to 1987 statistics, the autoroute carries approximately 125,000 to 150,000 vehicles per day, well in excess of the design daily traffic volume capacity of the expressway.[162]

An infrared thermographic survey conducted in 1989 revealed that approximately 14% of the concrete deck in the elevated sections of the Metropolitan Boulevard was deteriorated and had to be replaced at variable depths. However, the exact extent of the deteriorating concrete was not determined from the conditional field survey. This lack of knowledge prevented accurate estimates of time, equipment, materials, methods, and costs to be incurred during the repair work.

However, it seemed impossible to execute the proper rehabilitation procedures without a significant disruption of the traffic flow. For this reason, le Ministère des Transports du Québec (MTQ) decided to proceed with the necessary repair work during one single period, from April to October 1990.

Rehabilitation was undertaken only on the express lanes so as to keep the service lanes free of any encumbrance, providing an alternative for the users. The estimated cost of repair and rehabilitation on these elevated portions was approximately $39 million.[162] The exact extent of the distressed concrete was to be known only during execution of the work.

Seven specialty contractors were involved in the repair work on the elevated sections of the Metropolitan Blvd. Some of the aspects of the repair work included:[24,162]

- Demolition of the existing median barrier, previously moulded of polymer-modified concrete, and the construction of a new median divider with conventional Portland cement concrete (see Figure 4.7). The existing fence and light supports were temporarily removed and replaced within the new median barrier. In certain portions, steel or sliding formwork was used to facilitate casting of the new concrete.

Figure 4.7: Demolition of Existing Median Barrier[164]

- Removal and replacement of all existing expansion joints, along with the removal of contaminated concrete near the joint locations using mechanical chippers. The new joints were installed using latex-modified concrete, providing greater initial strength and better adhesion between the existing and the new concrete.On average, one out of every three expansion joints were eliminated and the structure was cast monolithically with the same type of latex-modified concrete. The initial strength developed by this type of concrete was 22 MPa (3,190 psi) after 24 hours, that is, about 75% of its final compressive strength.

- Removal of the asphalt wearing surface and all of the contaminated concrete in the elevated deck portions (see Figure 4.8). This was performed using either pneumatic hammers or robotic hydrodemolition equipment, including water-blasting machines exerting pressures up to 1400 kg/cm^2 (20,000 psi). The distressed areas were properly cleaned and reconstructed to the original road specifications using latex-modified concrete, having a 28-day compressive strength of 30 MPa (4350 psi).

- Placement of a waterproof membrane on the concrete deck surface, properly applied and soldered, to prevent the

Figure 4.8: Removal of Contaminated Concrete Deck Substrate[164]

intrusion of chloride ions into the newly repaired concrete. Approximately 200,000 m^2 of deck surface was covered (see Figure 4.9).

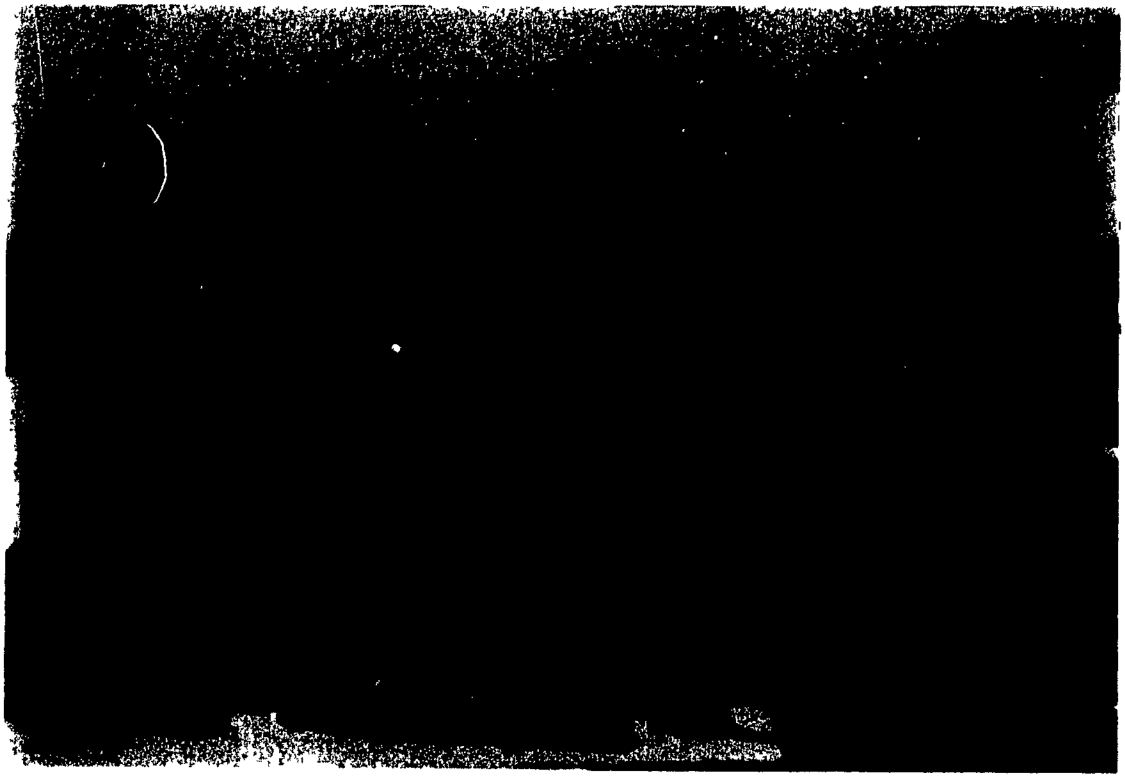


Figure 4.9: Application of Waterproof Membrane[164]

- Application of two layers of bituminous material after the installation of the waterproof membrane on the concrete deck. The particular mixture utilized was such as to reduce the phenomenon of scaling and abrasive wear. A different aggregate grading, along with more angular coarse aggregates, were used in combination with polymer-impregnated bitumen.

- Rehabilitation of the underside of the concrete deck slabs, along with the supporting columns. All distressed concrete was removed and replaced by shotcrete containing silica fumes and polypropylene fibres (see Figures 4.10 and 4.11). These additives help retard the initiation of cracking and increase the adhesion and resistance of the concrete. The replacement material was made more compact and thus more impermeable.

Figure 4.10: Concrete Removal by Hydrojetting[164]

Figure 4.11: Concrete Removal with Mechanical Chippers[164]

- Removal and replacement of the entire drainage system in the elevated sections of the expressway. All cast iron piping was removed and replaced by polyethylene ducts of 200 mm (8 in.) diameter, highly resistant to ultra-violet rays, vibration, impact loading, and freeze-thaw cycles. Roadside catch basins were replaced with new materials.
- Preservation of the existing underground drainage system. This will be cleaned periodically and monitored through a network of television cameras. Furthermore, additional manholes were installed to allow easier access in the system for the MTQ maintenance teams.

The rehabilitation project of the elevated sections of the Metropolitan Boulevard comprised of three distinct phases from April to October 1990. Phases I and II, each of a three month duration, dealt with repair work to be performed directly on the elevated deck. The provisions included alternate closing of expressway lanes, demolition, removal, and repair of deteriorated concrete, replacement and elimination of expansion joints, and installation of a new drainage system. Phase III of the project, with a duration of six months, was carried out simultaneously with the first two phases. It consisted of all restoration required to the existing structure and drainage system not involving access by the expressway lanes or the entry and exit ramps. The repair procedures consisted of removal of deteriorated concrete from the deck underside and columns, surface and reinforcement preparation, and vertical and overhead replacement with sound concrete. Additionally, installation of new piping and thorough cleaning of the underground drainage leading to the city's storm sewers was executed.[163] Most of the rehabilitation work on the elevated portions was completed by the end of October 1990, at an overall cost of approximately $85 million.[164]

4.3 SIR WALTER SCOTT PARKING GARAGE

Most parking structures have strength, serviceability, and durability problems associated with their unique structural requirements and exposure to the elements. Early signs of concrete deck deterioration are visible in many parking structures in Canada that are exposed to a deicer environment. These include reinforcement corrosion, surface scaling due to cyclic freeze-thaw damage, and through-slab water penetration. This was the case of the Sir Walter Scott Parking Garage, a two-level parking structure located in Côte St. Luc constructed about 15 years ago. The structure consists of two structural slabs (referred to as B1 and B2) and two slabs-on-grade (referred to as B3 and B4). The total surface area of the concrete slabs is approximately 33,000 sq. ft. (3066 m^2). Figure 4.12 shows a schematic cross-section of the parking structure.

The Sir Walter Scott Parking Garage displayed signs of distress (cracking) on the deck surface and on the slab soffits, as well as water retention (i.e., ponding) at various locations throughout the garage. It was decided to remedy the situation before further damage occurred. The delaminated areas of concrete were scaled and mapped by the contractor prior to any repair work carried out. The duration of the work

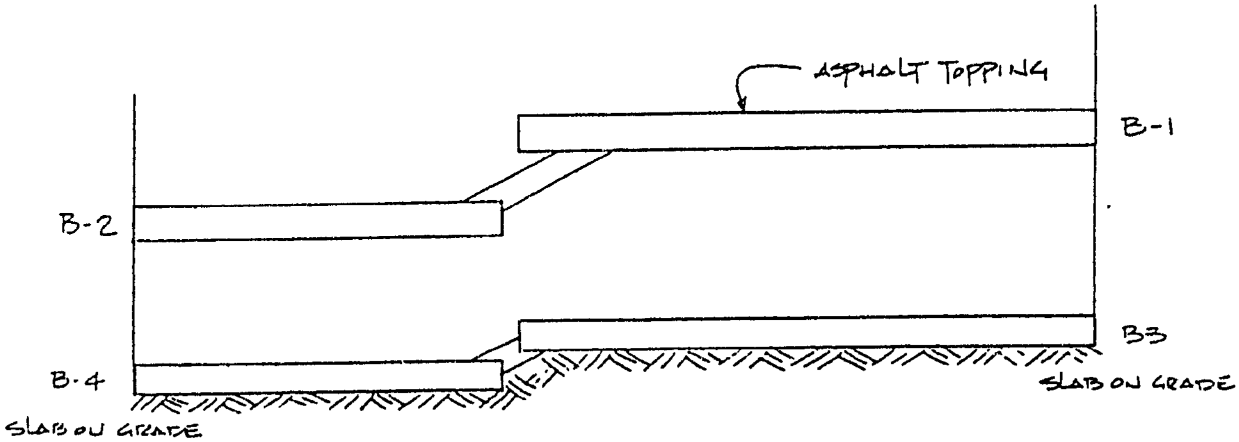


Figure 4.12: Parking Garage Slabs[165]

was estimated to be one month and the total cost to be approximately $150,000.

The major steps in the rehabilitation of the parking structure consisted as follows:[165]

- Removal of contaminated concrete on the deck surface. The defective areas were delineated by 1/2 in. (13 mm) deep saw-cuts. Demolition of the defective concrete proceeded until sound concrete was encountered. This was carried out to at least 3/4 to 1 in. (19 to 25 mm) beyond the level of the corroded reinforcement, wherever encountered, in order to allow for complete exposure of the rebars. The thickness of the concrete surface varied from 2 to 4 in. (51 to 102 mm). Figure 4.13 shows the surface delaminated areas of floor level B1.

- Cleaning of exposed corroded reinforcement by sandblasting and subsequent epoxy coating applied (see Figure 4.14). The substrate was airjet-sprayed to remove all latency. The concrete surface was kept under moist condition for two hours and then treated with a latex bonding agent. Six to eight percent of the emulsion was also used as an additive, prior to placing new concrete on the existing surface.

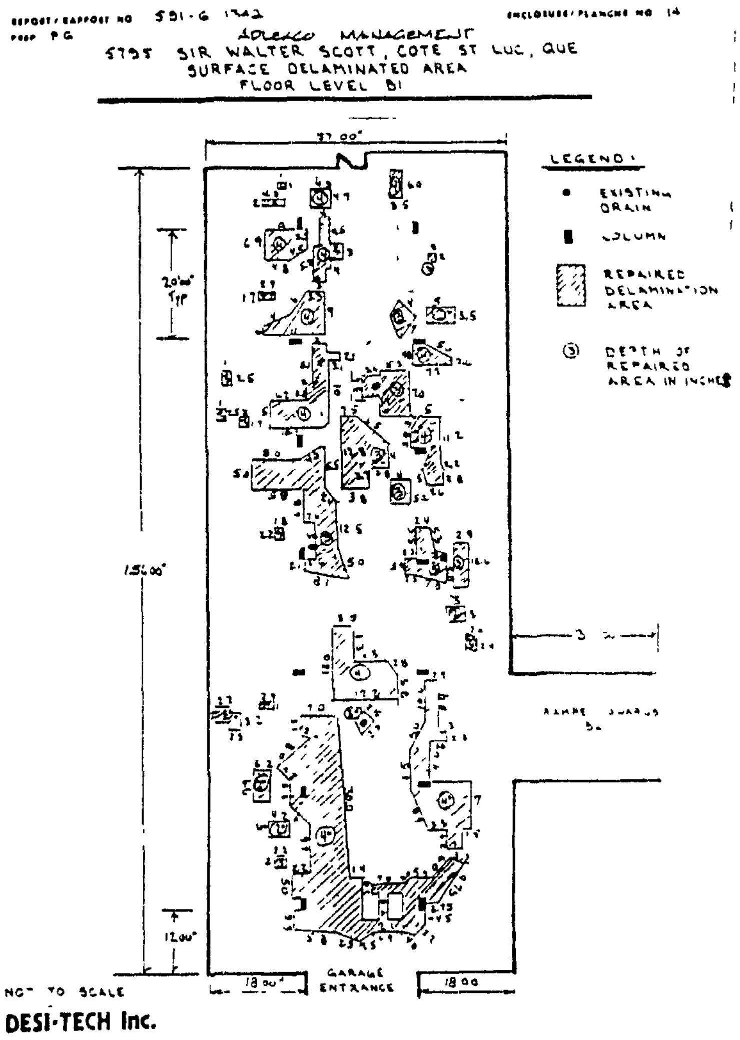


Figure 4.13: Surface Delaminated Areas - Floor Level B1[165]

- Replacement of the deck surface with a 30 MPa (4,350 psi), 3 in. (76 mm) slump concrete. A superplasticizer was added to the concrete mix for increased workability and strength. The fresh concrete surface was then water cured for a minimum period of five days.

- Application of a waterproofing membrane on the new concrete deck surfaces. Prior to the application, the slabs were thoroughly cleaned by high water pressure/air pressure method and then treated with a primer coat. A "Hydrotech" membrane was then installed, flood-coated at a temperature not exceeding 200°C (392°F). A "Remay" fabric was applied to the first coat of the membrane and then was flood-coated with a second

Figure 4.14: Cleaning Rebars by Sandblasting[165]

coat to achieve a thickness of 3/16 in. (4.8 mm). The membrane was turned up ± 6 in. (152 mm) along the columns and walls for additional protection against splashing of salts (see Figure 4.15).

- Application of an asphaltic wearing surface ("Trinidad Mastic") to a thickness varying between 3/4 to 1 in. (19 to 25 mm).

- Installation of twenty (20) additional drains in areas where water ponding occurred in order to ensure maximum surface drainage. The entire slab surfaces were flooded to verify watertightness and to locate areas where additional drains were required. Minor slope corrections were carried out around the drains. Figure 4.1) shows the locations of the drains installed. Additional pipe connections and flanges were also provided.

- Removal and replacement of all unsound concrete in the slab soffit regions. Prior to the repair of the soffit, all corroded electrical pipes had to be removed and

Figure 4.15: Fabric Reinforced Membrane Application[165]

replaced by new ones. Exposed rebars were cleaned by either sandblasting or air-blast and the rebars were epoxy coated. The substrate was then coated with a latex bonding agent before the application of the mortar. The mortar was then applied in thin layers.

- Injection of all cracks with a high penetrating epoxy agent.

The rehabilitation work was completed by the end of 1988 at a cost of $160,000.[165] It is important to remember that a maintenance program and its related monitoring must form an integral part of the general caretaking to ensure an extended service life of the repaired system. Regular sweeping by hand and/or mechanical means is required to remove debris and crystallized road salts during the winter period. This also

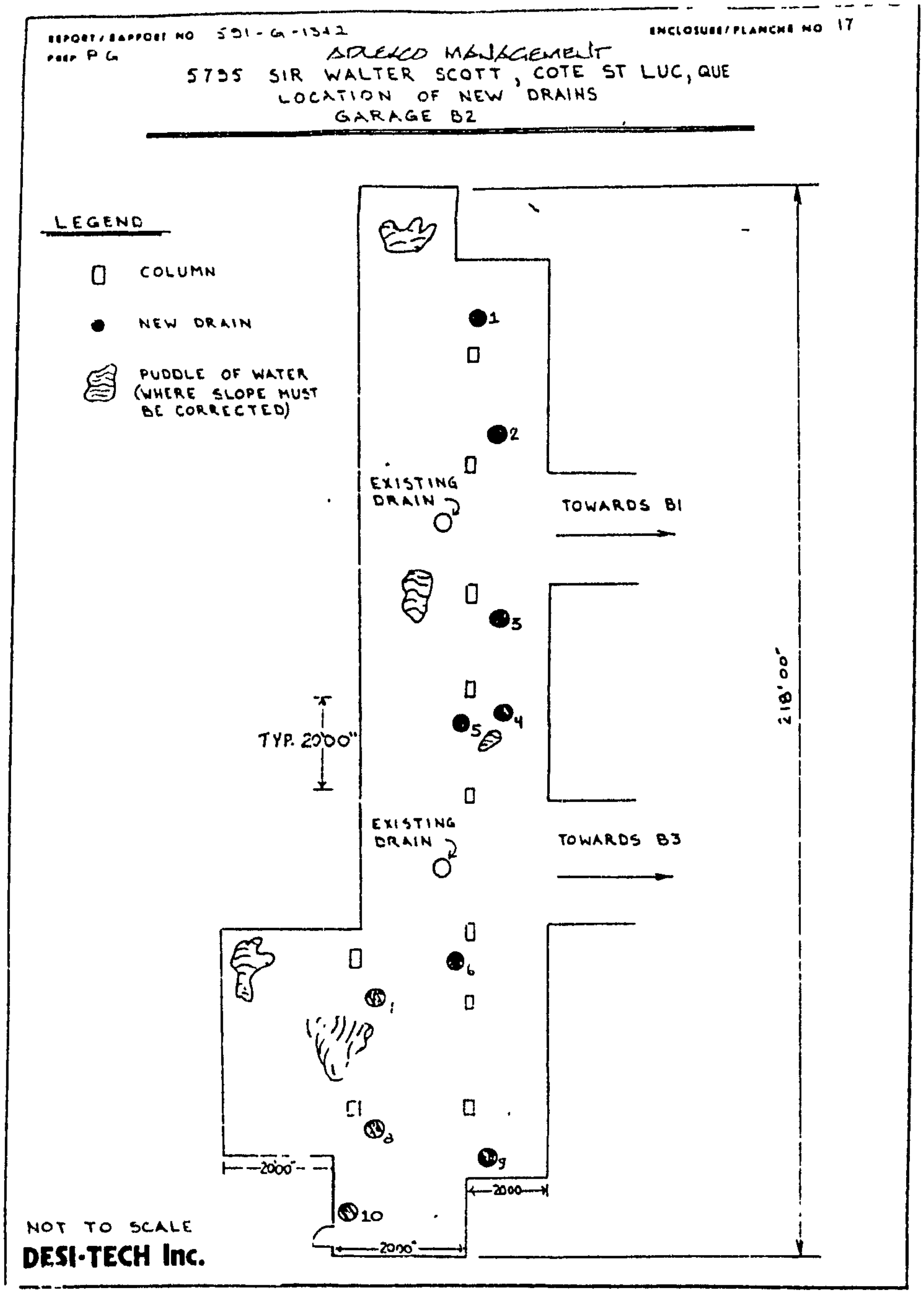


Figure 4.16: Location of New Drains - Floor Level B2[165]

helps to prevent clogging of the drainage system.

CHAPTER 5

REINFORCEMENT CORROSION RESEARCH

Most deterioration problems related to corrosion of reinforcement embedded in concrete are manifested and normally studied in the field. However, valuable information can be obtained from laboratory studies and testing of the resistance of the concrete to aggressive elements. From early investigations, and based on the results of various experiments and observations, information on the chloride content at the level of the reinforcement, and the onset and progress of corrosion process, has been obtained. Most of this information has been incorporated in the provisions of the various codes of practice presently used in construction in different parts of the world. Therefore, the design features of a new structure, that incorporate methods to provide effective protection against corrosion, are based essentially on the previous research results. Furthermore, experimental research and development has provided engineers and construction practitioners with suitable methods of repairing distressed concrete in existing structures.

5.1 REVIEW OF PAST RESEARCH WORK

This section reviews basically some of the laboratory studies performed over the last twenty years in the general area of corrosion of concrete-embedded reinforcing steel. Most of these are based on previous experimental research work. However, the main developments towards practice have occurred over the past twenty years. Tables 5.1 to 5.3 summarize chronologically most of the research studies undertaken mainly in English-speaking countries between 1970 to 1979, between 1980 to 1985, and from 1986 to the present.

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
R.F. Stratfull[75]	Measurement of half-cell potential of steel embedded in concrete specimens in laboratory tests and relation to visual observations of concrete cracking.	- Electrical potential measurements can indicate active or passive steel condition. - Differences in electrical half-cell potentials are associated with "solution potential" of steel as well as voltage gradients resulting from current flow. - In a voltage gradient, the measured half-cell may not necessarily reflect the true half-cell of the steel located nearest because the voltmeter can only indicate the highest voltage at that point. - To detect corrosion-caused electrical current flow, it is not always necessary to electrically connect the voltmeter to the reinforcing steel. - The best measure of electrical half-cell potential is a direct electrical connection to the reinforcing steel under consideration. - Under the condition of electrical current flow, all half-cell potential measurements are distorted by the arithmetic difference of the associated voltage gradients.
K.C. Clear[30]	Determination of the relative time to corrosion of reinforcing steel embedded in concrete slabs, fabricated from various mix designs and construction practices.	- Conventional bridge deck concrete, placed with strictest "quality" control, is not impermeable to chlorides. - The water-cement ratio of bridge deck concrete should be as close to 0.4 as possible. - Some method should be used to ensure a minimum in-place density of 98% of the rodded unit weight of concrete. - The minimum clear cover over reinforcing steel should be 2 in.(50.8 mm) for concrete with a water-cement ratio of 0.4 and 3 in.(76.2 mm) for concrete with a water-cement ratio of 0.5.
S. Prudil[76]	Concrete modelling of parameters affecting corrosion process.	- It is possible to model the progress of corrosion by a second degree parabola.
C.L. Page M.N. Al Khalaf A.G.B. Ritchie[77]	Effect of mix characteristics and steel surface condition on tensile strength of bond between steel and different mortars.	- Changes in properties of steel oxide film influence the bond strength. - The relationship between bond strength and potential resembles an electrocapillary curve.
M.A. Taylor[78]	Effect of ocean salts on compressive strength of concrete.	- Influence of ocean salts is affected by chemistry of cement. - Dramatic increase was noted in the 28-day compressive strength for Type II cement for either NaCl or ocean water, for up to 5% by weight of water.

Table 5.1: Experimental Investigations (1970 - 1979)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
E.M. Theissing P. Hest-Wardenier G. de Wind[79]	Effect of combining sodium chloride ($NaCl$) and calcium chloride $CaCl_2$) with various hardened cement pastes.	- Dominating chemical reactions occur with hydrated cement components and adsorption. - Acceleration by $CaCl_2$ leads to lower chloride concentrations in the final pore system. - In some cases, the $NaCl$ content of aggregate determines the final chloride concentration.
O.E. Gjørv Ø. Vennesland[80]	Diffusion of chloride ions from seawater into concrete of different water-cement ratios and cement types. Effect of cathodic protection on chloride penetration.	- Chloride will inevitably reach the level(s) of reinforcement. - The water-cement ratio effect is limited to the surface layer and short time periods. - The cement type has greater influence for greater depths of penetration and longer durations of chloride exposure. - Diffusion of chloride ions is dependent on the permeability and capacity of chloride binding, and on the ion exchange capacity of the system.

Table 5.1 (cont'd): Experimental Investigations (1970 - 1979)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
K.G. Kawadkav Krishnamoorthy[81]	Durability of concrete. Behaviour in salt solutions employing accelerated testing techniques such as the use of small-sized specimens and sodium chloride concentrations.	- Strong concentrations of common salt appears to cause loss of strength and microstructure changes of hardened cement. - Hydrostatic pressure produces accelerated effects of deterioration.
C.L. Page N.R. Short A. El Tarras[82]	Diffusion of chloride ions in hardened cement pastes. Influence of curing conditions, interfacial zones of segregation, and other cement types are studied.	- Diffusion of chloride ions in ordinary Portland cement pastes was higher than that for diffusion in normal aqueous solutions. - Curing conditions had a marked effect on the ability of the mature cement paste to transport particles. - Diffusion of chloride ions is strongly influenced by cement composition.
A.D. Jensen S. Chatterji P. Christensen N. Theulow H. Gudmundsson[83]	Alkali-silica reactivity of 35 sand types by both "German" and NaCl bath methods.	- NaCl beth method is preferable since it can be used to detect the alkali-silica reactivity of an aggregate. - Use of low alkali cement with a reactive aggregate may not be protective of external sodium salts migrating and concentrating.
C. Boqi H. Dinghai G. Hengquan Z. Yinghao[84]	Ten-year field exposure tests on endurance of reinforced concrete in harbor works (China).	- Damage/failure occurred mostly above the average high tide level. - No difference in reinforcement corrosion is found below the average high tide level. - No effect of W/C ratio on the endurance of concrete. - Penetration of chloride ions toward reinforcement can effectively be retarded by increasing thickness of concrete cover. - As cover thickness increases, the critical value of the chloride content resulting in reinforcement corrosion also increases. - Reinforcing bars in freshwater harbours are less rusty than those in seawater harbours. - Low-alloy steel bars rust more easily than ordinary carbon steel bars.
I.L.H. Hansson C.M. Hansson[85]	New experimental method to measure electrical resistivity of Portland cement-based materials.	- New technique is developed providing information on polarization of cement resulting from applied electrical field as well as both A.C. and D.C. electrical resistivities.
K.H. Wong P.E. Weyers P.D. Cady[86]	Effectiveness of alkyl-alkoxy silane treatment of concrete on reducing the rate of corrosmon of reinforcing steel in the presence of chlorides.	- Alkyl-alkoxy silane was effective in reducing the rate of rebar corrosion. - Allowing time after treatment to permit the ethanol carrier to evaporate and exposing the treated surface to water was beneficial. - Sodium chloride in concrete tends to increase the corrosion current. - Water-cement ratio in the range of 0.45 to 0.50 does not appear to have a significant effect on the corrosion process.

Table 5.2: Experimental Investigations (1980 - 1985)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
D.W. Hoffmann[87]	Changes in structure and chemistry of cement mortars stressed by a sodium chloride solution.	- One-sided stresses of cement mortars by sodium chloride show signs of distress at a particular depth of penetration.
H.G. Midgley J.M. Illston[88]	Measurement of penetration of chlorides into hardened cement pastes.	- The greater the water-cement ratio, the greater the depth of penetration by chloride ions. - The concentration of chloride ions is dependent on surrounding solution. - Chloride ions react with the anhydrous tricalcium aluminate (C_3A) in the remaining unhydrated cement. - Chloride ion distribution alters the pore size distribution (the greater the chloride content, the smaller the pores). - The higher the C_3A content of cement, the greater the resistance to reinforcement rusting since less chloride ions are left after the formation of chloroaluminate.
C.M. Hansson[89]	Electrochemical process in steel corrosion. Measurements of the rate of corrosion of steel.	- The currently used laboratory techniques of corrosion rate measurements of reinfovcing steel in concrete are explained and discussed.
C.M. Hansson Th. Frølund J.B. Markussen[90]	Effect of chloride cation type on corrosion of steel in concrete by chloride salts.	- Addition of $CaCl_2$ has two deleterious effects: i) more open pore structure, allowing easier diffusion and higher electrical conductivity; and ii) reduces pH of pore solution. - Lesser extent of corrosion if NaCl or KCl are added. - Neither the chloride content alone nor that of the pore solution alone can be used as a measure of the corrosion rate.
I.L.H. Hansson C.M. Hansson[91]	Factors controlling electrical conduction in cement-based materials are investigated.	- Concentration and mobility of ions in the pore solution, and the porosity and pore size distribution, are important factors of time dependency of the electrical conductivity of concrete.
B.B. Hope A.K. Ip D.G. Manning[92]	Corrosion and electrical impedance in concrete is investigated.	- Resistivity increases with age increase. - Resistivity increases with a water-cement ratio decrease. - Resistivity increases with moisture decrease. - Resistivity increases with temperature decrease. - Half-cell potential of steel is highly dependent on moisture content (potential increases with increasing moisture content).
P.J.M. Monteiro O.E. Gjørv P.K. Mehta[93]	Interface between corroding steel and cement paste containing chloride.	- Interfacial film of large lime crystals covered most of the steel surface. - Pore solution of concrete with silica fume contained a higher chloride/hydroxyl ion ratio for a given total chloride content.
B.B. Hope J.A. Page J.S. Poland[94]	Determination of chloride content of concrete.	- Results of hot and cold water extraction methods depend upon the subdivision of the sample and the nature, temperature, and duration of the extraction step.

Table 5.2 (cont'd): Experimental Investigations (1980 - 1985)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
C.L. Page N.R. Short W.R. Holden[95]	Influence of different cements on chloride-induced corrosion of reinforcing steel.	- Significant differences in pore solutions between sulphate-resisting Portland cement and ordinary Portland cement. - Diffusivities of chloride ions in hardened cement pastes have been used to rank cements in terms of their ability for limiting chloride ion supply to anodic corrosion sites.
D.N. Winslow[96]	High strength, low-alloy weathering steel as reinforcement in the presence of chloride ions.	- Under a typical exposure and salting schedule, high strength, low-alloy steel is much superior to plain carbon steel.
N.R. Buenfeld J.B. Newman[97]	Resistivity of mortars immersed in sea-water.	- All mixes tested showed increased resistivity upon exposure to sea-water. - This increase is due to two independent microstructural mechanisms: i) development of highly sensitive aragonite/brucite surface layer on sea-water exposed face; and ii) modification of cement paste pore structure resulting in volume reduction of larger pores.
K. Byfors C.M. Hansson J. Tritthart[98]	Pore solution expression as a method to determine the influence of mineral additives on chloride binding.	- Concrete mixing conditions do not have a great effect. - Differences in chloride binding appear to be related to both the original alkalinity of the cement and its fineness.
B.B. Hope J.A. Page A.K.C. Ip[99]	Corrosion rates of steel in concrete.	- Both DC polarization and AC impedance techniques yield similar values for polarization and charge transfer resistances. - Use DC polarization measurements only to estimate corrosion rates in simple corroding systems. - Mass transport of particles through the cement paste appeared to be a major factor in controlling the rate of corrosion in the active system. - Passive film resistance appeared to be a major factor in the non-corroding system.
Rasheeduzzafar F.H. Dakhil M.A. Bader[13]	Toward solving the concrete deterioration problem in the Arabian Gulf region.	- Type I cement performs better than Type V. - To produce a high quality, dense, and impervious concrete, a maximum water-cement ratio, minimum cement content, and an optimum binary aggregate proportioning should be specified.
P.S. Mangat K. Gurusamy[100]	Chloride diffusion in steel fibre reinforced marine concrete.	- Chloride concentrations are significantly greater in laboratory cured specimens relative to those cured on the beach. - Chloride concentrations increase with increasing crack widths, although the influence of small crack widths of ≤ 0.2 mm (0.008 in.) is marginal.

Table 5.3: Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
D.W.S. Ho R.K. Lewis[101]	Carbonation of concrete and its prediction.	- For concrete with limited initial curing, the water-cement ratio was the most reliable parameter in predicting resistance of concrete to carbonation. - Under short-term test conditions, carbonation proceeded in proportion to the square root of time. - Fly ash concrete have lower resistances to carbonation.
C.J. Newton J.M. Sykes[102]	Effect of salt additions on the alkalinity of $Ca(OH)_2$ solutions.	- Amount of salt addition required to change the pH value alters in a manner determined by the amount of excess solid $Ca(OH)_2$ present in solution. - Addition of NaCl causes no change in pH value.
C. Arya N.R. Buenfeld J.B. Newman[103]	Assessment of sample methods of determining the free chloride ion content of the cement paste.	- Several extraction techniques may be used to estimate the free chloride ion content of the cement paste. - The total chloride content will dictate the most appropriate technique. - The percentage of free chloride increases in direct proportion to the total chloride content. - Bound chloride content increases as total chloride content increases. This is almost certainly attributable to the associated cation.
R. Szilard O. Wallewik[104]	Effectiveness of concrete cover in corrosion protection of prestressing steel.	- Main factors influencing effectiveness of concrete cover are: i) concrete alkalinity (high strength); ii) permeability of cover; iii) quality of concrete; iv) thickness of cover; and v) corrosive environment. - Minimum concrete strength is necessary but not a sufficient requirement for good quality concrete. - Optimum water-cement ratio is in vicinity of 0.40-0.45. - Periodic wetting and drying by chemically aggressive liquids is a more critical condition than complete submergence.
K.C. Clear[7]	Effect of special treatments on reinforcing bar corrosion in concrete.	- Total impregnation of Portland cement (PC) concrete with methyl methacrylate and in subsequent polymerization appears to render concrete virtually impermeable. - Properly-consolidated, low water-cement ratio, Portland cement concrete overlay prevented substantial migration of chloride quantities to a 1 in. (25 mm) depth. - The styrene-butadiene, latex-modified Portland cement concrete also prevented substantial migration of chlorides to a 1 in. (25 mm) depth. - Epoxy-modified Portland cement concrete contained large, localized channels which caused quick corrosion initmation when channels coincided with reinforcing steel.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
J.R. Clifton H.F. Beeghly R.G. Mathey[8]	Feasibility of using organic coatings to protect steel reinforcing bars embedded in concrete bridge decks from rapid corrosion.	- Some epoxy coating, if properly applied, should adequately protect steel reinforcing bars from corrosion. - Epoxy-coated bars had acceptable bond and creep characteristics, enabling them to be used in existing bridge designs.
P. Smith[105]	Effects of two non-chloride accelerating agents on setting characteristics of Portland cement mortars.	- Low or moderate dosages of the two non-chloride accelerators can reduce time to achieve initial set by 1-2 hours. - More effective setting characteristics are obtained than for cement without accelerators. - Accelerators are more effective at 40°F (4.4°C) than at 70°F (21.1°C).
D. Chin[106]	A calcium, nitrite-based, non-corrosive, non-chloride accelerator.	- Admixture is effective in accelerating setting time and early strength development of normal and fly ash concrete. - The accelerator is not only non-corrosive, but it is actually a corrosion inhibitor. - Potential and linear polarization resistance measurement tests provide a quick indication of the potential corrosivity of a non-chloride accelerator.
S. Popovics[107]	Strength-increasing effects of a chloride-free accelerator.	- Accelerator increases strengths of a wide variety of cementitious compositions. - Greater strength increases with Type III cement. · Greater strength increases at higher curing temperatures. - Sizeable strength increases also at later ages (six months). - Greater strength increases with delayed addition.
J. Rose[108]	Effect of cementitious blast-furnace slag on chloride permeability of concrete.	- Permeability reductions are achieved as slag replacement level goes from 40 to 65% of total cementitious material by mass. - Concrete permeability, containing ground granular blast-furnace (GGBF) slag is less affected by increases in water-cement ratio than concrete containing regular Portland cement. - With cement containing ground granular blast furnace slag greater than 50%, detrimental effects of accelerated curing on concrete permeability are eliminated. - Concrete containing ground granular blast furnace slag may require less cover depth to protect reinforcing steel.
N.I. Fattuhi[109]	Effects of different curing regimes on rate of concrete carbonation.	- Rate of concrete carbonation decreased when water curing period increased. - Carbonation rate of prisms, water cured for 28 days, was only 17% of those air cured for the period of time.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
D.W.S. Ho R.K. Lewis[110]	Specification of concrete for reinforcement protection: performance criteria and compliance by strength.	- Alternative performance criteria can be based on water sorptivity and carbonation. - Exposed concrete would be expected to have a longer service life if maximum values of water sorptivity and carbonation are followed.
C. Foy M. Pigeon N. Banthia[111]	Freeze-thaw durability and de-icer salt scaling resistance of a 0.25 water-cement ratio concrete.	- Scaling is not a problem at a water-cement ratio of 0.25 since loss of mass was small, even for specimens with high air void spacing factors. - A critical air void spacing factor of 750 μm was determined. - Other factors to consider are: dispersion of cement grains and hydration products, formation of large capillaries, aggregate-cement paste interface, and use of silica fumes.
O.A. Kayyali the^NM.N. Haque[112]	Effect of carbonation on chloride concentretion in pore solution of mortars with and without flyash.	- Significant increase in chloride ions in pore solution occur as a result of carbonation. - More pronounced increase in flyash mortars was noted. - Prolonged initial curing helped to retain chloride bound within hydration compounds in the case of plain mortars.
C. Alonso C. Andrade J.A. Gonzalez[113]	Relation between resistivity and corrosion rate of reinforcements in carbonated mortar made with several cement types.	- When steel is passivated the corrosion rate is not affected by resistivity. - For active corrosion, concrete electrical resistivity seems to be a factor controlling the rate of corrosion. - A relationship exists between corrosion current and electrode resistance. - Partial immersion is the most aggressive condition influencing mortar resistivity.
H. Diab A. Bentur C.H. Wirguin L. Ben-Dor[114]	Diffusion of chloride ions through Portland cement and Portland cement-polymer pastes.	- Diffusion in Portland cement paste matrix was greater than that of the diffusion in the paste of similar water-cement ratio.
O.A. Kayyali M.N. Haque[115]	Chloride penetration and the ratio of chloride/hydroxyl ions in the pores of the cement paste.	- Long curing periods result in smaller pores where diffusion takes place at a low rate. - The pores of hardened cement paste in contact with chloride solution could acquire a larger proportion of the free chloride. - The ratio of chloride/hydroxyl ions is considered a principal parameter in determining depassivation of steel reinforcement. - Permeability of fluid in the pores decreases as a result of immersion in the chloride solution.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
C. Francois J.C. Maso[116]	Effect of damage in reinforced concrete due to carbonation or chloride penetration.	- Damage at grain/paste interfaces in tensile zones leads to an increase in penetration of aggressive ions. - The shape of the contaminated concrete zone is a narrow band around cracks.
T. Yonezawa V. Ashworth R.P.M. Procter[117]	Pore solution composition and chloride effects on the corrosion of steel in concrete.	- The mortar provides better protection to steel than alkaline solutions. - One of protective mechanisms of mortar is the pH control action of calcium hydroxide (CaOH) crystals located at steel-mortar interface. - For active corrosion to start, formation of voids at steel-mortar interface is necessary. - The threshold value of chloride content does not depend only on the chloride/hydroxyl ratio, but on steel-mortar interface conditions.
N.G. Thompson K.M. Lawson J.A. Beavers[118]	Monitoring cathodically protected steel in concrete structures with electrochemical impedance techniques.	- Upon application of cathodic protection, the reaction sequence goes from one of diffusion controlled (corrowion) to charge transfer control (reduction reactions). - Electrochemical impedance spectroscopy provides the corrosion engineer with a more direct indication of corrosion in a structure that is cathodically protected.
Rasheeduzzafar G.J. Al-Sulaimani A.S. Al-Gahtani S.S. Al-Saadoun[15]	Accelerated laboratory studies of concrete reinforcement corrosion.	- Type I cement is more advantageous over Type V cement. - Stainless steel clad reinforcement is beneficial. - Low water-cement ratio is advantageous. - Richer mixes are beneficial. - Finer aggregate grading and washed aggregate are beneficial. - Longer curing time is beneficial. - Greater reinforcement cover is beneficial.
L.J. Parrott D.C. Killoh[119]	Carbonation in 36-year old in-situ concrete (indoor and outdoor exposure).	- More severe carbonation for outdoor exposure. - The deepest penetration of carbon dioxide occurred in the interior exposure (humidity). - The steepness of the carbonation front should be considered in service life studies of reinforced concrete structures.
B.B. Hope[8]	Feasibility of using electrochemical measuring techniques to determine the relative corrosion rates of bare steel to that of epoxy-coated straight and fabricated steel.	- Considerable corrosion of uncoated steel bars and very little or no corrosion of epoxy-coated bars occurred. - Useful electrochemical measurements can be made of epoxy-coated bars fy means of lineer polarization, AC impedance, and Tafel plot techniques. - None of the coated rebars showed any signs of breakdown of the epoxy coating during the testing period.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
Rasheeduzzafar F.H. Dakhil A.S. Al-Gahtani S.S. Al-Saadoun[12]	Exposure site studies on the effect of cement composition on corrosion of reinforcing steel in concrete.	- Better performance of cement, having a higher tricalcium aluminate (C_3A) content, in terms of time to cracking and loss of metal. - The beneficial effect of the reaction between C_3A and chlorides becomes less perceptible as the level of chloride contamination increases.
T.P. Cheng J.T. Lee W.T. Tsai[120]	Corrosion of reinforcements in artificial sea-water and concentrated sulfate solution.	- Effects of chlorides and sulfate ions on the electrochemical properties and corrosion mechanisms of reinforcing steel were different. - Polymer impregnation treatment would increase concrete resistivity.
C. Arya N.R. Buenfeld J.B. Newman[121]	Factors influencing chloride-binding in concrete.	- Most important factors governing chloride binding introduced at time of mixing are: cement type, type and proportion of cement replacement material, and total chloride content. - Increased internal chloride binding with increased water-cement ratio, curing temperature, and age. - Level of binding increased with exposure time and chloride concentration of external solution. - Calcium chloride produced massive increases in binding in relation to sodium chloride.
M. Moukwa[122]	Deterioration of concrete in cold sea waters.	- Mineral additives, by densifying the matrix and improving the paste-aggregate interface, reduce the disruption of concrete. - Silica fumes appear to be more efficient than blast-furnace slag.
R.K. Dhir M.R. Jones H.E.H. Ahmed[123]	Determination of total and soluble chlorides in concrete.	- Water-soluble chloride content is shown to be independent of the method of extraction, providing the extraction period is equal to or greater than 24 hours. - X-Ray Fluorescence Spectometry is the only test method capable of directly testing concrete and the only technique which can determine the total chloride content. - The proportion of acid-soluble chlorides measured is dependent upon the strength and contact time of the acid.
F. Derrien G. Chahbazian J.J. Carpio A. Raharinaivo[124]	Determine the electrochemical behaviour of steel embedded in concrete and under a cathodic polarization.	- Chloride content enhances depassivation of steel. - When corrosion occurs, white deposit appears simultaneously with brown rust.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
Rasheeduzzafar S.S. Al-Sadoun A.S. Al-Gahtani F.H. Dakhil[125]	Effect of tricalcium aluminate (C_3A) content of cement on corrosion of reinforcing steel in concrete.	- The time to initiation of corrosion of concrete-embedded reinforcement is greatly influenced by the C_3A content of cement (the higher the content, the more beneficial to corrosion of reinforcement). - Higher C_3A content gives cement a superior ability to form a chloride structure, resulting in the formation of an insoluble calcium chloroaluminate compound that has an important role in the removal of chlorides.
M.J. Al-Hussaini C.M. Sangha B.A. Plunkett P.J. Walden[126]	Effect of chloride ion source on the free chloride ion percentages in ordinary Portland cement mortars.	- Sodium chloride presents a greater threat to reinforcement corrosion than calcium chloride at all concentrations up to 2% chloride ion by mass of cement. - Sodium chloride produces lower pH values than calcium chloride.
A.J. Al-Tayyib M.S. Khan I.M. Allam A.I. Al-Mana[127]	Corrosion behaviour of pre-rusted re-bars after placement in concrete.	- Initial rusting does not have an adverse effect on the corrosion resistance of rebars embedded in concrete.
C.M. Hansson B. Sørensen[87]	The threshold concentration of chloride in concrete for the initiation of reinforcement corrosion.	- Initiation time to onset of corrosion is strongly dependent on hardening condition, water-cement ratio, and type of cement. - Time to initiation is proportional to the logarithm of the electrical resistance. - Reducing the water-cement ratio has two synergistic effects: i) initial chloride content is increased due to higher pH in pore solution; and ii) paste porosity is considerably reduced. - 10% cement replacement with microsilica leads to reduction of the critical chloride concentration to approximately 1/3 of level for same cement without microsilica. - Fly ash considerably increases time to corrosion due to less porous structure. - Corrosion properties of profiled steel are at least as good as those of smooth steel. - The presence of a rust layer on steel prior to casting seems to have a positive effect on corrosion properties.
C. Valentini L. Berardo I. Alanis[128]	Influence of blast-furnace slags on the corrosion rate of steel in concrete.	- Corrosion currents and potentials show passivation trends for steel embedded in Portland cement (PC) mortars whether blended or not with blast-furnace slags up to 75%. - Corrosion current immediately after the curing period is independent of the amount of blast-furnace slags and is 10 times the current for pure PC mortar.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	$GENERAL CONCLUSIONS
N.S. Berke D.F. Shen K.M. Sundberg[59]	Comparison of polarization resistance technique to the corrosion macrocell technique.	- Both techniques can be used to determine corrosion rates of steel and aluminum in concrete until the lower reinforcement mat begins to show signs of corrosion. - The macrocell technique appears to underestimate the corrosion rate. - Calcium nitrite effectively delayed and reduced the corrosion of black steel, galvanized steel, and aluminum in concrete.
H.G. Wheat[60]	Corrosion rate determination on repaired reinforced concrete specimens.	- Repaired specimens showed rust staining, severe delamination, and cracking while control samples did not. - Corrosion rates in the repaired specimens were higher than in the control specimens due to a lower polarization resistance as measured by linear polarization technique.
A. Aguilar A.A. Sangüés R.G. Powers[61]	Corrosion measurements of reinforcing steel in partially submerged concrete slabs.	- Corrosion initiation in rebars takes place at the region where chlorides accumulate. This region develops above the water line as a result of capillary transport and water evaporation. - After initiation, corrosion proceeds by the formation of macrocells. Metal dissolution tends to occur in regions of greater electrolyte availability. Oxygen reduction occurs preferentially where concrete is not saturated with water. - In isolated rebar segments, corrosion is most extensive above the water line, in the area of chloride accumulation and rapid oxygen transport.
E. Escalante S. Ito[62]	Measuring the rate of corrosion of steel in concrete.	- A drying cycle, which causes local concentrations of chloride and oxygen, initiates steel corrosion. - Once initiated, the pH value at the anodic areas decreases, allowing corrosion to proceed more easily. - Oxygen controls the rate of corrosion, yet chloride affects the number of sites where corrosion initiates.
L. Lemoine F. Wenger J. Galland[129]	Study of corrosion of concrete reinforcement by electrochemical impedance measurement.	- Electrochemical impedance plots allow characterization of different mechanisms of corrosion of steel embedded in concrete. - This method can be used to benefit the study of the durability of reinforced concrete considering different environmental parameters and various concrete compositions. - The model does not allow obtaining of a quantitative value of the corrosion rate in the first step of the propagation.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
B. Elsener H. Böhni[63]	Potential mapping and corrosion of steel in concrete.	- An absolute potential value for identification of active corrosion does not exist. - The impedance spectroscopy technique is too time-consuming for on-site application. - Difficulties with the spatial distribution of the electrical signals do not allow interpretation of the impedance spectra with respect to the corrosion rate. - Galvanostatic pulse technique overcomes the difficulties in interpreting potential measurements and information on concrete resistivity can be obtained.
J.P. Broomfield P.E. Langford A.J. Ewins[64]	Design, construction, and use of a Potential Wheel and its application for corrosion determination of steel in concrete.	- A Potential Wheel for rapid scan surveying of corrosion damaged reinforced concrete was developed. - The wheel is ideal for rapid scanning of soffits, walls, and virtually any surface. - Laboratory testing has shown the wheel to be comparable to or better than a standard copper/copper sulfate half-cell in terms of reproducibility, stability, and temperature effects.
L. Metcalf[22]	"Time to corrosion" of reinforcing steel in concrete studies.	- According to corrosion potential and polarization resistance data, results of 4 months of specimens continuously immersed in NaCl solutions and specimens subject to 6 weeks wet-dry cycling indicated that the steel was still passive in both cases.
S. Goñi C. Andrade C.L. Page[130]	Influence of chloride ion on the corrosion of steel in high alumina cement mortar samples.	- The hexagonal to cubic conversion of the hydrated aluminates was produced by prolonged storage of all of the high alumina cement samples studied and was favoured by the presence of chloride ions. - Friedel's salt was formed in the presence of chloride ions but this compound was relatively unstable decomposing apperently in response to changes of pore solution composition with time. - The conversion of aluminates does not by itself produce depassivation of steel reinforcement in mortars containing up to 0.4% Cl^- by weight of cement. However, Friedel's salt decomposition and Cl^- liberation to the pore solution leads to the depassivation of steel in high alumina cement mortars containing 1% Cl^-. - High alumina cement is more aggressive than ordinary Portland cement for similar chloride content.
H.T. Cao Sirivivatnanon[131]	Corrosion rate study of steel in concrete of different strength levels and in concrete with different silica fume contents.	- The corrosion rate of steel embedded in saturated concrete can be reduced by increasing concrete strength, particularly in a chloride contaminated environment. - The use of 10% silica fume as cement replacement material in making 70 MPa concrete can have beneficial effect in terms of reduced corrosion rate. - Adverse effects may result from using silica fume at a higher replacement level of 20%.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
O.S.B. Al-Amoudi Rasheeduzzafar M. Maslehuddin[132]	Effect of salt inclusion in the ordinary Portland cement/Portland fly ash concrete on alkalinity, carbonation, and re-bar corrosion.	- There is an insignificant reduction in alkalinity in both ordinary Portland cement/ Portland fly ash concretes due to chloride contamination. - The corrosion of rebars was found to be influenced more by the chloride concentrations in the concrete, rather than by the presence of fly ash. - The depth of carbonation was higher in fly ash concrete specimens compared to ordinary Portland cement concretes both in chloride free and chloride contaminated concretes.
R.K. Dhir P.C. Hewlett Y.N. Chan[133]	The relationship between the intrinsic permeability and the carbonation of concrete.	- The depth of carbonation can be related to the intrinsic permeability. - The Figg air index (Dundee modified) is shown to correlate closely with the intrinsic permeability and thereby the carbonation of concrete. The Figg air index can be used to predict the potential carbonation resistance of concrete. - The rate of carbonation is most significantly influenced by the free water-cement ratio and the period of moist curing. Changes in the cement content, workability, and aggregate size do not have a marked effect on carbonation resistance of concrete. - The accelerated carbonation test was found to predict the normal exposure carbonation rate, at an equivalence of one week of accelerated exposure to 15 months of normal exposure.
J.A. González A. Molina E. Otero W. López[134]	The role of oxygen diffusion on the mechanism of steel corrosion in concrete.	- Under certain circumstances, the corrosion rate may be high, even though the supply of oxygen is small or negligible. - The corrosion mechanism appears to require the existence of some cathodic process which does not require oxygen diffusion. - The high corrosion rates of steel in concrete without oxygen can be explained by the existence of crevices at the steel/concrete interface, affording relatively low pH environments.
M. Shamim Khan[135]	The corrosion state of reinforcing steel in concrete at early ages.	- If, after casting, the concrete is completely immersed in water, the passive film will not form. This is attributed to the lack of oxygen at the steel/concrete interface under conditions of complete immersion in water. - The formation of the passive film may take a significantly long time even if the concrete is not completely immersed in water after casting. - In the field application of the linear polarization resistance technique, reliable corrosion-rate measurements may be made by placing the reference electrode on the surface of the concrete instead of embedding it at the level of the reinforcing steel, provided that the instrumentation used has provisions for the compensation of the IR drop.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
R.J. Detwiler K.O. Kjellsen O.E. Gjørv[136]	Resistance to chloride intrusion of concrete cured at different temperatures.	- In plain Portland cement concretes, elevated curing temperatures result in a coarser pore structure and a corresponding decrease in the resistance to Cl diffusion. - Concrete cured at a high temperature will be less durable than the same concrete cured to an equal degree of hydration at a lower temperature. - The lower the water-cement ratio, the more pronounced the effect of the curing temperature. - At a given curing temperature, a lower water-cement ratio results in a reduced rate of Cl^- diffusion. Lowering the water-cement ratio can compensate for the effects of an elevated curing temperature. - The effects of poor consolidation and/or bleeding are more significant than either the water-cement ratio or curing temperature. A refined pore structure is of little value in terms of durability if the concrete is full of entrapped air voids and bleed-water channels.
M. Shamim Khan A-H J.A.Tayyib[137]	Long-term corrosion resistance of reinforcing steel.	- The time to corrosion initiation of reinforcing steel in sulfur concrete is longer than that in Portland cement concrete. - Once the corrosion initiates, the corrosion rate of reinforcing steel in sulfur concrete is higher than that in a good-quality Portland cement concrete.
K. Kosa A.E. Naaman[138]	Deterioration of steel fibre reinforced concrete due to fibre corrosion.	- Severe corrosion exposure of steel fibre reinforced concrete can lead to significant reductions in minimum fibre diameter along each fibre. This in turn leads to a noticeable reduction in the peak strength in tension and bending, as well as a dramatic reduction in toughness. - The effect of corrosion on minimum fibre diameter gradually changes the type of failure from typical fibre pullout to fibre breakage before pullout. - Similar conclusions are drawn from the results of the group of tests using precorroded fibres.
C. Alonso C. Andrade[139]	Effect of nitrite as a corrosion inhibitor in contaminated and chloride-free carbonated mortars.	- Sodium nitrite may reduce and even completely avoid the aggressive effect of concrete carbonation. This protective characteristic is not enough when carbonation and chlorides are added together in the concrete mix. - Nitrites enhance their inhibiting action in wet concrete.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
M. Maslehuddin I.M. Allam G.J. Al-Sulaimani A.I. Al-Mani Abduljauwad[140]	Effect of rusting of reinforcing steel on its mechanical properties and bond with concrete.	- Weight loss in reinforcing steel samples, irrespective of size and composition, due to atmospheric corrosion increases with the period of exposure. - The effect of rusting by atmospheric pressure up to 16 months on the yield and ultimate strength of reinforcing steel is insignificant. - The elongation of fresh and rusted bars was above the ASTM A 615 requirements for Grade 60 steel. - Results indicate that variation in the residual composition (high, middle, and low) has little effect on the bond strength, yield, and ultimate tensile strength of both fresh and rusted bars.
B.B. Hope A.K.C. Ip[141]	Effects of calcium nitrite and stannous chloride on corrosion protection of reinforced concrete samples.	- Calcium nitrite [$Ca(No_2)_2$] exhibits promising corrosion inhibiting properties. The corrosion threshold level, in terms of the ratio of nitrite to chloride ions, is probably between 0.07 and 0.09. - Stannous chloride ($SnCl_2 \cdot 2H_2O$) is found to be ineffective for corrosion protection.
S. Feliu J.A. González S. Feliu Jr. M.C. Andrade[142]	Confinement of the electrical signal for in situ measurement of polarization resistance in reinforced concrete.	- The measurements made with the new technique demonstrate that practically all current applied from the central counterelectrode is picked up over the section of the reinforcement bounded by the position of sensors on the surface of the concrete. - This confirms the possibility of confining electrical signals, with the help of two extra reference electrodes (sensors), to determine the polarization resistance R_p in large reinforced concrete structures. - The accuracy of the measurements is independent of the magnitude of the value of R_p, unlike the guardring potentiostatic method, whose accuracy depends on the value of R_p.
A-H J.A. Tayyib M.S. Khan[143]	Corrosion rate measurements of reinforcing steel in concrete by electrochemical techniques.	- Electrochemical techniques can be used quickly to calculate the corrosion rate of reinforcing steel in concrete. - Tafel plot technique has: i) the advantage of determining the corrosion rate independently; and ii) the disadvantage that the potential perturbation of the reinforcing steel due to the large applied potential makes the specimen unsuitable for sensitive electrochemical measurements. - Linear polarization resistance technique has: i) the advantage that the specimens quickly recover their original open circuit potential after the test and can be used reliably for other tests; and ii) the disadvantage that it is dependent on the Tafel plot technique for the Tafel constants.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
B.B. Hope A.K.C. Ip[144]	Corrosion of steel in concrete made with slag cement.	- Corrosion of the steel in the mature concretes decreased with increasing slag content. This was accompanied by a corresponding higher concrete electrical resistivity and lower chloride diffusion rate. - Electrical resistivity of concrete made with slag cement appeared to be more sensitive to a change in storage condition than that of Portland cement concrete. Therefore, the corrosion rate of steel embedded in slag cement may be influenced by the ambient conditions to a larger extent than that in Portland cement concrete.
H. Roper D. Baweja[146]	Carbonation-chloride interactions and their influence on corrosion rates of steel in concrete.	- For normal reinforced concrete structural elements, the interactive effects of carbonation and chloride ion ingress lead to much more rapid corrosion than where the two phenomena occur independently. - Carbonation rates increase with increasing water-cement ratios. Carbonation rates decrease with increasing concrete density or with decreasing permeability. - Replacing cement with fly ash did not detrimentally affect the carbonation resistance of concrete and the addition of chloride ions to concrete mixes tended to reduce the carbonation of fly ash concretes tested.
S.R. Yeomans[147]	Comparative studies of galvanized and epoxy-coated steel reinforcement in concrete.	- Measurement of half-cell potentials has shown the beneficial effects of galvanizing in protecting black steel reinforcement from corrosion. - Galvanizing provides positive protection to steel where the coating is damaged, while repair to the damaged area provides additional protection. - Epoxy coating provides excellent protection to the steel as long as the coating was not damaged. - There is no significant difference between the ultimate bond strengths of black, hot dip galvanized and fusion bonded epoxy coated deformed reinforcement.
R.N. Swamy S. Tanikawa[148]	Control of steel corrosion in chloride contaminated concrete through ARON WALL (acrylic rubber type) surface coating.	- All uncoated specimens, both without and with added chlorides, showed extensive cracking on almost all sides. - Whether immersed or not, the presence of sodium chloride salt within the concrete reduced the adhesion strength. - Time of exposure has an important influence on both surface concentration of chlorides and the chloride profile. - The ARON WALL coating can prevent the intrusion of air, water, and chlorides into concrete, and provide excellent protection to steel in chloride contaminated concrete whilst maintaining its adhesion to concrete, integrity and continuity in continuous salt water exposure regimes.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
N.S. Berke M.J. Scali J.C. Regan D.F. Shen[149]	Long-term corrosion resistance of steel in silica fume and/or fly ash containing concretes.	- Silica fume and/or fly ash improve the long-term corrosion resistance of steel in concrete, with improved efficiency as water-cement ratios decrease. - Fly ash additions are much less efficient in reducing chloride ingress than silica fume. - The improved performance with silica fume is due to a decrease in concrete porosity, particularly at the aggregate-paste interface. - Concretes with high levels of fly ash are more susceptible to carbonation at cracks.
S. Misra T. Uomoto[150]	Reinforcement corrosion under simultaneous diverse exposure conditions.	- Corrosion was found only in portions that were subject to cyclic wetting and drying, or at the interface of the immersed and aerial portions. - The "underside" of the bars, where the bleeding water accumulates at the time of compaction of concrete, is more vulnerable to corrosion attack than the top half. - Water movement within the matrix plays a crucial role in determining the chloride concentration and could even lead to deposits of crystalline NaCl, etc. depending upon the exposure conditions. - Existence of flexural cracks does contribute to initiation of corrosion at the crack sites. This initial local corrosion becomes general depending on factors such as crack spacing, cover thickness, and characteristics of the covering concrete.
T. Ohta[151]	Corrosion of reinforcing steel in concrete exposed to sea air.	- The type of cement has great influence on the depth of chloride ion penetration. - The thickness of the concrete cover is the most important factor in the prevention of corrosion of the reinforcing steel. With a thin cover, the crack width has no influence on corrosion of reinforcing steel. - Epoxy coating is effective in improving corrosion protection.
L. Anqi L. Baoyu H. Guoping C. Yeibo S. Guolian[153]	Study on corrosion prevention in reinforced concrete containing condensed silica fume and its application.	- Incorporation of condensed silica fume in concrete can remarkably improve its compactibility, increase its ability to resist chloride penetration and carbonation, and raise its electrical resistivity. - Incorporating condensed silica fume is much more effective than reducing water-cement ratio and increasing the amount of cement in improving the durability of concrete.
J. Deja J. Malolepszy G. Jaskiewicz[154]	Influence of chloride corrosion on the durability of reinforcement in the concrete.	- There is excellent durability of the alkali activated slag mortars in an environment containing chloride ions. - The corrosion pits, high surface concentration of chloride, and significant weight losses indicate that the ordinary Portland cement mortar has weak protective influence on the reinforcing steel. - The additives to ordinary Portland cement mortar, such as limestone or silica fume, restrain corrosion of the reinforcement.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
J.T. Wolsiefer[155]	Utilization of silica fume concrete admixture to prevent reinforcing steel corrosion.	- The mineral admixture significantly lowers the concrete permeability to prevent chloride ingress to the reinforcing steel level, while simultaneously increasing the electrical resistance of the concrete to corrosion currents. - Design engineers can utilize the admixture to maintain structural design efficiency in terms of clear cover and dead weight.
V.F. Stepanova[156]	Corrosion of steel in lightweight concretes made with different types of lightweight aggregates.	- Reinforced concretes made with lightweight aggregates have satisfactory resistance to salt attack. - Structural-thermoinsulating concretes can be effective in protecting the steel only when their protective properties are improved by using a high cement content or a steel corrosion inhibitor.
R. Francois G. Arliguie[157]	Determine the relationship between the cracking in loaded reinforced concrete and the corrosion of embedded steel.	- Crack width has only an infinitesimal effect on the spread of corrosion. Thus, the significant parameter in reinforcement corrosion is the existence of cracks, but not their width. - A minimum theoretical concrete cover should be greatly in excess of 1 cm (0.39 in.) in order to avoid premature corrosion due to insufficient cover and porosity defects resulting from uncertainty as to the position of the reinforcement.
J.L. Gallias G. Arliguie J. Grandet[158]	Modification of steel corrosion compounds in reinforced concrete.	- In a first time, the steel corrosion compounds dissolve to form calcium ferrite hydrates and, in a second time, the hexagonal calcium ferrite hydrate is converted to the cubic form. - If the steel corrosion layer is fairly thin, the gradual dissolution of steel corrosion compounds and the formation of crystalline ferrite hydrate play an important role in decreasing the porosity of the corrosion layer and thereby improving the mechanical characteristics of the bond between the corroded steel and the concrete.
J.J.W. Gulikers J.G. van Mier[159]	Effect of patch repairs on the corrosion of steel reinforcement in concrete.	- Strong galvanic corrosion is to be expected when mineral mortars are applied for patch repairs. Alternating dry/humid conditions can accelerate the corrosion rate. - Application of Portland cement-mortar for local repair measures does not affect corrosion of steel in unrepaired concrete areas.
N. Takagi T. Miyagawa S. Amasaki T. Kojima[162]	Chloride corrosion of reinforcing steel in silica fume concrete exposed to marine environment.	- When saline solution is used as the mixing water, the corrosion potential of the silica fume concrete specimen becomes less noble, and results in the formation of large longitudinal cracks. - Although the chlorides penetrate into concrete from marine environment, the rate is decreased by the incorporation of silica fume.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

INVESTIGATOR(S)	TYPE OF RESEARCH	GENERAL CONCLUSIONS
P. Schiessl M. Raupach[180]	Macrocell steel corrosion in concrete caused by chlorides.	- The following parameters lead to a decrease of the corrosion rate: decreasing chloride content, decreasing water-cement ratio, increasing concrete cover, decreasing temperature and humidity, and use of chemical admixtures as cement replacements. - The corrosion process is influenced dominantly by the cathodic process outside or between the cracks. - Local repair of chloride induced corrosion damages may create corrosion outside the repaired area. After repair, the former anode can act only cathodically, causing accelerated corrosion of the steel outside of the repaired section.
M. Marosszeky D. Wang[161]	Ability of various reinforcement coating materials and repair mortars to prevent subsequent corrosion.	- Epoxy-based coatings are superior to the polymer-based coatings in preventing chloride induced corrosion. - Epoxy-based coatings with pinholes performed worse than without pinholes but comparatively, they performed much better than that polymer-based coatings. - The styrene butadiene rubber (SBR) repair mortar has the capacity to prevent chloride induced corrosion and is markedly superior to other polymer modified cementitious mortars. - The conventional cement mortar showed better resistance to corrosion than some of the polymer based materials. - Styrene butadiene rubber and acrylic polymer modified mortars provide greater protection against corrosion than common cement mortar in patch repair work.

Table 5.3 (cont'd): Experimental Investigations (1986 - present)

5.2 REINFORCEMENT CORROSION RESEARCH AND RECOMMENDATIONS

During the sixties and early seventies, construction boom occurred throughout Northern Europe and North America, resulting in considerable pressure on the industry to develop innovative techniques for increased production rates. Some of the structures built during that time have not lasted their service life and are showing significant signs of deterioration. Intrusion of chlorides in the concrete is now accepted as being the primary cause of corrosion of reinforcing steel. Some of the common sources of chloride salts include admixtures (such as calcium chloride), aggregates (sea dredged), exposure to marine conditions, and chemical de-icers. In these areas, the various research findings have led to recommendations, and finally, to official specifications and codes of practice for chloride-associated reinforcement corrosion.[4] The following two sections review the history and evolution of some of the recommendations for both the United Kingdom and North America, specifically the United States.

5.2.1 Official Specifications and Codes of Practice - UK

1885: Millar and Nichols[4] obtain patent for use of calcium chloride ($CaCl_2$) as an accelerator for Portland cement.

1948: The CP114 Code of Practice for the Structural Use of Reinforced Concrete in Buildings states that "Calcium chloride may be used to accelerate the rate of hardening of cement.

Usually, 1½% by weight of cement will be sufficient, and dangers exist with excess amounts."

1957: The Code of Practice for Structural Use of Reinforced Concrete is modified to:

> " Calcium chloride may be used to accelerate the rate of hardening of Portland cement concrete, but not more than 2% by weight of cement should be used."[4]

1959: The CP115 Code of Practice for Prestressed Concrete states:

> " Calcium chloride should not be used when steam curing is employed."[4]

1965: CP116 Code of Practice for Structural Use of Precast Concrete states:

> " i) Calcium chloride is not recommended either as an admixture or internally mixed with cement in any form of prestressed work with either pretensioned or post-tensioned steel;
>
> ii) The total amount of $CaCl_2$ in conventionally reinforced concrete should not exceed 2% (1.5% anhydrous $CaCl_2$) and should be dissolved in some of the mixing water; and
>
> iii) Where $CaCl_2$ is used in concrete, not less than 25 mm of cover should be given to all steel unless permanent protection is provided."[4]

1972: CP110 Code of Practice for the Structural Use of Concrete states:

> " i) Marine aggregates may be used provided that the chloride content expressed as anhydrous $CaCl_2$ by weight of cement does not exceed 1.0%;
>
> ii) For concrete with embedded metal, the anhydrous

$CaCl_2$ should never exceed 1.5% and therefore, extra-rapid hardening cements should never be used;

iii) It is important to ensure that the $CaCl_2$ is thoroughly mixed to minimize the variations in chloride concentrations; and

iv) The corrosion risk is further increased when concrete containing added chlorides is cured at elevated temperatures or subsequently exposed to warm environments."[4]

1977: CP110 Code of Practice for the Structural Use of Concrete amendments state:

" i) Calculations on the background content of chloride which could be expected from natural sources would be less than 0.06% by weight of cement; and

ii) The maximum total chloride content expressed as a percentage of chloride ion by weight of cement for:

- prestressed concrete, structural concrete that is steam cured, concrete for any use made with cement BS4027 or BS248 is 0.06, and
- reinforced concrete made with cement complying with BS12, plain concrete made with cement complying with BS12 and containing embedded metal, is 0.35 for 95% of test results with no results greater than 0.50."[4]

1985: BS8110 British Standard for Structural Use of Concrete states:

" i) $CaCl_2$ and chloride-based admixtures should never be added to reinforced concrete, prestressed concrete, and concrete containing embedded metal; and

ii) The maximum total chloride content expressed as a percentage of chloride ion by mass of cement for:
- prestressed concrete and heat-cured concrete containing embedded metal is 0.10,
- concrete made with cement complying to BS4027 or BS4348 is 0.20, and
- concrete containing embedded metal made with cement complying with BS12, BS146, BS426, or combinations with ground granular blast-furnace

> slag or Portland fly-ash is 0.40."[4]

1986: The Department of Transport Highways and Traffic Department Standard BD 27/86 states:

> " The total chloride ion content of the materials shall not exceed 0.3% of the mass of cement. Any chloride or admixtures containing chloride salts shall not be used."[4]

5.2.2 Official Specifications and Codes of Practice - USA

1954: ACI Committee 212, Admixtures for Concrete, suggests:

> " No limits on the quantity of $CaCl_2$ admixture which can be added to reinforced concrete exist. $CaCl_2$ does not cause corrosion of embedded steel."[4]

1974: ACI Committee 318, Building Code Requirements, states:

> " Concern of chloride ion content of mixing water (including that contributed as free moisture in the aggregate) to be used in prestressed concrete. Chloride ion contents greater than 400 or 500 ppm might be dangerous."[4]

1977: ACI Committee 201, Guide to Durable Concrete in agreement with ACI Committee 222, Corrosion of Metals in Concrete, states:

> " i) The maximum total chloride ion content expressed as a percentage of chloride ion by weight of cement for:
> - prestressed concrete is 0.06,
> - conventionally reinforced concrete in moist environments exposed to chlorides is 0.10,
> - conventionally reinforced concrete in moist environments not exposed to chlorides is 0.15, and
> - concrete for above ground buildings where the concrete would stay dry, no limit set; and
>
> ii) The threshold value for chloride content in

> concrete necessary for corrosion of embedded steel can be as low as 0.15% by weight of cement."[4]

1983: ACI Committee 318, Building Code Requirements, adopts more relaxed limits than those of ACI Committee 201.

> " The maximum total chloride content expressed as a percentage of chloride ion by weight of cement for:
> - prestressed concrete is 0.06,
> - conventionally reinforced concrete in a moist environment exposed to chlorides is 0.15, and
> - conventionally reinforced concrete in a moist environment not exposed to chlorides is 0.30."[4]

5.3 COMPARISON OF INTERNATIONAL DESIGN CODES

The problems of corrosion of reinforcing steel in concrete has been widespread, affecting many regions of the world. Based on local conditions and requirements, several construction standards have been developed appropriate to the particular situations encountered. The following is a comparative list of the various parameters dealing with the corrosion of reinforcement as set forth by several countries of the world. The ones considered are total and threshold chloride contents, depths of concrete cover, and any other additional specifications related to reinforcement corrosion.

<table>
<tr><th>COUNTRY</th><th>RECOMMENDATIONS AND CODES OF PRACTICE</th></tr>
<tr><td>**United States of America**</td><td>ACI Committee 318:[74] Maximum water-soluble chloride ion content (expressed as a percentage by weight of cement):
- prestressed concrete: 0.06 %
- reinforced concrete exposed to chloride in service: 0.15 %
- reinforced concrete dry or protected from moisture in service: 1.00 %
- all other reinforced concrete construction: 0.3 %.

ASTM Test Method C114:[30] To minimize risk of chloride-induced corrosion, maximum acid-soluble chloride contents (expressed as a percentage by weight of cement):
- prestressed concrete: 0.08 %
- reinforced concrete: 0.20 %.

ACI Committee 201:[30] Maximum water-soluble chloride ion content (expressed as a percentage by weight of cement):
- prestressed concrete: 0.06 %
- conventionally reinforced concrete in a moist environment and exposed to chlorides: 0.10 %
- conventionally reinforced concrete in a moist environment and not exposed to chlorides: 0.15 %
- above ground construction where concrete will stay dry: no limit.
- minimum cover: 50 mm (2 in) for bridge decks if water-cement ratio = 0.40.
- minimum cover: 65 mm (2.5 in) for bridge decks if water-cement ratio = 0.45.</td></tr>
<tr><td>**United Kingdom**[30]</td><td>British Code CP110: Maximum acid-soluble chloride ion content (expressed as a percentage by weight of cement):
- for 95% of test results with no result greater than 0.50 %: 0.35%
- low risk of corrosion up to 0.4 % chloride added to the concrete mix.</td></tr>
<tr><td>**Norway**[30]</td><td>Norwegian Code NS3474: Maximum acid-soluble chloride content (expressed as a percentage by weight of cement):
- reinforced concrete made with normal Portland cement: 0.6 %
- prestressed concrete: 0.002 %.</td></tr>
<tr><td>**Comité Euro-International du Béton (CEB)**[73]</td><td>Critical chloride content:
- if concrete is not carbonated: 0.05 % by weight of concrete OR 0.4 % by weight of cement.
- prestressed concrete: 0.025 % by weight of concrete OR 0.2 % by weight of cement.
- for severe chloride attack: recommended water-cement ratio < 0.5 and minimum concrete cover > 30 mm (1.2 in).
- nominal concrete cover: $C_{nom} = C_{min} + \Delta C$
where C_{min} depends on environmental conditions:
<table>
<tr><th>EXPOSURE</th><th>NORMAL REINFORCEMENT mm (in)</th><th>PRESTRESSED REINFORCEMENT mm (in)</th></tr>
<tr><td>- dry environment</td><td>15 (0.6)</td><td>25 (1.0)</td></tr>
<tr><td>- humid environment</td><td>30 (1.2)</td><td>35 (1.4)</td></tr>
<tr><td>- humid environment with frost and de-icing agents</td><td>40 (1.6)</td><td>50 (2.0)</td></tr>
<tr><td>- sea-water environment</td><td>40 (1.6)</td><td>50 (2.0)</td></tr>
</table>
and ΔC = 5 mm (0.2 in) for reinforcement with placement control,
= 10 mm (0.4 in) without placement control, and
= 20 mm (0.8 in) for inadequate concrete curing.</td></tr>
</table>

Table 5.4: International Recommendations and Codes Of Practice

COUNTRY	RECOMMENDATIONS AND CODES OF PRACTICE
Canada[146]	- Parking Structures: i) Concrete shall contain not more than 0.06% of water-soluble chloride ion by weight of cementing materials, including chlorides contained in admixtures, except where it can be shown that aggregates containing higher levels of chloride are not detrimental. ii) Calcium chloride admixtures or chloride-based admixtures shall not be used. - Reinforced Concrete Structures: No limits specified regarding chloride ion content expressed as a percentage of the weight of cementitious materials.

Table 5.4 (cont'd): International Recommendations and Codes Of Practice

5.4 RESEARCH AND DEVELOPMENT

5.4.1 Future Experimental Work

Many countries will be faced with corrosion problems affecting bridge decks, roads and highways, and other concrete structures for the next decade. Despite the numerous advancements made with experimental studies carried out over the past twenty years, more research work is required to combat the ever-increasing dilemma of reinforcement corrosion affecting both major and minor infrastructures. The following are some suggestions for possible topics to be investigated in future research and development:

1. Research regarding the role played by and the importance of chlorides, with respect to the loss of steel passivity in an alkaline concrete system, is needed.[6]

2. More research is required in the area of preventive techniques. This is limited at present to cathodic protection or coatings to either the reinforcing steel or concrete.[6]

3. Development of a means of eliminating one of the reactants leading to reinforcement corrosion is needed (i.e., non-corrosive steel, eliminating oxygen, or preventing diffusion of hydroxyl ions).[6]

4. There exists a need for further laboratory work dealing with the electrochemical reactions, that can be controlled to limit or prevent corrosion activity. This can include supplying sufficient electrons to anode or ferrous ions to solution in contact with anodic area to prevent oxidation, or supplying sufficient hydroxyl ions to cathodic area to reverse the electrochemical process.[6]

5. Better analytical procedures can be developed for determining the chloride content that truly influences the corrosion of reinforcing steel in concrete.[12]

6. More research is needed to establish the appropriate chloride limits for the concrete mix constituents. This can involve monitoring and collecting data on chlorides in admixtures, cements, aggregates, and mixing water.[6,12]

7. Additional study is needed on the role of the reinforcing steel in the corrosion process. Topics include: effect of alloying elements in steel; chemistry of chloride reactions with iron; resistance of weathering steels; and susceptibility of prestressing reinforcement in a chloride environment.[12]

Developments in the area of reinforcement corrosion need not be limited simply to laboratory work. Additional research is needed in the construction of new reinforced concrete structures. The general topics requiring further advancements include[6]:

1. Improved techniques to prevent chlorides and oxygen from reaching the steel reinforcement-cement paste interface.
2. Improved procedures to maintain a high-level of alkalinity at the steel-paste interface.
3. Role of crack widths with respect to movement of ions and molecules to and from the steel-paste interface.
4. Role of chemical inhibitors and cathodic protection providing an increased degree of assurance under a variety of conditions.

Further improvements dealing with methods of evaluation of existing structures in service are required. These include the following[6]:

1. Improved non-destructive methods of detecting corrosion. For example, improved potential and current flow measurement techniques.
2. Development of non-destructive methods for determining degree of actual corrosion damage in the structure.
3. Development of additional methods of stopping reinforcement corrosion already in progress.
4. Development of methods for adequately refurbishing a structure affected adversely by corrosion.
5. Correlation of surrounding environmental conditions and concrete parameters with respect to susceptibility of reinforcement corrosion.[12]

It is important to recall that concrete is actually destroyed by chemical aggression less frequently and less rapidly than what should be expected from laboratory results. Thus, the information provided by laboratory investigations is not necessarily significant for full-scale concrete structures, as the corrosion process is slow to develop under natural conditions. Another problem arises upon observation of existing structures. The data at the time of construction cannot always be reproduced with the required accuracy at the time of evaluation. This includes the mix proportions, water-cement ratio, and conditions of placement and compaction.[1]

5.4.2 Accelerated Electrochemical Laboratory Testing - McGill University

In general, laboratory corrosion tests performed should satisfy the following overall requirements[1]:

1. The physical-chemical characteristics of the corrosion process must not differ appreciably from those under field conditions;
2. All factors influencing corrosion must be considered in assessing the resistance of concrete; and
3. Tests should be as short and simple as possible.

Therefore, the proper selection of the correct testing method is important for the recognition of the major contributing factors to the corrosion process.

The first objective of the laboratory experimentation program at McGill University was to develop an accelerated method of testing concrete durability and analyzing the reinforcement corrosion process. Despite being accelerated, it was desirable to reproduce the actual process in the laboratory that differed as little as possible from that occurring in nature. The eventual aim of the program was to develop a method by which the duration of the testing could be reduced to a few weeks, without actually distorting the corrosion process.[1]

In order to achieve this, several measures were taken to render possible these truly "short-term" corrosion studies. The rapid testing was obtained partly by the following:

- constant impressed voltage between steel electrodes (anode and cathode) to promote increased exchange of ions and cations between them;
- intensity of aggressive chemical attack was increased by introducing stronger concentrations of sodium chloride (NaCl) electrolyte aqueous solutions;
- partial immersion of concrete specimens in aggressive electrolyte medium, to further enhance the detrimental effect of chlorides;
- minimum curing time of test specimens subject to aggressive chemical attack. As suggested by researchers[1], concrete exposed at an early age has less resistance to chemical attack than that having hardened over an extended period; and
- no chemical admixtures were introduced in the concrete mix to enhance its quality and thus retard the process of reinforcement corrosion.

By implementing the above items, the purpose of accelerating the natural corrosion process could be achieved. Chapter 5 describes the experimental set-up used to perform these accelerated electrochemical corrosion tests on the various concrete specimens. Two levels of testing were carried out: a preliminary phase to ascertain the influence of the various parameters, and the primary testing program to determine the effect of clear depth of cover on corrosion of steel reinforcing embedded in concrete.

CHAPTER 6

ACCELERATED ELECTROCHEMICAL CORROSION TESTING

As described previously, a program dealing with accelerated electrochemical corrosion testing of concrete specimens was conducted at McGill University from September 1990 to May 1991. The program consisted basically of two distinct phases. First, preliminary testing of several parameters were performed to help define the parameters of the experimental set-up. This was followed by the main objective of the test program, to study the importance of clear cover depth on the corrosion of reinforcement embedded in concrete. In a country such as Canada, the concrete mix constituents are strictly controlled in a regular manner. Therefore, it was deemed reasonable to assume that workmanship and proper placement are primary factors affecting the construction and/or rehabilitation of reinforced concrete structures. On numerous occasions, the specified depth of cover is not correctly implemented in the field and corrosion problems begin prematurely. Thus, depth of concrete cover plays a major role in promoting steel corrosion in both new and existing structures.

6.1 EXPERIMENTAL SET-UP

The specimens tested consist of concrete cylinders having a height of 6 in. (152 mm). A diameter of 3 in. (76 mm) was used for the preliminary testing, and subsequently varied according to the desired depth of the concrete cover by using molds of various sizes. Steel reinforcing bars, 12 in. (305 mm) long, were embedded within these concrete cylinders. The re-bars were wire-brushed and cleaned with methanol for approximately five minutes to remove any existing grease.

At a height of 4 in. (102 mm) from one end, 2 in. (51 mm) of the reinforcement bar was covered with very adhesive electroplater's tape, serving to protect the specimens from possible corrosion occurring at the steel-concrete interface. The steel re-bars were placed at a height of approximately 1 in. (25 mm) from the bottom of the cylinder. Therefore, 5 in. (127 mm) of the re-bar was exposed within the concrete medium, of which 4 in. (102 mm) were left uncovered. The remaining 7 in. (178 mm) were left protruding above the height of the cylinder. Figure 6.1 shows a schematic diagram of a typical concrete specimen. This will be subsequently referred to as a lollipop specimen.

6.1.1 Concrete Mix Parameters

The concrete mix consisted of: Type 10 Portland cement, fine sand, coarse aggregates (1/4 in. - 6.4 mm crushed stone), and water. A sieve analysis of both the fine and coarse aggregates was performed according to CSA Standards A23.2-M2A and A23.2-M5A.[66,67] In order to determine the particle size distribution, grading curves for both aggregate types were obtained. These are within the limits specified in the CSA Standard A23.1-M.[68] Appendix A summarizes the results of these tests.

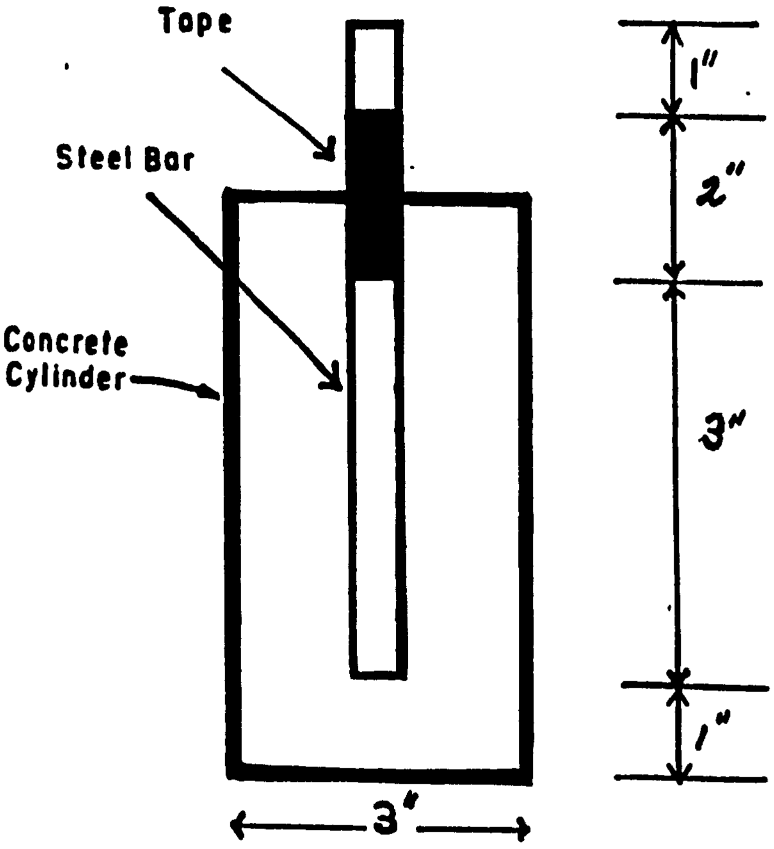


Figure 6.1: Schematic Diagram of the "Lollipop" Specimen

The cement-sand-stone ratio is based on the relative densities of the materials. A typical ratio of 1:2.24:2.92, used in a concrete topping for a bridge deck, was adopted for this test program.[70] Unless otherwise specified, a water-cement ratio of 0.45 was used. No specific admixtures, air entrainment, or superplasticizers were included in the concrete mix. The concrete specimens from each batch were cast and air cured for 24 hours, followed by the testing. Table 6.1 summarizes the quantities of the concrete batches prepared during the testing period. Additionally, five control specimens were cast and subsequently tested to an average compressive strength of approximately 25 MPa (see Appendix B).

6.1.2 Description of the Experimental Set-Up

Once the lollipop specimens were properly cast and cured, each was positioned centrally in a glass tank of dimensions 16 in. length by 8 in. width by 10 in. height (406 x 203 x 254 mm). A bare steel reinforcing bar, having a height of 12 in. (305 mm), was also located centrally within the tank. A 1/2 in. (13 mm) thick wood board, of dimensions 20 in. by 12 in. (508 mm x 305 mm), was placed on top of the tank. Appropriate-size holes were drilled to provide access and support for the protruding re-bars. The top of the wood board was used as the base for the electrical circuitry required to impress the necessary voltage. Moreover, the board prevented any evaporation of the aqueous electrolyte solution to be used in the glass tank. A schematic plan of the set-up is shown in

BATCH MIXES

SPECIMEN (CYLINDER) PROPERTIES:

Diameter = 3" = 0.0762 metres
Height = 6" = 0.1524 metres

Volume of 1 cylinder = surface area x height
= 0.000695 cubic metres
Waste volume = 10% of volume of 1 cylinder
= 0.0000695 cubic metres
Total mix volume = 0.000695 + 0.0000695
= 0.0007645 cubic metres.

AGGREGATE PROPERTIES:

Density of Cement = 355 kg/cubic metre
Density of Water = 160 kg/cubic metre
Cement/Sand/Stone ratio = 1/2.24/2.92

DATE	NUMBER OF CYLINDERS	TOTAL VOLUME $(m^3 x 10^{-6})$	WATER-CEMENT RATIO	CEMENT (g)	WATER (g)	SAND (g)	STONE (g)
10/09/90	2	1529	0.45	543	244	1216	1585
18-09-90	4	3058	0.45	1086	489	2432	3170
25-09-90	3	2293	0.45	814	366	1824	2377
22/10/90	1	764	0.30	271	81	608	792
22/10/90	1	764	0.40	271	109	608	792
22/10/90	1	764	0.50	271	136	608	792
22/10/90	1	764	0.60	271	163	608	792
22/10/90	1	764	0.70	271	190	608	792
29/10/90	5	3822	0.45	1357	611	3040	3962
11/12/90	10	9629	0.45	3418	1538	7657	9982
14/12/90	5	3822	0.45	1357	611	3040	3962
28/01/91	10	9629	0.45	3418	1538	7657	9982
18/03/91	18	14240	0.45	5055	2275	11,324	14,762

Table 6.1:: Summary Table Of Concrete Mixes

Figure 6.2.

Lead electrical wires were soldered to each end of 30 amp rated battery clips. These clips were connected to the protruding part of each re-bar. Three equally-spaced "connectors", to complete the electrical circuit, were mounted on the wooden board. One lead wire from each battery clip was "spliced" and inserted into each end "connector". The "connector" having the lead wire from the lollipop specimen was then connected to the positive terminal of a direct current (DC) power supply (RED colour). The negative terminal (BLACK colour) was linked to the middle "connector" by means of another electrical wire. In order to connect the negative terminal "connector" to the "connector" with the lead wire from the bare electrode, a "jumper" wire was used. Both ends of the "jumper" were fitted with connections that could be inserted snugly into the "connectors", thus enabling the "jumper" to be used as a switch. To "open" or "close" the electrical circuit, the "jumper" could be removed or inserted easily. Figure 6.3 illustrates the electrical circuitry.

The steel reinforcing bars act as **electrodes**, with the one connected to the positive terminal being the **anode** and the one connected to the negative terminal as the **cathode.**[15] In order to complete the circuit and permit the exchange of ions and cations between the two electrodes, an electrolyte solution was added. This contained a specified percentage of crystallized sodium chloride (NaCl) by weight of water. To minimize the presence of impurities possibly affecting the

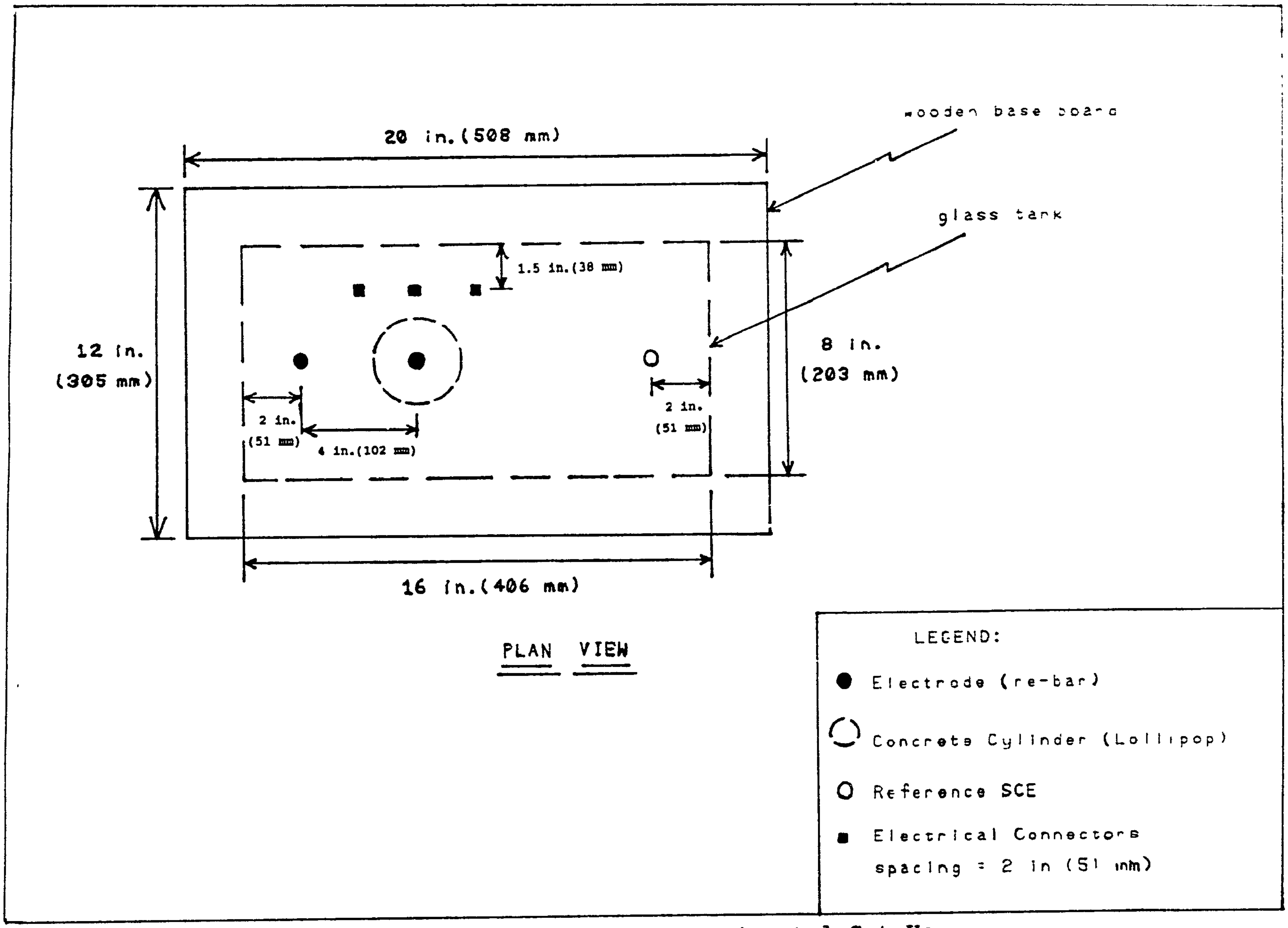


Figure 6.2: Layout of Experimental Set-Up
(Plan View)

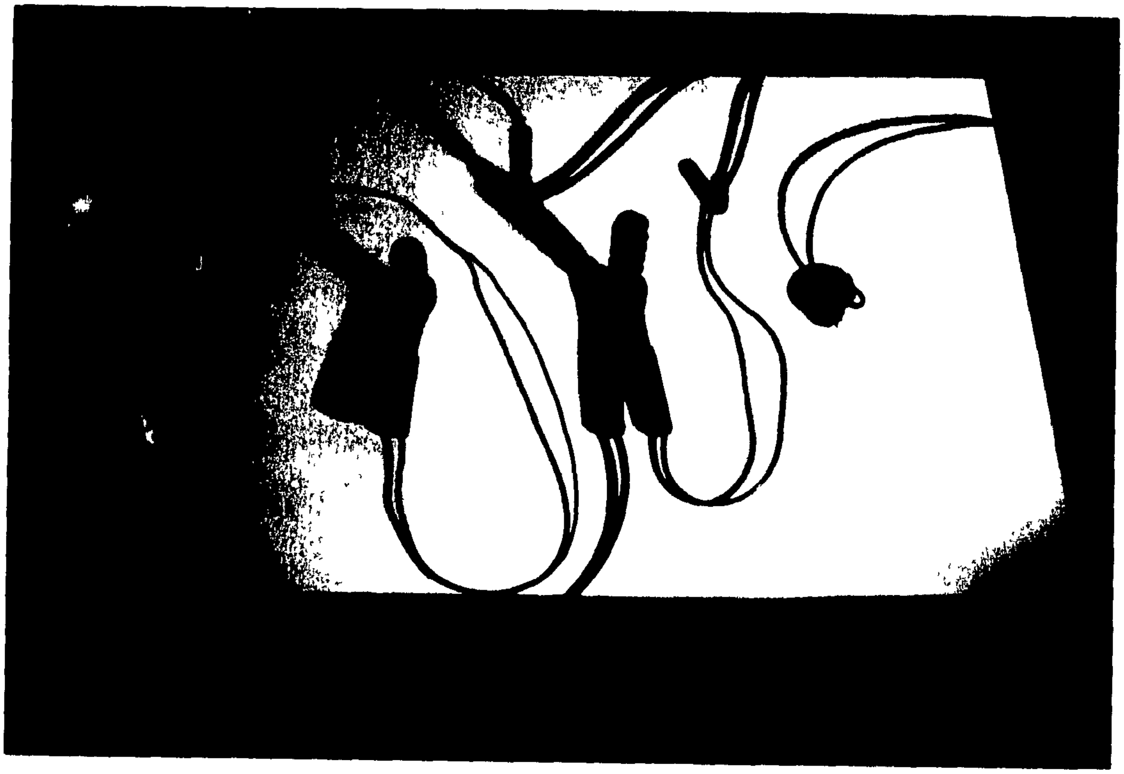


Figure 6.3: Electrical Circuitry

chemical reactions, distilled water was used. The glass tanks were filled to an approximate height of 5 in.(127 mm), leaving about the top 1 in. (25 mm) of the concrete cylinder not immersed in the solution.

As mentioned previously, the half-cell potential of steel embedded within concrete with respect to a reference electrode can be indicative of the condition of the steel.[22]

In order to determine the potentials of both electrodes, a reference saturated calomel electrode (SCE) was immersed in the electrolyte solution. This consisted of a mercury/mercury chloride reference element surrounded by saturated potassium chloride (KCl) contained in an outer tube. When immersed in the NaCl solution, electrical contact is made between the sample and the electrolyte at the opening located at the end of the electrode. This opening forms a conductive bridge between the reference electrode, the sample, and the indicating electrode.

In order to permit proper electrolyte flow during analysis, electrodes must have their re-fill holes open when taking measurements. A re-fill hole is a small circular opening located at the top of the reference electrode, where the spout of the re-fill bottle is inserted. Each electrode was periodically refilled with KCl solution to make sure that the electrolyte always covered the tip of the internal element. The level of the KCl electrolyte was maintained above the surface of the aqueous solution, assuring that the NaCl solution will not backflow into the electrode.[69]

This experimental set-up provided a clean and safe approach of accelerating the corrosion process. All of the electrical equipment and materials were utilized repeatedly for the various set-ups.

6.1.3 Measurements

Voltage and current measurements were recorded daily for each specimen. A HICKOK Digital Systems - Model DP100 was used as the voltmeter and a FLUKE 77 Multimeter (300 mA range) was used as the ammeter.

In order to measure the voltage of each electrode, the following steps were undertaken:

1. The positive-terminal probe of the voltmeter (RED colour) was connected to the lollipop anode, by means of the battery clip connectors, while the negative-terminal probe (BLACK colour) was connected to the SCE. Measurements were recorded when stable reading were obtained (approximately 5 to 10 minutes). Two sets of readings were recorded, one with the power operating (circuit "closed") and the other with the power interrupted (circuit "open"). The latter was achieved by removing the "jumper" between the "connectors".

2. The above step was repeated, however, the positive-terminal probe (RED colour) was connected to the bare electrode to measure its potential. Both Steps 1 and 2 were taken in the **normal polarity** position.

3. The polarity was reversed by exchanging the lead wires of the DC power supply in the appropriate "connectors". Therefore, the negative terminal lead wire (BLACK colour) was connected to the lollipop specimen, making it the cathode. The positive terminal lead wire (RED colour) was thus connected to the bare electrode, acting as the anode.

4. Two sets of readings were recorded for each electrode in the **reversed polarity** position. The negative-terminal probe of the voltmeter (BLACK colour) was connected to the respective electrodes, while the positive-terminal probe (RED colour) was connected to the SCE. Once again, the readings were recorded when stable values were obtained (approximately 5 to 10 minutes). Two sets of readings were recorded, both for the

"open" and the "closed" circuits.

The electrode voltage measured in the interrupted power mode (circuit "open") is referred to as the **polarization potential**. This reflects any chemical or physical changes that may be occurring on the metal surface. The voltage recorded in the operating power mode (circuit "closed") is referred to as the **operating potential**. This includes both the polarization potential and any voltage drop in the electrolyte solution between the electrode and the point of measurement.[15]

The current readings were recorded in the following manner:

1. The positive-terminal probe (RED colour) of the voltmeter was connected to the lollipop anode, while the negative-terminal probe (BLACK colour) was connected to the bare cathode by means of battery clip connectors. The "jumper" was then removed from the "connectors" and replaced by the probe ends of the ammeter. Once again, the positive-terminal probe (RED colour) was connected to the lollipop anode, whereas the negative-terminal probe (BLACK colour) was connected to the bare cathode. As soon as stable readings were obtained (approximately 5 to 10 minutes), simultaneous readings of both current and voltage were recorded. Figure 6.4 demonstrates the set-up for a typical current measurement.
2. In the reversed polarity position, Step 1 was repeated. Appropriate connections were made, that is, negative- (BLACK colour) and positive-terminal (RED colour) probes connected to the lollipop cathode and bare anode, respectively.

Figure 6.4: Simultaneous Voltage and Current Recording

Simultaneous voltage and current measurements were recorded.

The **resistance** of each electrode is computed as the difference between the operating and polarization potentials divided by the corresponding current.[15]

In between the daily recordings, the concrete lollipop was left connected to the positive terminal of the power supply (i.e., as an anode), while the bare steel reinforcing bar was connected to the negative terminal (i.e., as a cathode). This enabled the electrolytic process to continue, with the transfer of ions in the electrolyte solution.

6.2 PRELIMINARY TESTING

The preliminary testing lasted a duration of three months from September to November 1990. The main objective was twofold: firstly, it provided a means of varying several parameters in order to assess their effects on reinforcement corrosion, and secondly, it enabled these parameters to be established during the subsequent study for the proper assessment of the effect of depth of the clear cover. Each specimen tested was immersed for a period of 30 days. No. 15 deformed reinforcing bars were used for both electrodes. No voltage and current readings were recorded.

Four main series were investigated during the course of the preliminary testing:

1. Impressed voltage (4.5 V)
2. Spacing (distance) between electrodes (4 in.- 102 mm)
3. Water-cement (W/C) ratio (0.45)
4. Concentration of electrolyte solution (3.5% NaCl).

Only one parameter was varied at any one time. The above numbers in parentheses represent the standard values used when the parameter in question was NOT varied. Each test series is represented by a number, whereas every set-up within a series is represented by a letter. For example, Test #2C signifies the <u>third</u> (letter C) set-up in the <u>second</u> (number 2) test series. Each of the experimental set-ups is briefly discussed.

6.2.1 Impressed Voltage - Series #1

Five experiments used different levels of voltage for the tests. These levels were: 1.5 V, 3.0 V, 4.5 V, 6.0 V, and 10.0 V (set-ups #1A to #1E, respectively). By arranging 1.5 V cell batteries in series, the necessary voltage for each set-up was obtained. Smaller-sized re-bars were used (0.257 in. - 6.53 mm diameter) as electrodes. Both set-ups D and E resulted in the re-bar being consumed after only 17 days of immersion (see Figures 6.5 and 6.6). In all cases, significant formation of rust deposits were noted.

6.2.2 Spacing (Distance) Between Electrodes - Series #2

These experiments consisted of the various electrode spacings: 2 in. (51 mm), 4 in. (102 mm), and 6 in. (152 mm)

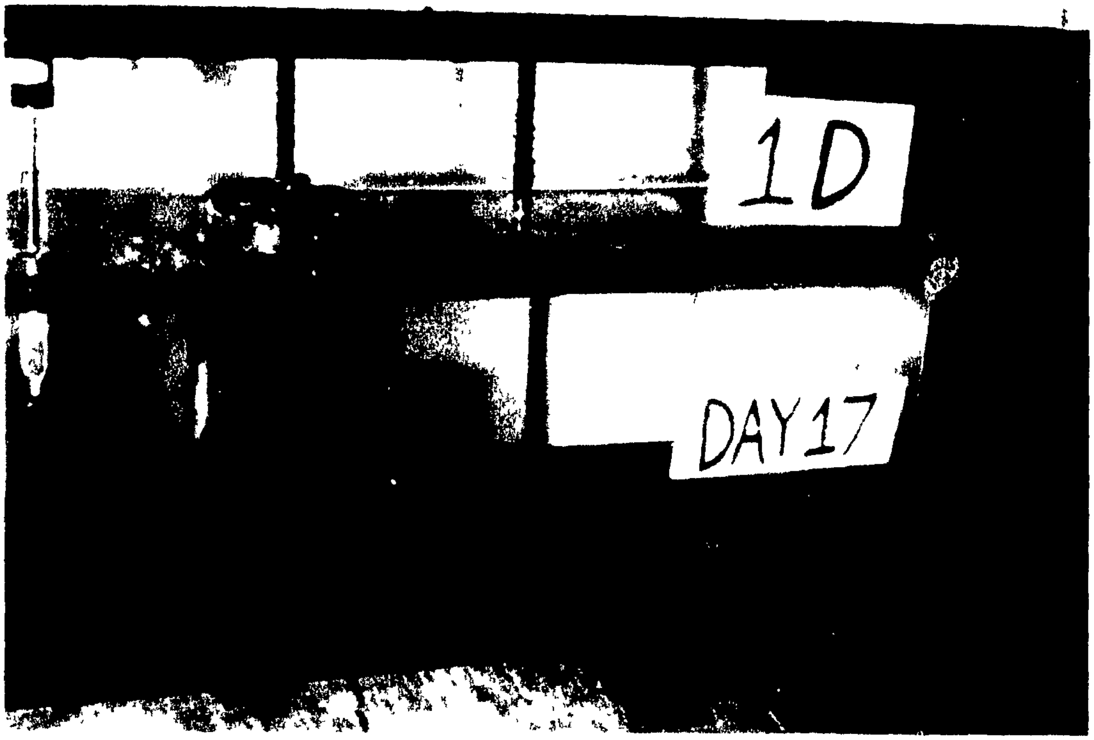


Figure 6.5: Experiment Set-Up #1D (Day 17)
Voltage Level: 6.0 V

Figure 6.6: Experiment Set-Up #1E (Day 17)
Voltage Level: 10.0 V

(set-ups #2A to #2C, respectively). No. 15 reinforcing bars were used as electrodes. Similar behaviour was observed in all three cases, with some accumulation of corrosion by-products along the base and height of the concrete cylinders.

6.2.3 Water-Cement Ratio - Series #3

The water-cement (W/C) ratios used were: 0.3, 0.4, 0.5, 0.6, and 0.7 (set-ups #3A to #3E, respectively). No discernible distinctions were observed between each set-up during the testing period. Slight variations in the initiation time of corrosion activity were noted.

6.2.4 Electrolyte Concentration (% NaCl) - Series #4

The strength of the electrolyte solution was varied in the following manner: 4%, 5%. 6%, and 10% NaCl by weight of distilled water (set-ups #4A to #4D, respectively). No distinguishable difference in behaviour was observed amongst the four specimens. At the end of the immersion period, all exhibited similar signs of corrosion.

6.2.5 Limitations and Conclusions

Upon completion of the preliminary testing, certain limitations and conclusions dealing with the parameters investigated could be drawn:

1. The electrolytic medium between electrodes consists basically of water with a percentage concentration of sodium chloride. In the case of electrochemical studies undertaken in such aqueous solutions, the available potential range is limited by the two electrode reactions[16]:

$$1/2\ O_2 + 2\ H^+ + 2\ e^- \rightleftharpoons H_2O \qquad (6.1)$$

$$1/2\ H_2 \rightleftharpoons H^+ + e^- \qquad (6.2)$$

The above equations indicate a range of potential voltages over which electrode chemical reactions in aqueous solutions will occur while preventing electrolysis of the aqueous medium. In this case, the range varies approximately from +1 V to -1 V. In some cases, this range can be extended by using electrode materials with a high overvoltage for either hydrogen or oxygen.[16] In this instance, use of steel anodes and cathodes could allow this range to be extended.

Nevertheless, it was deemed reasonable to conservatively limit the impressed voltage in all subsequent testing to a **maximum of 1 volt.**

2. As a result of the dimensions of the glass tanks, space restrictions were placed on the distance between the two electrodes. Since no actual difference was observed during the preliminary testing, a **spacing of 4 in. (102 mm)** was used in future tests. This allowed sufficient space for the reference SCE to be properly immersed in the electrolyte solution.

3. The water-cement ratio plays an important role in the onset of reinforcement corrosion. However, the preliminary testing demonstrated that this is not a predominant variable affecting the corrosion rate relative to the other tests. Therefore, for ease of concrete mixing and casting, a **water-cement ratio of 0.45** was used.

4. The range of the electrolyte concentrations did not produce any significant effects between the tests. In order to determine the effects of the NaCl electrolyte, two extreme **concentrations of 3.5% and 10% NaCl** were used.

It is important to note that sea water contains, on the average, 3.5 percent salts. The sodium chloride added must be properly dissolved to prevent salt deposits from forming. A mechanical mixer was used for this purpose.

5. In order to simulate the corrosion phenomenon realistically in larger-sized concrete structures, reinforcing bars commonly used in construction practice were used in the testing program. The reinforcement chosen were **No. 15 re-bars**

(0.63 in. - 16 mm diameter).

6. The glass tanks were thoroughly washed with a non-abrasive cleaning agent, rinsed properly, and wiped clean before each test was undertaken. This was done to ensure that no remnants of the previous set-up, such as hardened encrustations or ferric oxide deposits, would remain.

To summarize, the following parameters were established during the preliminary testing phase:

- Impressed voltage: 1.0 V
- Distance between electrodes: 4 in. (102 mm)
- Water-cement ratio: 0.45
- Electrolyte concentration: 3.5% and 10% NaCl

6.3 COVER THICKNESS VARIATIONS - SERIES #5 AND #6

Upon establishment of the parameters to be used, focus was placed on the range of cover depths to be studied. Nine test series were established. The variations of the concrete cover were achieved by means of PVC or plastic molds of varying the inside diameter dimensions. The range of clear cover depths analyzed are summarized in Table 6.2.

In some instances, exact cover depths could not be obtained due to difficulty of acquiring molds of specific sizes. To assess the influence of the various concrete covers on the corrosion activity, the immersion period was extended to **45 days**. Series #5 and #6 were tested from December 1990 to March 1991. The main difference between the two series was the strength of the electrolyte concentration. Test Series #5 used

SPECIMEN	MOLD INNER DIAMETER in. (mm)	NOMINAL BAR DIAMETER in. (mm)	CLEAR DEPTH OF CONCRETE COVER in. (mm)
A	1-1/4 (31.8)	0-10/16 (15.9)	0-5/16 (7.9)
B	1-1/2 (38.1)	0-10/16 (15.9)	0-7/16 (11.1)
C	2-0 (50.8)	0-10/16 (15.9)	0-11/16 (17.5)
D	2-1/2 (63.5)	0-10/16 (15.9)	0-15/16 (23.8)
E	3-0 (76.2)	0-10/16 (15.9)	1-3/16 (30.2)
F	3-1/2 (88.9)	0-10/16 (15.9)	1-7/16 (36.5)
G	4-0 (101.6)	0-10/16 (15.9)	1-11/16 (42.9)
H	4-10/16 (117.5)	0-10/16 (15.9)	2-0 (50.8)
I	5-10/16 (142.9)	0-10/16 (15.9)	2-1/2 (63.5)

TABLE 6.2: Mold Sizes And Clear Cover Depths

a 10% NaCl aqueous electrolyte solution, whereas Test Series #6 had a 3.5% NaCl solution by weight of distilled water.

6.3.1 Visual Observations

6.3.1.1 Test Series #5

Table 6.3 summarizes the visual observations recorded during the testing period for Series #5. For the first five concrete cover thicknesses (up to and including the Specimen E), there was a significant formation and accumulation of corrosion by-products, with the amount decreasing with an increased cover thickness. The products formed were of a dark reddish-black colour. Specimen F only showed initial signs of distress at the end of the 45-day duration. The largest cover depths exhibited no particular evidence of corrosion activity. The initial stages of corrosion-forming products for three specimens are shown in Figures 6.7, 6.8, and 6.9 (Specimens A, B, and D, respectively). Appendix C illustrates the various

VISUAL OBSERVATIONS

TEST SERIES #5 -- 10% NaCl

Specimen	Observation #1	Observation #2	Observation #3
A	DAY 2	DAY 4	DAY 7
B	DAY 5	DAY 7	DAY 10
C	DAY 9	DAY 10	DAY 12
D	DAY 13	DAY 15	DAY 17
E	DAY 17	DAY 21	DAY 23
F	DAY 23	---	---
G	---	---	---
H	---	---	---
I	---	---	---

TEST SERIES #6 - 3.5% NaCl

Specimen	Observation #1	Observation #2	Observation #3
A	DAY 2	DAY 4	DAY 7
B	DAY 4	DAY 6	DAY 7
C	DAY 12	DAY 15	DAY 18
D	DAY 26	DAY 36	---
E	DAY 44	---	---
F	---	---	---
G	---	---	---
H	---	---	---
I	---	---	---

LEGEND:

#1: Formation of "bubbles" at top of lollipop (first indication of active corrosion).

#2: Corrosion by-products forming along the lollipop height (indication of ongoing corrosion).

#3: Accumulation of by-products at base of lollipop (corrosion at an advanced state).

--- no indication of active corrosion observed.

Table 6.31 Visual Observations - Test Series #5 & #6

Figure 6.7: Experiment Specimen #5A (Day 2)
Concrete Cover Thickness: 5/16 in. (7.9 mm)

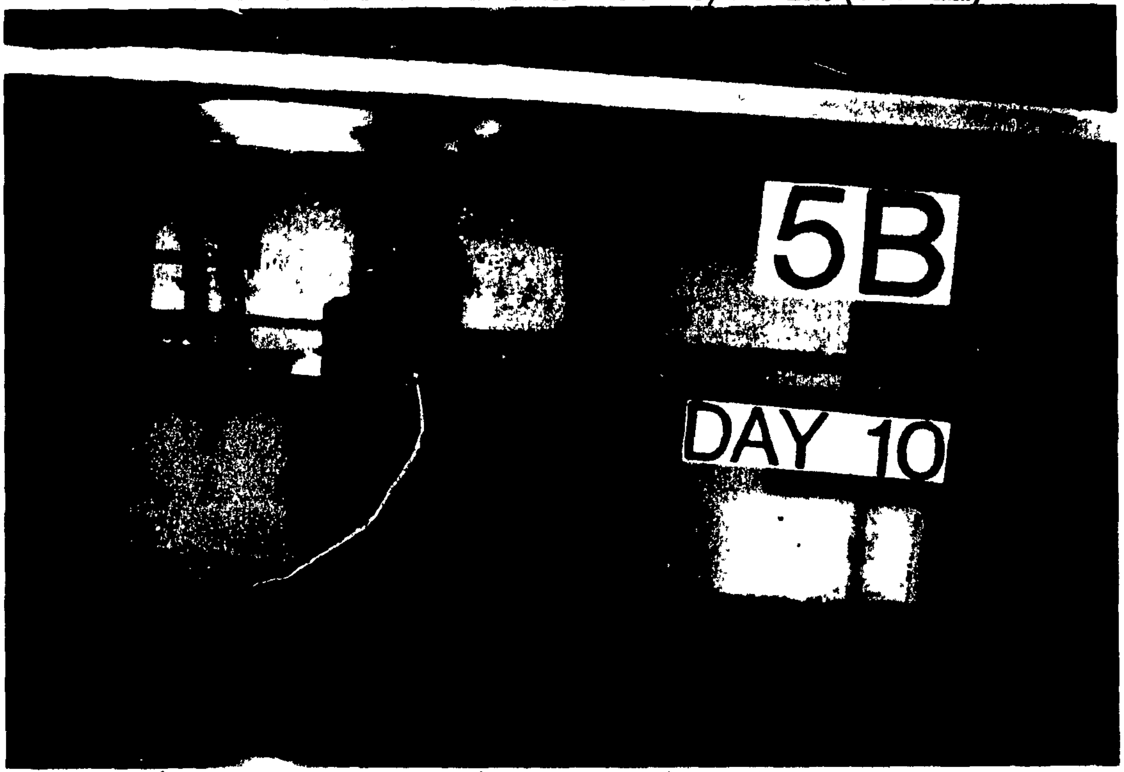


Figure 6.8: Experiment Specimen #5B (Day 10)
Concrete Cover Thickness: 7/16 in. (11.1 mm)

Figure 6.9: Experiment Specimen #5D (Day 30)
Concrete Cover Thickness: 15/16 in. (17.[illegible] mm)

testing stages of two specimens (C and G). It can be seen that an increase of 1 in. (25 mm) in concrete cover significantly alters the process of reinforcement corrosion. Due to the greater concrete cover thickness, more time elapses before oxygen, moisture, and/or chlorides penetrate through the concrete and reach the level of the steel reinforcing bar.

6.3.1.2 Test Series #6

The visual observations recorded for Series #6 are listed in Table 6.3. The three specimens with the smallest covers (A, B, and C) show evidence of corrosion level being in an advanced state. Specimens E and F exhibit signs of the corrosion activity being in its initial stages, while the rest of the specimens remained basically "corrosion-free". The corrosion products were essentially of the same colour as those formed in Series #5. Figures 6.10 and 6.11 illustrate the initial stages of corrosion activity for the Specimens A and B. The development throughout the immersion period for the two other Specimens (C and H) are presented in Appendix D.

6.3.2 Corrosion Products

To ensure that the proper chemical reactions were occurring in the aqueous solution medium, the products formed during the experimental period were analyzed chemically. Two

Figure 6.10: Experiment Specimen #6A (Day 10)
Concrete Cover Thickness: 5/16 in. (7.9 mm)

Figure 6.11: Experiment Specimen #6B (Day 20)
Concrete Cover Thickness: 7/16 in.(11.1 mm)

indicators were used: potassium ferrocyanide ($K_4Fe(CN)_6 \cdot 3H_2O$) and potassium ferricyanide ($K_3Fe(CN)_6$). The compound product was dissolved with hydrochloric acid (HCl) according to the following equation[72]:

$$Fe_2O_3 + 6HCl \rightarrow Fe^{3+} + Fe^{2+} + 3H_2O + 6Cl^- \qquad (6.3)$$

The reaction between the indicators and the compound product is given by the following equations[72]:

$$K^+ + Fe^{3+} + Fe(CN)_6^{-4} \rightarrow KFe_2(CN)_6 \qquad (6.4)$$

$$K^+ + Fe^{2+} + Fe(CN)_6^{-3} \rightarrow KFe_2(CN)_6 \qquad (6.5)$$

The formation of ferrous oxide (Fe^{2+}) cannot be measured quantitatively since it is a very unstable product, which oxidizes in the presence of air (oxygen). According to the above equations, it is assumed that both ferrous oxide (Fe^{2+}) and ferric oxide (Fe^{3+}) are present within the corrosion compound formed.

In order to determine the validity of this assumption, both ferri and ferro cyanides were used as indicators to react with the sample compounds obtained from each experimental specimen. In all the cases, the reaction resulted in a deep blue-green colour to appear, confirming the presence of both ferrous oxide (Fe^{2+}) and ferric oxide (Fe^{3+}).

6.3.3 Electrode Potential Measurements

6.3.3.1 Test Series #5

Daily readings of both the anode and cathode operating and polarization potentials, as previously defined, were recorded. These were done for both the normal and reversed polarity positions, that is, the lollipop specimens acting as anodes and cathodes, respectively. Appendix P presents a summary of the various test data. The operating potentials versus the reference SCE of the lollipop specimens in this series are illustrated graphically in Figures 6.12 and 6.13.

6.3.3.2 Test Series #6

A similar approach was used to record electrode the potentials of this series (see Appendix Q for data

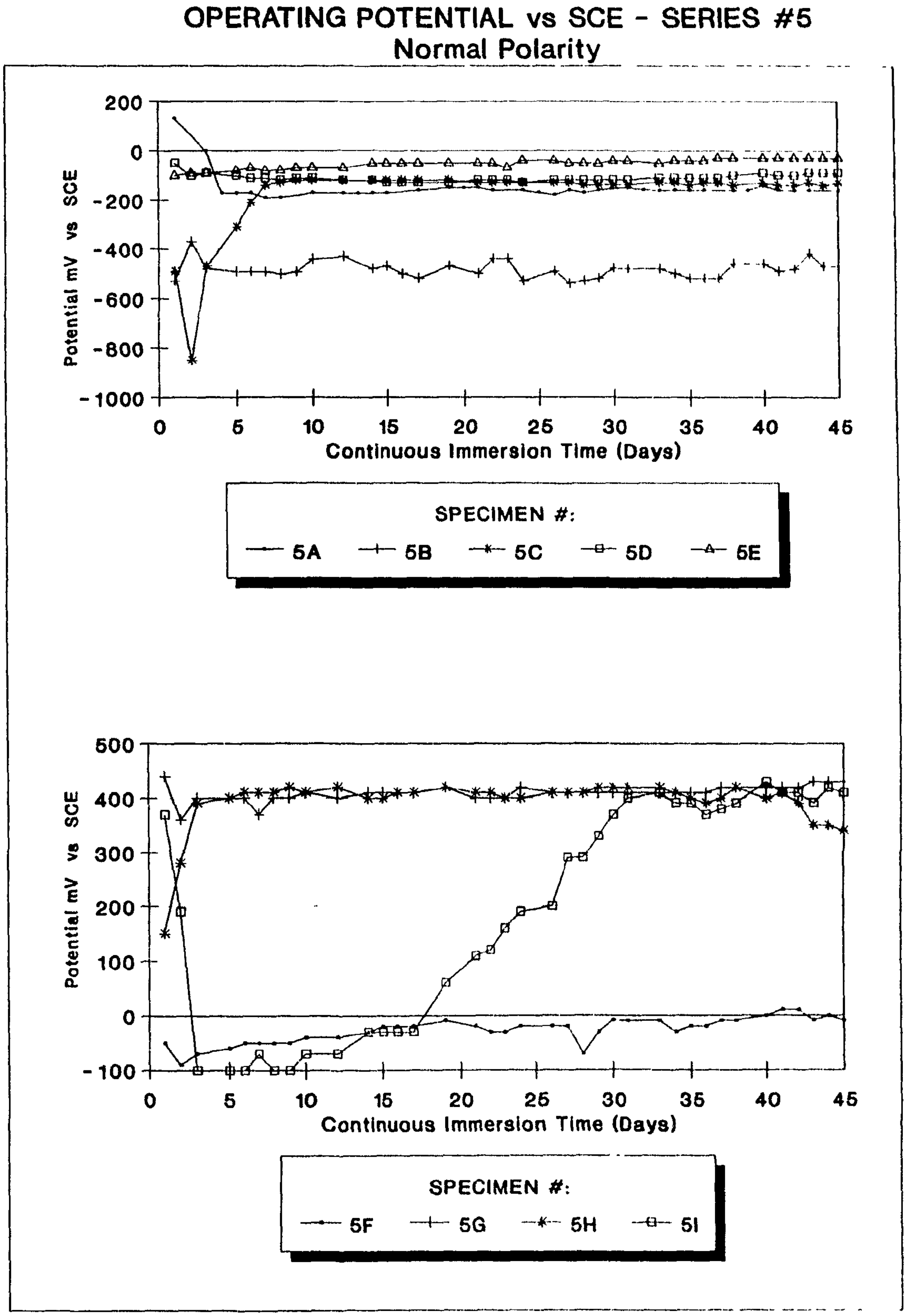


Figure 6.12: Operating Potentials
Normal Polarity - Test Series #5

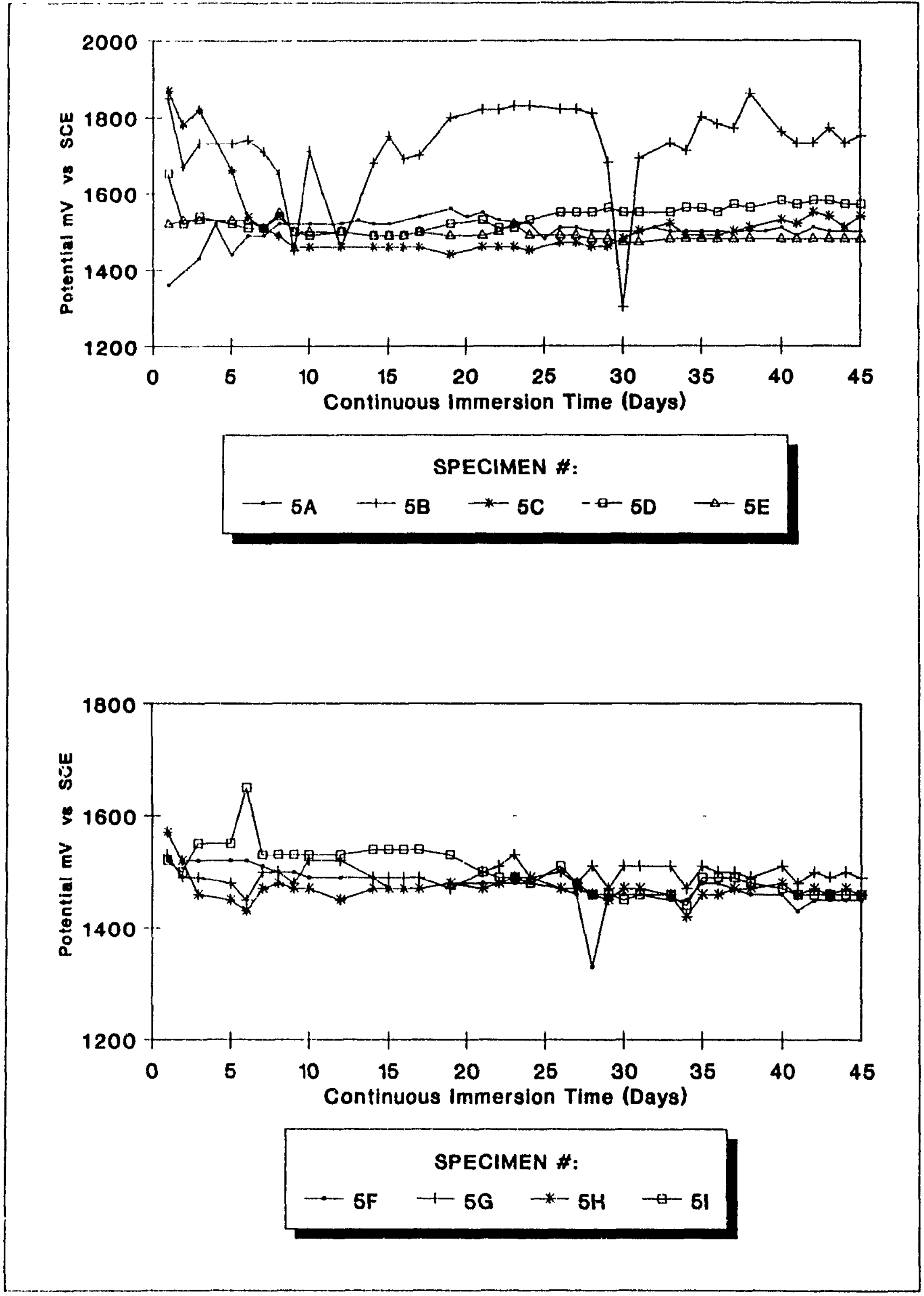

OPERATING POTENTIAL vs SCE - SERIES #5
Reversed Polarity

Figure 6.13: Operating Potentials
Reversed Polarity - Test Series #5

recordings). Figures 6.14 and 6.15 depict the operating potentials versus reference SCE measured during the immersion period.

6.3.4 Current Measurements

6.3.4.1 Test Series #5

Measurement of the current flow, in the milli-amp (mA) range, and the corresponding voltage (IR) drop in the electrolyte were recorded (see Appendix P). The variations of current flow can be seen in Figures 6.16 and 6.17, for both normal and reversed polarity positions.

6.3.4.2 Test Series #6

For this series, the current fluctuations and the voltage drops between the electrodes were recorded throughout the experimental test period (see Appendix Q). Figures 6.18 and 6.19 illustrate the current flow variation versus immersion time for each specimen tested.

6.3.5 Carbonation Depth Measurements

At the end of the immersion period (45 days), the concrete specimens were tested to determine exactly where a loss of alkalinity had occurred through carbonation. In order to do so, all lollipop samples were saw-cut along the height of the cylinder and as close as possible to the centrally-embedded re-bar (see Figure 6.20). The concrete surface was then sprayed with a chemical indicator solution which changes

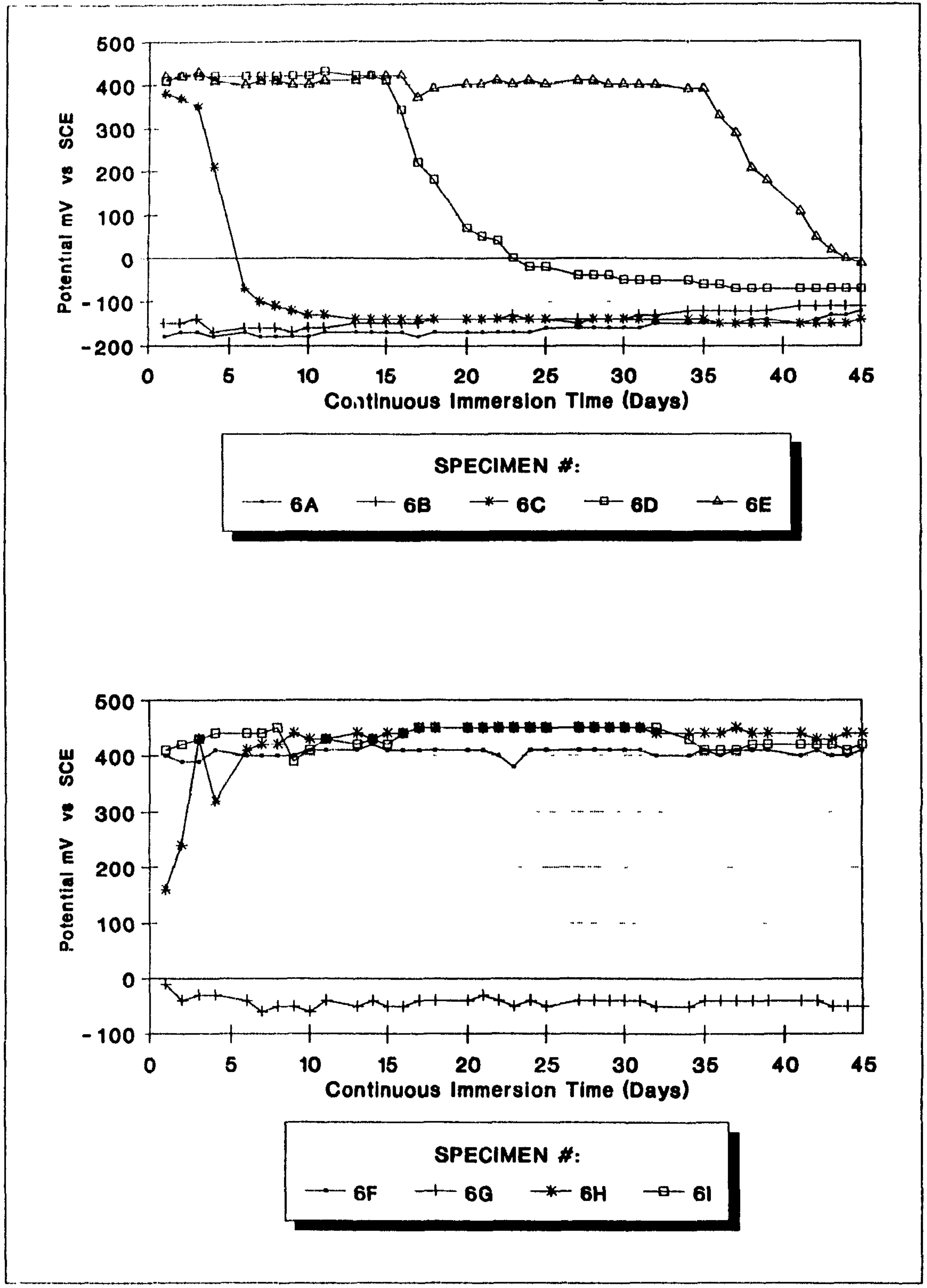

OPERATING POTENTIAL vs SCE - SERIES #6
Normal Polarity

Figure 6.14: Operating Potentials
Normal Polarity - Test Series #6

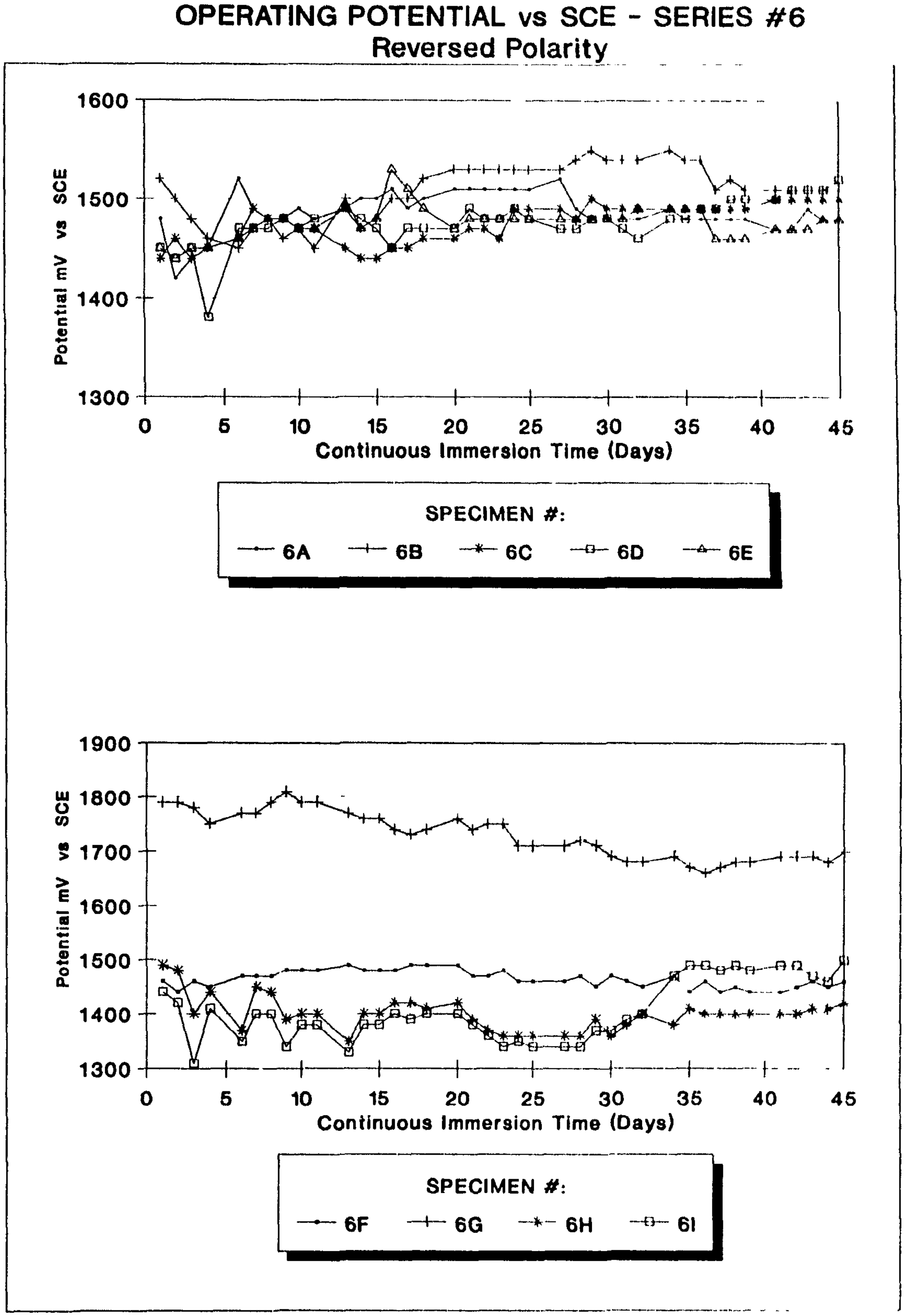


Figure 6.15: Operating Potentials
Reversed Polarity - Test Series #6

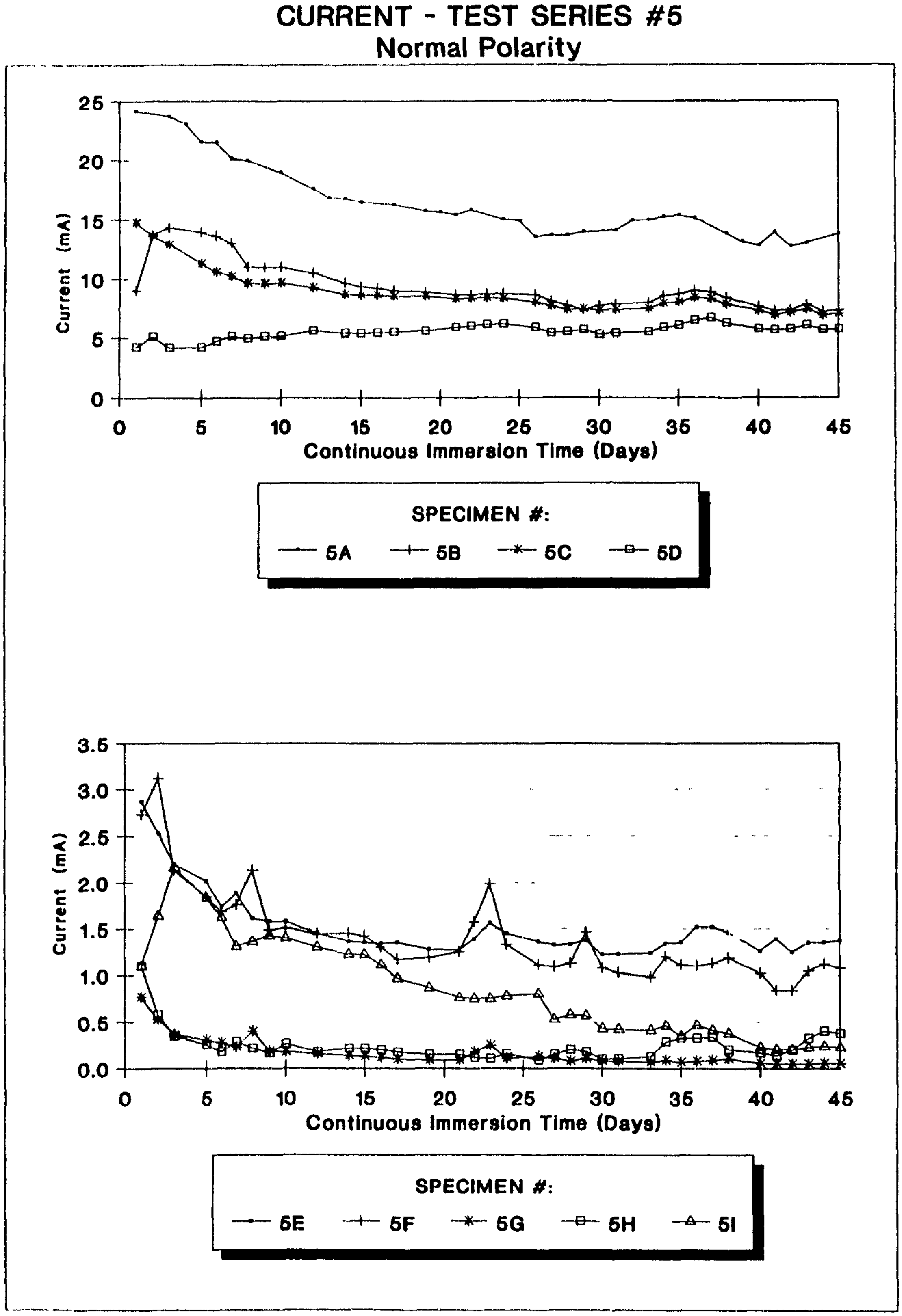


Figure 6.16: Current Flow
Normal Polarity - Test Series #5

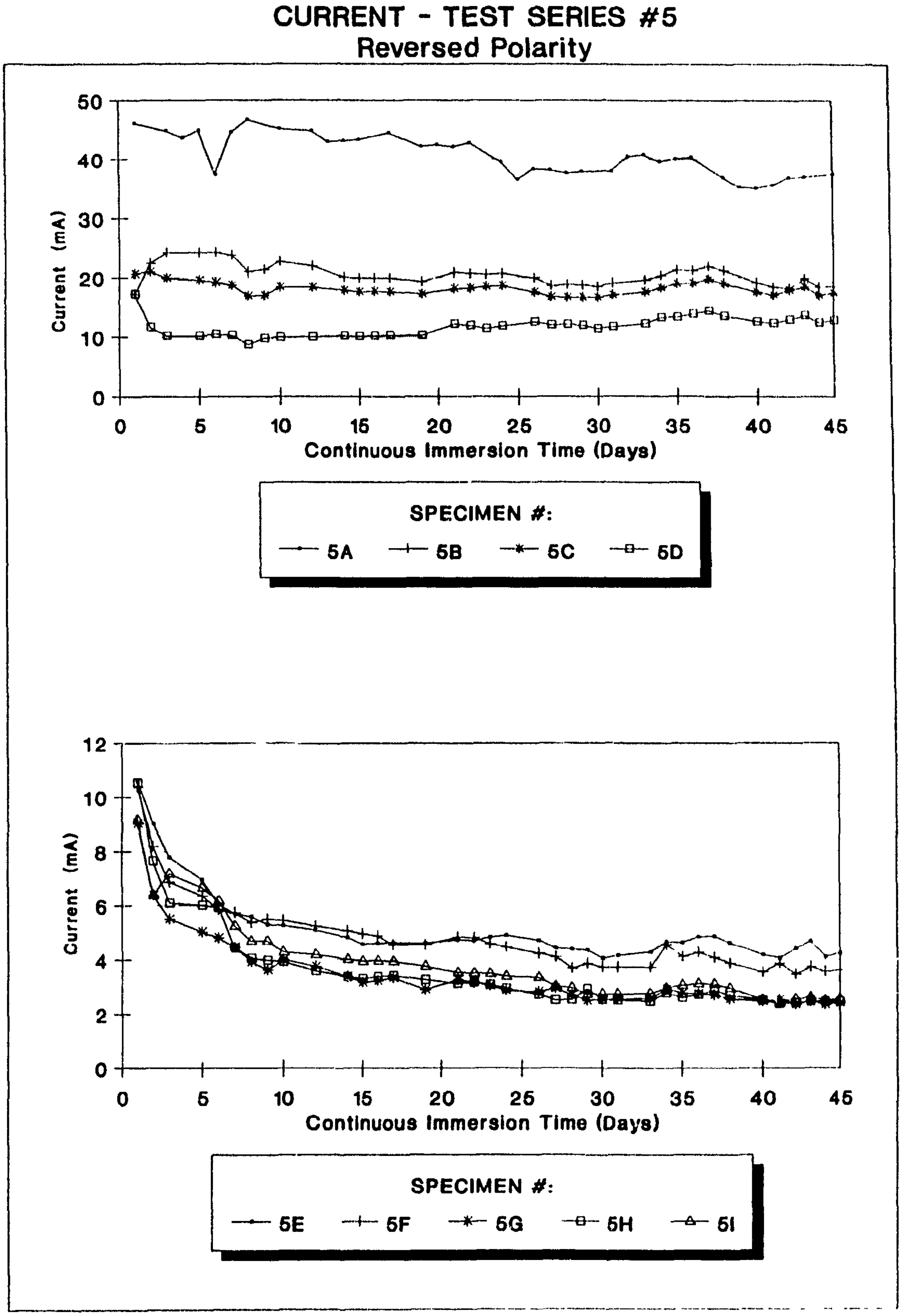


Figure 6.17: Current Flow
Reversed Polarity - Test Series #5

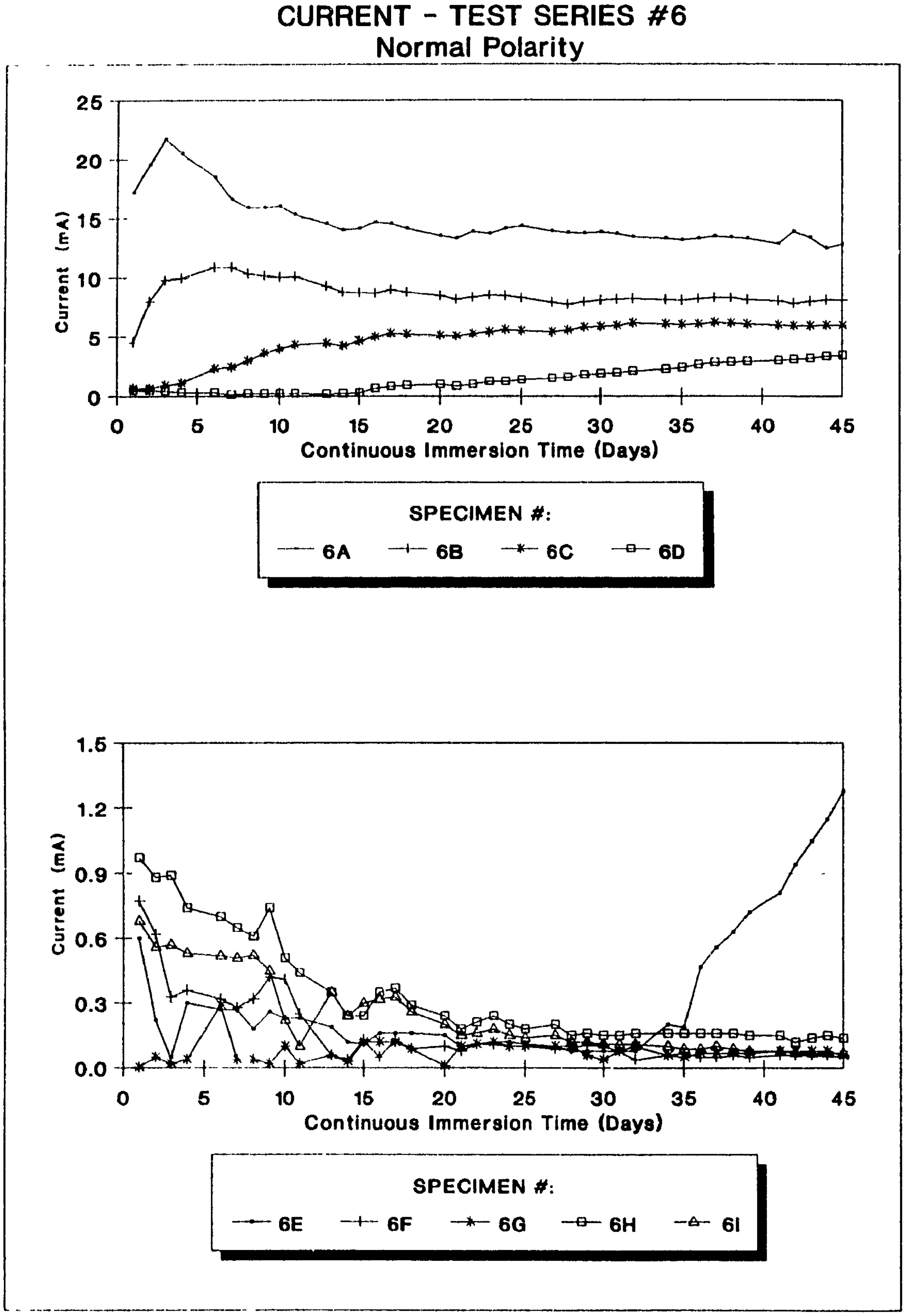


Figure 6.18: Current Flow
Normal Polarity - Test Series #6

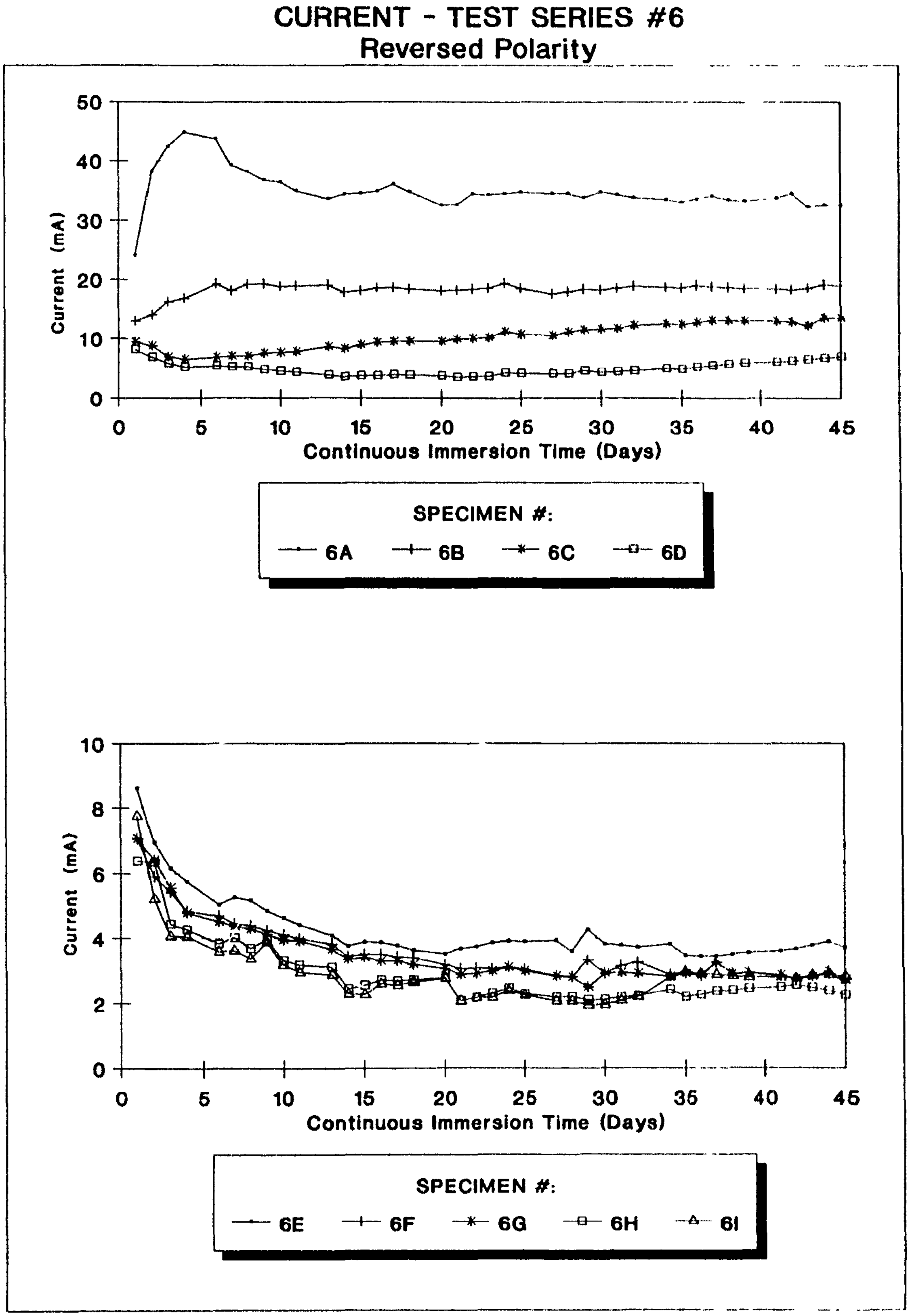


Figure 6.19: Current Flow
Reversed Polarity - Test Series #6

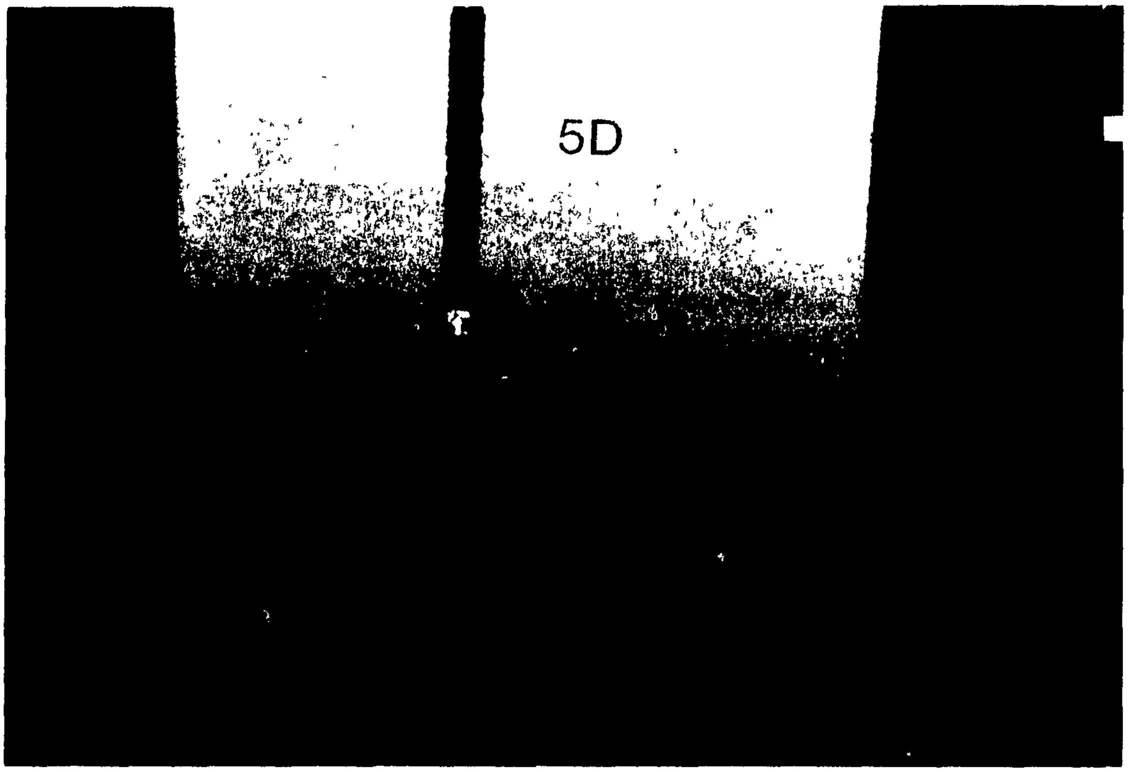


Figure 6.20: Saw-cut Lollipop Specimen (#5D)

colour according to the alkalinity of the concrete. A solution of phenolphthalein in dilute alcohol (50% volume of each component) was used. This indicator had a very strong pink colour, easily visible on any concrete that has retained its alkalinity, yet it was colourless on concrete which was no longer adequately alkaline to protect the reinforcing bar from corrosion.[4] Figure 6.21 shows the colour change of the phenolphthalein indicating the loss of alkalinity in the concrete.

The above procedure was repeated for all of the specimens. The depth of carbonation was measured as the

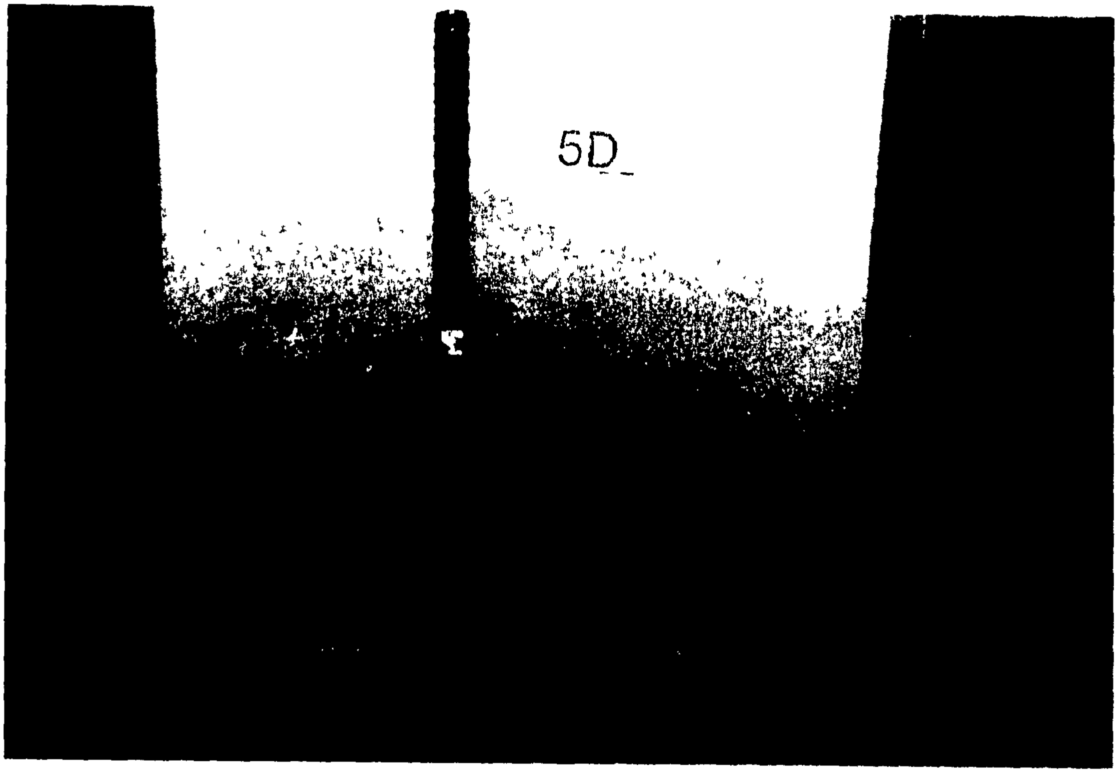


Figure 6.21: Lollipop Specimen (#5D) With Phenolphthalein Indicator

distance from the outer concrete edge to the location where a strong pink colour was present. Measurements were recorded of both the maximum and minimum depths of penetration. Appendix E lists the data obtained. Figure 6.22 illustrates graphically the variation of the average depth of penetration versus the concrete clear cover thickness.

6.3.6 Chloride Content

The chloride content of concrete plays an important role in the rate of reinforcement corrosion. Small chloride amounts can disrupt the oxide layer that should protect the steel re-

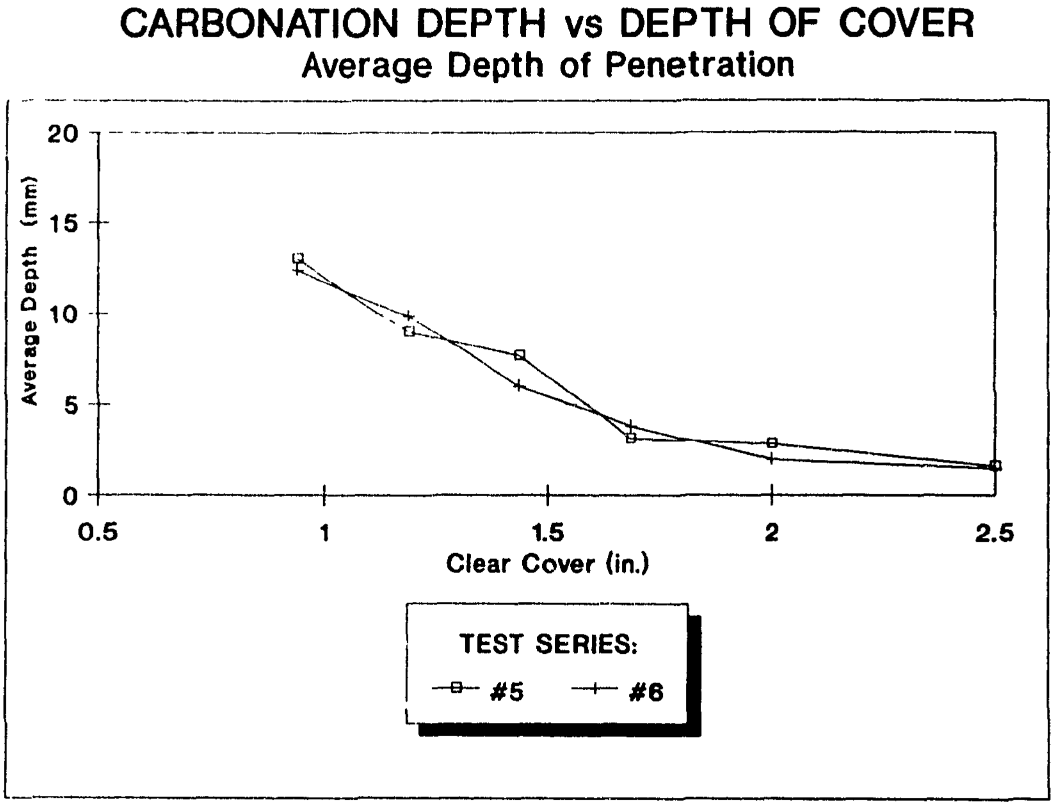


Figure 6.22: Average Carbonation Depth
Test Series #5 and #6

bar from rusting. Therefore, the determination of the chloride content is an important parameter to assess the condition of deteriorating concrete.[4]

One of two halves of the previously saw-cut specimens were used as test samples. Holes were drilled into the concrete, with a carbide drill bit, at three heights along the cylinder: 1.5 in.(38 mm), 3 in.(76 mm), and 4.5 in.(114 mm). At each location, the concrete dust produced was meticulously collected in small plastic bags and properly sealed. This quick and simple procedure allowed many samples to be taken in order to obtain representative results despite the possible variations between each specimen. Figure 6.23 shows a typical lollipop specimen after the extraction of concrete at the above three locations.

Figure 6.23: Locations of Extracted Concrete Samples

Chemical analysis was then performed on the samples obtained to determine the chloride content. The analysis was carried on in the laboratories of the Otto Maass Chemistry Building, McGill University. The procedure followed was according to the British Standard on Testing Concrete - Part 124.[34] The basis of the procedure is the Volhard Method, a precipitation titration method used for the indirect determination of the chloride content. A known excess of standard silver nitrate solution ($AgNO_3$) is added to the concrete sample, dispersed with a nitric acid solution (HNO_3). The excess is determined by back titration with a standard thiocyanate solution (KSCN). Ammonium ferric sulphate $FeNH_4(SO_4)_2 \cdot 12H_2O$ serves as the indicator to determine the appearance of the first permanent red colour.[28]

The chloride content is calculated as a percentage of the cement to the nearest 0.01% (m/m) using the following expression[34]:

$$J = (V_5 - (V_6 \cdot m/0.1)) * (0.003545/M_c) * (100/C_1) \qquad (6.6)$$

where V_5 = volume of silver nitrate solution ($AgNO_3$) (ml)

V_6 = volume of thiocyanate solution (KSCN) (ml)

m = molarity of thiocyanate solution (mol/L)

M_c = mass of concrete sample used (g)

C_1 = cement of concrete sample used (%)

The above equation may be modified according to the varying concentrations of silver nitrate and thiocyanate solutions.

Appendix F presents the results obtained for the chloride content for both Test Series #5 and #6. The cement content found in a concrete sample is determined in Appendix B. The variation of the chloride content along the cylinder height versus the depth of concrete cover is shown in Figure 6.24.

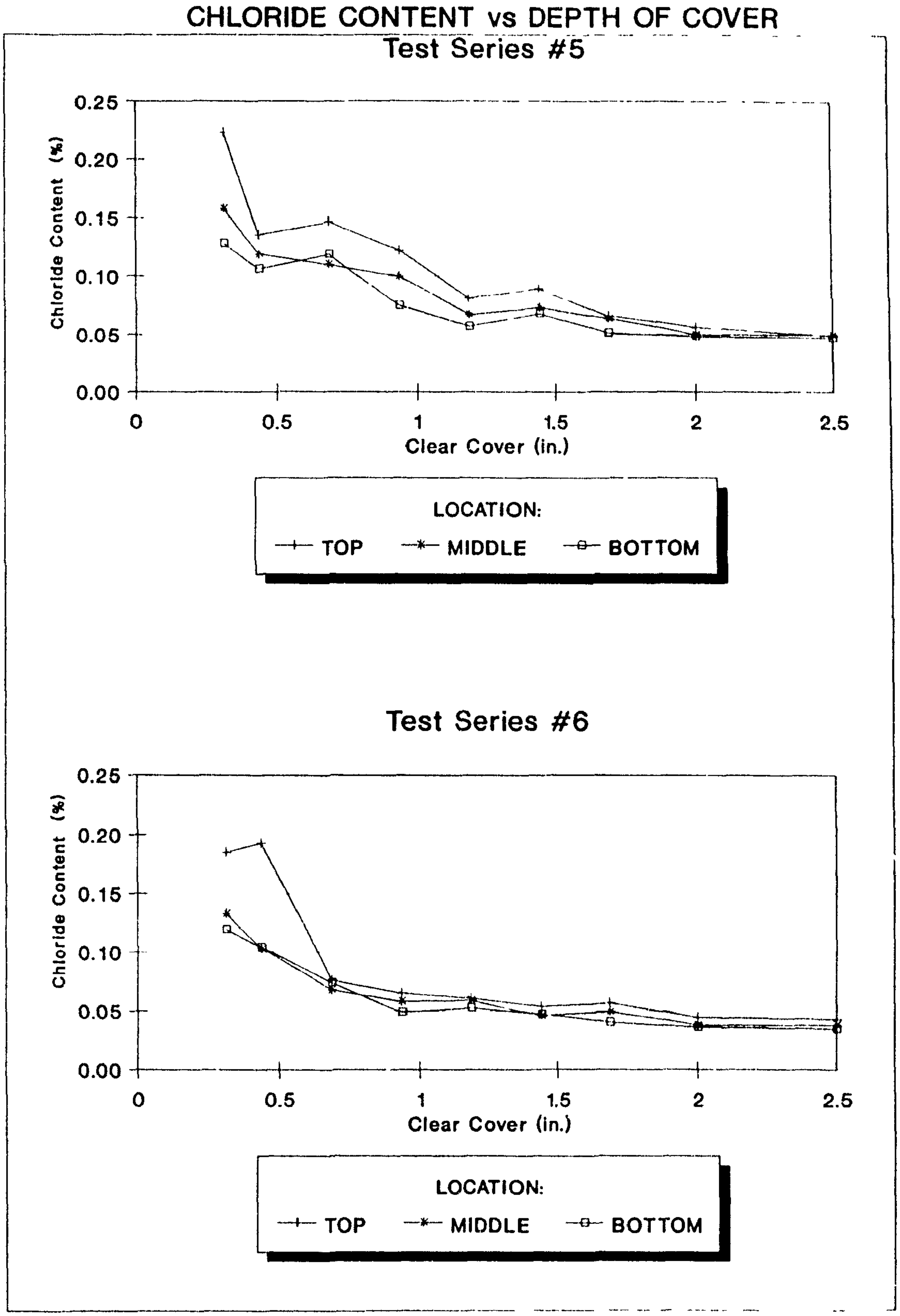


Figure 6.24: Chloride Content Variations
Test Series #5 and #6

6.3.7 Reinforcement Mass Measurements

Reinforcement weight loss provides information on the total metal loss due to corrosion and pitting. Before the start of each test series, all of the prepared re-bars were marked and weighed on a digital precision balance (Sartorius 1204 MP). After each lollipop specimen was saw-cut and all of the necessary testing completed, the concrete halves were crushed to remove the embedded reinforcing bars. All of the re-bars were then properly cleaned with a mechanical wire brush to remove any concrete remaining bonded and any "loose" rust formations along the height. These bars were weighed, and the loss occurring during the immersion period was determined as follows[18]:

$$\text{Weight Loss (\%)} = \frac{\left\{(\text{pre-exposure weight}) - (\text{post-exposure weight})\right\}}{(\text{pre-exposure weight})} * 100 \qquad (6.7)$$

The results for both Test Series #5 and #6 are presented in Appendix G. The variations in metal weight loss with the concrete cover thickness are illustrated in Figure 6.25.

6.3.8 Tensile Strength Measurements

The loss of structural integrity of a concrete structure can be attributed in part to the reduction in the cross-sectional area of the reinforcement and thereby, to a loss in its tensile strength. Five No. 15 re-bars of length 12 in.(305 mm) were tested to form the basis of comparison for the subsequent tensile testing of electrodes used in Series #5 and

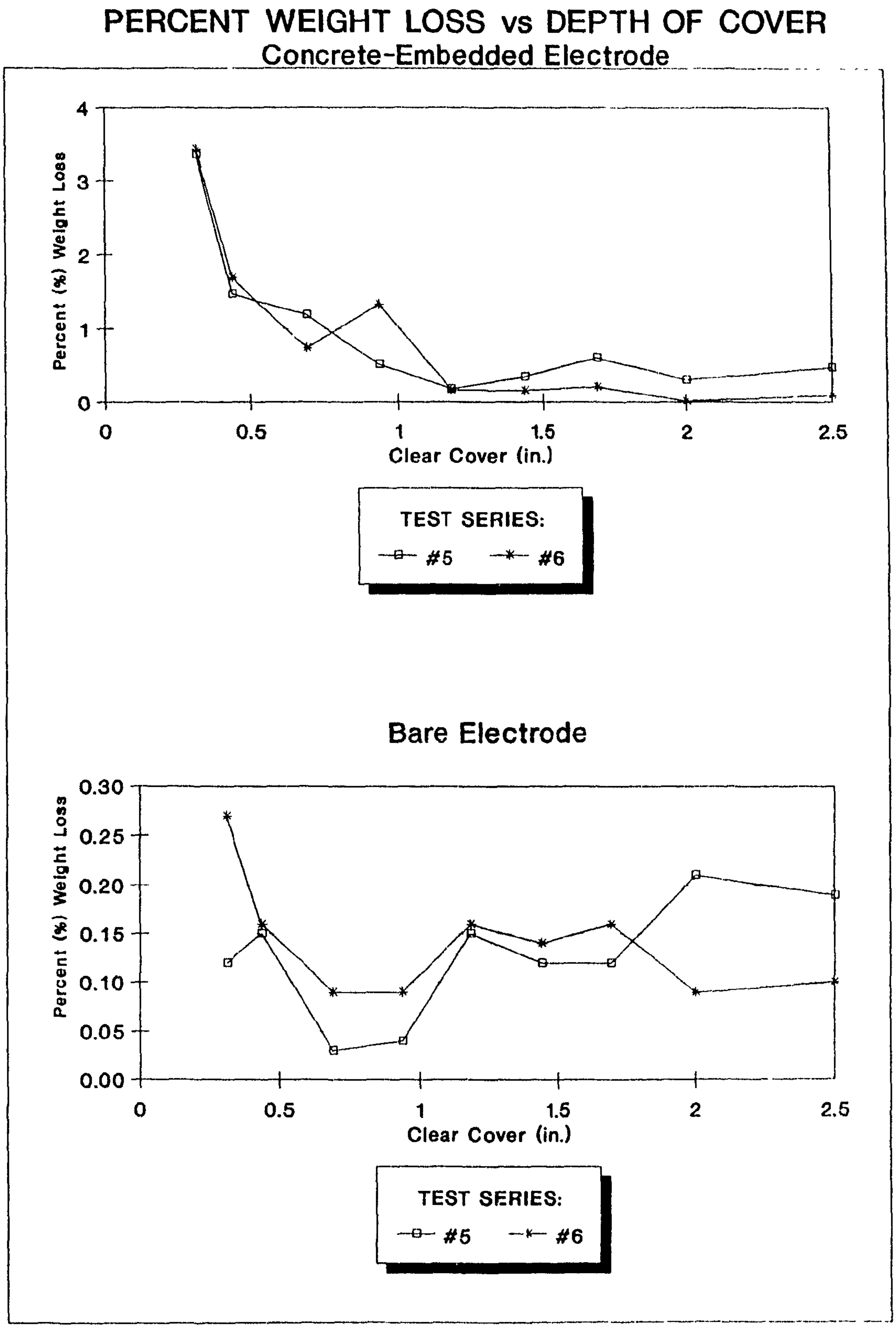


Figure 6.25: Percent Weight Loss
Test Series #5 and #6

#6. These "coupons" were tested using a Riehle Universal testing machine and a dial gauge to record the displacement measurements. The stress-strain characteristics obtained are presented in Appendix H and a typical stress-strain curve is shown in Figure 6.26.

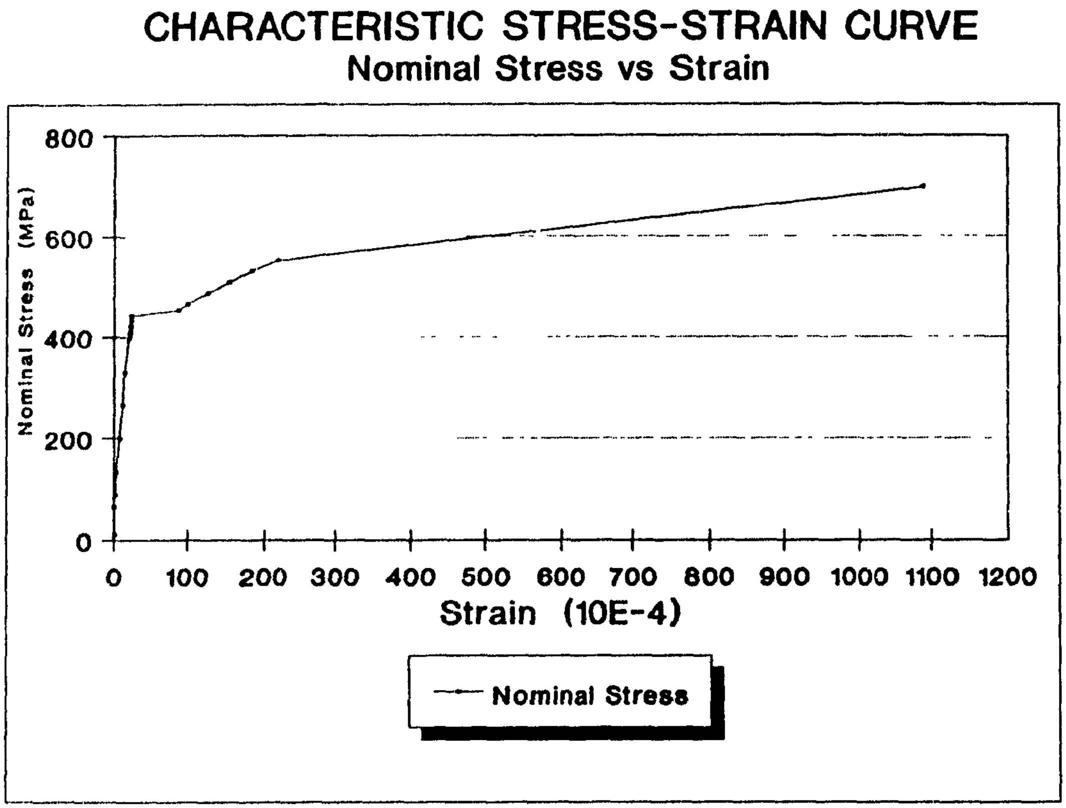


Figure 6.26: Stress-Strain Curve
Specimen #2

For the test series, the re-bar specimens were tested to obtain the yield and the ultimate stress characteristics. A summary of the results obtained is presented in Appendix H. Figures 6.27 and 6.28 compare the nominal and true ultimate stresses for both series. The nominal stress is calculated

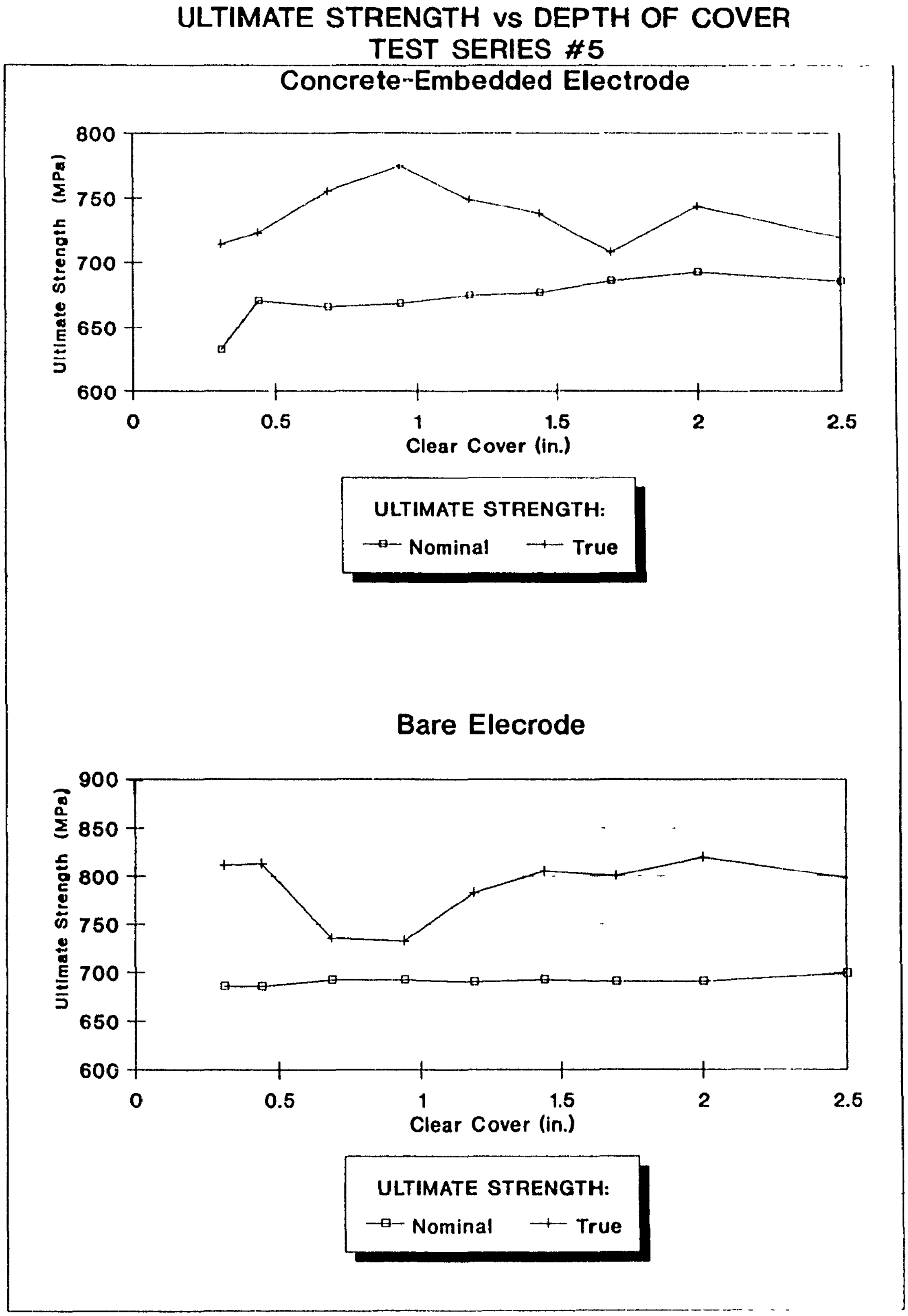


Figure 6.27: Ultimate Strength
Test Series #5

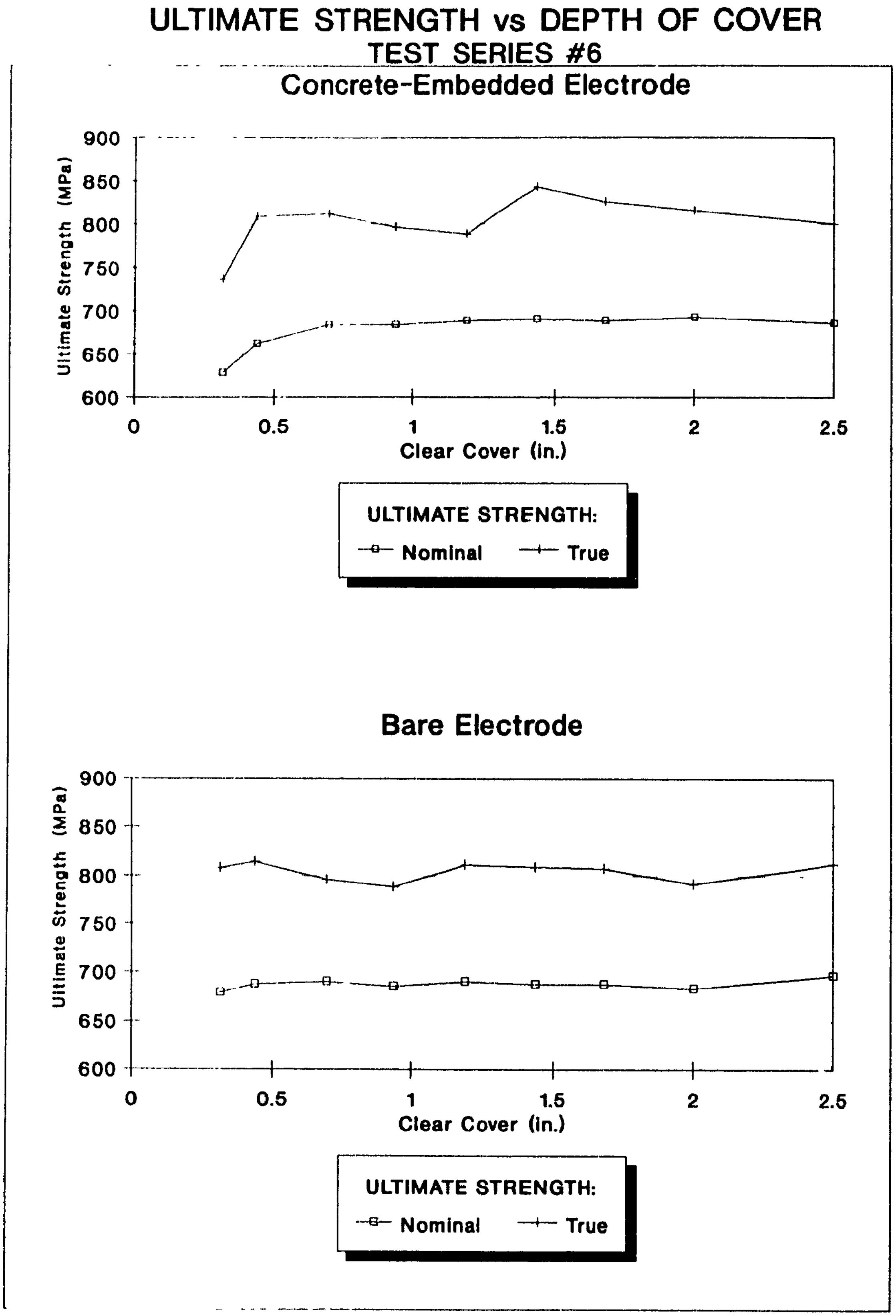


Figure 6.28: Ultimate Strength
Test Series #6

using the nominal (theoretical) diameter of the re-bar specimen. The true stress is calculated with an average diameter dimension measured using a Vernier scale, at four locations along the height of the re-bar specimen.

6.4 TEST SERIES #7

An additional series of tests was performed during the months of March and April 1991. This series consisted of five tests. Two tests consisted of normal reinforcing bars both acting as electrodes, i.e., neither of the two were embedded in a concrete environment. The other three tests consisted of both electrodes embedded in a concrete environment. These are discussed in the following sections.

6.4.1 Specimens #7A and #7B

The only difference between these two specimens was the strength of the electrolyte concentration. Specimen #7A was subject to a 10% NaCl situation whereas Specimen #7B had an electrolyte concentration strength of 3.5% NaCl by weight of water. The objective of these tests was to determine the interaction between the steel electrodes and the effect on rate of corrosion activity.

6.4.1.1 Visual Observations

Upon connection of the electrical circuitry, there was immediate visible flow of current and exchange of ions between the electrodes for each set-up. Ferric oxide corrosion products, having a dark reddish-brown colour, accumulated during the immersion period. Reduction of the cross-sectional areas of the re-bars acting as anodes was noted for both specimens. This continued until insufficient bar size remained to allow current flow through the circuit and the electrolyte. This occurred after 24 days for specimen A and after 30 days for specimen B, after which time, the experiment was terminated in both cases. Figures 6.29 and 6.30 illustrate both specimens at one particular stage during the testing period.

6.4.1.2 Voltage and Current Measurements

Daily electrode potential readings, as well as variations

Figure 6.29: Experiment Specimen #7A (Day 20)
Electrolyte Concentration: 10% NaCl

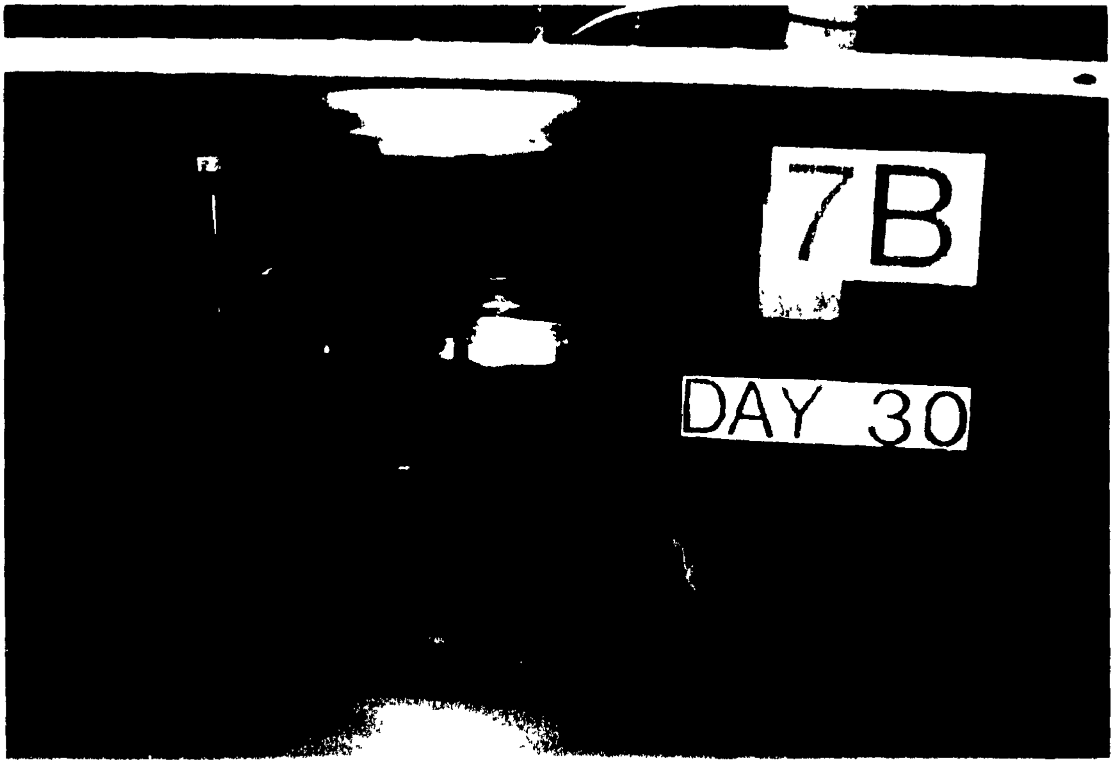


Figure 6.30: Experiment Specimen #7B (Day 30)
Electrolyte Concentration: 3.5% NaCl

of current, were recorded for the specimens A and B. The data collected can be found in Appendix R. The electrode operating potentials versus reference SCE are shown in Figure 6.31. The current readings are plotted versus the immersion time in Figure 6.32.

6.4.1.3 Reinforcement Mass Measurements

As mentioned in Section 6.3.7, all re-bars were properly cleaned and weighed before and after the period of exposure. The data obtained is illustrated in Figure 6.33 and presented in Appendix G.

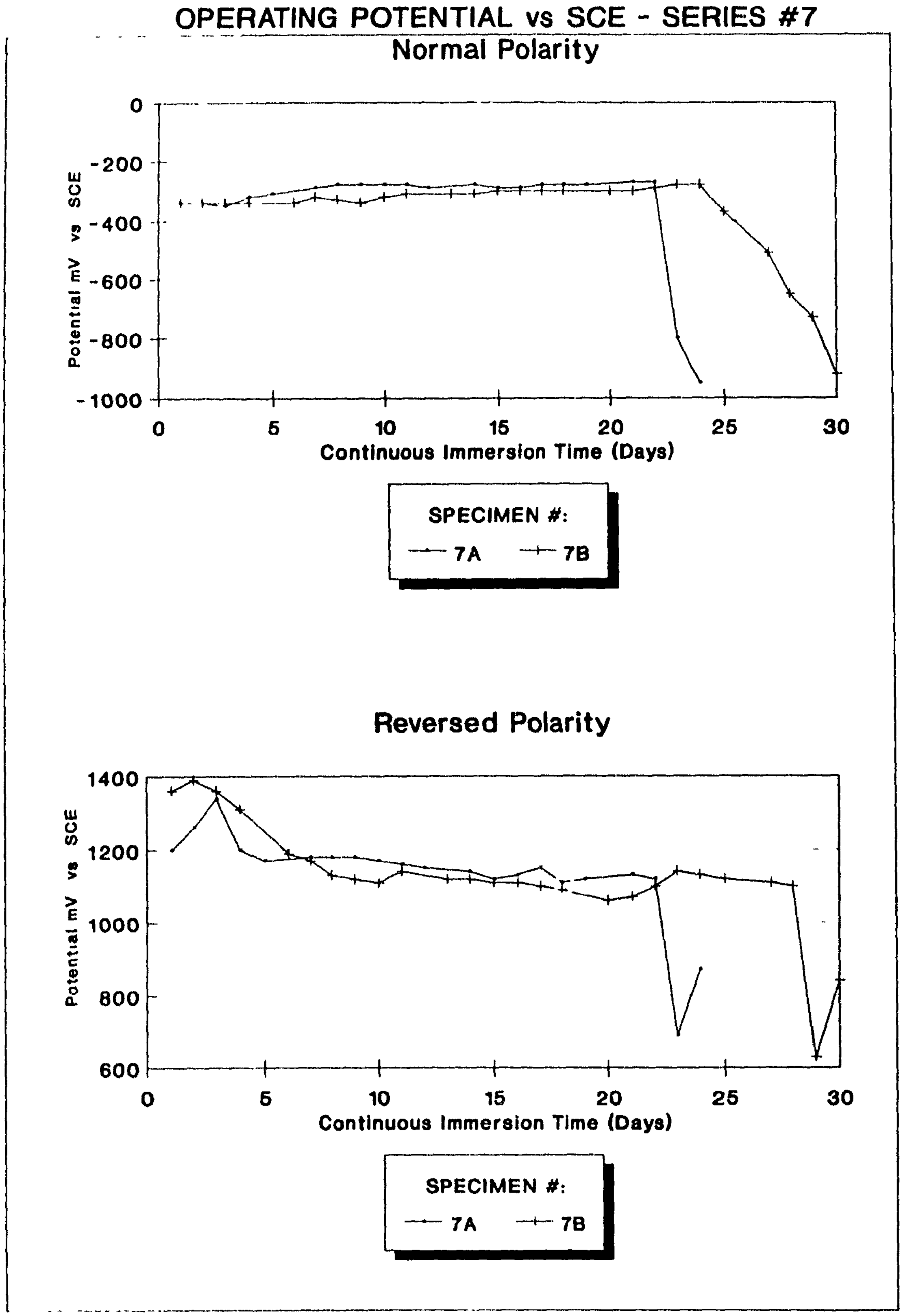
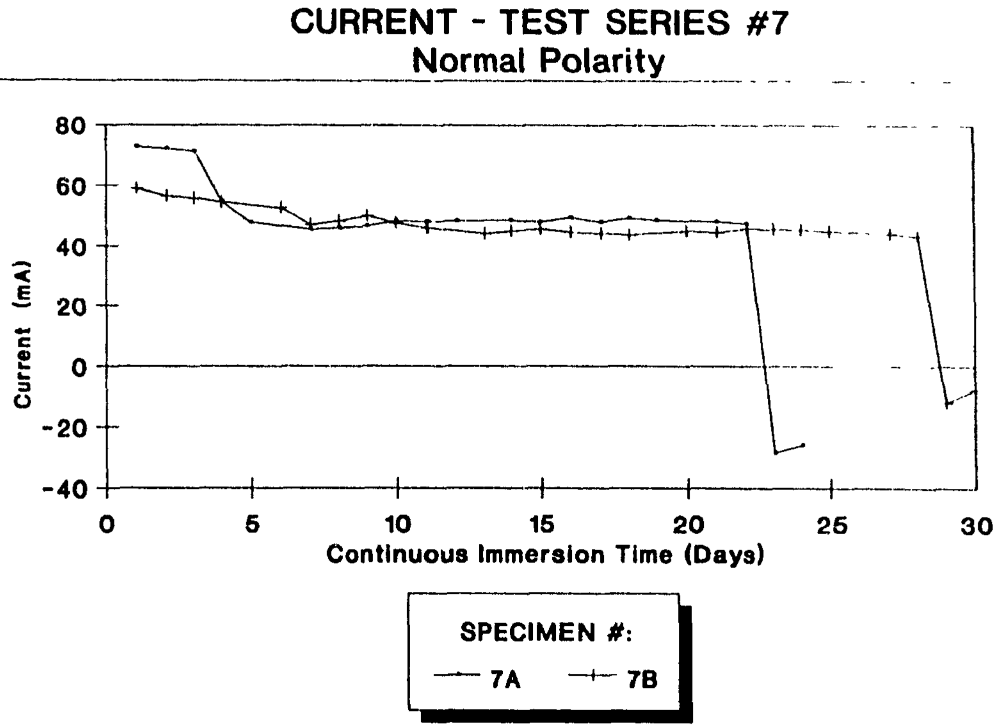


Figure 6.31: Operating Potentials
Bare Electrodes - Test Series #7



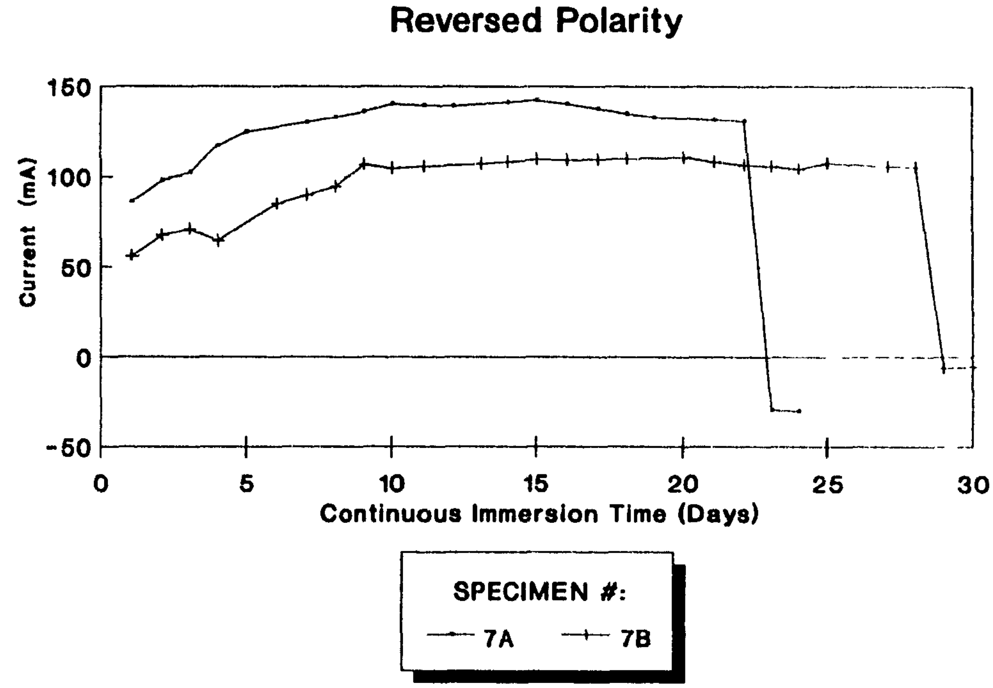


Figure 6.32: Current Flow
Bare Electrodes - Test Series #7

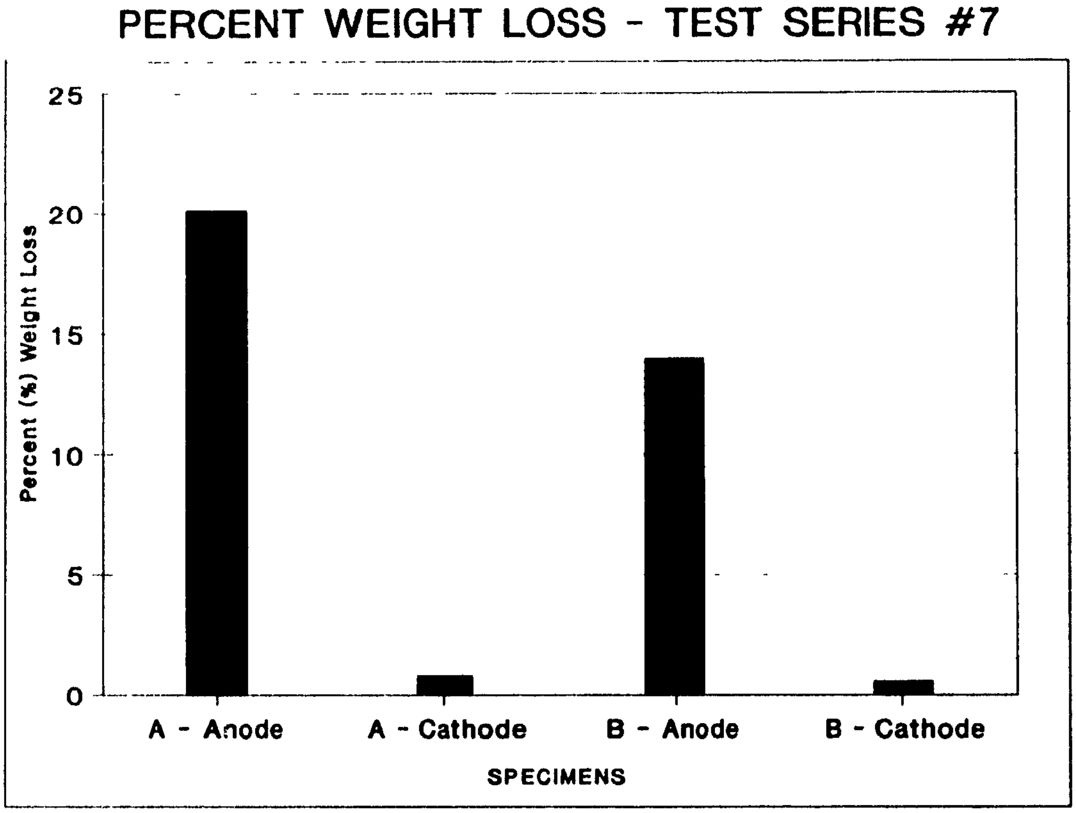


Figure 6.33: Percent Weight Loss
Specimens #7A and #7B

6.4.1.4 Tensile Strength Measurements

Both the anode and the cathode were tested for their tensile strengths. The yield and the ultimate stress characteristics were recorded and are presented in Appendix H. Figure 6.34 represents the stress variations determined for both electrodes.

6.4.2 Specimens #7C, #7D, and #7E

The lollipop specimens, acting as anodes in the normal polarity mode, had varying clear covers, whereas those acting as cathodes had the same depth of cover. Table 6.4 summarizes

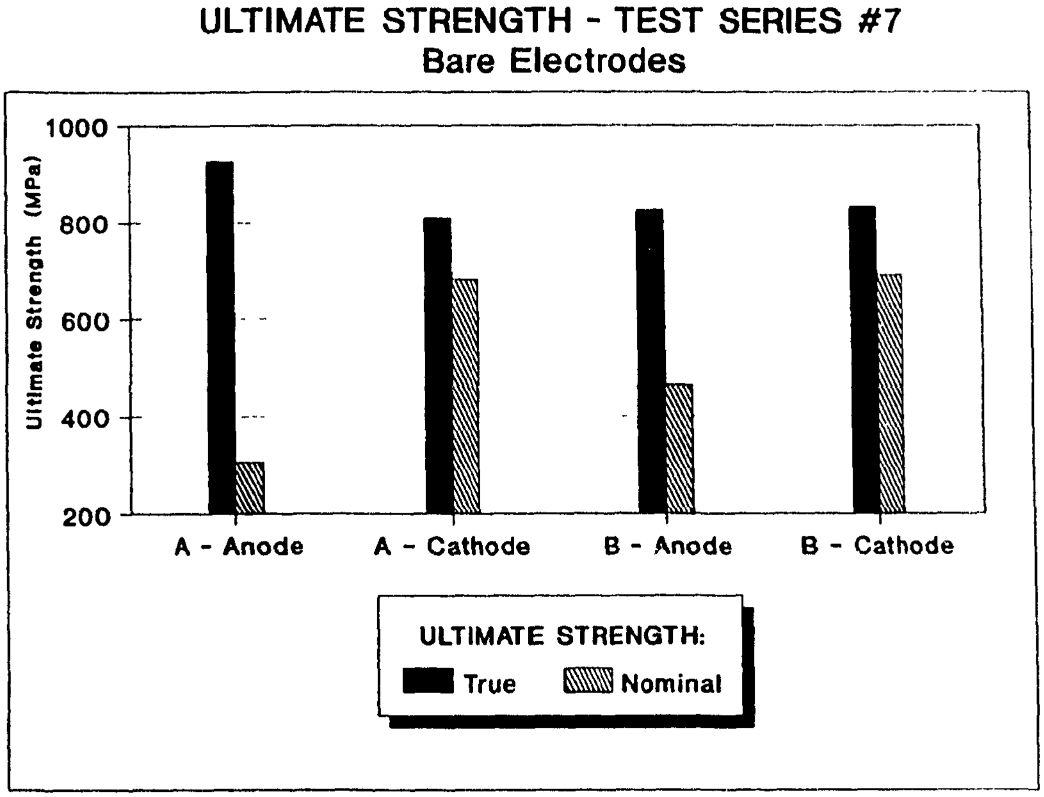


Figure 6.34: Ultimate Strength Variation Bare Electrodes - Test Series #7

NORMAL POLARITY MODE

SPECIMEN	LOLLIPOP - ANODE in. (mm)	LOLLIPOP - CATHODE in. (mm)
C	0-7/16 (11.11)	1-3/16 (30.16)
D	2-0 (50.80)	1-3/16 (30.16)
E	1-3/16 (30.16)	1-3/16 (30.16)

TABLE 6.4: Clear Depth Of Concrete Cover Specimens #7C, #7D, and #7E

the exact values used for each specimen. The duration of the testing period was 45 days and the strength of the electrolyte solution was 3.5% NaCl. The objective was to study the effect of varying clear covers of the anode while protecting the cathode re-bar with concrete.

6.4.2.1 Visual Observations

The lollipop anode specimen having the smallest cover (Specimen C) was the only one to exhibit any evidence of active corrosion through the formation of corrosion products. The other two specimens (Specimens D and E) displayed no signs of corrosion activity. Figures 6.35 to 6.37 illustrate the three specimens at the completion of the testing period.

6.4.2.2 Voltage and Current Measurements

Recordings of both potential and current readings were

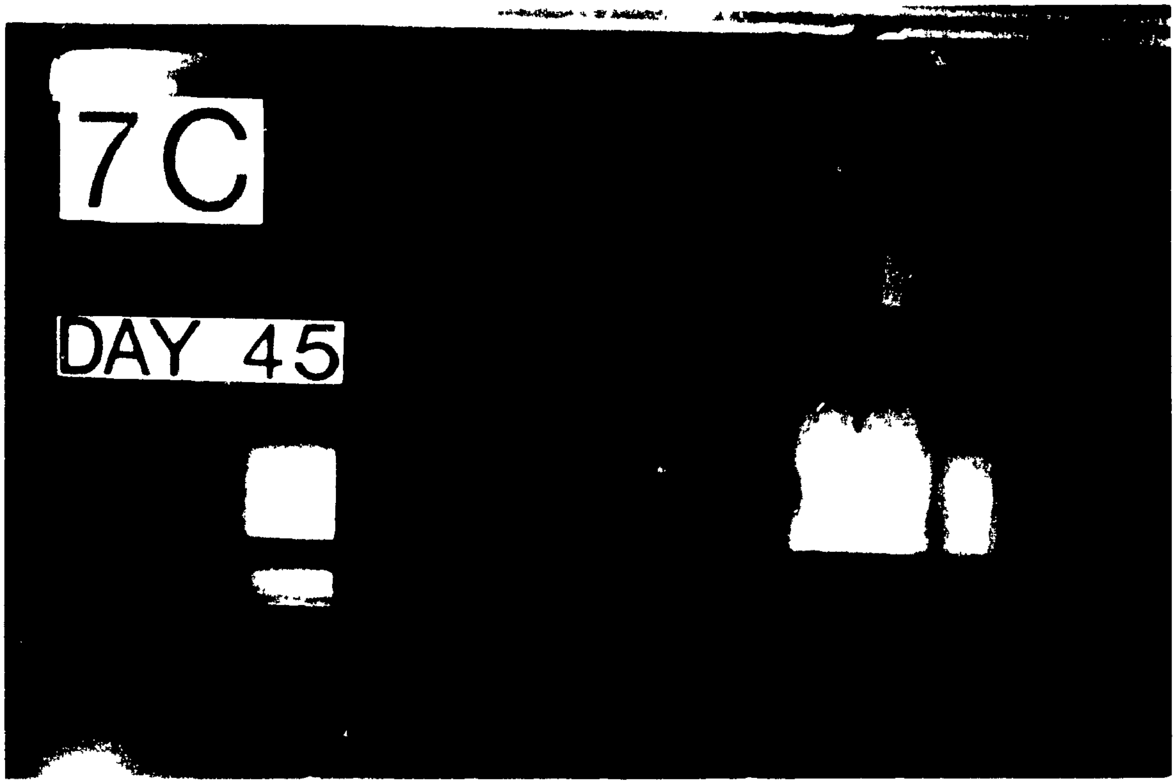


Figure 6.35: Experiment Specimen #7C (Day 45)
Anode Cover Thickness: 7/16 in. (11.1 mm)

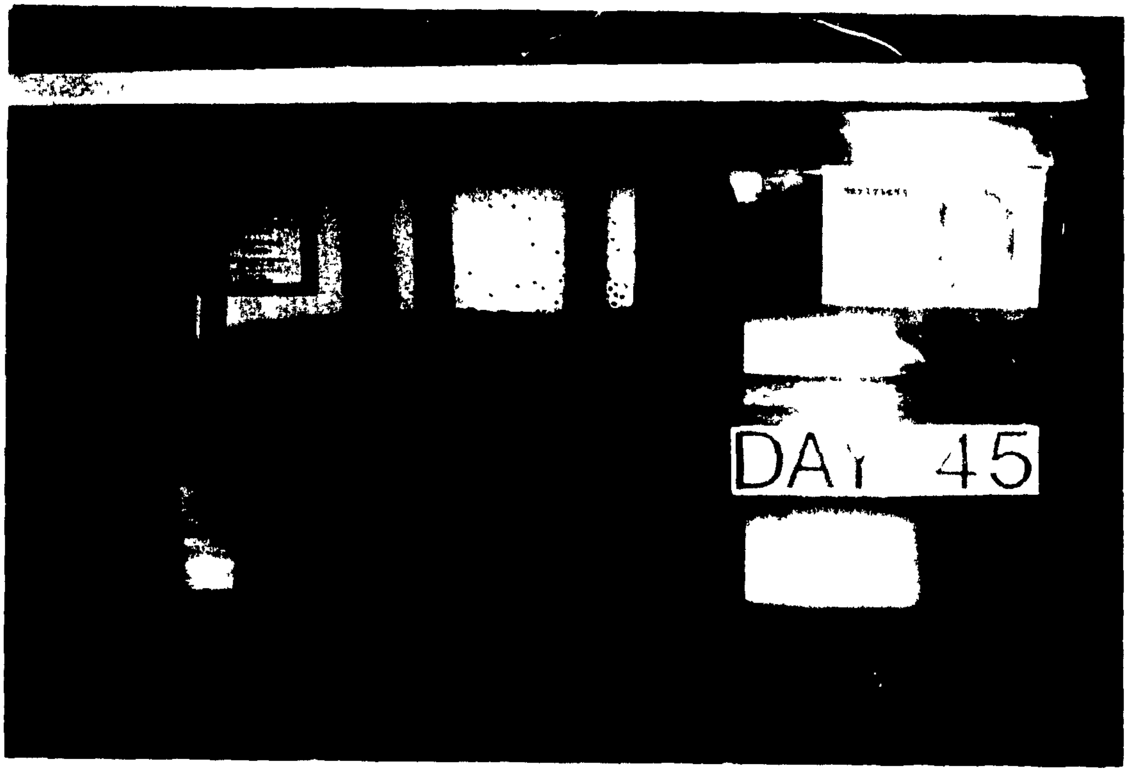


Figure 6.36: Experiment Specimen #7D (Day 45)
Anode Cover Thickness: 2 in.(50.8 mm)

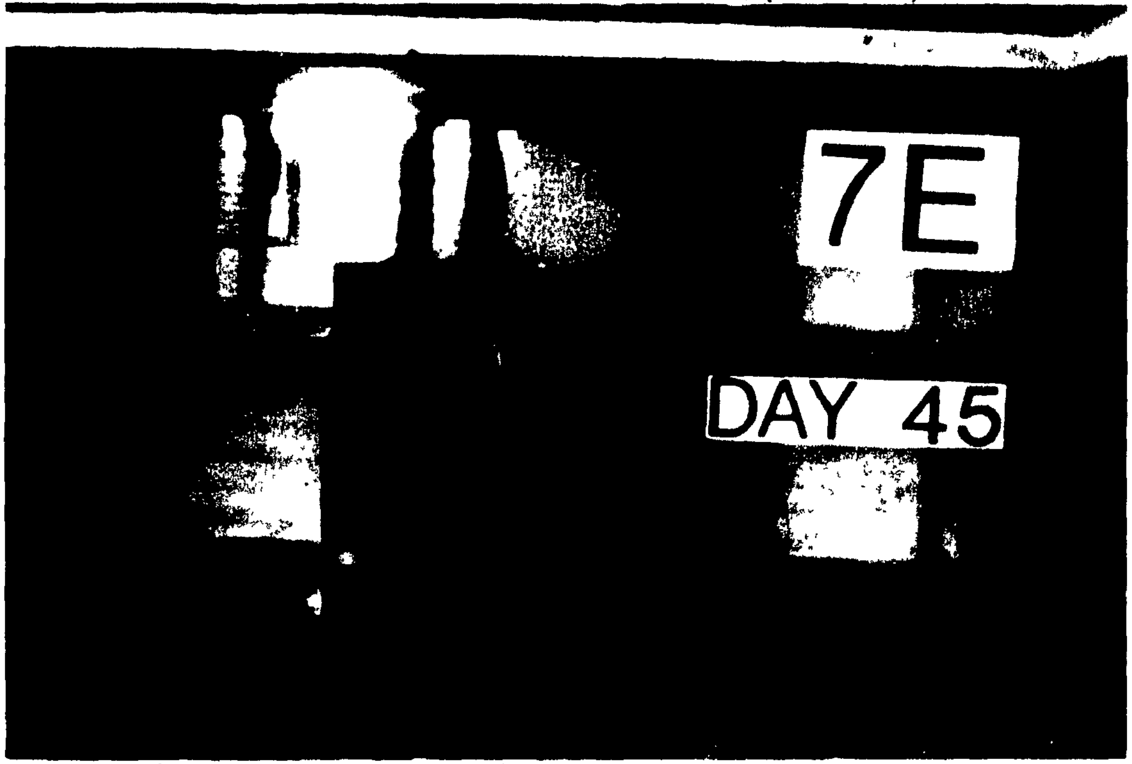


Figure 6.37: Experiment Specimen #7E (Day 45)
Anode Cover Thickness: 1-3/16 in.(30.2 mm)

taken throughout the testing period. This data can be found in Appendix R. The operating potentials versus the reference SCE are plotted in Figure 6.38, while the variations in current flow between the concrete-embedded electrodes are illustrated in Figure 6.39.

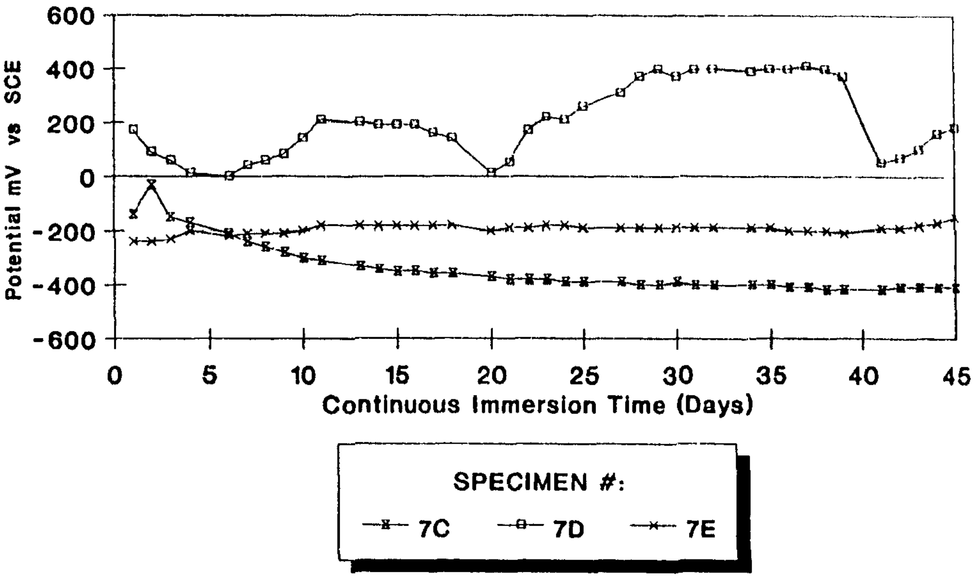
6.4.2.3 Reinforcement Mass Measurements

Measurements of the reinforcing bar weights were recorded and are presented in Appendix G. Figure 6.40 compares the percentage weight loss of each electrode used in the three set-ups.

6.4.2.4 Tensile Strength Measurements

To determine the load-carrying capabilities of the re-bars, tensile tests were performed on all the electrodes. Appendix H presents the data obtained from these tests (yield and ultimate stress characteristics). Comparisons between true and nominal ultimate stresses are shown in Figure 6.41.

OPERATING POTENTIAL vs SCE - SERIES #7
Varying Anode Clear Covers
Normal Polarity



Cathode Clear Cover= 1-3/16 in.(30.2 mm)
Reversed Polarity

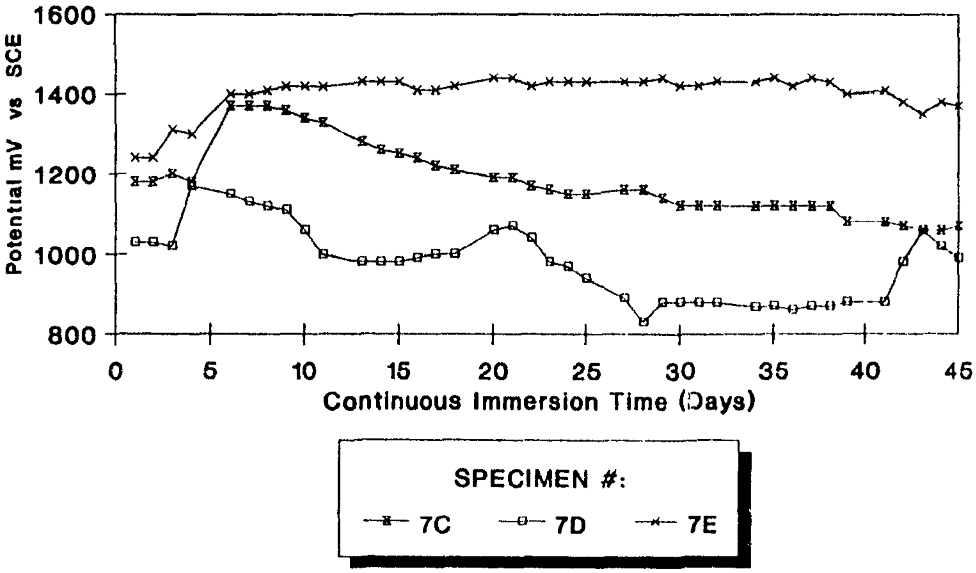
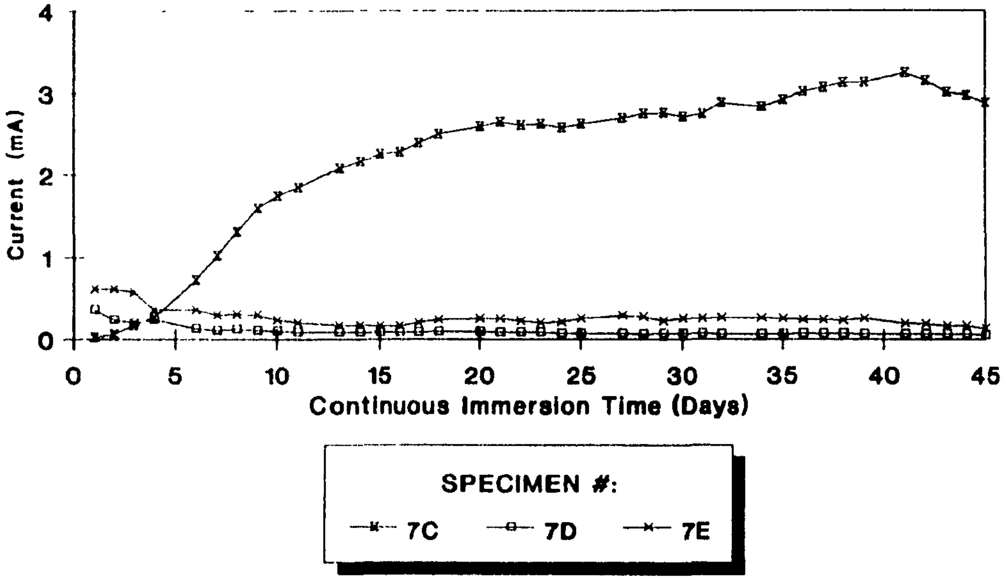


Figure 6.38: Operating Potentials
Concrete-Embedded Electrodes - Test Series #7

CURRENT - TEST SERIES #7
Varying Anode Clear Covers
Normal Polarity



Cathode Clear Cover= 1-3/16 in.(30.2 mm)
Reversed Polarity

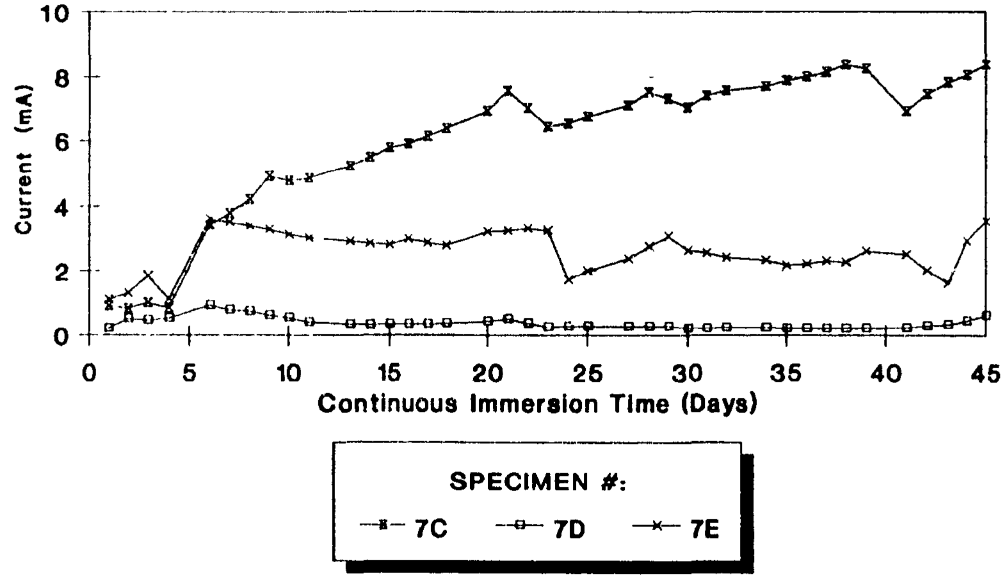


Figure 6.39: Current Flow
Concrete-Embedded Electrodes - Test Series #7

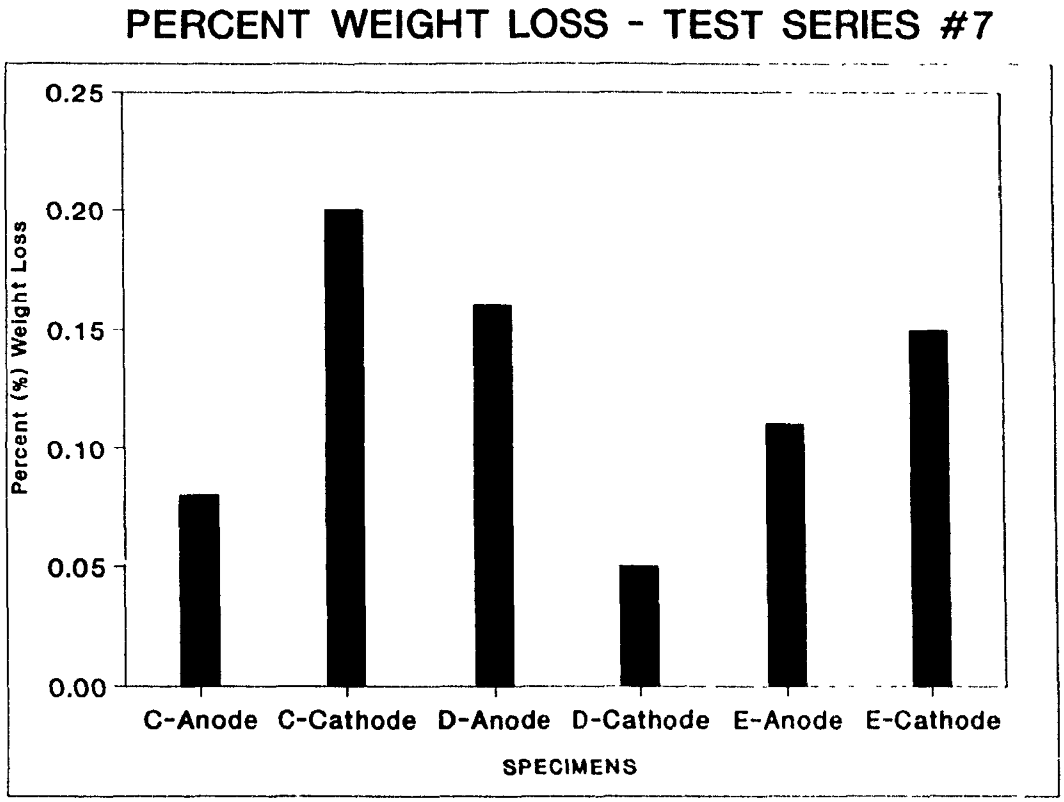


Figure 6.40: Percent Weight Loss
Specimens #7C, #7D, and #7E

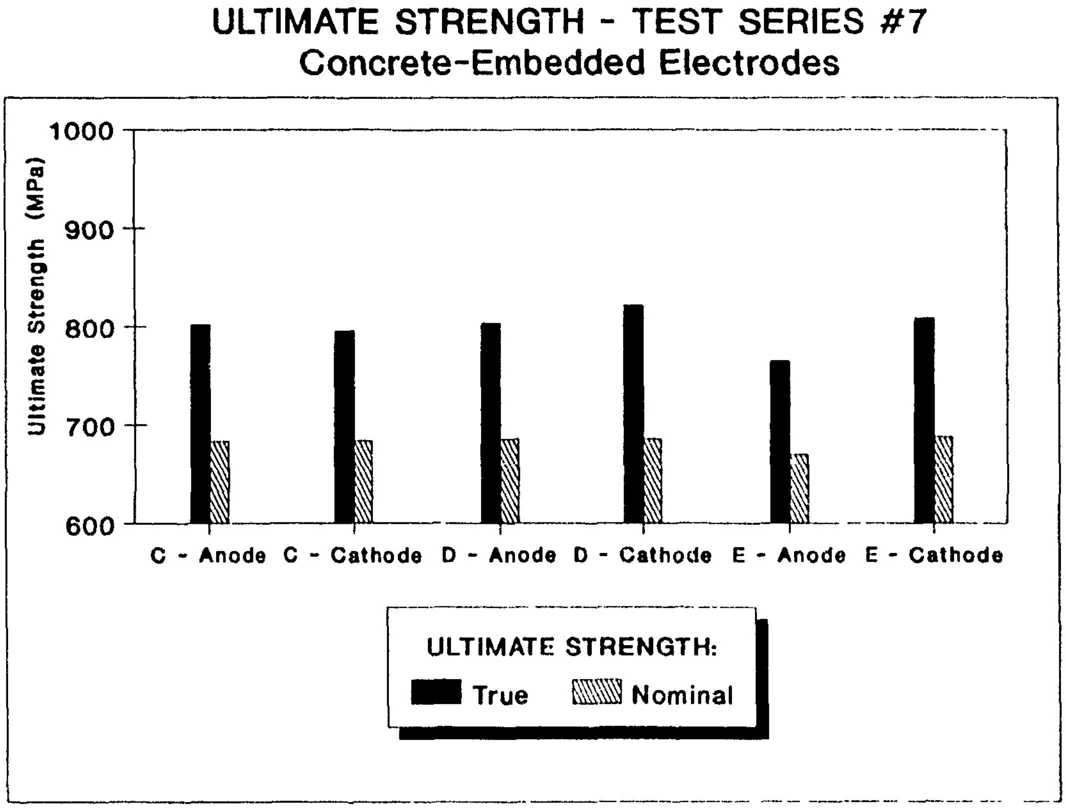


Figure 6.41: Ultimate Strength Variation
Concrete-Embedded Electrodes - Test Series #7

CHAPTER 7

ANALYSIS AND DISCUSSION

The main objective of this accelerated electrochemical corrosion testing program is to assess, both qualitatively and quantitatively, the effects of the clear depth of concrete cover on the level of corrosion activity. This was achieved mainly through Test Series #5, #6, and #7. The results presented in Chapter 6 are analyzed and discussed in this Chapter. In addition, several conclusions are drawn from these results and comparisons made with the previous experimental work of similar nature.

7.1 CORRELATION OF RESULTS

In order to analyze the results obtained for the three test series, comparisons must be made with similar experimental tests conducted previously. These are discussed in the following sections.

7.1.1 Electrode "Polarization" Resistance - R_p

From the measured voltage potentials and the current measurements recorded (see Appendices P, Q, and R), the resistance at each electrode can be computed for both the normal and reversed polarity positions. It is equal to the difference between the electrode operating and polarization potentials divided by the corresponding current.[15] Figures 7.1 to 7.5 illustrate the polarization resistance of the lollipop specimens of Series #5 and #6, whereas the resistances of the bare electrodes and of the concrete-embedded electrodes of Series #7 is shown in Figures 7.6 and 7.7.

7.1.1.1 Normal Polarity Position

In the normal polarity mode, the concrete-embedded electrode acts as an anode (connected to the positive terminal of the power supply). The current is interrupted until an essentially constant polarization potential E at that electrode is obtained. The chemical reaction is assumed to be that of the oxygen half-cell[15]:

$$2OH \rightleftarrows 1/2O_2 + H_2O + 2e^- \qquad (7.1)$$

The hydroxyl ions, OH^-, yield free oxygen and water. Under the continuous influence of the current discharge, this reaction may ultimately consume the alkalinity of the concrete at the steel surface, resulting in corrosion.

ELECTRODE RESISTANCE - TEST SERIES #5
Concrete-Embedded - Normal Polarity

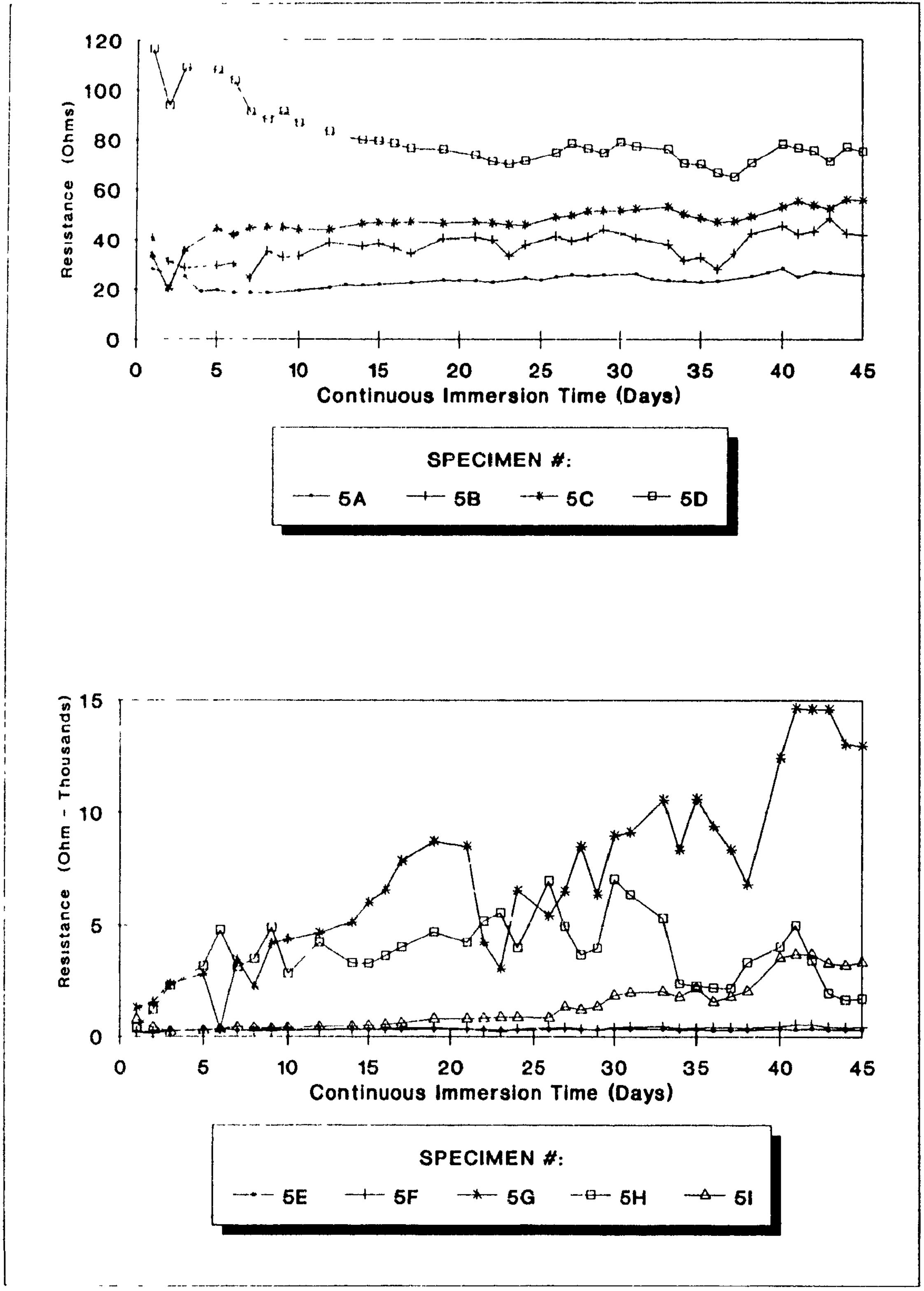


Figure 7.1: Electrode Resistance
Normal Polarity - Test Series #5

ELECTRODE RESISTANCE - TEST SERIES #5
Concrete-Embedded - Reversed Polarity

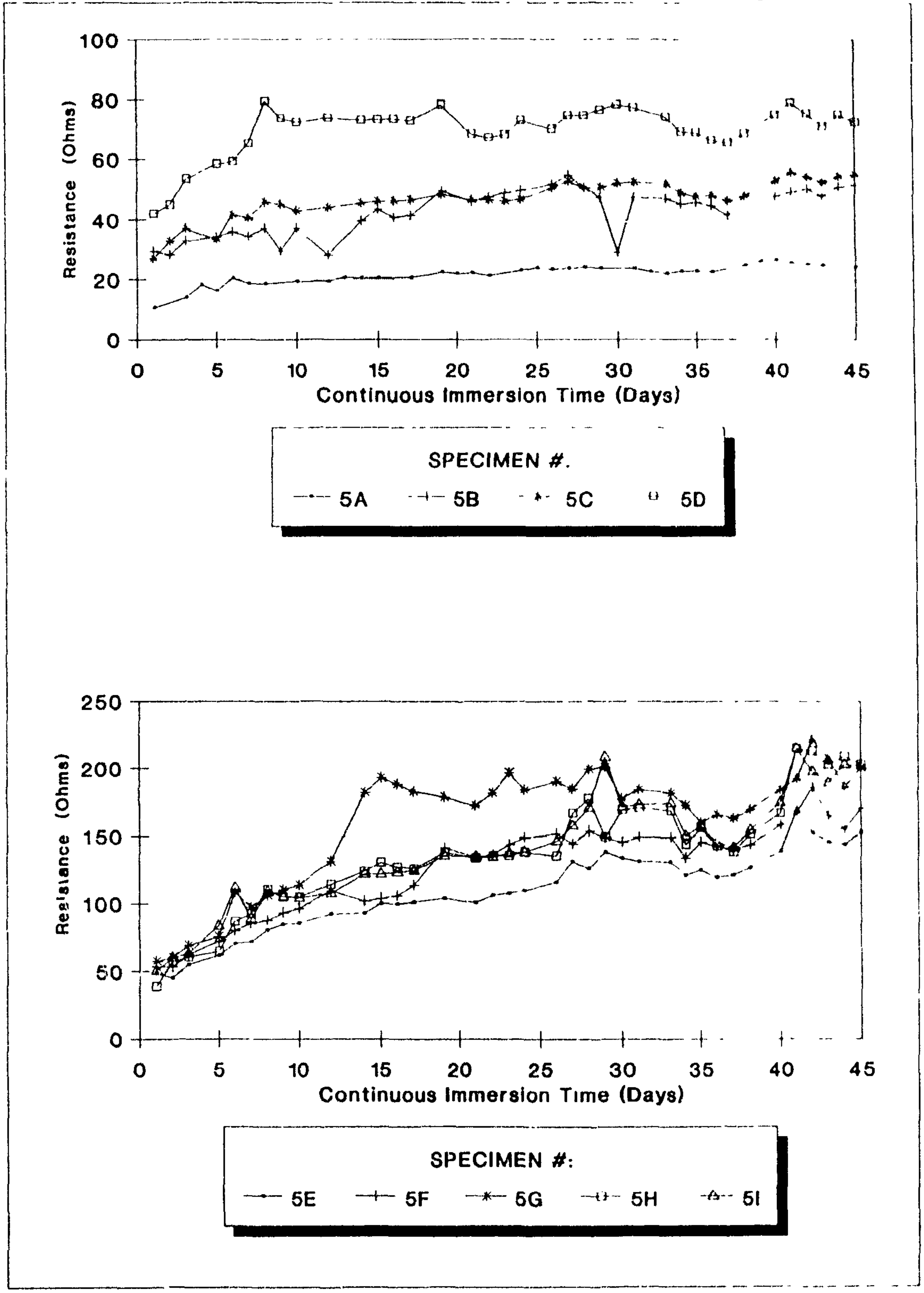


Figure 7.2: Electrode Resistance
Reversed Polarity - Test Series #5

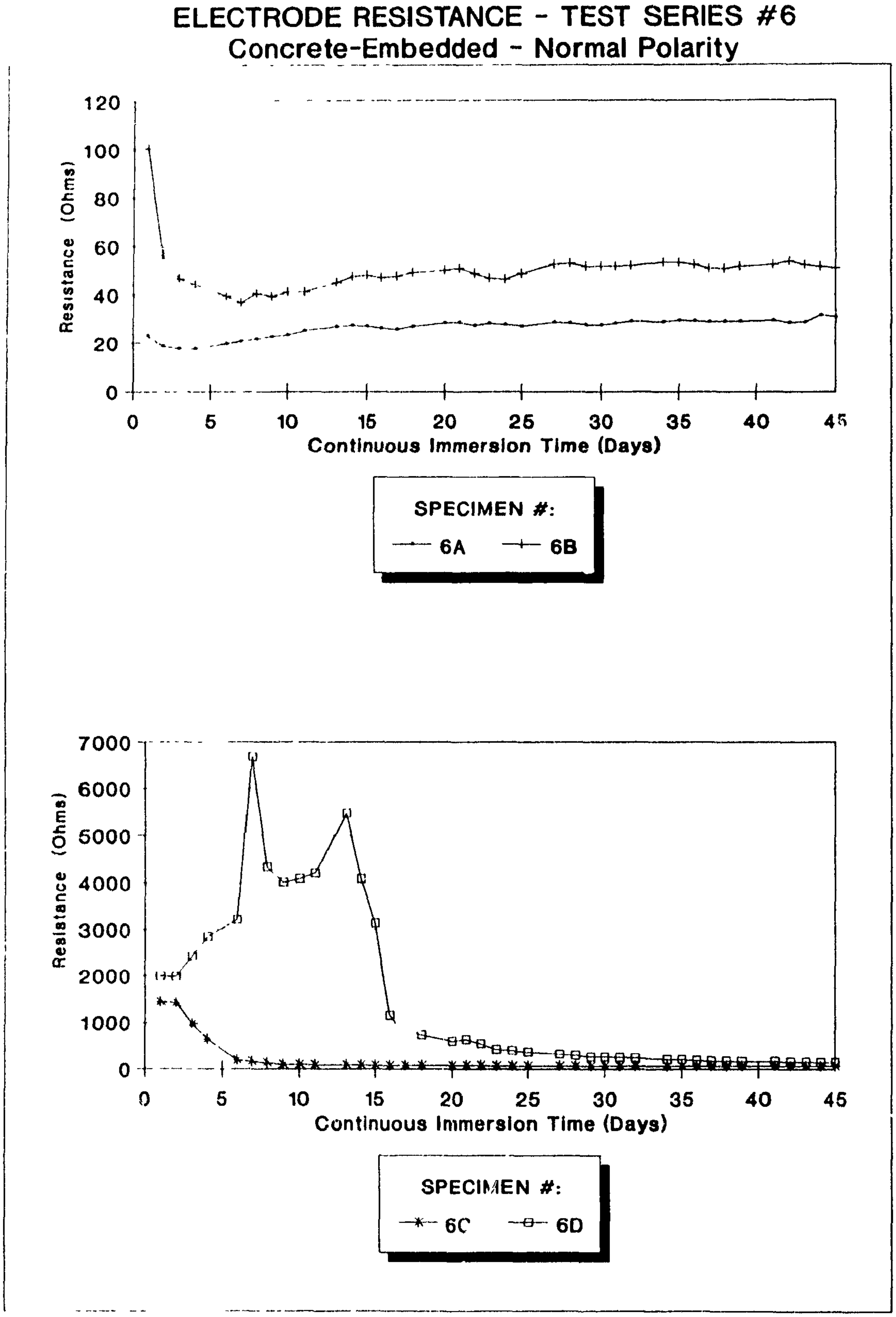


Figure 7.3: Electrode Resistance
Normal Polarity - Test Series #6

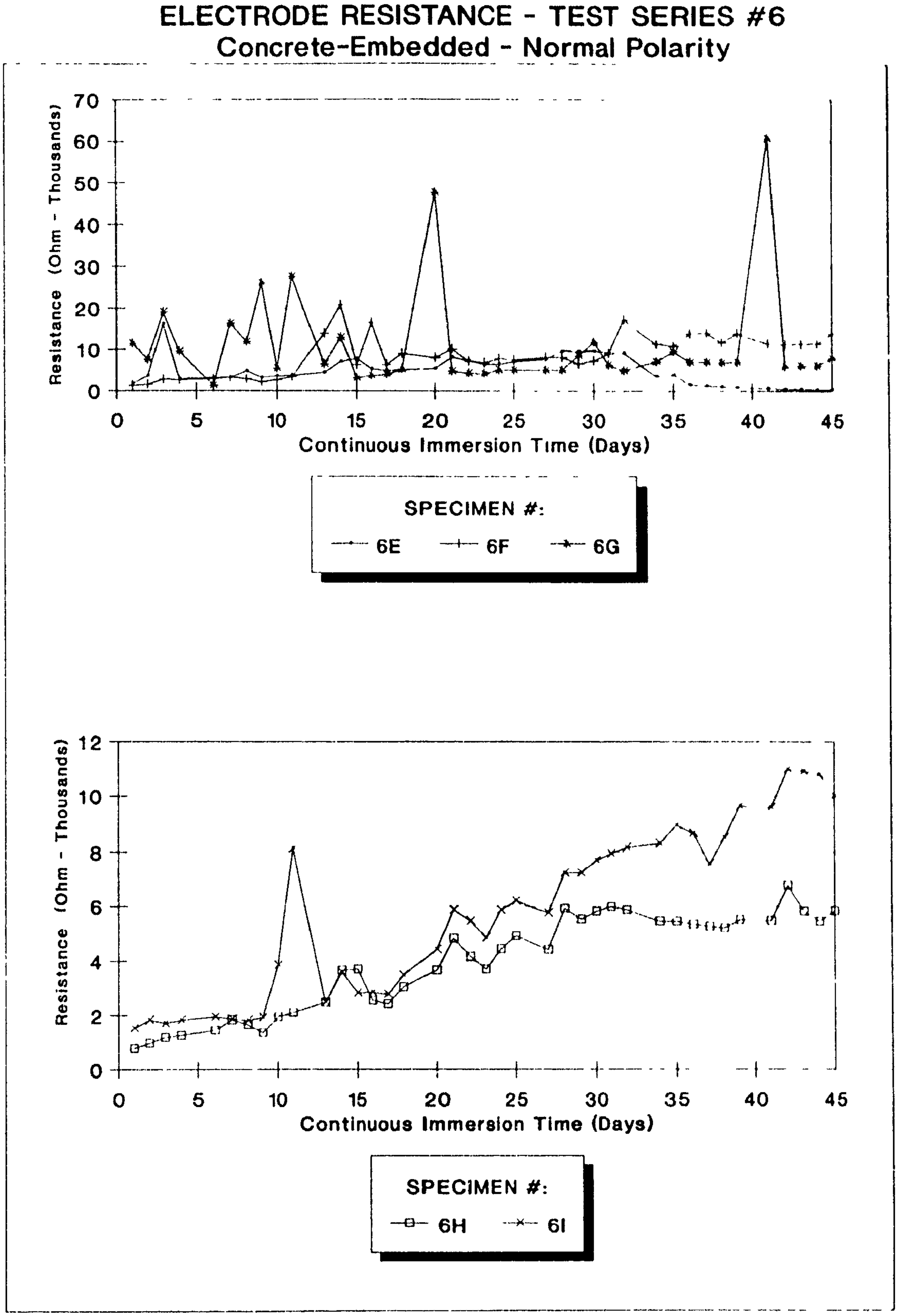
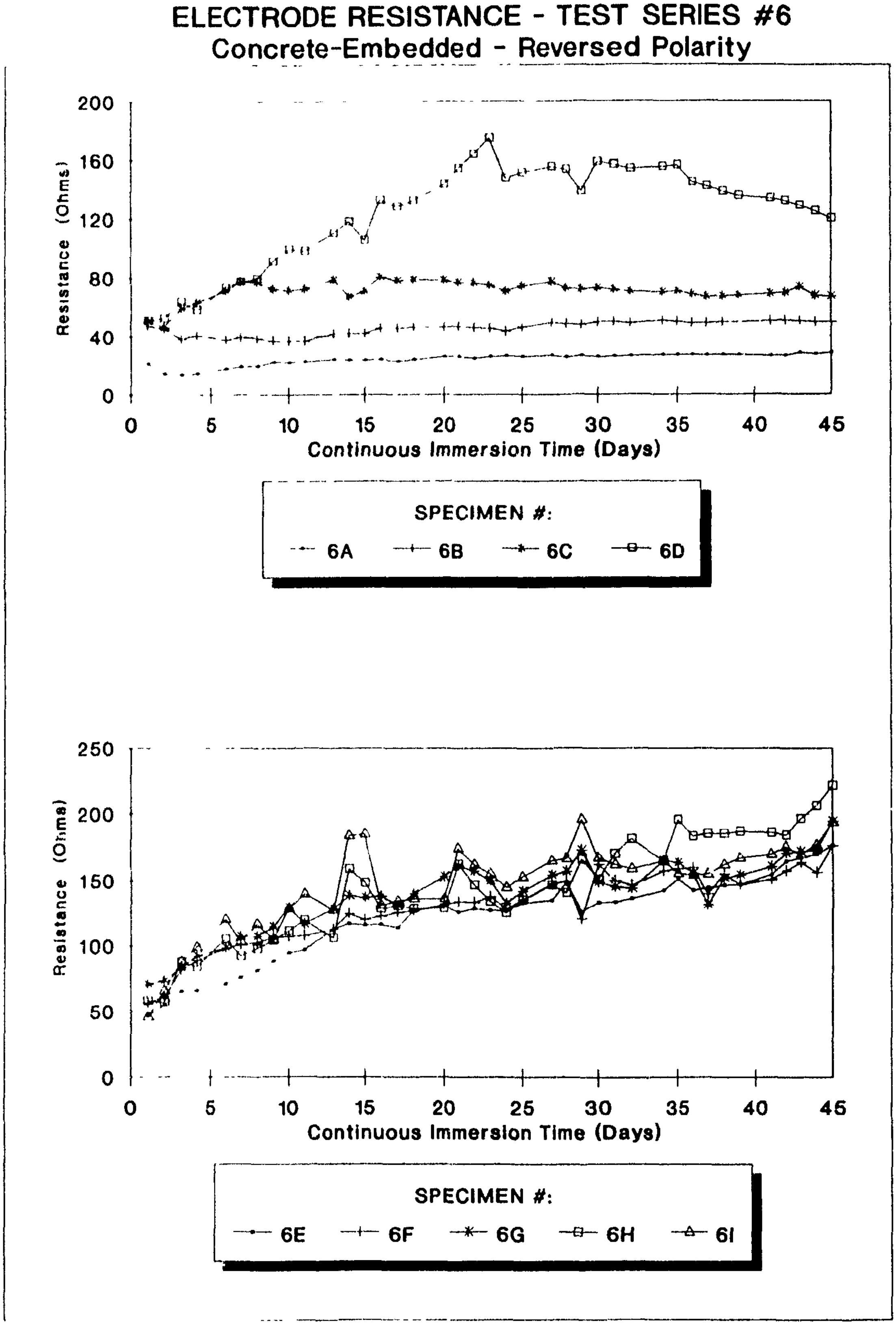


Figure 7.4: Electrode Resistance
Normal Polarity - Test Series #6

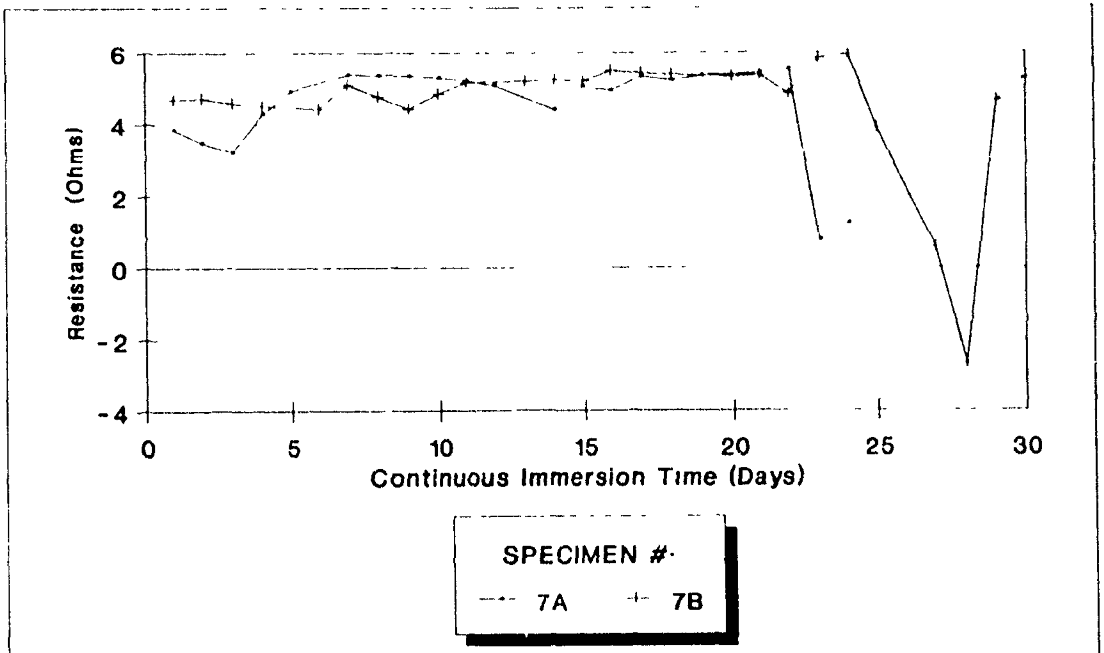


ELECTRODE RESISTANCE - TEST SERIES #6
Concrete-Embedded - Reversed Polarity

Figure 7.5: Electrode Resistance
Reversed Polarity - Test Series #6

ELECTRODE RESISTANCE - TEST SERIES #7

Bare Anode



Bare Cathode

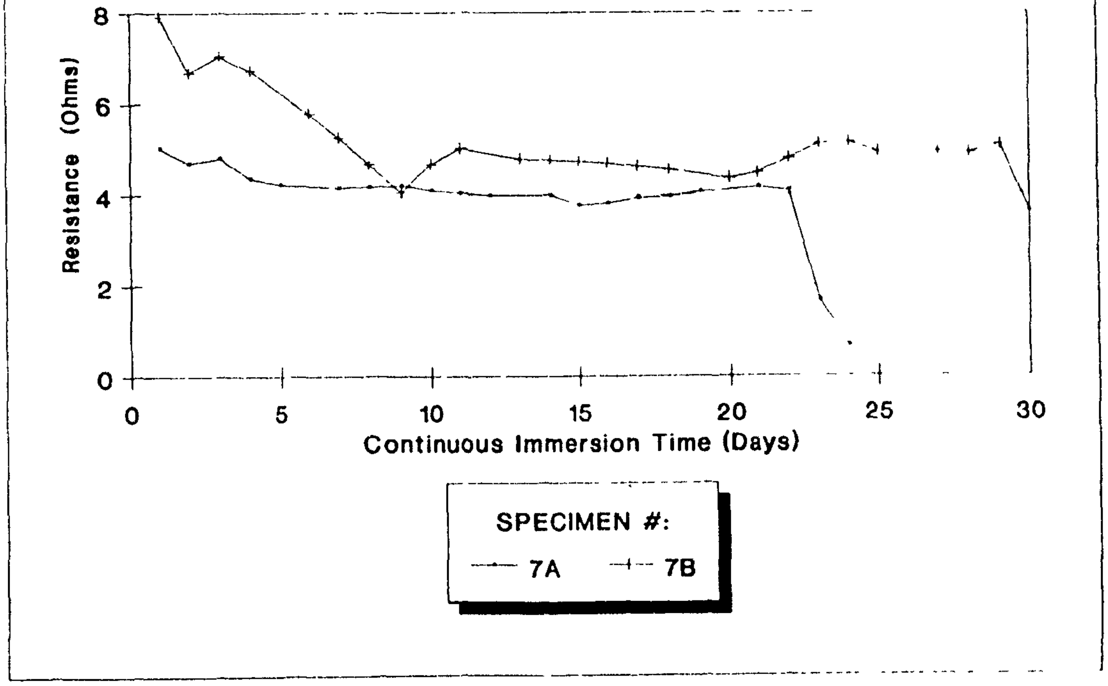
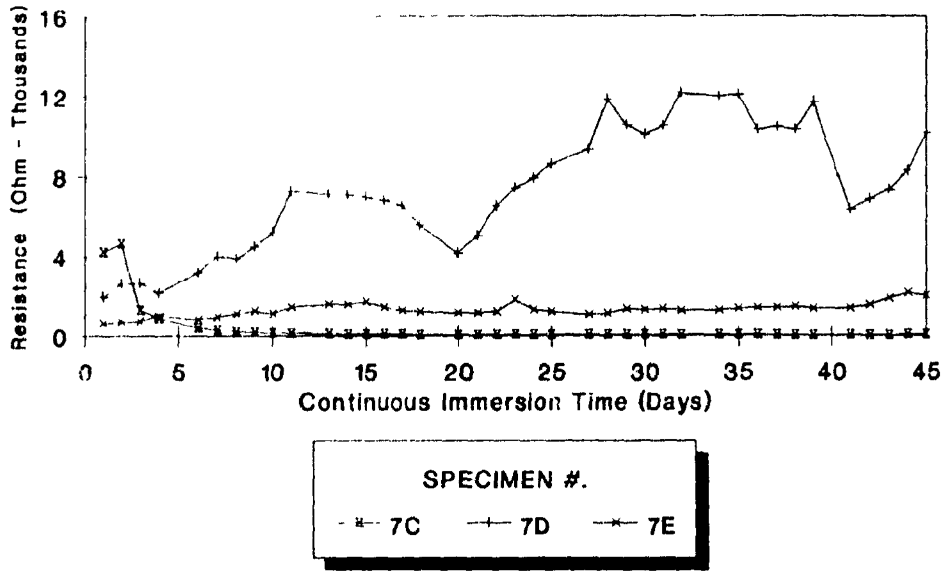
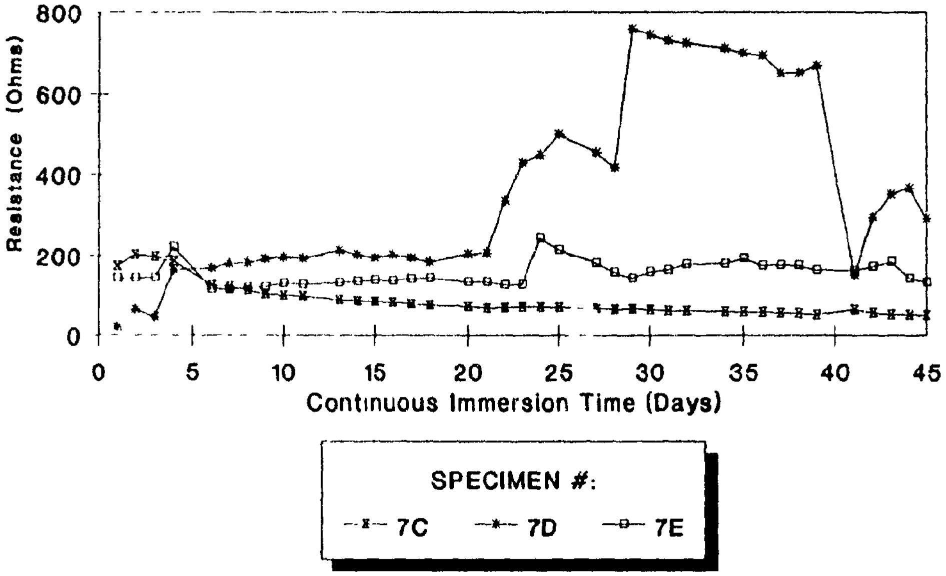


Figure 7.6: Electrode Resistance
Bare Electrodes - Test Series #7



ELECTRODE RESISTANCE - TEST SERIES #7
Varying Anode Clear Covers
Concrete-Embedded - Normal Polarity



Cathode Clear Cover= 1-3/16 in.(30.2 mm)
Concrete-Embedded - Reversed Polarity

Figure 7.7: Electrode Resistance
Concrete-Embedded Electrodes - Test Series #7

The oxygen half-cell potential with respect to the reference SCE is given by[15]:

$$E = -0.987 + 0.059\ \mathrm{pH} - 0.015 \log O_2 \quad \text{volts} \tag{7.2}$$

Assuming that oxygen gas is evolved at atmospheric pressure, then;

$$\log O_2 = \log 1 = 0 \tag{7.3}$$

Therefore, the half-cell potential equation becomes[15]:

$$E = -0.987 + 0.059\ \mathrm{pH} \tag{7.4}$$

For each of the polarization potentials recorded, the pH value at the steel surface can be calculated. The variations in the pH values are presented in Appendix I.

7.1.1.2 Reversed Polarity Position

In the reversed mode, the concrete-coated electrode exhibits cathodic characteristics and behaves similar to a hydrogen half-cell at a pH value approximately that of the surrounding concrete. The reaction occurring at the metal surface consists of the electrolysis of water and evolution of hydrogen gas according to the following equation[15]:

$$2H_2O + 2e^- \rightleftarrows H_2 + 2OH^- \tag{7.5}$$

The potential for this half reaction with respect to the reference SCE is[15]:

$$E = 0.242 + 0.059\ \mathrm{pH} + 0.030 \log H_2 \quad \text{volts} \tag{7.6}$$

Assuming that hydrogen is evolved at atmospheric pressure;

$$\log H_2 = \log 1 = 0 \tag{7.7}$$

Therefore, the half-cell potential equation becomes[15]:

$$E = 0.242 + 0.059\ \mathrm{pH} \tag{7.8}$$

Appendix I presents the pH values obtained for the various tests, indicating the variations at the steel surface.

7.1.2 Effect of Immersion Time on Corrosion

The effect of the immersion period, along with the impressed voltage of 1 V, on each specimen can be determined based on the resistance offered. For each "system", this can be calculated as follows:

$$R = \frac{V}{I} \tag{7.9}$$

where R = resistance provided by the electrode specimen
I = current measurement between electrodes
V = voltage measurement between electrodes

The reciprocal of the resistance, i.e. I/V, is plotted versus the immersion time. Figure 7.8 illustrates this for specimens A of Series #5 and #6 for both polarity positions. The graphs revealing the effect of immersion time on corrosion for the other systems are included in Appendix J.

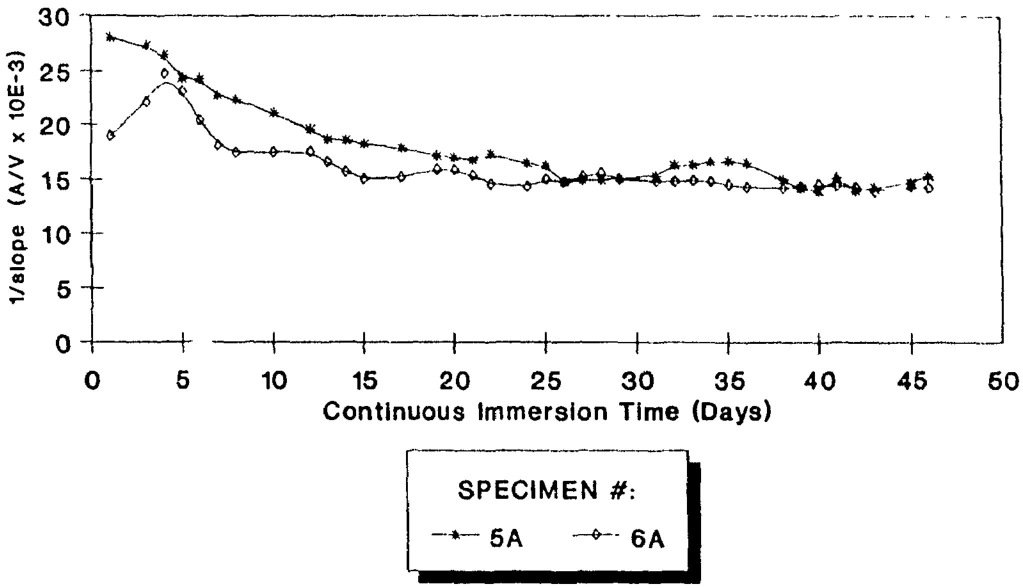
7.1.3 Corrosion Current - i_{corr}

The corrosion current i_{corr} is an indicator of the level of reinforcement corrosion activity. This nominal current can be calculated by applying the Stern-Geary equation[61]:

$$i_{corr} = \frac{B}{R_p} \tag{7.10}$$

EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 5/16 in.(7.9 mm)

Normal Polarity



Reversed Polarity

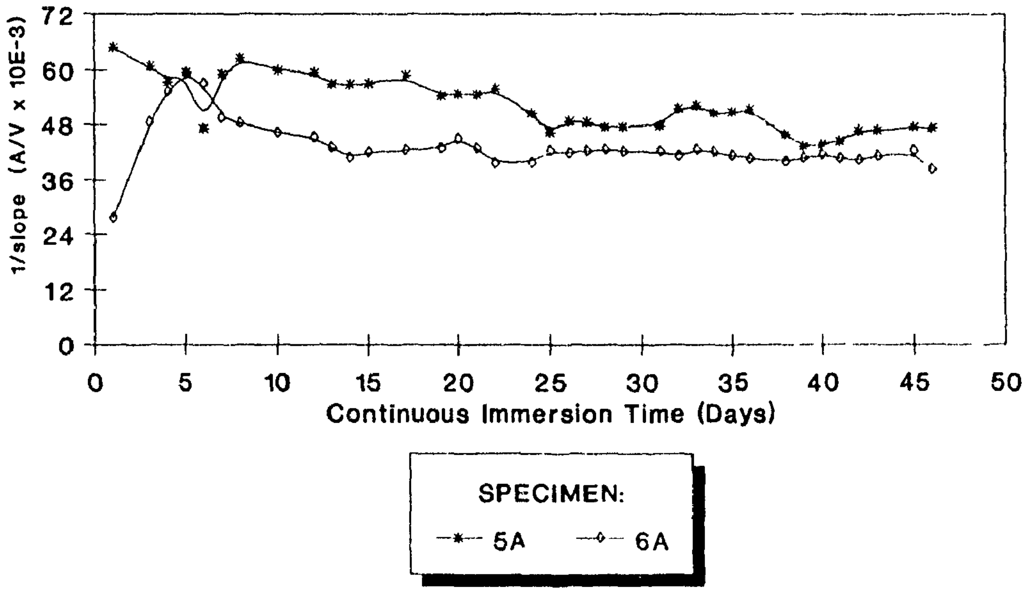


Figure 7.8: Specimens #5A and #6A
Effect of Immersion Time on Corrosion

where i_{corr} = corrosion current ($\mu A/cm^2$)

B = corrosion constant (assumed to be 26 mV for active iron)

R_p = polarization resistance (ohms)

The corrosion current can be calculated for every polarization resistance determined (see Section 7.1.1). The corrosion current for one of the test series (#5) is shown in Figure 7.9. Appendix K presents the graphs of the current variations for the remainder of the specimens.

7.1.4 Electrical Conductance - G

The electrical conductance G is a parameter indicating the ease of electrical flow through a substance or its solution. In this case, it describes the ease of passage of the current through a concrete-embedded steel medium. Thus, the electrical conductance can be calculated by taking the reciprocal of the polarization resistance, $1/R_p$ (units 1/ohms). The logarithm of the conductance, log G, is plotted versus immersion time in Figure 7.10. The conductance for each experimental specimen is summarized in Appendix L.

7.1.5 Oxidation Rate

The three test series provided the means of comparing different ways to evaluate the severity of the corrosion activity. A reliable indicator of the onset of steel corrosion are electrode operating potentials versus reference SCE. Nevertheless, these do not provide a means of measuring

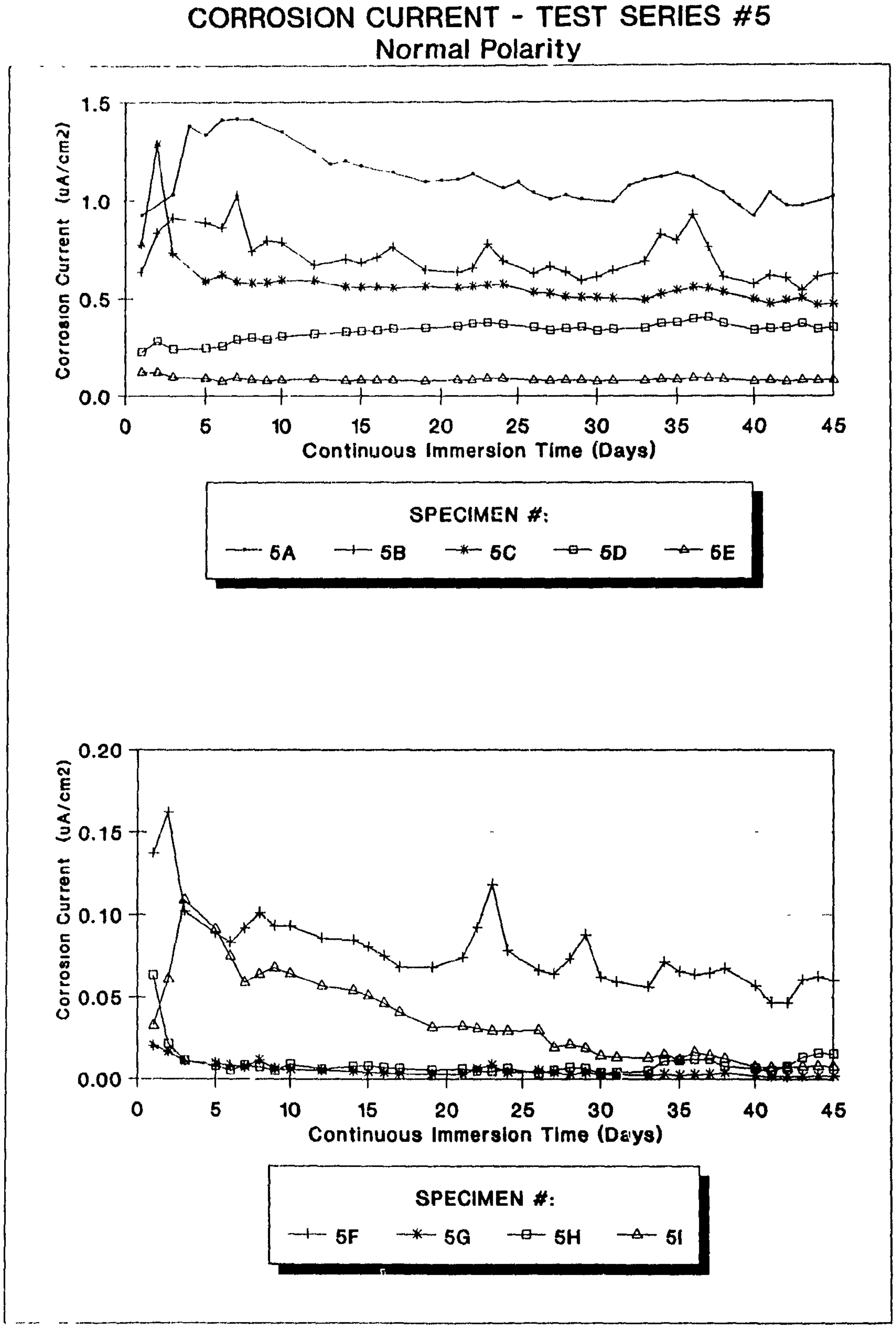


Figure 7.9: Corrosion Current
Normal Polarity - Test Series #5

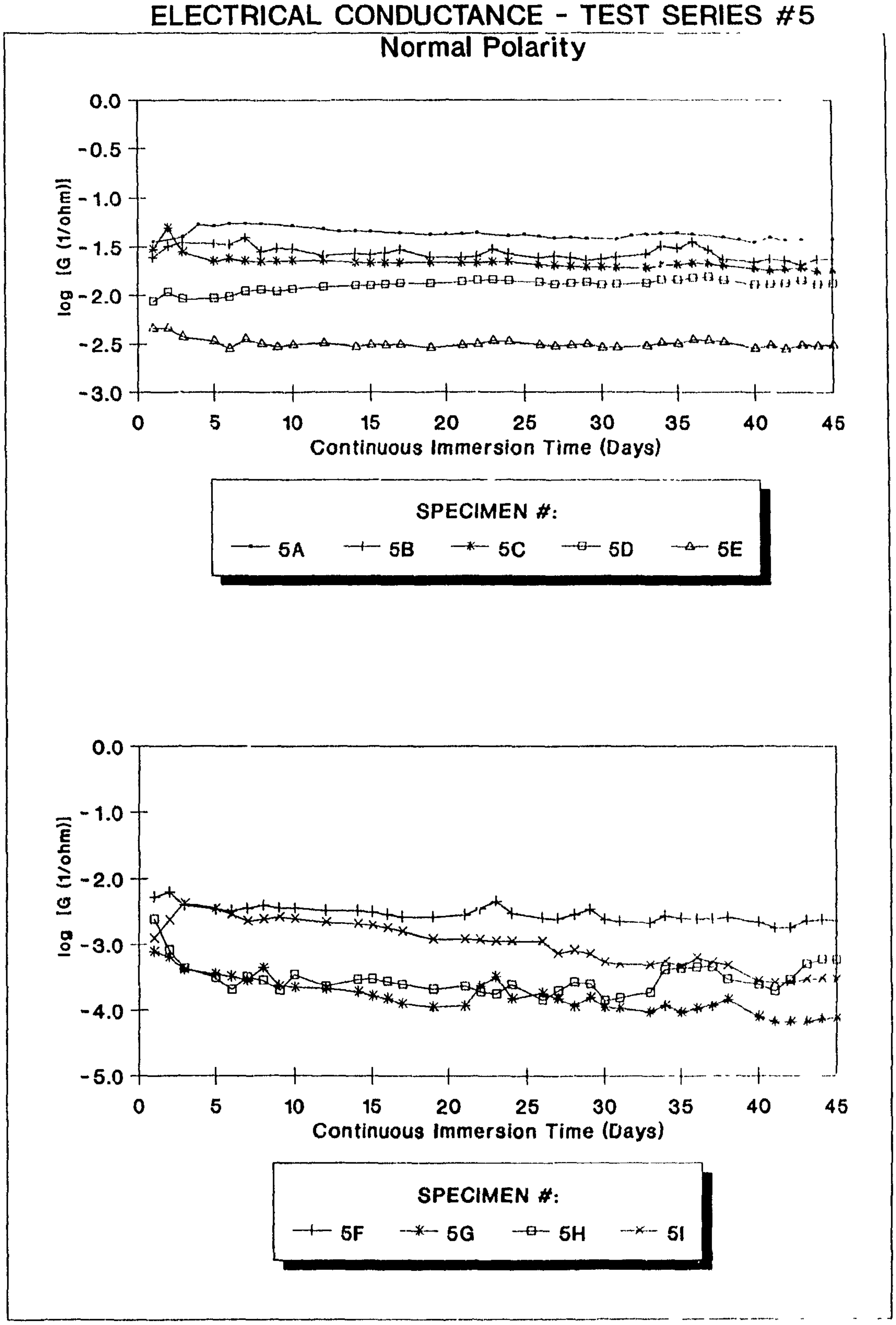


Figure 7.10: Electrical Conductance
Normal Polarity - Test Series #5

quantitacively the possible loss of metal. Since the main electrochemical reaction occurring at the concrete-embedded anodes is oxygen reduction, a metal calculation rate can be determined according to the following equation[61]:

$$\frac{dw}{dt} = \frac{I*M_w}{n*F} \tag{7.11}$$

where dw/dt = iron oxidation rate (g/sec)

M_w = molar weight of iron (55.847 g/mol)

n = oxidation state (assumed to be +2)

F = Faraday's constant ($9.648 \cdot 10^4$ Coulombs/mol)

Both the maximum and minimum values of current, as well as the average value, are used to determine the maximum, minimum, and average iron oxidation rates for the concrete-embedded electrodes of every specimen (see Appendix M). By multiplying the average oxidation rate by the duration of the immersion period (45 days), the average mass loss of the concrete-embedded steel re-bar can be obtained (see Appendix M). A direct comparison is made between the calculated and the gravimetric (measured) mass loss (see Figures 7.11 and 7.12). The iron oxidation rate equation can be applied to both concrete-embedded end/or bare steel electrodes.

7.1.6 Other Relations

7.1.6.1 Corrosion Current i_{corr} versus Resistance

The relationship between the corrosion current i_{corr} and the polarization resistance R_p offered by the steel electrodes embedded within the concrete will be studied in this section.

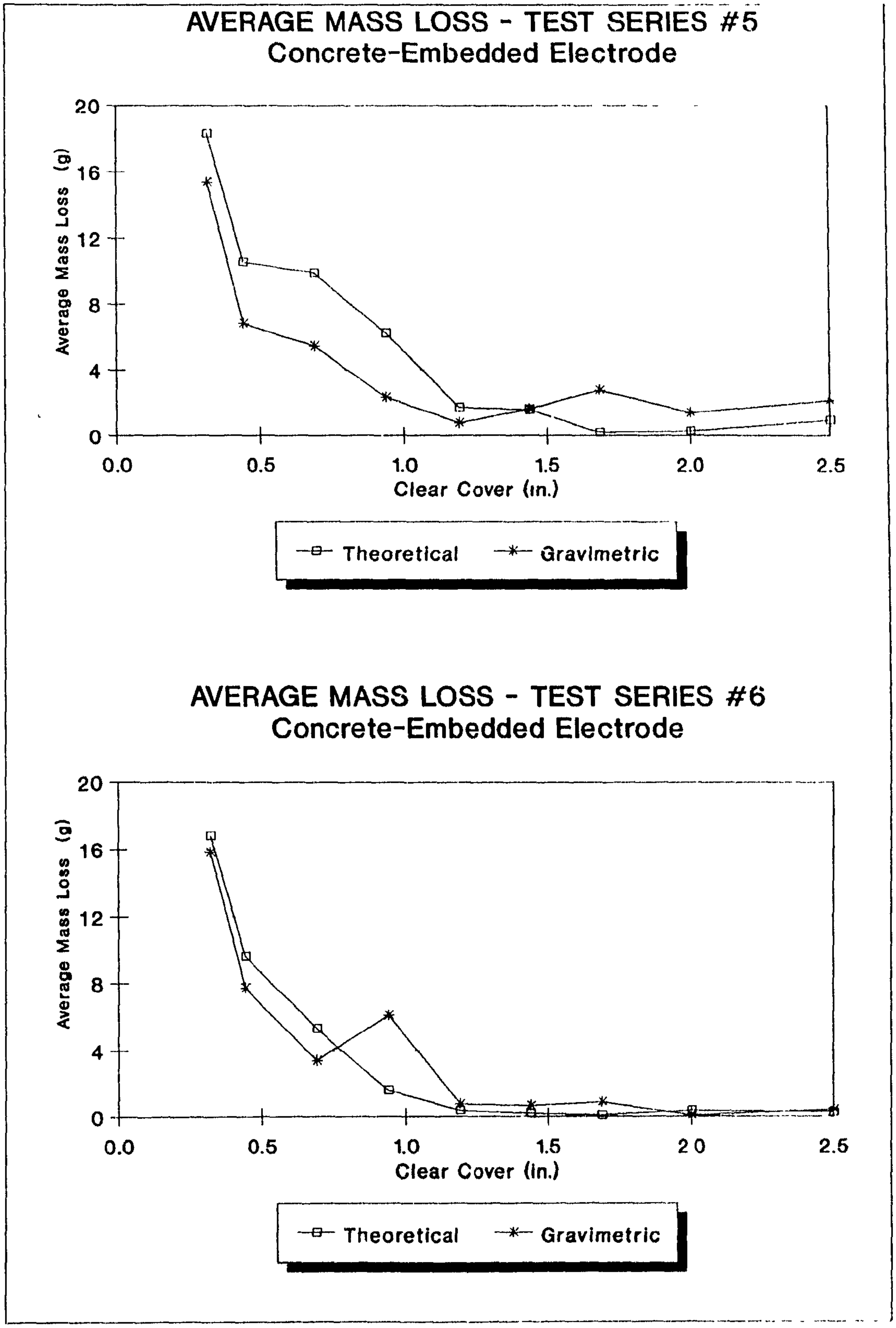


Figure 7.11: Test Series #5 and #6
Theoretical versus Gravimetric Mass Loss

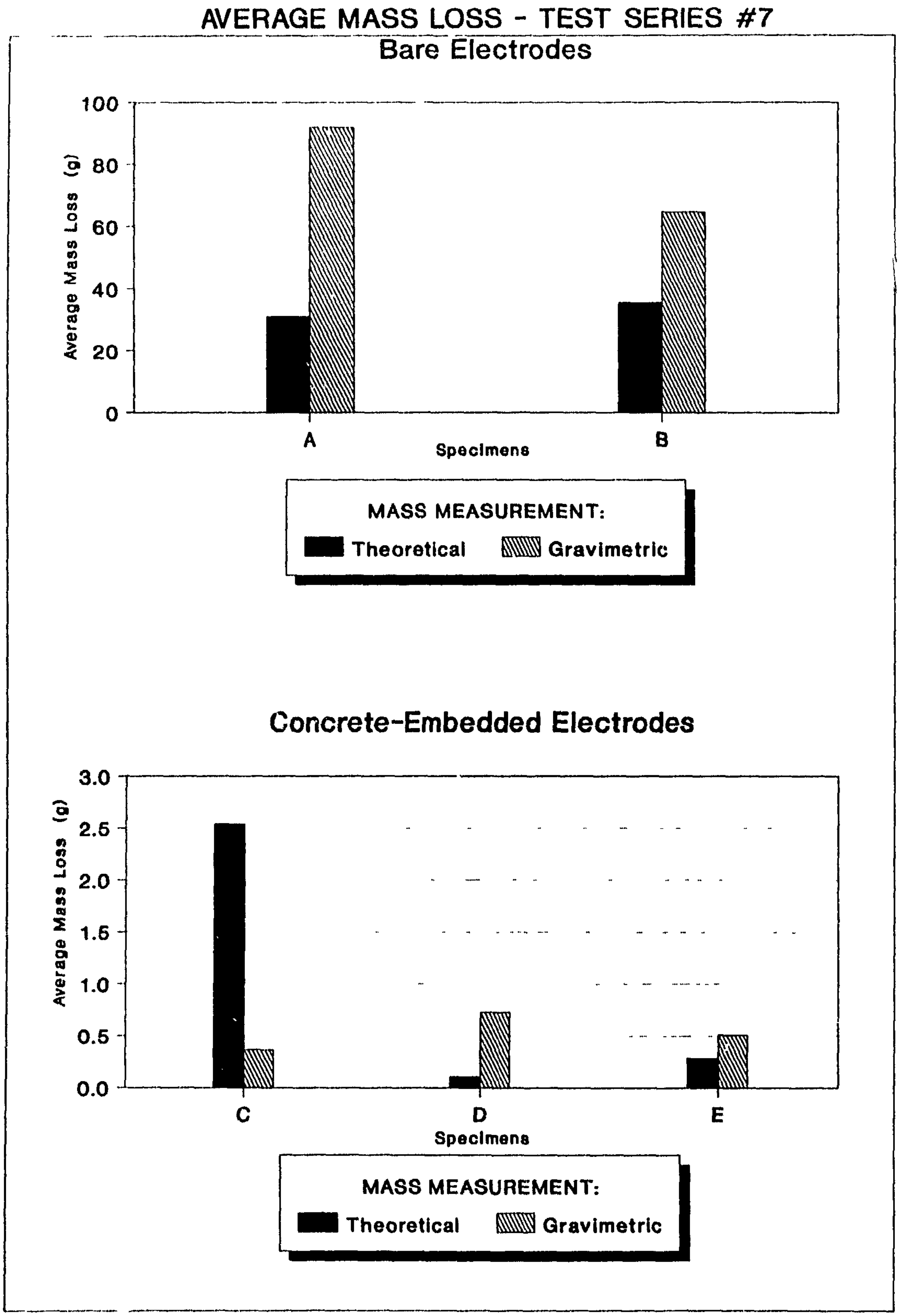


Figure 7.12: Test Series #7
Theoretical versus Gravimetric Mass Loss

Appropriate corrosion current (i_{corr}) - electrode polarization resistance (R_p) results were plotted for each of the specimens and for both polarity positions (see Appendix N). For depths of concrete cover thickness up to and including 1-3/16 in. (30.2 mm), for Specimens A to E in Test Series No.5 and No.6, there exists an inversely proportional relationship between the corrosion current and the electrode polarization resistance. An increase in the corrosion current is accompanied by a corresponding decrease in the polarization resistance of the concrete-embedded specimen.

For depths of clear cover exceeding 1-3/16 in. (30.2 mm), for Specimens F to I in Test Series No.5 and No.6, the relationship between the two parameters is non-linear. An increase in the corrosion current is accompanied by a rapid exponential decrease in the polarization resistance. This is due to the fact that the concrete offers high initial resistance, approximately a few thousand ohms, and the sharp decrease occurs only when a sufficient amount of corrosion current is allowed to flow through the system. This reflects the decrease in resistivity of the surrounding concrete and thus, an accompanying increase in the corrosion activity.

7.1.6.2 Mass Loss versus Chloride Content

The gravimetric mass loss of the concrete-embedded electrodes can be plotted as a function of the average chloride content as determined from chemical analysis. Figure 7.13 depicts graphically the role of the concrete chloride content on reinforcement oxidation.

It can be seen that despite slight variations in both the chloride content and gravimetric mass loss results, the relationship obtained is linear. An increase in the overall chloride content in the concrete can result in a corresponding substantial loss of mass of the reinforcing steel embedded within, thus resulting in a reduction of the load carrying capacity of the structure, which under adverse conditions, may lead to structural failure.

7.2 INTERPRETATION OF RESULTS

7.2.1 Effect of Cover Depth

Both Test Series #5 and #6 seem to clearly indicate that an increase in the overall depth of clear cover retards the onset of the reinforcing steel corrosion embedded within concrete. This can be supported by the following:

1. No significant distress observations were visible for the three specimens having the largest covers (G, H, and I respectively), whereas the three specimens having the smallest covers (A, B, and C, respectively) demonstrated indications of active corrosion levels before the completion of the testing period. Furthermore, the smaller the cover, the faster the observed formation of ferric oxides. Similar effects were observed for Test Series #6 (see Table 6.3).

2. Large negative electrode operating potentials versus SCE were measured for the lollipop specimens having the smallest cover, whereas those with larger covers had larger operating

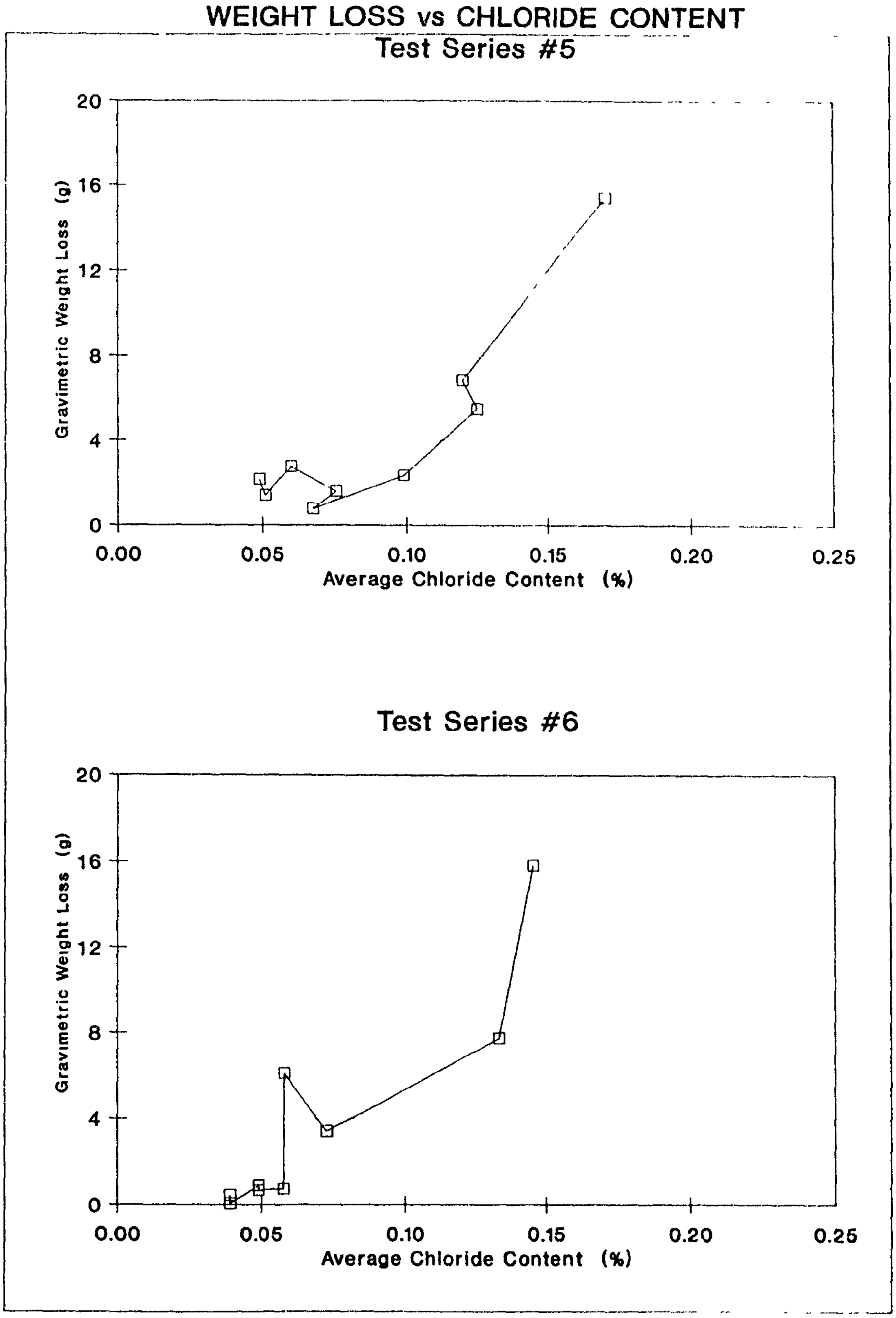


Figure 7.13: Test Series #5 and #6
Weight Loss versus Chloride Content

potentials. This is consistent with the observations in Item 1 above, with active corrosion observed for potentials of approximately -200 mV or less versus SCE (see Figures 6.12 to 6.15). This can be interpreted as a 90-95% probability of corrosion occurrence. Reversal of potential values from positive to negative indicates initiation of corrosion. No signs of active corrosion were noted for the reversed polarity position.

3. The test specimens having smaller concrete cover thicknesses allowed greater current flows, for both polarity positions (see Figures 6.16 to 6.19). For both test series, a large current was measured for the reversed polarity than for the normal polarity mode.

4. The carbonation depth reached the level of reinforcement only in the first specimen (D) tested. An increased cover thickness seemed to retard the penetration of carbon dioxide within the concrete (see Figure 6.22 and Appendix E).

5. A trend can be detected from the results of the tests for chloride content of the specimens. An increase in the cover depth results in chloride content reductions (see Figure 6.24 and Appendix F). For both series, this holds true along the entire height of the concrete specimen (i.e., top, middle, and bottom samples extracted).

6. The reinforcement mass loss decreases as the concrete cover increases (see Figure 6.25 and Appendix G). This trend is consistent for the first five specimens of each series. A 1/8 in. (3.2 mm) cover thickness increase (set-up A to B)

results in a decrease of mass loss by more than one-half of the original amount. As expected, the losses for the cathodic electrodes were minimal.

7. Loss of load carrying capabilities were noted for four specimens with smaller concrete covers (see Figures 6.27 and 6.28 and Appendix H). Increased concrete cover resulted in a higher observed ultimate stress when the embedded steel bar was tested. No loss of ultimate tensile strength was measured for the cathodic electrodes. Yield stress characteristics of all specimens remained unaffected. Additionally, as expected, in all cases, the true ultimate stress was greater than the nominal ultimate stress.

8. For both series, in the normal polarity position, the four specimens with the smallest covers (Specimens A to D inclusive) exhibited a resistance below 100 ohms, whereas those with larger covers had resistances whose magnitude was several thousand ohms (see Figures 7.1 to 7.5).

9. Lollipop specimens for both series have average pH values below that of concrete (normal pH value for concrete is 12). This reflects a loss in concrete alkalinity at the metal surface. Since average pH values for larger-sized cover depths are slightly below that of concrete, initiation of alkalinity loss is a possibility (see Appendix I). The average pH values for the cathodic electrodes are equal or somewhat greater than that of concrete.

10. The "system" resistance provided by the specimens in the normal polarity position increased with an increase in the

depth of the concrete cover (see Figure 7.8 and Appendix J). There is no large fluctuation in the reversed polarity mode.

11. The corrosion current i_{corr} is directly proportional to the thickness of the concrete cover for both polarity modes (see Figure 7.9 and Appendix K). The specimen with the smallest concrete cover thickness (Specimen A) has an i_{corr} magnitude of approximately ten-fold that of the specimen with the largest cover thickness (Specimen I).

12. The electrical conductance G is inversely proportional to the thickness of the clear cover (see Figure 7.10 and Appendix L). The smallest concrete cover thickness (Specimen A) is about four times as electrically conductive as the specimen with the largest concrete cover (Specimen I).

13. The theoretical metal oxidation rate computed decreases with increased cover thickness (see Appendix M). This agrees well with gravimetric measurements recorded (see Item 6).

14. The slopes of the i_{corr} versus electrode resistance curves increase in steepness with a corresponding decrease in the concrete cover thickness (see Appendix N).

15. Smaller depths of the concrete cover thickness resulted in significant increases in both the metal loss and the average chloride content for both test series (see Figure 7.13).

7.2.2 Effect of Electrolyte Solution (% NaCl)

Having discussed the relative occurrence of the effect of concrete cover thickness in each specimen within a particular test series, the focus shifts to comparing the results between similar specimens of Series #5 and #6. It is important to note that the only difference between the series is the concentration of the electrolyte solution (10% and 3.5% NaCl by weight of water, respectively). The following comments can be made:

1. No major difference is evident in the time to initiate corrosion for the three specimens with the smallest covers (Specimens A, B, and C). It was observed that corrosion activity took twice as long to initiate in Specimens D and E of Series #6 than in those of Series #5. The specimens of Series #5 exhibited a more advanced corrosion level at the end of the testing period than those of Series #6. Furthermore, one additional specimen (Specimen F) showed evidence of corrosion only in Series #5 (see Table 6.3).
2. The operating potentials were of larger negative values for Series #5 than for Series #6 (see Figures 6.12 to 6.15).
3. For each of the range of the concrete cover thicknesses tested, the current flow through Series #5 specimens was always greater than that of Series #6 (see Appendix O).
4. Slight differences in the carbonation test results yield no definite comparative conclusions for the two series (see Figure 6.22 and Appendix E).
5. The stronger electrolyte solution resulted in higher chloride contents (see Figure 6.24 and Appendix F).
6. No consistent trend can be established from the gravimetric measurements (see Figure 6.25 and Appendix G).

7. The four specimens of Series #5 having the smallest concrete covers (Specimens A to D) have a lower ultimate tensile stress than the corresponding specimens from Series #6. For the remainder of the specimens, no discernible difference is noted between the two (see Appendix H).

8. An increased electrolyte concentration caused the following: a decrease in polarization resistance, a decrease in "system" ohmic resistance, slight increases in corrosion current and electrical conductance, and a noticeable increase in the metal oxidation rates (see Figures 7.1 to 7.12 and Appendix I to N).

9. No discernible difference was detected in the average pH values at the metal surface between the test series (see Appendix I).

10. Test Series #5 demonstrated greater steel electrode weight loss with respect to average chloride content than Series #6 (see Figure 7.13). This is mainly due to the greater strength of the electrolyte solution.

7.2.3 Effect of Concrete

Test Series #7 was conducted to demonstrate the importance of the alkaline environment provided by the concrete at the metal surface. Specimens A and B demonstrate the corrosion process on bare electrodes. These can be compared to specimens of Series #5 and #6 having the smaller concrete covers. Specimens C, D, and E demonstrate cathodic behaviour of concrete-embedded electrodes. These can be compared to Specimens B, H, and E respectively of Series #6, both sets having the same anodic concrete cover thickness and subject to the same electrolyte concentration.

Based on the experiments conducted, the following observations can be made:

1. The severity of the corrosion level was observed for those electrodes tested in the absence of concrete (testing period was terminated after approximately 30 days). The concrete-embedded cathodic electrodes showed signs of retarding the corrosion activity.
2. Large negative operating potentials were attained for Specimens A and B (approximately -1000 mV versus SCE), while similarities were noted between Specimens C, D, and E and the potentials of Series #6 (see Figures 6.31 and 6.38).
3. The bare electrode tests permitted a current flow greater than twice that of the smallest-sized lollipop specimens of the previous series (see Figure 6.32). No discernible difference was noted for the other specimens in Test Series #7 (see Figure 6.39).
4. The mass losses of Specimens A and B were approximately six and four times those of the smallest-sized covers of Series #5 and #6 respectively (see Appendix G). No mass loss was noted for Specimen C, representing a reduction of greater than seven times when compared with the corresponding lollipop specimen of Series #6. No differences in mass were noted for the other two specimens.
5. Significant reductions in the true ultimate strengths were

noted for both Specimens A and B. Specimen A failed in tension before the yield capacity was attained, whereas Specimen B failed immediately after yielding. The ultimate stresses for the remainder of the specimens did not vary appreciably when compared to the corresponding samples of Series #6 (see Appendix H).

6. The specimens with bare electrodes showed the following response: significant decrease in "polarization" and "system" resistances, increase in corrosion current and electrical conductance, and average pH values less than that of concrete (see Figure 7.6 and Appendix I to L). Oxidation rates of Specimens A and B are respectively three and five times greater than those of the previous series with the smallest concrete cover thicknesses (see Appendix M).

7. The specimens with concrete protection of cathodic electrodes responded as follows: an increase in "polarization" and "system" ohmic resistances, a slight decrease in corrosion current and electrical conductance, and average pH values similar to that of concrete (see Figure 7.7 and Appendix I to L). Concrete-embedded electrodes caused a decrease in the theoretical oxidation rate computed (see Appendix M).

7.3 COMPARISON OF RESULTS

Based on the interpretations and relations of the data obtained, the laboratory test method seems a valid means of electrochemically accelerating the corrosion process. This is justified by the correlation of the following parameters to several experimental works performed recently:

i) The range of the corrosion current, i_{corr}, values determined fall within the expected spectrum of values obtained from previous testing by Andrade et al.[58]

ii) The electrical conductance, G, values fall within the expected range of 0 to -5 ohm^{-} (the logarithm of the conductance is plotted versus time), according to the tests by Aguilar et al.[61]

iii) Testing performed by Escalante et al[62] indicate a decreasing effect of concrete resistance on reinforcement corrosion as immersion time increases. A similar trend was established for all specimens tested in the accelerated manner.

iv) The relationship between the corrosion current, i_{corr}, and the electrode polarization resistance R_p, as determined by Andrade at al[58] , was similar to the one established for the lollipop specimens tested.

v) The oxidation rate expression, brought forth by Aguilar at al[61] , was used to predict within experimental error the weight reductions of the steel reinforcing electrodes embedded within the concrete. The only exceptions to this were the two test Specimens A and B of Test Series #7, where only deformed reinforcing bars were used as electrodes (no presence of concrete).

CHAPTER 8

SUMMARY AND CONCLUSIONS

The results of the accelerated electrochemical corrosion tests, presented in Chapters 6 and 7, can be summarized and the following conclusions can be drawn concerning the corrosion of steel reinforcement embedded in concrete:

1. The visual observations recorded are good indicators of the level of the corrosion activity occurring within the reinforced concrete. These can include rust staining, formation of gaseous substances ("bubbles"), and ferric oxide deposits.
2. The lollipop specimens having operating potential versus a saturated calomel reference electrode (SCE) values lower than **0 mV** exhibited signs of corrosion. Despite the fact that higher negative values indicate a more advanced state of corrosion, the engineer should be cautious that any recorded

measurement below the **0 mV** value may indicate the potential for reinforcement corrosion. Additionally, any specimen whose operating potential varies from positive to negative values during the test period signifies the passing of reinforcing steel from a passive to an active state.

3. The current flow through the concrete-steel system allows an accurate comparison of the relative effective resistances of the various systems, and therefore that of the concrete. This can be seen readily from the results obtained for Test Series No.5 and No.6, plotted in Figures 8.1 and 8.2. The trend indicates that, for both test series, an electrical current reading of **3 mA** and above signifies corrosion activity at the level of the reinforcing steel. Increasing current flow values indicates a greater probability that the effect of the concrete resistance has diminished. A marked decrease in the current flow, accompanied by a corresponding increase in the concrete electrode resistance, occurs when the depth of clear cover is approximately **1½ in. (38 mm)**. Therefore, it is recommended that a minimum cover of at least **1½ in. (38 mm)** over the reinforcing steel be specified in order to ensure that the concrete will offer the corrosion protection in the design requirements.

4. The severity of exposure conditions of concrete influences the initiation and rate of reinforcement corrosion. This was verified by exposing the concrete specimens to varying strengths of the electrolyte solution. Nevertheless, the effect of the sodium chloride solution is secondary when

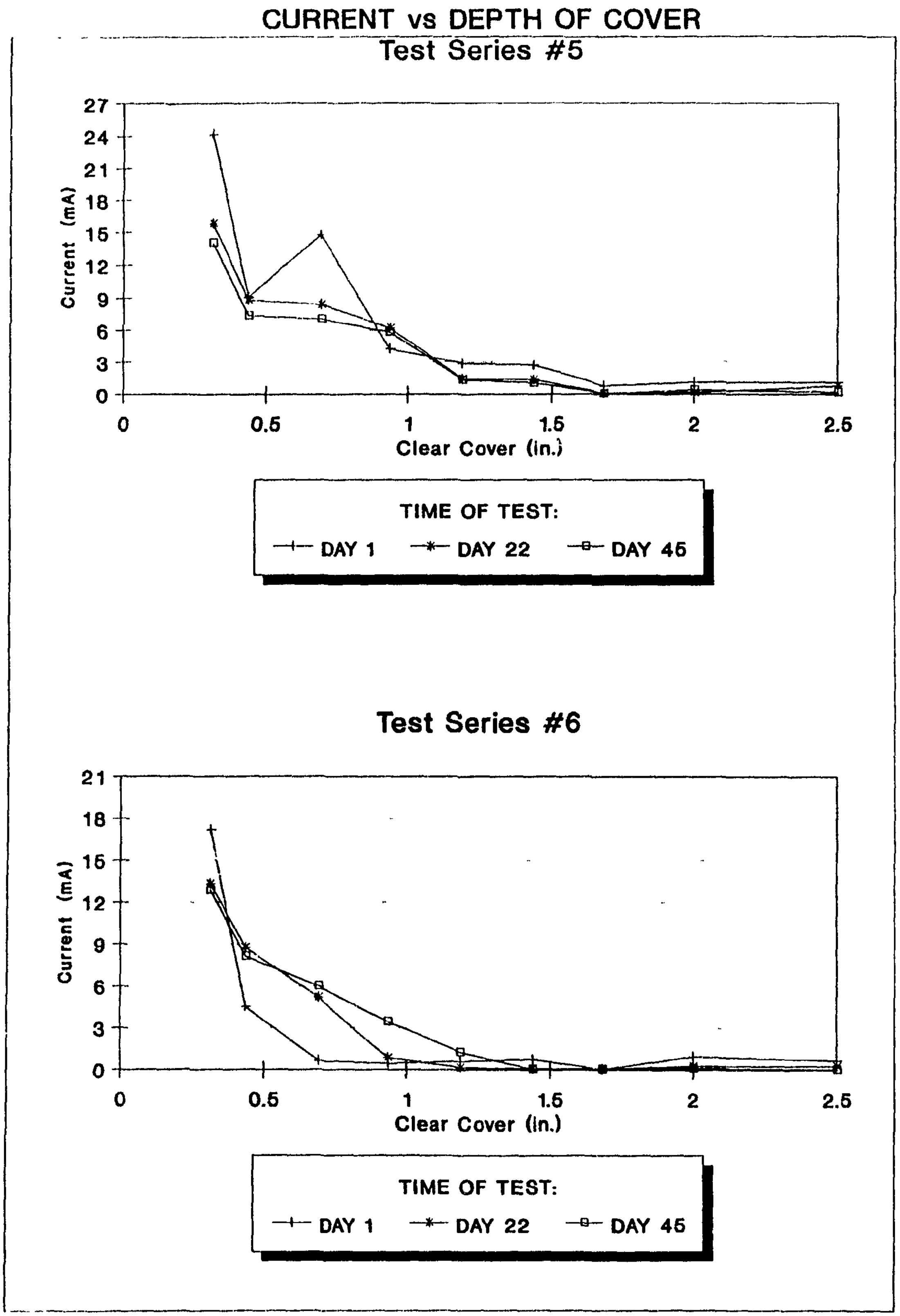


Figure 8.1: Depth of Cover as a Function of Current Flow

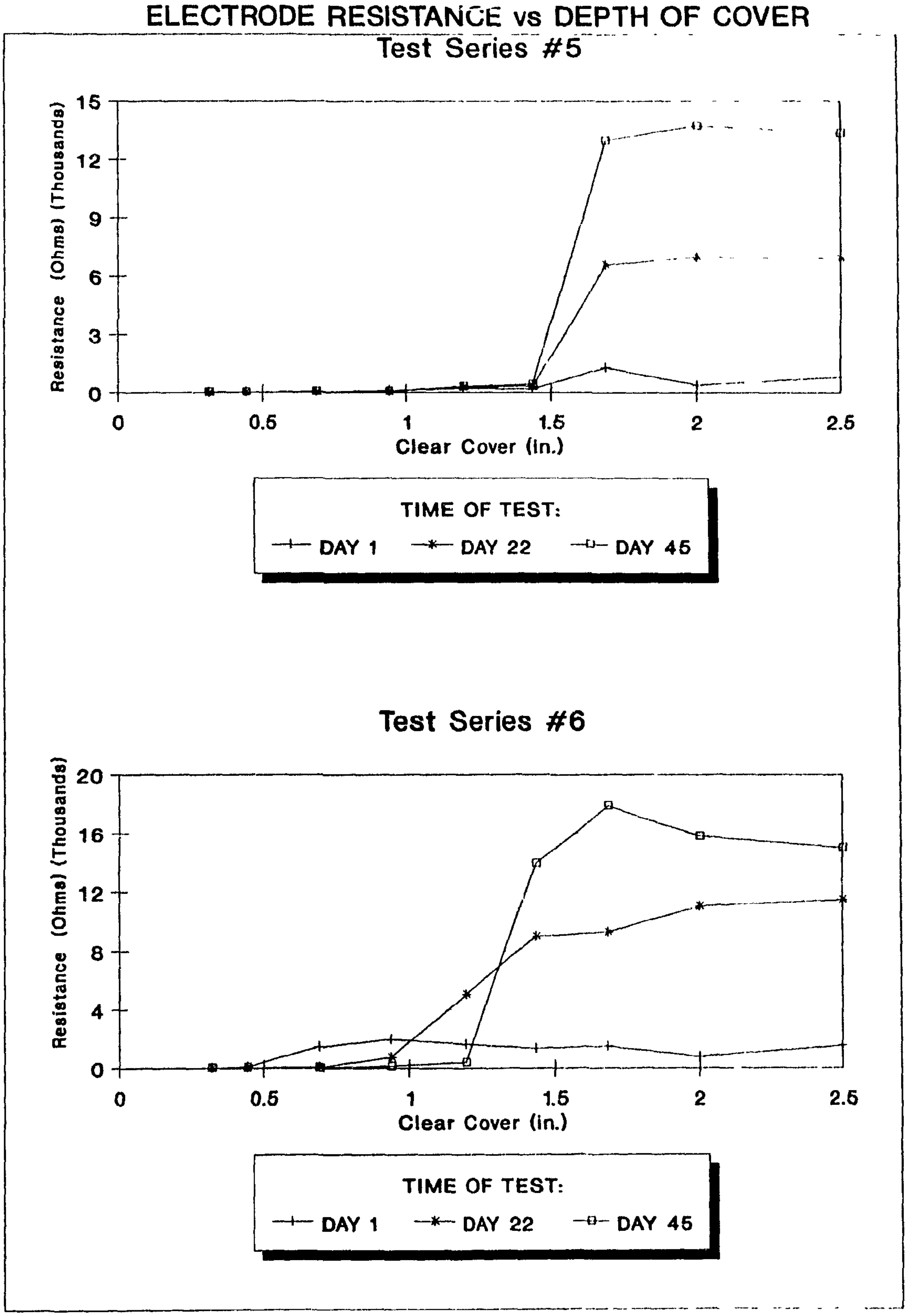


Figure 8.2: Depth of Cover as a Function of Electrode Resistance

compared with that of the concrete cover depth.

5. As seen in Test Series No.7 (Specimens A and B), reinforcement corrosion activity reaches an advanced state in the absence of the concrete cover. Embedding the cathodic-acting electrode in a concrete environment results in the corrosion process being "throttled", with a decrease in the rate of ion exchange between the anodic and cathodic areas.

6. Loss of structural integrity is a very important consideration in the evaluation of an existing structure. As demonstrated through the mass loss of the reinforcing steel and the accompanying reductions in its ultimate tensile strength, these significant reductions in bar sizes and cross-sectional area may lead to serious consequences and possible damage.

7. Higher chloride contents exist at the top location along the height of the concrete cylinders than at the bottom location. Therefore, for concrete exposed to marine environment, the areas near the tidal water level ("splash" zones) are more prone to corrosion of the steel reinforcement than those completely submerged beneath the sea water. The main reason is the unavailability of oxygen at greater immersion depths, a component essential for the promotion of the corrosion process. Hence, this condition must be considered in the design of concrete located in tidal zones.

8. The chloride content is normally greater at the concrete surface than at a location near the steel reinforcement embedded within the concrete. The difference between these two

locations depends invariably upon the thickness and quality of the concrete cover thickness. Additionally, it must be emphasized that an **increased concrete cover thickness is no substitute for poor quality concrete cover**. A higher quality concrete cover is more effective in the protection of the steel reinforcement than a more permeable concrete cover of greater thickness.

As mentioned previously, a minimum recommended thickness of clear concrete cover of **1½ in. (38 mm)** must be provided at all times to ensure that the service life of the structure is prolonged. For extremely harsh exposure conditions and/or when the concrete is subjected to a severe chloride attack, a minimum clear cover thickness of **2 in. (51 mm)** is recommended to retard the onset of corrosion. Furthermore, proper design, maintenance, and repair procedures must be followed rigorously to ensure that a relatively chloride-free concrete environment is established.

8.1 Recommendations For Future Accelerated Electrochemical Testing

The initial efforts to test the corrosion process of concrete lollipop specimens can be perceived as a first step in developing a more intricate accelerated electrochemical experimental program to be developed further. With the aid of the experimental set-up described in Chapter 6, the various parameters influencing the various aspects of steel reinforcement corrosion can be tested and appropriate conclusions can be drawn. The following general areas of interest can be examined:

- **concrete mix constituents**: cement types and content; aggregate types and grading; air entrainment; superplasticizers; chemical admixtures (fly ash, ground granulated blast furnace slag, silica fume, pozzolans).
- **concrete properties**: compressive strength; water-cement ratio; curing period; consolidation.
- **reinforcing steel**: stressed and bent rebars; prestressing tendons; chemical (epoxy) coatings; non-corrosive steels; plain steels; black steels; pre-rusted rebars.
- **other parameters**: protective waterproofing membranes; sealing compounds; concrete overlays; latex-modified and epoxy-modified concrete.

In order to improve the accuracy of any future results obtained from the experimental work described earlier, it may be necessary to implement some or all of the following suggestions:

- The connection of both steel electrodes to an automatic data recording device for daily measurements of the current flow, and of operating and polarization potentials with respect to a saturated calomel reference electrode.
- The tank may be sealed with silicone between the top edges and the base board to prevent any accidental disturbance of the experimental set-up.

- A tube, connected to a small pump and generator apparatus, can be immersed directly in the electrolyte solution to continuously replenish the consumption of sodium chloride and thus, maintain the desired strength of the electrolyte solution (i.e., replenishing any amount of chlorides lost through consumption or evaporation).
- The period of testing, i.e., continuous immersion time, may be extended to a period beyond 45 days (1080 hours) for further observations.

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APPENDIX A

Sieve Analysis Results

This appendix summarizes the results of sieve analysis of the aggregates (fine and coarse) performed at the Geotechnical Research Centre at McGill University. The grading or particle-size distribution curves are included and compared with the limits specified in the CSA Standard A23.1-M.[67,68]

GEOTECHNICAL RESEARCH CENTRE

SOIL MECHANICS LABORATORY

SIEVE ANALYSIS - FINE AGGREGATE

SIEVE NUMBER	SIEVE OPENING (mm)	WEIGHT SIEVE (g)	WEIGHT SIEVE + SOIL (g)	WEIGHT SOIL RETAINED (g)	PERCENT RETAINED (%)	CUMULATIVE PERCENT RETAINED (%)	PERCENT FINER (%)
10	2.000	438.34	438.97	0.63	0.17	0.17	99.83
30	0.595	420.08	474.75	54.67	15.18	15.35	84.65
50	0.297	374.48	572.31	197.83	54.94	70.29	29.71
100	0.150	354.59	449.87	95.28	26.46	96.75	3.25
200	0.075	495.00	502.01	7.01	1.95	98.70	1.30
PAN	-----	278.21	278.68	4.68	1.30	100.00	0.00

SIEVE ANALYSIS - COARSE AGGREGATE

SIEVE NUMBER	SIEVE OPENING (mm)	WEIGHT SIEVE (g)	WEIGHT SIEVE + SOIL (g)	WEIGHT SOIL RETAINED (g)	PERCENT RETAINED (%)	CUMULATIVE PERCENT RETAINED (%)	PERCENT FINER (%)
1/2	12.70	541.62	542.29	0.67	0.10	0.10	99.90
5/16	8.00	571.07	868.13	297.06	42.82	42.92	57.08
4	4.76	591.89	970.89	379.00	54.63	97.55	2.45
10	2.00	438.34	447.44	9.10	1.31	98.86	1.14
30	0.595	420.08	421.05	0.97	0.14	99.00	1.00
50	0.297	374.48	374.73	0.25	0.04	99.04	0.96
100	0.150	354.59	354.84	0.25	0.04	99.08	0.92
200	0.075	495.00	495.35	0.35	0.05	99.13	0.87
PAN	-----	278.21	278.31	6.12	0.88	100.00	0.00

Table A-1: Results of Sieve Analysis

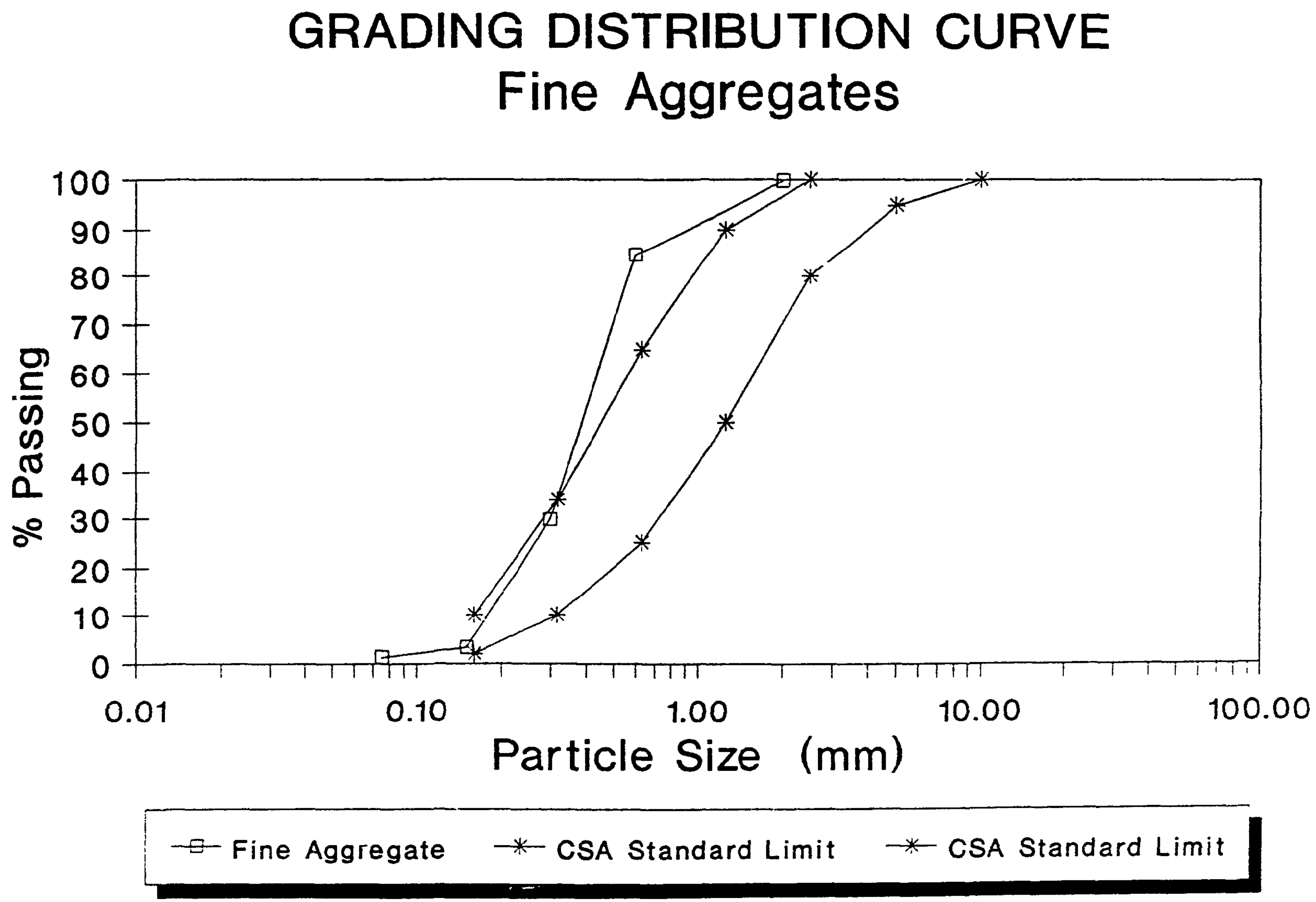

GRADING DISTRIBUTION CURVE
Fine Aggregates
% Passing
100
90
80
70
60
50
40
30
20
10
0
0.01
0.10
1.00
10.00
100.00
Particle Size (mm)
Fine Aggregate
CSA Standard Limit
CSA Standard Limit

Figure A-1

GRADING DISTRIBUTION CURVE
Coarse Aggregates

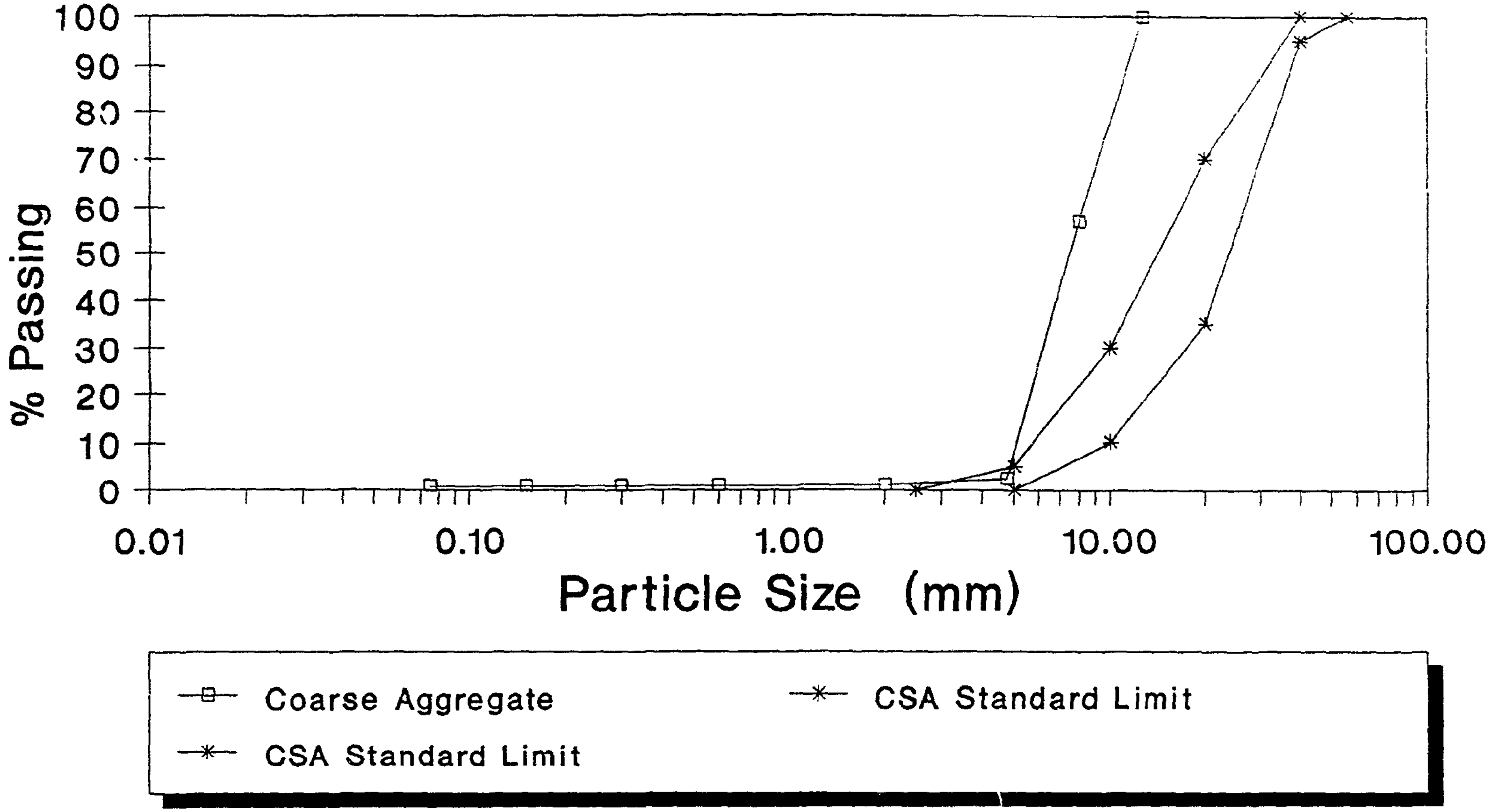


Figure A-2

APPENDIX B

Compressive Strength Results

This appendix reports the results of the compressive strength tests performed on five control specimens in the Structures laboratory at McGill University. The average compressive strength f_c' was approximately 24 MPa. Calculations to determine the cement content, both in one cylinder and in 5 g of concrete, are also shown.

CONTROL CYLINDERS

CYLINDER #	MASS OF MOLD (g)	TOTAL MASS (wet concrete + mold) (g)	WET CONCRETE (g)	fc' (psi)	fc' (MPa)
#1	215.1	1953.7	1738.6	3352.3	23.1
#2	216.7	1943.5	1726.8	3584.1	24.7
#3	214.5	1922.3	1707.8	3311.6	22.8
#4	218.0	1978.1	1760.1	3447.4	23.8
#5	213.7	1920.9	1707.2	3692.4	25.5
		TOTAL	8640.5		
		AVERAGE	1728.1	3477.6	24.0

Total mass in 1 cu. metre = 355 + 160 + (2.24*355) + (2.92*355)
= 2346.8 kg

Cement content = 261.41 g

Cement content in 5 g of concrete: 0.756 g or
15.13 %

Table B-1: RESULTS OF COMPRESSIVE STRENGTH TESTS

APPENDIX C

Test Series #5

Specimens C and G

Photographs of the conditions of two specimens in Test Series #5, namely Specimens C and G, at different ages, are shown in the following pages. The only difference between the two is an increase in the concrete cover thickness by 1 in. (25 mm). The initiation and progress of the corrosion activity can be clearly seen for Specimen C, whereas no visible signs of distress are noted in the case of Specimen G. At the end of the continuous immersion period (45 days), large amounts of ferric oxide products had accumulated near Specimen C, yet this was not the case for Specimen G.

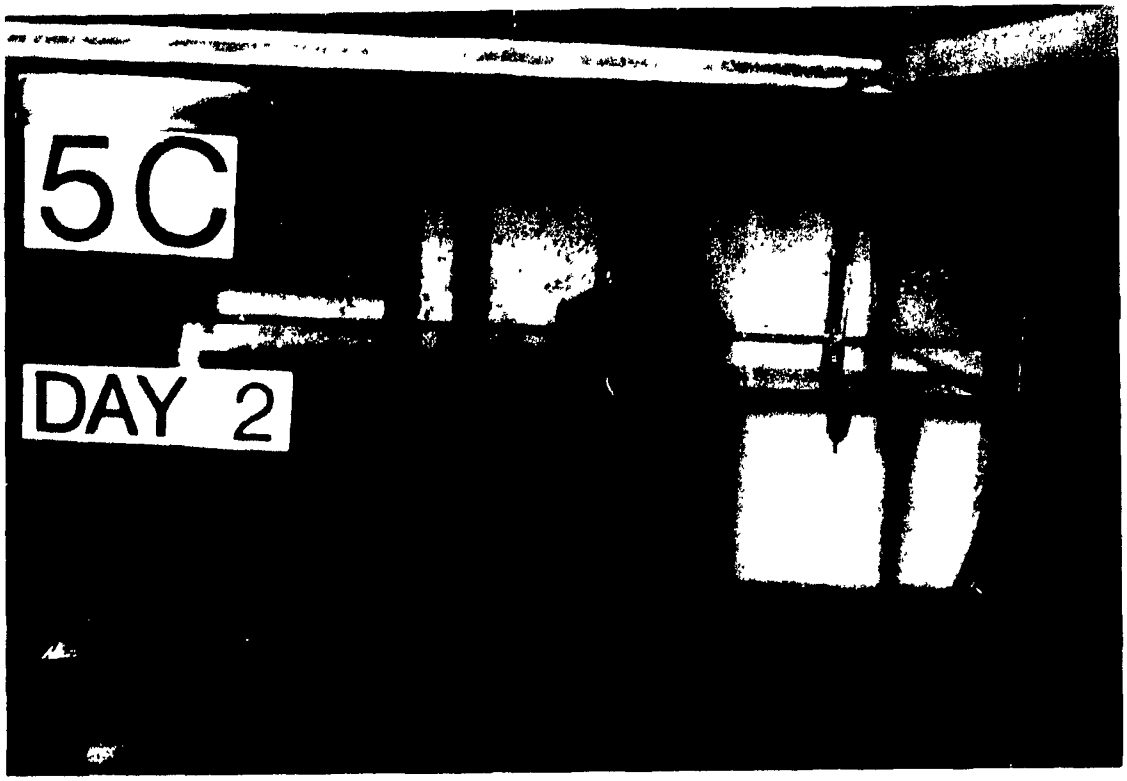


Figure C-1: Experiment Specimen #5C (Day 2)
Concrete Cover Thickness: 11/16 in.(17 5 mm)

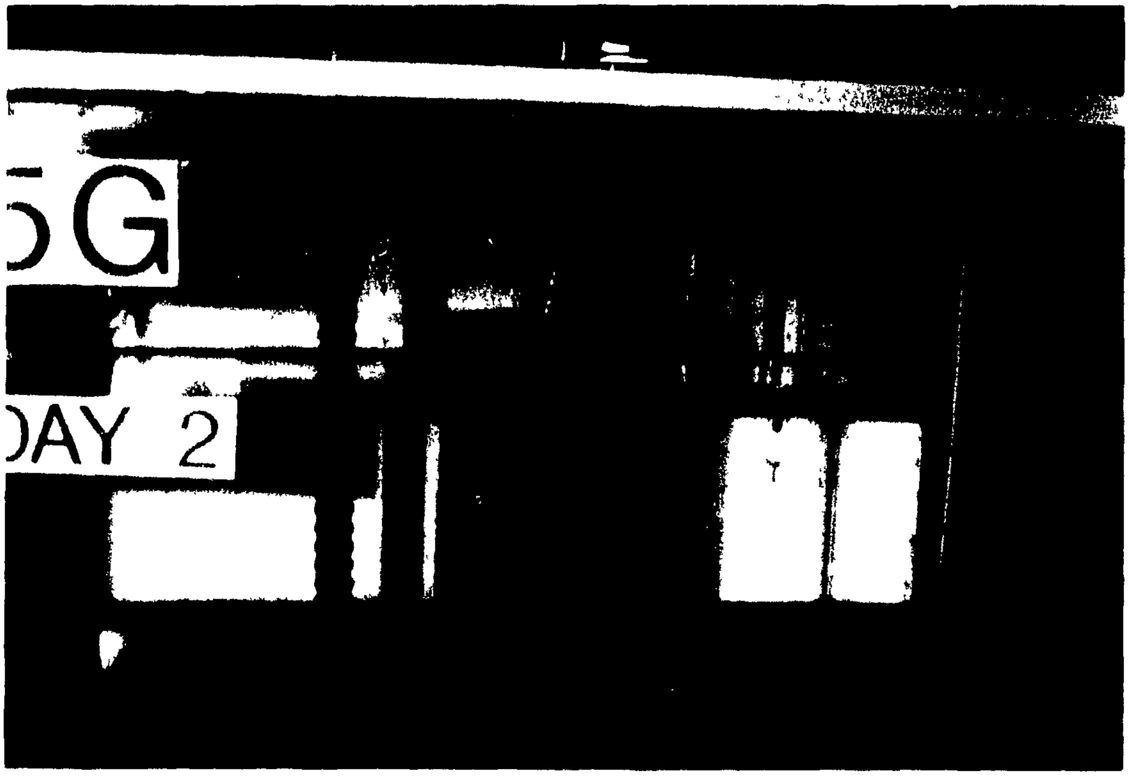


Figure C-2: Experiment Specimen #5G (Day 2)
Concrete Cover Thickness: 1-11/16 in.(42.9 mm)

Figure C-3: Experiment Specimen #5C (Day 10)
Concrete Cover Thickness: 11/16 in. (17.5 mm)

Figure C-4: Experiment Specimen #5G (Day 10)
Concrete Cover Thickness: 1-11/16 in. (42.9 mm)

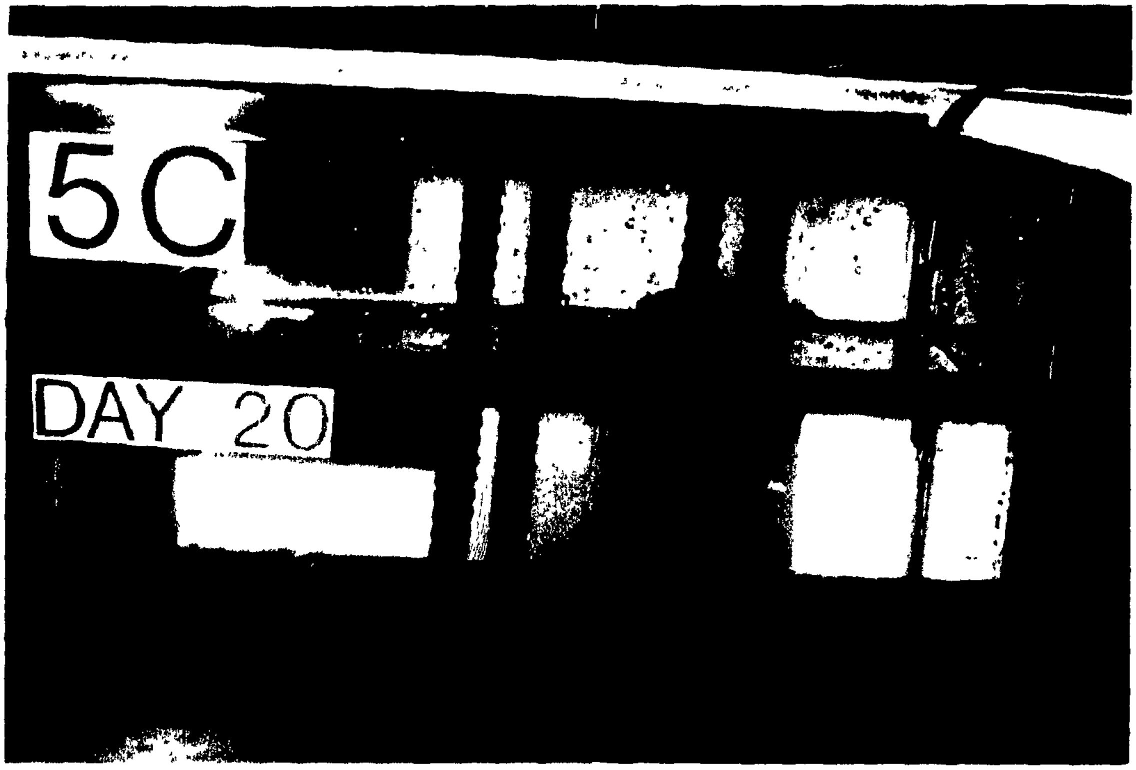


Figure C-5: Experiment Specimen #5C (Day 20)
Concrete Cover Thickness: 11/16 in. (17.5 mm)

Figure C-6: Experiment Specimen #5G (Day 20)
Concrete Cover Thickness: 1-11/16 in. (42.9 mm)

Figure C-7: Experiment Specimen #5C (Day 30)
Concrete Cover Thickness: 11/16 in. (17.5 mm)

Figure C-8: Experiment Specimen #5G (Day 30)
Concrete Cover Thickness: 1-11/16 in. (42.9 mm)

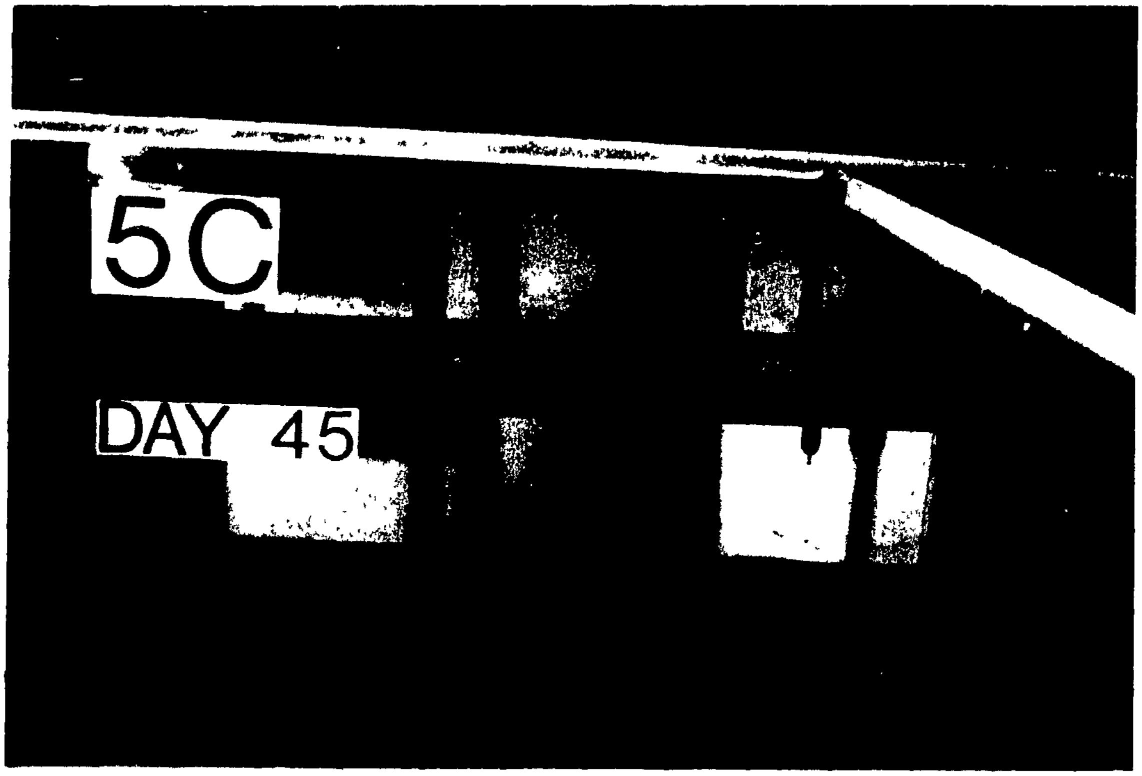


Figure C-9: Experiment Specimen #5C (Day 45)
Concrete Cover Thickness: 11/16 in. (17.5 mm)

Figure C-10: Experiment Specimen #5G (Day 45)
Concrete Cover Thickness: 1-11/16 in. (42.9 mm)

APPENDIX D

Test Series #6

Specimens C and H

This appendix includes photographs of two set-ups, Specimens C and H, tested as part of Series #6. An increase of 1-5/16 in. (33.3 mm) of concrete cover thickness is the only difference between the two specimens. As seen, the concrete-embedded electrode of Specimen C is clearly in an active state, while that of Specimen H remains relatively passive throughout the testing period (45 days). It is important to note the accumulation of the reddish-brown corrosion by-products forming at the base of the Specimen C.

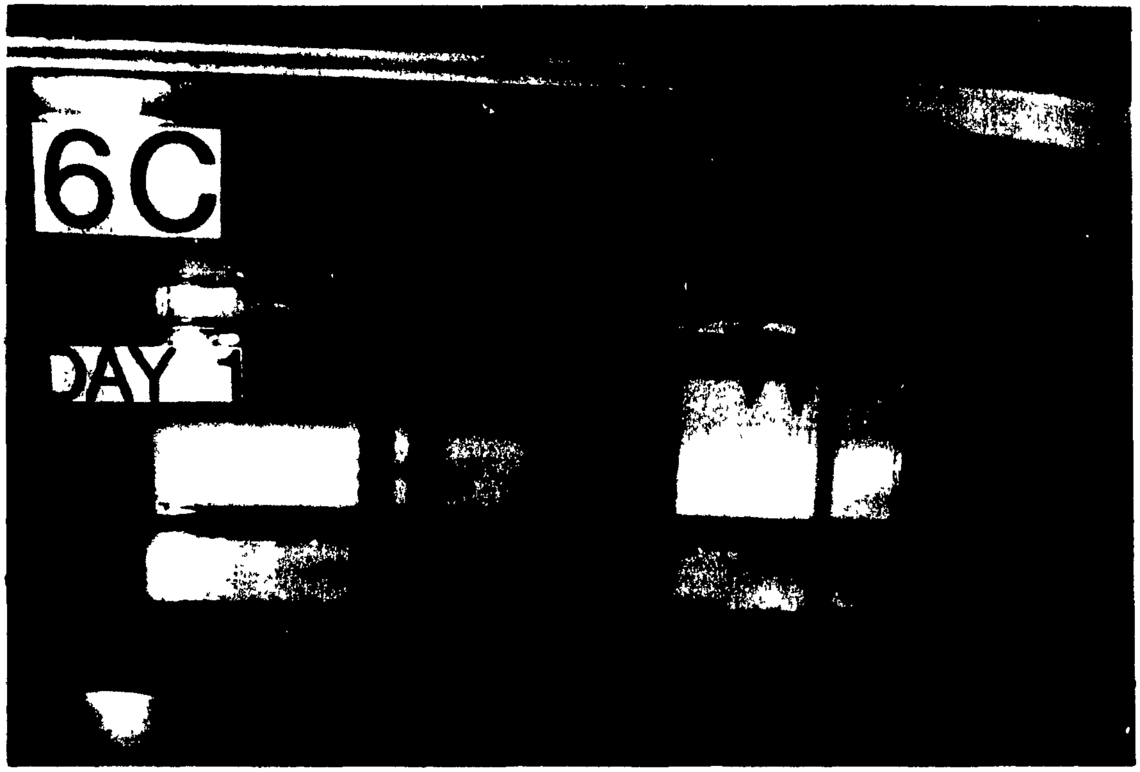


Figure D-1: Experiment Specimen #6C (Day 1)
Concrete Cover Thickness: 11/16 in. (17.5 mm)

Figure D-2: Experiment Specimen #6H (Day 1)
Concrete Cover Thickness: 2 in. (50.8 mm)

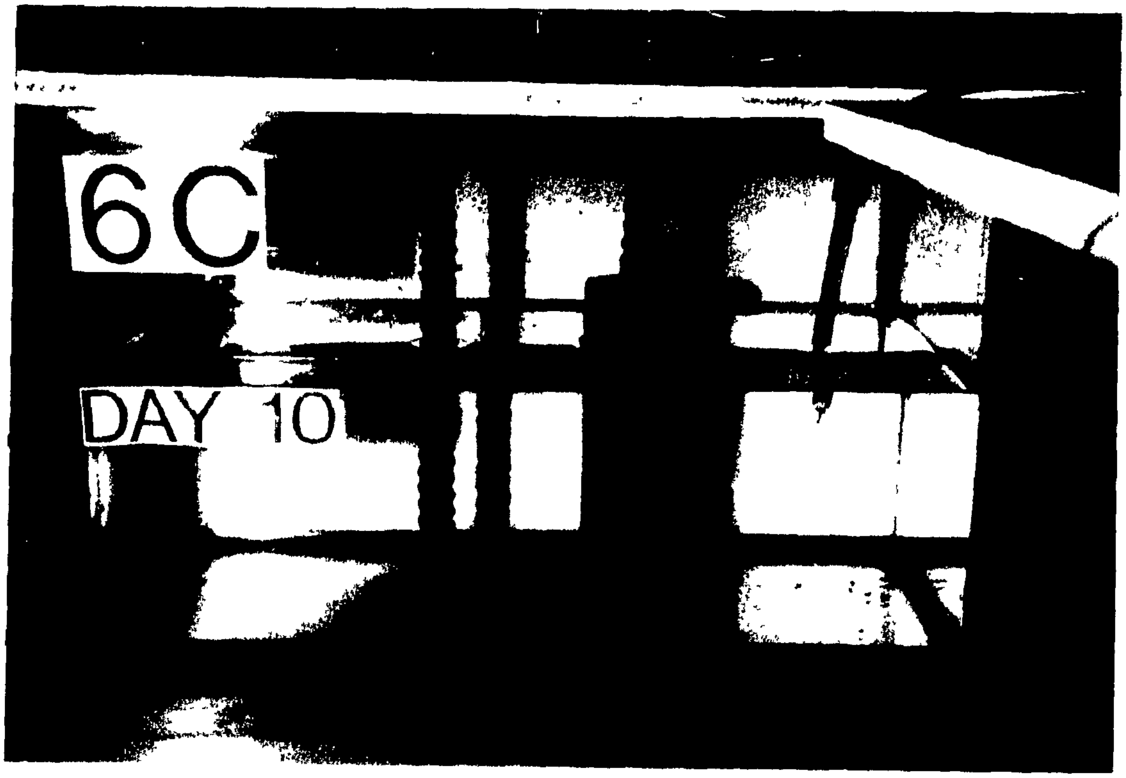


Figure D-3: Experiment Specimen #6C (Day 10)
Concrete Cover Thickness: 11/16 in. (17.5 mm)

Figure D-4: Experiment Specimen #6H (Day 10)
Concrete Cover Thickness: 2 in. (50.8 mm)

Figure D-5: Experiment Specimen #6C (Day 20)
Concrete Cover Thickness: 11/16 in.(17.5 mm)

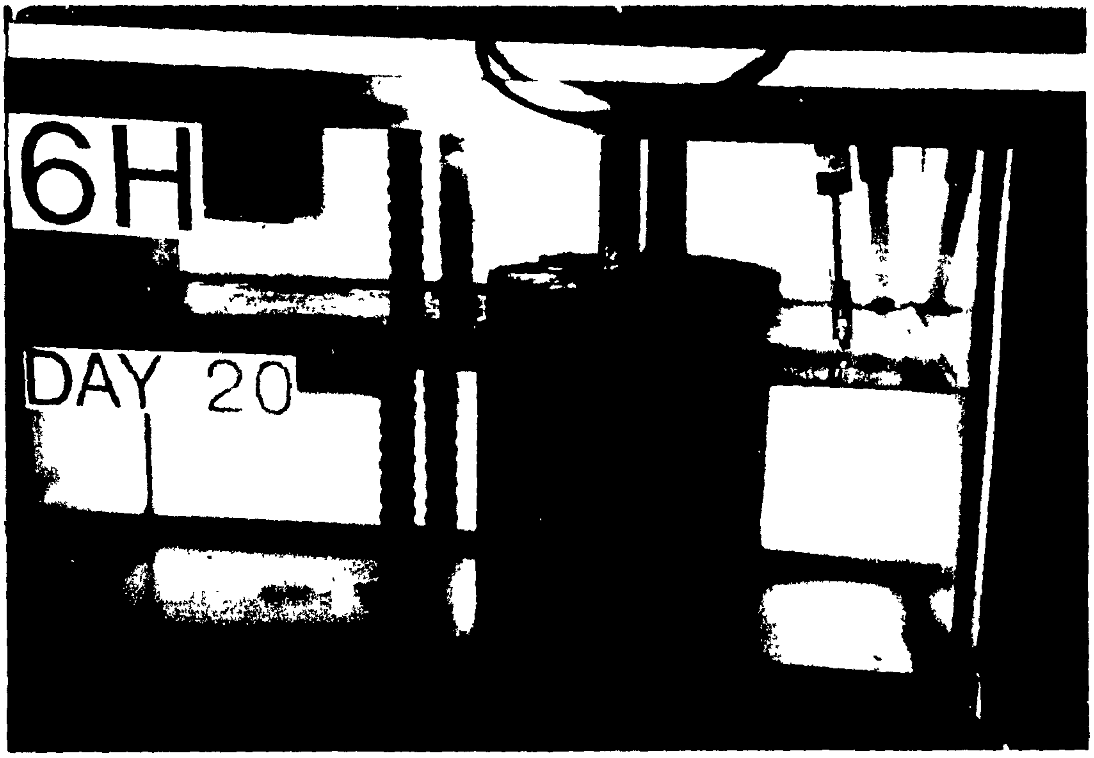


Figure D-6: Experiment Specimen #6H (Day 20)
Concrete Cover Thickness: 2 in.(50.8 mm)

Figure D-7: Experiment Specimen #6C (Day 30)
Concrete Cover Thickness: 11/16 in.(17.5 mm)

Figure D-8: Experiment Specimen #6H (Day 30)
Concrete Cover Thickness: 2 in.(50.8 mm)

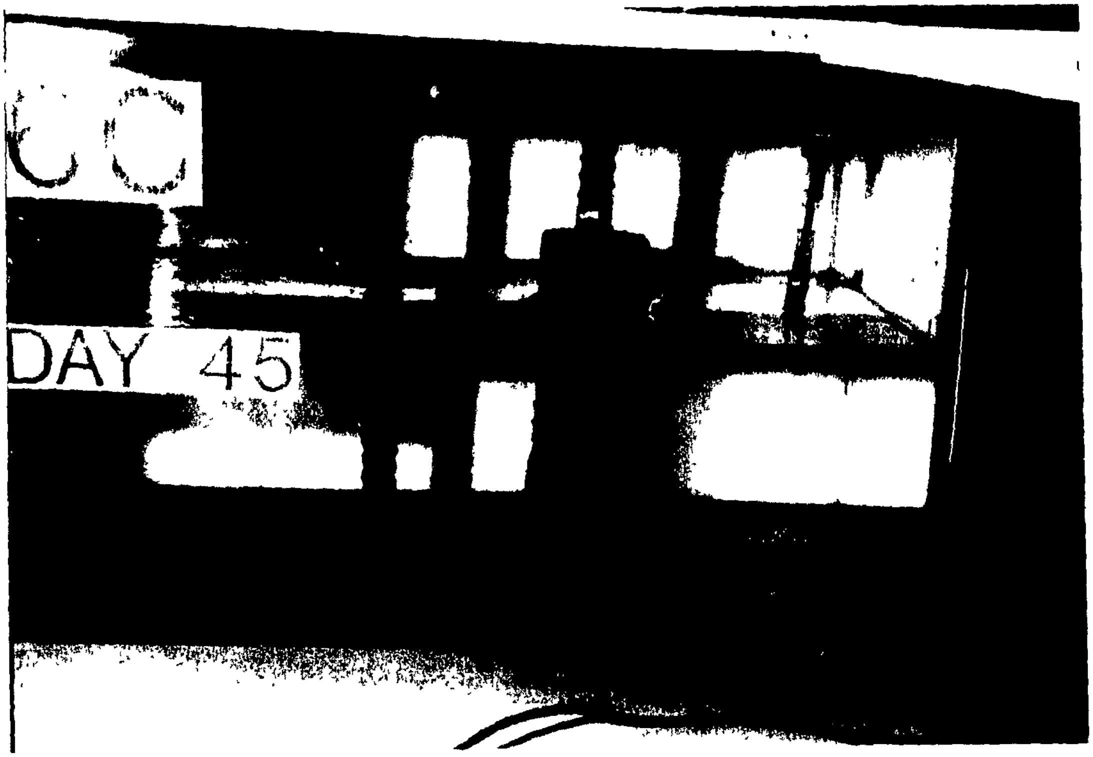


Figure D-9: Experiment Specimen #6C (Day 45)
Concrete Cover Thickness: 11/16 in. (17.5 mm)

Figure D-10: Experiment Specimen #6H (Day 45)
Concrete Cover Thickness: 2 in. (50.8 mm)

APPENDIX E

Carbonation Test Results

Results of carbonation depth measurements on the saw-cut concrete samples are presented in the following pages. It is important to note that saw-cutting of three specimens in each series, namely A, B, and C, was not possible due to the small thickness of the concrete cover.

CARBONATION DEPTH - TEST SERIES #5

SPECIMEN	
A	Carbonation test not performed due to thin concrete cover (5/16 in. or 7.9 mm) over the reinforcing steel. The specimen could not be saw-cut.
B	Carbonation test not performed due to thin concrete cover (7/16 in. or 11.1 mm) over the reinforcing steel. The specimen could not be saw-cut.
C	Carbonation test not performed due to thin concrete cover (11/16 in. or 17.5 mm) over the reinforcing steel. The specimen could not be saw-cut.

		MAXIMUM (mm)	MINIMUM (mm)	AVERAGE (mm)
D	*	21.3	4.7	13.0
E		14.0	4.0	9.0
F		12.0	3.3	7.7
G		6.3	0.0	3.2
H		5.7	0.0	2.8
I		3.3	0.0	1.7

* = carbonation depth up to the outside face of the reinforcing bar.

Table E-1: RESULTS OF CARBONATION DEPTH MEASUREMENTS

CARBONATION DEPTH - TEST SERIES #6

SPECIMEN	
A	Carbonation test not performed due to thin concrete cover (5/16 in. or 7.9 mm) over the reinforcing steel. The specimen could not be saw-cut.
B	Carbonation test not performed due to thin concrete cover (7/16 in. or 11.1 mm) over the reinforcing steel. The specimen could not be saw-cut.
C	Carbonation test not performed due to thin concrete cover (11/16 in. or 17.5 mm) over the reinforcing steel The specimen could not be saw-cut.

		MAXIMUM (mm)	MINIMUM (mm)	AVERAGE (mm)
D	*	22.7	3.0	12.8
E		15.7	4.0	9.8
F		9.3	2.7	6.0
G		5.7	2.0	3.8
H		4.0	0.0	2.0
I		3.0	0.0	1.5

* = carbonation depth up to the outside face of the reinforcing bar

Table E-2: RESULTS OF CARBONATION DEPTH MEASUREMENTS

APPENDIX F

Chloride Analysis Results

The chemical analysis of the chloride content in concrete was based on the Volhard testing method.[34] The tests were conducted in the laboratories of the Otto Maass Chemistry Building at McGill University. Concrete samples were collected and tested at three locations for each specimen (top, middle, and bottom). The cement content, needed to calculate the chloride content in the concrete, was previously determined in Appendix B and proportioned according to the weight of the samples used (if varied from 5 g).

DETERMINATION OF CHLORIDE CONTENT

m = molarity of standardized thiocyanate solution
(varies according to standardization once a week)

Cl = cement content of sample used
15.127 % for 5 g. of sample

SPECIMEN #	DATE	Sample (g)	AgNO3 (ml)	THIOCYANATE			Chloride Content (%)
				Initial (ml)	Final (ml)	Volume (ml)	
5A (top)	11-03-91	2.5004	16	18.12	26.30	8.18	0.223
5A (middle)	11-03-91	2.4986	12	10.99	18.12	7.13	0.158
5A (bottom)	11-03-91	2.5030	8	8.70	10.99	2.29	0.128
5B (top)	11-03-91	2.4936	8	18.11	19.83	1.72	0.135
5B (middle)	11-03-91	2.5000	8	14.80	18.11	3.31	0.119
5B (bottom)	11-03-91	2.5050	8	10.16	14.80	4.64	0.106
5C (top)	06-05-91	2.4925	8	22.70	23.95	1.25	0.146
5C (middle)	06-05-91	2.5085	8	11.80	22.70	10.90	0.110
5C (bottom)	06-05-91	2.5079	8	3.48	11.70	8.22	0.119
5D (top)	06-05-91	2.5236	8	12.49	19.51	7.02	0.122
5D (middle)	06-05-91	2.5015	8	24.40	38.09	13.69	0.100
5D (bottom)	06-05-91	2.5025	8	19.51	40.19	20.68	0.075
5E (top)	07-05-91	2.5187	8	3.23	21.90	18.67	0.081
5E (middle)	07-05-91	2.5002	8	21.90	44.78	22.88	0.067
5E (bottom)	07-05-91	2.4999	8	0.00	25.36	25.36	0.058
5F (top)	07-05-91	2.5106	8	18.44	35.10	16.66	0.089
5F (middle)	07-05-91	2.5120	8	4.43	25.37	20.94	0.073
5F (bottom)	07-05-91	2.5000	8	25.37	48.00	22.63	0.068
5G (top)	07-05-91	2.5026	8	1.20	24.10	22.90	0.066
5G (middle)	07-05-91	2.5070	8	24.10	47.73	23.63	0.064
5G (bottom)	07-05-91	2.5041	8	17.35	44.60	27.25	0.051
5H (top)	08-05-91	2.5090	8	1.30	27.00	25.70	0.056
5H (middle)	08-05-91	2.4995	8	0.40	28.00	27.60	0.049
5H (bottom)	08-05-91	2.5006	8	1.90	29.80	27.90	0.048
5I (top)	08-05-91	2.5005	8	2.40	30.18	27.78	0.049
5I (middle)	08-05-91	2.5032	8	1.31	28.72	27.41	0.050
5I (bottom)	08-05-91	2.5018	8	1.39	29.61	28.22	0.047

Table F-1: RESULTS OF CHLORIDE CONTENT ANALYSIS

DETERMINATION OF CHLORIDE CONTENT

m = molarity of standardized thiocyanate solution
(varies according to standardization once a week)

C1 = cement content of sample used
15.127 % for 5 g. of sample

SPECIMEN #	DATE	Sample (g)	AgNO3 (ml)	THIOCYANATE			Chloride Content (%)
				Initial (ml)	Final (ml)	Volume (ml)	
6A (top)	08-05-91	2.5129	16	1.40	32.59	31.19	0.184
6A (middle)	08-05-91	2.5098	8	2.00	6.31	4.31	0.133
6A (bottom)	09-05-91	2.5011	8	1.08	8.83	7.75	0.119
6B (top)	09-05-91	2.5000	12	8.83	16.67	7.84	0.193
6B (middle)	09-05-91	2.5026	8	16.67	28.33	11.66	0.103
6B (bottom)	09-05-91	2.5006	8	28.33	39.62	11.29	0.104
6C (top)	09-05-91	2.5053	8	0.40	18.60	18.20	0.076
6C (middle)	09-05-91	2.5020	8	18.60	38.78	20.18	0.068
6C (bottom)	09-05-91	2.5005	8	1.00	19.89	18.89	0.074
6D (top)	10-05-91	2.5070	8	19.89	40.75	20.86	0.065
6D (middle)	10-05-91	2.5042	8	0.57	23.25	22.68	0.058
6D (bottom)	10-05-91	2.5082	8	23.25	48.15	24.90	0.049
6E (top)	10-05-91	2.5030	8	0.00	22.05	22.05	0.061
6E (middle)	10-05-91	2.5043	8	22.05	44.41	22.36	0.059
6E (bottom)	10-05-91	2.5002	8	0.00	24.10	24.10	0.053
6F (top)	10-05-91	2.5006	8	24.10	47.89	23.79	0.054
6F (middle)	27-06-91	2.5172	8	0.69	26.15	25.46	0.046
6F (bottom)	27-06-91	2.5091	8	15.13	40.65	25.52	0.046
6G (top)	27-06-91	2.5245	8	1.05	23.89	22.84	0.057
6G (middle)	27-06-91	2.5161	8	23.89	48.78	24.89	0.049
6G (bottom)	27-06-91	2.5052	8	2.33	29.40	27.07	0.040
6H (top)	27-06-91	2.5159	8	1.30	27.43	26.13	0.044
6H (middle)	27-06-91	2.5035	8	1.58	29.21	27.63	0.038
6H (bottom)	27-06-91	2.5052	8	0.61	28.73	28.12	0.036
6I (top)	27-06-91	2.5073	8	3.79	30.26	26.47	0.043
6I (middle)	27-06-91	2.5017	8	3.97	31.61	27.64	0.038
6I (bottom)	27-06-91	2.5076	8	8.20	36.64	28.44	0.035

Table F-2: RESULTS OF CHLORIDE CONTENT ANALYSIS

APPENDIX G

Mass Measurement Results

All of the steel reinforcing bars used as electrodes for each experimental specimen were accurately weighed before and after the period of exposure (testing) on a digital balance. The actual weight losses, along with the percent loss of mass, were measured and are presented in the following pages.

MASS OF ELECTRODES - TEST SERIES #5

	CONCRETE-EMBEDDED				BARE ELECTRODE			
SPECIMEN	BEFORE (g)	AFTER (g)	LOSS (g)	LOSS (%)	BEFORE (g)	AFTER (g)	LOSS (g)	LOSS (%)
A	458.45	443.06	15.39	3.36	459.02	458.47	0.55	0.12
B	463.12	456.30	6.82	1.47	457.23	456.54	0.69	0.15
C	459.48	454.02	5.46	1.19	462.84	462.72	0.12	0.03
D	458.51	456.18	2.33	0.51	459.79	459.60	0.19	0.04
E	463.07	462.29	0.78	0.17	461.53	460.83	0.70	0.15
F	461.44	459.85	1.59	0.34	459.98	459.41	0.57	0.12
G	458.69	455.94	2.75	0.60	455.55	455.02	0.53	0.12
H	459.07	457.67	1.40	0.30	459.61	458.65	0.96	0.21
I	459.37	457.23	2.14	0.47	457.16	456.29	0.87	0.19

MASS OF ELECTRODES - TEST SERIES #6

	CONCRETE-EMBEDDED				BARE ELECTRODE			
SPECIMEN	BEFORE (g)	AFTER (g)	LOSS (g)	LOSS (%)	BEFORE (g)	AFTER (g)	LOSS (g)	LOSS (%)
A	460.94	445.11	15.83	3.43	457.24	456.00	1.24	0.27
B	458.08	450.33	7.75	1.69	460.91	460.19	0.72	0.16
C	466.74	463.32	3.42	0.73	457.32	456.93	0.39	0.09
D	460.01	453.89	6.12	1.33	457.94	457.51	0.43	0.09
E	461.45	460.69	0.76	0.16	465.92	465.16	0.76	0.16
F	455.32	454.65	0.67	0.15	456.33	455.70	0.63	0.14
G	455.48	454.58	0.90	0.20	454.42	453.71	0.71	0.16
H	464.57	464.52	0.05	0.01	458.98	458.55	0.43	0.09
I	457.21	456.78	0.43	0.09	464.91	464.45	0.46	0.10

Table G-1: RESULTS OF MASS MEASUREMENTS

MASS OF ELECTRODES - TEST SERIES #7

	CONCRETE-EMBEDDED				BARE ELECTRODE			
SPECIMEN	BEFORE (g)	AFTER (g)	LOSS (g)	LOSS (%)	BEFORE (g)	AFTER (g)	LOSS (g)	LOSS (%)
A	457.73	365.57	92.16	20.13	450.62	446.86	3.76	0.83
B	464.06	399.28	64.78	13.96	451.22	448.57	2.65	0.59
C	454.62	454.25	0.37	0.08	455.56	454.63	0.93	0.20
D	456.82	456.09	0.73	0.16	457.71	457.46	0.25	0.05
E	450.50	449.99	0.51	0.11	458.21	457.53	0.68	0.15

Table G-2: RESULTS OF MASS MEASUREMENTS

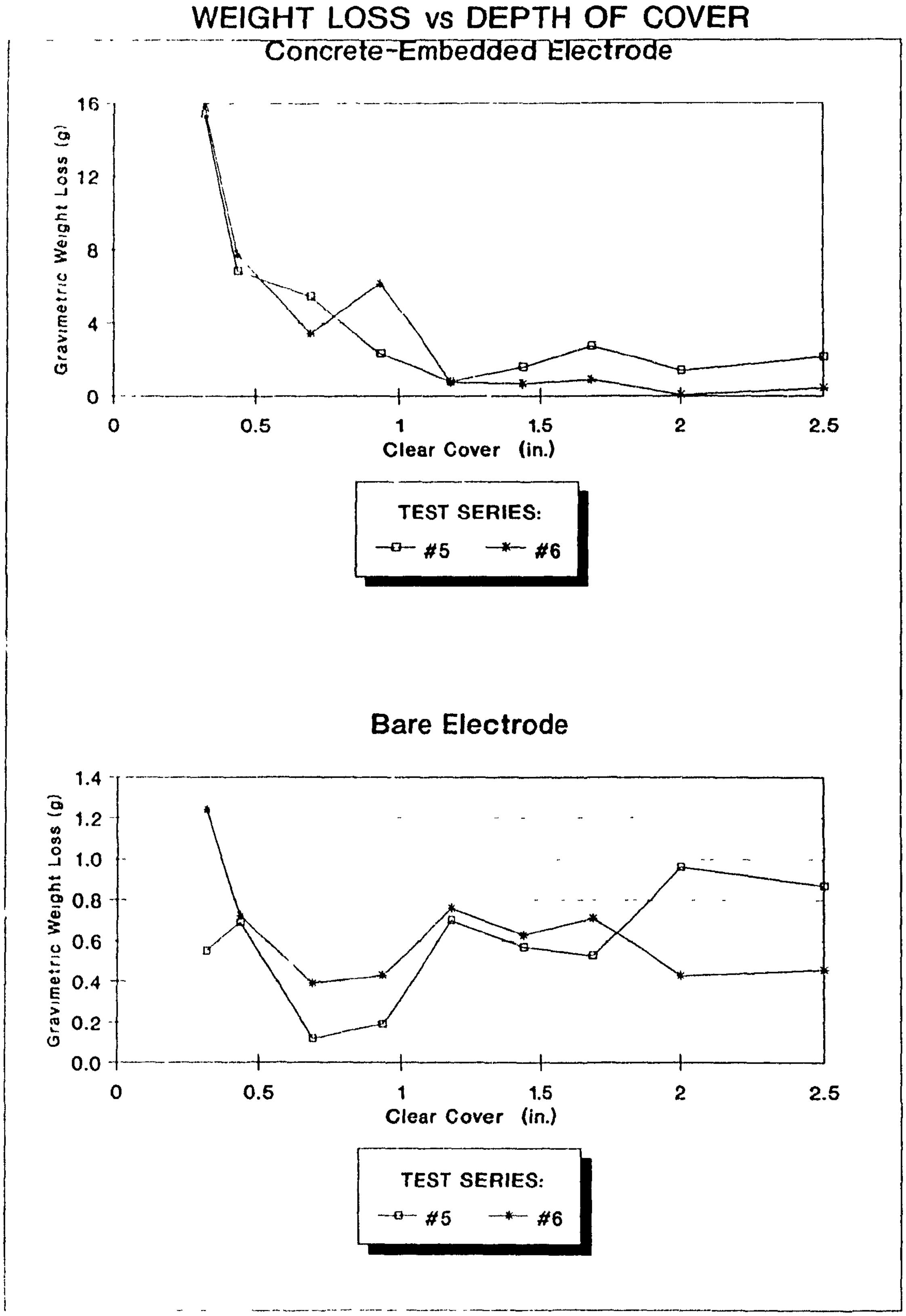
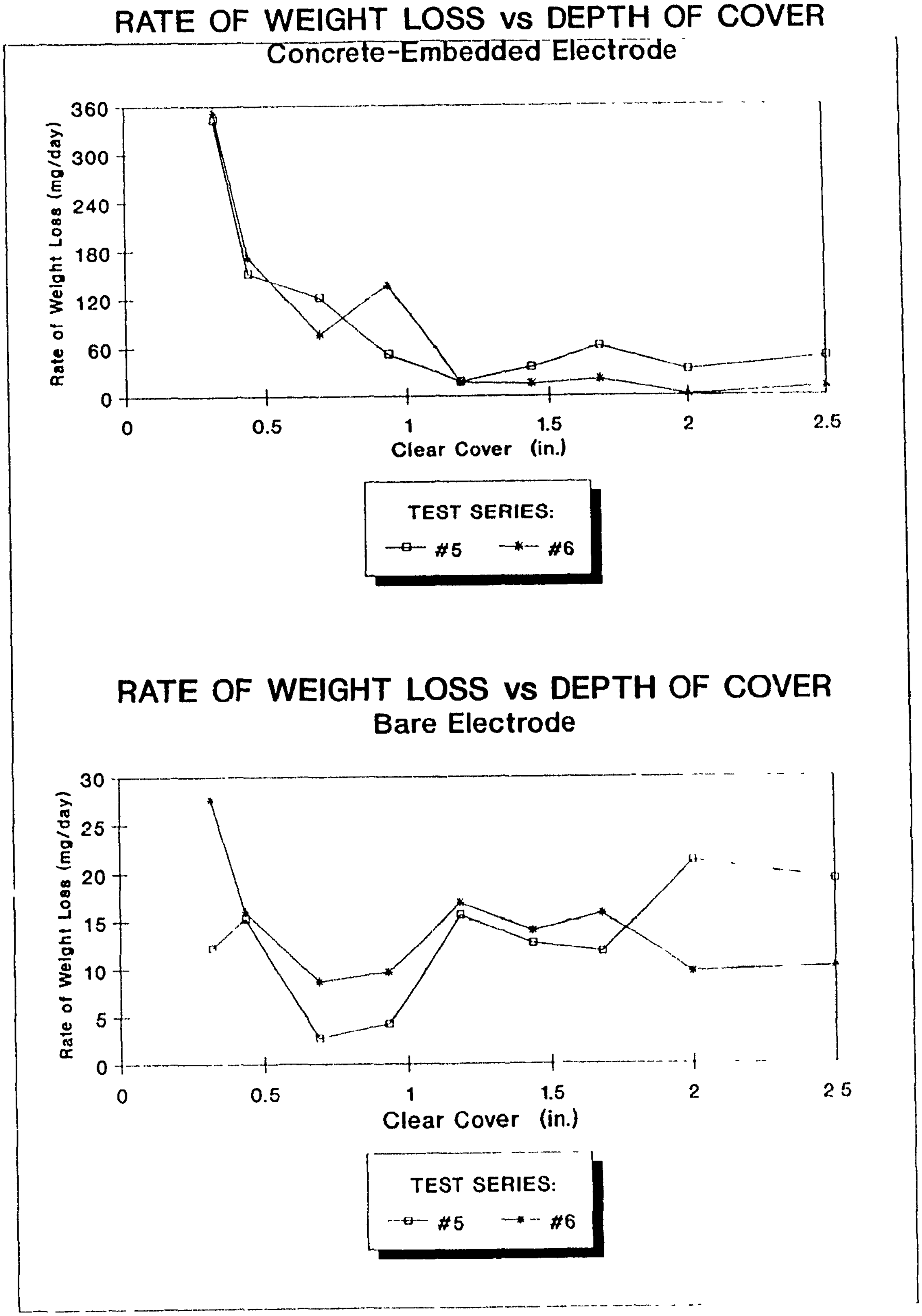


Figure G-1: Weight Loss vs Depth of Cover



RATE OF WEIGHT LOSS vs DEPTH OF COVER
Concrete-Embedded Electrode

RATE OF WEIGHT LOSS vs DEPTH OF COVER
Bare Electrode

Figure G-2: Rate of Weight Loss vs Depth of Cover

APPENDIX H

Tensile Strength Results

The results of tensile strength tests performed on the electrodes used are presented in this appendix. Both the yield and ultimate strength characteristics, for both the anodes and cathodes, are presented. The true ultimate stresses are then compared to the nominal stresses. These include the results of tests on five specimens, 12 in. (305 mm) long, tested to obtain the typical stress-strain response.

TENSION TESTS - CONTROL SPECIMENS

Specimen #: 1
Date: 15-01-1991

Gauge length: 2 in.
Average diameter: 0.637 in.
Nominal diameter: 0.630 in.

	LOAD (kips)	TRUE STRENGTH (ksi)	TRUE STRENGTH (MPa)	NOMINAL STRENGTH (MPa)	ELONGATION (x10E-4)	STRAIN
	0.5	1.6	10.8	11.1	0	0
	3.0	9.4	64.9	66.4	0	0
	6.0	18.8	129.8	132.7	6	0.0003
	9.0	28.2	194.7	199.1	10	0.0005
	12.0	37.7	259.6	265.4	17	0.0009
	15.0	47.1	324.5	331.8	24	0.0012
	18.0	56.5	389.4	398.1	32	0.0016
	19.0	59.6	411.1	420.2	35	0.0018
Yield	19.2	60.2	415.4	424.7	36	0.0018
	19.5	61.2	421.9	431.3	106	0.0053
	20.0	62.8	432.7	442.4	196	0.0098
	20.5	64.3	443.5	453.4	224	0.0112
	21.0	65.9	454.3	464.5	246	0.0123
	21.5	67.5	465.1	475.5	278	0.0139
Ultimate	30.8	96.6	666.3	681.2		

Table H-1: RESULTS OF TENSILE STRENGTH TESTS
CONTROL SPECIMEN #1

TENSION TESTS - CONTROL SPECIMENS

Specimen #: 2
Date: 15-01-1991

Gauge length: 2 in.
Average diameter: 0.629 in.
Nominal diameter: 0.630 in.

	LOAD (kips)	TRUE STRENGTH (ksi)	TRUE STRENGTH (MPa)	NOMINAL STRENGTH (MPa)	ELONGATION (x10E-4)	STRAIN
	0.5	1.6	11.1	11.1	0	0
	3.0	9.7	66.6	66.4	0	0
	4.0	12.9	88.8	88.5	2	0.0001
	6.0	19.3	133.1	132.7	6	0.0003
	9.0	29.0	199.7	199.1	14	0.0007
	12.0	38.6	266.3	265.4	21	0.0011
	15.0	48.3	332.8	331.8	28	0.0014
	18.0	57.9	399.4	398.1	39	0.0020
	18.5	59.5	410.5	409.2	41	0.0021
	19.0	61.1	421.6	420.2	43	0.0022
	19.5	62.8	432.7	431.3	45	0.0023
Yield	20.0	64.4	443.8	442.4	46	0.0023
	20 5	66.0	454.9	453.4	174	0.0087
	21.0	67.6	466.0	464.5	199	0.0100
	22.0	70.8	488.1	486.6	254	0.0127
	23.0	74.0	510.3	508.7	310	0.0155
	24.0	77.2	532.5	530.8	368	0.0184
	25.0	80.5	554.7	553.0	436	0.0218
Ultimate	31.6	101.7	701.2	698.9		

Table H-2: RESULTS OF TENSILE STRENGTH TESTS
CONTROL SPECIMEN #2

TENSION TESTS - CONTROL SPECIMENS

Specimen #: 3
Date: 15-01-1991
Gauge length: 2 in.
Average diameter: 0.628 in.
Nominal diameter: 0.630 in.

	LOAD (kips)	TRUE STRENGTH (ksi)	TRUE STRENGTH (MPa)	NOMINAL STRENGTH (MPa)	ELONGATION (x10E-4)	STRAIN
	0.5	1.6	11.1	11.1	0	0
	3.0	9.7	66.8	66.4	5	0.0003
	6.0	19.4	133.6	132.7	11	0.0006
	9.0	29.1	200.3	199.1	18	0.0009
	12.0	38.7	267.1	265.4	25	0.0013
	15.0	48.4	333.9	331.8	32	0.0016
	18.0	58.1	400.7	398.1	40	0.0020
	18.5	59.7	411.8	409.2	42	0.0021
	19.0	61.3	422.9	420.2	44	0.0022
Yield	19.4	62.6	431.8	429.1	46	0.0023
	19.5	63.0	434.1	431.3	80	0.0040
	20.0	64.6	445.2	442.4	180	0.0090
	20.5	66.2	456.3	453.4	208	0.0104
	21.0	67.8	467.4	464.5	231	0.0116
	22.0	71.0	489.7	486.6	290	0.0145
	23.0	74.3	512.0	508.7	353	0.0177
	24.0	77.5	534.2	530.8	414	0.0207
	25.0	80.7	556.5	553.0	491	0.0246
Ultimate	31.0	100.1	690.0	685.7		

Table H-3: RESULTS OF TENSILE STRENGTH TESTS
CONTROL SPECIMEN #3

TENSION TESTS - CONTROL SPECIMENS

Specimen #: 4
Date: 15-01-1991

Gauge length: 2 in
Average diameter 0.618 in
Nominal diameter: 0.630 in.

	LOAD (kips)	TRUE STRENGTH (ksi)	TRUE STRENGTH (MPa)	NOMINAL STRENGTH (MPa)	ELONGATION (x10E-4)	STRAIN
	0.5	1.7	11.5	11.1	0	0
	3.0	10.0	69.0	66.4	0	0.0000
	6.0	20.0	137.9	132.7	3	0.0002
	9.0	30.0	206.9	199.1	8	0.0004
	12.0	40.0	275.8	265.4	15	0.0008
	15.0	50.0	344.8	331.8	22	0.0011
	18.0	60.0	413.7	398.1	31	0.0016
	18.5	61.7	425.2	409.2	32	0.0016
	19.0	63.3	436.7	420.2	33	0.0017
Yield	19.4	64.7	445.9	429.1	34	0.0017
Ultimate	30.8	102.7	708.0	681.2		

Table H-4: RESULTS OF TENSILE STRENGTH TESTS
CONTROL SPECIMEN #4

TENSION TESTS - CONTROL SPECIMENS

Specimen #:	5	Gauge length:	2 in.
Date:	15-01-1991	Average diameter:	0.633 in.
		Nominal diameter:	0.630 in.

	LOAD (kips)	TRUE STRENGTH (ksi)	TRUE STRENGTH (MPa)	NOMINAL STRENGTH (MPa)	ELONGATION (x10E-4)	STRAIN
	0.5	1.6	11.0	11.1	0	0
	3.0	9.5	65.7	66.4	7	0.0004
	6.0	19.1	131.5	132.7	14	0.0007
	9.0	28.6	197.2	199.1	21	0.0011
	12.0	38.1	262.9	265.4	28	0.0014
	15.0	47.7	328.6	331.8	35	0.0018
	18.0	57.2	394.4	398.1	46	0.0023
	18.5	58.8	405.3	409.2	48	0.0024
	19.0	60.4	416.3	420.2	52	0.0026
Yield	19.4	61.6	425.0	429.1	54	0.0027
	19.5	62.0	427.2	431.3	55	0.0028
	20.0	63.6	438.2	442.4	204	0.0102
	20.5	65.1	449.1	453.4	230	0.0115
	21.0	66.7	460.1	464.5	257	0.0129
	22.0	69.9	482.0	486.6	311	0.0156
	23.0	73.1	503.9	508.7	373	0.0187
	24.0	76.3	525.8	530.8	438	0.0219
	25.0	79 4	547.7	553.0	512	0.0256
Ultimate	31.0	98.5	679.2	685.7		

Table H-5: RESULTS OF TENSILE STRENGTH TESTS
CONTROL SPECIMEN #5

TENSION TESTS - TEST SERIES #5

Specimen Types: ANODES
Date: 25-03-1991

YIELD STRENGTHS

Specimen #	Average Diameter (in.)	LOAD (kips)	TRUE YIELD STRENGTH (ksi)	TRUE YIELD STRENGTH (MPa)	NOMINAL YIELD STRENGTH (MPa)
A	0.593	20.2	73.1	504.3	446.8
B	0.607	19.4	67.2	463.0	429.1
C	0.592	19.6	71.3	491.8	433.5
D	0.585	19.2	71.4	492.5	424.7
E	0.598	19.6	69.8	481.2	433.5
F	0.604	19.2	67.1	462.8	424.7
G	0.620	19.6	64.9	447.6	433.5
H	0.608	19.9	68.5	472.6	440.2
I	0.615	19.5	65.6	452.6	431.3

ULTIMATE STRENGTHS

Specimen #	Average Diameter (in.)	LOAD (kips)	TRUE ULTIMATE STRENGTH (ksi)	TRUE ULTIMATE STRENGTH (MPa)	NOMINAL ULTIMATE STRENGTH (MPa)
A	0.593	28.6	103.6	714.0	632.6
B	0.607	30.3	104.9	723.1	670.2
C	0.592	30.1	109.5	755.2	665.8
D	0.585	30.2	112.4	774.7	668.0
E	0.598	30.5	108.6	748.7	674.6
F	0.604	30.6	107.0	737.6	676.8
G	0.620	31.0	102.7	708.0	685.7
H	0.608	31.3	107.8	743.3	692.3
I	0.615	31.0	104.4	719.5	685.7

Note: Specimens A, B, and C exhibited a brittle response upon failure

Table H-6: RESULTS OF TENSILE STRENGTH TESTS
TEST SERIES #5 - ANODE SPECIMENS

TENSION TESTS - TEST SERIES #5

Specimen Types: CATHODES
Date: 28-02-1991

YIELD STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE YIELD STRENGTH (ksi)	TRUE YIELD STRENGTH (MPa)	NOMINAL YIELD STRENGTH (MPa)
A	0.579	19.2	72.9	502.8	424.7
B	0.579	19.4	73.8	508.9	429.1
C	0.611	19.6	66.8	460.9	433.5
D	0.613	19.8	67.2	463.3	437.9
E	0.592	19.6	71.3	491.8	433.5
F	0.584	19.8	73.9	509.6	437.9
G	0.585	19.6	72.9	502.8	433.5
H	0.578	19.6	74.7	515.0	433.5
I	0.590	20.1	73.6	507.8	444.6

ULTIMATE STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE ULTIMATE STRENGTH (ksi)	TRUE ULTIMATE STRENGTH (MPa)	NOMINAL ULTIMATE STRENGTH (MPa)
A	0.579	31.0	117.7	811.8	685.7
B	0.579	31.0	117.9	813.2	685.7
C	0.611	31.3	106.8	736.0	692.3
D	0.613	31.3	106.2	732.4	692.3
E	0.592	31.2	113.5	782.8	690.1
F	0.584	31.3	116.9	805.7	692.3
G	0.585	31.2	116.1	800.3	690.1
H	0.578	31.2	118.9	819.8	690.1
I	0.590	31.6	115.8	798.3	698.9

Note: Specimens A, B, and C exhibited a brittle response upon failure

Table H-7: RESULTS OF TENSILE STRENGTH TESTS
TEST SERIES #5 - CATHODE SPECIMENS

TENSION TESTS - TEST SERIES #6

Specimen Types: ANODES
Date: 02-05-1991

YIELD STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE YIELD STRENGTH (ksi)	TRUE YIELD STRENGTH (MPa)	NOMINAL YIELD STRENGTH (MPa)
A	0.582	19.6	73.8	508.8	433.5
B	0.570	19.5	76.6	527.8	431.3
C	0.578	19.7	75.1	517.7	435.7
D	0.584	19.7	73.7	507.9	435.7
E	0.589	19.5	71.7	494.3	431.3
F	0.570	19.5	76.4	526.9	431.3
G	0.575	19.6	75.5	520.4	433.5
H	0.581	19.8	74.8	515.8	437.9
I	0.583	19.4	72.7	501.1	429.1

ULTIMATE STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE ULTIMATE STRENGTH (ksi)	TRUE ULTIMATE STRENGTH (MPa)	NOMINAL ULTIMATE STRENGTH (MPa)
A	0.582	28.4	106.9	737.3	628.2
B	0.570	29.9	117.4	809.3	661.3
C	0.578	30.9	117.8	812.0	683.4
D	0.584	30.9	115.6	796.7	683.4
E	0.589	31.1	114.3	788.3	687.9
F	0.570	31.2	122.3	843.0	690.1
G	0.575	31.1	119.8	825.8	687.9
H	0.581	31.3	118.3	815.4	692.3
I	0.583	31.0	116.1	800.7	685.7

Note: Specimens A, B, and C exhibited a brittle response upon failure

Table H-8: RESULTS OF TENSILE STRENGTH TESTS
TEST SERIES #6 - ANODE SPECIMENS

TENSION TESTS - TEST SERIES #6

Specimen Types: CATHODES
Date: 02-05-1991

YIELD STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE YIELD STRENGTH (ksi)	TRUE YIELD STRENGTH (MPa)	NOMINAL YIELD STRENGTH (MPa)
A	0.578	19.2	73.3	505.4	424.7
B	0.579	19.5	74.1	510.6	431.3
C	0.587	19.6	72.5	500.2	433.5
D	0.588	19.6	72.3	498.5	433.5
E	0.581	19.7	74.3	512.3	435.7
F	0.581	19.5	73.6	507.1	431.3
G	0.582	19.6	73.8	508.8	433.5
H	0.586	19.6	72.8	501.9	433.5
I	0.584	19.9	74.4	513.1	440.2

ULTIMATE STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE ULTIMATE STRENGTH (ksi)	TRUE ULTIMATE STRENGTH (MPa)	NOMINAL ULTIMATE STRENGTH (MPa)
A	0.578	30.7	117.2	808.1	679.0
B	0.579	31.1	118.1	814.4	687.9
C	0.587	31.2	115.5	796.2	690.1
D	0.588	31.0	114.4	788.5	685.7
E	0.581	31.2	117.7	811.4	690.1
F	0.581	31.1	117.3	808.8	687.9
G	0.582	31.1	117.1	807.4	687.9
H	0.586	30.9	114.8	791.3	683.4
I	0.584	31.5	117.8	812.2	696.7

Note: Specimens A, B, and C exhibited a brittle response upon failure

Table H-9: RESULTS OF TENSILE STRENGTH TESTS
TEST SERIES #6 - CATHODE SPECIMENS

TENSION TESTS - TEST SERIES #7

Date: 17-06-1991
Specimen Types: ANODES

YIELD STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE YIELD STRENGTH (ksi)	TRUE YIELD STRENGTH (MPa)	NOMINAL YIELD STRENGTH (MPa)
A	0.362	----	----	----	----
B	0.473	20.0	113.8	784.8	442.4
C	0.582	19.4	73.0	503.7	429.1
D	0.582	19.6	73.7	508.0	433.5
E	0.590	20.1	73.6	507.8	444.6

ULTIMATE STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE ULTIMATE STRENGTH (ksi)	TRUE ULTIMATE STRENGTH (MPa)	NOMINAL ULTIMATE STRENGTH (MPa)
A	0.362	13.8	134.5	927.0	305.2
B	0.473	21.0	119.5	824.0	464.5
C	0.582	30.9	116.4	802.2	683.4
D	0.582	31.0	116.5	803.4	685.7
E	0.590	30.3	111.0	765.4	670.2

Table H-10: RESULTS OF TENSILE STRENGTH TESTS
TEST SERIES #7 - ANODE SPECIMENS

TENSION TESTS - TEST SERIES #7

Date: 17-06-1991
Specimen Types: CATHODES

YIELD STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE YIELD STRENGTH (ksi)	TRUE YIELD STRENGTH (MPa)	NOMINAL YIELD STRENGTH (MPa)
A	0.578	19.4	74.1	510.7	429.1
B	0.573	19.6	76.0	524.1	433.5
C	0.584	19.7	73.5	507.1	435.7
D	0.576	19.6	75.3	519.5	433.5
E	0.581	19.7	74.3	512.3	435.7

ULTIMATE STRENGTHS

Specimen	Average Diameter (in.)	LOAD (kips)	TRUE ULTIMATE STRENGTH (ksi)	TRUE ULTIMATE STRENGTH (MPa)	NOMINAL ULTIMATE STRENGTH (MPa)
A	0.578	30.7	117.2	808.1	679.0
B	0.573	31.1	120.6	831.5	687.9
C	0.584	30.9	115.4	795.4	683.4
D	0.576	31.0	119.2	821.7	685.7
E	0.581	31.1	117.3	808.8	687.9

Table H-11: RESULTS OF TENSILE STRENGTH TESTS
TEST SERIES #7 - CATHODE SPECIMENS

APPENDIX I

Electrode Polarization Potentials

Using the corresponding half-cell potential equations for the normal or the reversed polarity positions, the pH values at the metal surface were determined for every operating potential E recorded for each specimen in a test series. These figures, along with the average pH values, are presented in this appendix. Additionally, charts are plotted to depict these results.

ELECTRODE POLARIZATION POTENTIALS
NORMAL POLARITY

Half Cell Potential Equation: E = -0.987 + (0.059 * pH)

TEST SERIES #5

5A	5B	5C	5D	5E	5F	5G	5H	5I
7.41	1.47	0.12	7.58	4.36	7.07	7.07	11.47	8.08
6.56	3.34	-2.42	6.90	5.71	6.73	8.93	9.61	8.08
6.39	1.64	0.97	7.41	5.20	6.39	8.59	9.78	6.39
6.73	1.47	2.83	7.24	5.20	6.56	8.76	9.44	6.22
7.07	1.47	5.71	6.73	5.03	6.90	9.10	9.10	5.37
7.24	2.83	6.56	6.90	6.39	7.41	9.61	8.42	5.71
7.24	1.81	7.07	7.41	6.90	6.56	8.25	10.80	5.71
7.75	2.32	7.41	6.90	6.56	8.76	10.12	9.78	5.71
7.75	3.00	7.41	7.41	6.90	8.76	10.29	10.63	5.88
7.58	2.49	7.75	6.73	7.92	8.59	10.97	10.97	5.37
7.75	2.49	7.75	7.41	8.08	8.59	11.47	11.14	6.22
7.75	2.66	7.75	7.41	8.42	8.76	10.46	11.31	5.54
7.75	2.66	7.75	7.41	8.42	8.76	10.29	11.31	5.54
7.92	2.66	7.92	7.41	8.42	8.76	10.46	11.47	5.71
7.92	2.66	7.92	7.41	8.42	8.76	10.46	11.81	5.71
7.92	2.32	7.92	7.41	8.93	8.93	10.63	12.83	8.08
7.92	3.34	7.92	7.41	8.25	8.76	10.63	13.00	8.08
7.92	4.36	7.92	7.41	7.92	8.76	10.63	13.17	8.08
7.75	1.98	7.92	7.07	8.59	8.93	11.64	12.83	8.25
7.92	2.32	7.92	7.24	8.42	8.93	11.64	13.00	8.25
7.92	2.15	7.92	7.41	8.42	8.93	11.47	11.14	9.27
7.92	2.32	7.92	7.58	8.59	8.76	12.15	11.31	9.61
7.92	2.49	7.92	7.58	8.42	8.93	11.81	11.64	8.93
7.92	3.00	7.92	7.58	8.76	8.76	11.47	11.98	9.44
7.92	3.17	7.92	7.75	8.93	8.76	11.31	11.98	9.44
8.08	3.51	7.75	7.75	8.93	8.76	11.14	12.15	9.44
8.08	3.51	7.75	7.75	9.10	8.76	10.97	11.81	9.44
8.08	3.17	7.75	7.58	8.76	8.76	11.14	10.63	10.46
8.08	3.68	7.75	7.58	8.76	8.76	10.97	11.14	10.29
8.08	2.83	7.75	7.41	8.76	8.76	10.97	10.97	10.63
8.08	2.83	7.92	7.58	8.76	8.76	11.14	11.98	10.12
8.08	3.00	7.92	7.58	8.76	8.76	11.14	11.98	10.12
8.08	3.17	7.92	7.75	8.59	8.76	11.47	11.81	10.46
8.08	3.17	7.92	7.75	8.59	8.76	11.47	11.81	10.46
8.08	3.17	7.92	7.75	8.76	8.76	11.47	11.81	10.46
8.08	3.51	7.92	7.75	8.76	8.76	10.80	11.31	10.80
8.08	3.51	7.92	7.75	8.59	8.76	10.80	11.47	10.63

AVERAGE VALUES:

5A	5B	5C	5D	5E	5F	5G	5H	5I
7.75	2.74	6.91	7.42	7.90	8.41	10.59	11.32	8.16

Table I-1: ELECTRODE POLARIZATION POTENTIALS
TEST SERIES #5 - NORMAL POLARITY

ELECTRODE POLARIZATION POTENTIALS
REVERSED POLARITY

Half Cell Potential Equation: E = 0.242 + (0.059 * pH)

TEST SERIES #5

5A	5B	5C	5D	5E	5F	5G	5H	5I
10.64	18.61	18.10	11.66	13.02	12.34	13.02	15.56	13.86
9.46	13.36	14.37	12.85	14.88	14.20	14.54	14.20	14.71
8.27	11.66	14.20	12.85	14.54	14.37	14.71	14.37	14.37
7.93	11.32	13.02	11.66	14.54	13.86	14.54	13.86	12.68
8.27	10.64	8.61	10.98	14.54	13.69	11.66	11.49	12.17
7.25	11.15	8.61	10.14	14.54	13.19	14.03	13.86	14.03
7.08	10.64	8.10	10.31	14.54	13.36	14.37	13.36	13.19
6.92	9.80	7.59	9.29	13.69	12.68	14.20	13.69	13.53
6.92	10.47	7.25	9.12	13.69	12.34	14.03	13.86	14.20
6.92	10.14	6.92	8.78	13.36	11.49	13.36	13.53	14.20
6.75	10.98	6.92	8.61	13.53	12.51	10.64	13.69	13.69
6.58	10.81	6.92	8.61	13.36	12.17	10.81	13.53	13.86
6.41	10.81	6.75	8.61	13.36	12.00	10.81	13.53	13.69
6.41	10.81	6.75	8.61	13.36	12.00	10.81	13.53	13.69
6.41	10.14	6.24	7.93	13.02	9.97	12.17	13.36	13.19
6.41	10.47	6.24	7.76	13.02	9.97	11.83	13.69	13.19
6.41	10.14	6.24	7.93	12.85	9.80	11.66	13.69	13.19
6.24	9.97	6.07	8.44	12.85	9.80	11.49	14.03	13.02
6.24	9.46	5.73	7.25	12.00	9.63	12.17	14.20	13.02
6.41	9.29	5.73	7.25	11.83	9.97	12.17	14.54	13.19
6.24	9.46	5.90	6.92	11.32	10.64	11.66	13.69	12.85
6.24	10.31	6.24	6.92	11.66	8.78	12.34	13.02	12.17
6.24	9.29	6.41	6.75	10.81	10.81	12.34	13.02	10.98
6.07	8.78	6.24	6.92	11.49	11.49	13.86	13.53	12.51
6.07	9.29	6.24	6.92	11.49	11.15	13.53	13.53	12.51
6.07	9.63	6.07	6.75	11.49	10.98	13.53	13.53	12.51
6.07	9.29	6.24	6.75	11.32	10.14	12.34	13.19	12.68
5.90	9.97	5.90	6.75	11.15	10.81	13.86	13.69	12.85
5.90	9.97	5.73	6.75	11.15	10.64	13.53	14.03	13.53
5.90	10.31	5.90	6.58	10.98	11.15	13.69	14.03	13.53
5.73	10.31	6.07	6.75	10.98	11.15	13.86	13.86	13.36
5.73	10.14	6.07	6.58	11.15	11.15	13.86	13.86	13.19
5.73	9.80	5.56	6.07	9.29	9.12	12.68	12.00	11.83
5.73	9.63	5.56	6.07	9.63	9.63	12.34	12.00	12.00
5.73	9.80	5.56	6.24	9.46	9.97	12.34	12.17	12.17
5.90	9.29	5.73	6.75	10.98	11.15	13.86	12.17	12.17
5.90	9.29	5.73	6.75	9.97	9.97	13.02	12.17	12.00
AVERAGE VALUES:								
6.62	10.41	7.34	8.16	12.29	11.30	12.86	13.49	13.07

Table I-2: ELECTRODE POLARIZATION POTENTIALS
TEST SERIES #5 - REVERSED POLARITY

ELECTRODE POLARIZATION POTENTIALS
NORMAL POLARITY

Half Cell Potential Equation: $E = -0.987 + (0.059 * pH)$

TEST SERIES #6

6A	6B	6C	6D	6E	6F	6G	6H	6I
6.90	6.39	7.75	8.08	7.07	6.05	8.76	6.56	6.05
7.58	6.56	7.75	8.08	10.46	7.41	9.61	6.22	6.56
7.24	6.73	7.92	6.73	10.29	7.92	9.78	6.05	7.41
7.58	6.39	8.42	9.44	9.10	7.75	9.78	6.22	7.58
7.75	6.73	7.92	9.10	8.93	8.08	9.78	6.39	7.07
7.75	7.41	7.92	9.10	8.93	8.25	4.69	3.51	8.08
7.75	6.90	7.75	9.10	8.93	8.25	7.75	6.73	8.25
7.41	7.24	7.92	9.44	9.27	8.25	7.07	7.24	8.76
7.41	6.93	7.58	9.95	9.61	5.37	6.56	7.07	9.27
7.41	6.93	7.58	9.78	9.27	9.27	6.73	8.25	10.29
7.41	6.93	7.58	9.95	9.27	9.61	9.27	9.44	9.10
7.41	7.24	7.58	9.95	9.27	9.61	9.44	9.10	9.44
7.41	7.07	7.58	9.95	9.44	9.61	9.44	9.27	9.27
7.41	7.24	7.41	9.61	9.27	9.61	8.25	9.10	8.59
7.41	7.07	7.07	9.27	9.44	9.78	7.92	9.10	8.59
7.41	7.07	7.24	8.76	9.61	9.95	7.92	9.27	9.10
7.41	7.24	7.41	8.08	9.61	9.95	7.92	9.44	9.44
7.41	7.41	7.41	8.42	9.61	9.95	7.92	9.61	9.44
7.41	7.58	7.58	8.08	9.95	10.12	7.92	9.44	9.44
7.41	7.75	7.58	7.92	10.46	10.46	7.07	9.27	9.61
7.41	7.58	7.58	7.92	10.46	10.63	7.24	9.27	9.44
7.41	7.58	7.58	7.92	10.46	10.97	7.24	9.27	9.61
7.41	7.41	7.41	7.75	10.46	11.31	7.24	9.27	9.61
7.41	7.41	7.58	7.75	10.46	11.31	7.24	9.27	9.61
7.75	7.58	7.41	7.75	10.63	11.31	7.41	9.44	9.61
7.58	7.41	7.24	7.41	10.46	11.14	8.08	9.61	10.12
7.58	7.41	7.24	7.24	10.80	11.47	7.41	9.10	9.61
7.58	7.24	7.24	6.90	11.14	11.81	7.58	8.42	9.10
7.75	7.24	7.07	7.24	11.14	11.98	8.76	9.44	9.78
7.75	7.24	7.07	6.90	10.63	10.80	8.08	9.44	9.95
7.75	7.41	7.07	7.07	9.95	11.64	7.75	9.78	10.46
7.75	7.58	7.07	7.07	9.95	11.64	7.92	10.12	10.80
7.75	7.58	7.07	6.90	9.61	11.64	7.92	10.12	10.80
7.75	7.58	7.07	7.07	9.10	11.81	7.75	10.12	10.80
7.92	7.75	7.07	7.07	8.76	11.98	7.75	10.29	10.80
7.92	7.75	7.24	7.07	8.42	12.15	7.92	10.29	10.97
7.92	7.75	7.24	7.07	8.25	11.98	7.75	10.29	10.80
7.75	7.75	7.41	7.07	8.08	11.81	7.58	10.29	10.80
7.92	7.92	7.41	7.07	8.08	11.81	7.92	10.46	11.81
AVERAGE VALUES:								
7.56	7.28	7.46	8.13	9.61	10.11	7.95	8.76	9.38

Table I-3: ELECTRODE POLARIZATION POTENTIALS
TEST SERIES #6 - NORMAL POLARITY

ELECTRODE POLARIZATION POTENTIALS
REVERSED POLARITY

Half Cell Potential Equation: $E = 0.242 + (0.059 * pH)$

TEST SERIES #6

6A	6B	6C	6D	6E	6F	6G	6H	6I
12.51	11.32	12.34	13.53	13.69	13.86	17.76	14.88	14.20
10.81	10.64	13.86	14.20	13.86	14.20	18.27	14.88	14.20
10.47	10.64	13.53	14.20	13.69	13.19	18.27	13.02	12.00
9.46	9.12	13.53	14.20	14.03	13.19	18.10	14.20	13.02
8.61	8.44	12.51	14.20	14.03	13.02	18.44	12.34	11.49
8.44	8.78	12.00	14.20	14.03	13.19	17.93	14.20	13.36
8.44	8.61	12.00	14.03	13.86	13.19	18.44	14.20	13.02
7.08	8.78	11.83	13.69	13.69	13.36	18.61	12.51	11.66
7.76	8.95	11.66	13.36	13.36	13.53	17.59	13.36	12.34
7.59	8.78	11.32	13.86	13.53	13.69	18.44	13.19	12.17
7.59	7.93	9.12	13.86	13.36	13.86	17.93	13.19	12.17
7.42	8.10	10.98	13.69	13.36	13.69	17.76	13.02	12.17
7.42	8.10	9.63	13.86	13.36	13.86	17.93	13.19	12.17
7.25	7.08	7.76	12.68	14.20	13.69	17.59	14.03	13.86
7.25	7.08	7.93	12.34	14.20	13.86	17.93	14.03	13.69
7.08	7.25	8.10	12.34	13.36	13.86	17.76	13.86	13.53
7.08	7.59	8.10	12.17	13.02	14.03	17.76	13.86	13.19
7.08	7.42	8.10	12.17	13.19	13.86	17.59	13.69	13.19
7.08	7.59	7.93	11.32	12.85	13.86	17.76	13.69	13.02
6.24	7.59	7.93	10.64	12.68	13.86	18.10	13.69	13.02
6.07	7.59	7.93	10.81	12.68	13.86	17.93	13.69	12.85
6.07	7.42	7.76	10.47	12.34	13.69	17.59	13.69	12.85
5.90	7.25	7.42	10.31	12.00	13.53	17.59	13.53	12.85
6.07	7.25	7.42	10.47	12.00	13.69	17.59	13.69	12.68
5.73	7.25	7.42	10.47	11.83	13.69	17.59	13.53	12.68
5.90	6.41	6.75	9.63	12.34	12.85	17.08	13.53	13.69
5.73	6.41	6.75	9.12	12.51	12.68	17.25	13.02	13.69
5.73	6.41	6.58	8.95	12.51	12.34	17.25	12.85	13.69
5.73	6.07	6.41	8.10	12.00	13.19	16.75	12.51	13.02
5.73	6.24	6.24	8.27	12.34	12.34	16.07	12.51	13.53
5.56	6.24	6.41	8.61	12.85	13.02	16.58	12.68	13.53
5.39	6.07	6.41	8.27	12.17	12.68	17.08	12.17	13.53
5.56	5.90	6.24	7.93	12.00	12.85	16.92	12.17	13.36
5.56	6.07	6.24	7.93	11.83	13.02	16.75	11.83	13.19
5.73	5.90	6.24	7.76	11.32	13.02	16.75	11.83	13.02
5.39	5.90	6.24	7.59	10.64	13.19	16.58	11.66	12.85
5.56	5.73	6.07	7.59	10.14	12.85	16.24	11.49	12.68
5.73	5.56	5.90	7.42	9.80	12.85	15.56	11.49	12.00
5.22	5.56	6.07	7.42	9.80	12.85	15.73	11.49	12.00
AVERAGE VALUES:								
6.95	7.46	8.63	11.07	12.68	13.36	17.46	13.14	12.95

Table I-4: ELECTRODE POLARIZATION POTENTIALS
TEST SERIES #6 - REVERSED POLARITY

ELECTRODE POLARIZATION POTENTIALS
NORMAL POLARITY

Half Cell Potential Equation: $E = -0.987 + (0.059 * pH)$

TEST SERIES #7

7C	7D	7E
13.00	7.58	5.88
11.64	7.41	5.37
10.46	8.59	5.71
9.78	7.92	7.41
7.92	9.78	7.92
7.24	9.95	8.42
6.90	9.95	7.41
6.39	9.78	6.90
6.05	10.29	8.76
6.22	10.46	8.76
6.73	10.46	9.10
6.73	10.46	8.93
6.73	10.46	8.93
6.73	10.80	9.78
6.90	10.63	9.27
6.90	10.63	8.76
6.90	10.63	8.59
6.73	10.63	8.59
6.73	10.80	9.10
6.56	10.46	7.41
6.73	10.97	8.93
6.73	10.97	8.42
6.73	10.97	8.42
6.73	10.97	8.08
6.56	11.14	8.42
6.73	10.97	7.92
6.73	11.14	7.92
6.73	11.14	7.92
6.73	11.31	7.75
6.73	11.14	7.75
6.73	11.31	7.75
6.73	11.31	7.75
6.73	11.31	7.75
6.90	11.14	7.24
7.24	11.14	8.93
6.90	10.97	8.76
6.73	10.97	8.59
6.56	10.97	7.92
6.56	11.31	9.61
AVERAGE VALUES:		
7.22	10.48	8.12

Table I-5: Electrode Polarization Potentials
Test Series #7 - Normal Polarity

ELECTRODE POLARIZATION POTENTIALS
REVERSED POLARITY

Half Cell Potential Equation: E = 0.242 + [illegible]59 * pH)

TEST SERIES #7

7C	7D	7E
13.19	13.36	14.20
13.02	12.85	13.69
12.85	12.68	13.53
13.19	14.20	13.69
11.83	12.68	12.51
11.15	12.68	12.85
10.98	12.68	12.85
10.14	12.68	13.19
10.47	12.00	13.02
10.14	11.49	13.36
9.46	11.15	13.53
9.12	11.32	13.53
8.78	11.32	13.53
8.44	11.49	12.85
8.27	11.49	12.85
8.27	11.66	13.19
7.59	12.17	13.02
7.25	12.34	12.85
7.42	11.32	12.85
7.76	10.47	13.02
7.42	10.14	13.02
7.42	9.46	12.85
7.42	8.78	12.85
7.25	8.10	12.85
6.92	7.08	12.85
7.08	8.10	12.85
7.08	7.93	12.85
6.92	7.93	12.85
7.08	7.76	13.02
6.92	7.93	13.19
6.92	7.93	13.36
6.92	8.10	13.36
6.92	8.10	13.36
6.92	8.27	12.34
6.41	10.14	12.85
6.75	10.98	13.36
6.92	11.83	13.69
6.75	10.47	12.17
6.75	9.63	11.15
AVERAGE VALUES:		
8.51	10.53	13.05

Table I-6: ELECTRODE POLARIZATION POTENTIALS
TEST SERIES #7 - REVERSED POLARITY

pH OF CONCRETE-EMBEDDED ELECTRODES
TEST SERIES #5

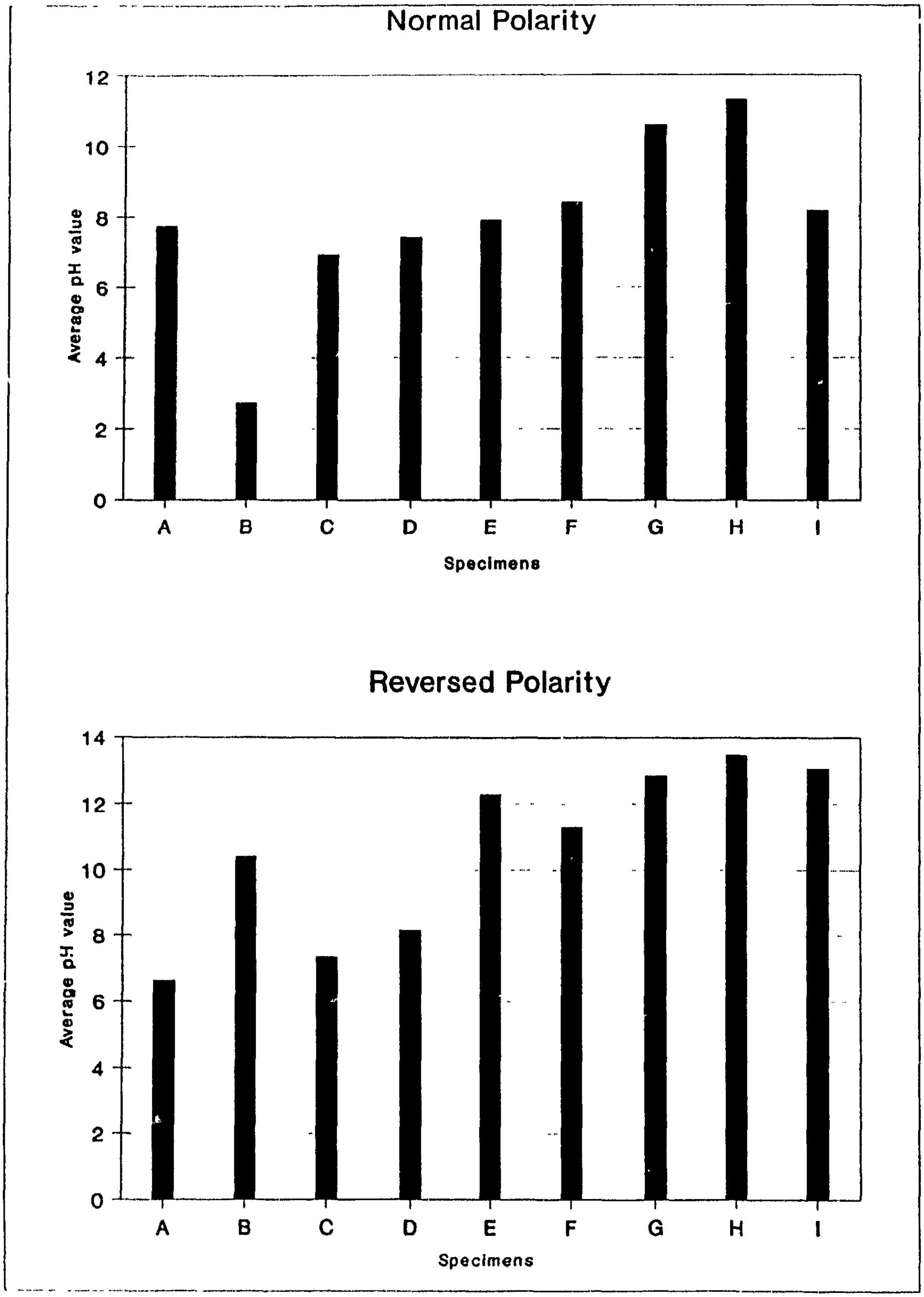


Figure I-1: pH of Concrete-Embedded Electrodes
Test Series #5

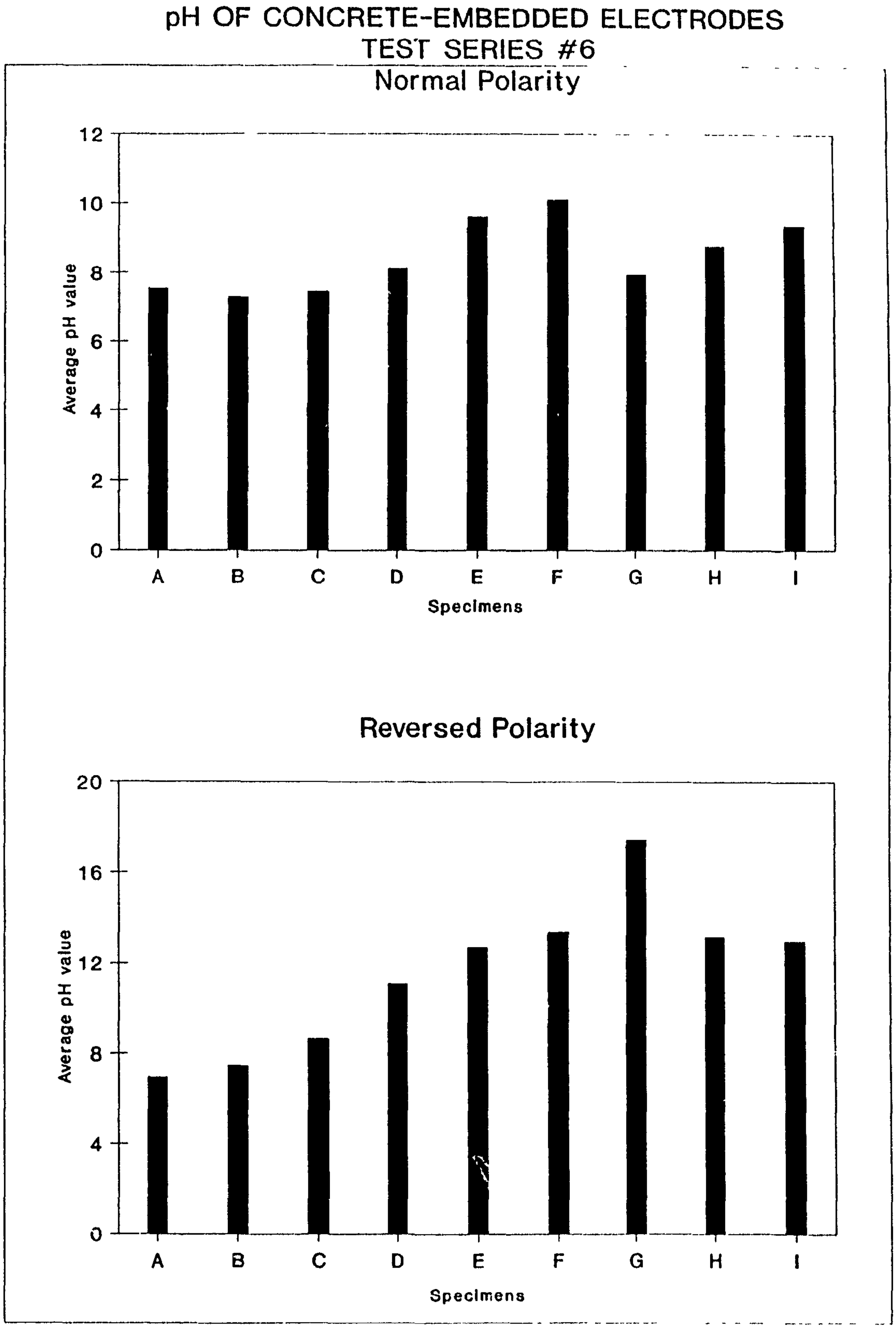


Figure I-2: pH of Concrete-Embedded Electrodes
Test Series #6

pH OF CONCRETE-EMBEDDED ELECTRODES
TEST SERIES #7

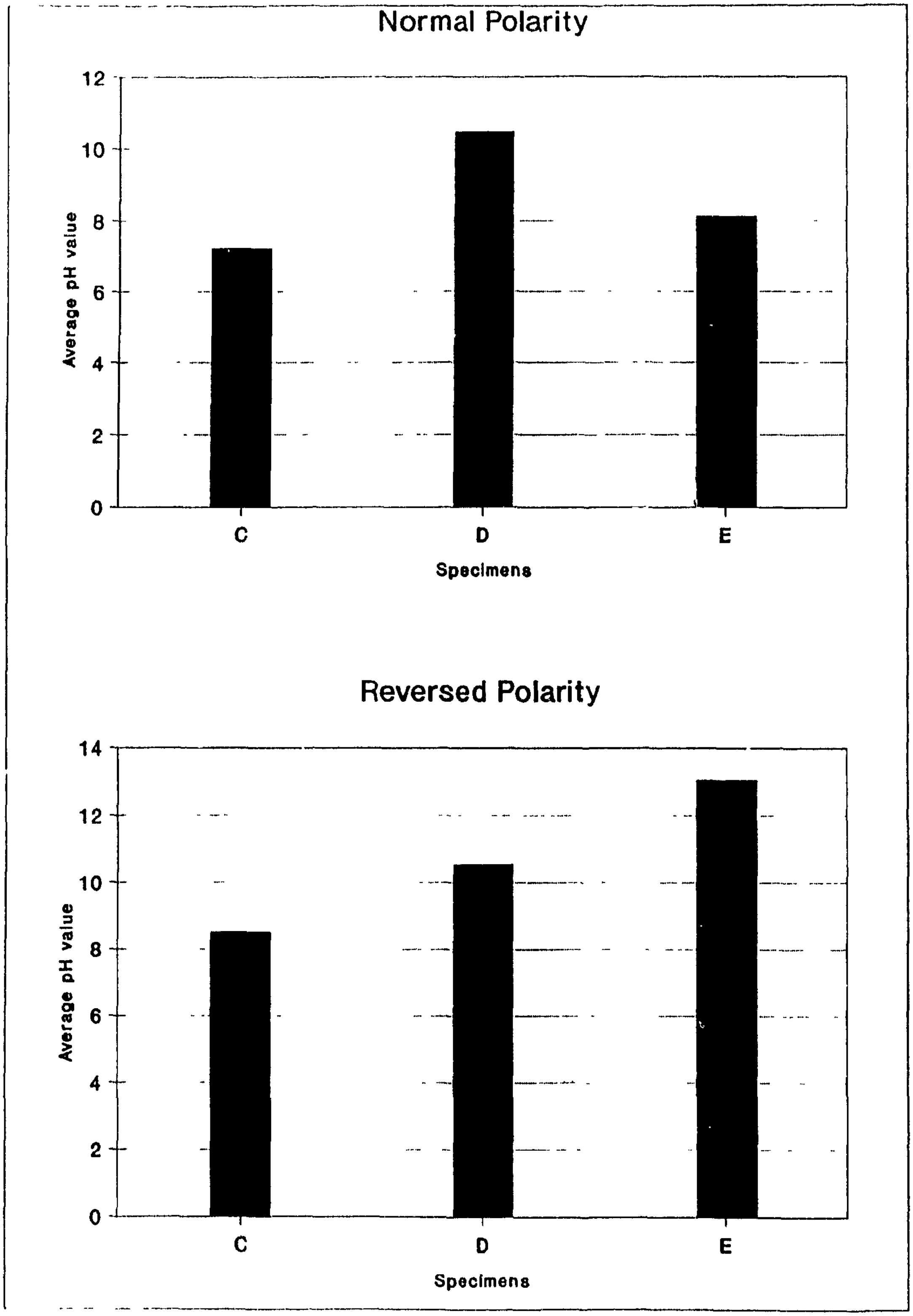
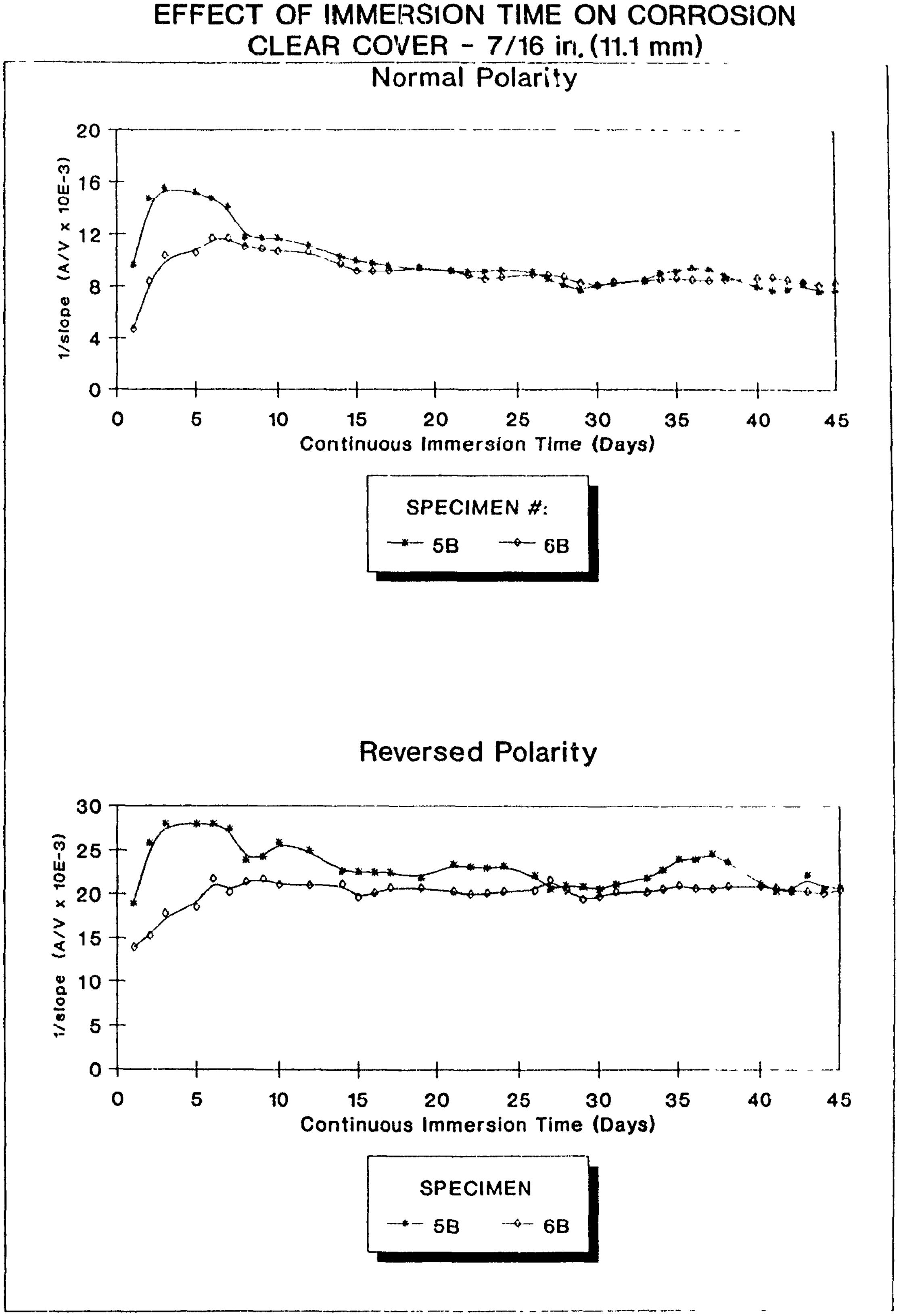


Figure I-3: pH of Concrete-Embedded Electrodes
Test Series #7

APPENDIX J

Electrode Resistance Results

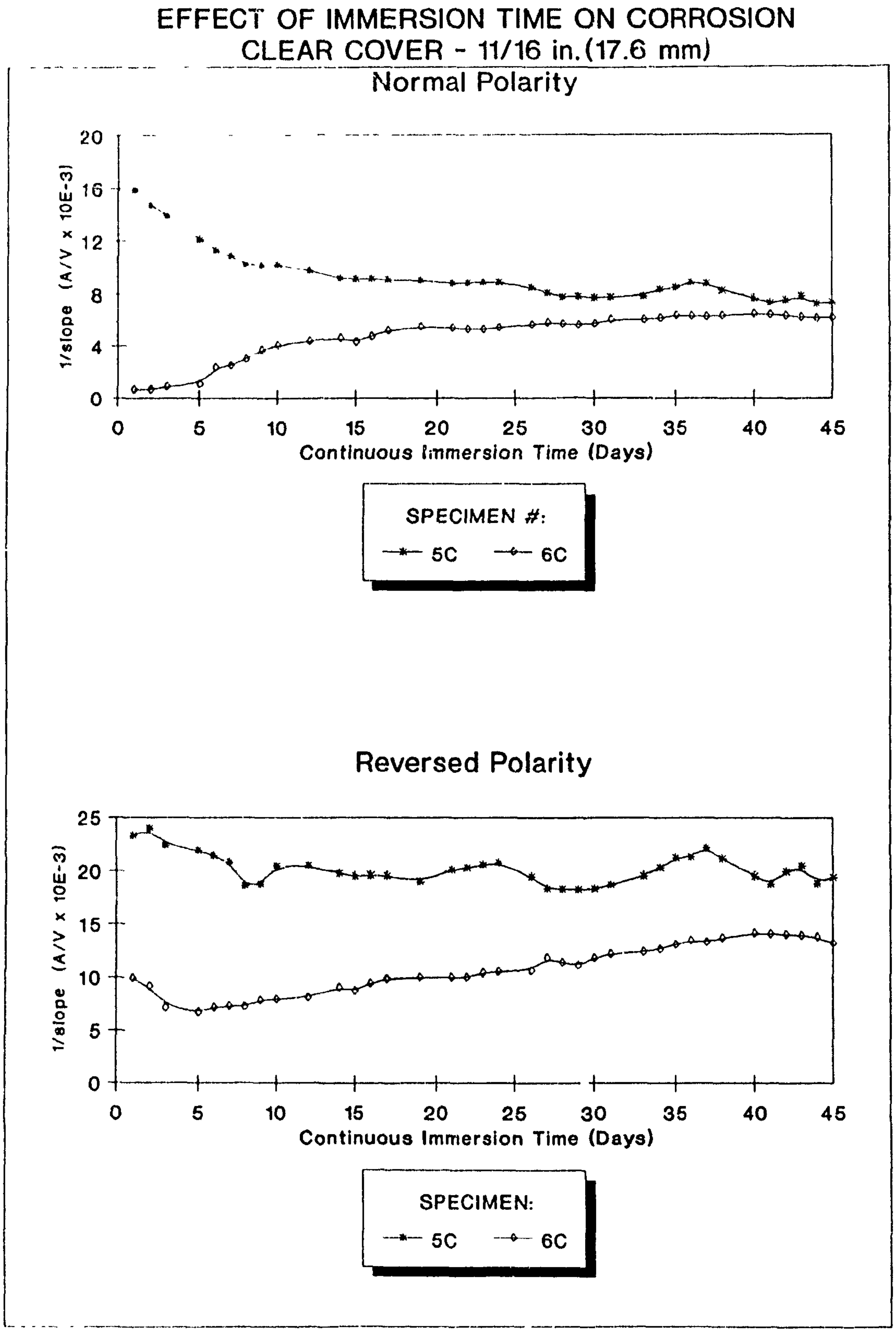
The following graphs represent the ohmic resistance offered by the pair of electrodes, not the "polarization" resistance of each electrode. It is computed by considering the measured current, A, and the corresponding voltage, V, across the "system". In this case, 1/resistance (i.e., A/V) is plotted to illustrate the effect of immersion time on corrosion. Corresponding specimens from Test Series #5 and #6, having the same cover depth, are compared, while those of the specimens in Test Series #7 are also presented.


EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 7/16 in. (11.1 mm)

Normal Polarity

Reversed Polarity

Figure J-1: Specimens #5B and #6B
Effect of Immersion Time on Corrosion



EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 11/16 in.(17.6 mm)

Normal Polarity

Reversed Polarity

Figure J-2: Specimens #5C and #6C
Effect of Immersion Time on Corrosion

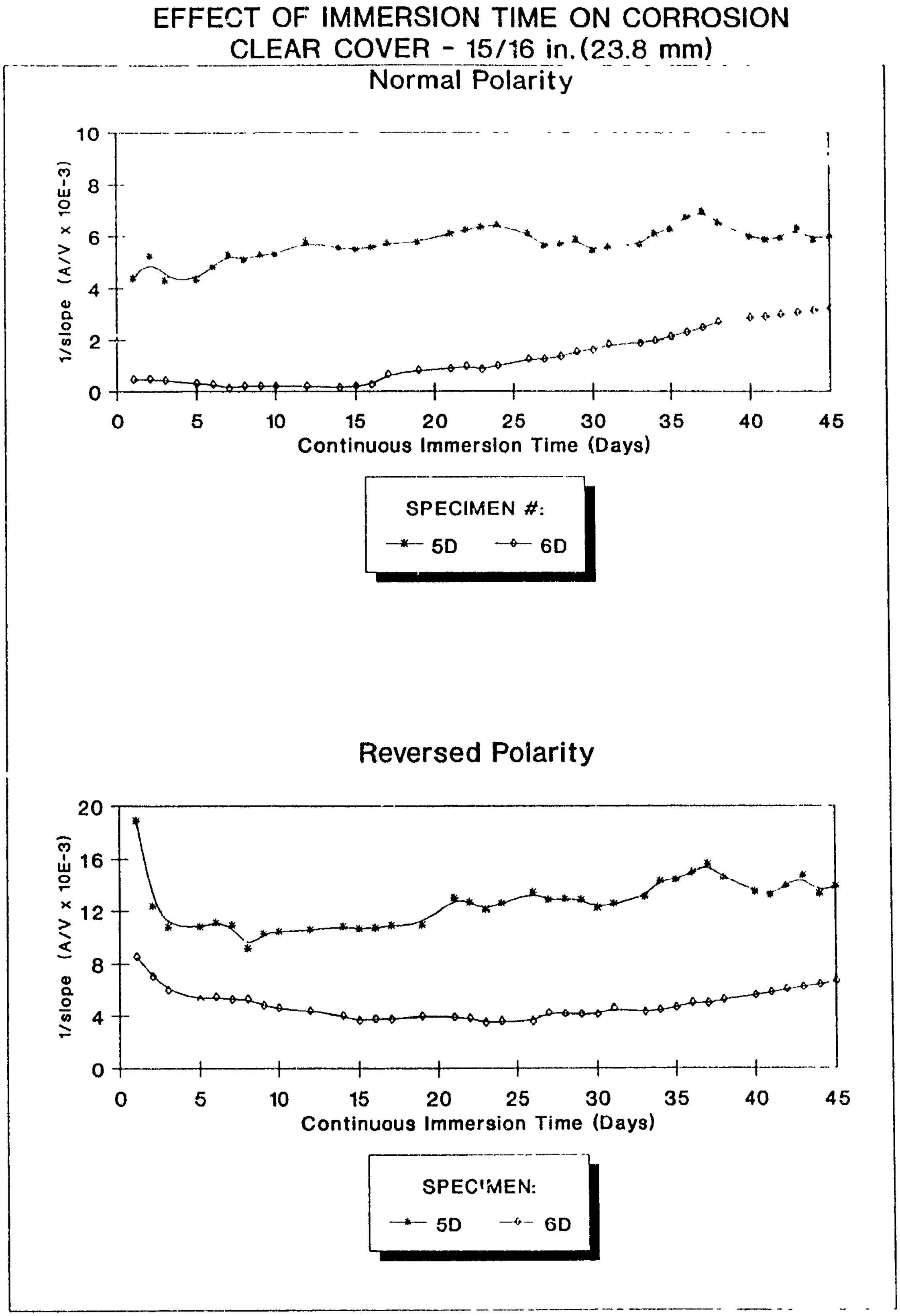
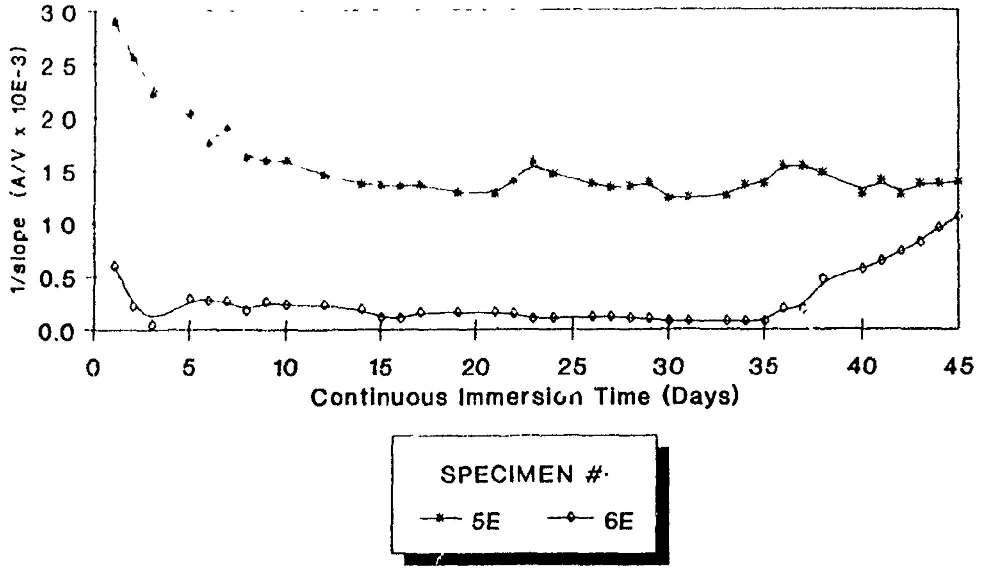


Figure J-3: Specimens #5D and #6D
Effect of Immersion Time on Corrosion

EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 1-3/16 in.(30.2 mm)

Normal Polarity



Reversed Polarity

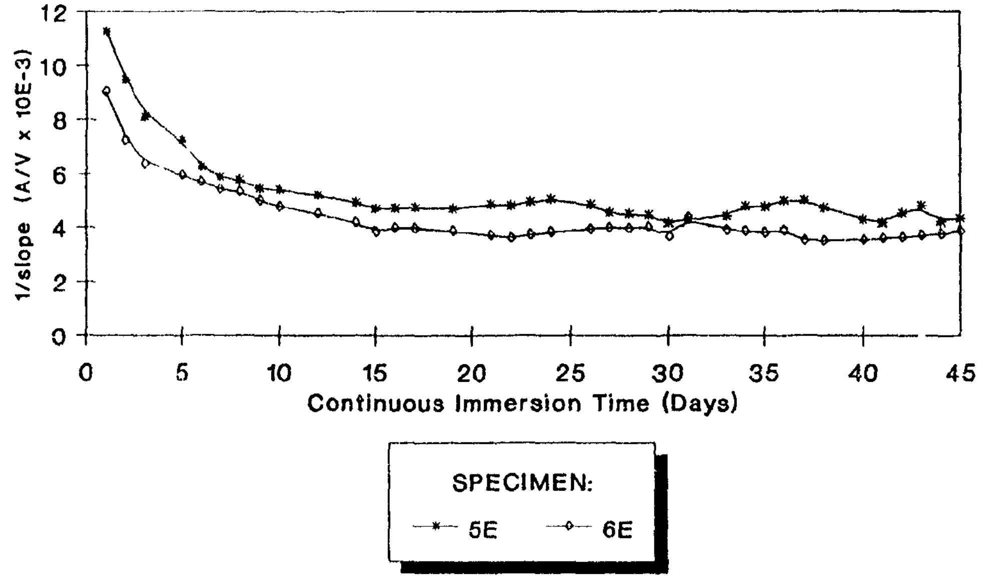


Figure J-4: Specimens #5E and #6E
Effect of Immersion Time on Corrosion

EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 1-7/16 in.(36.5 mm)

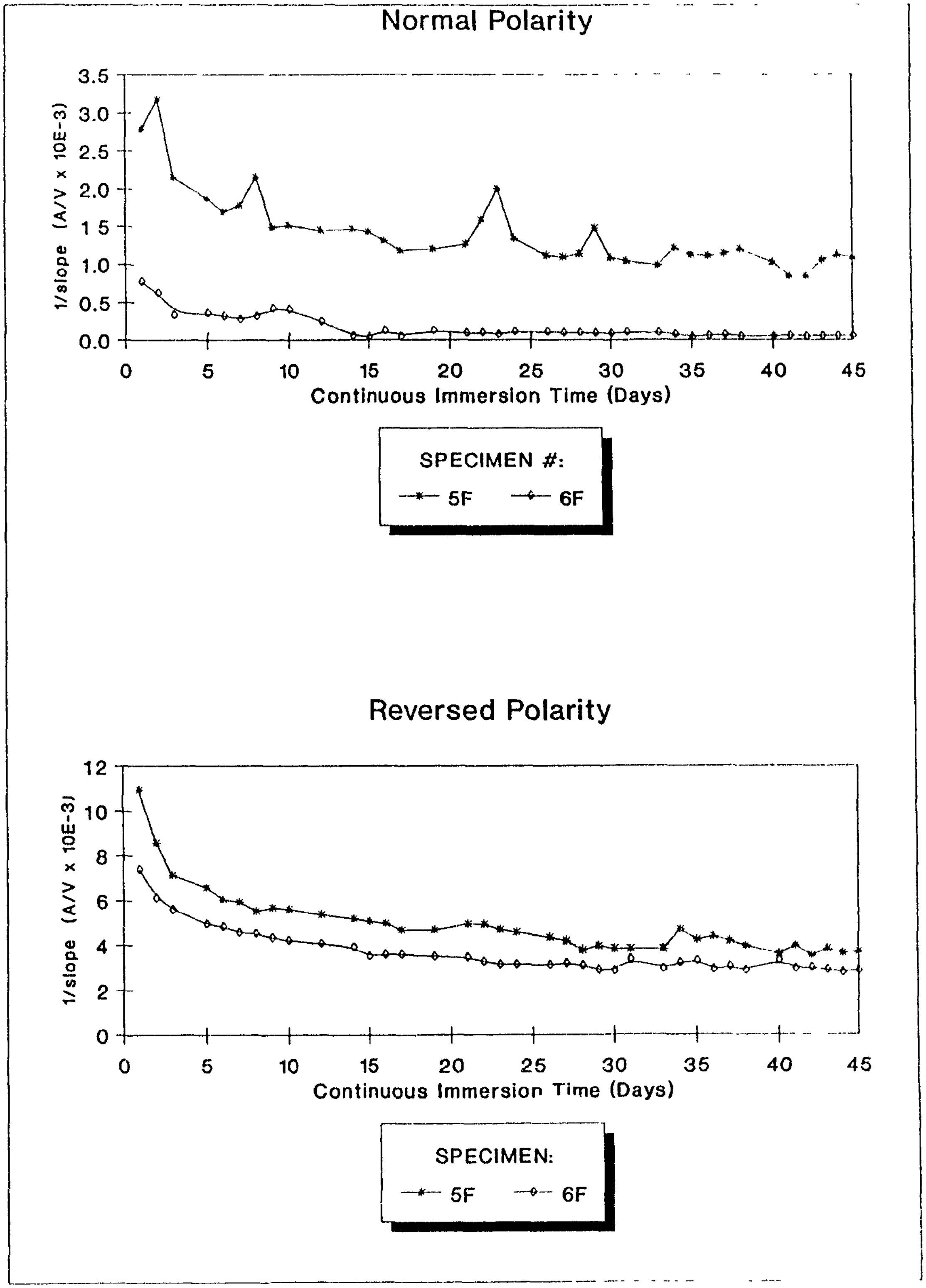
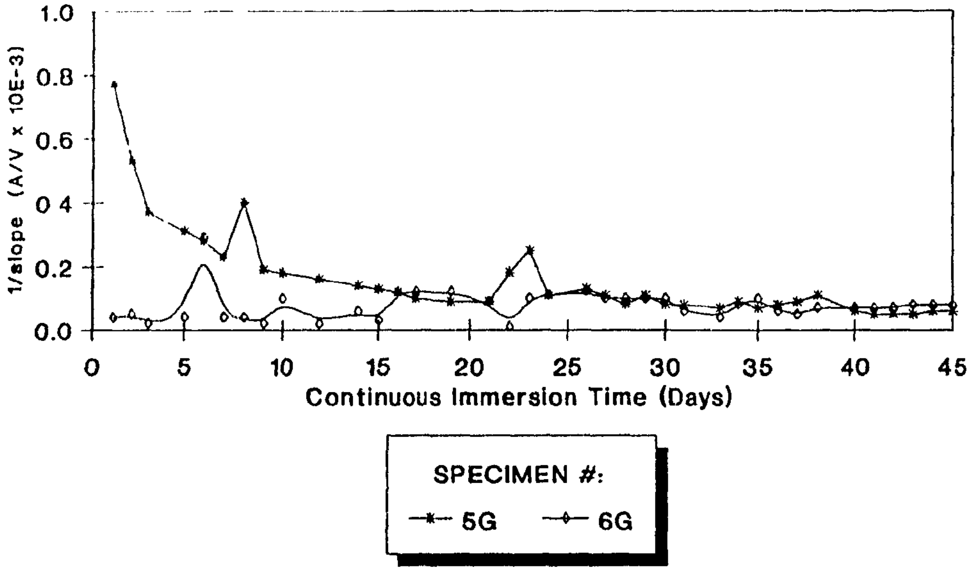


Figure J-5: Specimens #5F and #6F
Effect of Immersion Time on Corrosion

EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 1-11/16 in.(42.9 mm)

Normal Polarity



Reversed Polarity

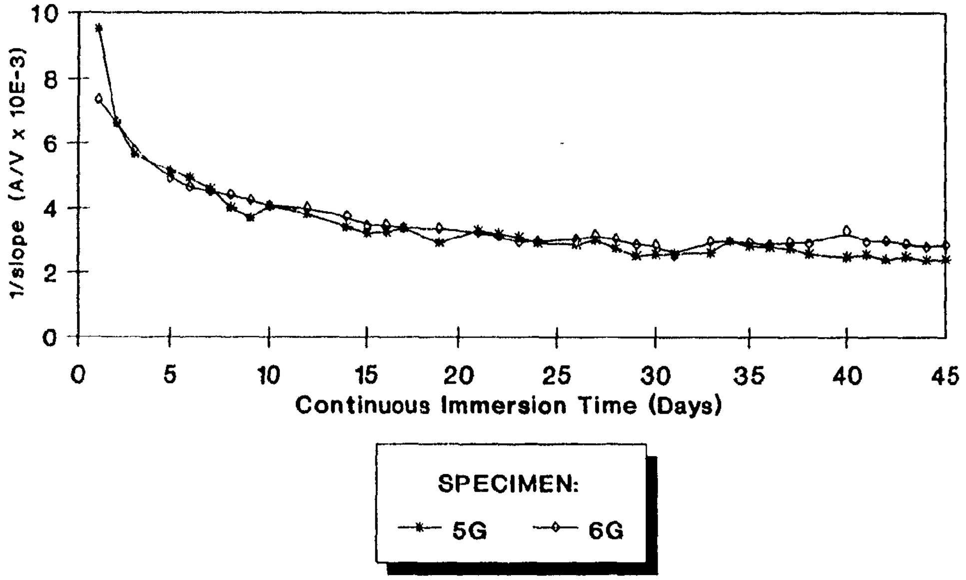
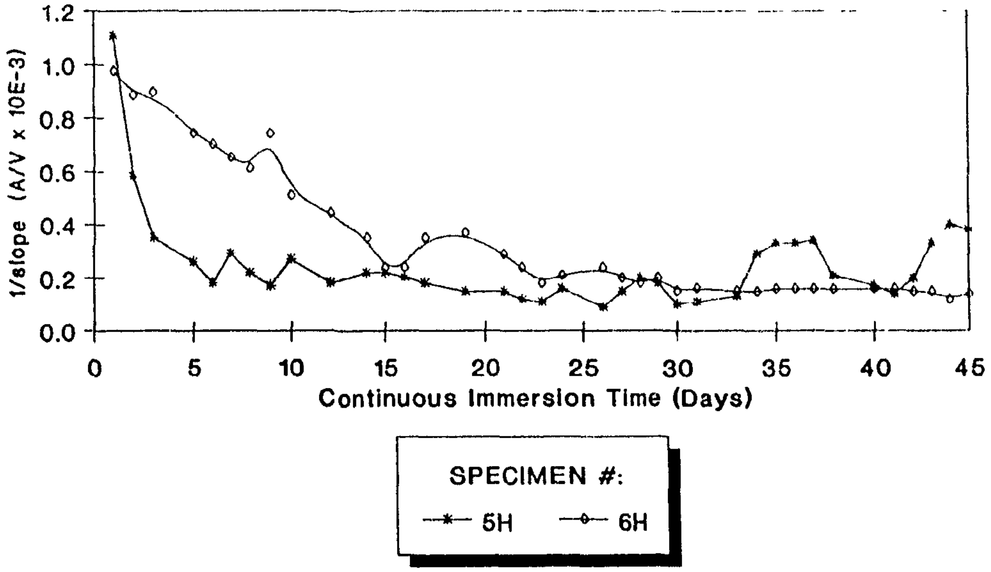


Figure J-6: Specimens #5G and #6G
Effect of Immersion Time on Corrosion

EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 2 in.(50.8 mm)

Normal Polarity



Reversed Polarity

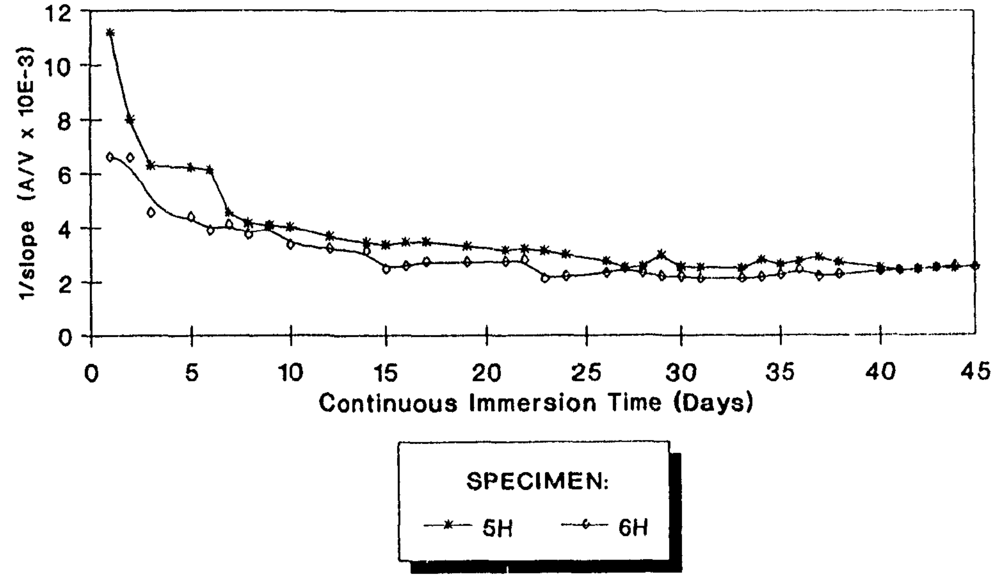
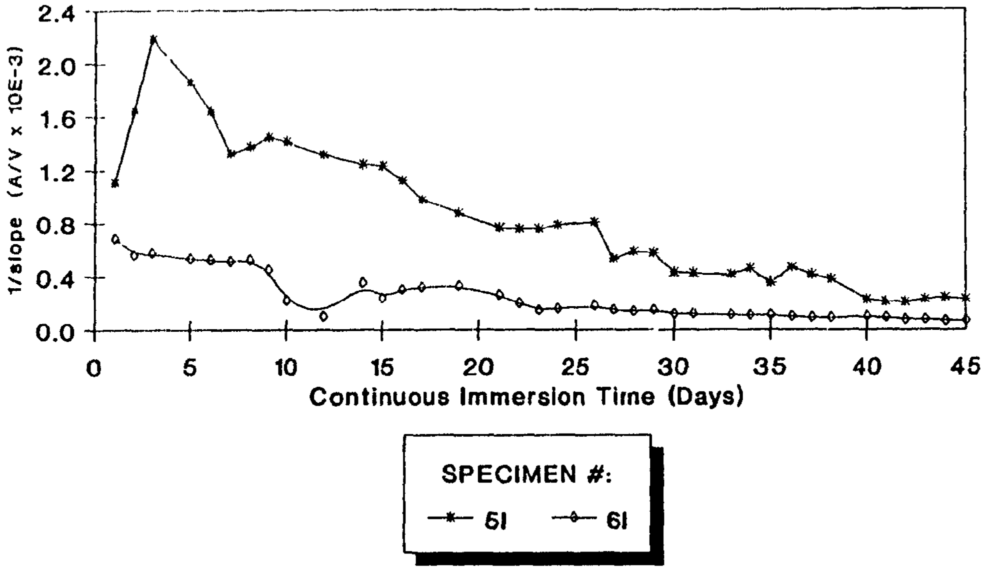


Figure J-7: Specimens #5H and #6H
Effect of Immersion Time on Corrosion

EFFECT OF IMMERSION TIME ON CORROSION
CLEAR COVER - 2.5 in.(63.5 mm)

Normal Polarity



Reversed Polarity

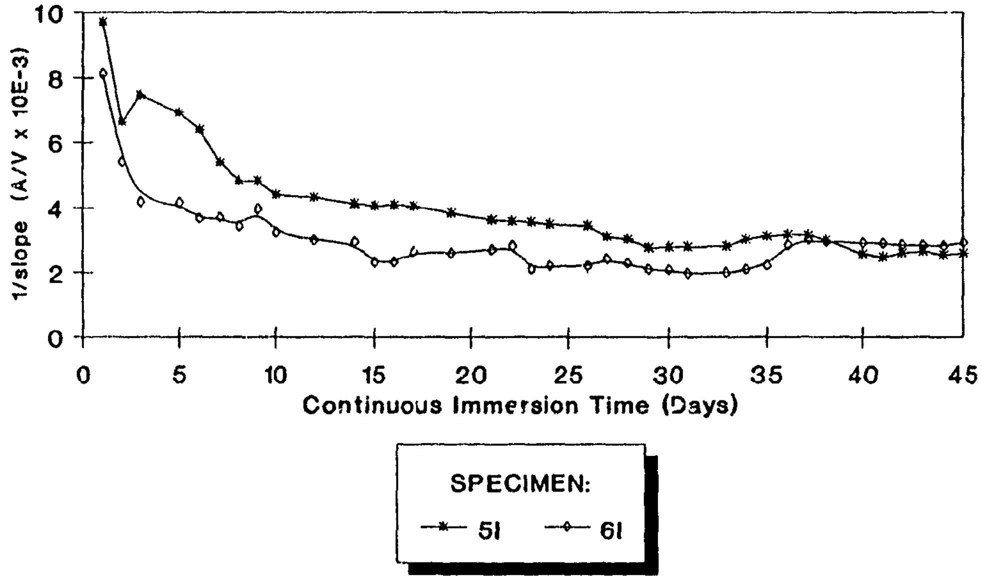
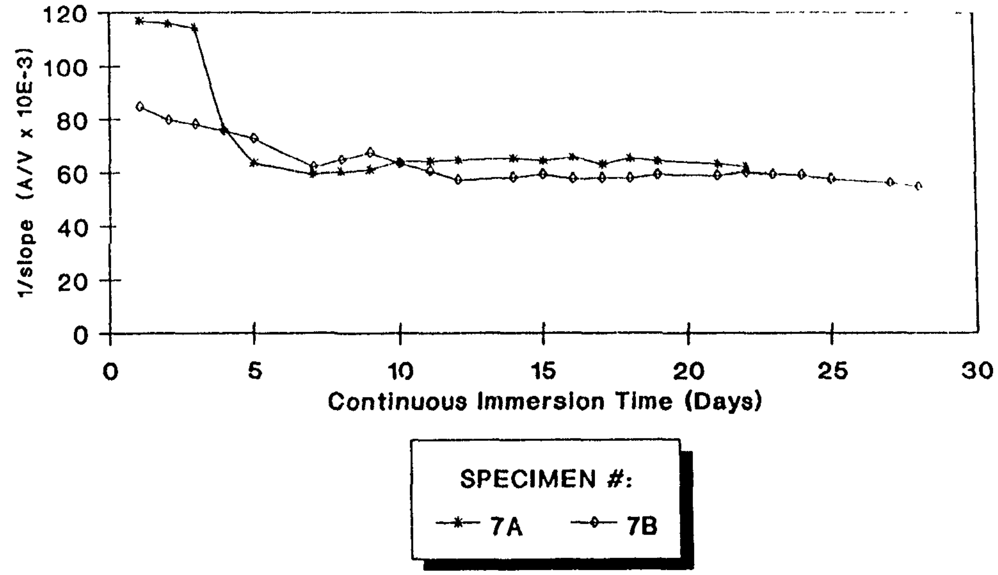


Figure J-8: Specimens #51 and #61
Effect of Immersion Time on Corrosion

EFFECT OF IMMERSION TIME ON CORROSION
TEST SERIES #7

Normal Polarity - Bare Anode



Reversed Polarity - Bare Cathode

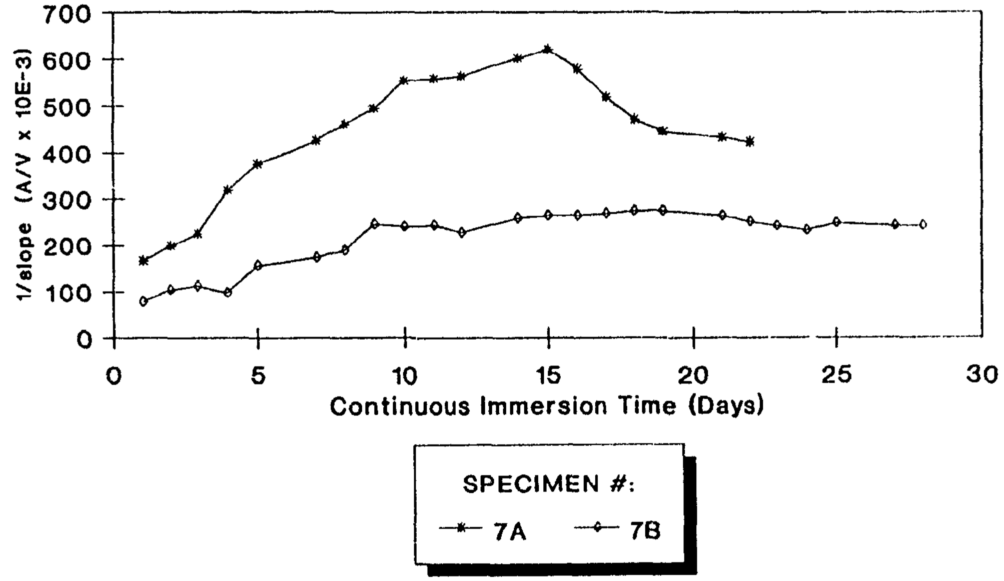
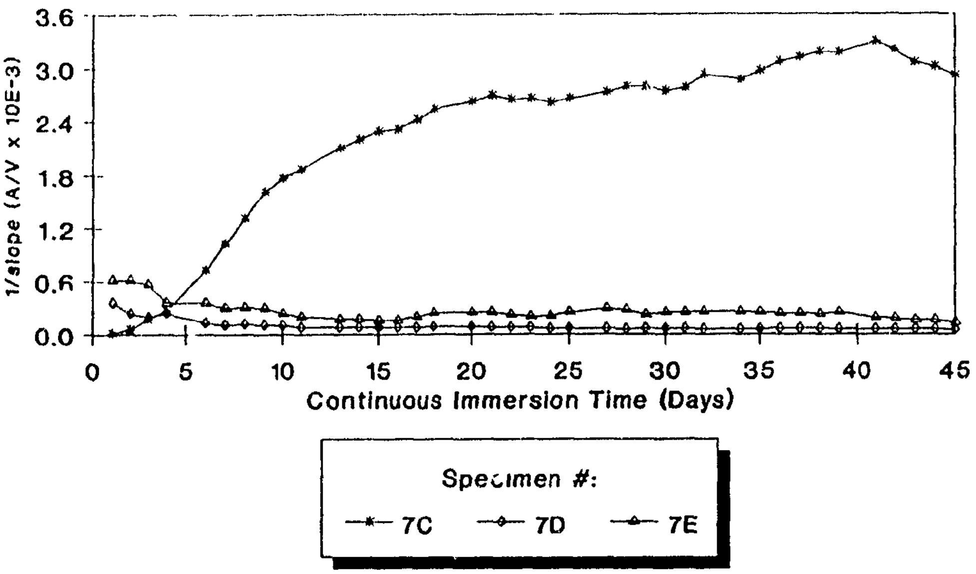


Figure J-9: Specimens #7A and #7B
Effect of Immersion Time on Corrosion

EFFECT OF IMMERSION TIME ON CORROSION
TEST SERIES #7

Varying Anode Covers - Normal Polarity



Cathode Clear Cover= 1-3/16 in.(30.2 mm)
Reversed Polarity

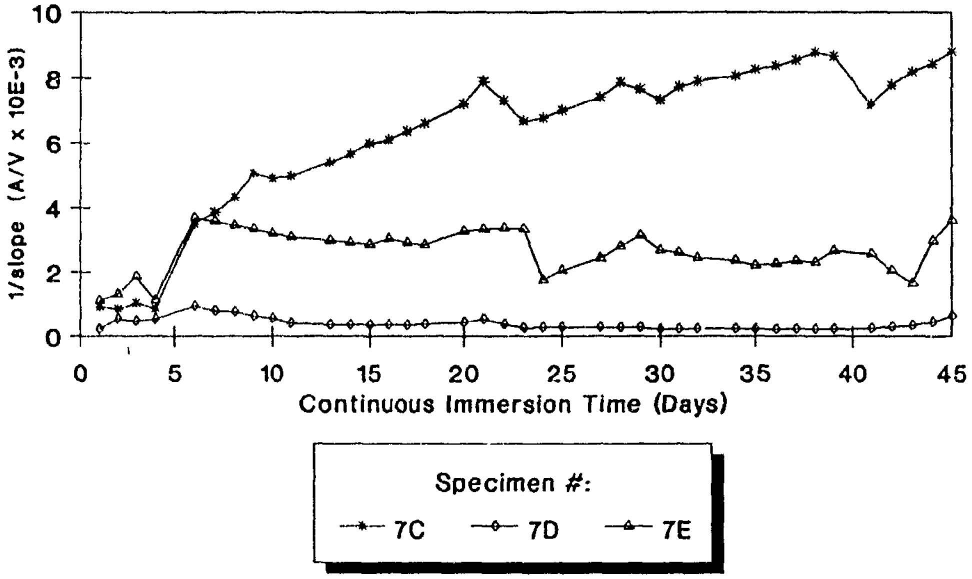


Figure J-10: Specimens #7C, #7D, and #7E
Effect of Immersion Time on Corrosion

APPENDIX K

Corrosion Current Results

The corrosion current, i_{corr}, is one of the indicators of the corrosion activity occurring at the lollipop specimens. Graphs of i_{corr} vs immersion time, for both polarity positions, are presented in this appendix.

CORROSION CURRENT - TEST SERIES #5
Reversed Polarity

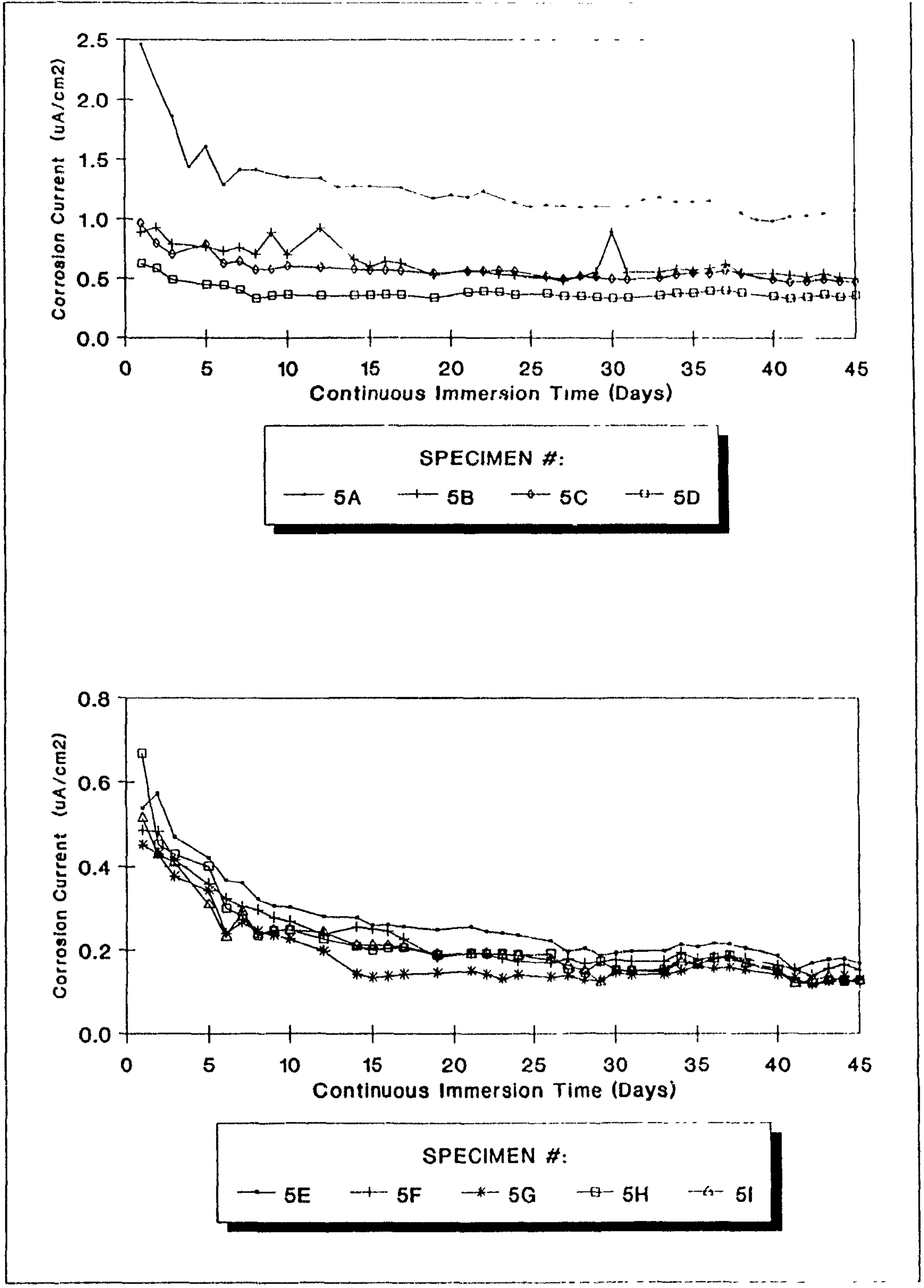
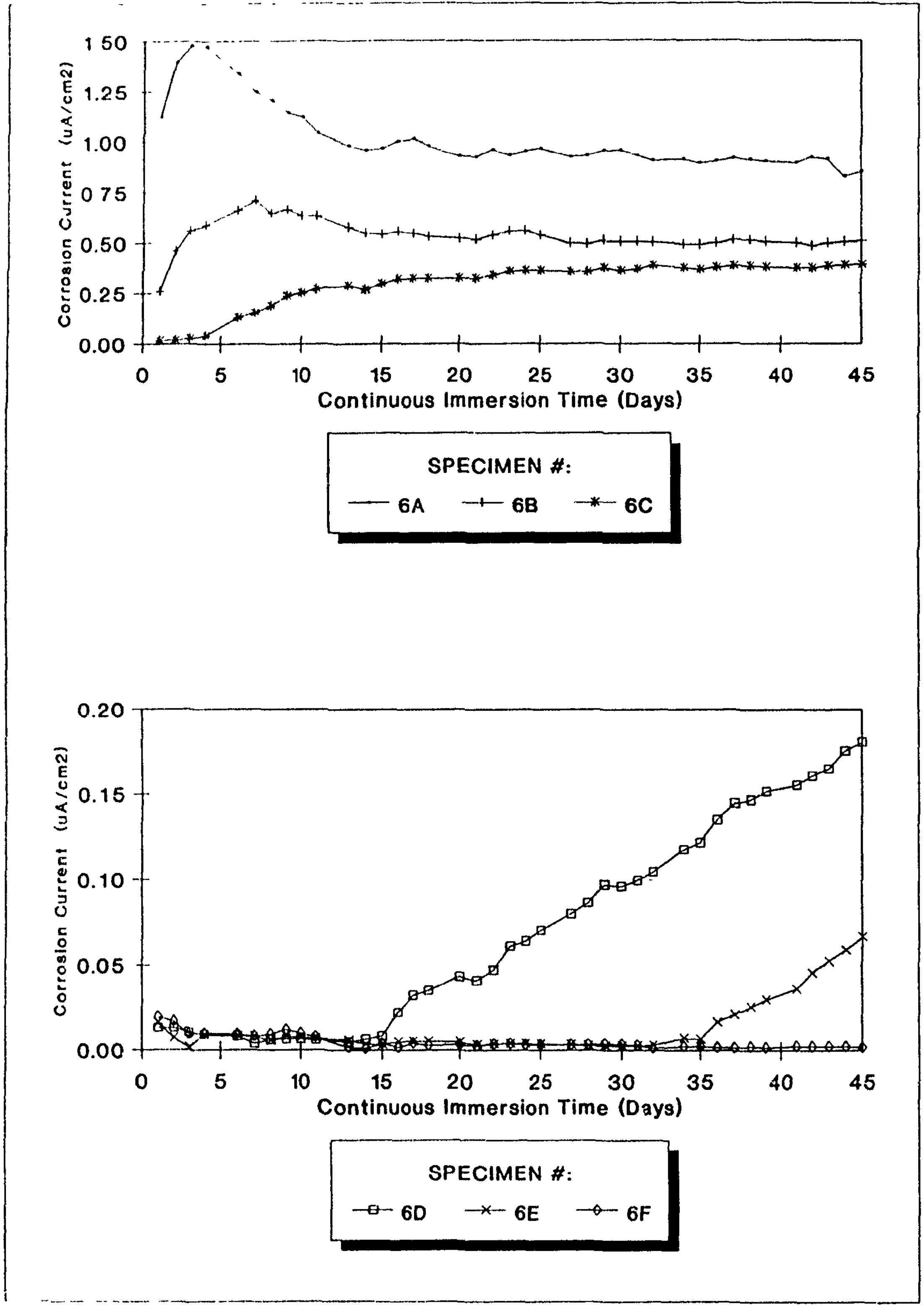


Figure K-1: Corrosion Current
Reversed Polarity - Test Series #5



CORROSION CURRENT - TEST SERIES #6
Normal Polarity

Figure K-2: Corrosion Current
Normal Polarity - Test Series #6

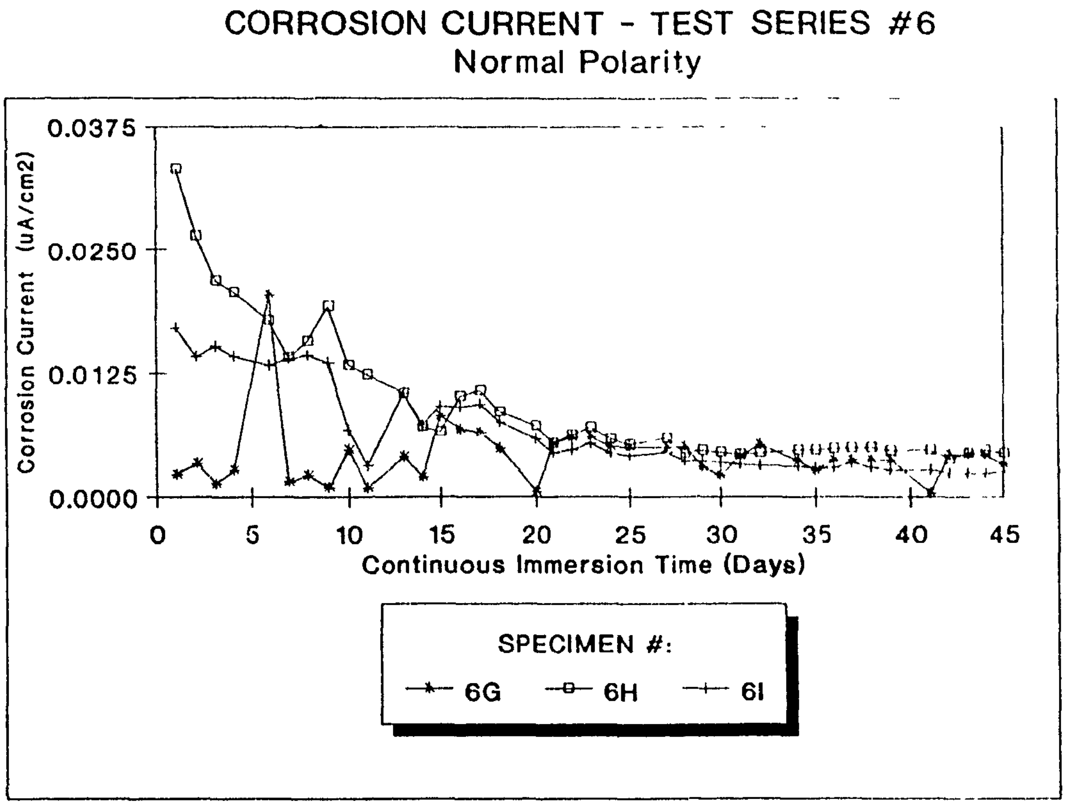


Figure K-3: Corrosion Current
Normal Polarity - Test Series #6

CORROSION CURRENT - TEST SERIES #6
Reversed Polarity

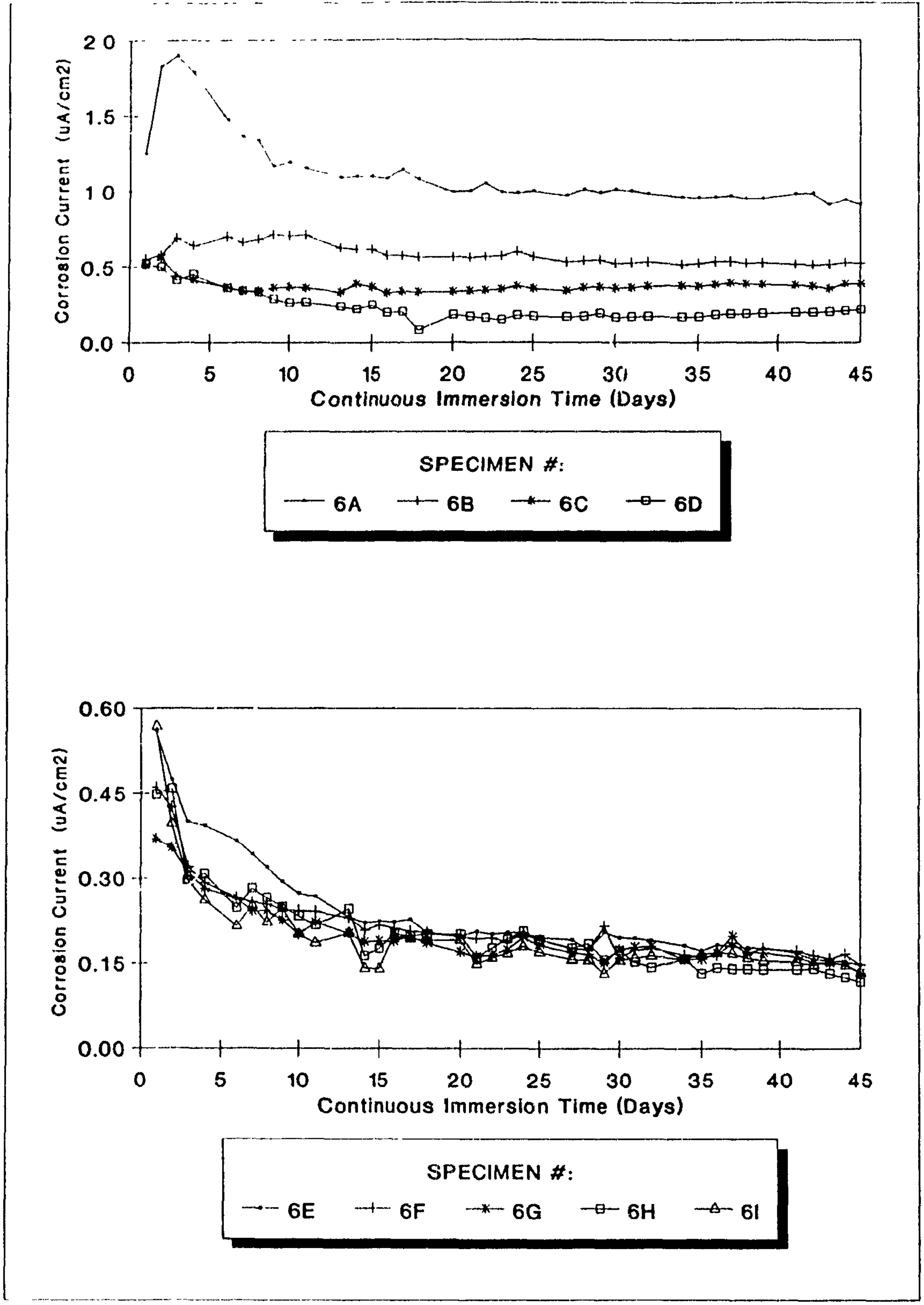
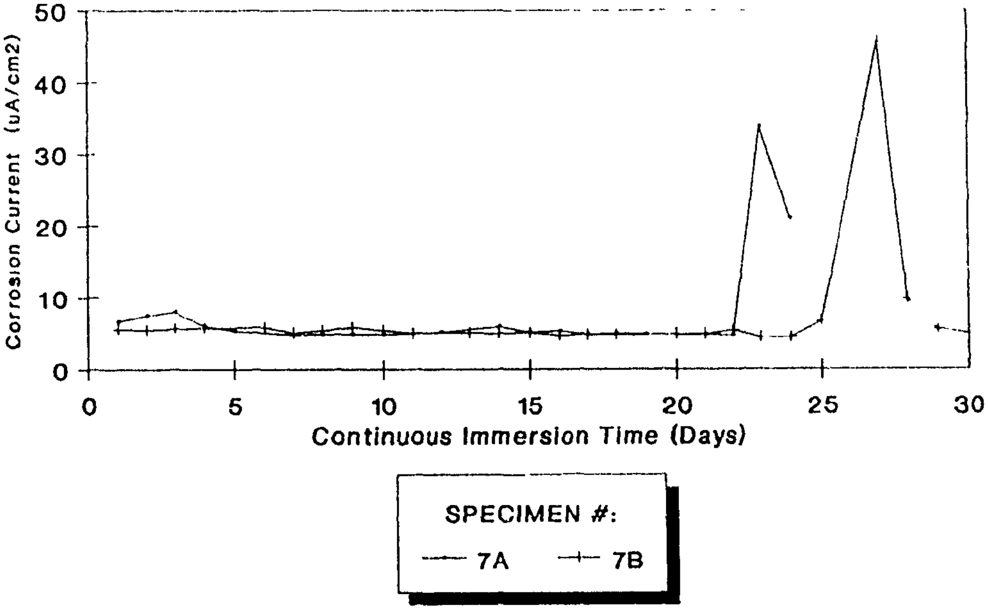


Figure K-4: Corrosion Current
Reversed Polarity - Test Series #6

CORROSION CURRENT - TEST SERIES #7

Normal Polarity



Reversed Polarity

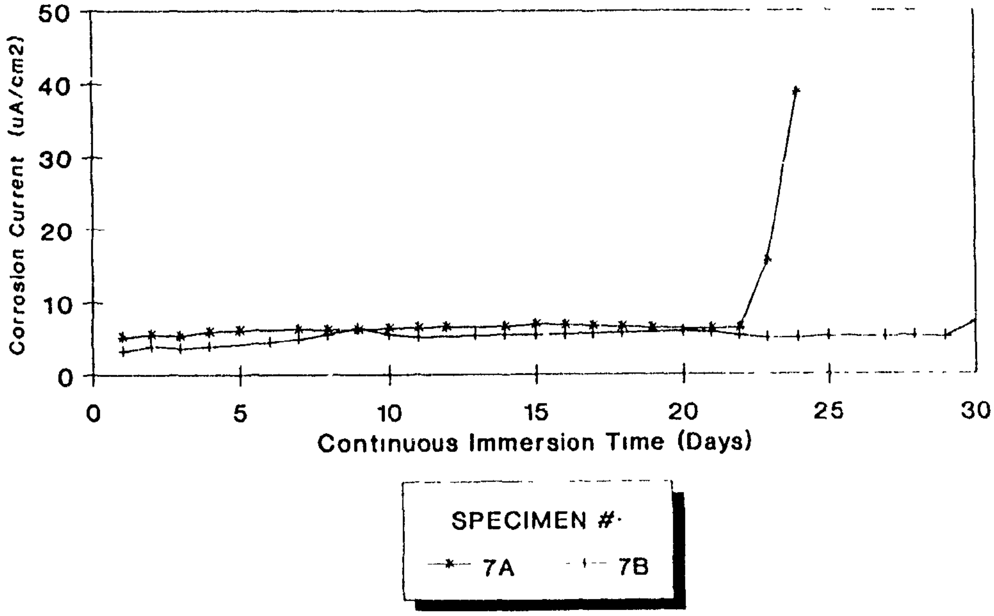
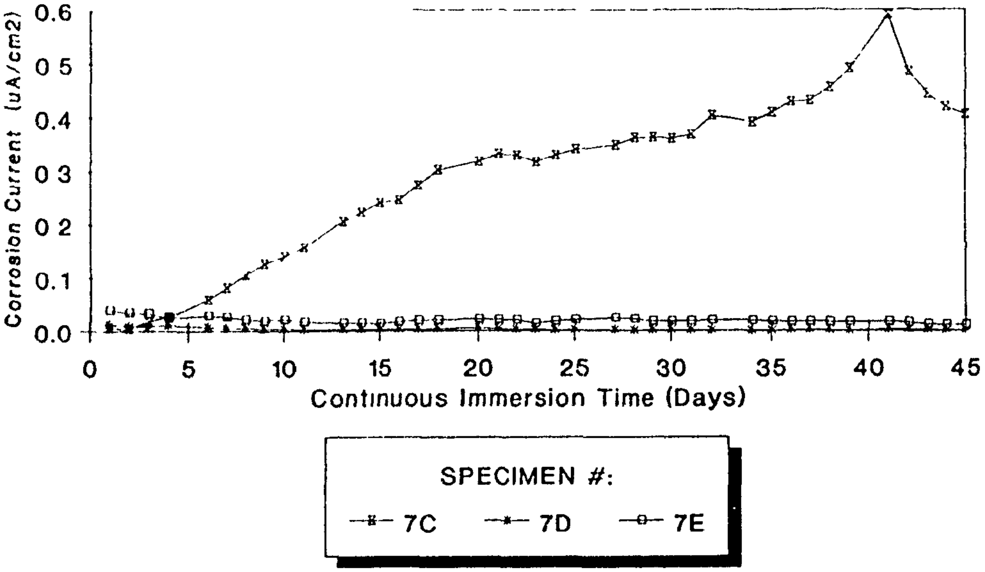


Figure K-5: Corrosion Current
Test Series #7

CORROSION CURRENT - TEST SERIES #7

Varying Anode Clear Covers
Normal Polarity



Cathode Clear Cover= 1-3/16 in (30.2 mm)
Reversed Polarity

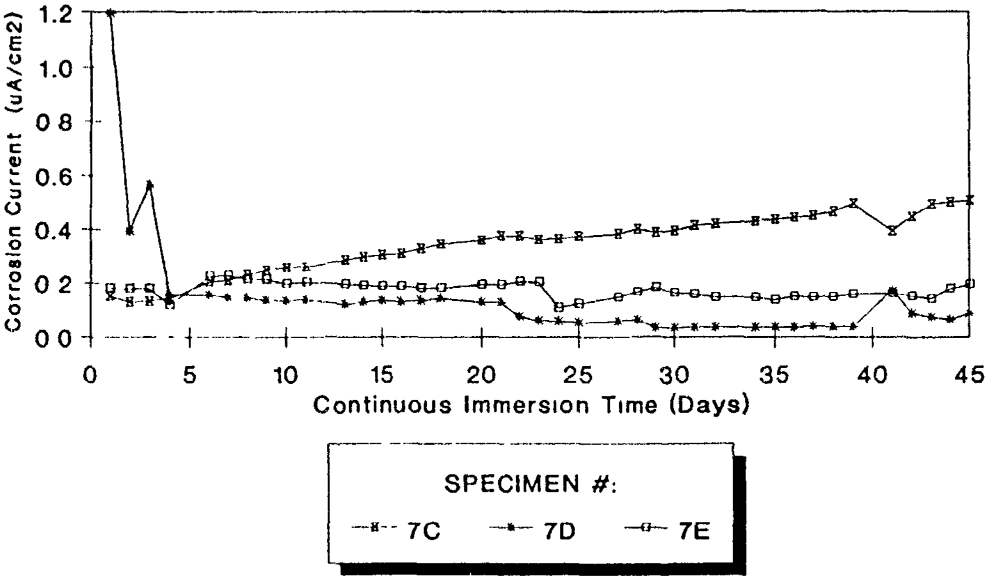


Figure K-6: Corrosion Current
Test Series #7

APPENDIX L

Electrical Conductance Results

The electrical conductance, G, is computed as the logarithm of the inverse of the electrode "polarization" resistance of each specimen. The variations of conductance, for each specimen of the test series, is shown in the following pages.

ELECTRICAL CONDUCTANCE - TEST SERIES #5
Reversed Polarity

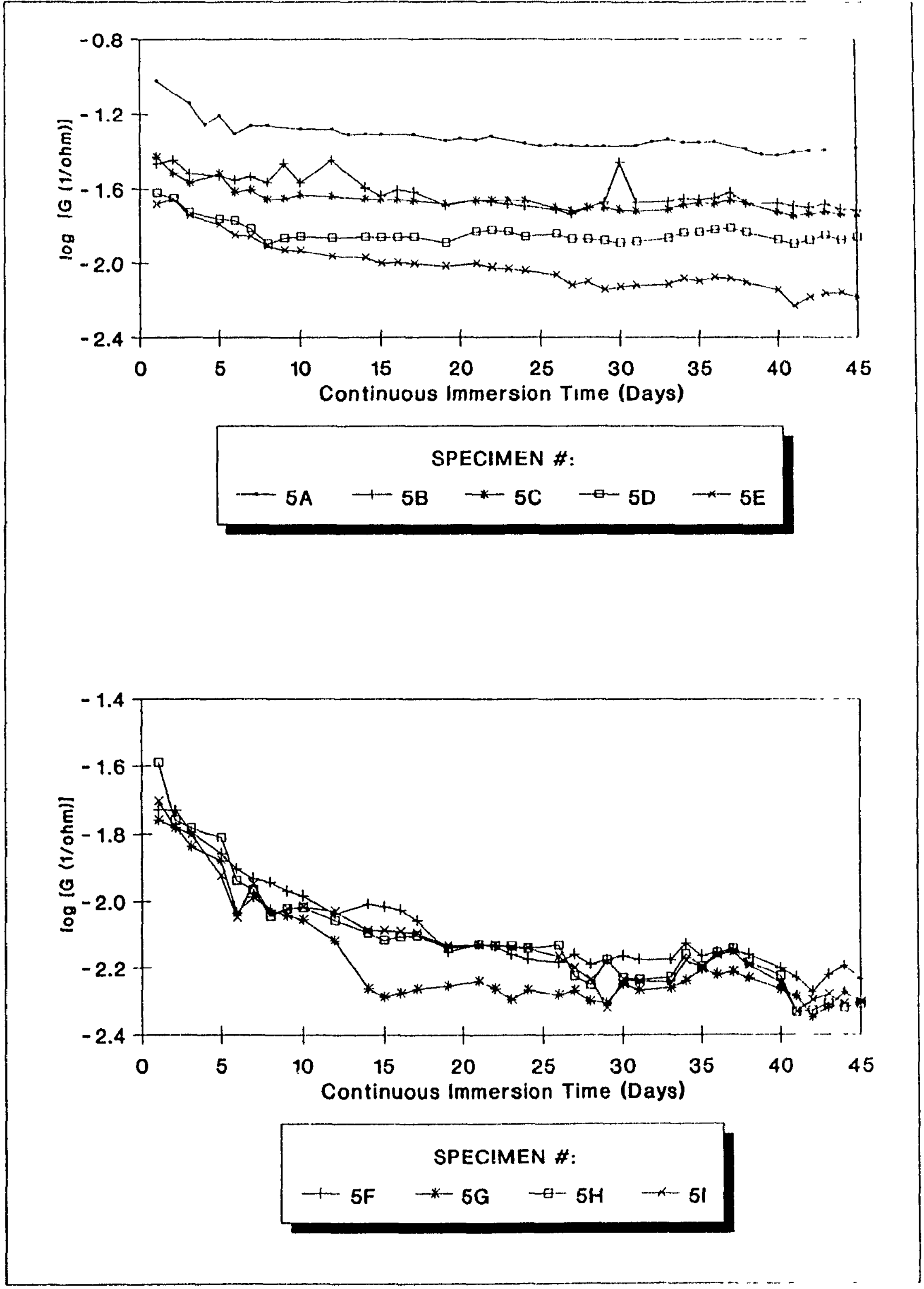


Figure L-1: Electrical Conductance
Reversed Polarity - Test Series #5

ELECTRICAL CONDUCTANCE - TEST SERIES #6
Normal Polarity

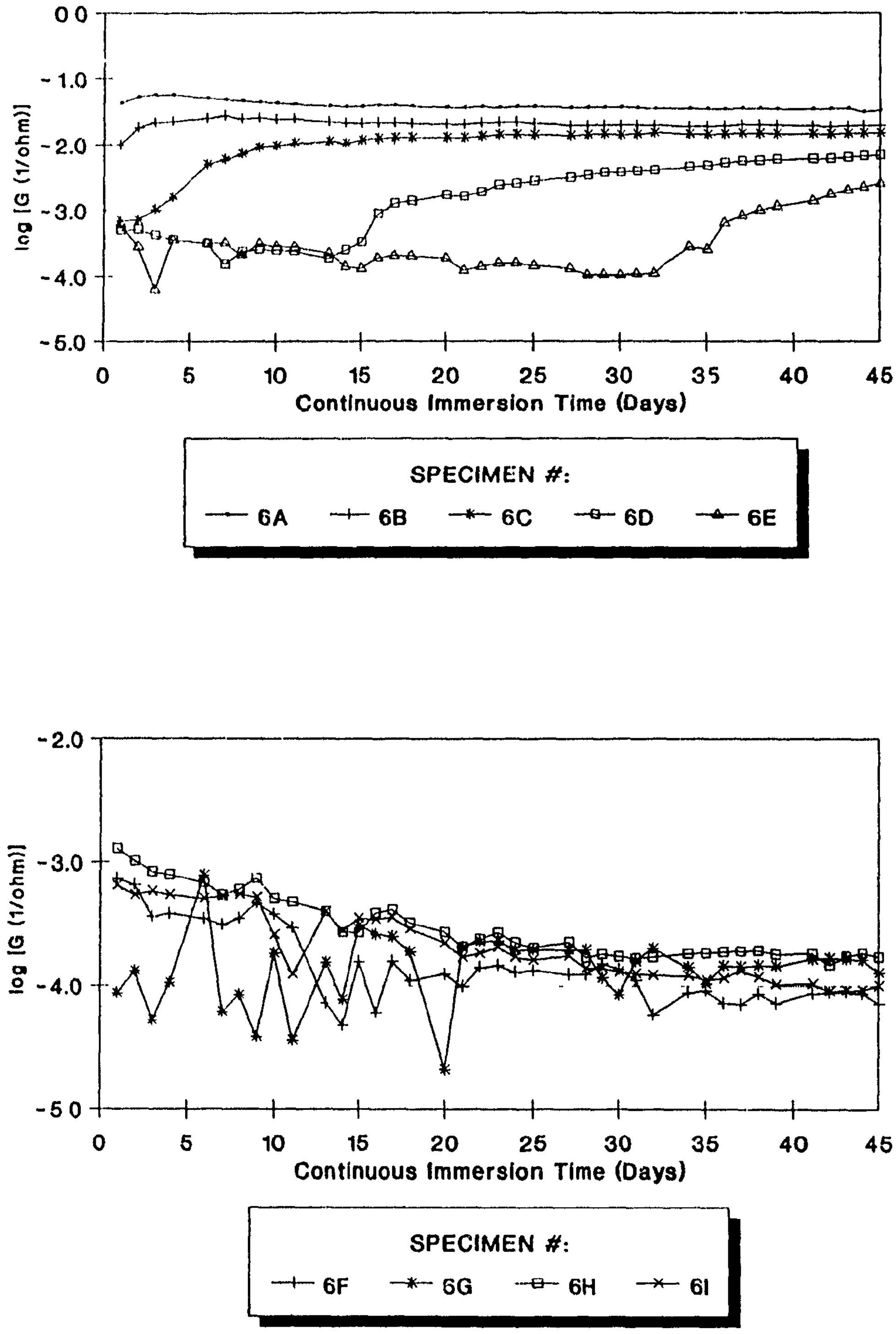


Figure L-2: Electrical Conductance
Normal Polarity - Test Series #6

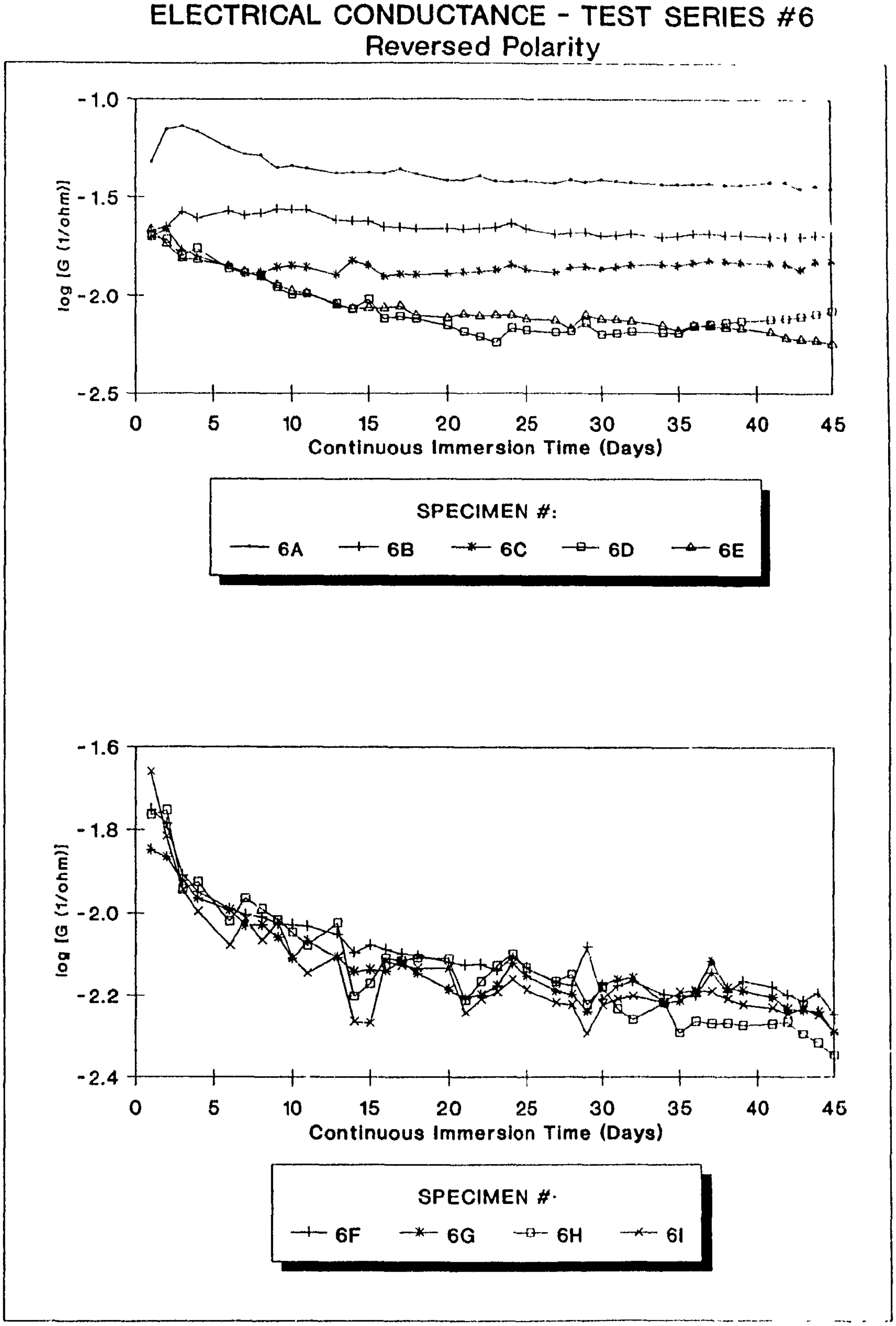


Figure L-3: Electrical Conductance
Reversed Polarity - Test Series #6

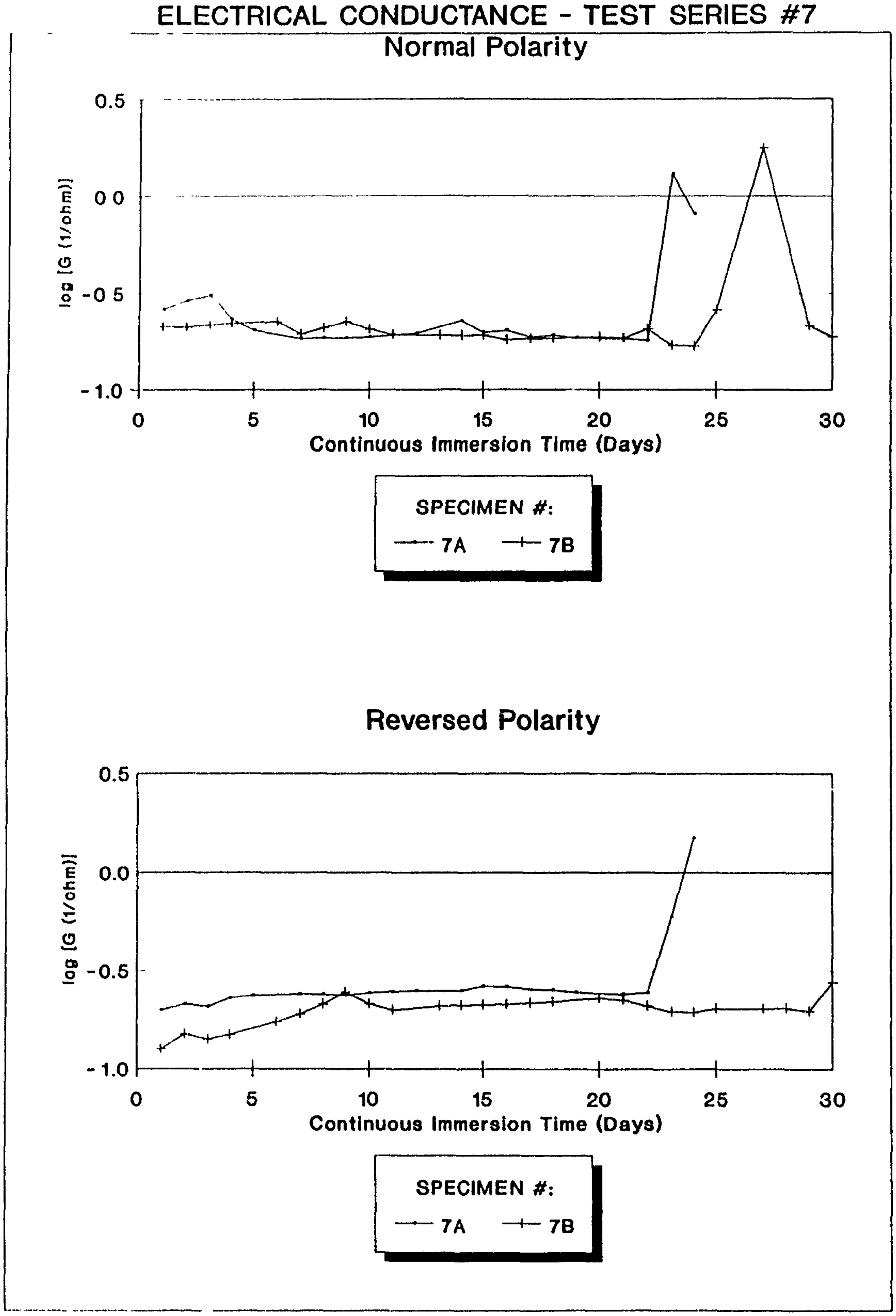
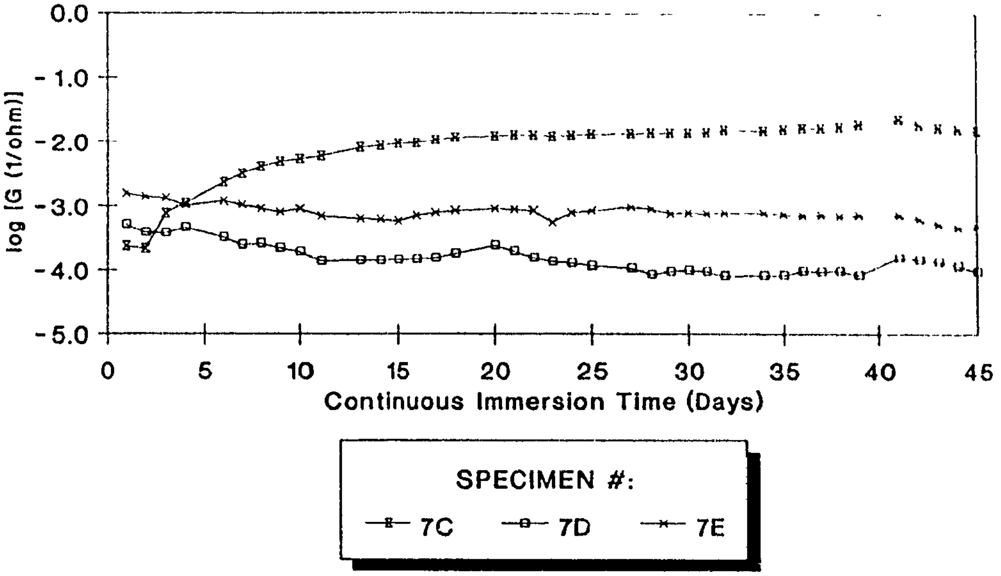


Figure L-4: Electrical Conductance
Test Series #7

ELECTRICAL CONDUCTANCE - TEST SERIES #7

Varying Anode Clear Covers
Normal Polarity



Cathode Clear Cover= 1-3/16 in (30.2 mm)
Reversed Polarity

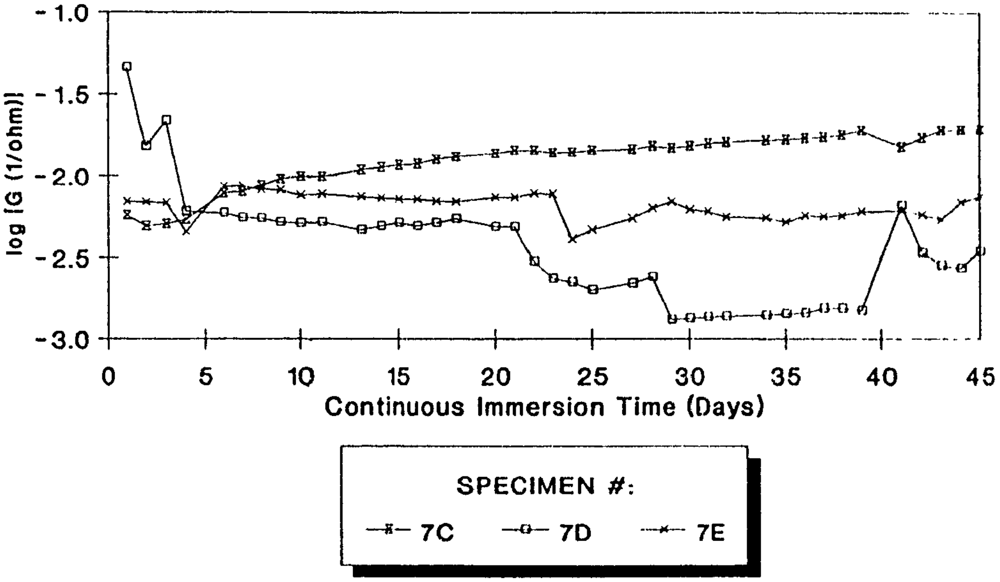


Figure L-5: Electrical Conductance
Test Series #7

APPENDIX M

Metal Oxidation Rates

This appendix presents the calculated rate of metal oxidation as predicted by theoretical formulation, based on the measured current values. For each specimen, the maximum, the minimum, and the average current values are used to compute the corresponding oxidation rates. The average rate is then multiplied by the immersion period (45 days) to predict the average mass loss of each specimen. This in turn is compared with the gravimetric measurements presented in Appendix G.

IRON OXIDATION RATES
CONCRETE-EMBEDDED ELECTRODES

EQUATION: $dw/dt = (I * Mw)/(n * F)$

where dw/dt = metal oxidation rate (g/s)
I = current (A)
Mw = molar weight of iron (g)
n = oxidation state (assume +2)
F = Faraday's constant (A s)

	CURRENT (mA)			OXIDATION RATE (mg/day)		
SPECIMEN #	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE
5A	24.15	12.80	16.267	603.90	320.08	406.77
5B	14.34	7.24	9.382	358.59	181.04	234.61
5C	14.77	6.94	8.801	369.34	173.54	220.08
5D	6.74	4.19	5.547	168.54	104.78	138.71
5E	2.87	1.22	1.515	71.77	30.51	37.88
5F	3.12	0.84	1.407	78.02	21.01	35.18
5G	0.77	0.05	0.164	19.25	1.25	4.10
5H	1.10	0.09	0.248	27.51	2.25	6.20
5I	2.16	0.21	0.831	54.01	5.25	20.78
6A	21.74	12.51	14.967	543.63	312.83	374.27
6B	10.88	4.53	8.595	272.07	113.28	214.93
6C	6.21	0.63	4.743	155.29	15.75	118.60
6D	3.45	0.13	1.419	86.27	3.25	35.48
6E	1.28	0.05	0.326	32.01	1.25	8.15
6F	0.77	0.04	0.162	19.25	1.00	4.05
6G	0.29	0.01	0.077	7.25	0.25	1.93
6H	0.97	0.12	0.329	24.26	3.00	8.23
6I	0.68	0.07	0.233	17.00	1.75	5.83
7A	72.70	45.60	52.032	1817.94	1140.28	1301.12
7B	58.90	43.40	47.649	1472.86	1085.27	1191.52
7C	3.24	0.02	2.256	81.02	0.50	56.41
7D	0.36	0.05	0.096	9.00	1.25	2.40
7E	0.61	0.13	0.261	15.25	3.25	6.53

Table M-1: Iron Oxidation Rates
Concrete-Embedded Electrodes

IRON OXIDATION RATES
CATHODES

EQUATION: $dw/dt = (I * Mw)/(n * F)$

where dw/dt = metal oxidation rate (g/s)
I = current (A)
Mw = molar weight of iron (g)
n = oxidation state (assume +2)
F = Faraday's constant (A s)

	CURRENT (mA)			OXIDATION RATE (mg/day)		
SPECIMEN #	MAXIMUM	MINIMUM	AVERAGE	MAXIMUM	MINIMUM	AVERAGE
5A	46.70	35.10	40.542	1167.79	877.71	1013.80
5B	24.27	17.22	20.480	606.90	430.61	512.13
5C	21.09	16.63	18.134	527.38	415.85	453.46
5D	17.24	8.73	11.782	431.11	218.30	294.62
5E	10.60	4.07	5.126	265.06	101.77	128.18
5F	10.39	3.46	4.798	259.81	86.52	119.98
5G	9.04	2.35	3.400	226.06	58.76	85.02
5H	10.54	2.39	3.567	263.56	59.76	89.20
5I	9.18	2.44	3.864	229.56	61.01	96.62
6A	44.90	12.51	14.967	1122.77	312.83	374.27
6B	19.31	12.90	18.226	482.87	322.58	455.76
6C	13.56	6.49	10.287	339.08	162.29	257.24
6D	8.14	3.43	4.859	203.55	85.77	121.50
6E	8.62	3.44	4.252	215.55	86.02	106.33
6F	7.08	2.62	3.556	177.04	65.52	88.92
6G	7.05	2.49	3.484	176.29	62.27	87.12
6H	6.37	2.09	2.897	159.29	52.26	72.44
6I	7.76	1.94	2.931	194.05	48.51	73.29
7A	142.20	86.30	128.289	3555.87	2158.03	3208.01
7B	110.60	55.90	98.129	2765.68	1397.84	2453.83
7C	8.38	0.84	6.070	209.55	21.01	151.79
7D	0.93	0.22	0.391	23.26	5.50	9.78
7E	3.59	1.11	2.605	89.77	27.76	65.14

Table M-2: IRON OXIDATION RATES
CATHODES

COMPARISON OF MASS LOSS
THEORETICAL versus GRAVIMETRIC

		THEORETICAL		GRAVIMETRIC	
SPECIMEN #	IMMERSION PERIOD (days)	AVERAGE OXIDATION RATE (mg/day)	AVERAGE MASS LOSS (g)	AVERAGE MASS LOSS (g)	DIFFERENCE (g)
5A	45	406.77	18.30	15.39	-2.91
5B	45	234.61	10.56	6.82	-3.74
5C	45	220.08	9.90	5.46	-4.44
5D	45	138.71	6.24	2.33	-3.91
5E	45	37.88	1.70	0.78	-0.92
5F	45	35.18	1.58	1.59	0.01
5G	45	4.10	0.18	2.75	2.57
5H	45	6.20	0.28	1.40	1.12
5I	45	20.78	0.94	2.14	1.20
6A	45	374.27	16.84	15.83	-1.01
6B	45	214.93	9.67	7.75	-1.92
6C	45	118.60	5.34	3.42	-1.92
6D	45	35.48	1.60	6.12	4.52
6E	45	8.15	0.37	0.76	0.39
6F	45	4.05	0.18	0.67	0.49
6G	45	1.93	0.09	0.90	0.81
6H	45	8.23	0.37	0.05	-0.32
6I	45	5.83	0.26	0.43	0.17
7A	24	1301.12	31.23	92.16	60.93
7B	30	1191.52	35.75	64.78	29.03
7C	45	56.41	2.54	0.37	-2.17
7D	45	2.40	0.11	0.73	0.62
7E	45	6.53	0.29	0.51	0.22

Table M-3: THEORETICAL vs GRAVIMETRIC MASS LOSS

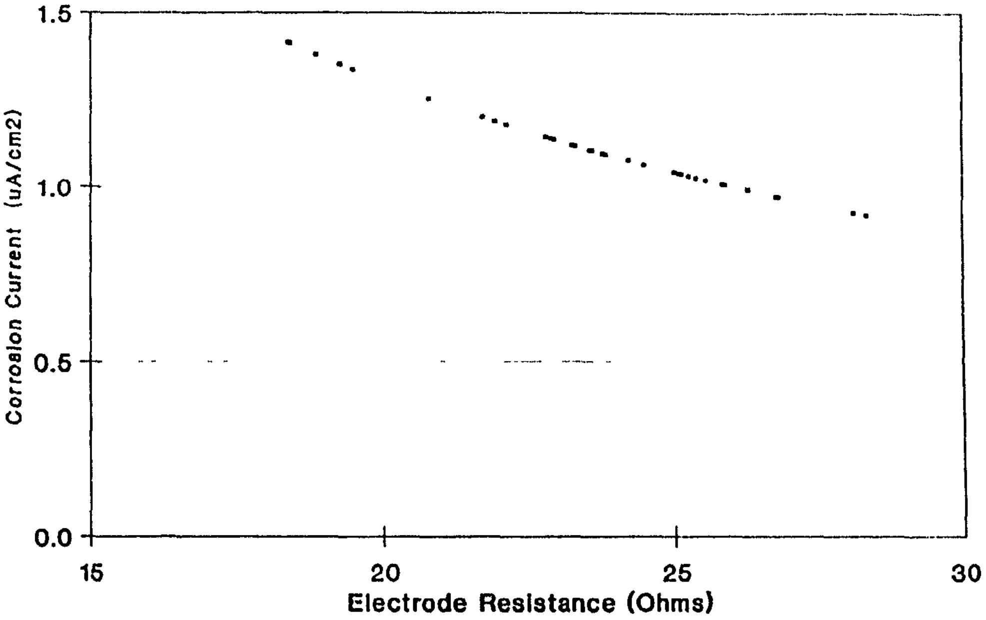
APPENDIX N

Corrosion Current vs Electrode Polarization Resistance Results

The following graphs represent the trend developed between the corrosion current, i_{corr}, and the electrode "polarization" resistance for each specimen. Best-fit curves are drawn to represent these trends. Both polarity modes are illustrated.

CORROSION CURRENT vs RESISTANCE

Concrete-Embedded Anode - Specimen #5A



Concrete-Embedded Anode - Specimen #5B

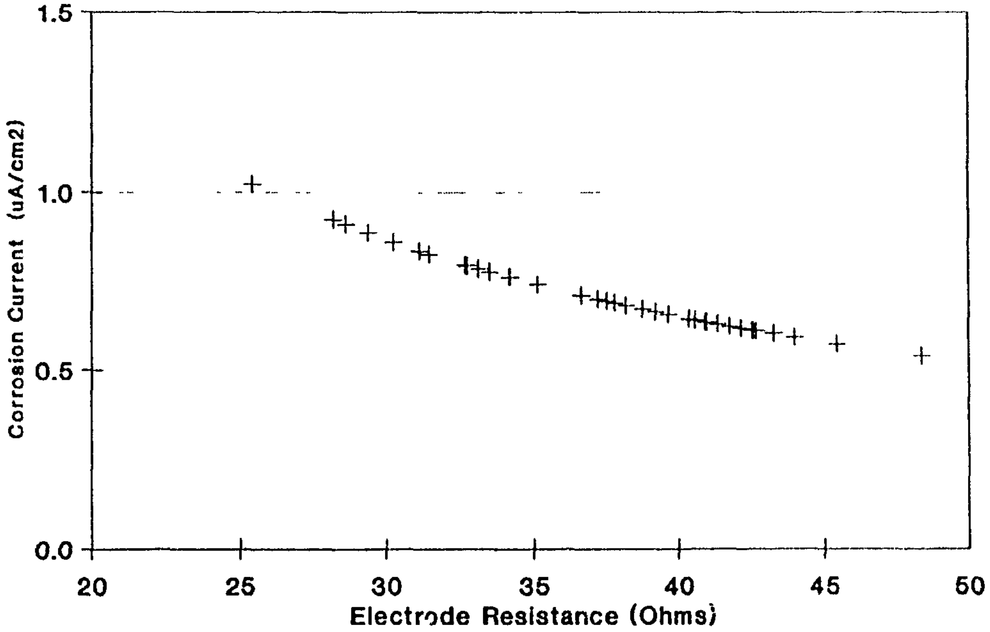


Figure N-1: Corrosion Current vs Resistance
Specimens #5A and #5B

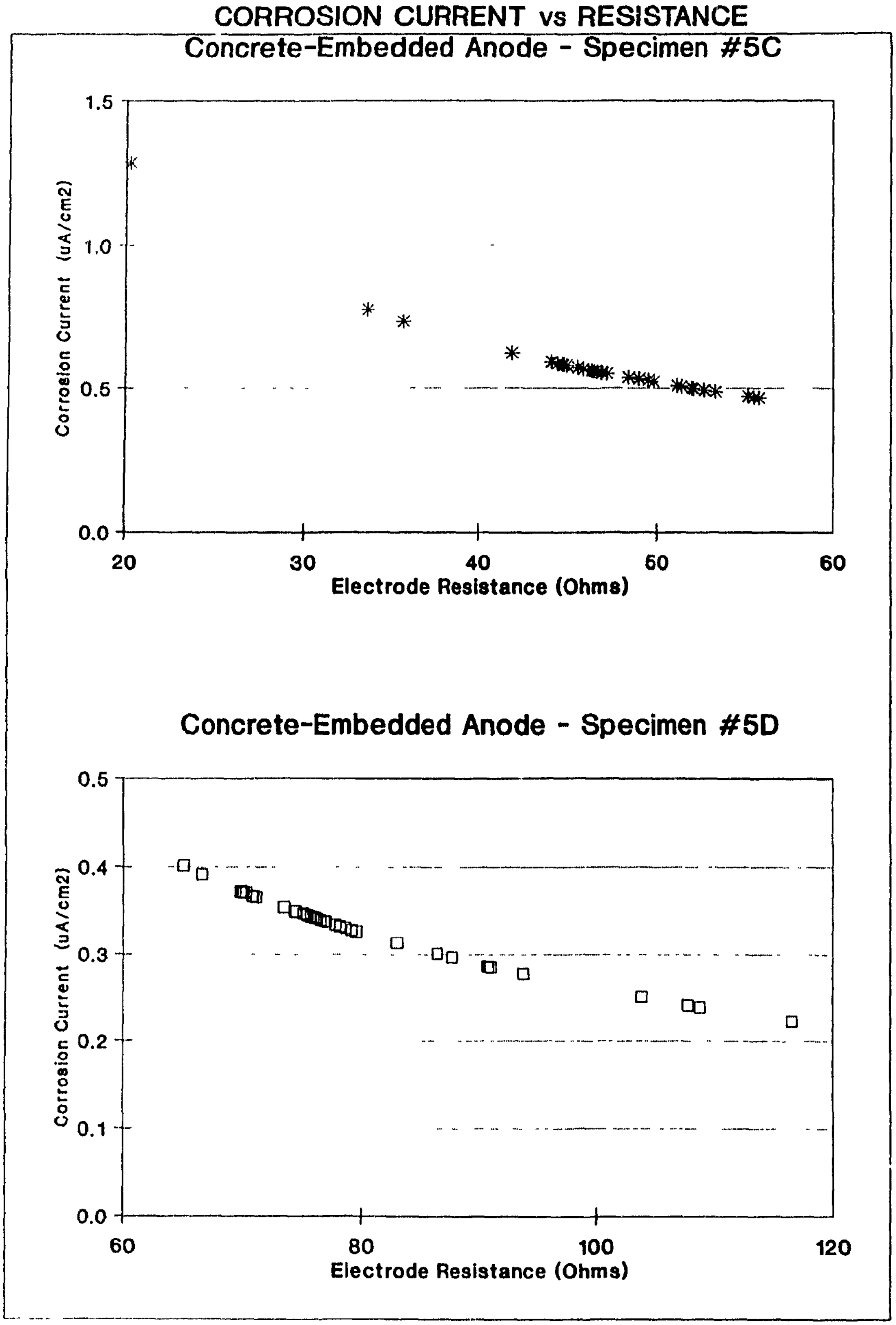
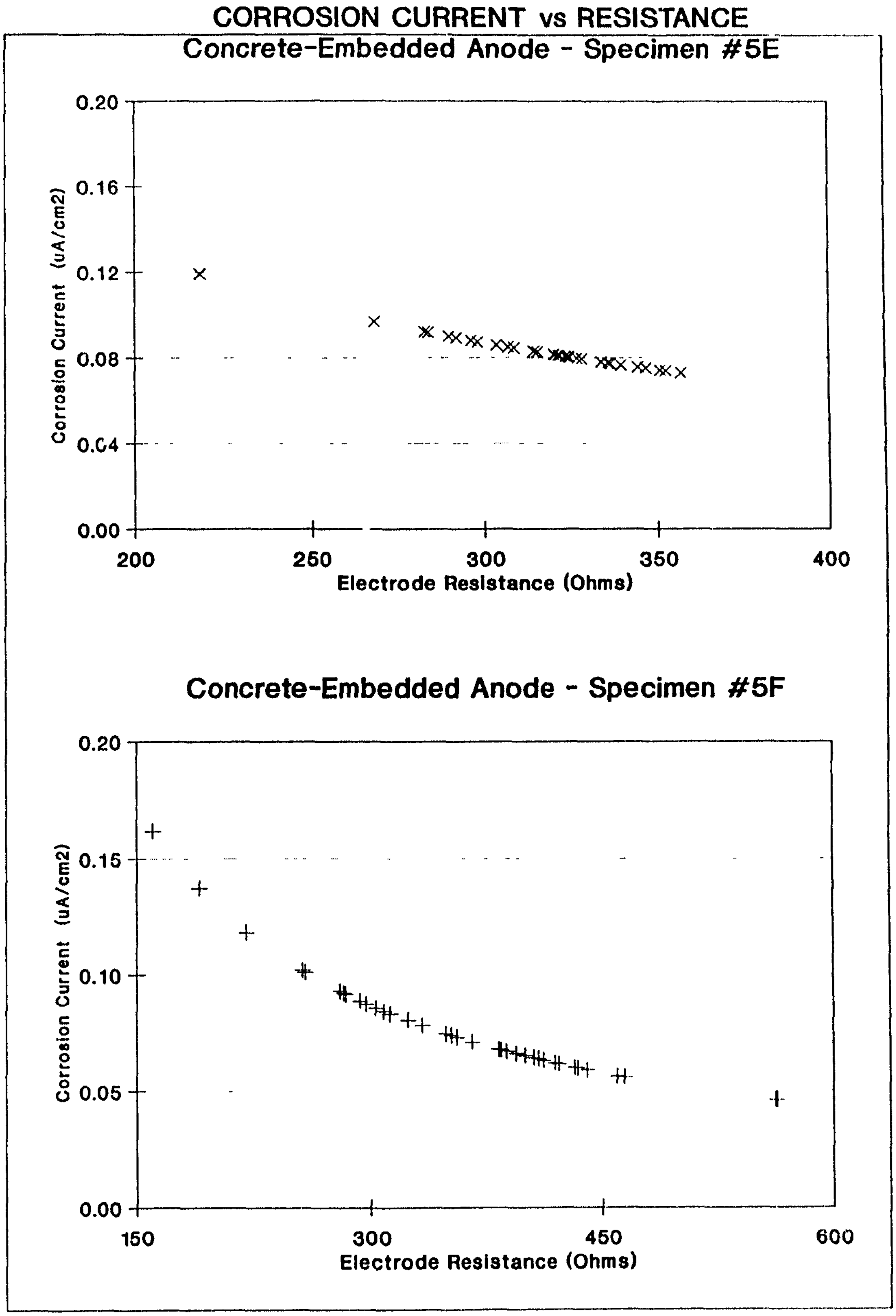


Figure N-2: Corrosion Current vs Resistance
Specimens #5C and #5D



CORROSION CURRENT vs RESISTANCE

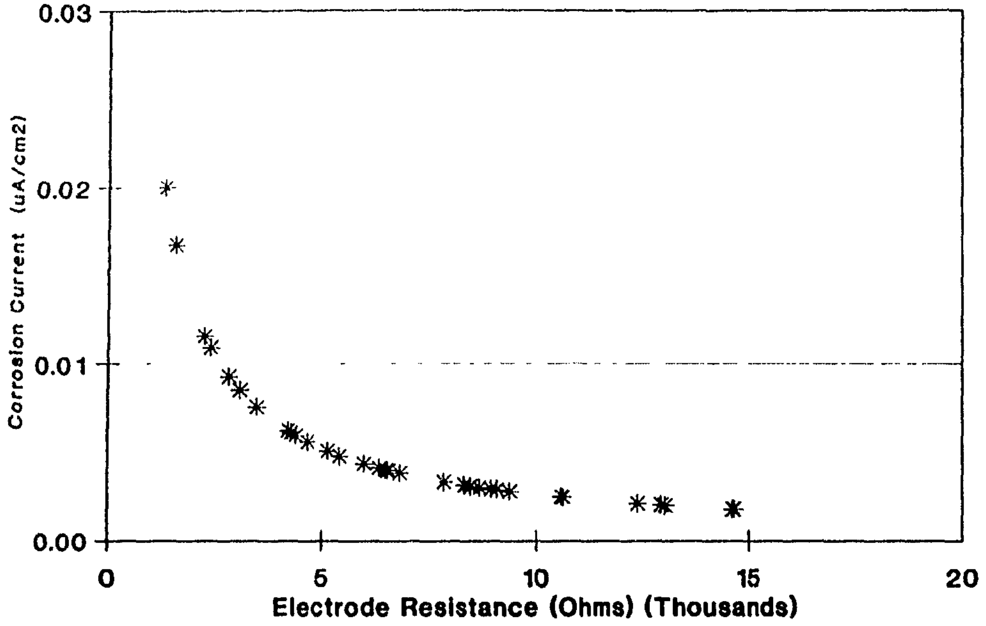
Concrete-Embedded Anode - Specimen #5E

Concrete-Embedded Anode - Specimen #5F

Figure N-3: Corrosion Current vs Resistance Specimens #5E and #5F

CORROSION CURRENT vs RESISTANCE

Concrete-Embedded Anode - Specimen #5G



Concrete-Embedded Anode - Specimen #5H

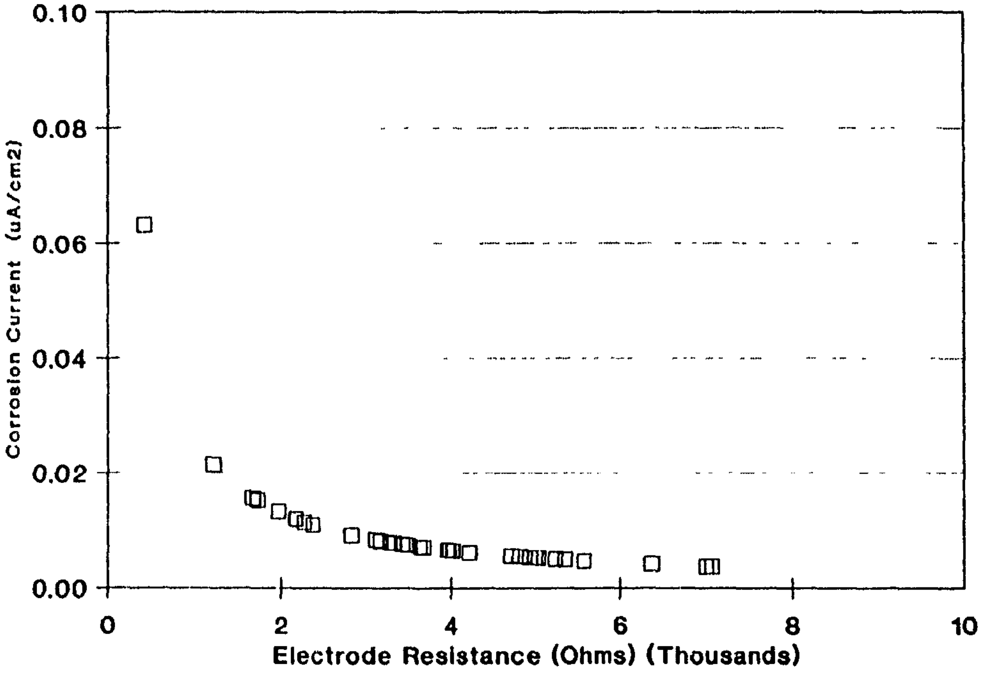


Figure N-4: Corrosion Current vs Resistance
Specimens #5G and #5H

CORROSION CURRENT vs RESISTANCE
Concrete-Embedded Anode - Specimen #5I

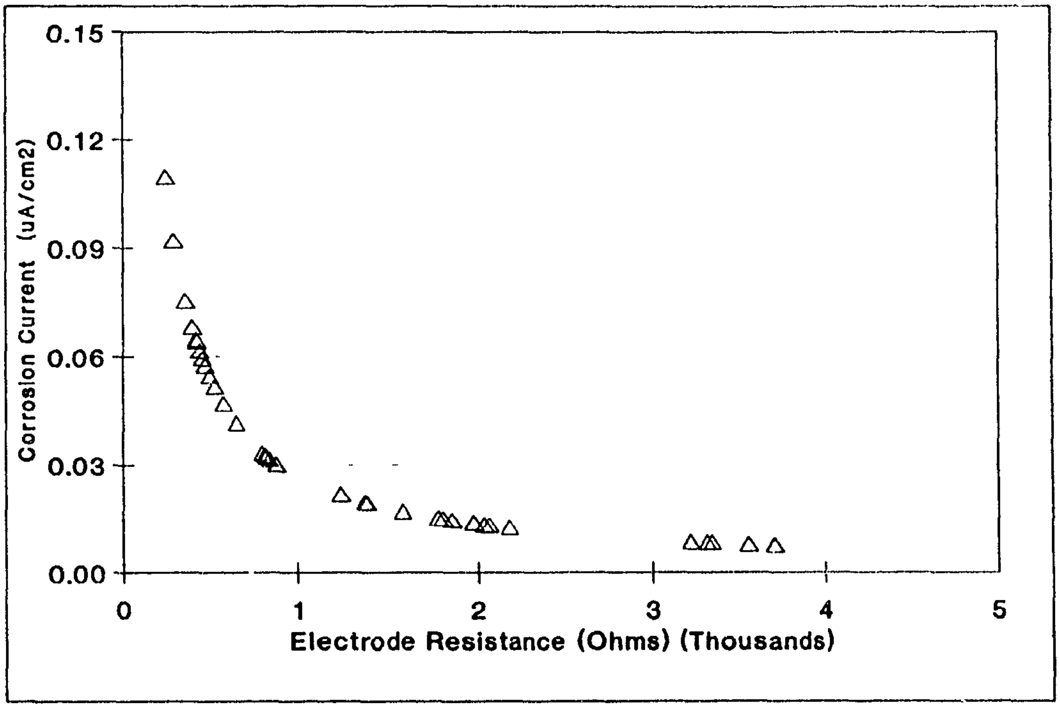
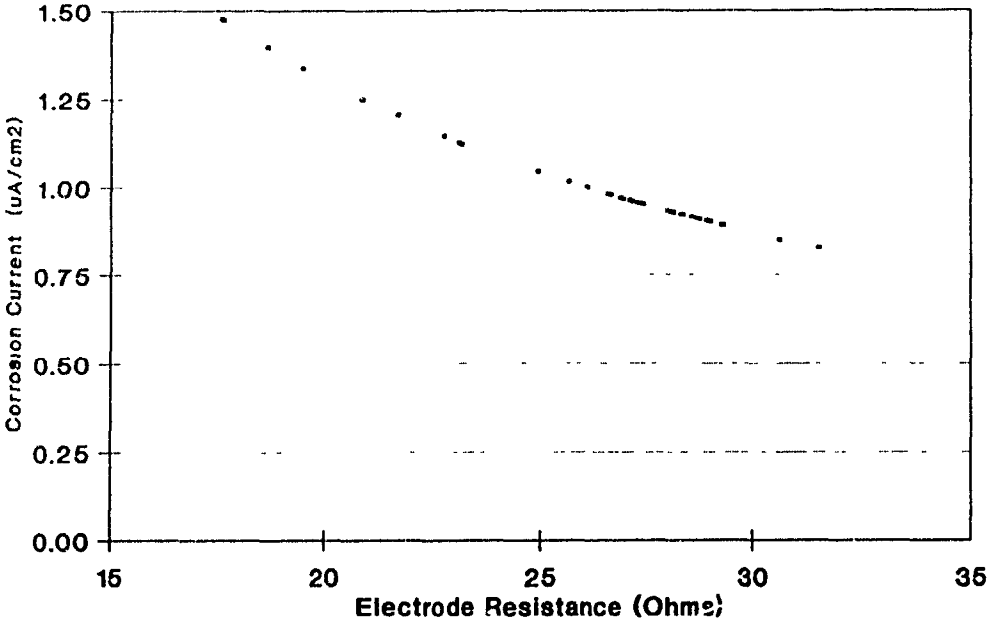


Figure N-5: Corrosion Current vs Resistance
Specimen #5I

CORROSION CURRENT vs RESISTANCE

Concrete-Embedded Anode - Specimen #6A



Concrete-Embedded Anode - Specimen #6B

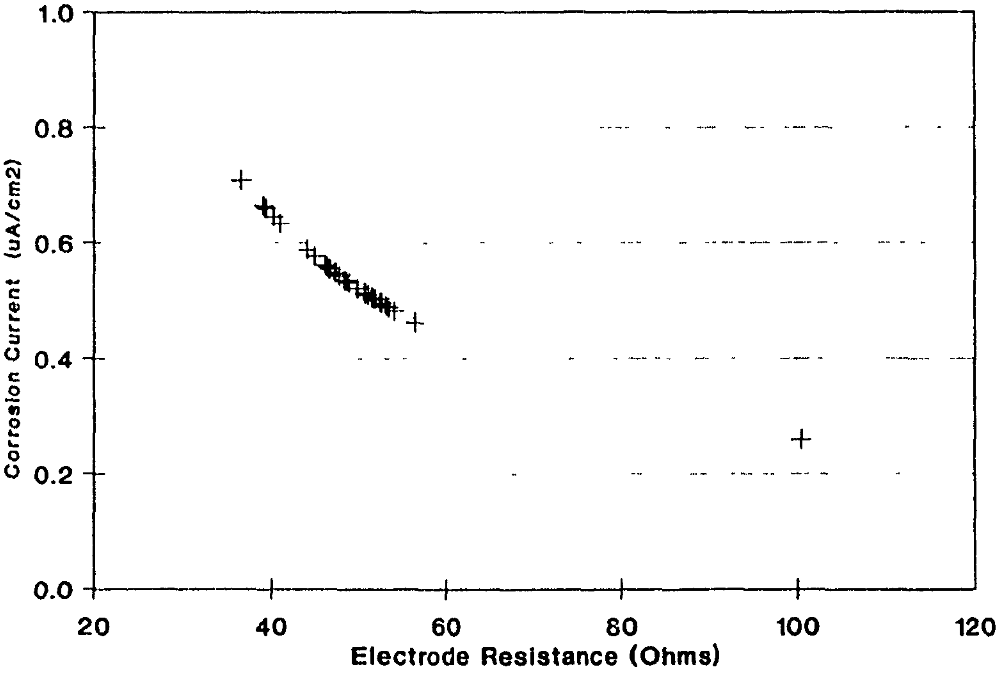
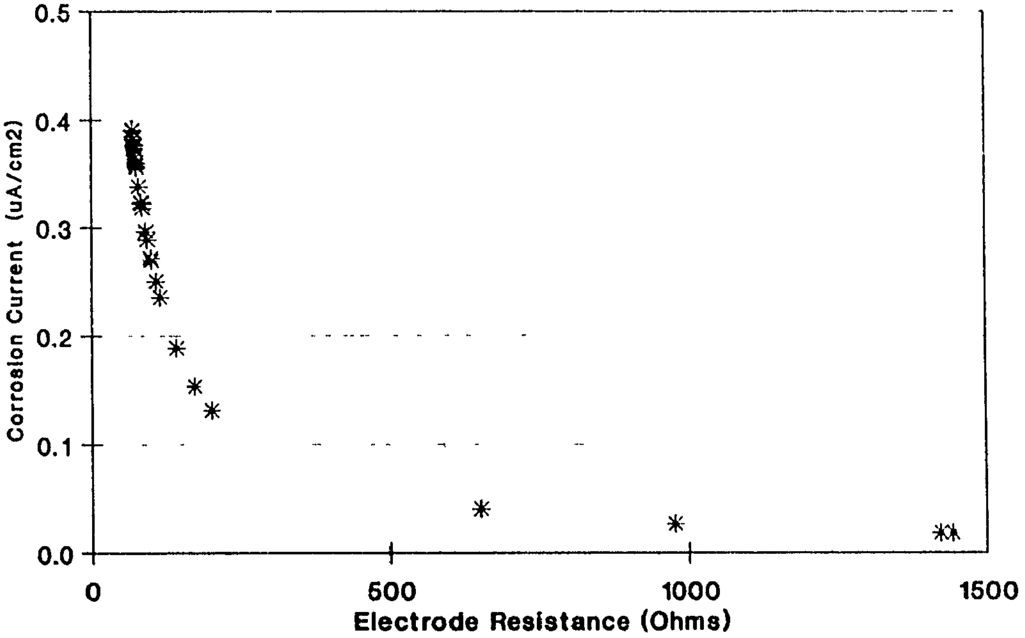


Figure N-6: Corrosion Current vs Resistance
Specimens #6A and #6B



CORROSION CURRENT vs RESISTANCE

Concrete-Embedded Anode - Specimen #6C

Concrete-Embedded Anode - Specimen #6D

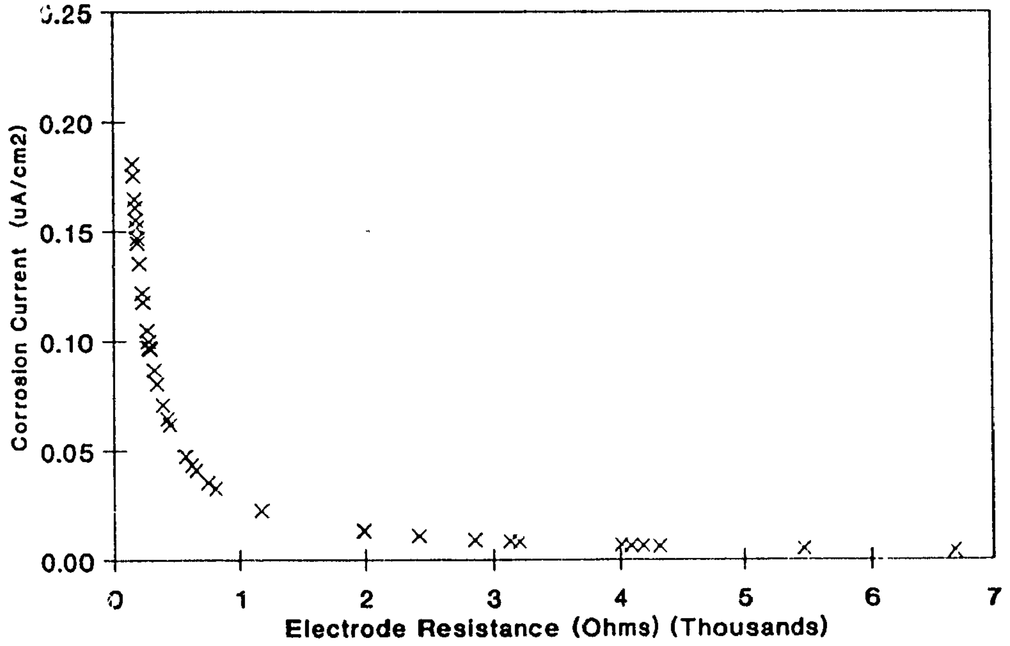


Figure N-7: Corrosion Current vs Resistance
Specimens #6C and #6D

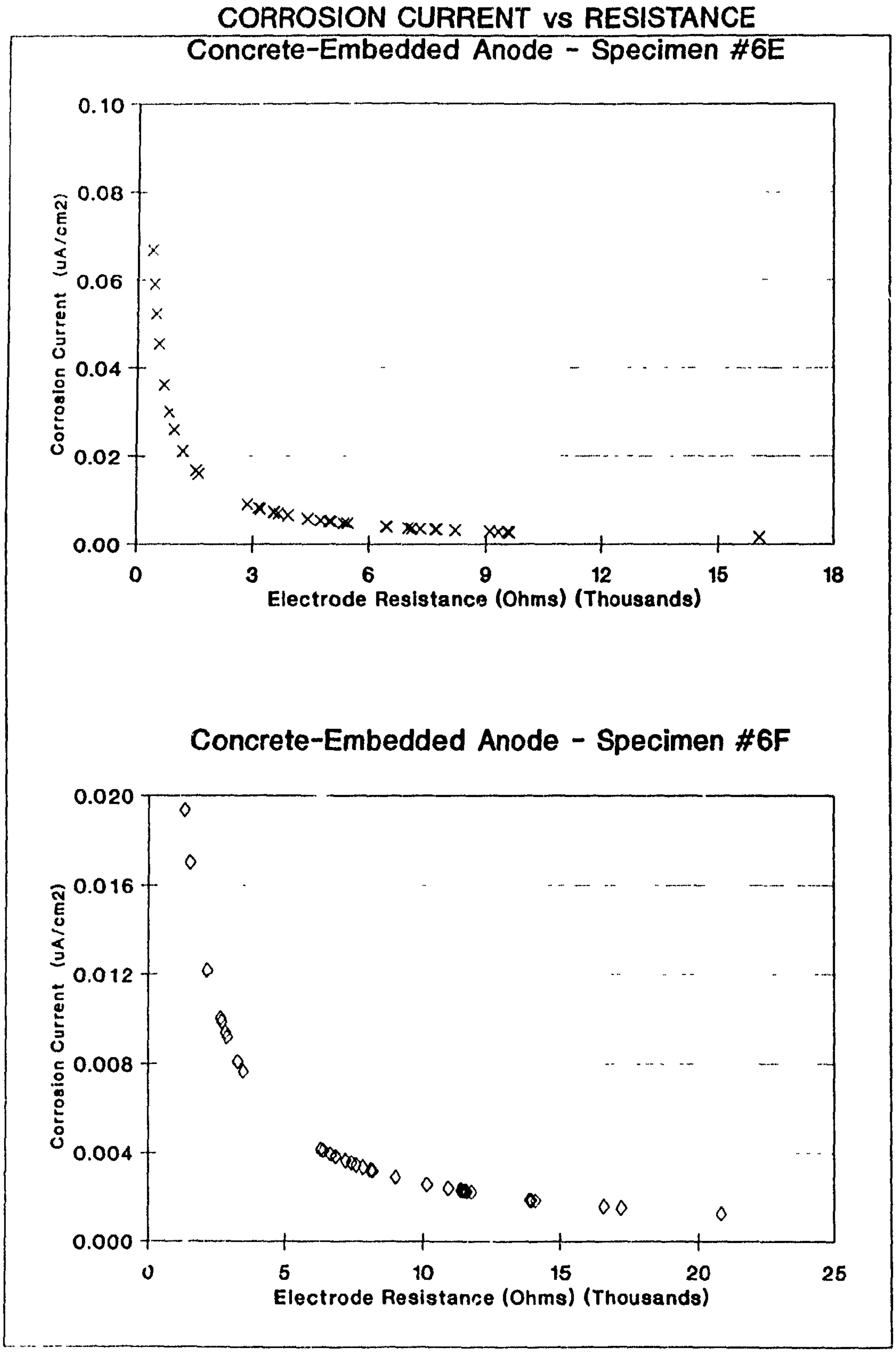


Figure N-8: Corrosion Current vs Resistance
Specimens #6E and #6F

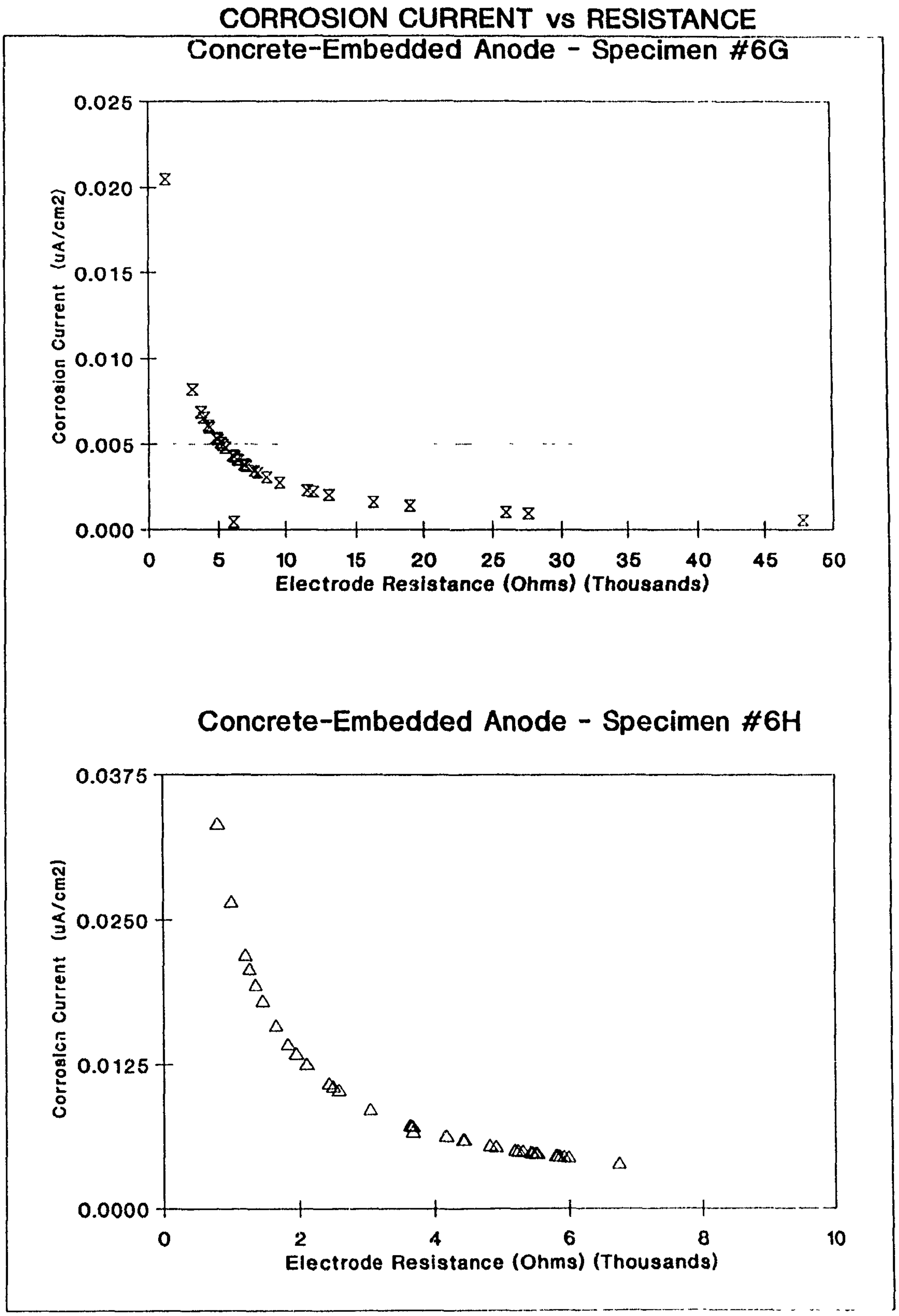
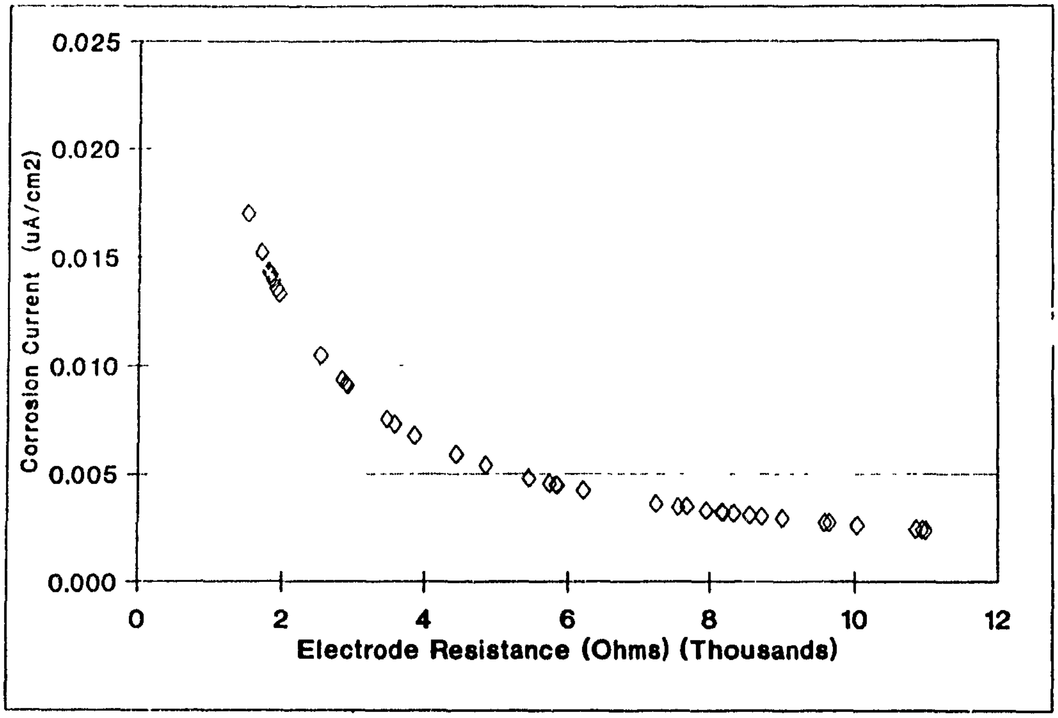


Figure N-9: Corrosion Current vs Resistance
Specimens #6G and #6H

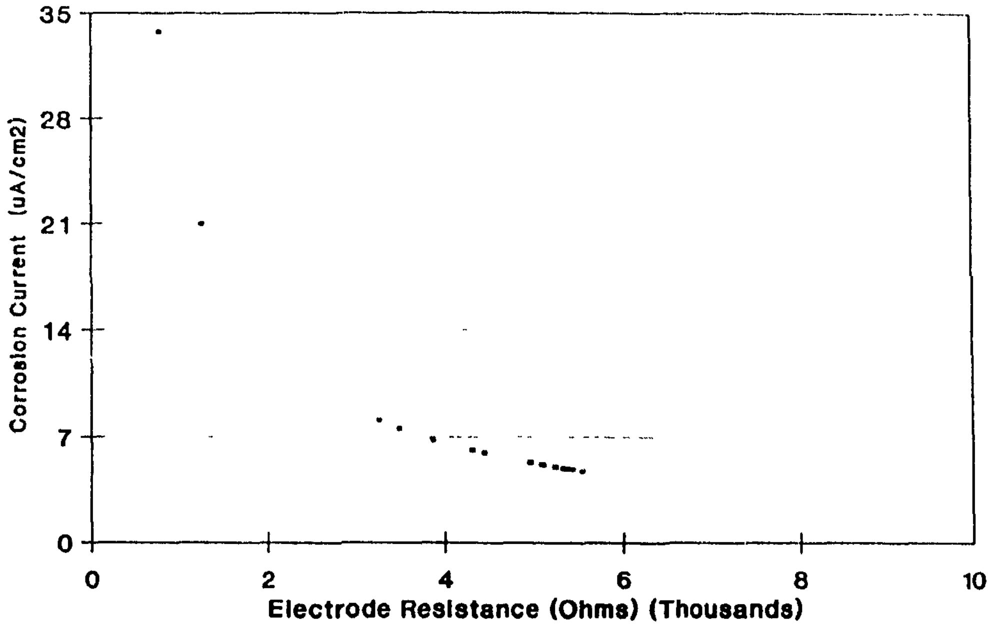


CORROSION CURRENT vs RESISTANCE
Concrete-Embedded Anode - Specimen #6l

Figure N-10: Corrosion Current vs Resistance
Specimen #6l

CORROSION CURRENT vs RESISTANCE

Bare Anode - Specimen #7A



Bare Anode - Specimen #7B

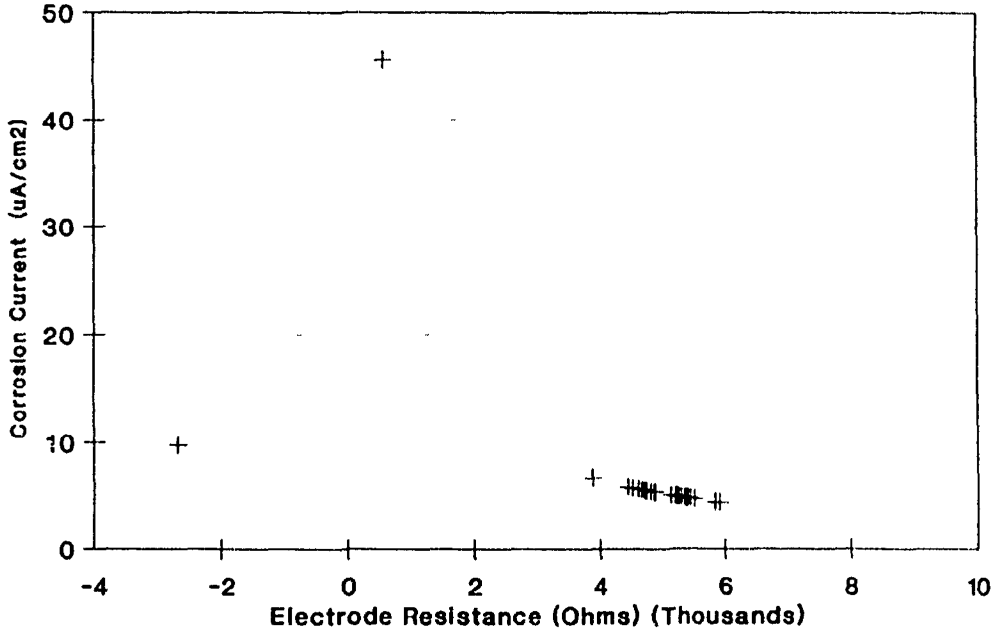
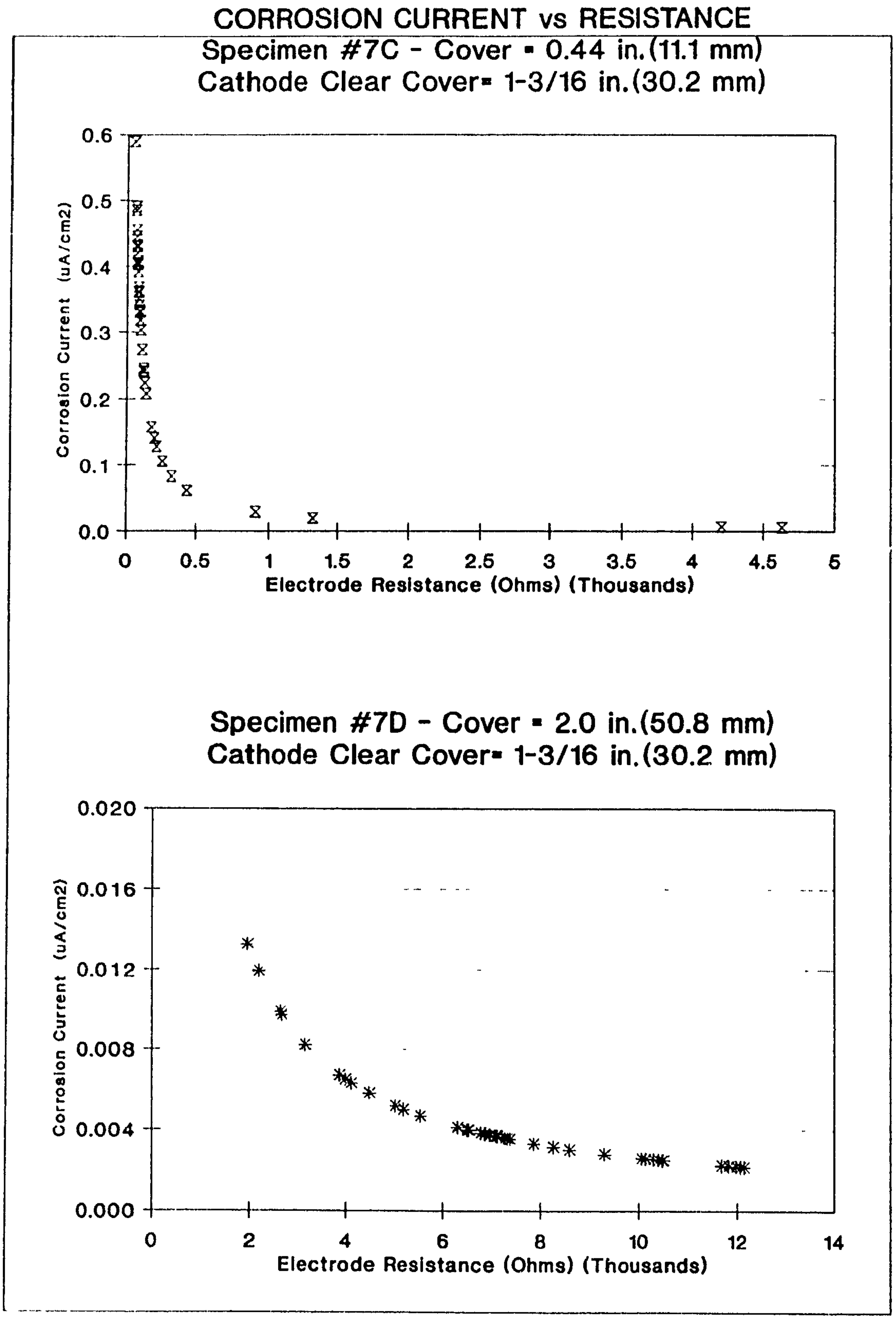


Figure N-11: Corrosion Current vs Resistance
Specimens #7A and #7B



CORROSION CURRENT vs RESISTANCE

Specimen #7C - Cover = 0.44 in.(11.1 mm)
Cathode Clear Cover= 1-3/16 in.(30.2 mm)

Specimen #7D - Cover = 2.0 in.(50.8 mm)
Cathode Clear Cover= 1-3/16 in.(30.2 mm)

Figure N-12: Corrosion Current vs Resistance
Specimens #7C and #7D

CORROSION CURRENT vs RESISTANCE
Specimen #7E- Cover= 1-3/16 in.(30.2 mm)
Cathode Clear Cover= 1-3/16 in.(30.2 mm)

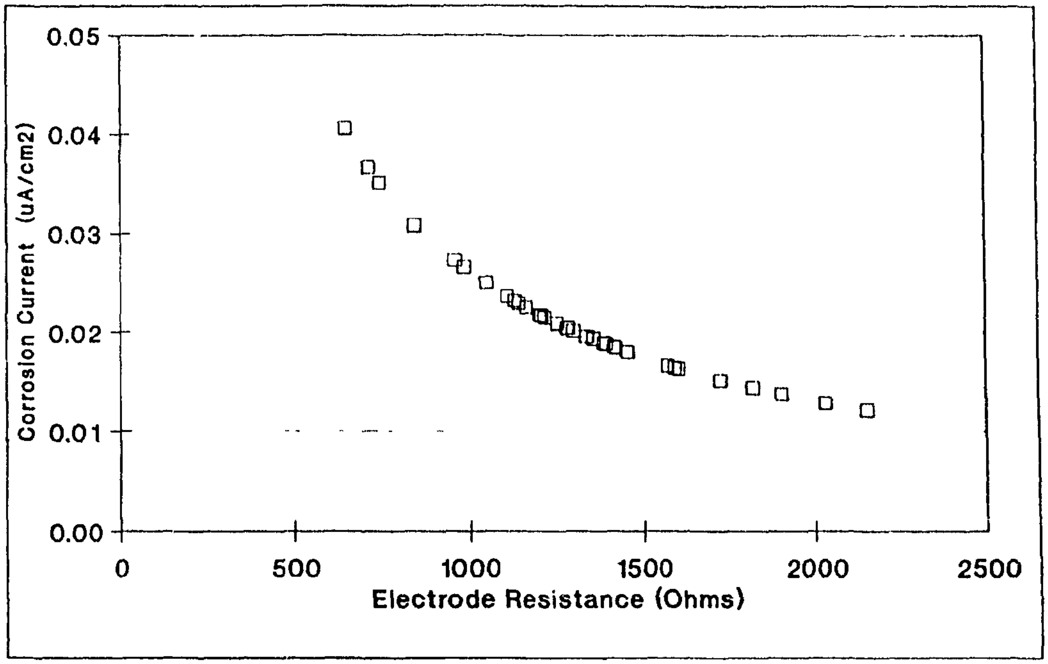


Figure N-13: Corrosion Current vs Resistance
Specimen #7E

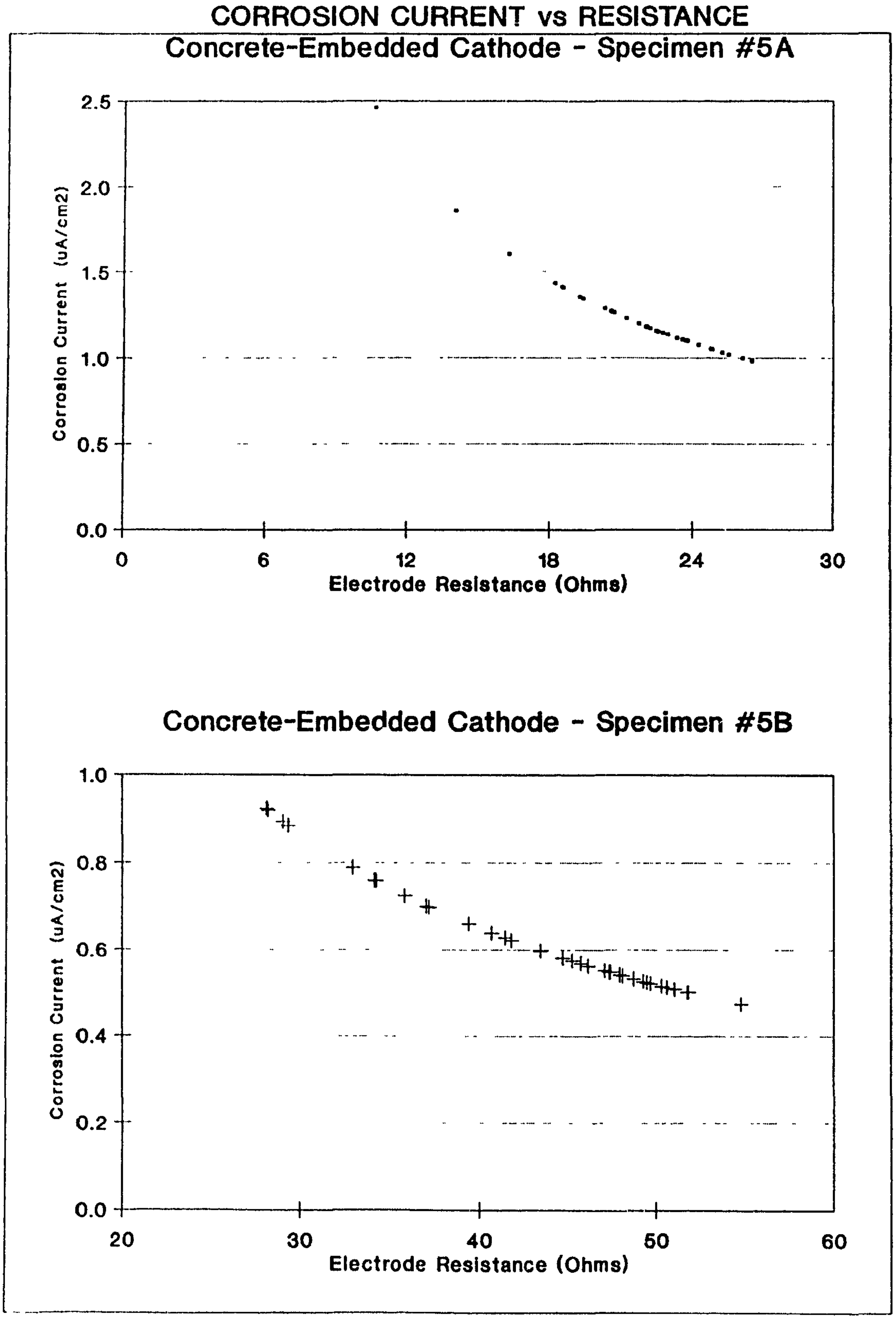


Figure N-14: Corrosion Current vs Resistance
Specimens #5A and #5B

CORROSION CURRENT vs RESISTANCE

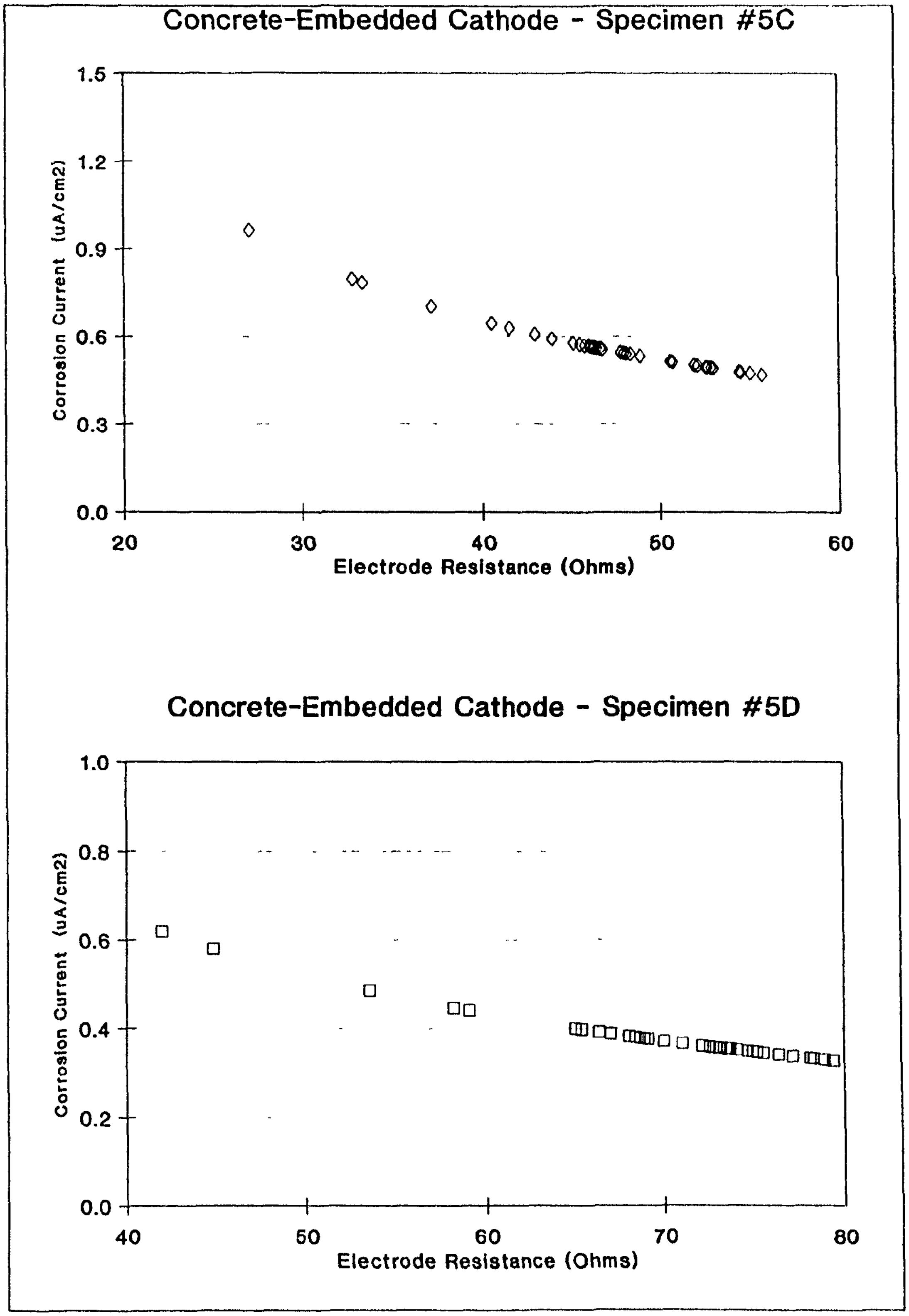
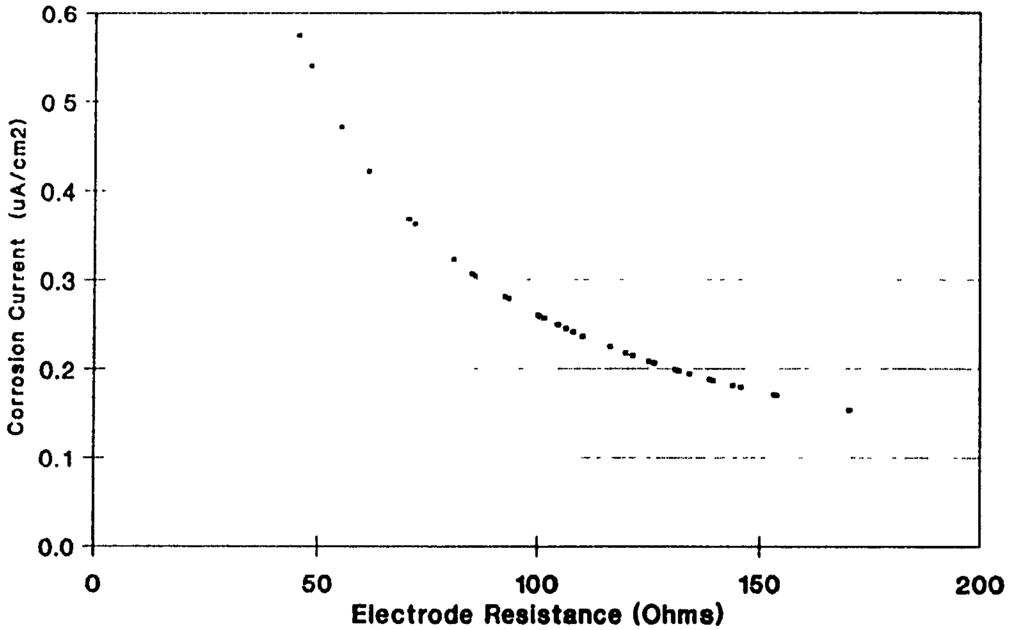


Figure N-15: Corrosion Current vs Resistance
Specimens #5C and #5D

CORROSION CURRENT vs RESISTANCE

Concrete-Embedded Cathode - Specimen #5E



Concrete-Embedded Cathode - Specimen #5F

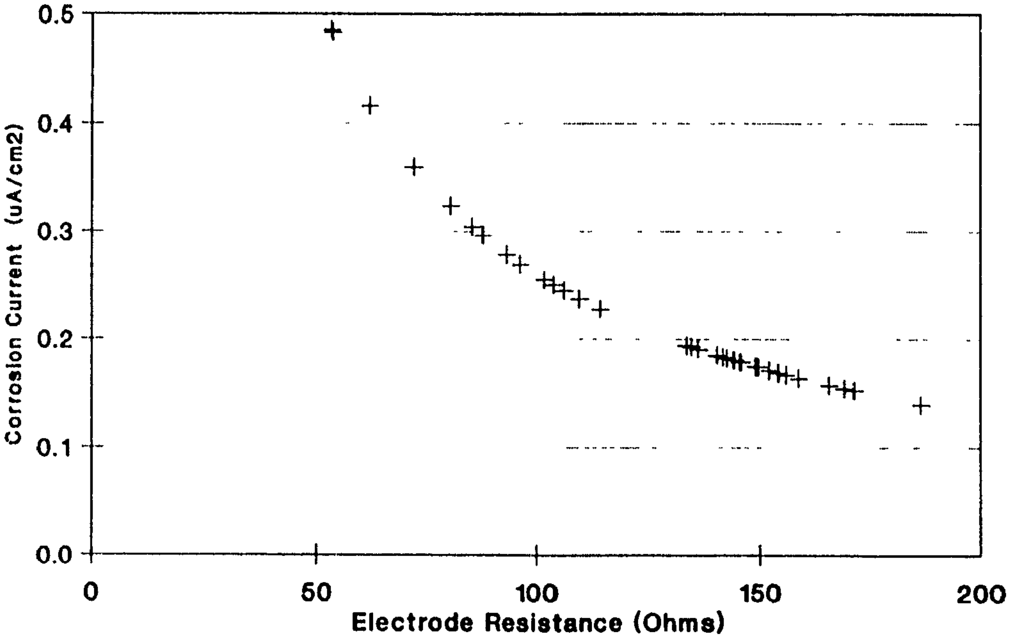
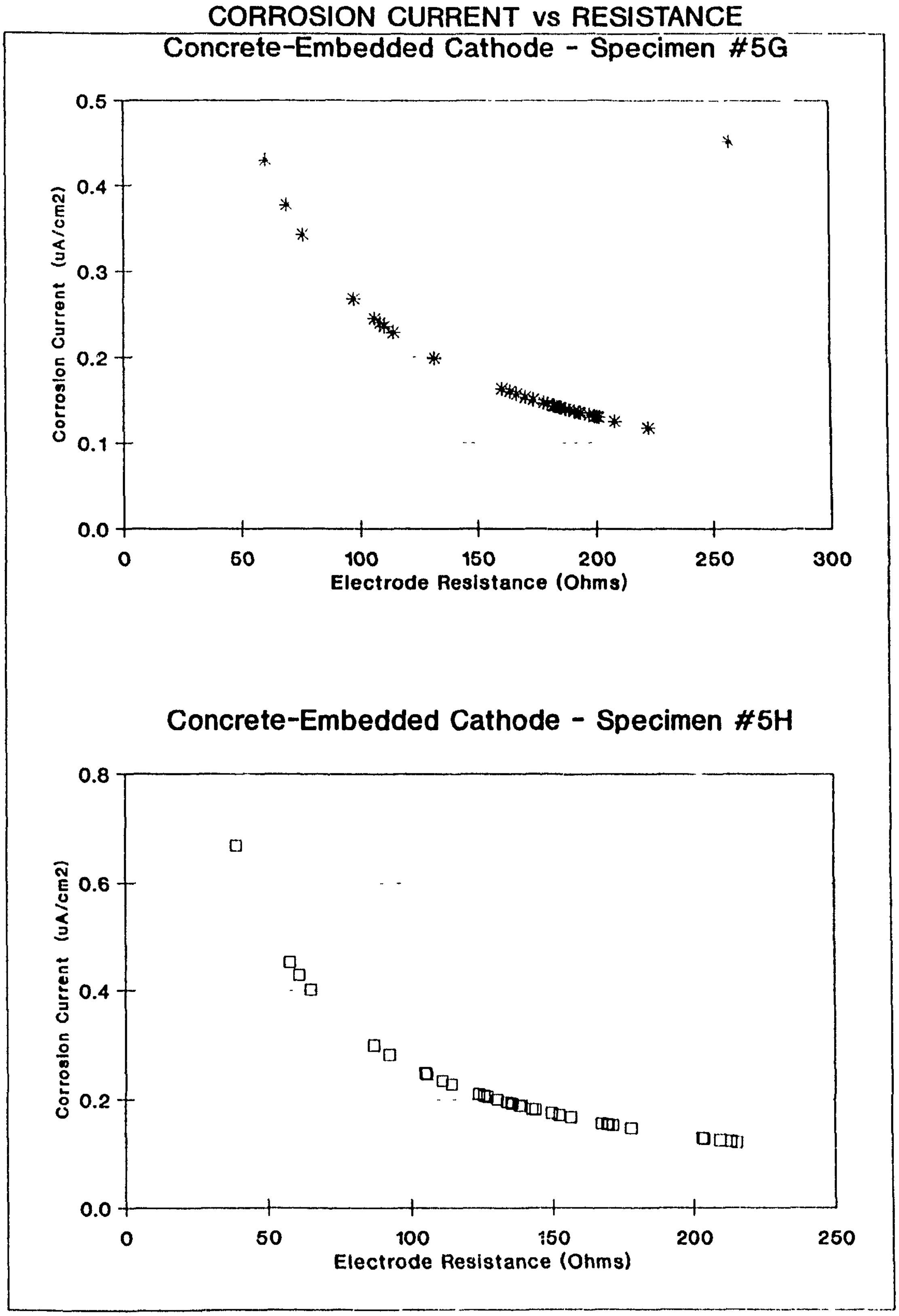


Figure N-16: Corrosion Current vs Resistance
Specimens #5E and #5F


CORROSION CURRENT vs RESISTANCE
Concrete-Embedded Cathode - Specimen #5G

Concrete-Embedded Cathode - Specimen #5H

Figure N-17: Corrosion Current vs Resistance
Specimens #5G and #5H

CORROSION CURRENT vs RESISTANCE
Concrete-Embedded Cathode - Specimen #5I

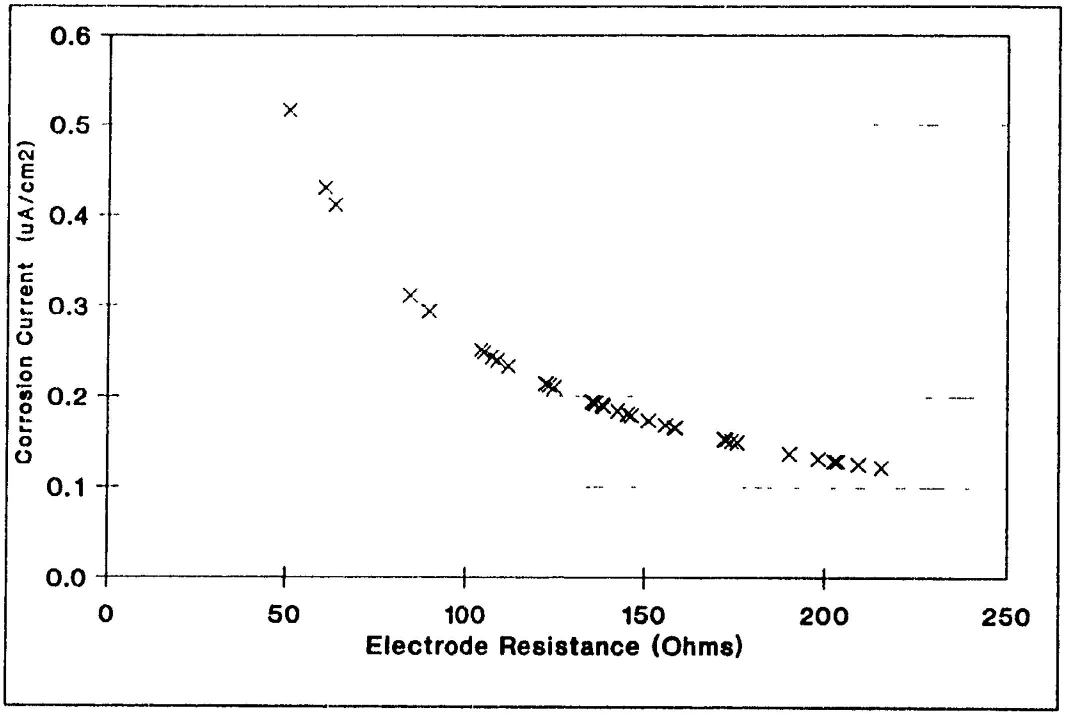


Figure N-18: Corrosion Current vs Resistance
Specimen #5I

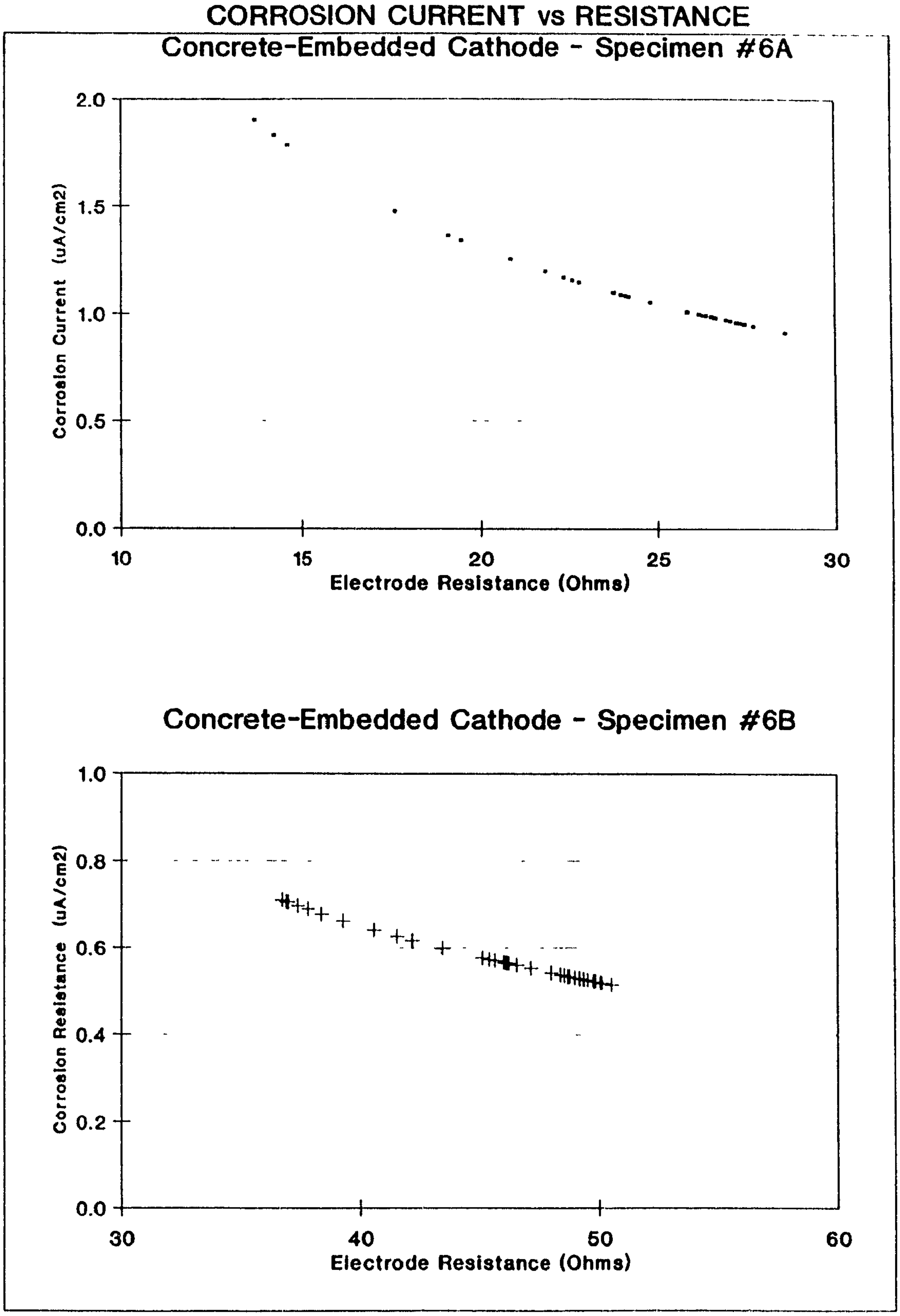
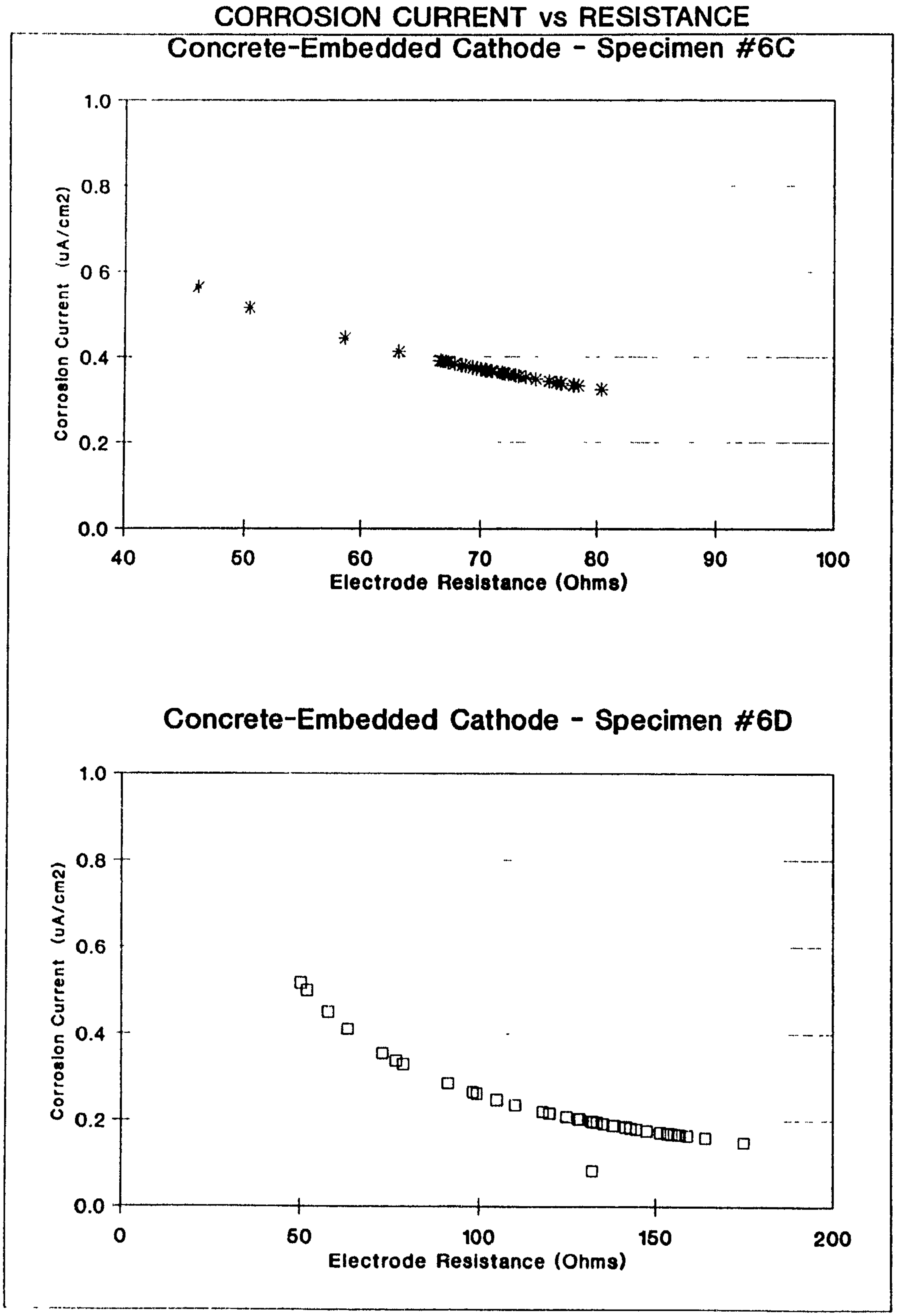


Figure N-19: Corrosion Current vs Resistance
Specimens #6A and #6B

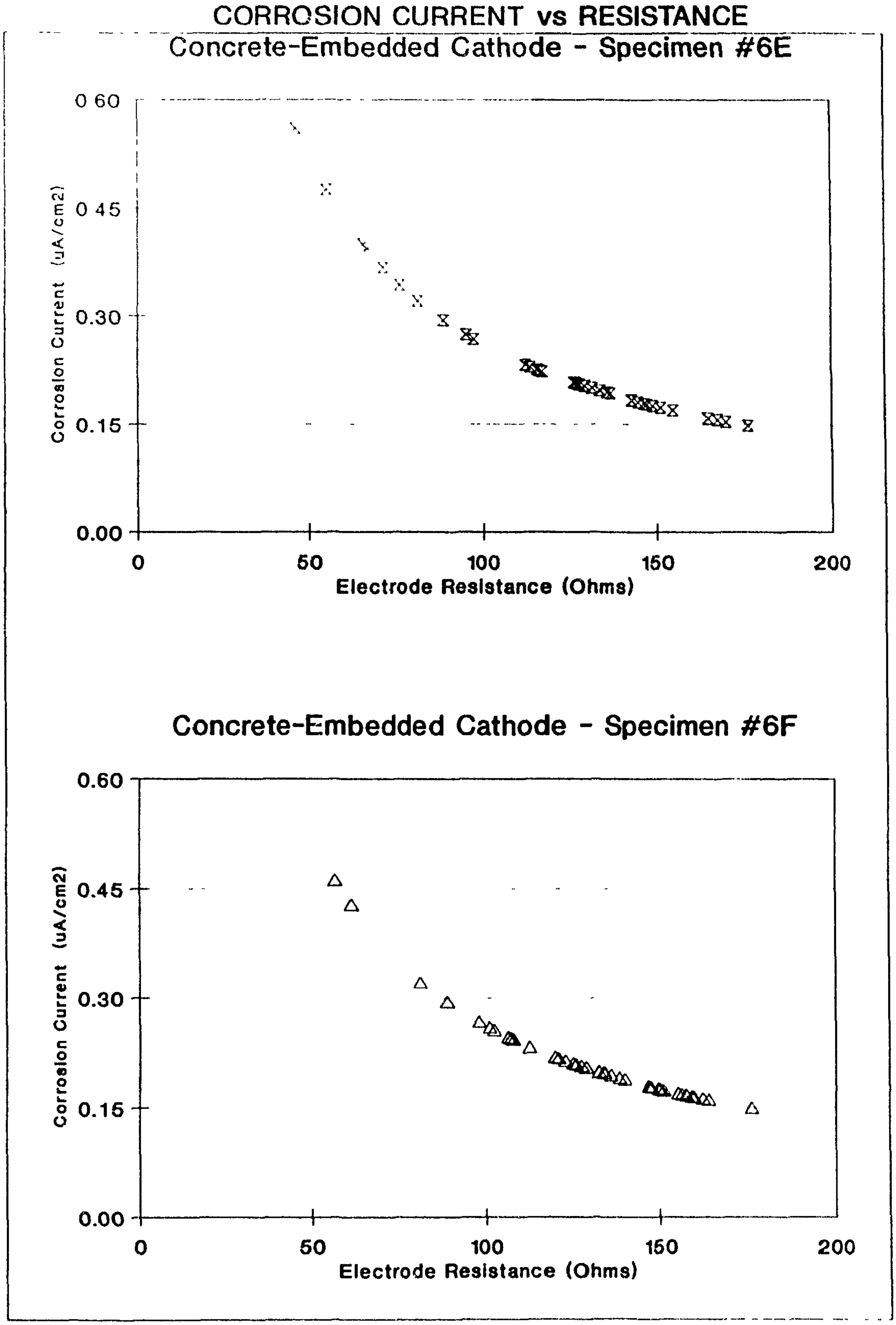


CORROSION CURRENT vs RESISTANCE

Concrete-Embedded Cathode - Specimen #6C

Concrete-Embedded Cathode - Specimen #6D

Figure N-20: Corrosion Current vs Resistance
Specimens #6C and #6D


CORROSION CURRENT vs RESISTANCE

Concrete-Embedded Cathode - Specimen #6E

Concrete-Embedded Cathode - Specimen #6F

Figure N-21: Corrosion Current vs Resistance
Specimens #6E and #6F

CORROSION CURRENT vs RESISTANCE

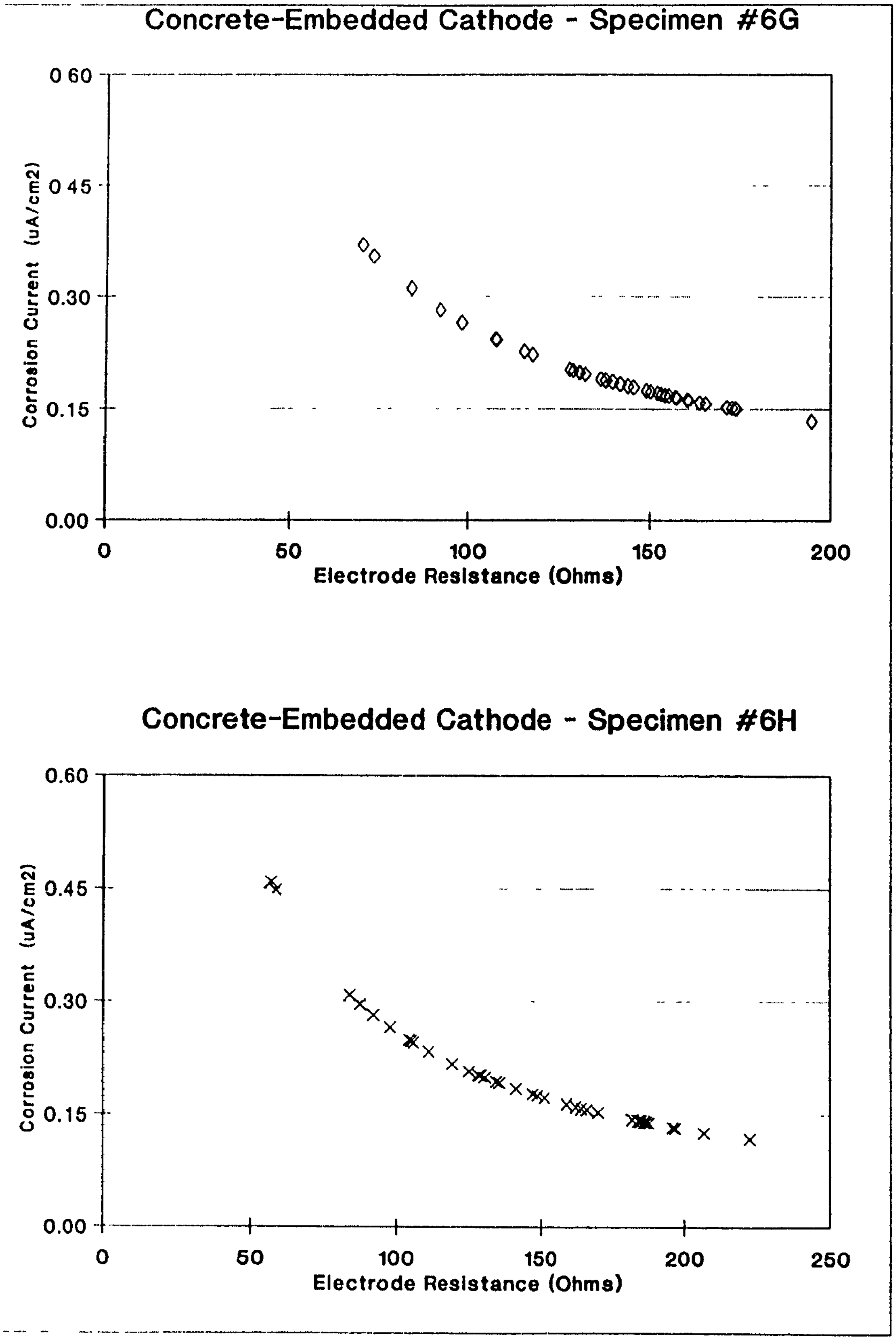


Figure N-22: Corrosion Current vs Resistance
Specimens #6G and #6H

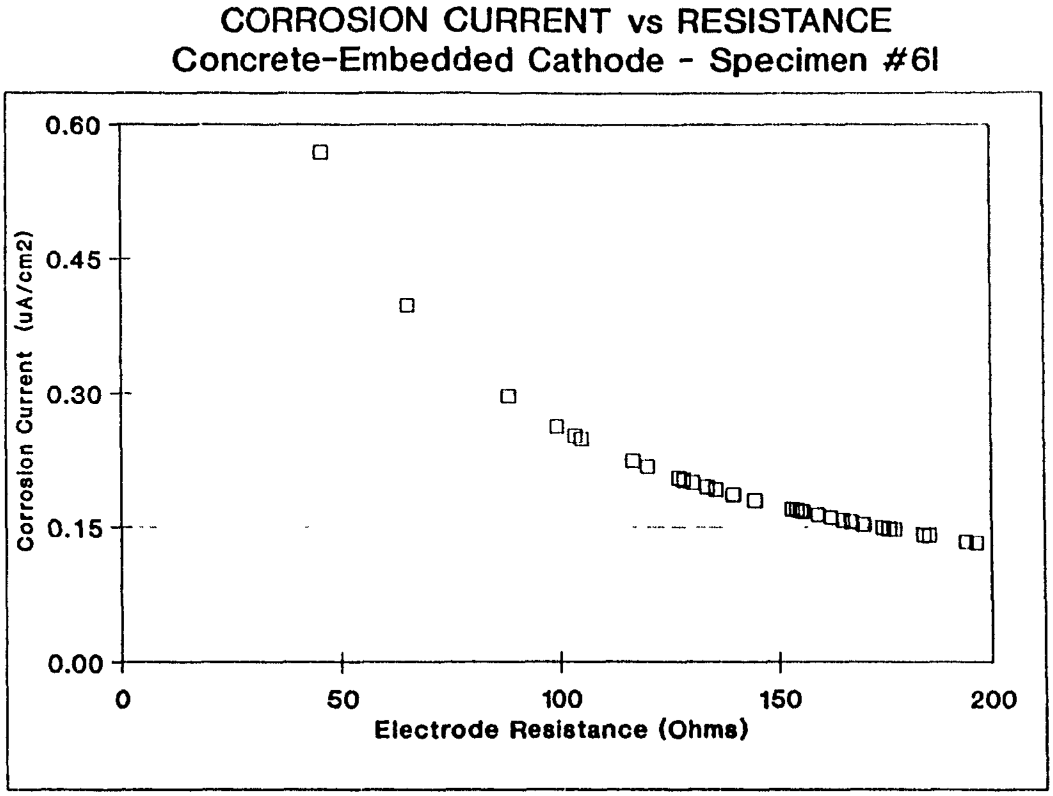


Figure N-23: Corrosion Current vs Resistance
Specimen #6I

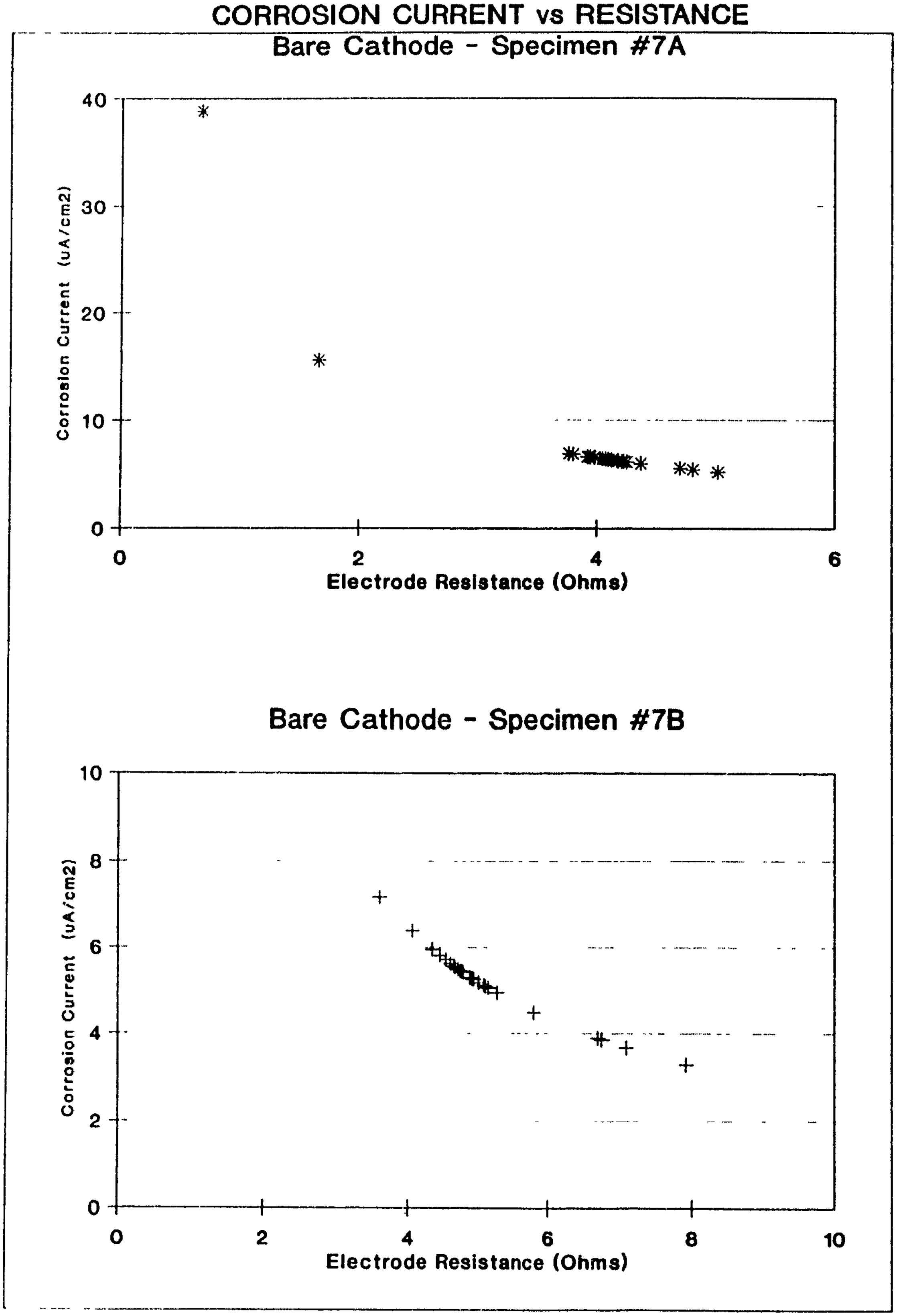
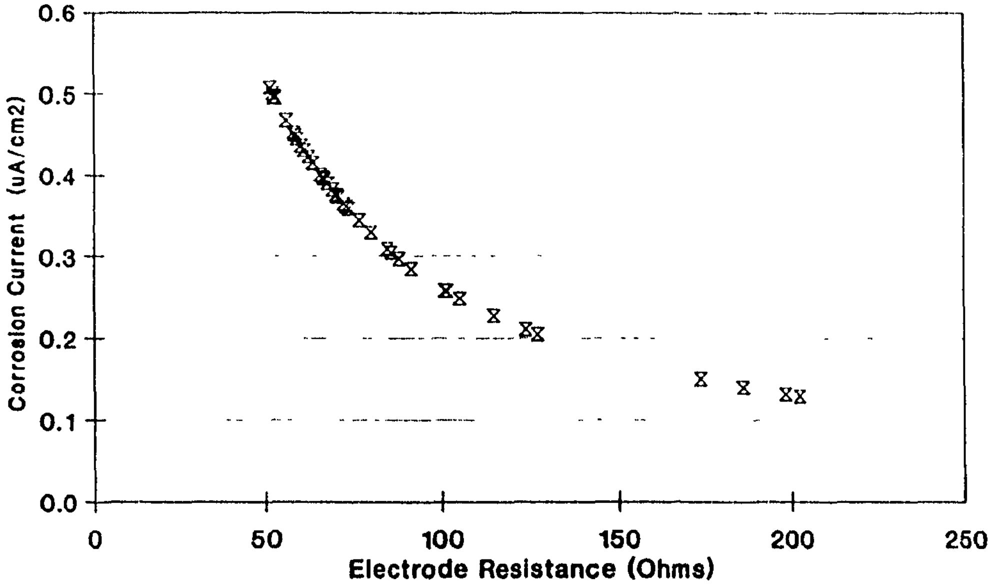


Figure N-24: Corrosion Current vs Resistance
Specimens #7A and #7B

CORROSION CURRENT vs RESISTANCE
Cathode Cover = 1-3/16 in.(30.2 mm)

Specimen #7C - Cover = 0.44 in.(11.1 mm)



Specimen #7D - Cover = 2.0 in.(50.8 mm)

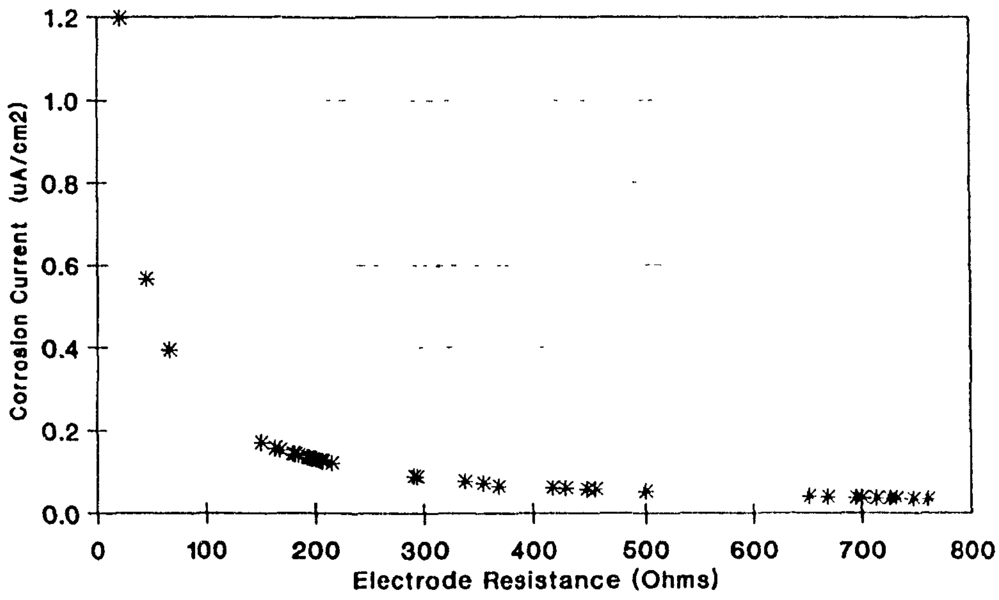


Figure N-25: Corrosion Current vs Resistance
Specimens #7C and #7D

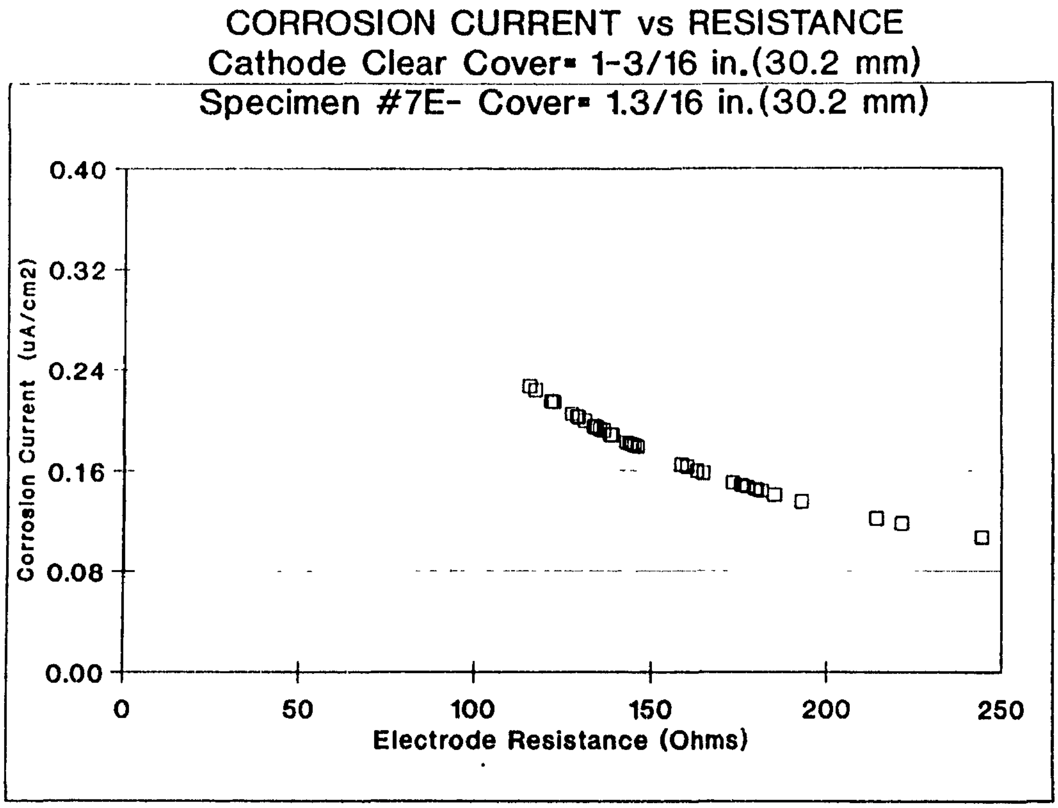


Figure N-26: Corrosion Current vs Resistance
Specimen #7E

APPENDIX O

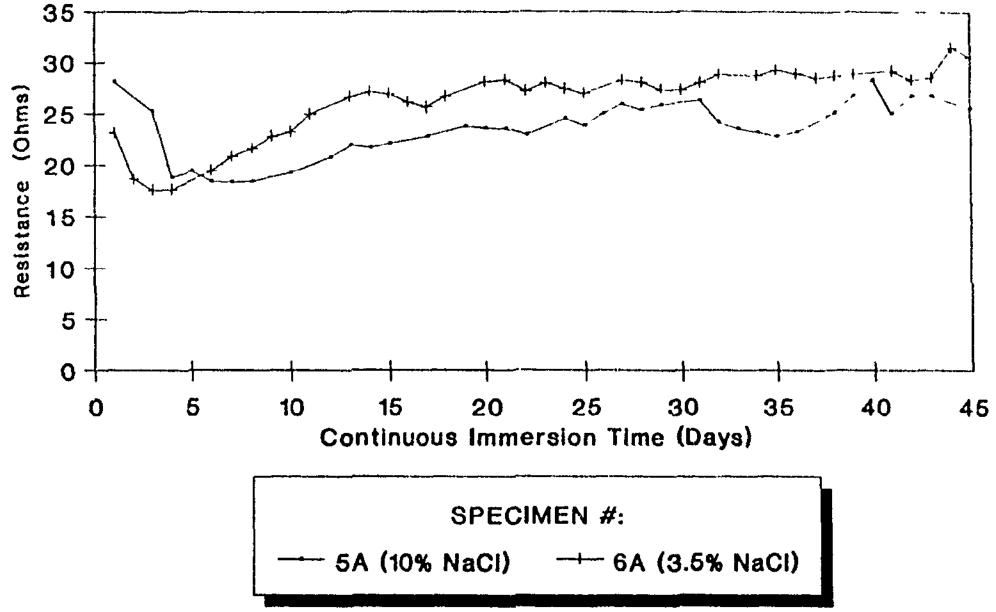
Test Series #5 and #6

Comparison of Resistance and Current Results

In order to assess the effect of the strength of electrolyte solution on the corrosion activity, specimens from both Test Series #5 and #6 having the same thickness of the concrete cover are compared directly. This is done in the following pages, with comparisons being made for both the current variation and the electrode "polarization" resistance. Both normal and reversed polarity positions are considered.

CLEAR COVER - 5/16 in. (7.9 mm)

Normal Polarity: "Lollipop" Resistance



Reversed Polarity: "Lollipop" Resistance

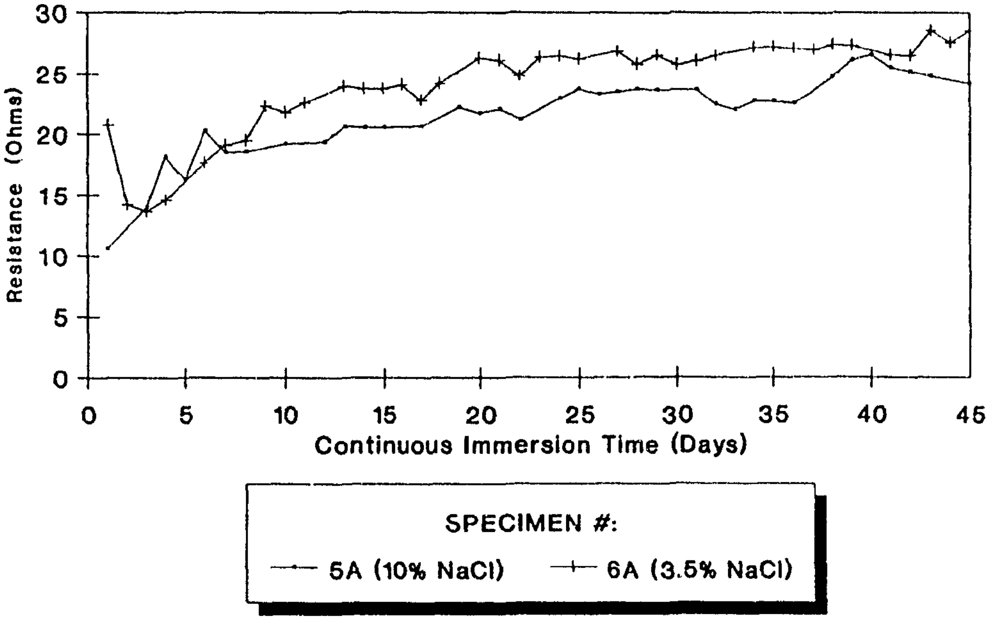
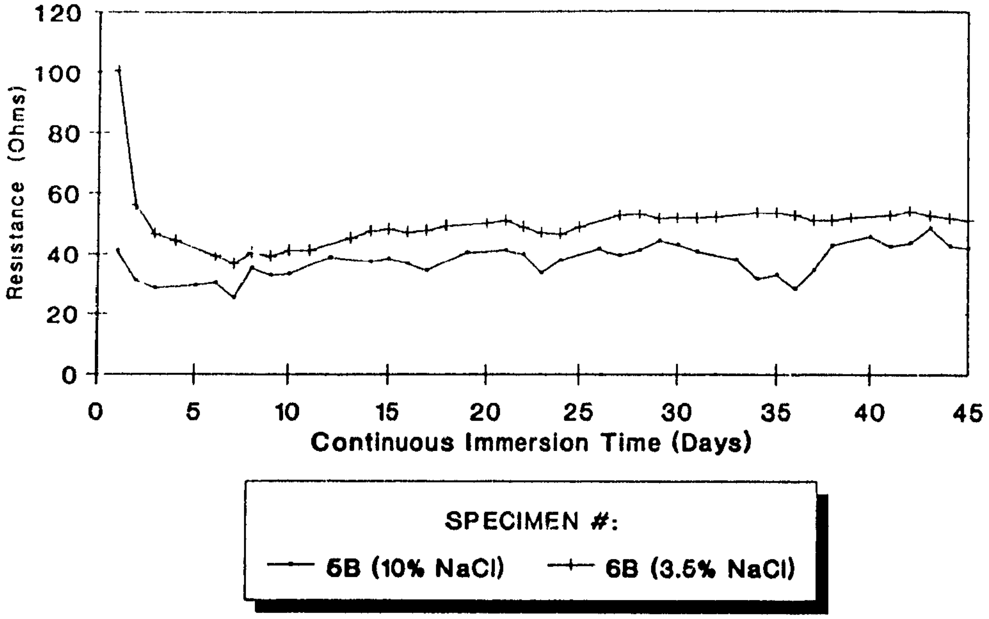


FIGURE O-1: Effect of Electrolyte Solution
"Lollipop" Resistance - Specimens #5A and #6A

CLEAR COVER - 7/16 in. (11.1 mm)

Normal Polarity: "Lollipop" Resistance



Reversed Polarity: "Lollipop" Resistance

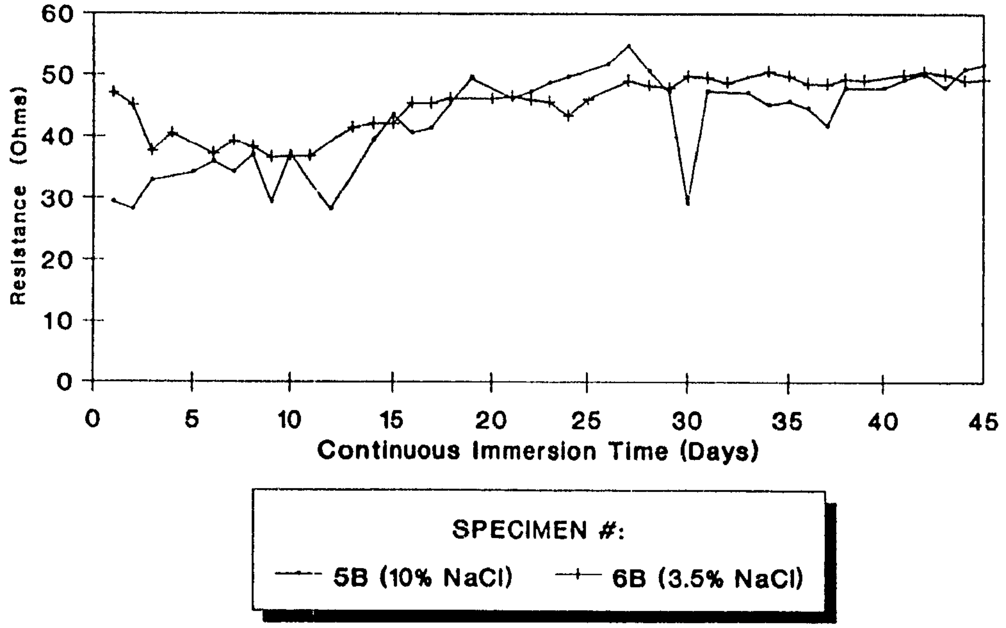
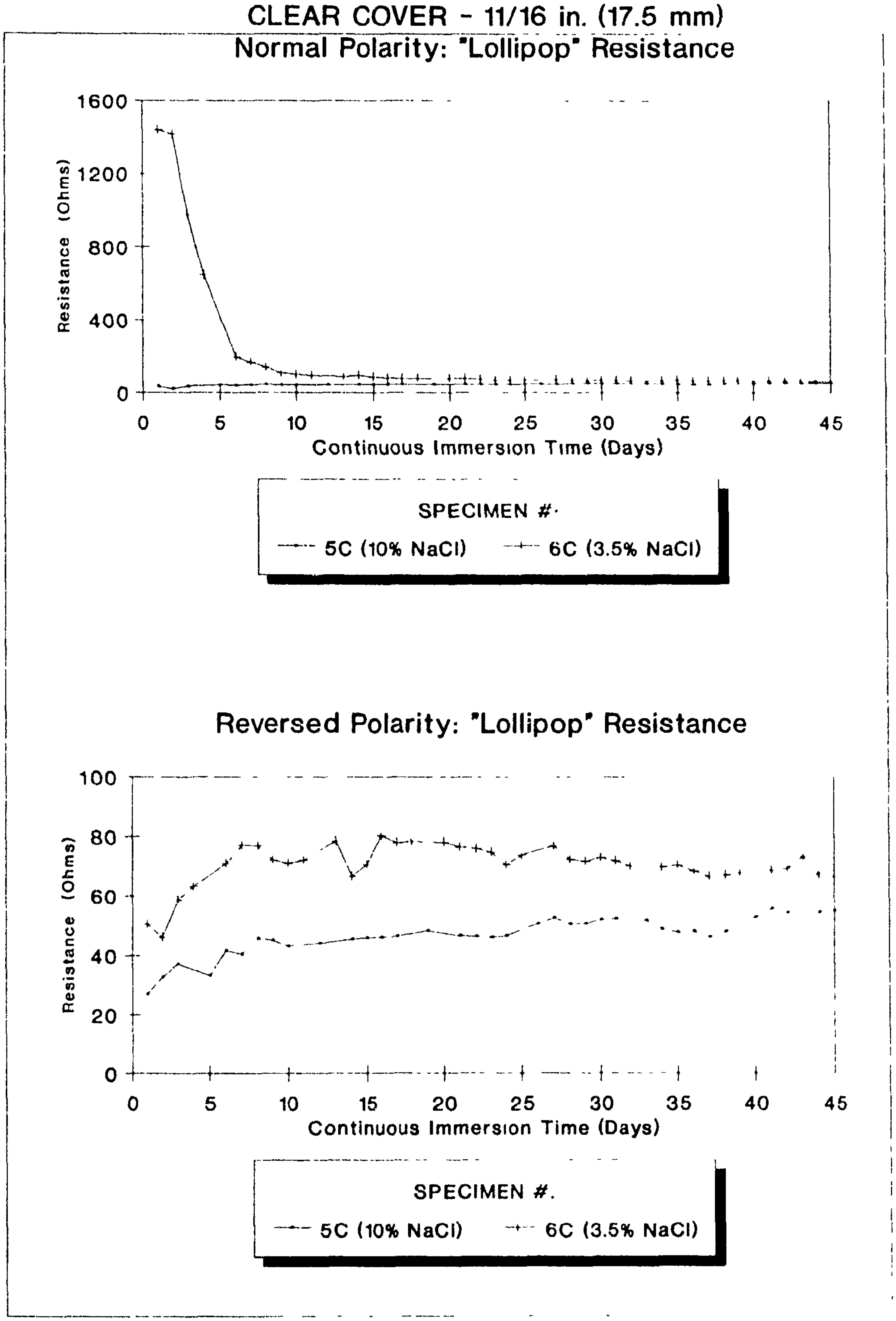


FIGURE O-2: Effect of Electrolyte Solution "Lollipop" Resistance - Specimens #5B and #6B


CLEAR COVER - 11/16 in. (17.5 mm)

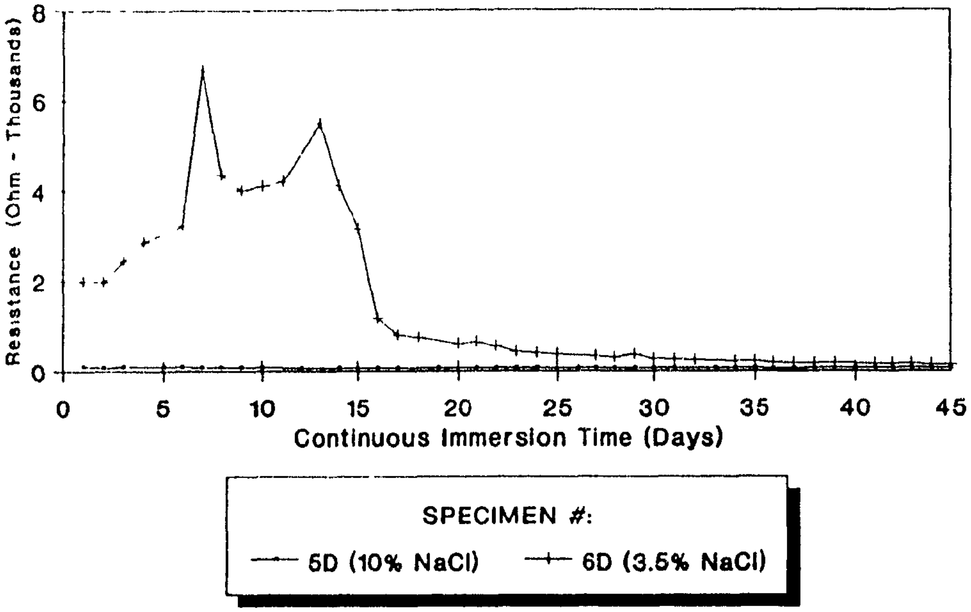
Normal Polarity: "Lollipop" Resistance

Reversed Polarity: "Lollipop" Resistance

FIGURE O-3: Effect of Electrolyte Solution "Lollipop" Resistance - Specimens #5C and #6C

CLEAR COVER - 15/16 in. (23.8 mm)

Normal Polarity: "Lollipop" Resistance



Reversed Polarity: "Lollipop" Resistance

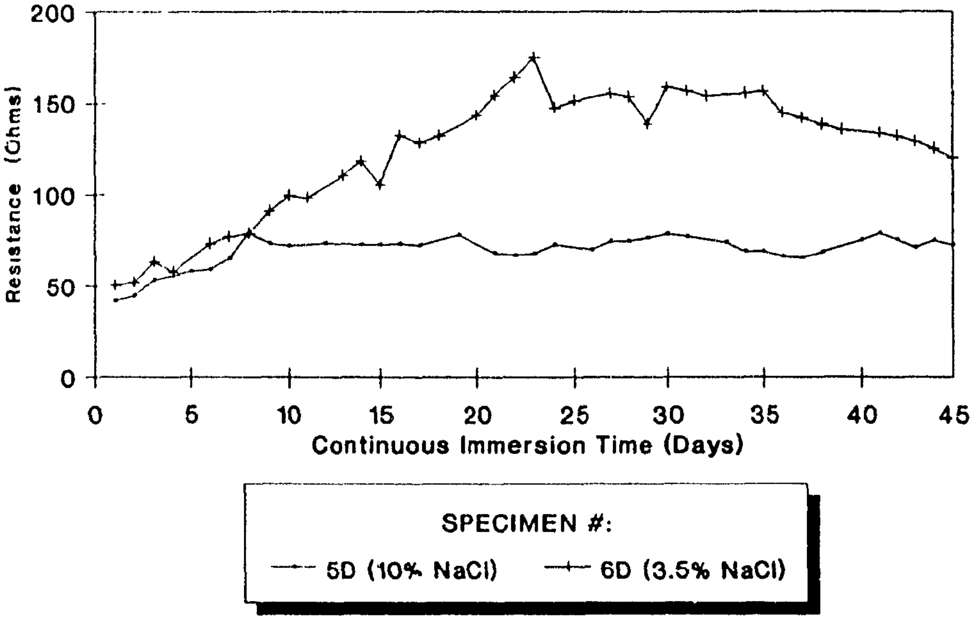
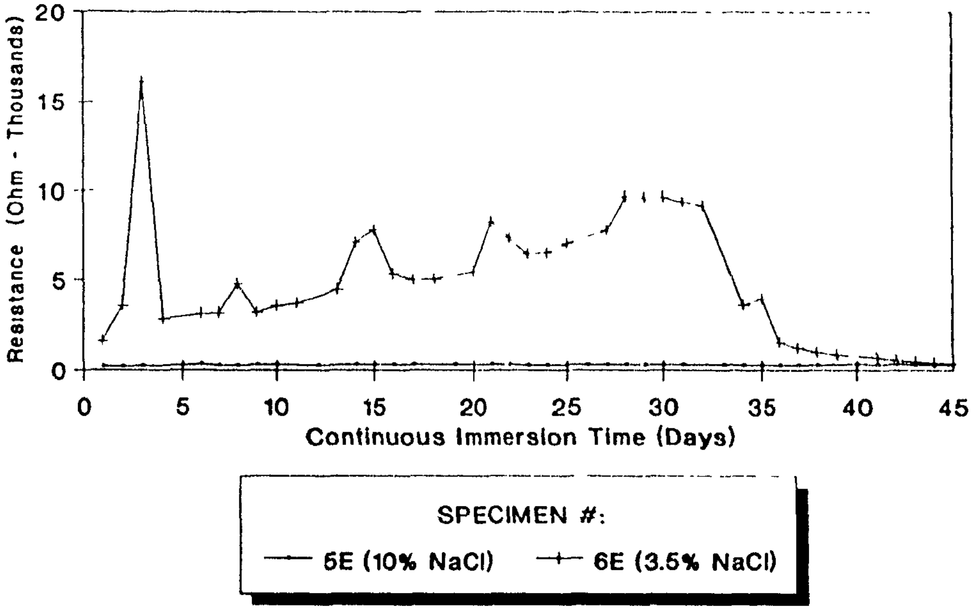


FIGURE O-4: Effect of Electrolyte Solution "Lollipop" Resistance - Specimens #5D and #6D

CLEAR COVER - 1-3/16 in. (30.2 mm)

Normal Polarity: "Lollipop" Resistance



Reversed Polarity: "Lollipop" Resistance

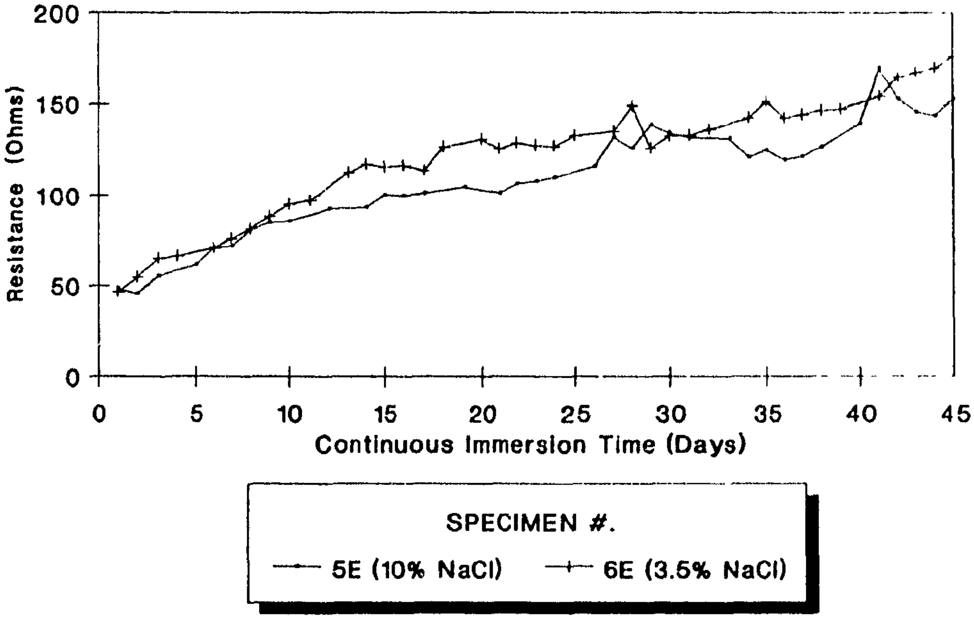
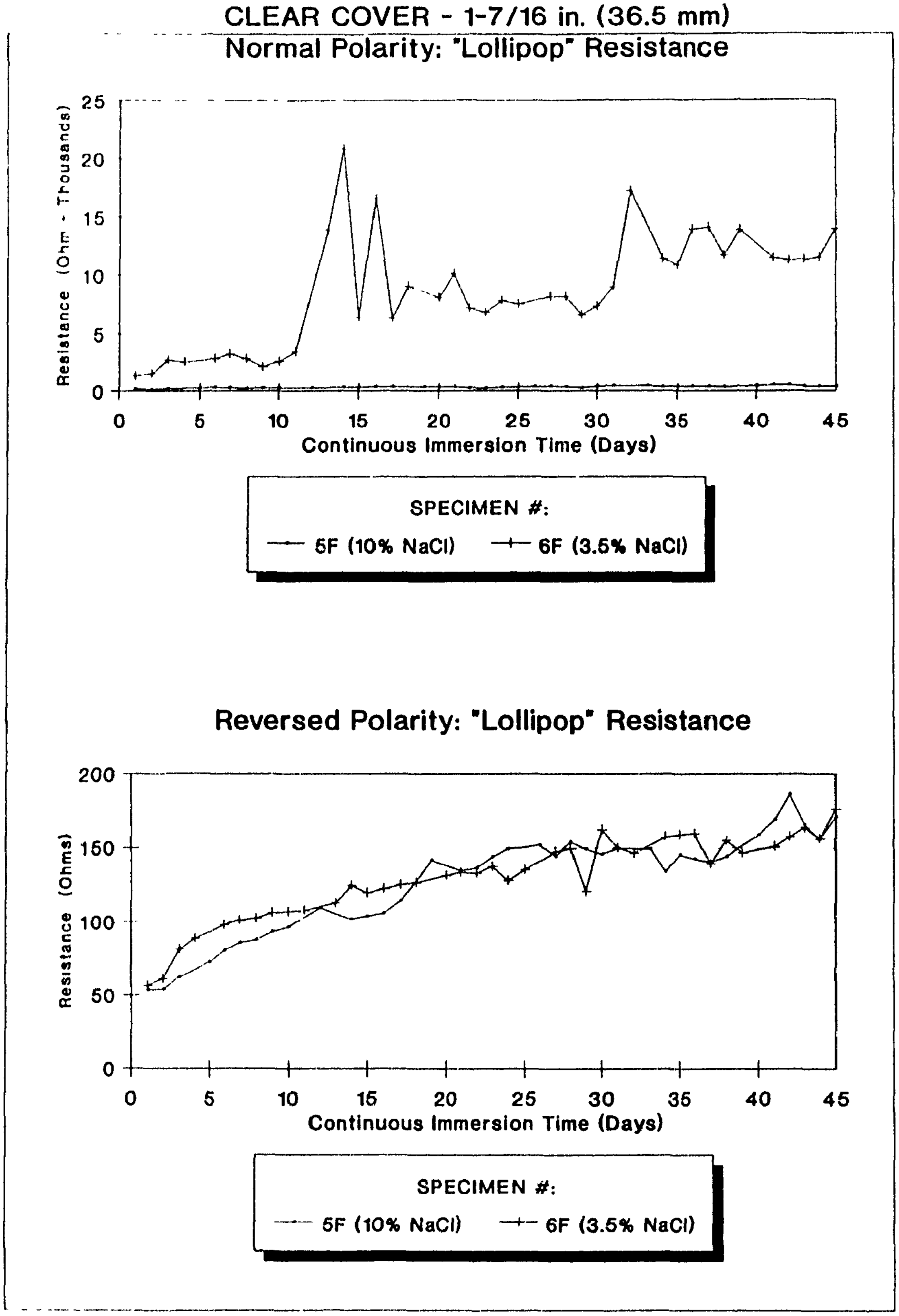


FIGURE O-5: Effect of Electrolyte Solution "Lollipop" Resistance - Specimens #5E and #6E



CLEAR COVER - 1-7/16 in. (36.5 mm)

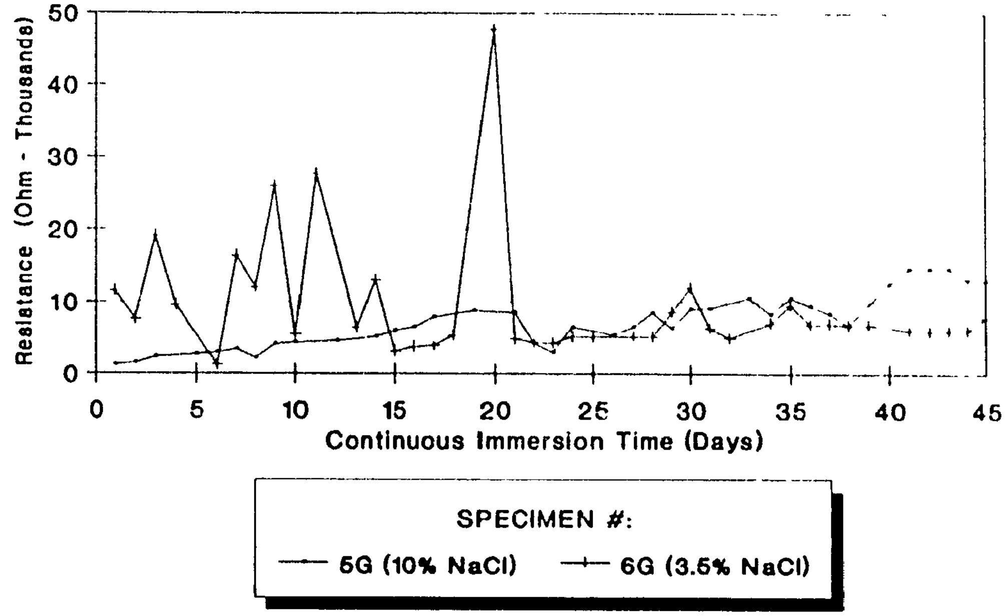
Normal Polarity: "Lollipop" Resistance

Reversed Polarity: "Lollipop" Resistance

FIGURE O-6: Effect of Electrolyte Solution "Lollipop" Resistance - Specimens #5F and #6F

CLEAR COVER - 1-11/16 in. (42.9 mm)

Normal Polarity: "Lollipop" Resistance



Reversed Polarity: "Lollipop" Resistance

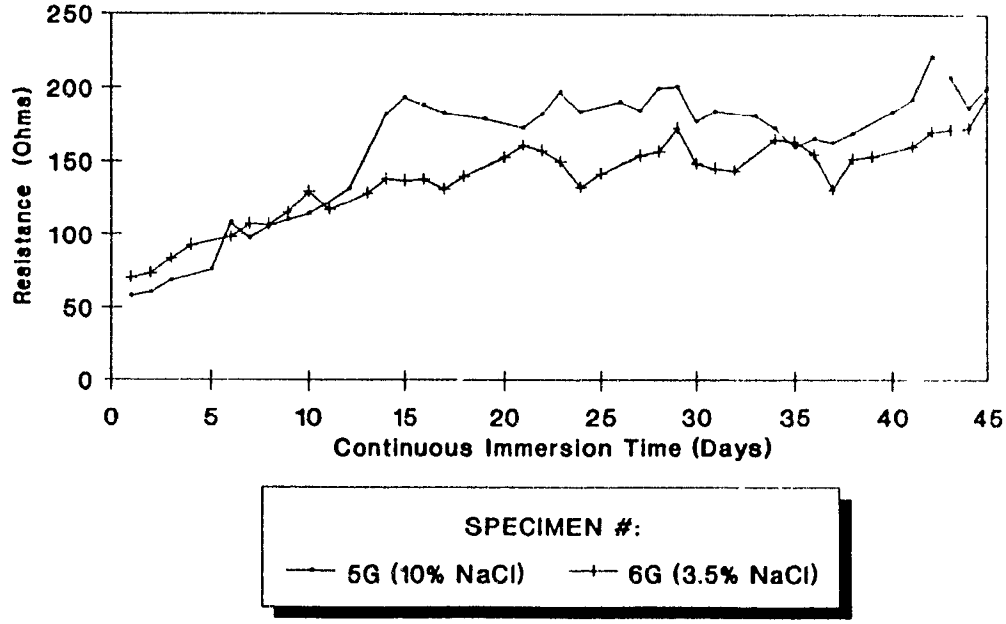
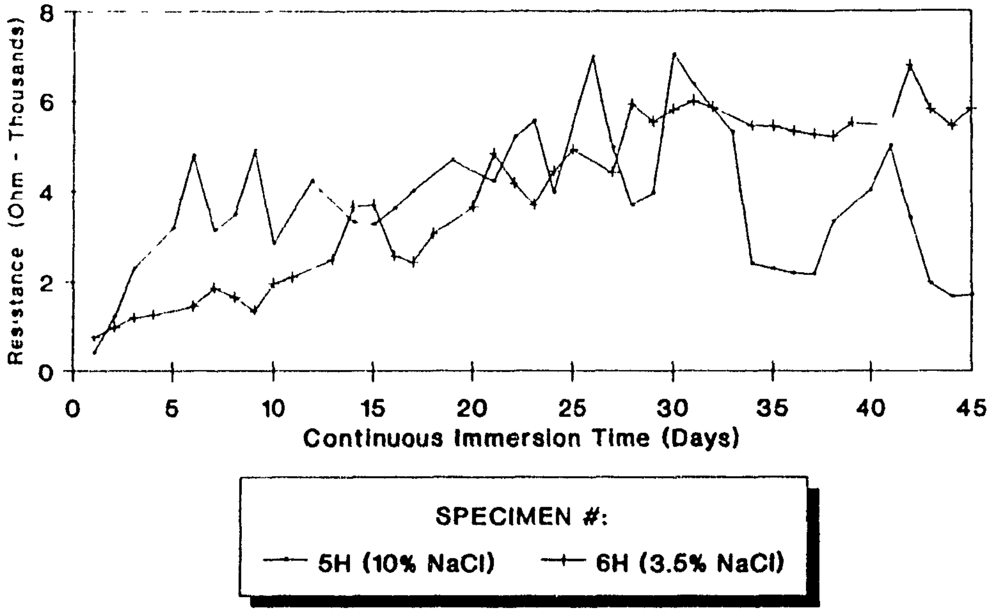


FIGURE O-7: Effect of Electrolyte Solution
"Lollipop" Resistance - Specimens #5G and #6G

CLEAR COVER - 2 in. (50.8 mm)

Normal Polarity: "Lollipop" Resistance



Reversed Polarity: "Lollipop" Resistance

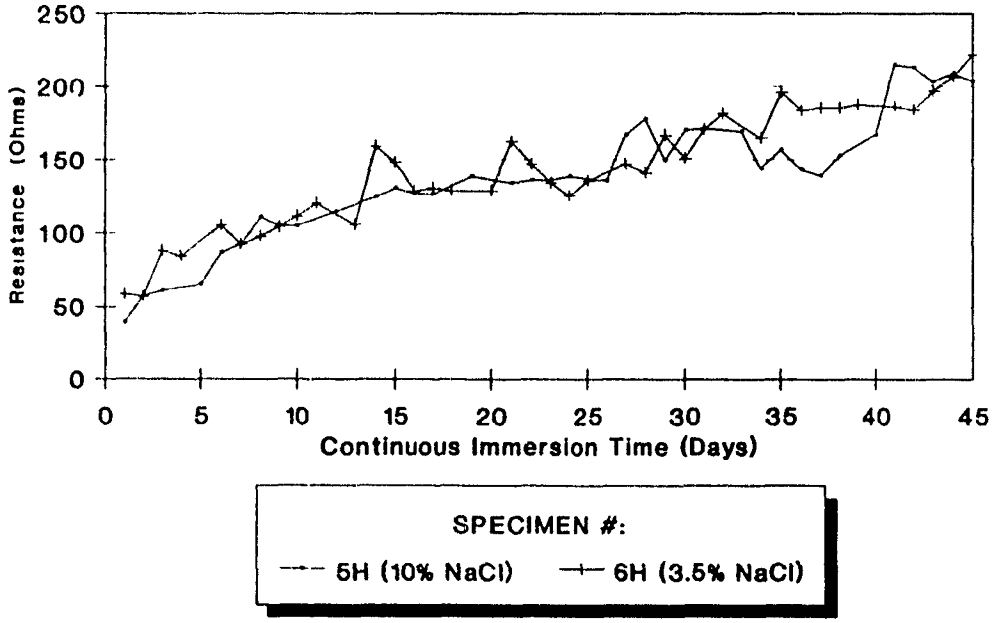
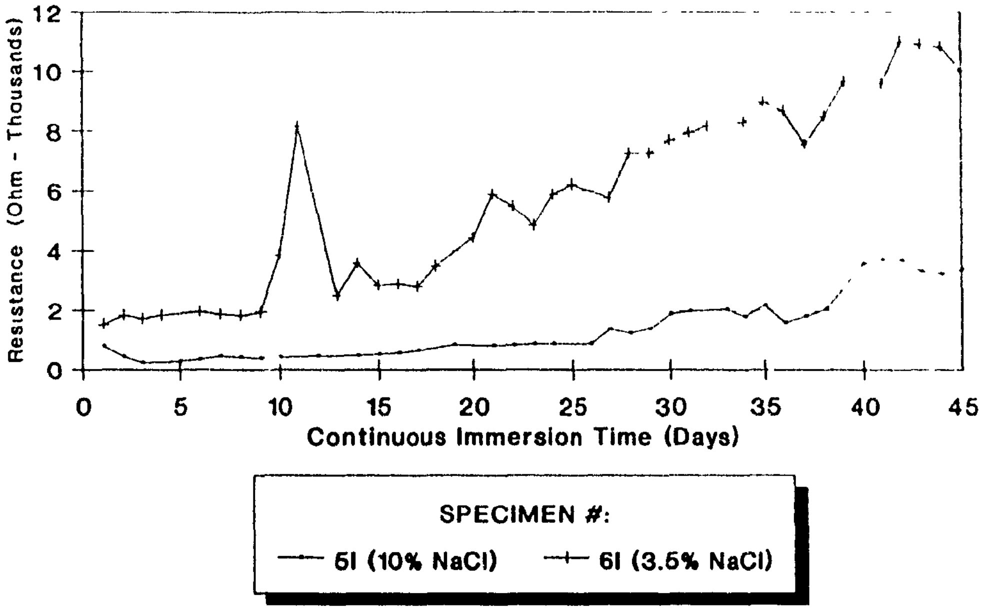


FIGURE O-8: Effect of Electrolyte Solution
"Lollipop" Resistance - Specimens #5H and #6H

CLEAR COVER - 2.5 in. (63.5 mm)

Normal Polarity: "Lollipop" Resistance



Reversed Polarity: "Lollipop" Resistance

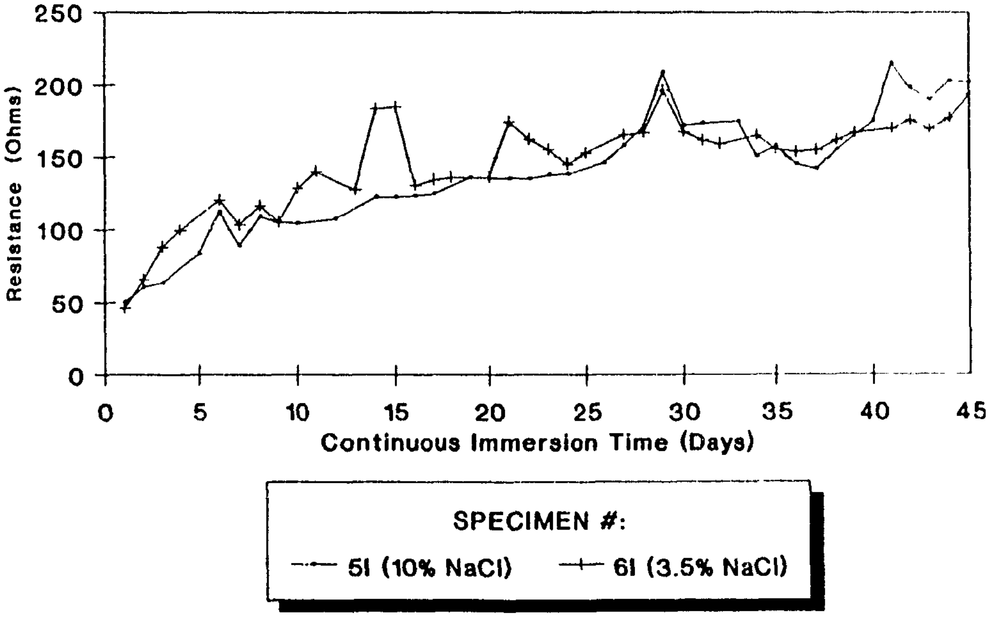
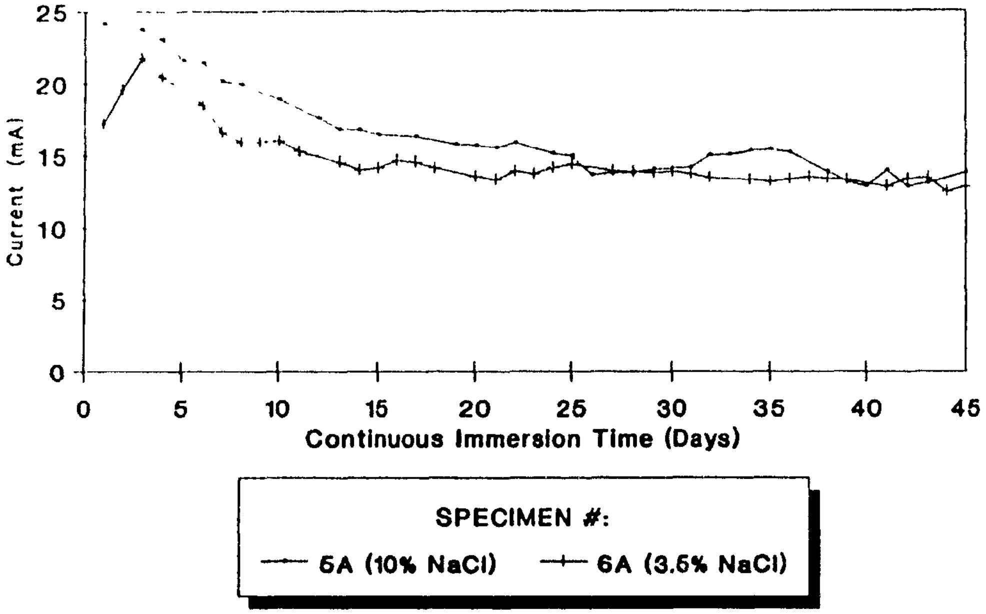


FIGURE O-9: Effect of Electrolyte Solution "Lollipop" Resistance - Specimens #51 and #61

CLEAR COVER - 5/16 in. (7.9 mm)

Current - Normal Polarity



Current - Reversed Polarity

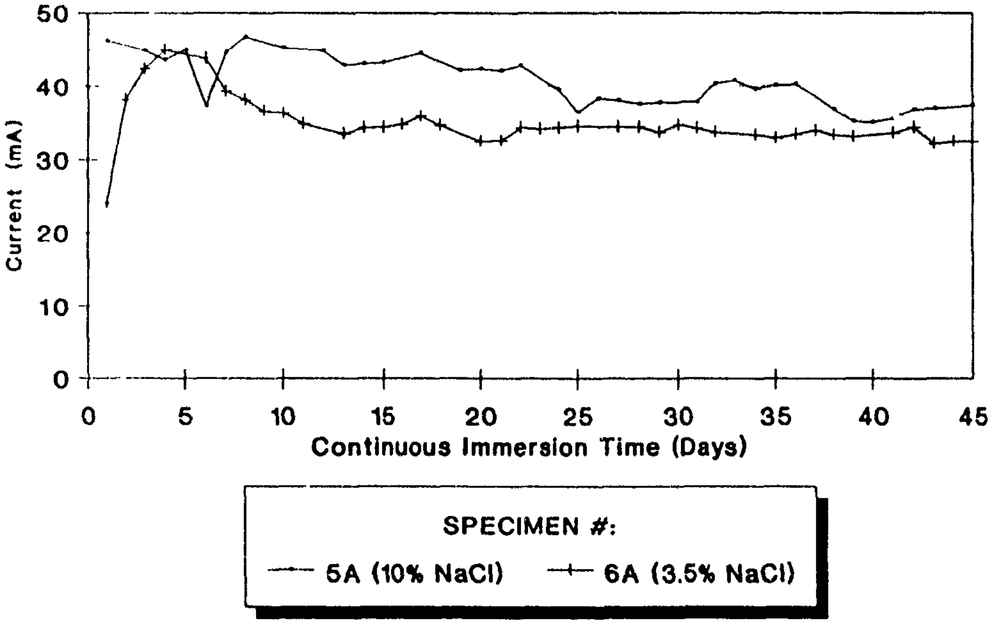
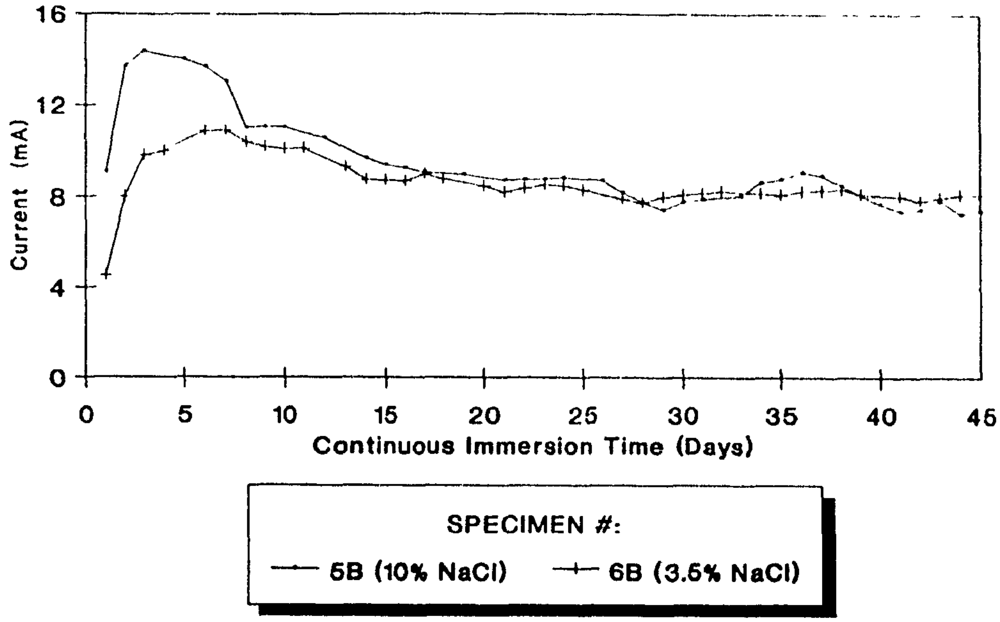


FIGURE O-10: Effect of Electrolyte Solution
Current - Specimens #5A and #6A

CLEAR COVER - 7/16 in. (11.1 mm)

Current - Normal Polarity



Current - Reversed Polarity

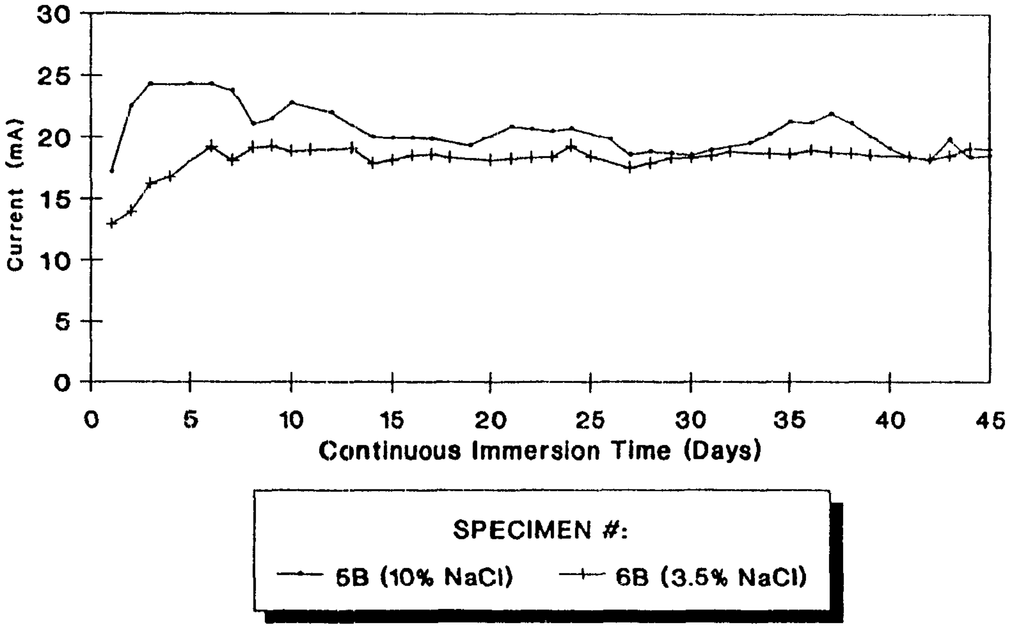
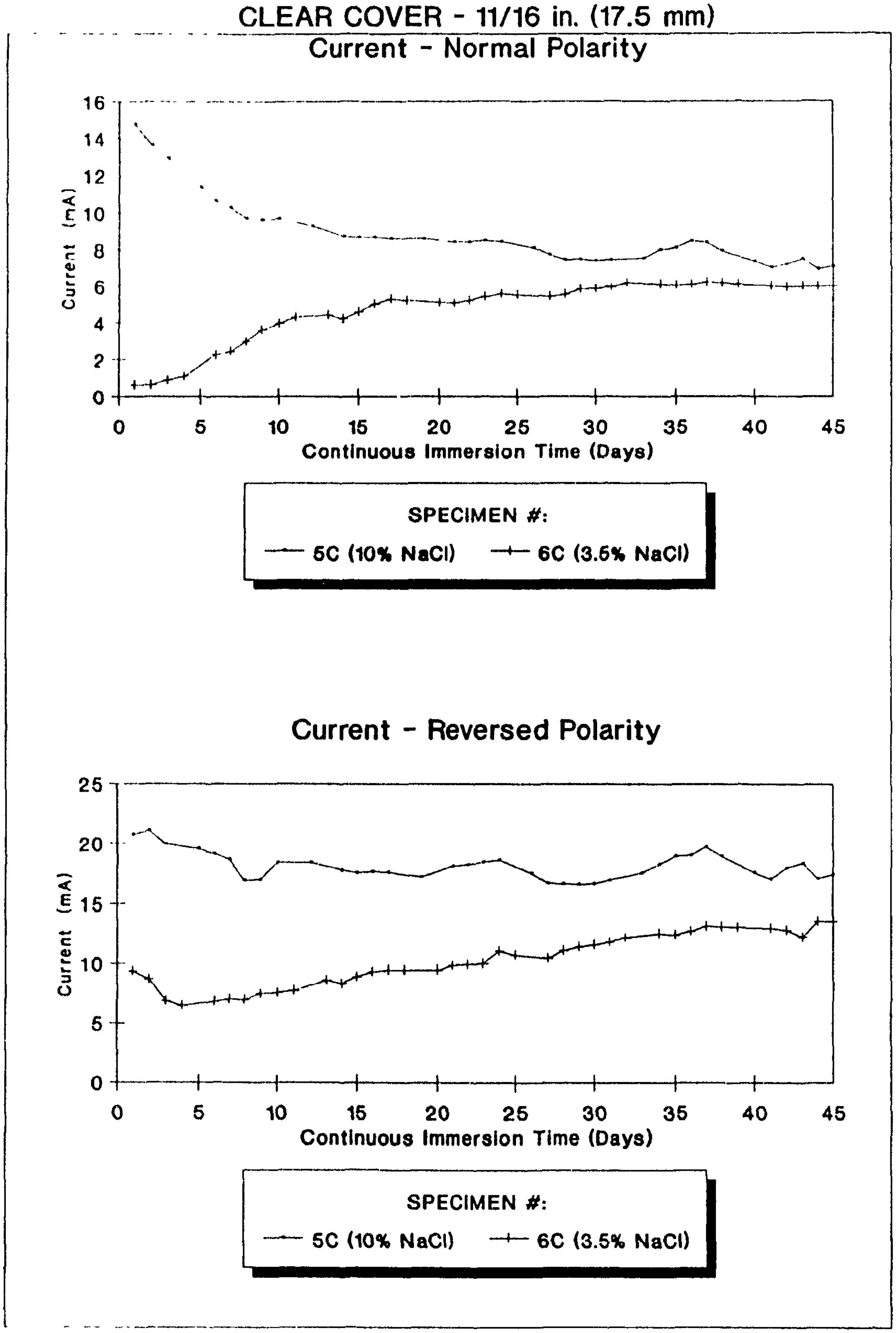


FIGURE O-11: Effect of Electrolyte Solution Current - Specimens #5B and #6B



CLEAR COVER - 11/16 in. (17.5 mm)

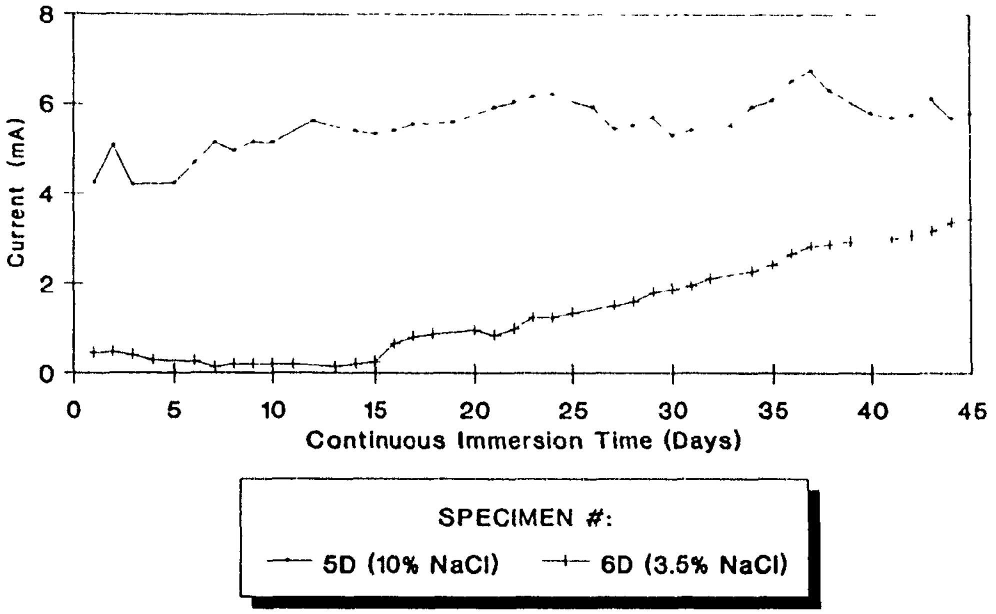
Current - Normal Polarity

Current - Reversed Polarity

FIGURE O-12: Effect of Electrolyte Solution
Current - Specimens #5C and #6C

CLEAR COVER - 15/16 in. (23.8 mm)

Current - Normal Polarity



Current - Reversed Polarity

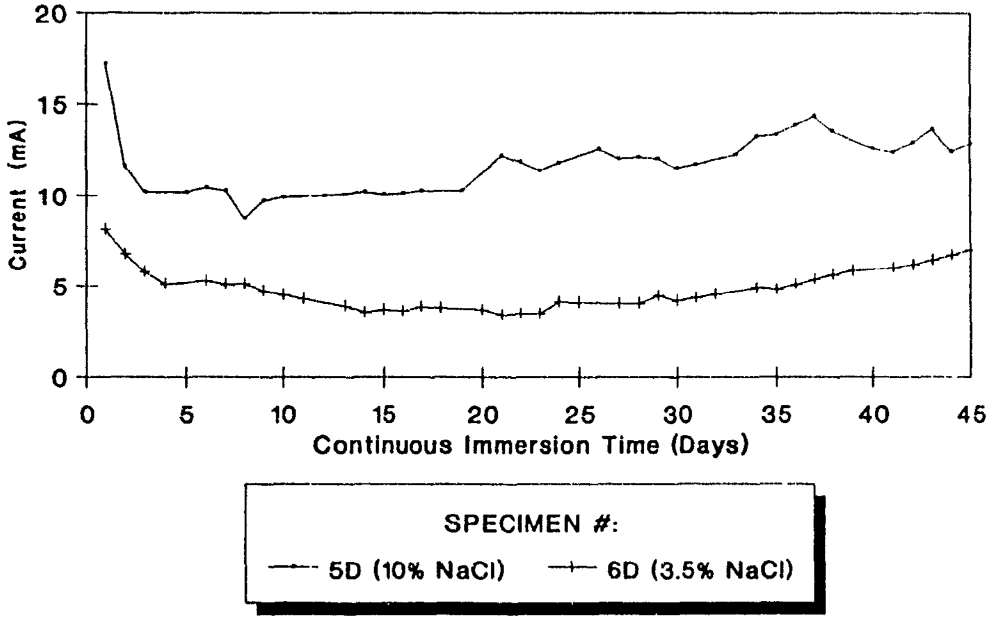
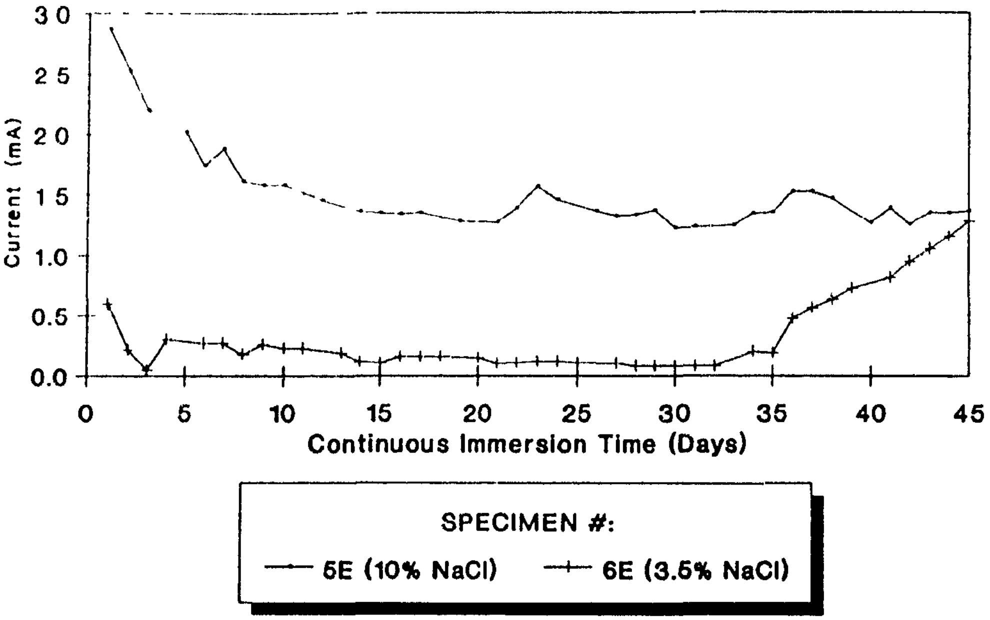


FIGURE O-13: Effect of Electrolyte Solution
Current - Specimens #5D and #6D

CLEAR COVER - 1-3/16 in. (30.2 mm)

Current - Normal Polarity



Current - Reversed Polarity

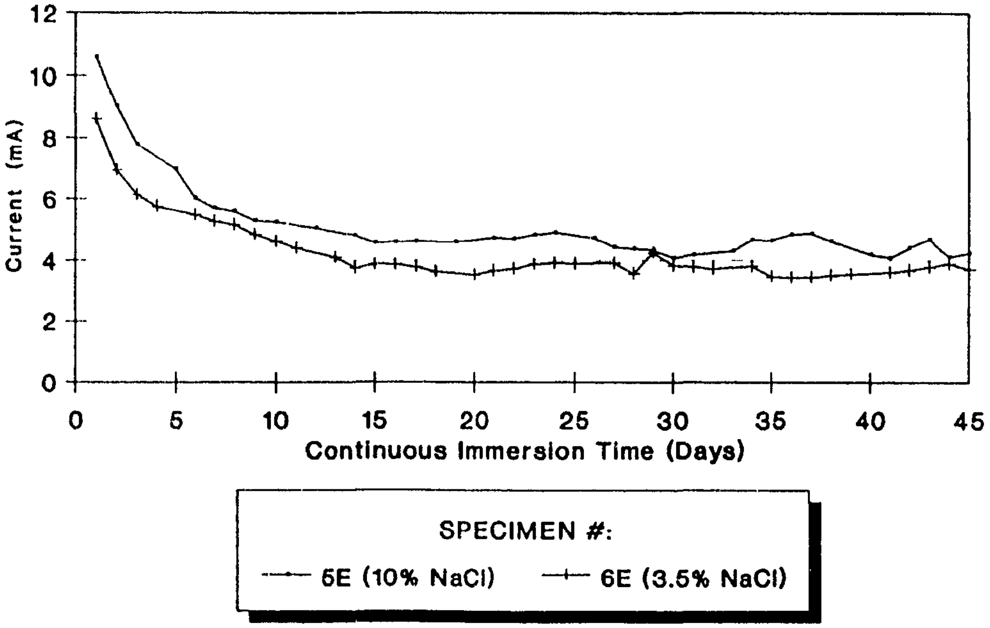


FIGURE O-14: Effect of Electrolyte Solution
Current - Specimens #5E and #6E

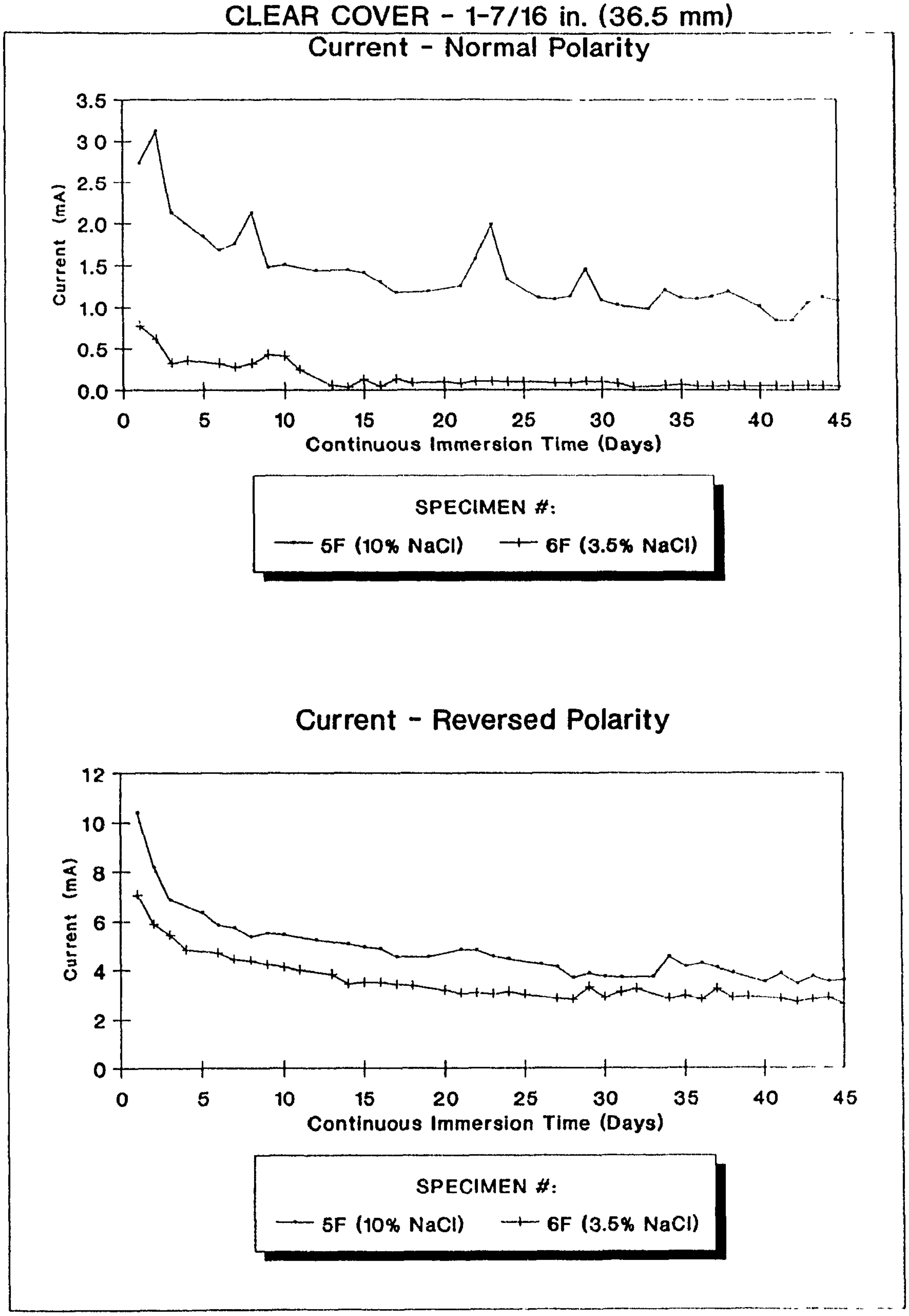
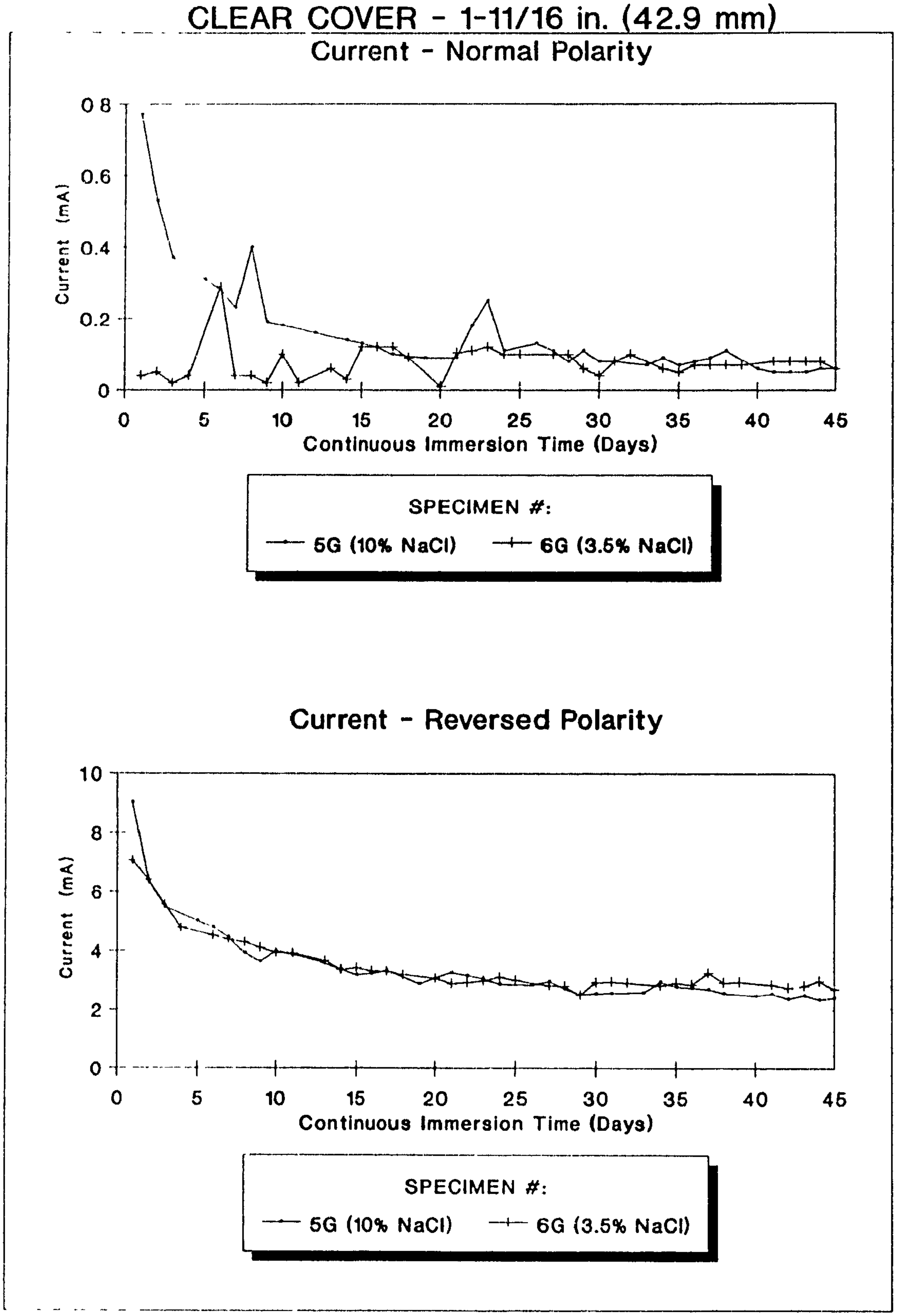


FIGURE O-15: Effect of Electrolyte Solution Current - Specimens #5F and #6F


CLEAR COVER - 1-11/16 in. (42.9 mm)

Current - Normal Polarity

Current - Reversed Polarity

FIGURE O-16: Effect of Electrolyte Solution Current - Specimens #5G and #6G

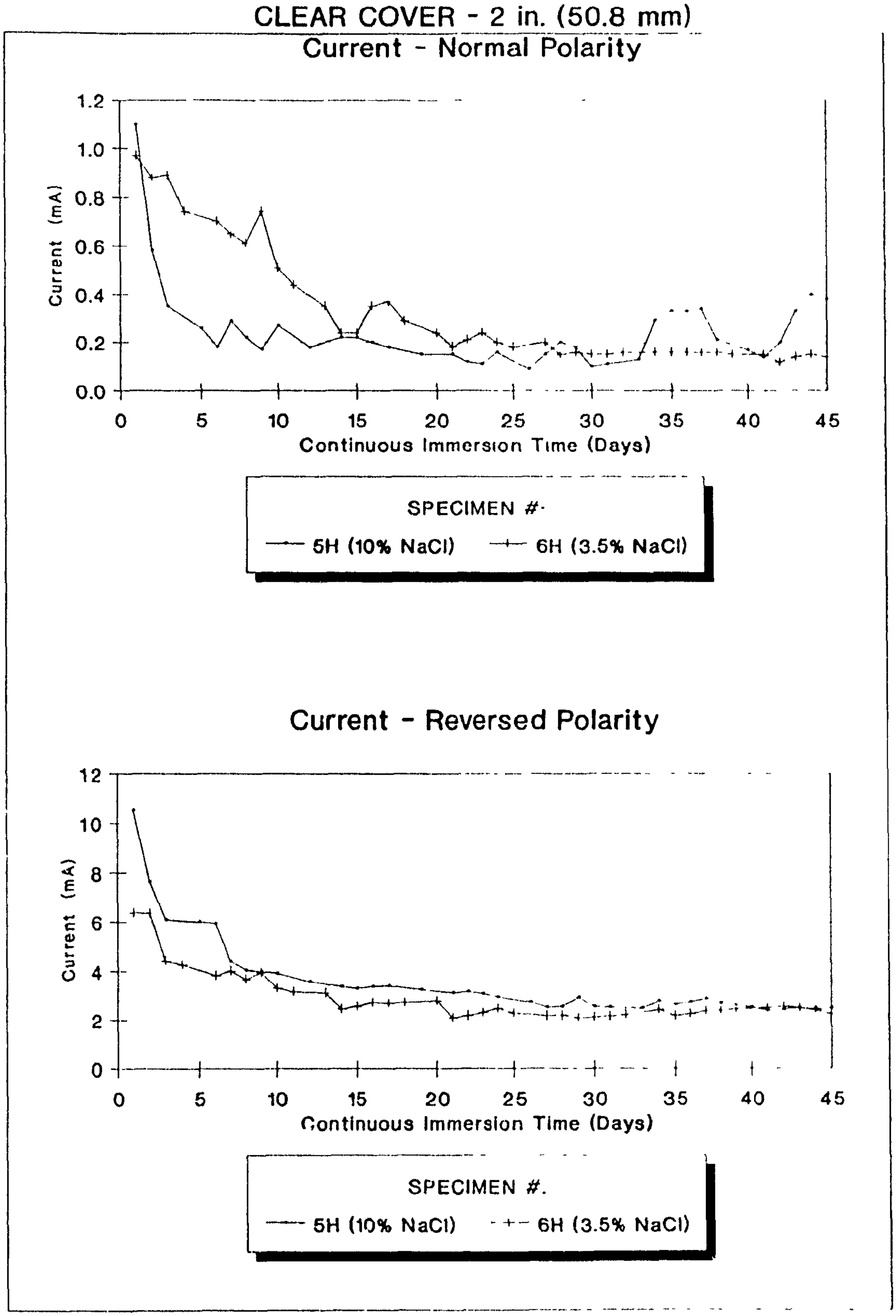
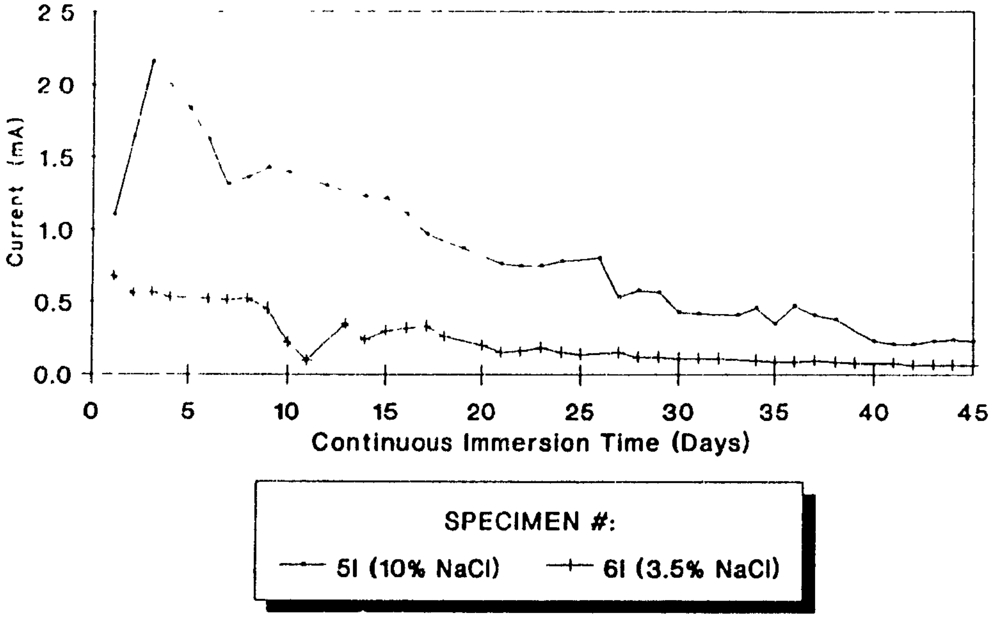


FIGURE O-17: Effect of Electrolyte Solution Current - Specimens #5H and #6H

CLEAR COVER - 2.5 in. (63.5 mm)

Current - Normal Polarity



Current - Reversed Polarity

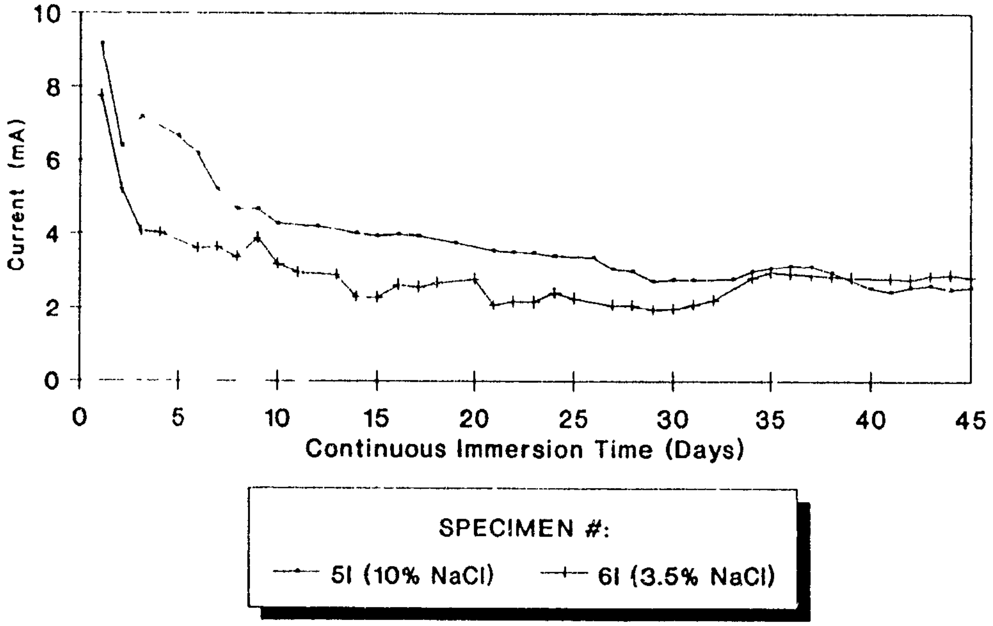


FIGURE O-18: Effect of Electrolyte Solution Current - Specimens #5I and #6I

APPENDIX P

Test Series #5

Potential and Current Measurements

This appendix lists the daily recordings of both the voltage potentials and current measurements for each of the specimens in Test Series #5. The data includes recordings of both normal and reversed polarity modes. The electrode "polarization" resistances, calculated as discussed in Section 6.1.1, are also presented.

SPECIMEN #: 5A

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 7.9 mm (5/16 in.)

Starting Date: December 15, 1990
Ending Date: January 29, 1991
Immersion Period 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE		ANODE	CATHODE
			ON	OFF	ON	OFF		
15-12-90	24.15	0.863	0.13	-0.55	-0.79	-0.63	28.12	-6.42
17-12-90	23.72	0.869	0.00	-0.60	-0.93	-0.84	25.25	-3.58
18-12-90	23.08	0.872	-0.17	-0.61	-1.16	-0.99	18.85	-7.37
19-12-90	21.57	0.889	-0.17	-0.59	-1.18	-1.03	19.47	-7.00
20-12-90	21.46	0.884	-0.17	-0.57	-1.16	-1.04	18.41	-5.59
21-12-90	20.19	0.891	-0.19	-0.56	-1.17	-1.03	18.38	-6.93
22-12-90	19.95	0.894	-0.19	-0.56	-1.17	-1.03	18.40	-7.02
24-12-90	18.91	0.898	-0.17	-0.53	-1.14	-1.03	19.25	-5.82
26-12-90	17.57	0.899	-0.17	-0.53	-1.15	-1.03	20.77	-6.83
27-12-90	16.81	0.901	-0.17	-0.54	-1.14	-1.03	21.89	-6.54
28-12-90	16.74	0.902	-0.17	-0.53	-1.14	-1.04	21.68	-5.97
29-12-90	16.44	0.905	-0.17	-0.53	-1.12	-1.03	22.08	-5.47
31-12-90	16.30	0.915	-0.16	-0.53	-1.14	-1.03	22.76	-6.75
02-01-91	15.75	0.922	-0.15	-0.52	-1.15	-1.03	23.75	-7.62
03-01-91	15.67	0.924	-0.15	-0.52	-1.14	-1.04	23.55	-6.38
04-01-91	15.47	0.926	-0.15	-0.52	-1.14	-1.04	23.53	-6.46
05-01-91	15.85	0.916	-0.16	-0.52	-1.13	-1.02	22.90	-6.94
07-01-91	15.08	0.918	-0.16	-0.52	-1.13	-1.02	24.47	-7.29
08-01-91	14.91	0.921	-0.17	-0 53	-1.11	-1.02	23.81	-6.04
09-01-91	13.60	0.926	-0.18	-0.52	-1.15	-1.03	25.00	-8.82
10-01-91	13.75	0.925	-0.16	-0.52	-1.16	-1.03	25.89	-9.45
11-01-91	13.75	0.925	-0.17	-0.52	-1.16	-1.03	25.38	-9.45
12-01-91	13.97	0.927	-0.16	-0.52	-1.16	-1.00	25.84	-11.52
14-01-91	14.12	0.928	-0.15	-0.52	-1.15	-1.00	26.27	-10.98
15-01-91	14.96	0.924	-0.16	-0.52	-1.16	-1.01	24.20	-10.03
16-01-91	14.98	0.923	-0.16	-0.51	-1.15	-1.02	23.56	-8.68
17-01-91	15.28	0.923	-0.16	-0.51	-1.15	-1.02	23.23	-8.51
18-01-91	15.36	0.927	-0.16	-0.51	-1.16	-1.01	22.85	-9.77
19-01-91	15.16	0.925	-0.16	-0.51	-1.15	-1.03	23.28	-7.92
21-01-91	13.85	0.932	-0.16	-0.51	-1.16	-1.03	25.13	-9.39
22-01-91	13.16	0.935	-0.16	-0.51	-1.16	-0.99	26.75	-13.30
23-01-91	12.85	0.932	-0.14	-0.51	-1.16	-0.98	28.33	-14.09
24-01-91	13.96	0.924	-0.16	-0.51	-1.16	-0.98	25.07	-12 68
25-01-91	12.84	0.926	-0.16	-0.51	-1.15	-1.00	26.79	-11.68
26-01-91	13.08	0.925	-0.16	-0.51	-1.16	-1.00	26.76	-12.23
28-01-91	13.53	0.924	-0.16	-0.51	-1.15	-1.01	26.24	-10.50
29-01-91	14.06	0.922	-0.16	-0.51	-1.15	-1.03	24.89	-8.61

SPECIMEN #: 5A

VARIABLES:	Impressed Voltage: 1.0 V Distance Between Electrodes: 4 in. (101.6 mm) Water-Cement Ratio: 0.45 (24 hours curing) Electrolyte Solution: 10.0% NaCl Electrodes: Non-Epoxy No.15 Clear Cover: 7.9 mm (5/16 in.)

Starting Date: December 15, 1990
Ending Date: January 29, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	OFF	ANODE ON	OFF	Electrode Resistance (Ohms) CATHODE	ANODE
15-12-90	46.16	0.713	1.36	0.87	0.50	0.64	10.57	-3.16
17-12-90	44.80	0.736	1.43	0.80	0.49	0.70	14.00	-4.69
18-12-90	43.60	0.762	1.52	0.73	0.48	0.75	18.17	-6.08
19-12-90	44.90	0.755	1.44	0.71	0.48	0.70	16.21	-4.94
20-12-90	37.40	0.796	1.49	0.73	0.52	0.68	20.27	-4.28
21-12-90	44.60	0.756	1.49	0.67	0.50	0.72	18.45	-4.96
22-12-90	46.70	0.747	1.52	0.66	0.54	0.71	18.50	-3.68
24-12-90	45.20	0.755	1.52	0.65	0.53	0.71	19.23	-3.92
26-12-90	44.80	0.755	1.52	0.65	0.54	0.71	19.35	-3.77
27-12-90	42.90	0.755	1.53	0.65	0.55	0.70	20.58	-3.71
28-12-90	43.10	0.761	1.52	0.64	0.55	0.69	20.51	-3.36
29-12-90	43.30	0.760	1.52	0.63	0.55	0.69	20.53	-3.14
31-12-90	44.50	0.759	1.54	0.62	0.58	0.71	20.65	-3.01
02-01-91	42.20	0.777	1.56	0.62	0.57	0.71	22.20	-3.36
03-01-91	42.40	0.774	1.54	0.62	0.57	0.71	21.72	-3.28
04-01-91	42.10	0.771	1.55	0.62	0.56	0.71	22.09	-3.61
05-01-91	42.80	0.767	1.53	0.62	0.55	0.70	21.19	-3.71
07-01-91	39.50	0.783	1.52	0.61	0.54	0.69	22.94	-3.75
08-01-91	36.50	0.791	1.48	0.61	0.49	0.66	23.75	-4.60
09-01-91	38.30	0.785	1.51	0.62	0.50	0.65	23.32	-3.99
10-01-91	38.10	0.785	1.51	0.61	0.50	0.65	23.54	-3.88
11-01-91	37.60	0.795	1.50	0.61	0.57	0.65	23.75	-2.29
12-01-91	37.80	0.795	1.50	0.61	0.51	0.66	23.68	-3.97
14-01-91	37.90	0.795	1.50	0.60	0.50	0.66	23.67	-4.14
15-01-91	40.40	0.785	1.51	0.60	0.50	0.66	22.48	-3.94
16-01-91	40.80	0.783	1.50	0.60	0.50	0.66	22.03	-3.92
17-01-91	39.60	0.784	1.50	0.60	0.50	0.66	22.75	-4.07
18-01-91	40.10	0.791	1.50	0.59	0.50	0.66	22.74	-4.06
19-01-91	40.30	0.785	1.50	0.59	0.50	0.66	22.56	-4.07
21-01-91	36.90	0.807	1.50	0.59	0.50	0.66	24.74	-4.50
22-01-91	35.20	0.814	1.50	0.58	0.50	0.65	26.11	-4.23
23-01-91	35.10	0.803	1.51	0.58	0.52	0.65	26.52	-3.73
24-01-91	35.60	0.805	1.49	0.58	0.49	0.65	25.51	-4.38
25-01-91	36.90	0.794	1.51	0.58	0.50	0.66	25.23	-4.31
26-01-91	37.00	0.794	1.50	0.58	0.51	0.65	24.78	-3.89
28-01-91	37.60	0.791	1.50	0.59	0.51	0.65	24.18	-3.54
29-01-91	37.40	0.792	1.50	0.59	0.51	0.64	24.25	-3.66

SPECIMEN #: 5B

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 11.1 mm (7/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	ANODE OFF	CATHODE ON	CATHODE OFF	Electrode Resistance (Ohms) ANODE	CATHODE
13-12-90	9.07	0.940	-0.53	-0.90	-1.46	-1.32	41.01	-15.66
14-12-90	13.71	0.930	-0.37	-0.79	-1.32	-1.17	31.15	-11.09
15-12-90	14.34	0.921	-0.48	-0.89	-1.39	-1.27	28.59	-8.51
17-12-90	14.01	0.922	-0.49	-0.90	-1.37	-1.28	29.34	-6.64
18-12-90	13.66	0.924	-0.49	-0.90	-1.36	-1.30	30.23	-4.54
19-12-90	13.06	0.927	-0.49	-0.82	-1.33	-1.16	25.42	-12.94
20-12-90	11.04	0.941	-0.50	-0.88	-1.25	-1.07	35.14	-16.30
21-12-90	11.02	0.942	-0.49	-0.85	-1.40	-1.29	32.76	-9.98
22-12-90	11.02	0.942	-0.44	-0.81	-1.35	-1.24	33.12	-9.98
24-12-90	10.55	0.945	-0.43	-0.84	-1.28	-1.23	38.77	-4.74
26-12-90	9.67	0.941	-0.48	-0.84	-1.40	-1.29	37.23	-11.38
27-12-90	9.38	0.943	-0.47	-0.83	-1.39	-1.29	38.17	-10.66
28-12-90	9.22	0.944	-0.50	-0.83	-1.40	-1.30	36.66	-10.85
29-12-90	9.04	0.945	-0.52	-0.83	-1.41	-1.31	34.18	-11.06
31-12-90	8.94	0.955	-0.47	-0.83	-1.41	-1.30	40.38	-12.30
02-01-91	8.71	0.959	-0.50	-0.85	-1.43	-1.33	40.99	-11.48
03-01-91	8.72	0.959	-0.44	-0.79	-1.37	-1.28	39.68	-10.32
04-01-91	8.75	0.958	-0.44	-0.73	-1.41	-1.22	33.49	-21.71
05-01-91	8.82	0.955	-0.53	-0.87	-1.43	-1.34	37.53	-10.20
07-01-91	8.70	0.955	-0.49	-0.85	-1.41	-1.34	41.38	-8.05
08-01-91	8.16	0.958	-0.54	-0.86	-1.40	-1.30	39.22	-12.25
09-01-91	7.76	0.962	-0.53	-0.85	-1.37	-1.32	40.98	-6.44
10-01-91	7.37	0.966	-0.52	-0.84	-1.38	-1.31	43.96	-9.50
11-01-91	7.76	0.962	-0.48	-0.81	-1.38	-1.29	42.65	-11.60
12-01-91	7.88	0.962	-0.48	-0.80	-1.34	-1.27	40.61	-8.88
14-01-91	8.02	0.963	-0.48	-0.78	-1.31	-1.24	37.78	-8.73
15-01-91	8.61	0.957	-0.50	-0.78	-1.33	-1.20	31.48	-15.10
16-01-91	8.75	0.957	-0.52	-0.80	-1.34	-1.24	32.69	-11.43
17-01-91	9.05	0.957	-0.52	-0.77	-1.31	-1.16	28.18	-16.57
18-01-91	8.93	0.963	-0.52	-0.82	-1.35	-1.24	34.15	-12.32
19-01-91	8.48	0.962	-0.46	-0.82	-1.35	-1.23	42.57	-14.15
21-01-91	7.68	0.963	-0.46	-0.81	-1.38	-1.22	45.44	-20.83
22-01-91	7.35	0.965	-0.49	-0.80	-1.39	-1.27	42.18	-16.33
23-01-91	7.40	0.958	-0.48	-0.80	-1.38	-1.25	43.24	-17.57
24-01-91	7.88	0.956	-0.42	-0.80	-1.33	-1.26	48.35	-8.88
25-01-91	7.24	0.956	-0.47	-0.78	-1.33	-1.23	42.54	-13.81
26-01-91	7.37	0.956	-0.47	-0.78	-1.34	-1.24	41.79	-13.57

SPECIMEN #: 5B

VARIABLES

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 11.1 mm (7/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	CATHODE OFF	ANODE ON	ANODE OFF	Electrode Resistance (Ohms) CATHODE	ANODE
13-12-90	17.22	0.910	1.85	1.34	0.82	0.96	29.38	-8.19
14-12-90	22.46	0.870	1.67	1.03	0.70	0.85	28.14	-6.86
15-12-90	24.27	0.867	1.73	0.93	0.69	0.88	32.96	-7.66
17-12-90	24.26	0.867	1.73	0.91	0.69	0.88	34.17	-7.67
18-12-90	24.26	0.866	1.74	0.87	0.70	0.88	35.86	-7.54
19-12-90	23.79	0.868	1.71	0.90	0.70	0.83	34.26	-5.55
20-12-90	21.11	0.885	1.65	0.87	0.68	0.80	37.09	-5.59
21-12-90	21.45	0.883	1.45	0.82	0.57	0.72	29.37	-6.81
22-12-90	22.73	0.877	1.71	0.86	0.58	0.82	37.22	-10.69
24-12-90	21.99	0.881	1.46	0.84	0.55	0.82	28.24	-12.55
26-12-90	20.02	0.885	1.68	0.89	0.67	0.84	39.41	-8.19
27-12-90	19.95	0.885	1.75	0.88	0.67	0.84	43.46	-8.22
28-12-90	19.94	0.885	1.69	0.88	0.67	0.84	40.67	-8.53
29-12-90	19.92	0.885	1.70	0.88	0.67	0.84	41.42	-8.63
31-12-90	19.37	0.887	1.80	0.84	0.74	0.88	49.46	-7.12
02-01-91	20.89	0.893	1.82	0.86	0.77	0.91	46.10	-6.27
03-01-91	20.68	0.893	1.82	0.84	0.76	0.90	47.29	-6.67
04-01-91	20.55	0 894	1.83	0.83	0.76	0.90	48.71	-6.96
05-01-91	20.74	0.893	1.83	0.80	0.74	0.89	49.66	-7.18
07-01-91	19.91	0.897	1.82	0.79	0.73	0.88	51.68	-7.48
08-01-91	18.62	0.903	1.82	0.80	0.69	0.88	54.73	-10.53
09-01-91	18.89	0.902	1.81	0.85	0.70	0.86	50.61	-8.05
10-01-91	18.81	0.902	1.68	0.79	0.67	0.77	47.32	-5.26
11-01-91	18.60	0.903	1.30	0.76	0.73	0.76	29.09	-1.77
12-01-91	19.04	0.900	1.69	0.79	0.71	0.81	47.37	-5.36
14-01-91	19 56	0.896	1.73	0.81	0.69	0.85	47.03	-8.13
15-01-91	20.34	0.893	1.71	0.79	0.70	0.79	45.18	-3.98
16-01-91	21.30	0.885	1.80	0.83	0.75	0.86	45.68	-5.21
17-01-91	21.24	0.885	1.78	0.83	0.75	0.83	44.68	-4.14
18-01-91	21.93	0.890	1.77	0.85	0.76	0.86	41.77	-4.70
19-01-91	21.20	0.893	1.86	0.85	0.75	0.89	47.88	-6.56
21-01-91	19.16	0.903	1.76	0.84	0.74	0.89	47.91	-7.78
22-01-91	18.49	0.906	1.73	0.82	0.73	0.90	49.27	-9.03
23-01-91	18.21	0.895	1.73	0.81	0.73	0.89	50.30	-9.17
24-01-91	19.86	0.891	1.77	0.82	0.73	0.89	48.04	-7.96
25-01-91	18.44	0.893	1.73	0.79	0.73	0.88	50.98	-8.13
26-01-91	18 57	0.892	1.75	0.79	0.73	0.88	51.75	-8.02

SPECIMEN #: 5C

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes 4 in (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No 15
Clear Cover: 17.5 mm (11/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	Electrode Potentials (V) ANODE OFF	Electrode Potentials (V) CATHODE ON	Electrode Potentials (V) CATHODE OFF	Electrode Resistance (Ohms) ANODE	Electrode Resistance (Ohms) CATHODE
13-12-90	14.77	0.930	-0.49	-0.98	-1.43	-1.35	33.65	-5.42
14-12-90	13.65	0.930	-0.85	-1.13	-1.32	-1.12	20.22	-14.65
15-12-90	12.94	0.931	-0.47	-0.93	-1.40	-1.29	35.55	-8.50
17-12-90	11.36	0.938	-0.31	-0.82	-1.28	-1.15	44.37	-11.44
18-12-90	10.64	0.942	-0.21	-0.65	-1.16	-1.04	41.82	-11.28
19-12-90	10.28	0.945	-0.14	-0.60	-1.11	-0.93	44.65	-17.12
20-12-90	9.68	0.948	-0.13	-0.57	-1.12	-0.97	44.94	-14.88
21-12-90	9.61	0.948	-0.12	-0.55	-1.11	-0.99	44.75	-13.32
22-12-90	9.65	0.947	-0.12	-0.55	-1.11	-0.99	44.04	-12.95
24-12-90	9.27	0.950	-0.12	-0.53	-1.11	-1.00	44.01	-12.30
26-12-90	8.72	0.950	-0.12	-0.53	-1.12	-0.99	46.33	-14.22
27-12-90	8.68	0.951	-0.12	-0.53	-1.12	-1.00	46.66	-14.40
28-12-90	8.67	0.951	-0.12	-0.53	-1.12	-0.99	46.48	-14.76
29-12-90	8.60	0.952	-0.12	-0.52	-1.12	-0.99	46.86	-15.00
31-12-90	8.58	0.954	-0.12	-0.52	-1.11	-0.98	46.39	-15.62
02-01-91	8.38	0.955	-0.13	-0.52	-1.12	-0.99	46.90	-15.63
03-01-91	8.41	0.955	-0.13	-0.52	-1.12	-1.00	46.49	-14.27
04-01-91	8.48	0.954	-0.13	-0.52	-1.12	-1.00	45.87	-14.74
05-01-91	8.43	0.953	-0.13	-0.52	-1.12	1.00	45.55	-15.07
07-01-91	8.08	0.955	-0.13	-0.52	-1.12	-0.97	48.89	-18.56
08-01-91	7.71	0.957	-0.13	-0.52	-1.12	-1.01	49.42	-15.05
09-01-91	7.43	0.958	-0.14	-0.52	-1.13	-1.00	51.14	-17.36
10-01-91	7.47	0.958	-0.14	-0.52	-1.13	-1.00	51.41	-17.67
11-01-91	7.39	0.959	-0.14	-0.52	-1.12	-1.00	51.42	-17.19
12-01-91	7.44	0.959	-0.14	-0.52	-1.12	-0.98	52.02	-18.82
14-01-91	7.52	0.959	-0.13	-0.53	-1.12	-0.97	52.79	-20.08
15-01-91	7.98	0.956	-0.13	-0.53	-1.12	-0.95	49.75	-22.06
16-01-91	8.07	0.955	-0.14	-0.53	-1.12	-0.98	48.33	-17.72
17-01-91	8.46	0.954	-0.13	-0.53	-1.12	-0.94	46.93	-21.39
18-01-91	8.37	0.955	-0.13	-0.53	-1.12	-0.97	47.19	-18.40
19-01-91	7.91	0.957	-0.14	-0.52	-1.13	-0.99	48.93	-16.69
21-01-91	7.34	0.960	-0.13	-0.52	-1.13	-1.00	52.72	-17.44
22-01-91	7.01	0.961	-0.14	-0.52	-1.13	-0.99	55.21	-20.68
23-01-91	7.19	0.960	-0.14	-0.52	-1.13	-0.99	53.41	-20.03
24-01-91	7.48	0.958	-0.13	-0.52	-1.13	-0.99	52.14	-18.58
25-01-91	6.94	0.961	-0.14	-0.52	-1.12	-0.99	55.76	-18.59
26-01-91	7.06	0.960	-0.13	-0.52	-1.13	-0.99	55.52	-19.83

SPECIMEN #: 5C

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes Non-Epoxy No.15
Clear Cover 17.5 mm (11/16 in.)

Starting Date: December 12, 1990
Ending Date January 26, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

			Electrode Potentials (V)				Electrode	
DATE	I	Volt	CATHODE		ANODE		Resistance (Ohms)	
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
13-12-90	20.74	0.890	1.87	1.31	0.85	0.98	27.00	-5.88
14-12-90	21.09	0.880	1.78	1.09	0.76	0.89	32.72	-5.88
15-12-90	19.94	0.892	1.82	1.08	0.77	0.92	37.11	-7.52
17-12-90	19.56	0.893	1.66	1.01	0.64	0.80	33.23	-7.87
18-12-90	19.17	0.895	1.54	0.75	0.55	0.69	41.47	-7.09
19-12-90	18.70	0.898	1.51	0.75	0.52	0.62	40.48	-5.03
20-12-90	16.92	0.909	1.49	0.72	0.52	0.61	45.74	-5.26
21-12-90	16.98	0.906	1.46	0.69	0.47	0.58	45.11	-6.60
22-12-90	18.41	0.900	1.46	0.67	0.47	0.59	42.97	-6.30
24-12-90	18.41	0.900	1.46	0.65	0.47	0.59	43.94	-6.25
26-12-90	17.83	0.903	1.46	0.65	0.47	0.59	45.49	-6.67
27-12-90	17.60	0.904	1.46	0.65	0.47	0.58	45.97	-6.70
28-12-90	17.68	0.904	1.46	0.64	0.47	0.59	46.04	-6.90
29-12-90	17.64	0.904	1.46	0.64	0.47	0.59	46.54	-7.09
31-12-90	17.23	0.907	1.44	0.61	0.46	0.60	48.29	-7.95
02-01-91	18.12	0.902	1.46	0.61	0.47	0.61	46.69	-7.62
03-01-91	18.24	0.900	1.46	0.61	0.47	0.61	46.38	-7.95
04-01-91	18.47	0.898	1.46	0.60	0.47	0.62	46.18	-8.18
05-01-91	18.63	0.896	1.45	0.58	0.47	0.63	46.70	-8.37
07-01-91	17.55	0.903	1.47	0.58	0.47	0.57	50.54	-6.04
08-01-91	16.71	0.910	1.47	0.59	0.48	0.65	52.78	-10.41
09-01-91	16.68	0.910	1.46	0.61	0.47	0.59	50.54	-7.43
10-01-91	16.63	0.910	1.46	0.62	0.47	0.58	50.69	-6.55
11-01-91	16.65	0.910	1.48	0.61	0.48	0.61	52.07	-7.63
12-01-91	16.97	0.907	1.50	0.61	0.49	0.62	52.50	-7.60
14-01-91	17.61	0.904	1.52	0.60	0.51	0.64	51.90	-7.10
15-01-91	18.29	0.902	1.49	0.61	0.51	0.63	48.82	-6.29
16-01-91	19.00	0.896	1.49	0.59	0.51	0.63	47.74	-6.68
17-01-91	19.08	0.895	1.49	0.58	0.50	0.64	48.06	-7.34
18-01-91	19.76	0.893	1.50	0.59	0.51	0.64	46.26	-6.68
19-01-91	18.99	0.897	1.51	0.60	0.50	0.63	47.92	-6.58
21-01-91	17.64	0.905	1.53	0.60	0.53	0.63	52.95	-5.44
22-01-91	17.06	0.907	1.52	0.57	0.52	0.69	55.69	-9.85
23-01-91	17.99	0.902	1.55	0.57	0.55	0.69	54.36	-7.95
24-01-91	18.43	0.899	1.54	0.57	0.54	0.69	52.63	-8.03
25-01-91	17.09	0.906	1.51	0.58	0.54	0.68	54.48	-7.90
26-01-91	17.47	0.902	1.54	0.58	0.54	0.67	55.01	-7.50

SPECIMEN #· 5D

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution· 10.0% NaCl
Electrodes· Non-Epoxy No.15
Clear Cover 23 8 mm (15/16 in)

Starting Date· December 12, 1990
Ending Date. January 26, 1991
Immersion Period 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON		Electrode Potentials (V) CATHODE ON		Electrode Resistance (Ohms) ANODE	
			ON	OFF	ON	OFF	ANODE	CATHODE
13-12-90	4.24	0.970	-0.05	-0.54	-1.05	-0.96	116.51	-20.28
14-12-90	5.08	0.972	-0.10	-0.58	-1.09	-0.93	93.70	-32.09
15-12-90	4.19	0.977	-0.09	-0.55	-1.09	-0.90	108.83	-46.06
17-12-90	4.23	0.976	-0.10	-0.56	-1.09	-0.89	107.80	-48.46
18-12-90	4.69	0.973	-0.11	-0.59	-1.11	-0.88	103.62	-49.47
19-12-90	5.14	0.971	-0.11	-0.58	-1.10	-0.93	90.86	-34.05
20-12-90	4.96	0.974	-0.12	-0.55	-1.12	-0.97	87.70	-29.03
21-12-90	5.15	0.973	-0.11	-0.58	-1.11	-0.94	91.07	-33.20
22-12-90	5.14	0.972	-0.11	-0.55	-1.11	-0.93	86 38	-34.82
24-12-90	5.61	0.969	-0.12	-0.59	-1.12	-0.95	82.89	-31.37
26-12-90	5.39	0.971	-0.12	-0.55	-1.11	-0.96	79.59	-28.20
27-12-90	5.34	0.971	-0.13	-0.55	-1.12	-0 97	79.21	-26.59
28-12-90	5.41	0.970	-0.13	-0.55	-1.12	-0 97	78 19	-26.62
29-12-90	5.54	0.969	-0.13	-0.55	-1.13	-0.97	76 17	-27.80
31-12-90	5.59	0.969	-0.13	-0.55	-1.13	-0.98	75 67	-26.12
02-01-91	5.91	0.968	-0.12	-0 55	-1.12	-0.98	73.43	-24.37
03-01-91	6.04	0.968	-0.12	-0.55	-1 12	-0.98	70 86	-23.18
04-01-91	6.15	0.966	-0.12	-0.55	-1.12	-0.98	69.92	-22.44
05-01-91	6.21	0.965	-0.13	-0.57	-1.12	-0 95	71.18	-27.86
07-01-91	5.92	0.967	-0.12	-0.56	-1.12	-0 96	74.32	-27.36
08-01-91	5.45	0.968	-0.12	-0 55	-1.11	-0.96	78 17	-28.99
09-01-91	5.52	0.968	-0.12	-0.54	-1.11	-0.97	76.09	-26.99
10-01-91	5.70	0.968	-0.12	-0.54	-1.11	-0.96	74.39	-27.37
11-01-91	5.30	0.971	-0.12	-0.54	-1.12	-0.96	78.68	-29.06
12-01-91	5.42	0.970	-0.12	-0.53	-1.11	-0.97	76 94	-26.75
14-01-91	5.51	0.969	-0.11	-0.53	-1.11	-0.97	75.86	-25.23
15-01-91	5.92	0.968	-0.11	-0.53	-1.11	-0.98	70 10	-23.31
16-01-91	6.08	0.967	-0.11	-0.54	-1.11	-0.95	69.90	-25.99
17-01-91	6.50	0.965	-0.11	-0.54	-1.11	-0.95	66.46	-24.62
18-01-91	6.74	0.964	-0.11	-0.55	-1 11	-0.94	64.84	-25.22
19-01-91	6.30	0.965	-0.10	-0.54	-1.09	-0.93	70.32	-25.56
21-01-91	5.80	0.967	-0.09	-0.54	-1.09	-0.93	77.76	-27 93
22-01-91	5.70	0.968	-0.10	-0.53	-1.10	-0.94	76 49	-27.89
23-01-91	5.76	0.968	-0.10	-0.53	-1.10	-0.94	75.35	-26.74
24-01-91	6.12	0.965	-0.09	-0.53	-1.09	-0.94	70.92	-24.84
25-01-91	5.68	0.967	-0 09	-0.53	-1.09	-0.95	76.76	-24.82
26-01-91	5.80	0.966	-0.09	-0.53	-1.09	-0.95	75.00	-24.31

SPECIMEN #: 5D

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover 23.8 mm (15/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE	I	Volt	CATHODE		ANODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
13-12-90	17.24	0.910	1.65	0.93	0.64	0.81	41.94	-9.63
14-12-90	11.61	0.936	1.52	1.00	0.54	0.63	44.79	-7.92
15-12-90	10.19	0.944	1.54	1.00	0.54	0.62	53.48	-8.34
17-12-90	10.21	0.944	1.52	0.93	0.54	0.62	58.18	8.23
18-12-90	10.45	0.942	1.51	0.89	0.53	0.61	59.04	-7.56
19-12-90	10.29	0.944	1.51	0.84	0.52	0.61	65.01	-9.04
20-12-90	8.73	0.952	1.54	0.85	0.53	0.61	79.38	-9.16
21-12-90	9.73	0.947	1.50	0.79	0.50	0.64	73.48	-14.70
22-12-90	9.89	0.947	1.49	0.78	0.50	0.62	72.09	-11.32
24-12-90	10.00	0.946	1.50	0.76	0.50	0.62	73.60	-11.80
26-12-90	10.20	0.942	1.49	0.75	0.50	0.59	72.84	-8.82
27-12-90	10.08	0.944	1.49	0.75	0.49	0.59	73.02	-9.52
28-12-90	10.15	0.943	1.49	0.75	0.49	0.59	73.10	-9.26
29-12-90	10.28	0.942	1.50	0.75	0.50	0.59	72.67	-8.85
31-12-90	10.29	0.942	1.52	0.71	0.52	0.61	78.13	-9.23
02-01-91	12.16	0.934	1.53	0.70	0.54	0.62	68.34	-7.15
03-01-91	11.86	0.936	1.51	0.71	0.52	0.62	66.95	-8.18
04-01-91	11.37	0.938	1.51	0.74	0.51	0.62	67.99	-9.32
05-01-91	11.78	0.936	1.53	0.67	0.54	0.64	72.84	-8.57
07-01-91	12.52	0.931	1.55	0.67	0.55	0.64	69.97	-7.43
08-01-91	12.02	0.934	1.55	0.65	0.56	0.65	74.63	-7.90
09-01-91	12.09	0.934	1.55	0.65	0.55	0.65	74.61	-7.86
10-01-91	12.02	0.934	1.56	0.64	0.56	0.65	76.37	-6.82
11-01-91	11.49	0.937	1.55	0.65	0.55	0.65	78.33	-8.79
12-01-91	11.73	0.935	1.55	0.65	0.55	0.66	77.15	-8.78
14-01-91	12.26	0.934	1.55	0.64	0.55	0.66	73.98	-8.97
15-01-91	13.28	0.927	1.56	0.64	0.56	0.66	69.05	-7.91
16-01-91	13.36	0.926	1.56	0.64	0.56	0.67	68.86	-7.93
17-01-91	13.86	0.925	1.55	0.64	0.57	0.67	66.31	-7.50
18-01-91	14.38	0.923	1.57	0.63	0.57	0.67	65.37	-6.68
19-01-91	13.53	0.926	1.56	0.64	0.57	0.66	68.59	-7.17
21-01-91	12.59	0.932	1.58	0.63	0.58	0.66	74.90	-6.67
22-01-91	12.37	0.932	1.57	0.60	0.57	0.67	78.90	-7.84
23-01-91	12.95	0.929	1.58	0.60	0.58	0.66	75.52	-6.49
24-01-91	13.66	0.925	1.58	0.61	0.58	0.67	71.01	-6.15
25-01-91	12.43	0.931	1.57	0.64	0.57	0.67	75.14	-7.48
26-01-91	12.88	0.927	1.57	0.64	0.57	0.67	72.52	-7.45

SPECIMEN #: 5E

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 30.2 mm (1-3/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	ANODE OFF	CATHODE ON	CATHODE OFF	Electrode Resistance (Ohms) ANODE	CATHODE
13-12-90	2.87	0.990	-0.10	-0.73	-1.12	-0.80	218.47	-111.50
14-12-90	2.53	0.987	-0.09	-0.65	-1.08	-0.88	218.18	-77.87
15-12-90	2.20	0.991	-0.09	-0.68	-1.04	-0.85	268.64	-87.27
17-12-90	2.02	0.991	-0.08	-0.68	-1.05	-0.82	296.04	-115.35
18-12-90	1.74	0.991	-0.07	-0.69	-1.05	-0.81	352.30	-138.51
19-12-90	1.88	0.990	-0.08	-0.61	-1.02	-0.90	282.45	-64.89
20-12-90	1.61	0.994	-0.08	-0.58	-1.05	-0.93	313.66	-77.02
21-12-90	1.58	0.994	-0.07	-0.60	-1.03	-0.90	336.08	-84.81
22-12-90	1.58	0.994	-0.07	-0.58	-1.04	-0.91	320.89	-84.18
24-12-90	1.45	0.995	-0.07	-0.52	-0.98	-0.88	308.28	-68.97
26-12-90	1.36	0.996	-0.05	-0.51	-1.00	-0.90	336.76	-69.85
27-12-90	1.35	0.996	-0.05	-0.49	-1.02	-0.93	321.48	-64.44
28-12-90	1.34	0.995	-0.05	-0.49	-1.02	-0.91	323.88	-81.34
29-12-90	1.35	0.995	-0.05	-0.49	-1.02	-0.91	322.96	-79.26
31-12-90	1.28	0.996	-0.05	-0.49	-1.02	-0.93	344.53	-74.22
02-01-91	1.27	0.995	-0.05	-0.46	-1.01	-0.92	326.77	-67.72
03-01-91	1.39	0.995	-0.05	-0.50	-1.02	-0.94	319.42	-58.27
04-01-91	1.56	0.994	-0.07	-0.52	-1.04	-0.94	291.67	-62.18
05-01-91	1.45	0.995	-0.04	-0.48	-1.02	-0.89	297.93	-91.03
07-01-91	1.36	0.995	-0.04	-0.49	-1.01	-0.88	324.26	-94.12
08-01-91	1.32	0.995	-0.05	-0.49	-1.01	-0.89	334.09	-93.18
09-01-91	1.33	0.995	-0.05	-0.48	-1.01	-0.91	324.06	-72.93
10-01-91	1.37	0.994	-0.05	-0.49	-1.01	-0.89	319.71	-86.13
11-01-91	1.22	0.994	-0.04	-0.47	-1.02	-0.90	346.72	-96.72
12-01-91	1.23	0.993	-0.04	-0.46	-1.02	-0.92	339.84	-82.11
14-01-91	1.24	0.992	-0.05	-0.46	-1.03	-0.93	333.87	-78.23
15-01-91	1.34	0.991	-0.04	-0.45	-1.03	-0.94	306.72	-70.90
16-01-91	1.35	0.991	-0.04	-0.47	-1.04	-0.90	314.81	-101.48
17-01-91	1.52	0.989	-0.04	-0.47	-1.03	-0.91	283.55	-80.92
18-01-91	1.52	0.991	-0.03	-0.47	-1.03	-0.89	289.47	-92.11
19-01-91	1.46	0.992	-0.03	-0.47	-1.01	-0.88	303.42	-91.78
21-01-91	1.26	0.993	-0.03	-0.47	-1.03	-0.87	350.79	-123.81
22-01-91	1.39	0.992	-0.03	-0.48	-1.03	-0.87	324.46	-115.83
23-01-91	1.25	0.992	-0.03	-0.48	-1.03	-0.87	356.80	-131.20
24-01-91	1.35	0.991	-0.03	-0.47	-1.03	-0.87	326.67	-120.74
25-01-91	1.35	0.992	-0.03	-0.47	-1.02	-0.90	328.15	-92.59
26-01-91	1.37	0.992	-0.03	-0.48	-1.03	-0.89	323.36	-101.46

SPECIMEN #: 5E

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 30.2 mm (1-3/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Polarity)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE (D-M-Y)	I (mA)	Volt (V)	CATHODE ON	CATHODE OFF	ANODE ON	ANODE OFF	CATHODE	ANODE
13-12-90	10.60	0.940	1.52	1.01	0.52	0.69	48.30	-15.94
14-12-90	9.04	0.953	1.53	1.12	0.53	0.61	45.35	-8.96
15-12-90	7.78	0.960	1.53	1.10	0.54	0.61	55.27	-9.77
17-12-90	6.96	0.963	1.53	1.10	0.54	0.61	61.78	-9.91
18-12-90	6.04	0.967	1.53	1.10	0.54	0.60	70.70	-10.10
19-12-90	5.70	0.969	1.51	1.10	0.53	0.58	71.93	-10.35
20-12-90	5.60	0.971	1.55	1.10	0.54	0.61	80.71	-13.39
21-12-90	5.30	0.974	1.50	1.05	0.52	0.61	84.91	-16.98
22-12-90	5.26	0.975	1.50	1.05	0.52	0.60	85.55	-15.21
24-12-90	5.08	0.975	1.50	1.03	0.51	0.59	92.52	-16.34
26-12-90	4.82	0.976	1.49	1.04	0.50	0.57	93.36	-13.90
27-12-90	4.58	0.977	1.49	1.03	0.50	0.57	100.44	-15.72
28-12-90	4.60	0.976	1.49	1.03	0.50	0.58	100.00	-17.17
29-12-90	4.63	0.976	1.50	1.03	0.50	0.58	101.51	-16.63
31-12-90	4.60	0.978	1.49	1.01	0.49	0.57	104.35	-17.39
02-01-91	4.74	0.976	1.49	1.01	0.49	0.57	101.27	-16.88
03-01-91	4.71	0.977	1.50	1.00	0.50	0.59	106.16	-18.90
04-01-91	4.83	0.976	1.52	1.00	0.52	0.60	107.66	-17.60
05-01-91	4.92	0.975	1.49	0.95	0.49	0.58	109.76	-17.89
07-01-91	4.73	0.975	1.49	0.94	0.49	0.58	116.07	-18.82
08-01-91	4.44	0.977	1.49	0.91	0.49	0.58	131.76	-20.95
09-01-91	4.40	0.979	1.48	0.93	0.49	0.58	126.14	-21.36
10-01-91	4.36	0.980	1.48	0.88	0.48	0.58	138.53	-22.25
11-01-91	4.07	0.977	1.47	0.92	0.48	0.57	134.15	-22.36
12-01-91	4.18	0.976	1.47	0.92	0.48	0.58	131.82	-22.49
14-01-91	4.31	0.975	1.48	0.92	0.49	0.58	131.09	-21.35
15-01-91	4.67	0.973	1.48	0.91	0.49	0.58	121.20	-18.63
16-01-91	4.64	0.972	1.48	0.90	0.49	0.58	125.00	-19.40
17-01-91	4.86	0.971	1.48	0.90	0.50	0.59	119.75	-18.93
18-01-91	4.88	0.973	1.48	0.89	0.49	0.58	121.31	-19.06
19-01-91	4.63	0.975	1.48	0.89	0.49	0.57	126.57	-18.57
21-01-91	4.20	0.977	1.48	0.90	0.48	0.57	139.29	-22.14
22-01-91	4.08	0.977	1.48	0.79	0.47	0.59	169.85	-27.94
23-01-91	4.41	0.975	1.48	0.81	0.48	0.58	153.06	-22.22
24-01-91	4.68	0.973	1.48	0.80	0.49	0.58	145.51	-20.73
25-01-91	4.11	0.975	1.48	0.89	0.48	0.57	143.80	-20.92
26-01-91	4.24	0.975	1.48	0.83	0.49	0.57	153.54	-17.92

SPECIMEN #: 5F

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 36.5 mm (1-7/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	ANODE OFF	CATHODE ON	CATHODE OFF	Electrode Resistance (Ohms) ANODE	CATHODE
13-12-90	2.73	0.980	-0.05	-0.57	-1.05	-0.91	189.38	-50.92
14-12-90	3.12	0.984	-0.09	-0.59	-0.10	-0.89	160.58	253.21
15-12-90	2.13	0.992	-0.07	-0.61	-1.07	-0.87	254.93	-94.84
17-12-90	1.85	0.992	-0.06	-0.60	-1.04	-0.86	292.97	-97.84
18-12-90	1.68	0.991	-0.05	-0.58	-1.02	-0.85	312.50	-98.81
19-12-90	1.76	0.991	-0.05	-0.55	-1.01	-0.85	283.52	-89.77
20-12-90	2.13	0.990	-0.05	-0.60	-0.80	-0.83	256.81	18.31
21-12-90	1.48	0.994	-0.05	-0.47	-1.01	-0.84	279.73	-112.84
22-12-90	1.51	0.995	-0.04	-0.47	-1.00	-0.82	279.47	-115.23
24-12-90	1.44	0.995	-0.04	-0.48	-1.00	-0.83	303.47	-121.53
26-12-90	1.45	0.995	-0.03	-0.48	-0.95	-0.79	308.28	-109.66
27-12-90	1.42	0.995	-0.02	-0.47	-0.89	-0.72	323.24	-116.90
28-12-90	1.30	0.995	-0.02	-0.47	-0.89	-0.73	347.69	-125.38
29-12-90	1.17	0.996	-0.02	-0.47	-0.98	-0.73	382.05	-210.26
31-12-90	1.19	0.996	-0.01	-0.47	-0.96	-0.78	383.19	-158.82
02-01-91	1.25	0.995	-0.02	-0.46	-0.95	-0.78	351.20	-131.20
03-01-91	1.57	0.994	-0.03	-0.47	-0.88	-0.75	282.17	-82.17
04-01-91	1.98	0.992	-0.03	-0.47	-0.82	-0.72	219.70	-50.51
05-01-91	1.33	0.996	-0.02	-0.46	-0.97	-0.78	332.33	-145.11
07-01-91	1.11	0.996	-0.02	-0.46	-1.00	-0.80	392.79	-172.07
08-01-91	1.09	0.995	-0.02	-0.46	-0.99	-0.75	406.42	-217.43
09-01-91	1.13	0.995	-0.07	-0.47	-1.02	-0.76	354.87	-234.51
10-01-91	1.46	0.993	-0.03	-0.46	-1.01	-0.75	297.26	-175.34
11-01-91	1.08	0.994	-0.01	-0.47	-1.01	-0.73	420.37	-262.96
12-01-91	1.03	0.994	-0.01	-0.47	-1.00	-0.73	439.81	-263.11
14-01-91	0.98	0.994	-0.01	-0.47	-1.01	-0.73	464.29	-282.65
15-01-91	1.20	0.992	-0.03	-0.47	-1.01	-0.78	365.00	-192.50
16-01-91	1.11	0.992	-0.02	-0.47	-1.02	-0.78	398.20	-213.51
17-01-91	1.10	0.992	-0.02	-0.47	-1.01	-0.80	410.00	-187.27
18-01-91	1.13	0.992	-0.01	-0.47	-0.99	-0.80	403.54	-169.03
19-01-91	1.19	0.995	-0.01	-0.47	-0.96	-0.77	386.55	-159.66
21-01-91	1.02	0.994	0.00	-0.47	-0.96	-0.77	459.80	-178.43
22-01-91	0.84	0.995	0.01	-0.47	-0.99	-0.74	560.71	-301.19
23-01-91	0.84	0.995	0.01	-0.47	-0.99	-0.74	561.90	-304.76
24-01-91	1.05	0.993	-0.01	-0.47	-1.02	-0.73	431.43	-277.14
25-01-91	1.12	0.993	-0.00	-0.47	-1.00	-0.70	437.86	-260.71
26-01-91	1.08	0.993	-0.01	-0.47	-1.00	-0.71	433.33	-263.89

SPECIMEN #: 5F

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 36.5 mm (1-7/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	OFF	ANODE ON	OFF	Electrode Resistance (Ohms) CATHODE	ANODE
13-12-90	10.39	0.950	1.52	0.97	0.52	0.67	53.51	-14.15
14-12-90	8.18	0.955	1.52	1.08	0.53	0.62	53.79	-10.76
15-12-90	6.88	0.965	1.52	1.09	0.53	0.61	62.50	-11.19
17-12-90	6.36	0.966	1.52	1.06	0.53	0.61	72.33	-13.21
18-12-90	5.85	0.968	1.52	1.05	0.53	0.62	80.34	-15.21
19-12-90	5.74	0.969	1.51	1.02	0.52	0.60	85.37	-14.29
20-12-90	5.37	0.973	1.50	1.03	0.51	0.57	87.71	-11.36
21-12-90	5.51	0.972	1.50	0.99	0.51	0.59	93.28	-13.79
22-12-90	5.45	0.973	1.49	0.97	0.51	0.59	96.33	-15.78
24-12-90	5.24	0.974	1.49	0.92	0.50	0.59	109.35	-17.75
26-12-90	5.06	0.975	1.49	0.98	0.49	0.58	101.78	-17.79
27-12-90	4.95	0.975	1.47	0.96	0.49	0.59	103.84	-19.60
28-12-90	4.87	0.976	1.47	0.95	0.49	0.59	105.95	-21.36
29-12-90	4.56	0.977	1.47	0.95	0.48	0.59	114.04	-23.90
31-12-90	4.56	0.978	1.48	0.83	0.48	0.59	141.67	-24.34
02-01-91	4.84	0.975	1.48	0.83	0.48	0.60	134.92	-23.97
03-01-91	4.81	0.976	1.48	0.82	0.48	0.59	136.38	-22.87
04-01-91	4.59	0.977	1.48	0.82	0.48	0.58	144.01	-22.00
05-01-91	4.47	0.978	1.48	0.81	0.47	0.59	148.99	-26.62
07-01-91	4.24	0.978	1.47	0.83	0.47	0.59	152.12	-27.12
08-01-91	4.11	0.979	1.46	0.87	0.47	0.57	144.28	-24.57
09-01-91	3.69	0.983	1.33	0.76	0.41	0.59	154.20	-49.86
10-01-91	3.86	0.982	1.46	0.88	0.47	0.57	149.22	-23.58
11-01-91	3.74	0.982	1.46	0.92	0.47	0.57	145.72	-26.74
12-01-91	3.73	0.978	1.46	0.90	0.47	0.57	149.60	-27.08
14-01-91	3.74	0.978	1.45	0.89	0.46	0.57	149.20	-28.34
15-01-91	4.57	0.973	1.45	0.84	0.46	0.58	133.92	-25.60
16-01-91	4.14	0.975	1.48	0.88	0.48	0.59	145.41	-25.60
17-01-91	4.28	0.975	1.48	0.87	0.48	0.59	142.52	-25.00
18-01-91	4.09	0.976	1.47	0.90	0.48	0.58	140.34	-24.69
19-01-91	3.88	0.979	1.46	0.90	0.46	0.57	144.07	-28.35
21-01-91	3.54	0.981	1.46	0.90	0.46	0.57	158.76	-31.64
22-01-91	3.87	0.978	1.43	0.78	0.43	0.58	168.99	-37.98
23-01-91	3.46	0.980	1.45	0.81	0.45	0.57	186.42	-34.68
24-01-91	3.74	0.977	1.45	0.83	0.45	0.57	165.78	-32.89
25-01-91	3.56	0.979	1.45	0.90	0.46	0.56	155.90	-28.09
26-01-91	3.62	0.978	1.45	0.83	0.45	0.56	170.99	-30.39

SPECIMEN #: 5G

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 42.9 mm (1-11/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	ANODE OFF	CATHODE ON	CATHODE OFF	Electrode Resistance (Ohms) ANODE	CATHODE
13-12-90	0.77	1.000	0.44	-0.57	-0.86	-0.75	1301.30	-145.45
14-12-90	0.53	0.998	0.36	-0.46	-0.66	-0.61	1552.83	-100.00
15-12-90	0.37	0.999	0.40	-0.48	-0.61	-0.59	2389.19	-48.65
17-12-90	0.31	0.999	0.40	-0.47	-0.61	-0.59	2806.45	-67.74
18-12-90	0.28	0.998	0.40	-0.45	-0.61	-0.59	3053.57	-89.29
19-12-90	0.23	0.999	0.37	-0.42	-0.64	-0.61	3434.78	-113.04
20-12-90	0.40	0.999	0.40	-0.50	-0.67	-0.59	2252.50	-202.50
21-12-90	0.19	0.999	0.40	-0.39	-0.62	-0.51	4163.16	-557.89
22-12-90	0.18	1.000	0.41	-0.38	-0.62	-0.60	4361.11	-94.44
24-12-90	0.16	1.000	0.40	-0.34	-0.61	-0.59	4650.00	-112.50
26-12-90	0.14	1.000	0.41	-0.31	-0.60	-0.59	5150.00	-85.71
27-12-90	0.13	1.000	0.41	-0.37	-0.60	-0.59	6007.69	-107.69
28-12-90	0.12	1.000	0.41	-0.38	-0.60	-0.59	6566.67	-91.67
29-12-90	0.10	1.000	0.41	-0.37	-0.60	-0.59	7830.00	-80.00
31-12-90	0.09	1.000	0.42	-0.37	-0.59	-0.59	8711.11	-22.22
02-01-91	0.09	1.000	0.40	-0.36	-0.61	-0.59	8488.89	-222.22
03-01-91	0.18	1.000	0.40	-0.36	-0.62	-0.59	4244.44	-172.22
04-01-91	0.25	1.000	0.40	-0.36	-0.64	-0.59	3056.00	-200.00
05-01-91	0.11	1.000	0.42	-0.30	-0.59	-0.58	6554.55	-100.00
07-01-91	0.13	1.000	0.41	-0.30	-0.60	-0.59	5438.46	-115.38
08-01-91	0.11	1.000	0.41	-0.31	-0.60	-0.59	6509.09	-109.09
09-01-91	0.08	1.000	0.41	-0.27	-0.60	-0.59	8500.00	-87.50
10-01-91	0.11	0.999	0.41	-0.29	-0.59	-0.59	6354.55	-45.45
11-01-91	0.08	0.999	0.41	-0.31	-0.59	-0.58	8975.00	-75.00
12-01-91	0.08	0.999	0.41	-0.32	-0.59	-0.59	9100.00	-62.50
14-01-91	0.07	0.999	0.41	-0.33	-0.59	-0.59	10557.1	-71.43
15-01-91	0.09	0.998	0.41	-0.34	-0.59	-0.58	8322.22	-66.67
16-01-91	0.07	0.998	0.41	-0.33	-0.59	-0.58	10600.0	-42.86
17-01-91	0.08	0.997	0.41	-0.34	-0.58	-0.58	9400.00	-50.00
18-01-91	0.09	0.998	0.42	-0.34	-0.58	-0.58	8344.44	-55.56
19-01-91	0.11	1.000	0.42	-0.33	-0.58	-0.57	6836.36	-100.00
21-01-91	0.06	0.999	0.42	-0.33	-0.58	-0.58	12433.33	-50.00
22-01-91	0.05	0.999	0.42	-0.31	-0.58	-0.58	14640.00	-60.00
23-01-91	0.05	0.998	0.42	-0.31	-0.58	-0.57	14600.00	-60.00
24-01-91	0.05	0.998	0.43	-0.31	-0.57	-0.57	14600.00	-60.00
25-01-91	0.06	0.999	0.43	-0.35	-0.57	-0.56	13066.67	-66.67
26-01-91	0.06	0.999	0.43	-0.35	-0.57	-0.57	12983.33	-33.33

SPECIMEN #: 5G

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 42.9 mm (1-11/16 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	CATHODE OFF	ANODE ON	ANODE OFF	Electrode Resistance (Ohms) CATHODE	ANODE
13-12-90	9.04	0.950	1.53	1.01	0.54	0.65	57.52	-12.39
14-12-90	6.38	0.965	1.49	1.10	0.49	0.59	60.50	-16.14
15-12-90	5.50	0.973	1.49	1.11	0.49	0.58	68.91	-17.64
17-12-90	5.02	0.974	1.48	1.10	0.46	0.58	75.90	-22.31
18-12-90	4.80	0.974	1.45	0.93	0.46	0.57	108.33	-24.17
19-12-90	4.46	0.975	1.50	1.07	0.51	0.59	97.31	-17.94
20-12-90	3.93	0.981	1.50	1.09	0.51	0.59	106.11	-20.61
21-12-90	3.62	0.983	1.48	1.08	0.49	0.57	110.22	-22.93
22-12-90	3.99	0.980	1.52	1.07	0.52	0.60	113.78	-17.79
24-12-90	3.75	0.983	1.52	1.03	0.52	0.59	131.20	-20.27
26-12-90	3.37	0.984	1.49	0.87	0.50	0.59	182.49	-27.60
27-12-90	3.17	0.985	1.49	0.88	0.50	0.58	193.38	-26.18
28-12-90	3.22	0.985	1.49	0.88	0.49	0.58	188.51	-28.26
29-12-90	3.33	0.984	1.49	0.88	0.49	0.58	183.18	-28.53
31-12-90	2.89	0.987	1.47	0.96	0.49	0.58	179.24	-30.45
02-01-91	3.25	0.984	1.50	0.94	0.50	0.60	173.23	-28.31
03-01-91	3.16	0.984	1.51	0.93	0.51	0.59	182.28	-24.68
04-01-91	3.05	0.985	1.53	0.92	0.51	0.59	197.05	-25.90
05-01-91	2.87	0.986	1.49	0.96	0.50	0.58	184.32	-27.87
07-01-91	2.83	0.986	1.50	0.96	0.51	0.59	190.81	-26.15
08-01-91	2.96	0.986	1.48	0.93	0.49	0.58	185.14	-29.39
09-01-91	2.71	0.988	1.51	0.97	0.50	0.58	199.63	-28.41
10-01-91	2.50	0.990	1.47	0.97	0.49	0.55	201.20	-23.60
11-01-91	2.54	0.985	1.51	1.06	0.49	0.58	177.56	-33.46
12-01-91	2.56	0.985	1.51	1.04	0.50	0.58	184.77	-32.03
14-01-91	2.58	0.984	1.51	1.04	0.51	0.58	181.78	-27.91
15-01-91	2.94	0.983	1.47	0.97	0.49	0.56	173.13	-26.19
16-01-91	2.78	0.983	1.51	1.06	0.50	0.57	160.07	-25.90
17-01-91	2.74	0.983	1.50	1.04	0.50	0.57	166.06	-26.64
18-01-91	2.70	0.984	1.50	1.05	0.50	0.57	163.33	-25.19
19-01-91	2.56	0.986	1.49	1.06	0.50	0.56	169.92	-26.17
21-01-91	2.46	0.986	1.51	1.06	0.51	0.57	184.15	-23.17
22-01-91	2.54	0.985	1.48	0.99	0.48	0.56	192.52	-34.65
23-01-91	2.37	0.985	1.50	0.97	0.50	0.56	221.94	-28.69
24-01-91	2.48	0.985	1.49	0.97	0.49	0.56	208.06	-28.63
25-01-91	2.35	0.985	1.50	1.06	0.49	0.56	187.23	-27.23
26-01-91	2.40	0.985	1.49	1.01	0.49	0.56	200.42	-27.92

SPECIMEN #: 5H

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 50.8 mm (2 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
13-12-90	1.10	0.992	0.15	-0.31	-0.92	-0.64	411.82	-260.00
14-12-90	0.58	0.995	0.28	-0.42	-0.74	-0.68	1217.24	-89.66
15-12-90	0.35	0.996	0.39	-0.41	-0.63	-0.59	2291.43	-114.29
17-12-90	0.26	0.997	0.40	-0.43	-0.60	-0.58	3180.77	-76.92
18-12-90	0.18	0.997	0.41	-0.45	-0.59	-0.57	4788.89	-66.67
19-12-90	0.29	0.996	0.41	-0.49	-0.60	-0.57	3127.59	-86.21
20-12-90	0.22	0.997	0.41	-0.35	-0.58	-0.58	3490.91	0.00
21-12-90	0.17	0.998	0.42	-0.41	-0.59	-0.58	4900.00	-58.82
22-12-90	0.27	0.997	0.41	-0.36	-0.60	-0.58	2848.15	-88.89
24-12-90	0.18	0.997	0.42	-0.34	-0.59	-0.58	4222.22	-83.33
26-12-90	0.22	0.995	0.40	-0.33	-0.60	-0.59	3318.18	-77.27
27-12-90	0.22	0.995	0.40	-0.32	-0.61	-0.59	3286.36	-86.36
28-12-90	0.20	0.995	0.41	-0.32	-0.59	-0.59	3620.00	-40.00
29-12-90	0.18	0.996	0.41	-0.31	-0.59	-0.59	4005.56	0.00
31-12-90	0.15	0.998	0.42	-0.29	-0.58	-0.59	4693.33	13.33
02-01-91	0.15	0.998	0.41	-0.23	-0.59	-0.59	4213.33	-60.00
03-01-91	0.12	0.998	0.41	-0.22	-0.60	-0.59	5191.67	-83.33
04-01-91	0.11	0.998	0.40	-0.21	-0.60	-0.59	5545.45	-100.00
05-01-91	0.16	0.997	0.40	-0.23	-0.60	-0.59	3968.75	-68.75
07-01-91	0.09	0.997	0.41	-0.22	-0.59	-0.58	6977.78	-100.00
08-01-91	0.15	0.997	0.41	-0.33	-0.59	-0.58	4960.00	-86.67
09-01-91	0.20	0.997	0.41	-0.32	-0.60	-0.58	3670.00	-95.00
10-01-91	0.18	0.998	0.42	-0.30	-0.59	-0.58	3950.00	-83.33
11-01-91	0.10	0.998	0.42	-0.28	-0.58	-0.58	7040.00	-60.00
12-01-91	0.11	0.998	0.42	-0.28	-0.58	-0.58	6354.55	-81.82
14-01-91	0.13	0.998	0.42	-0.27	-0.59	-0.58	5307.69	-76.92
15-01-91	0.29	0.997	0.41	-0.29	-0.60	-0.57	2389.66	-103.45
16-01-91	0.33	0.996	0.40	-0.36	-0.60	-0.58	2281.82	-75.76
17-01-91	0.33	0.996	0.39	-0.33	-0.60	-0.58	2187.88	-66.67
18-01-91	0.34	0.997	0.40	-0.34	-0.60	-0.58	2170.59	-64.71
19-01-91	0.21	0.997	0.42	-0.28	-0.58	-0.57	3333.33	-71.43
21-01-91	0.17	0.997	0.40	-0.28	-0.60	-0.57	4023.53	-176.47
22-01-91	0.14	0.997	0.41	-0.29	-0.59	-0.57	4992.86	-107.14
23-01-91	0.20	0.996	0.39	-0.29	-0.60	-0.58	3425.00	-135.00
24-01-91	0.33	0.995	0.35	-0.29	-0.64	-0.58	1963.64	-187.88
25-01-91	0.40	0.994	0.35	-0.32	-0.64	-0.60	1665.00	-95.00
26-01-91	0.38	0.995	0.34	-0.31	-0.64	-0.60	1710.53	-105.26

SPECIMEN #: 5H

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 50.8 mm (2 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			CATHODE		ANODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
13-12-90	10.54	0.940	1.57	1.16	0.57	0.70	38.90	-12.43
14-12-90	7.66	0.956	1.52	1.08	0.53	0.63	57.44	-12.79
15-12-90	6.10	0.966	1.46	1.09	0.49	0.57	60.66	-12.95
17-12-90	6.02	0.966	1.45	1.06	0.47	0.56	64.78	-14.95
18-12-90	5.93	0.966	1.43	0.92	0.45	0.56	86.85	-18.04
19-12-90	4.44	0.975	1.47	1.06	0.49	0.57	92.34	-18.47
20-12-90	4.06	0.975	1.48	1.03	0.50	0.58	110.84	-19.95
21-12-90	3.99	0.977	1.47	1.05	0.49	0.57	105.26	-20.05
22-12-90	3.92	0.977	1.47	1.06	0.49	0.55	104.59	-15.31
24-12-90	3.59	0.978	1.45	1.04	0.48	0.56	114.21	-22.56
26-12-90	3.38	0.977	1.47	1.05	0.48	0.56	124.26	-21.01
27-12-90	3.29	0.978	1.47	1.04	0.49	0.56	130.70	-21.58
28-12-90	3.38	0.977	1.47	1.04	0.48	0.54	127.22	-18.64
29-12-90	3.41	0.977	1.47	1.04	0.48	0.54	126.10	-19.06
31-12-90	3 25	0.981	1.48	1.03	0.50	0.57	138.46	-23.08
02-01-91	3.13	0.982	1.47	1.05	0.50	0.57	134.19	-22.04
03-01-91	3.17	0.981	1.48	1.05	0.49	0.57	135.65	-22.40
04-01-91	3.09	0.982	1.49	1.07	0.50	0.57	135.92	-22.98
05-01-91	2.96	0.982	1.49	1.08	0.49	0.57	138.51	-24.66
07-01-91	2.73	0.983	1.47	1.10	0.48	0.56	135.53	-30.40
08-01-91	2.51	0.985	1.47	1.05	0.47	0.56	167.33	-34.26
09-01-91	2.53	0.985	1.46	1.01	0.47	0.56	177.87	-35.18
10-01-91	2.94	0.983	1.45	1.01	0.46	0.54	149.66	-26.19
11-01 91	2.53	0.985	1.47	1.04	0.47	0.56	169.96	-32.81
12-01-91	2.51	0.985	1.47	1.04	0.46	0.56	171.31	-37.05
14-01-91	2.48	0.985	1.46	1.04	0.46	0.56	169.35	-39.52
15-01-91	2.78	0.984	1.42	1.02	0.44	0.55	143.88	-39.21
16-01-91	2.62	0.984	1.46	1.05	0.46	0.56	156.49	-34.73
17-01-91	2.73	0.984	1.46	1.07	0.47	0.55	142.86	-28.94
18-01-91	2.88	0.983	1.47	1.07	0.48	0.55	138.89	-25.35
19-01-91	2.69	0.984	1.47	1.06	0.48	0.55	152.42	-27.88
21-01-91	2.51	0.985	1.48	1.06	0.48	0.55	167.33	-29.88
22-01-91	2.39	0.984	1.46	0.95	0.46	0.55	215.06	-36.82
23-01-91	2.43	0.985	1.47	0.95	0.47	0.54	213.17	-29.22
24-01-91	2.47	0.985	1.46	0.96	0.47	0.54	203.24	-28.34
25-01-91	2.46	0.982	1.47	0.96	0.47	0.56	209.35	-36.18
26-01-91	2.47	0.958	1.46	0.96	0.47	0.55	203 64	-32.79

SPECIMEN #: 5I

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 63.5 mm (2-1/2 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	OFF	CATHODE ON	OFF	Electrode Resistance (Ohms) ANODE	CATHODE
13-12-90	1.10	0.997	0.37	-0.51	-0.63	-0.63	798.18	-1.82
14-12-90	1.64	0.998	0.19	-0.51	-0.79	-0.73	426.83	-37.20
15-12-90	2.16	0.987	-0.10	-0.61	-1.08	-0.98	238.43	-44.91
17-12-90	1.84	0.988	-0.10	-0.62	-1.08	-0.95	284.24	-69.57
18-12-90	1.62	0.989	-0.10	-0.67	-1.08	-0.93	347.53	-95.06
19-12-90	1.31	0.991	-0.07	-0.65	-1.02	-0.89	441.98	-103.05
20-12-90	1.36	0.991	-0.10	-0.65	-1.08	-0.91	408.09	-127.94
21-12-90	1.43	0.991	-0.10	-0.65	-1.02	-0.93	383.92	-63.64
22-12-90	1.40	0.991	-0.07	-0.64	-1.00	-0.91	405.00	-66.43
24-12-90	1.30	0.992	-0.07	-0.67	-0.98	-0.87	456.92	-88.46
26-12-90	1.23	0.990	-0.03	-0.62	-0.92	-0.83	481.30	-72.36
27-12-90	1.22	0.990	-0.03	-0.66	-0.91	-0.83	510.66	-70.49
28-12-90	1.11	0.991	-0.03	-0.66	-0.92	-0.83	563.06	-81.08
29-12-90	0.97	0.993	-0.03	-0.65	-0.92	-0.83	638.14	-98.97
31-12-90	0.87	0.993	0.06	-0.65	-0.87	-0.80	821.84	-88.51
02-01-91	0.76	0.994	0.11	-0.51	-0.83	-0.76	811.84	-86.84
03-01-91	0.75	0.994	0.12	-0.51	-0.80	-0.74	840.00	-86.67
04-01-91	0.75	0.994	0.16	-0.51	-0.77	-0.71	884.00	-81.33
05-01-91	0.78	0.994	0.19	-0.50	-0.76	-0.71	883.33	-61.54
07-01-91	0.80	0.993	0.20	-0.50	-0.73	-0.67	877.50	-68.75
08-01-91	0.53	0.995	0.29	-0.44	-0.70	-0.65	1366.04	-84.91
09-01-91	0.58	0.995	0.29	-0.42	-0.67	-0.64	1231.03	-51.72
10-01-91	0.57	0.995	0.33	-0.46	-0.64	-0.61	1377.19	-50.88
11-01-91	0.43	0.995	0.37	-0.43	-0.62	-0.59	1860.47	-60.47
12-01-91	0.42	0.996	0.40	-0.43	-0.60	-0.58	1976.19	-59.52
14-01-91	0.41	0.996	0.41	-0.43	-0.59	-0.56	2034.15	-75.61
15-01-91	0.46	0.995	0.39	-0.43	-0.60	-0.57	1786.96	-69.57
16-01-91	0.35	0.996	0.39	-0.37	-0.60	-0.58	2180.00	-65.71
17-01-91	0.47	0.995	0.37	-0.38	-0.62	-0.60	1587.23	-36.17
18-01-91	0.41	0.996	0.38	-0.36	-0.61	-0.59	1812.20	-43.90
19-01-91	0.38	0.996	0.39	-0.39	-0.59	-0.57	2063.16	-55.26
21-01-91	0.23	0.997	0.43	-0.39	-0.57	-0.57	3552.17	21.74
22-01-91	0 21	0.996	0.41	-0.37	-0.59	-0.57	3690.48	-109.52
23-01-91	0 21	0.996	0.41	-0.37	-0.59	-0.56	3695.24	-133.33
24-01-91	0.23	0.996	0.39	-0.37	-0.61	-0.57	3321.74	-160.87
25-01-91	0.24	0.995	0.42	-0.35	-0.57	-0.55	3225.00	-75.00
26-01-91	0.23	0.996	0.41	-0.36	-0.59	-0.55	3352.17	-178.26

SPECIMEN #: 5I

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 63 5 mm (2-1/2 in.)

Starting Date: December 12, 1990
Ending Date: January 26, 1991
Immersion Period 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

			Electrode Potentials (V)				Electrode	
DATE	I	Volt	CATHODE		ANODE		Resistance (Ohms)	
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
13-12-90	9.18	0.945	1.52	1.06	0.53	0.66	50.44	-13.73
14-12-90	6.39	0.963	1.50	1.11	0.51	0.62	60.56	-17.53
15-12-90	7.17	0.960	1.55	1.09	0.53	0.63	63.32	-12.97
17-12-90	6.67	0.963	1.55	0.99	0.60	0.62	83.81	-3.15
18-12-90	6.17	0.965	1.65	0.96	0.64	0.73	111.99	-14.75
19-12-90	5.23	0.970	1.53	1.07	0.54	0.61	88.91	-13.96
20-12-90	4.68	0.973	1.53	1.02	0.53	0.62	108.97	-20.09
21-12-90	4.68	0.973	1.53	1.04	0.54	0.64	105.13	-21.37
22-12-90	4.28	0.975	1.53	1.08	0.55	0.66	104.21	-25.23
24-12-90	4.20	0.975	1.53	1.08	0.55	0.66	107.38	-25.71
26-12-90	4.01	0.975	1.54	1.05	0.55	0.61	122.19	-15.71
27-12-90	3.95	0.975	1.54	1.06	0.55	0.61	122.28	-16 20
28-12-90	3.97	0.975	1.54	1.05	0.55	0.61	123.17	-14.61
29-12-90	3.95	0.975	1.54	1.05	0.55	0.61	124.56	-13.92
31-12-90	3.75	0.978	1.53	1.02	0.53	0.60	136.00	-19.20
02-01-91	3.53	0.978	1.50	1.02	0.52	0.58	135.41	-16.15
03-01-91	3.50	0.978	1.49	1.02	0.52	0.58	134.86	-16.57
04-01-91	3.48	0.978	1.49	1.01	0.51	0.57	137.64	-16.38
05-01-91	3.40	0.979	1.48	1.01	0.50	0.57	138.24	-19.12
07-01-91	3.36	0.979	1.51	1.02	0.51	0.56	146 13	-14.29
08-01-91	3.04	0.982	1.48	1.00	0.50	0.57	158.22	-22.04
09-01-91	2.97	0.982	1.46	0.96	0.49	0.55	171.38	-22.90
10-01-91	2.72	0.983	1.46	0.89	0.44	0.54	208.82	-36.03
11-01-91	2.74	0.983	1.45	0.98	0.47	0.53	171.90	-24.45
12-01-91	2.75	0.983	1.46	0.98	0.47	0.54	173.45	-24.73
14-01-91	2.76	0.983	1.46	0.98	0.47	0.54	175.00	-24.28
15-01-91	2.98	0.983	1.44	0.99	0.45	0.53	150.67	-28.19
16-01-91	3.07	0.982	1.49	1.00	0.49	0.56	157.65	-21.82
17-01-91	3.13	0.982	1.49	1.04	0.50	0.55	145.05	-18.21
18-01-91	3.11	0.982	1.49	1.04	0.49	0.54	142.12	-16.40
19-01-91	2.95	0.983	1.48	1.03	0.49	0.55	155.25	-18.64
21-01-91	2.54	0.985	1.47	1.02	0.47	0.54	175.20	-27.56
22-01-91	2 44	0.984	1.46	0.94	0.46	0.54	215.16	-32.79
23-01-91	2.56	0.984	1.46	0.95	0.48	0 54	198.05	-24.61
24-01-91	2.61	0.984	1.46	0.96	0.47	0.54	190.04	-27.20
25-01-91	2 50	0.982	1 46	0.96	0.48	0.55	203 20	-30.80
26-01-91	2.55	0 983	1 46	0.95	0.48	0.54	202 35	-23 92

APPENDIX Q

Test Series #6

Potential and Current Measurements

Daily recordings of voltage and current readings, for both the normal and reversed polarity positions, are presented for the Test Series #6. These also include the electrode "polarization" resistances for each specimen tested.

SPECIMEN #: 6A

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 7.9 mm (5/16 in.)

Starting Date: February 5, 1991
Ending Date: March 22, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	OFF	CATHODE ON	OFF	Electrode Resistance (Ohms) ANODE	CATHODE
06-02-91	17.17	0.905	-0.18	-0.58	-1.18	-0.96	23.12	-13.05
07-02-91	19.58	0.886	-0.17	-0.54	-1.18	-0.99	18.64	-9.81
08-02-91	21.74	0.879	-0.17	-0.56	-1.18	-0.97	17.62	-9.80
09-02-91	20.50	0.891	-0.18	-0.54	-1.19	-0.97	17.66	-10.63
11-02-91	18.50	0.906	-0.17	-0.53	-1.18	-0.97	19.46	-11.30
12-02-91	16.61	0.918	-0.18	-0.53	-1.19	-0.97	20.83	-13.31
13-02-91	15.91	0.914	-0.18	-0.53	-1.19	-0.97	21.62	-14.02
14-02-91	15.91	0.912	-0.18	-0.55	-1.18	-1.01	22.75	-10.69
15-02-91	16.00	0.915	-0.18	-0.55	-1.18	-0.99	23.19	-11.62
16-02-91	15.28	0.921	-0.17	-0.55	-1.17	-0.99	24.93	-11.78
18-02-91	14.52	0.927	-0.17	-0.55	-1.16	-0.99	26.58	-11.78
19-02-91	13.98	0.932	-0.17	-0.55	-1.17	-0.98	27.11	-13.73
20-02-91	14.13	0.930	-0.17	-0.55	-1.17	-0.99	26.89	-13.09
21-02-91	14.65	0.925	-0.17	-0.55	-1.16	-0.99	26.08	-11.60
22-02-91	14.51	0.919	-0.18	-0.55	-1.17	-0.99	25.64	-12.54
23-02-91	14.11	0.923	-0.17	-0.55	-1.16	-0.99	26.65	-12.12
25-02-91	13.51	0.930	-0.17	-0.55	-1.17	-0.99	28.05	-13.25
26-02-91	13.28	0.931	-0.17	-0.55	-1.17	-0.99	28.24	-13.55
27-02-91	13.84	0.928	-0.17	-0.55	-1.17	-0.99	27.17	-13.08
28-02-91	13.70	0.931	-0.17	-0.55	-1.18	-0.94	27.96	-17.66
01-03-91	14.12	0.927	-0.17	-0.55	-1.17	-0.93	27.41	-17.21
02-03-91	14.35	0.924	-0.16	-0.55	-1.17	-0.92	26.97	-17.28
04-03-91	13.90	0.932	-0.16	-0.55	-1.17	-0.94	28.27	-16.76
05-03-91	13.79	0.934	-0.16	-0.55	-1.17	-0.93	28.06	-17.40
06-03-91	13.75	0.935	-0.16	-0.53	-1.17	-0.92	27.35	-17.96
07-03-91	13.82	0.931	-0.16	-0.54	-1.17	-0.94	27.28	-16.79
08-03-91	13.69	0.932	-0.16	-0.54	-1.16	-0.93	27.98	-16.65
09-03-91	13.43	0.933	-0.15	-0.54	-1.16	-0.94	28.82	-16.75
11-03-91	13.30	0.934	-0.15	-0.53	-1.15	-0.93	28.65	-16.54
12-03-91	13.16	0.935	-0.15	-0.53	-1.16	-0.93	29.26	-17.78
13-03-91	13.31	0.934	-0.15	-0.53	-1.15	-0.92	28.93	-17.05
14-03-91	13.48	0.932	-0.15	-0.53	-1.15	-0.92	28.49	-16.77
16-03-91	13.30	0.935	-0.14	-0.53	-1.15	-0.92	28.87	-17.07
18-03-91	12.85	0.933	-0.15	-0.52	-1.15	-0.93	29.18	-17.28
19-03-91	13.36	0.933	-0.14	-0.52	-1.15	-0.92	28.29	-17.14
20-03-91	13.40	0.945	-0.13	-0.52	-1.15	-0.948	28.58	-15.07
22-03-91	12.84	0.951	-0.12	-0.52	-1.15	-0.925	30.61	-17.52

SPECIMEN #: 6A

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 7.9 mm (5/16 in.)

Starting Date: February 5, 1991
Ending Date: March 22, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	CATHODE OFF	ANODE ON	ANODE OFF	Electrode Resistance (Ohms) CATHODE	ANODE
06-02-91	24.09	0.867	1.48	0.98	0.48	0.69	20.80	-8.80
07-02-91	38.20	0.786	1.42	0.88	0.44	0.64	14.21	-5.42
08-02-91	42.40	0.767	1.44	0.86	0.43	0.65	13.68	-4.58
09-02-91	44.90	0.759	1.45	0.80	0.46	0.66	14.59	-3.41
11-02-91	43.80	0.769	1.52	0.75	0.51	0.70	17.65	-4.95
12-02-91	39.30	0.794	1.49	0.74	0.49	0.69	19.11	-5.24
13-02-91	38.20	0.790	1.48	0.74	0.49	0.70	19.45	-5.52
14-02-91	36.70	0.795	1.48	0.66	0.48	0.69	22.32	-5.64
15-02-91	36.40	0.805	1.49	0.70	0.49	0.68	21.79	-5.25
16-02-91	34.90	0.814	1.48	0.69	0.49	0.68	22.58	-5.62
18-02-91	33.60	0.825	1.49	0.69	0.48	0.69	23.93	-5.98
19-02-91	34.40	0.819	1.50	0.68	0.50	0.68	23.72	-5.15
20-02-91	34.50	0.815	1.50	0.68	0.50	0.68	23.74	-5.07
21-02-91	34.80	0.812	1.51	0.67	0.51	0.68	24.05	-4.86
22-02-91	36.00	0.801	1.49	0.67	0.50	0.67	22.78	-4.67
23-02-91	34.70	0.811	1.50	0.66	0.51	0.67	24.15	-4.78
25-02-91	32.50	0.822	1.51	0.66	0.51	0.68	26.25	-5.08
26-02-91	32.60	0.823	1.51	0.66	0.51	0.67	26.10	-5.00
27-02-91	34.40	0.815	1.51	0.66	0.50	0.67	24.77	-4.88
28-02-91	34.20	0.818	1.51	0.61	0.50	0.69	26.32	-5.32
01-03-91	34.40	0.815	1.51	0.60	0.51	0.69	26.45	-5.26
02-03-91	34.60	0.813	1.51	0.60	0.51	0.68	26.21	-5.09
04-03-91	34.50	0.819	1.52	0.59	0.51	0.69	26.84	-5.22
05-03-91	34.50	0.821	1.49	0.60	0.48	0.67	25.80	-5.45
06-03-91	33.80	0.823	1.48	0.58	0.47	0.66	26.51	-5.65
07-03-91	34.70	0.817	1.48	0.59	0.47	0.68	25.79	-5.88
08-03-91	34.30	0.818	1.48	0.58	0.48	0.68	26.12	-5.92
09-03-91	33.80	0.820	1.48	0.58	0.48	0.67	26.54	-5.68
11-03-91	33.40	0.824	1.49	0.58	0.48	0.67	27.16	-5.84
12-03-91	33.00	0.827	1.48	0.58	0.48	0.67	27.24	-5.67
13-03-91	33.50	0.824	1.48	0.57	0.48	0.69	27.13	-6.12
14-03-91	34.00	0.819	1.48	0.56	0.48	0.70	26.97	-6.56
16-03-91	33.20	0.826	1.48	0.57	0.48	0.66	27.35	-5.48
18-03-91	33.70	0.819	1.47	0.58	0.46	0.66	26.56	-5.79
19-03-91	34.50	0.816	1.47	0.56	0.47	0.70	26.49	-6.72
20-03-91	32.20	0.843	1.49	0.57	0.47	0.65	28.54	-5.59
22-03-91	32.50	0.845	1.48	0.55	0.46	0.67	28.55	-6.37

SPECIMEN #: 6B

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 11.1 mm (7/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE	I	Volt	ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
30-01-91	4.53	0.973	-0.15	-0.61	-1.17	-0.91	100.44	-56.73
31-01-91	7.99	0.958	-0.15	-0.60	-1.15	-0.95	56.20	-25.28
01-02-91	9.82	0.948	-0.14	-0.59	-1.16	-0.90	46.54	-26.99
02-02-91	9.98	0.946	-0.17	-0.61	-1.17	-0.92	44.19	-25.45
04-02-91	10.86	0.930	-0.16	-0.59	-1.16	-0.96	39.41	-18.60
05-02-91	10.88	0.935	-0.16	-0.55	-1.15	-1.01	36.67	-12.59
06-02-91	10.38	0.942	-0.16	-0.58	-1.16	-0.97	40.27	-17.92
07-02-91	10.17	0.938	-0.17	-0.56	-1.16	-1.01	39.13	-14.26
08-02-91	10.07	0.943	-0.16	-0.57	-1.15	-0.98	41.01	-17.38
09-02-91	10.09	0.950	-0.16	-0.57	-1.16	-0.98	41.03	-17.34
11-02-91	9.30	0.956	-0.15	-0.57	-1.15	-0.97	45.05	-18.71
12-02-91	8.74	0.959	-0.15	-0.56	-1.16	-0.97	47.37	-21.74
13-02-91	8.70	0.953	-0.15	-0.57	-1.16	-0.97	47.93	-21.38
14-02-91	8.68	0.951	-0.15	-0.56	-1.15	-0.98	46.89	-19.47
15-02-91	8.96	0.953	-0.15	-0.57	-1.14	-0.91	47.54	-25.00
16-02-91	8.76	0.955	-0.14	-0.57	-1.14	-0.97	48.97	-19.63
18-02-91	8.44	0.960	-0.14	-0.56	-1.14	-0.98	49.88	-19.08
19-02-91	8.17	0.963	-0.14	-0.55	-1.14	-0.96	50.67	-22.40
20-02-91	8.32	0.962	-0.14	-0.54	-1.14	-0.99	48.68	-18.03
21-02-91	8.49	0.959	-0.13	-0.53	-1.14	-1.02	46.76	-14.37
22-02-91	8.44	0.952	-0.14	-0.54	-1.14	-1.01	46.33	-15.76
23-02-91	8.27	0.955	-0.14	-0.54	-1.14	-1.00	48.49	-16.93
25-02-91	7.88	0.961	-0.14	-0.55	-1.13	-0.99	52.28	-18.02
26-02-91	7.72	0.962	-0.14	-0.55	-1.14	-0.99	52.85	-19.95
27-02-91	7.96	0.961	-0.14	-0.54	-1.14	-0.98	51.38	-19.60
28-02-91	8.07	0.961	-0.14	-0.55	-1.14	-0.93	51.43	-26.52
01-03-91	8.14	0.959	-0.13	-0.55	-1.14	-0.92	51.60	-26.90
02-03-91	8.21	0.957	-0.13	-0.56	-1.13	-0.90	51.77	-28.50
04-03-91	8.13	0.963	-0.12	-0.56	-1.13	-0.92	53.14	-26.32
05-03-91	8.09	0.964	-0.12	-0.56	-1.13	-0.90	53.28	-28.43
06-03-91	8.21	0.965	-0.12	-0.55	-1.13	-0.91	52.38	-27.04
08-03-91	8.30	0.961	-0.12	-0.54	-1.12	-0.91	50.72	-25.54
09-03-91	8.12	0.962	-0.12	-0.54	-1.12	-0.90	51.48	-26.48
11-03-91	8.03	0.963	-0.11	-0.53	-1.12	-0.90	52.30	-27.52
12-03-91	7.82	0.964	-0.11	-0.53	-1.12	-0.90	53.84	-28.39
13-03-91	7.97	0.963	-0.11	-0.53	-1.12	-0.89	52.45	-28.23
15-03-91	8.12	0.962	-0.11	-0.52	-1.12	-0.90	50.99	-26.72

SPECIMEN #: 6B

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 11.1 mm (7/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE (D-M-Y)	I (mA)	Volt (V)	CATHODE ON	CATHODE OFF	ANODE ON	ANODE OFF	CATHODE	ANODE
30-01-91	12.90	0.926	1.52	0.91	0.51	0.71	47.05	-15.19
31-01-91	13.94	0.916	1.50	0.87	0.50	0.67	45.05	-12.48
01-02-91	16.23	0.914	1.48	0.87	0.48	0.68	37.71	-12.69
02-02-91	16.80	0.909	1.46	0.78	0.47	0.68	40.54	-12.20
04-02-91	19.21	0.884	1.45	0.74	0.48	0.65	37.27	-9.16
05-02-91	18.09	0.896	1.47	0.76	0.49	0.65	39.25	-8.84
06-02-91	19.15	0.895	1.48	0.75	0.49	0.63	38.33	-7.62
07-02-91	19.28	0.888	1.46	0.76	0.48	0.59	36.62	-5.81
08-02-91	18.83	0.895	1.47	0.77	0.47	0.58	36.86	-5.95
09-02-91	18.92	0.902	1.45	0.76	0.46	0.56	36 79	-5.66
11-02-91	19.10	0.904	1.50	0.71	0.49	0.63	41.52	-6.96
12-02-91	17.88	0.910	1.47	0.72	0.47	0.59	42.11	-6.99
13-02-91	18.13	0.901	1.48	0.72	0.48	0.59	42.14	-5.85
14-02-91	18.53	0.895	1.50	0.66	0.50	0.66	45.33	-8.31
15-02-91	18.64	0.902	1.50	0.66	0.50	0.65	45.33	-7.89
16-02-91	18.39	0.905	1.52	0.67	0.50	0.64	46.06	-7.83
18-02-91	18.16	0.908	1.53	0.69	0.50	0.64	46.15	-7.60
19-02-91	18.25	0.907	1.53	0.68	0.52	0.63	46.47	-6.03
20-02-91	18.35	0.904	1.53	0.69	0.52	0.63	45.94	-5.99
21-02-91	18.43	0.901	1.53	0.69	0.53	0.63	45.58	-5.43
22-02-91	19.31	0.892	1.53	0.69	0.53	0.63	43.40	-5.23
23-02-91	18.47	0.899	1.53	0.68	0.53	0.64	46.02	-5.47
25-02-91	17.59	0.905	1.53	0.67	0.54	0.64	49.01	-5.86
26-02-91	17.93	0.905	1.54	0.67	0.54	0.63	48.35	-5.41
27-02-91	18.37	0.905	1.55	0.67	0.54	0.63	47.96	-5.06
28-02-91	18.34	0.905	1.54	0.62	0.54	0.67	49.84	-7.20
01-03-91	18.57	0.902	1.54	0.62	0.54	0.67	49.54	-7.22
02-03-91	18.89	0.898	1.54	0.62	0.54	0.67	48.76	-7.20
04-03-91	18.73	0.905	1.55	0.60	0.53	0.66	50.51	-7.31
05-03-91	18.68	0.907	1.54	0.61	0.53	0.67	49.79	-7.28
06-03-91	18.98	0.905	1.54	0.61	0.53	0.66	48.68	-6.74
08-03-91	18.72	0.904	1.52	0.59	0.51	0.67	49.36	-8.60
09-03-91	18.60	0.905	1.51	0.60	0.51	0.66	49.19	-8.44
11-03-91	18.48	0.906	1.51	0.59	0.51	0.66	50.05	-8.17
12-03-91	18.27	0.907	1.51	0.59	0.51	0.65	50.52	-7.94
13-03-91	18.55	0.905	1.51	0.58	0.51	0.66	50.13	-8.25
15-03-91	19.11	0.904	1.51	0.57	0.51	0.67	49.40	-8.32

SPECIMEN #: 6C

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 17.5 mm (11/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE			
			ON	OFF	ON	OFF	ANODE	CATHODE
30-01-91	0.63	0.995	0.38	-0.53	-0.71	-0.57	1441.27	-214.29
31-01-91	0.63	0.995	0.37	-0.53	-0.68	-0.57	1419.05	-184.13
01-02-91	0.89	0.995	0.35	-0.52	-0.62	-0.52	976.40	-115.73
02-02-91	1.08	0.994	0.21	-0.49	-0.75	-0.60	646.30	-145.37
04-02-91	2.30	0.986	-0.07	-0.52	-1.02	-0.78	197.83	-105.65
05-02-91	2.46	0.985	-0.10	-0.52	-1.07	-0.83	169.11	-97.97
06-02-91	2.98	0.985	-0.11	-0.53	-1.09	-0.86	137.92	-78.86
07-02-91	3.60	0.980	-0.12	-0.52	-1.10	-0.91	110.28	-53.33
08-02-91	3.95	0.978	-0.13	-0.54	-1.10	-0.88	103.80	-56.20
09-02-91	4.30	0.976	-0.13	-0.54	-1.10	-0.88	95.58	-52.09
11-02-91	4.46	0.975	-0.14	-0.54	-1.09	-0.87	89.91	-48.88
12-02-91	4.23	0.976	-0.14	-0.54	-1.11	-0.87	96.45	-56.97
13-02-91	4.60	0.975	-0.14	-0.54	-1.12	-0.87	87.61	-54.35
14-02-91	5.01	0.973	-0.14	-0.55	-1.11	-0.91	81.64	-39.72
15-02-91	5.30	0.971	-0.14	-0.57	-1.11	-0.84	80.57	-51.32
16-02-91	5.20	0.971	-0.14	-0.56	-1.11	-0.88	80.38	-45.00
18-02-91	5.11	0.972	-0.14	-0.55	-1.11	-0.93	80.63	-35.62
19-02-91	5.10	0.972	-0.14	-0.55	-1.12	-0.90	80.78	-43.73
20-02-91	5.24	0.971	-0.14	-0.54	-1.12	-0.94	76.91	-35.11
21-02-91	5.44	0.971	-0.14	-0.54	-1.11	-0.98	72.79	-23.53
22-02-91	5.59	0.970	-0.14	-0.54	-1.11	-0.97	72.09	-24.69
23-02-91	5.53	0.970	-0.14	-0.54	-1.11	-0.96	72.33	-26.58
25-02-91	5.45	0.971	-0.15	-0.55	-1.11	-0.95	73.21	-29.17
26-02-91	5.56	0.971	-0.14	-0.54	-1.12	-0.95	72.84	-30.58
27-02-91	5.84	0.968	-0.14	-0.55	-1.13	-0.94	69.52	-31.92
28-02-91	5.86	0.968	-0.14	-0.56	-1.12	-0.86	72.18	-43.86
01-03-91	5.95	0.967	-0.14	-0.56	-1.12	-0.85	70.76	-45.55
02-03-91	6.16	0.966	-0.14	-0.56	-1.12	-0.84	67.53	-45.78
04-03-91	6.09	0.965	-0.14	-0.57	-1.12	-0.88	69.79	-39.90
05-03-91	6.02	0.966	-0.14	-0.57	-1.13	-0.87	71.43	-44.02
06-03-91	6.09	0.965	-0.15	-0.57	-1.13	-0.87	69.13	-42.04
08-03-91	6.17	0.965	-0.15	-0.57	-1.14	-0.89	68.07	-39.87
09-03-91	6.09	0.965	-0.15	-0.57	-1.13	-0.89	68.97	-39.74
11-03-91	6.00	0.966	-0.15	-0.57	-1.13	-0.89	69.83	-40.00
12-03-91	5.93	0.966	-0.15	-0.56	-1.13	-0.89	69.81	-40.13
13-03-91	5.96	0.966	-0.15	-0.56	-1.13	-0.90	67.95	-39.43
15-03-91	6.00	0.966	-0.14	-0.55	-1.13	-0.90	66.50	-38.50

SPECIMEN #: 6C

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 17.5 mm (11/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

			Electrode Potentials (V)				Electrode	
DATE	I	Volt	CATHODE		ANODE		Resistance (Ohms)	
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
30-01-91	9.38	0.948	1.44	0.97	0.45	0.60	50.43	-15.14
31-01-91	8.68	0.952	1.46	1.06	0.46	0.61	46.08	-16.59
01-02-91	6.86	0.962	1.44	1.04	0.45	0.61	58.60	-24.64
02-02-91	6.49	0.964	1.45	1.04	0.46	0.58	63.17	-18.80
04-02-91	6.84	0.962	1.46	0.98	0.46	0.57	70.91	-16.37
05-02-91	6.99	0.962	1.49	0.95	0.48	0.51	76.97	-3.86
06-02-91	6.95	0.962	1.48	0.95	0.48	0.57	76.83	-12.95
07-02-91	7.49	0.958	1.48	0.94	0.47	0.55	72.10	-10.68
08-02-91	7.57	0.958	1.47	0.93	0.48	0.55	71.07	-9.78
09-02-91	7.77	0.957	1.47	0.91	0.47	0.55	72.07	-9.91
11-02-91	8.59	0.953	1.45	0.78	0.45	0.56	78.35	-11.87
12-02-91	8.30	0.955	1.44	0.89	0.45	0.55	66.75	-13.13
13-02-91	8.91	0.951	1.44	0.81	0.44	0.56	70.59	-12.68
14-02-91	9.33	0.950	1.45	0.70	0.45	0.59	80.39	-14.79
15-02-91	9.46	0.949	1.45	0.71	0.45	0.58	77.91	-13.95
16-02-91	9.47	0.949	1.46	0.72	0.45	0.58	78.35	-13.83
18-02-91	9.46	0.948	1.46	0.72	0.45	0.58	78.01	-13.85
19-02-91	9.84	0.946	1.47	0.72	0.47	0.58	76.52	-10.67
20-02-91	9.96	0.946	1.47	0.71	0.46	0.58	75.90	-11.35
21-02-91	10.05	0.945	1.46	0.71	0.47	0.57	74.73	-10.75
22-02-91	11.11	0.939	1.49	0.71	0.49	0.57	70.48	-7.65
23-02-91	10.72	0.941	1.49	0.70	0.48	0.58	73.88	-9.05
25-02-91	10.48	0.943	1.49	0.68	0.48	0.59	76.91	-10.88
26-02-91	11.12	0.941	1.48	0.68	0.48	0.59	72.39	-9.62
27-02-91	11.46	0.938	1.50	0.68	0.48	0.59	71.82	-9.77
28-02-91	11.63	0.938	1.49	0.64	0.49	0.65	73.00	-13.50
01-03-91	11.85	0.936	1.49	0.64	0.49	0.65	71.90	-13.67
02-03-91	12.24	0.934	1.49	0.63	0.49	0.65	70.02	-13.56
04-03-91	12.53	0.931	1.49	0.62	0.49	0.66	69.67	-13.09
05-03-91	12.44	0.932	1.49	0.61	0.49	0.65	70.42	-12.70
06-03-91	12.74	0.929	1.49	0.62	0.50	0.65	68.37	-12.01
08-03-91	13.11	0.928	1.49	0.61	0.50	0.66	66.97	-12.43
09-03-91	13.05	0.929	1.49	0.61	0.50	0.67	67.74	-12.72
11-03-91	12.99	0.929	1.50	0.61	0.51	0.67	68.67	-12.78
12-03-91	12.84	0.929	1.50	0.61	0.51	0.67	69.31	-12.31
13-03-91	12.28	0.927	1.50	0.60	0.51	0.67	73.29	-13.44
15-03-91	13.56	0.926	1.50	0.60	0.51	0.68	66.74	-12.54

SPECIMEN #: 6D

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 23.8 mm (15/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE	I	Volt	ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
30-01-91	0.46	0.997	0.41	-0.51	-0.63	-0.57	1991.30	-115.22
31-01-91	0.47	0.996	0.42	-0.51	-0.61	-0.57	1978.72	-74.47
01-02-91	0.42	0.996	0.42	-0.59	-0.58	-0.57	2419.05	-26.19
02-02-91	0.30	0.997	0.42	-0.43	-0.58	-0.57	2843.33	-60.00
04-02-91	0.27	0.997	0.42	-0.45	-0.59	-0.58	3211.11	-48.15
05-02-91	0.13	0.998	0.42	-0.45	-0.59	-0.58	6684.62	-100.00
06-02-91	0.20	0.998	0.42	-0.45	-0.59	-0.58	4330.00	-15.00
07-02-91	0.21	0.999	0.42	-0.43	-0.59	-0.58	4004.76	-57.14
08-02-91	0.20	0.998	0.42	-0.40	-0.59	-0.58	4090.00	-65.00
09-02-91	0.20	0.998	0.43	-0.41	-0.58	-0.58	4195.00	-25.00
11-02-91	0.15	0.998	0.42	-0.40	-0.58	-0.57	5473.33	-46.67
12-02-91	0.20	0.998	0.42	-0.40	-0.58	-0.57	4090.00	-50.00
13-02-91	0.26	0.998	0.41	-0.40	-0.59	-0.57	3134.62	-53.85
14-02-91	0.65	0.996	0.34	-0.42	-0.65	-0.60	1161.54	-73.85
15-02-91	0.82	0.995	0.22	-0.44	-0.73	-0.66	798.78	-86.59
16-02-91	0.88	0.994	0.18	-0.47	-0.79	-0.72	737.50	-78.41
18-02-91	0.96	0.993	0.07	-0.51	-0.85	-0.77	601.04	-87.50
19-02-91	0.85	0.995	0.05	-0.49	-0.95	-0.71	636.47	-274.12
20-02-91	0.99	0.993	0.04	-0.51	-0.94	-0.77	551.52	-164.65
21-02-91	1.24	0.993	0.00	-0.52	-0.93	-0.81	423.39	-93.55
22-02-91	1.24	0.994	-0.02	-0.52	-1.01	-0.80	405.65	-175.81
23-02-91	1.35	0.993	-0.02	-0.52	-1.01	-0.84	368.89	-125.19
25-02-91	1.51	0.992	-0.04	-0.53	-1.00	-0.87	324.50	-86.75
26-02-91	1.60	0.992	-0.04	-0.53	-1.05	-0.85	300.63	-119.37
27-02-91	1.80	0.991	-0.04	-0.53	-1.04	-0.84	267.78	-111.67
28-02-91	1.87	0.991	-0.05	-0.55	-1.05	-0.80	270.05	-131.02
01-03-91	1.96	0.990	-0.05	-0.56	-1.05	-0.78	260.71	-139.80
02-03-91	2.11	0.988	-0.05	-0.58	-1.05	-0.75	248.34	-144.55
04-03-91	2.27	0.987	-0.05	-0.56	-1.06	-0.81	221.15	-111.45
05-03-91	2.43	0.986	-0.06	-0.58	-1.06	-0.80	213.58	-107.82
06-03-91	2.66	0.985	-0.06	-0.57	-1.06	-0.82	192.11	-90.98
08-03-91	2.87	0.984	-0.07	-0.58	-1.07	-0.82	177.00	-87.11
09-03-91	2.93	0.984	-0.07	-0.57	-1.07	-0.82	170.99	-85.67
11-03-91	3.01	0.983	-0.07	-0.57	-1.07	-0.81	167.44	-86.38
12-03-91	3.08	0.983	-0.07	-0.57	-1.07	-0.81	161.69	-86.69
13-03-91	3.17	0.982	-0.07	-0.57	-1.07	-0.81	157.73	-82.65
15-03-91	3.45	0.980	-0.07	-0.57	-1.07	-0.81	143.77	-77.10

SPECIMEN #: 6D

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 23.8 mm (15/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE	I	Volt	CATHODE		ANODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
30-01-91	8.14	0.955	1.45	1.04	0.45	0.58	50.25	-15.85
31-01-91	6.77	0.963	1.44	1.08	0.44	0.57	51.99	-18.61
01-02-91	5.77	0.967	1.45	1.08	0.45	0.57	63.26	-20.10
02-02-91	5.12	0.972	1.38	1.08	0.40	0.57	57.81	-32.03
04-02-91	5.30	0.971	1.47	1.08	0.47	0.57	73.21	-18.68
05-02-91	5.12	0.972	1.47	1.08	0.47	0.57	76.95	-18.55
06-02-91	5.14	0.972	1.47	1.07	0.47	0.57	78.99	-18.48
07-02-91	4.71	0.974	1.48	1.05	0.48	0.57	91.08	-18.26
08-02-91	4.51	0.975	1.47	1.03	0.48	0.57	99.33	-19.07
09-02-91	4.29	0.976	1.48	1.06	0.48	0.56	98.14	-19.11
11-02-91	3.90	0.978	1.49	1.06	0.49	0.57	110.26	-21.03
12-02-91	3.56	0.981	1.48	1.05	0.48	0.57	118.26	-26.97
13-02-91	3.70	0.979	1.47	1.06	0.47	0.57	105.14	-26.76
14-02-91	3.65	0.979	1.45	0.99	0.45	0.53	132.60	-20.82
15-02-91	3.88	0.978	1.47	0.97	0.49	0.56	128.09	-18.56
16-02-91	3.81	0.978	1.47	0.97	0.48	0.55	132.28	-18.90
18-02-91	3.70	0.978	1.47	0.96	0.48	0.55	142.97	-18.11
19-02-91	3.43	0.979	1.49	0.96	0.48	0.55	154.23	-19.53
20-02-91	3.48	0.979	1.48	0.91	0.49	0.58	163.79	-26.15
21-02-91	3.51	0.980	1.48	0.87	0.49	0.59	174.93	-28.49
22-02-91	4.13	0.977	1.49	0.88	0.49	0.59	147.46	-24.70
23-02-91	4.08	0.977	1.48	0.86	0.48	0.59	151.23	-25.74
25-02-91	4.04	0.977	1.47	0.85	0.48	0.58	155.20	-26.73
26-02-91	4.04	0.978	1.47	0.86	0.48	0.58	153.22	-26.98
27-02-91	4.48	0.975	1.48	0.86	0.48	0.59	138.62	-24.33
28-02-91	4.21	0.976	1.48	0.81	0.47	0.59	158.67	-27.32
01-03-91	4.38	0.975	1.47	0.78	0.47	0.59	156.62	-27.63
02-03-91	4.55	0.975	1.46	0.77	0.47	0.59	153.63	-27.03
04-03-91	4.89	0.972	1.48	0.72	0.48	0.61	155.21	-25.56
05-03-91	4.83	0.972	1.48	0.73	0.48	0.60	156.11	-25.47
06-03-91	5.12	0.972	1.49	0.75	0.48	0.61	144.53	-24.02
08-03-91	5.65	0.970	1.50	0.71	0.49	0.63	138.23	-23.72
09-03-91	5.84	0.968	1.50	0.71	0.50	0.64	135.62	-23.46
11-03-91	6.02	0.967	1.50	0.70	0.51	0.64	133.55	-22.92
12-03-91	6.19	0.965	1.51	0.69	0.51	0.65	131.99	-22.62
13-03-91	6.44	0.964	1.51	0.69	0.51	0.67	128.73	-23.60
15-03-91	7.00	0.962	1.52	0.68	0.52	0.67	120.14	-21.71

SPECIMEN #: 6E

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 30.2 mm (1-3/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	ANODE OFF	CATHODE ON	CATHODE OFF	Electrode Resistance (Ohms) ANODE	CATHODE
30-01-91	0.60	0.995	0.42	-0.57	-0.61	-0.57	1633.33	-56.67
31-01-91	0.22	0.996	0.42	-0.37	-0.58	-0.58	3581.82	-22.73
01-02-91	0.05	0.998	0.43	-0.38	-0.57	-0.57	16120.00	20.00
02-02-91	0.30	0.998	0.41	-0.45	-0.60	-0.58	2856.67	-46.67
04-02-91	0.27	0.995	0.40	-0.46	-0.60	-0.59	3151.85	-51.85
05-02-91	0.27	0.995	0.41	-0.46	-0.60	-0.58	3196.30	-55.56
06-02-91	0.18	0.998	0.41	-0.46	-0.60	-0.59	4800.00	-44.44
07-02-91	0.26	0.996	0.40	-0.44	-0.60	-0.59	3219.23	-53.85
08-02-91	0.23	0.996	0.40	-0.42	-0.60	-0.59	3560.87	-65.22
09-02-91	0.23	0.998	0.41	-0.44	-0.59	-0.58	3695.65	-52.17
11-02-91	0.19	0.998	0.41	-0.44	-0.59	-0.58	4478.95	-57.89
12-02-91	0.12	0.999	0.42	-0.44	-0.57	-0.58	7125.00	75.00
13-02-91	0.11	0.998	0.42	-0.43	-0.58	-0.58	7763.64	36.36
14-02-91	0.16	0.998	0.42	-0.44	-0.60	-0.58	5362.50	-93.75
15-02-91	0.16	0.998	0.37	-0.43	-0.63	-0.62	5006.25	-50.00
16-02-91	0.16	0.998	0.39	-0.42	-0.61	-0.60	5056.25	-100.00
18-02-91	0.15	0.997	0.40	-0.42	-0.61	-0.59	5453.33	-80.00
19-02-91	0.10	0.998	0.40	-0.42	-0.60	-0.59	8220.00	-80.00
20-02-91	0.11	0.998	0.41	-0.40	-0.60	-0.59	7354.55	-72.73
21-02-91	0.12	0.998	0.40	-0.37	-0.60	-0.59	6450.00	-75.00
22-02-91	0.12	0.998	0.41	-0.37	-0.60	-0.59	6475.00	-58.33
23-02-91	0.11	0.998	0.40	-0.37	-0.60	-0.59	7036.36	-63.64
25-02-91	0.10	0.998	0.41	-0.37	-0.60	-0.59	7730.00	-50.00
26-02-91	0.08	0.999	0.41	-0.37	-0.60	-0.59	9637.50	-62.50
27-02-91	0.08	0.998	0.40	-0.36	-0.60	-0.59	9575.00	-87.50
28-02-91	0.08	0.999	0.40	-0.37	-0.60	-0.59	9625.00	-75.00
01-03-91	0.08	0.999	0.40	-0.35	-0.60	-0.59	9337.50	-75.00
02-03-91	0.08	0.999	0.40	-0.33	-0.60	-0.60	9100.00	-75.00
04-03-91	0.20	0.997	0.39	-0.33	-0.61	-0.60	3585.00	-90.00
05-03-91	0.19	0.996	0.39	-0.36	-0.61	-0.60	3968.42	-57.89
06-03-91	0.47	0.995	0.33	-0.40	-0.66	-0.61	1565.96	-121.28
08-03-91	0.63	0.995	0.21	-0.42	-0.76	-0.68	1004.76	-128.57
09-03-91	0.72	0.995	0.18	-0.45	-0.82	-0.72	868.06	-138.89
11-03-91	0.81	0.994	0.11	-0.47	-0.89	-0.78	720.99	-138.27
12-03-91	0.94	0.994	0.05	-0.49	-0.95	-0.81	573.40	-153.19
13-03-91	1.05	0.993	0.02	-0.50	-0.86	-0.82	497.14	-40.95
15-03-91	1.28	0.995	-0.01	-0.51	-1.01	-0.84	389.06	-134.38

SPECIMEN #: 6E

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 30.2 mm (1-3/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Emedded Cathode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE	I	Volt	CATHODE		ANODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
30-01-91	8.62	0.952	1.45	1.05	0.46	0.58	46.40	-14.15
31-01-91	6.94	0.961	1.44	1.06	0.45	0.57	54.76	-18.01
01-02-91	6.15	0.965	1.45	1.05	0.46	0.57	65.04	-18.54
02-02-91	5.75	0.968	1.45	1.07	0.45	0.58	66.09	-21.22
04-02-91	5.50	0.967	1.46	1.07	0.47	0.58	70.91	-18.91
05-02-91	5.27	0.969	1.47	1.07	0.48	0.57	75.90	-18.60
06-02-91	5.17	0.970	1.48	1.06	0.48	0.57	81.24	-19.15
07-02-91	4.86	0.972	1.48	1.05	0.48	0.58	88.48	-20.78
08-02-91	4.63	0.973	1.47	1.03	0.47	0.57	95.03	-21.81
09-02-91	4.42	0.975	1.47	1.04	0.47	0.57	97.29	-22.40
11-02-91	4.09	0.977	1.49	1.03	0.48	0.57	112.47	-23.47
12-02-91	3.76	0.979	1.47	1.03	0.47	0.57	117.02	-26.33
13-02-91	3.89	0.978	1.48	1.03	0.47	0.57	115.68	-25.71
14-02-91	3.87	0.978	1.53	1.08	0.52	0.61	116.28	-24.81
15-02-91	3.78	0.978	1.51	1.08	0.51	0.60	113.76	-24.34
16-02-91	3.63	0.978	1.49	1.03	0.50	0.58	126.72	-21.49
18-02-91	3.52	0.979	1.47	1.01	0.49	0.57	130.68	-22.16
19-02-91	3.66	0.980	1.48	1.02	0.49	0.57	125.68	-21.31
20-02-91	3.73	0.979	1.48	1.00	0.49	0.57	128.69	-21.98
21-02-91	3.86	0.978	1.48	0.99	0.49	0.58	127.20	-22.80
22-02-91	3.90	0.978	1.48	0.99	0.49	0.58	126.92	-22.31
23-02-91	3.88	0.978	1.48	0.97	0.49	0.57	132.73	-21.13
25-02-91	3.92	0.978	1.48	0.95	0.49	0.56	134.95	-20.15
26-02-91	3.58	0.981	1.48	0.95	0.49	0.56	148.88	-19.55
27-02-91	4.25	0.975	1.48	0.94	0.48	0.56	126.12	-18.12
28-02-91	3.82	0.979	1.48	0.97	0.49	0.58	132.72	-23.56
01-03-91	3.78	0.979	1.48	0.98	0.49	0.58	133.07	-23.81
02-03-91	3.72	0.979	1.49	0.98	0.50	0.59	136.02	-24.19
04-03-91	3.81	0.977	1.49	0.95	0.49	0.59	142.52	-24.67
05-03-91	3.46	0.979	1.49	0.97	0.49	0.57	151.16	-23.12
06-03-91	3.44	0.979	1.49	1.00	0.49	0.57	142.44	-22.67
08-03-91	3.51	0.979	1.46	0.95	0.48	0.57	146.15	-26.78
09-03-91	3.55	0.979	1.46	0.94	0.47	0.58	147.04	-28.45
11-03-91	3.61	0.978	1.47	0.91	0.48	0.58	154.57	-26.59
12-03-91	3.67	0.978	1.47	0.87	0.48	0.58	164.58	-28.07
13-03-91	3.78	0.978	1.47	0.84	0.48	0.59	167.46	-28.31
15-03-91	3.72	0.978	1.48	0.82	0.47	0.59	176.34	-31.45

SPECIMEN #: 6F

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 36.5 mm (1-7/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
30-01-91	0.77	0.994	0.40	-0.63	-0.67	-0.57	1342.86	-136.36
31-01-91	0.62	0.995	0.39	-0.55	-0.63	-0.58	1527.42	-87.10
01-02-91	0.33	0.996	0.39	-0.52	-0.60	-0.58	2760.61	-66.67
02-02-91	0.36	0.998	0.41	-0.53	-0.60	-0.58	2588.89	-75.00
04-02-91	0.32	0.995	0.40	-0.51	-0.60	-0.58	2828.13	-62.50
05-02-91	0.28	0.996	0.40	-0.50	-0.61	-0.59	3207.14	-67.86
06-02-91	0.32	0.996	0.40	-0.50	-0.61	-0.59	2831.25	-56.25
07-02-91	0.42	0.997	0.40	-0.50	-0.61	-0.59	2133.33	-42.86
08-02-91	0.41	0.995	0.41	-0.67	-0.61	-0.58	2631.71	-53.66
09-02-91	0.25	0.997	0.41	-0.44	-0.60	-0.58	3400.00	-52.00
11-02-91	0.06	0.999	0.41	-0.42	-0.60	-0.59	13916.67	-166.67
12-02-91	0.04	0.999	0.42	-0.42	-0.59	-0.58	20850.00	-175.00
13-02-91	0.13	0.998	0.41	-0.42	-0.58	-0.58	6376.92	23.08
14-02-91	0.05	0.998	0.41	-0.42	-0.59	-0.59	16560.00	-40.00
15-02-91	0.13	0.998	0.41	-0.41	-0.59	-0.59	6284.62	-53.85
16-02-91	0.09	0.998	0.41	-0.40	-0.59	-0.59	9011.11	-44.44
18-02-91	0.10	0.998	0.41	-0.40	-0.59	-0.59	8060.00	-60.00
19-02-91	0.08	0.998	0.41	-0.40	-0.58	-0.59	10137.50	25.00
20-02-91	0.11	0.998	0.40	-0.39	-0.59	-0.58	7136.36	-27.27
21-02-91	0.11	0.998	0.38	-0.37	-0.59	-0.58	6781.82	-90.91
22-02-91	0.10	0.998	0.41	-0.36	-0.58	-0.58	7780.00	-40.00
23-02-91	0.10	0.998	0.41	-0.34	-0.59	-0.58	7530.00	-60.00
25-02-91	0.09	0.998	0.41	-0.32	-0.59	-0.58	8133.33	-77.78
26-02-91	0.09	0.999	0.41	-0.32	-0.59	-0.58	8144.44	-66.67
27-02-91	0.11	0.998	0.41	-0.32	-0.59	-0.58	6627.27	-36.36
28-02-91	0.10	0.999	0.41	-0.33	-0.59	-0.59	7360.00	-70.00
01-03-91	0.08	0.999	0.41	-0.31	-0.59	-0.58	8987.50	-125.00
02-03-91	0.04	0.999	0.40	-0.29	-0.60	-0.59	17225.00	-250.00
04-03-91	0.06	0.997	0.40	-0.28	-0.60	-0.59	11400.00	-66.67
05-03-91	0.07	0.998	0.41	-0.35	-0.59	-0.59	10871.43	-85.71
06-03-91	0.05	0.998	0.40	-0.30	-0.60	-0.59	13940.00	-220.00
08-03-91	0.06	0.998	0.41	-0.30	-0.59	-0.59	11700.00	-66.67
09-03-91	0.05	0.998	0.41	-0.29	-0.59	-0.59	13900.00	-80.00
11-03-91	0.06	0.998	0.40	-0.28	-0.59	-0.59	11466.67	0.00
12-03-91	0.06	0.998	0.41	-0.27	-0.59	-0.59	11300.00	0.00
13-03-91	0.06	0.998	0.40	-0.28	-0.59	-0.59	11333.33	-66.67
15-03-91	0.05	0.999	0.41	-0.29	-0.59	-0.59	13980.00	-100.00

SPECIMEN #: 6F

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 36.5 mm (1-7/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			CATHODE		ANODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
30-01-91	7.08	0.959	1.46	1.06	0.46	0.58	56.50	-16.95
31-01-91	5.90	0.966	1.44	1.08	0.45	0.57	61.02	-20.17
01-02-91	5.42	0.968	1.46	1.02	0.46	0.57	81.18	-21.59
02-02-91	4.84	0.973	1.45	1.02	0.46	0.58	88.84	-23.35
04-02-91	4.70	0.972	1.47	1.01	0.48	0.58	97.87	-21.28
05-02-91	4.46	0.973	1.47	1.02	0.48	0.58	100.90	-22.42
06-02-91	4.40	0.973	1.47	1.02	0.48	0.58	102.27	-21.59
07-02-91	4.23	0.975	1.48	1.03	0.49	0.58	106.38	-21.28
08-02-91	4.11	0.975	1.48	1.04	0.49	0.58	107.06	-21.65
09-02-91	3.99	0.977	1.48	1.05	0.49	0.57	107.77	-21.55
11-02-91	3.82	0.978	1.49	1.06	0.50	0.58	112.57	-21.47
12-02-91	3.45	0.981	1.48	1.05	0.48	0.58	124.64	-27.54
13-02-91	3.51	0.981	1.48	1.06	0.48	0.58	119.66	-26.78
14-02-91	3.51	0.980	1.48	1.05	0.49	0.57	122.51	-23.93
15-02-91	3.43	0.980	1.49	1.06	0.49	0.57	125.36	-24.20
16-02-91	3.39	0.980	1.49	1.06	0.49	0.58	126.84	-24.48
18-02-91	3.19	0.981	1.49	1.07	0.49	0.58	131.66	-25.39
19-02-91	3.07	0.982	1.47	1.06	0.47	0.57	133.55	-33.55
20-02-91	3.08	0.982	1.47	1.06	0.47	0.57	133.12	-30.52
21-02-91	3.05	0.983	1.48	1.06	0.48	0.56	137.70	-26.56
22-02-91	3.12	0.982	1.46	1.06	0.46	0.57	128.21	-32.69
23-02-91	3.03	0.983	1.46	1.05	0.47	0.56	135.31	-30.03
25-02-91	2.85	0.984	1.46	1.04	0.48	0.55	147.37	-27.02
26-02-91	2.81	0.985	1.47	1.05	0.47	0.56	149.47	-31.32
27-02-91	3.32	0.982	1.45	1.05	0.46	0.55	120.48	-29.82
28-02-91	2.90	0.984	1.47	1.00	0.47	0.57	162.07	-36.21
01-03-91	3.14	0.983	1.46	0.99	0.46	0.57	150.00	-37.58
02-03-91	3.25	0.982	1.45	0.97	0.45	0.58	146.46	-39.08
04-03-91	2.86	0.983	1.47	1.02	0.47	0.57	157.34	-35.31
05-03-91	2.98	0.982	1.44	0.97	0.45	0.57	159.06	-40.94
06-03-91	2.82	0.983	1.46	1.01	0.47	0.57	159.57	-36.52
08-03-91	2.90	0.983	1.45	1.00	0.46	0.57	155.17	-38.97
09-03-91	2.93	0.982	1.44	1.01	0.46	0.56	146.76	-31.77
11-03-91	2.85	0.983	1.44	1.01	0.47	0.57	150.88	-35.44
12-03-91	2.73	0.984	1.45	1.02	0.47	0.57	157.51	-37.73
13-03-91	2.81	0.983	1.46	1.00	0.47	0.57	163.70	-38.43
15-03-91	2.62	0.985	1.46	1.00	0.47	0.57	176.34	-40.84

SPECIMEN #: 6G

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 42.9 mm (1-11/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE	I	Volt	ANODE		CATHODE		ANODE	CATHODE
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF		
30-01-91	0.04	0.998	-0.01	-0.47	-0.91	-0.95	11475.00	1050.00
31-01-91	0.05	0.998	-0.04	-0.42	-0.89	-0.92	7600.00	640.00
01-02-91	0.02	0.998	-0.03	-0.41	-0.85	-0.94	19000.00	4350.00
02-02-91	0.04	0.999	-0.03	-0.41	-0.88	-0.91	9500.00	775.00
04-02-91	0.29	0.995	-0.04	-0.41	-0.90	-0.92	1272.41	79.31
05-02-91	0.04	0.997	-0.06	-0.71	-0.88	-0.90	16300.00	450.00
06-02-91	0.04	0.998	-0.05	-0.53	-0.88	-0.89	11875.00	325.00
07-02-91	0.02	0.998	-0.05	-0.57	-0.90	-0.96	25950.00	2750.00
08-02-91	0.10	0.997	-0.06	-0.60	-0.84	-0.85	5450.00	30.00
09-02-91	0.02	0.999	-0.04	-0.59	-0.90	-0.94	27600.00	2200.00
11-02-91	0.06	0.999	-0.05	-0.44	-0.87	-0.90	6433.33	483.33
12-02-91	0.03	0.999	-0.04	-0.43	-0.91	-0.90	12966.67	-400.00
13-02-91	0.12	0.998	-0.05	-0.43	-0.92	-0.90	3191.67	-150.00
14-02-91	0.12	0.998	-0.05	-0.50	-0.88	-0.90	3800.00	158.33
15-02-91	0.12	0.998	-0.04	-0.52	-0.87	-0.88	4000.00	75.00
16-02-91	0.09	0.998	-0.04	-0.52	-0.85	-0.86	5277.78	111.11
18-02-91	0.01	0.998	-0.04	-0.52	-0.82	-0.84	47700.00	1900.00
19-02-91	0.10	0.998	-0.03	-0.52	-0.88	-0.83	4860.00	-490.00
20-02-91	0.11	0.998	-0.04	-0.52	-0.86	-0.83	4363.64	-209.09
21-02-91	0.12	0.998	-0.05	-0.57	-0.85	-0.86	4283.33	83.33
22-02-91	0.10	0.998	-0.04	-0.56	-0.85	-0.85	5140.00	20.00
23-02-91	0.10	0.998	-0.05	-0.56	-0.85	-0.87	5150.00	230.00
25-02-91	0.10	0.998	-0.04	-0.56	-0.86	-0.91	5150.00	550.00
26-02-91	0.10	0.999	-0.04	-0.56	-0.88	-0.89	5118.00	90.00
27-02-91	0.06	0.998	-0.04	-0.55	-0.89	-0.89	8533.33	-83.33
28-02-91	0.04	0.999	-0.04	-0.51	-0.91	-0.89	11900.00	-550.00
01-03-91	0.08	0.998	-0.04	-0.55	-0.90	-0.87	6337.50	-400.00
02-03-91	0.10	0.998	-0.05	-0.54	-0.90	-0.86	4940.00	-400.00
04-03-91	0.06	0.997	-0.05	-0.47	-0.90	-0.87	7050.00	-416.67
05-03-91	0.05	0.998	-0.04	-0.51	-0.90	-0.85	9520.00	-880.00
06-03-91	0.07	0.998	-0.04	-0.53	-0.90	-0.86	6900.00	-657.14
08-03-91	0.07	0.997	-0.04	-0.52	-0.90	-0.87	6828.57	-414.29
09-03-91	0.07	0.998	-0.04	-0.53	-0.90	-0.87	6928.57	-514.29
11-03-91	0.08	0.998	-0.04	-0.53	-0.90	-0.87	6075.00	-337.50
12-03-91	0.08	0.998	-0.04	-0.52	-0.90	-0.87	6000.00	-375.00
13-03-91	0.08	0.998	-0.05	-0.53	-0.91	-0.87	6050.00	-550.00
15-03-91	0.06	0.999	-0.05	-0.52	-0.89	-0.89	7866.67	-100.00

SPECIMEN #: 6G

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 42.9 mm (1-11/16 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	OFF	ANODE ON	OFF	Electrode Resistance (Ohms) CATHODE	ANODE
30-01-91	7.05	0.959	1.79	1.29	0.73	0.86	70.50	-18.58
31-01-91	6.41	0.963	1.79	1.32	0.73	0.85	73.48	-18.88
01-02-91	5.57	0.967	1.78	1.32	0.71	0.81	83.66	-17.41
02-02-91	4.79	0.973	1.75	1.31	0.71	0.83	92.28	-23.80
04-02-91	4.52	0.972	1.77	1.33	0.74	0.84	98.23	-23.89
05-02-91	4.38	0.974	1.77	1.30	0.73	0.84	107.31	-23.29
06-02-91	4.29	0.974	1.79	1.33	0.75	0.85	106.99	-24.48
07-02-91	4.12	0.975	1.81	1.34	0.77	0.87	114.81	-25.00
08-02-91	3.95	0.976	1.79	1.28	0.71	0.81	129.11	-24.81
09-02-91	3.92	0.977	1.79	1.33	0.76	0.84	117.09	-21.94
11-02-91	3.67	0.979	1.77	1.30	0.75	0.83	128.07	-22.89
12-02-91	3.37	0.981	1.76	1.29	0.76	0.84	138.28	-21.96
13-02-91	3.41	0.981	1.76	1.30	0.79	0.84	136.95	-14.37
14-02-91	3.31	0.981	1.74	1.28	0.74	0.82	138.07	-26.28
15-02-91	3.30	0.981	1.73	1.30	0.74	0.81	130.91	-23.33
16-02-91	3.19	0.981	1.74	1.29	0.73	0.81	139.81	-24.14
18-02-91	3.07	0.982	1.76	1.29	0.72	0.80	153.09	-25.08
19-02-91	2.89	0.983	1.74	1.28	0.76	0.80	160.90	-12.11
20-02-91	2.92	0.983	1.75	1.29	0.75	0.80	157.53	-17.12
21-02-91	2.98	0.982	1.75	1.31	0.74	0.81	150.00	-24.16
22-02-91	3.10	0.982	1.71	1.30	0.73	0.80	132.58	-24.19
23-02-91	2.99	0.983	1.71	1.28	0.73	0.80	141.81	-24.08
25-02-91	2.82	0.984	1.71	1.28	0.73	0.80	154.26	-24.82
26-02-91	2.80	0.985	1.72	1.28	0.75	0.80	157.14	-18.57
27-02-91	2.49	0.980	1.71	1.28	0.74	0.80	173.09	-24.10
28-02-91	2.93	0.984	1.69	1.25	0.71	0.85	148.81	-47.10
01-03-91	2.94	0.984	1.68	1.26	0.71	0.85	145.24	-47.62
02-03-91	2.90	0.984	1.68	1.26	0.71	0.85	143.79	-47.59
04-03-91	2.81	0.983	1.69	1.23	0.71	0.83	165.48	-40.93
05-03-91	2.91	0.982	1.67	1.19	0.70	0.84	163.92	-47.42
06-03-91	2.86	0.983	1.66	1.22	0.72	0.83	155.24	-39.86
08-03-91	2.92	0.983	1.68	1.24	0.72	0.83	152.05	-36.64
09-03-91	2.94	0.982	1.68	1.23	0.72	0.82	154.08	-34.69
11-03-91	2.86	0.983	1.69	1.23	0.72	0.82	160.49	-35.66
12-03-91	2.75	0.984	1.69	1.22	0.72	0.82	170.91	-37.09
13-03-91	2.81	0.983	1.69	1.20	0.72	0.82	172.24	-38.08
15-03-91	2.72	0.985	1.70	1.17	0.72	0.82	194.49	-37.87

SPECIMEN #: 6H

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 50.8 mm (2 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
30-01-91	0.97	0.994	0.16	-0.60	-0.86	-0.63	782.47	-243.30
31-01-91	0.88	0.994	0.24	-0.62	-0.82	-0.68	982.95	-157.95
01-02-91	0.89	0.993	0.43	-0.63	-0.64	-0.46	1191.01	-200.00
02-02-91	0.74	0.994	0.32	-0.62	-0.69	-0.59	1259.46	-136.49
04-02-91	0.70	0.997	0.41	-0.61	-0.65	-0.52	1455.71	-182.86
05-02-91	0.65	0.998	0.42	-0.78	-0.68	-0.52	1841.54	-246.15
06-02-91	0.61	0.998	0.42	-0.59	-0.63	-0.53	1655.74	-172.13
07-02-91	0.74	0.997	0.44	-0.56	-0.62	-0.51	1350.00	-152.70
08-02-91	0.51	0.999	0.43	-0.57	-0.60	-0.52	1956.86	-166.67
09-02-91	0.44	0.999	0.43	-0.50	-0.60	-0.53	2097.73	-159.09
11-02-91	0.35	0.999	0.44	-0.43	-0.58	-0.53	2480.00	-137.14
12-02-91	0.24	0.999	0.43	-0.45	-0.57	-0.53	3662.50	-154.17
13-02-91	0.24	0.999	0.44	-0.44	-0.56	-0.53	3691.67	-120.83
14-02-91	0.35	0.998	0.44	-0.45	-0.57	-0.52	2560.00	-142.86
15-02-91	0.37	0.998	0.45	-0.45	-0.57	-0.52	2418.92	-129.73
16-02-91	0.29	0.998	0.45	-0.44	-0.57	-0.53	3051.72	-124.14
18-02-91	0.24	0.999	0.45	-0.43	-0.57	-0.53	3650.00	-141.67
19-02-91	0.18	0.999	0.45	-0.42	-0.56	-0.52	4822.22	-172.22
20-02-91	0.21	0.999	0.45	-0.43	-0.56	-0.53	4166.67	-161.90
21-02-91	0.24	0.999	0.45	-0.44	-0.57	-0.54	3691.67	-116.67
22-02-91	0.20	0.999	0.45	-0.44	-0.55	-0.54	4435.00	-85.00
23-02-91	0.18	0.999	0.45	-0.44	-0.56	-0.54	4916.67	-111.11
25-02-91	0.20	0.999	0.45	-0.44	-0.57	-0.54	4410.00	-130.00
26-02-91	0.15	0.999	0.45	-0.44	-0.55	-0.54	5920.00	-73.33
27-02-91	0.16	0.999	0.45	-0.43	-0.55	-0.54	5525.00	-87.50
28-02-91	0.15	0.999	0.45	-0.42	-0.56	-0.54	5800.00	-113.33
01-03-91	0.15	0.999	0.45	-0.45	-0.56	-0.54	5986.67	-100.00
02-03-91	0.16	0.999	0.44	-0.49	-0.56	-0.55	5856.25	-87.50
04-03-91	0.16	0.998	0.44	-0.43	-0.56	-0.55	5450.00	-106.25
05-03-91	0.16	0.998	0.44	-0.43	-0.56	-0.54	5437.50	-112.50
06-03-91	0.16	0.998	0.44	-0.41	-0.56	-0.54	5325.00	-93.75
08-03-91	0.16	0.998	0.44	-0.39	-0.56	-0.54	5206.25	-100.00
09-03-91	0.15	0.998	0.44	-0.39	-0.56	-0.55	5506.67	-73.33
11-03-91	0.15	0.998	0.44	-0.38	-0.56	-0.55	5460.00	-86.67
12-03-91	0.12	0.999	0.43	-0.38	-0.57	-0.55	6775.00	-108.33
13-03-91	0.14	0.999	0.43	-0.38	-0.57	-0.56	5807.14	-78.57
15-03-91	0.14	0.999	0.44	-0.37	-0.56	-0.55	5821.43	-64.29

SPECIMEN #: 6H

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 50.8 mm (2 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			CATHODE		ANODE			
			ON	OFF	ON	OFF	CATHODE	ANODE
30-01-91	6.37	0.964	1.49	1.12	0.50	0.61	58.08	-18.68
31-01-91	6.35	0.964	1.48	1.12	0.49	0.59	56.69	-16.69
01-02-91	4.44	0.975	1.40	1.01	0.45	0.52	87.84	-15.77
02-02-91	4.27	0.975	1.44	1.08	0.45	0.55	84.31	-24.59
04-02-91	3.82	0.980	1.37	0.97	0.40	0.52	104.97	-31.68
05-02-91	4.01	0.979	1.45	1.08	0.45	0.56	92.27	-27.18
06-02-91	3.68	0.982	1.44	1.08	0.46	0.55	97.83	-26.63
07-02-91	3.96	0.979	1.39	0.98	0.41	0.50	104.29	-23.48
08-02-91	3.32	0.984	1.40	1.03	0.42	0.51	111.45	-25.00
09-02-91	3.17	0.984	1.40	1.02	0.43	0.52	119.87	-27.76
11-02-91	3.12	0.985	1.35	1.02	0.43	0.50	105.77	-22.76
12-02-91	2.45	0.987	1.40	1.01	0.40	0.50	159.18	-40.41
13-02-91	2.56	0.986	1.40	1.02	0.40	0.50	148.44	-38.28
14-02-91	2.72	0.985	1.42	1.07	0.43	0.53	128.68	-37.50
15-02-91	2.68	0.985	1.42	1.07	0.43	0.51	130.60	-28.73
16-02-91	2.72	0.985	1.41	1.06	0.42	0.52	128.68	-36.76
18-02-91	2.79	0.985	1.42	1.06	0.41	0.52	129.03	-37.28
19-02-91	2.09	0.989	1.39	1.05	0.38	0.51	162.68	-61.24
20-02-91	2.18	0.989	1.37	1.05	0.38	0.48	146.79	-45.87
21-02-91	2.31	0.988	1.36	1.05	0.37	0.44	134.20	-29.87
22-02-91	2.47	0.988	1.36	1.05	0.37	0.45	125.51	-34.01
23-02-91	2.29	0.988	1.36	1.05	0.36	0.45	135.37	-37.99
25-02-91	2.18	0.989	1.36	1.04	0.36	0.45	146.79	41.74
26-02-91	2.20	0.991	1.36	1.05	0.37	0.45	140.91	-37.27
27-02-91	2.10	0.991	1.39	1.04	0.39	0.45	166.67	-29.05
28-02-91	2.12	0.991	1.36	1.04	0.36	0.45	150.94	-40.57
01-03-91	2.17	0.989	1.38	1.01	0.38	0.48	170.51	-45.16
02-03-91	2.22	0.987	1.40	1.00	0.40	0.53	181.53	-56.76
04-03-91	2.41	0.985	1.38	0.98	0.38	0.53	164.73	-61.41
05-03-91	2.19	0.987	1.41	0.98	0.41	0.53	195.89	-54.34
06-03-91	2.25	0.986	1.40	0.99	0.40	0.52	183.56	-52.89
08-03-91	2.40	0.986	1.40	0.96	0.40	0.52	185.42	-51.67
09-03-91	2.44	0.986	1.40	0.94	0.39	0.53	187.30	-53.69
11-03-91	2.49	0.985	1.40	0.94	0.40	0.53	186.35	-53.82
12-03-91	2.56	0.985	1.40	0.93	0.40	0.53	184.37	-50.00
13-03-91	2.48	0.986	1.41	0.92	0.41	0.53	196.77	-51.21
15-03-91	2.26	0.987	1.42	0.92	0.42	0.54	221.68	-51.33

SPECIMEN #: 6I

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 63.5 mm (2-1/2 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	ANODE OFF	CATHODE ON	CATHODE OFF	Electrode Resistance (Ohms) ANODE	CATHODE
30-01-91	0.68	0.995	0.41	-0.63	-0.64	-0.49	1530.88	-225.00
31-01-91	0.56	0.995	0.42	-0.60	-0.64	-0.51	1828.57	-239.29
01-02-91	0.57	0.995	0.43	-0.55	-0.63	-0.53	1710.53	-175.44
02-02-91	0.53	0.996	0.44	-0.54	-0.56	-0.56	1835.85	-1.89
04-02-91	0.52	0.996	0.44	-0.57	-0.56	-0.56	1955.77	-1.92
05-02-91	0.51	0.996	0.44	-0.51	-0.56	-0.56	1864.71	-9.80
06-02-91	0.52	0.996	0.45	-0.50	-0.56	-0.56	1813.46	0.00
07-02-91	0.45	0.997	0.39	-0.47	-0.59	-0.54	1920.00	-108.89
08-02-91	0.22	0.999	0.41	-0.44	-0.56	-0.50	3854.55	-245.45
09-02-91	0.10	0.999	0.43	-0.38	-0.56	-0.55	8150.00	-170.00
11-02-91	0.35	0.999	0.42	-0.45	-0.59	-0.55	2488.57	-111.43
12-02-91	0.24	0.999	0.43	-0.43	-0.57	-0.55	3579.17	-100.00
13-02-91	0.30	0.998	0.42	-0.44	-0.58	-0.55	2843.33	-113.33
14-02-91	0.32	0.998	0.44	-0.48	-0.57	-0.52	2868.75	-150.00
15-02-91	0.33	0.998	0.45	-0.48	-0.57	-0.52	2790.91	-154.55
16-02-91	0.26	0.998	0.45	-0.45	-0.57	-0.53	3469.23	-161.54
18-02-91	0.20	0.999	0.45	-0.43	-0.56	-0.53	4425.00	-160.00
19-02-91	0.15	0.999	0.45	-0.43	-0.55	-0.52	5860.00	-193.33
20-02-91	0.16	0.999	0.45	-0.43	-0.56	-0.53	5462.50	-175.00
21-02-91	0.18	0.999	0.45	-0.42	-0.56	-0.54	4833.33	-133.33
22-02-91	0.15	0.999	0.45	-0.43	-0.55	-0.53	5840.00	-106.67
23-02-91	0.14	0.999	0.45	-0.42	-0.56	-0.54	6207.14	-121.43
25-02-91	0.15	0.999	0.45	-0.42	-0.57	-0.55	5746.67	-146.67
26-02-91	0.12	0.999	0.45	-0.42	-0.55	-0.55	7233.33	-25.00
27-02-91	0.12	0.999	0.45	-0.42	-0.55	-0.55	7233.33	0.00
28-02-91	0.11	0.999	0.45	-0.39	-0.55	-0.54	7681.82	-100.00
01-03-91	0.11	0.999	0.45	-0.42	-0.55	-0.54	7945.45	-90.91
02-03-91	0.11	0.999	0.45	-0.45	-0.55	-0.54	8172.73	-81.82
04-03-91	0.10	0.998	0.43	-0.41	-0.57	-0.54	8300.00	-330.00
05-03-91	0.09	0.998	0.41	-0.40	-0.59	-0.59	8966.67	11.11
06-03-91	0.09	0.998	0.41	-0.37	-0.59	-0.59	8677.78	0.00
08-03-91	0.09	0.998	0.42	-0.35	-0.58	-0.58	8511.11	0.00
09-03-91	0.08	0.999	0.42	-0.35	-0.58	-0.58	9650.00	-12.50
11-03-91	0.08	0.999	0.42	-0.35	-0.58	-0.58	9587.50	0.00
12-03-91	0.07	0.999	0.42	-0.34	-0.58	-0.58	10971.43	14.29
13-03-91	0.07	0.999	0.42	-0.35	-0.58	-0.58	10914.29	-14.29
15-03-91	0.07	0.999	0.42	-0.29	-0.58	-0.59	10028.57	14.29

SPECIMEN #: 6I

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hours curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: 63.5 mm (2-1/2 in.)

Starting Date: January 29, 1991
Ending Date: March 15, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	CATHODE OFF	ANODE ON	ANODE OFF	Electrode Resistance (Ohms) CATHODE	ANODE
30-01-91	7.76	0.956	1.44	1.08	0.44	0.58	45.75	-16.88
31-01-91	5.22	0.969	1.42	1.08	0.43	0.53	65.52	-19.16
01-02-91	4.06	0.976	1.31	0.95	0.37	0.47	87.93	-25.62
02-02-91	4.04	0.976	1.41	1.01	0.42	0.55	99.26	-30.69
04-02-91	3.59	0.981	1.35	0.92	0.37	0.51	120.06	-41.23
05-02-91	3.62	0.982	1.40	1.03	0.41	0.54	103.59	-35.08
06-02-91	3.36	0.983	1.40	1.01	0.42	0.53	116.67	-35.12
07-02-91	3.87	0.981	1.34	0.93	0.36	0.47	105.17	-30.75
08-02-91	3.18	0.984	1.38	0.97	0.40	0.49	128.62	-27.67
09-02-91	2.95	0.985	1.38	0.96	0.40	0.51	140.00	-36.95
11-02-91	2.88	0.985	1.33	0.96	0.40	0.48	127.43	-28.12
12-02-91	2.29	0.988	1.38	0.96	0.38	0.48	183.84	-46.29
13-02-91	2.28	0.987	1.38	0.96	0.38	0.48	185.09	-44.30
14-02-91	2.60	0.986	1.40	1.06	0.41	0.52	130.77	-42.69
15-02-91	2.55	0.986	1.39	1.05	0.41	0.49	134.12	-31.76
16-02-91	2.66	0.986	1.40	1.04	0.41	0.49	136.09	-31.95
18-02-91	2.77	0.985	1.40	1.02	0.41	0.50	136.10	-31.77
19-02-91	2.08	0.989	1.38	1.02	0.38	0.49	174.52	-50.96
20-02-91	2.17	0.989	1.36	1.01	0.37	0.46	162.21	-41.01
21-02-91	2.17	0.989	1.34	1.01	0.36	0.44	155.30	-35.94
22-02-91	2.39	0.988	1.35	1.00	0.35	0.45	144.77	-41.00
23-02-91	2.24	0.988	1.34	1.00	0.35	0.45	153.13	-45.09
25-02-91	2.07	0.989	1.34	1.00	0.34	0.44	165.22	-50.24
26-02-91	2.06	0.992	1.34	0.99	0.34	0.45	166.99	-51.94
27-02-91	1.94	0.992	1.37	0.99	0.37	0.44	196.39	-38.66
28-02-91	1.96	0.992	1.37	1.05	0.37	0.50	167.35	-66.33
01-03-91	2.08	0.990	1.39	1.05	0.38	0.51	162.02	-62.98
02-03-91	2.20	0.988	1.40	1.05	0.40	0.53	159.09	-57.73
04-03-91	2.80	0.984	1.47	1.01	0.35	0.57	165.00	-78.96
05-03-91	2.95	0.983	1.49	1.04	0.50	0.57	155.59	-26.78
06-03-91	2.90	0.983	1.49	1.04	0.49	0.57	154.14	-28.28
08-03-91	2.84	0.984	1.49	1.03	0.49	0.57	161.97	-31.34
09-03-91	2.80	0.984	1.48	1.02	0.49	0.57	167.14	-30.36
11-03-91	2.79	0.984	1.49	1.01	0.49	0.57	170.25	-29.03
12-03-91	2.77	0.984	1.49	1.00	0.49	0.57	175.81	-29.60
13-03-91	2.86	0.984	1.47	0.99	0.48	0.57	169.93	-32.17
15-03-91	2.82	0.984	1.50	0.95	0.50	0.58	193.97	-27.30

APPENDIX R

Test Series #7

Potential and Current Measurements

This appendix includes the voltage and current measurements recorded daily for each specimen of Test Series #7, for both polarity modes. The electrode "polarization" resistance of each specimen is also included.

SPECIMEN #: 7A

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4"
Water-Cement Ratio: ---
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15

Starting Date: March 25, 1991
Ending Date: April 18, 1991
Immersion Period: 24 days

NORMAL POLARITY

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
26-03-91	72.70	0.623	-0.34	-0.62	-1.34	-0.94	3.85	-5.49
27-03-91	72.10	0.624	-0.34	-0.59	-1.34	-1.00	3.47	-4.72
28-03-91	71.30	0.625	-0.35	-0.58	-1.34	-1.02	3.23	-4.49
29-03-91	54.70	0.715	-0.32	-0.56	-1.33	-1.01	4.28	-5.85
30-03-91	47.80	0.755	-0.31	-0.54	-1.31	-0.99	4.92	-6.74
01-04-91	45.60	0.770	-0.29	-0.53	-1.30	-1.00	5.39	-6.69
02-04-91	46.10	0.767	-0.28	-0.53	-1.29	-0.96	5.38	-7.22
03-04-91	46.60	0.764	-0.28	-0.53	-1.29	-0.92	5.36	-8.05
04-04-91	48.30	0.755	-0.28	-0.53	-1.29	-0.94	5.30	-7.27
05-04-91	48.20	0.753	-0.28	-0.53	-1.28	-0.91	5.21	-7.61
06-04-91	48.40	0.751	-0.29	-0.53	-1.29	-0.99	5.08	-6.12
08-04-91	48.60	0.747	-0.28	-0.50	-1.27	-0.98	4.40	-5.95
09-04-91	47.90	0.745	-0.29	-0.54	-1.28	-1.00	5.05	-5.85
10-04-91	49.30	0.751	-0.29	-0.54	-1.29	-1.01	4.93	-5.68
11-04-91	47.90	0.762	-0.28	-0.54	-1.29	-0.96	5.34	-6.91
12-04-91	49.20	0.754	-0.28	-0.54	-1.29	-1.01	5.22	-5.69
13-04-91	48.50	0.758	-0.28	-0.54	-1.29	-1.01	5.36	-5.77
15-04-91	48.00	0.763	-0.27	-0.53	-1.28	-1.02	5.42	-5.42
16-04-91	47.40	0.769	-0.27	-0.53	-1.28	-1.02	5.53	-5.49
17-04-91	-28.48	-0.264	-0.80	-0.77	-0.56	-0.66	0.77	-3.48
18-04-91	-25.90	-0.417	-0.95	-0.92	-0.55	-0.63	1.24	-3.24

SPECIMEN #: 7A

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4"
Water-Cement Ratio: ---
Electrolyte Solution: 10.0% NaCl
Electrodes: Non-Epoxy No.15

Starting Date: March 25, 1991
Ending Date: April 18, 1991
Immersion Period: 24 days

REVERSED POLARITY

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	OFF	ANODE ON	OFF	Electrode Resistance (Ohms) CATHODE	ANODE
26-03-91	86.30	0.520	1.20	0.77	0.21	0.84	5.02	-7.29
27-03-91	97.80	0.495	1.26	0.80	0.26	0.88	4.70	-6.38
28-03-91	102.50	0.456	1.34	0.85	0.36	0.90	4.81	-5.30
29-03-91	117.20	0.369	1.20	0.69	0.23	0.89	4.36	-5.66
30-03-91	124.80	0.333	1.17	0.64	0.21	0.87	4.24	-5.30
01-04-91	130.00	0.306	1.18	0.64	0.22	0.83	4.17	-4.72
02-04-91	132.90	0.288	1.18	0.62	0.22	0.76	4.20	-4.11
03-04-91	136.10	0.275	1.18	0.61	0.21	0.70	4.22	-3.60
04-04-91	140.30	0.253	1.17	0.59	0.20	0.72	4.11	-3.65
05-04-91	139.50	0.250	1.16	0.60	0.20	0.69	4.05	-3.49
06-04-91	139.10	0.247	1.15	0.60	0.21	0.67	3.98	-3.36
08-04-91	141.30	0.235	1.14	0.58	0.18	0.67	3.98	-3.48
09-04-91	142.20	0.229	1.12	0.58	0.18	0.67	3.78	-3.43
10-04-91	140.10	0.242	1.13	0.60	0.18	0.68	3.81	-3.51
11-04-91	137.80	0.265	1.15	0.61	0.19	0.68	3.93	-3.59
12-04-91	134.80	0.286	1.11	0.58	0.16	0.72	3.95	-4.22
13-04-91	132.70	0.297	1.12	0.58	0.14	0.72	4.07	-4.39
15-04-91	131.40	0.304	1.13	0.58	0.11	0.72	4.16	-4.63
16-04-91	130.70	0.309	1.12	0.59	0.06	0.71	4.09	-4.99
17-04-91	-29.33	-0.201	0.69	0.74	0.88	0.79	1.67	-2.83
18-04-91	-30.02	-0.028	0.87	0.89	0.87	0.78	0.67	-3.10

SPECIMEN #: 7B

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4"
Water-Cement Ratio: ---
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15

Starting Date· March 19, 1991
Ending Date: April 18, 1991
Immersion Period: 30 days

NORMAL POLARITY

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) ANODE ON	OFF	CATHODE ON	OFF	Electrode Resistance (Ohms) ANODE	CATHODE
20-03-91	58.90	0.695	-0.34	-0.61	-1.34	-1.14	4.69	-3.41
21-03-91	56.40	0.709	-0.34	-0.61	-1.35	-0.92	4.72	-7.55
22-03-91	55.80	0.713	-0.34	-0.60	-1.35	-0.95	4.59	-7.10
23-03-91	54.60	0.722	-0.34	-0.59	-1.35	-0.96	4.51	-7.22
25-03-91	52.60	0.725	-0.34	-0.57	-1.34	-0.97	4.43	-7.07
26-03-91	47.00	0.761	-0.32	-0.56	-1.34	-0.96	5.11	-7.96
27-03-91	48.30	0.746	-0.33	-0.56	-1.34	-0.97	4.78	-7.62
28-03-91	49.90	0.739	-0.34	-0.56	-1.34	-0.98	4.43	-7.23
29-03-91	47.60	0.754	-0.32	-0.55	-1.33	-0.92	4.85	-8.51
30-03-91	46.00	0.762	-0.31	-0.55	-1.32	-0.92	5.17	-8.70
01-04-91	44.20	0.775	-0.31	-0.54	-1.32	-0.94	5.20	-8.53
02-04-91	44.90	0.772	-0.31	-0.54	-1.32	-0.94	5.23	-8.44
03-04-91	45.60	0.769	-0.30	-0.54	-1.31	-0.93	5.20	-8.33
04-04-91	44.60	0.774	-0.30	-0.54	-1.31	-0.93	5.49	-8.54
05-04-91	44.20	0.763	-0.30	-0.54	-1.31	-0.94	5.43	-8.33
06-04-91	43.80	0.758	-0.30	-0.53	-1.30	-0.95	5.39	-8.13
08-04-91	45.10	0.765	-0.30	-0.54	-1.30	-0.94	5.32	-7.92
09-04-91	44.60	0.761	-0.30	-0.54	-1.30	-0.92	5.36	-8.54
10-04-91	45.90	0.768	-0.29	-0.51	-1.31	-0.92	4.84	-8.45
11-04-91	45.60	0.774	-0.28	-0.55	-1.30	-0.93	5.83	-8.00
12-04-91	45.50	0.775	-0.28	-0.55	-1.29	-0.94	5.91	-7.67
13-04-91	44.90	0.779	-0.37	-0.54	-1.29	-0.94	3.88	-7.68
15-04-91	44.10	0.785	-0.51	-0.54	-1.29	-0.95	0.57	-7.69
16-04-91	43.40	0.791	-0.65	-0.53	-1.29	-0.95	-2.67	-7.81
17-04-91	-11.86	-0.175	-0.73	-0.67	-0.51	-0.63	4.64	-10.03
18-04-91	-7.78	-0.364	-0.92	-0.88	-0.53	-0.62	5.27	-11.31

SPECIMEN #: 7B

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4"
Water-Cement Ratio: ---
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15

Starting Date: March 19, 1991
Ending Date: April 18, 1991
Immersion Period: 30 days

REVERSED POLARITY

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V) CATHODE ON	OFF	ANODE ON	OFF	Electrode Resistance (Ohms) CATHODE	ANODE
20-03-91	55.90	0.712	1.36	0.92	0.36	0.80	7.92	-7.85
21-03-91	67.50	0.649	1.39	0.93	0.38	0.79	6.68	-6.09
22-03-91	71.10	0.632	1.36	0.86	0.35	0.87	7.06	-7.33
23-03-91	64.50	0.667	1.31	0.88	0.31	0.87	6.73	-8.67
25-03-91	85.10	0.545	1.19	0.70	0.23	0.88	5.79	-7.69
26-03-91	89.90	0.520	1.17	0.69	0.20	0.88	5.26	-7.49
27-03-91	94.70	0.501	1.13	0.69	0.19	0.87	4.69	-7.17
28-03-91	106.70	0.433	1.12	0.68	0.19	0.87	4.07	-6.43
29-03-91	104.90	0.436	1.10	0.61	0.21	0.86	4.67	-6.22
30-03-91	105.80	0.435	1.14	0.61	0.18	0.85	5.02	-6.27
01-04-91	107.30	0.472	1.12	0.61	0.21	0.73	4.78	-4.90
02-04-91	108.40	0.420	1.12	0.60	0.21	0.70	4.76	-4.52
03-04-91	109.80	0.415	1.11	0.60	0.21	0.69	4.73	-4.36
04-04-91	109.40	0.415	1.11	0.59	0.21	0.68	4.69	-4.33
05-04-91	109.70	0.408	1.10	0.59	0.21	0.68	4.62	-4.26
06-04-91	110.00	0.401	1.09	0.59	0.23	0.68	4.55	-4.15
08-04-91	110.60	0.401	1.06	0.58	0.21	0.72	4.36	-4.59
09-04-91	108.20	0.410	1.07	0.58	0.20	0.70	4.47	-4.67
10-04-91	106.50	0.423	1.10	0.59	0.21	0.70	4.80	-4.60
11-04-91	105.70	0.437	1.14	0.60	0.22	0.69	5.11	-4.47
12-04-91	104.40	0.449	1.13	0.59	0.19	0.68	5.14	-4.74
13-04-91	107.60	0.432	1.12	0.59	0.19	0.69	4.93	-4.67
15-04-91	105.80	0.436	1.11	0.58	0.18	0.70	4.94	-4.85
16-04-91	105.60	0.437	1.10	0.58	0.18	0.70	4.90	-4.96
17-04-91	-5.90	-0.153	0.63	0.66	0.79	0.73	5.08	-10.51
18-04-91	-5.24	-0.025	0.84	0.86	0.82	0.72	3.63	-19.27

SPECIMEN #: 7C

VARIABLES:

Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hrs. curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: anode - 7/16 in. (11.1 mm)
cathode - 1-3/16 in. (30.2 mm)
Starting Date: March 19, 1991
Ending Date: May 3, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
20-03-91	0.02	0.999	-0.14	-0.22	-1.14	-1.01	4200.00	-6500.00
21-03-91	0.06	0.999	-0.03	-0.30	-1.03	-1.00	4633.33	-500.00
22-03-91	0.17	0.999	-0.15	-0.37	-1.15	-1.10	1323.53	-294.12
23-03-91	0.27	0.998	-0.17	-0.41	-1.17	-1.10	903.70	-259.26
25-03-91	0.72	0.995	-0.21	-0.52	-1.21	-1.09	431.94	-166.67
26-03-91	1.02	0.994	-0.24	-0.56	-1.23	-1.08	317.65	-147.06
27-03-91	1.31	0.993	-0.26	-0.58	-1.25	-1.08	248.09	-129.77
28-03-91	1.60	0.992	-0.28	-0.61	-1.28	-1.07	205.00	-131.25
29-03-91	1.75	0.991	-0.30	-0.63	-1.30	-1.08	186.29	-125.71
30-03-91	1.85	0.989	-0.31	-0.62	-1.32	-1.07	165.95	-135.14
01-04-91	2.08	0.988	-0.33	-0.59	-1.34	-1.07	125.96	-129.81
02-04-91	2.17	0.988	-0.34	-0.59	-1.34	-1.07	116.59	-124.42
03-04-91	2.26	0.987	-0.35	-0.59	-1.34	-1.07	107.96	-119.47
04-04-91	2.28	0.987	-0.35	-0.59	-1.36	-1.07	106.14	-127.19
05-04-91	2.39	0.987	-0.36	-0.58	-1.36	-1.08	95.40	-117.15
06-04-91	2.50	0.986	-0.36	-0.58	-1.36	-1.07	86.00	-116.00
08-04-91	2.59	0.985	-0.37	-0.58	-1.37	-1.08	81.85	-111.97
09-04-91	2.65	0.985	-0.38	-0.59	-1.38	-1.08	78.49	-113.21
10-04-91	2.61	0.985	-0.38	-0.59	-1.38	-1.08	78.93	-114.94
11-04-91	2.62	0.985	-0.38	-0.60	-1.38	-1.07	82.06	-118.32
12-04-91	2.58	0.986	-0.39	-0.59	-1.39	-1.08	79.07	-120.16
13-04-91	2.62	0.986	-0.39	-0.59	-1.39	-1.08	76.34	-118.32
15-04-91	2.69	0.985	-0.39	-0.59	-1.39	-1.07	74.72	-118.96
16-04-91	2.75	0.985	-0.40	-0.59	-1.39	-1.08	72.00	-112.73
17-04-91	2.75	0.985	-0.40	-0.60	-1.40	-1.08	72.00	-116.36
18-04-91	2.70	0.985	-0.39	-0.59	-1.40	-1.08	72.22	-118.52
19-04-91	2.74	0.985	-0.40	-0.59	-1.41	-1.08	70.80	-120.44
20-04-91	2.88	0.984	-0.40	-0.59	-1.40	-1.08	64.58	-111.11
22-04-91	2.83	0.985	-0.40	-0.59	-1.41	-1.08	66.43	-116.61
23-04-91	2.92	0.984	-0.40	-0.59	-1.41	-1.07	63.70	-116.44
24-04-91	3.02	0.984	-0.41	-0.59	-1.42	-1.08	60.60	-112.58
26-04-91	3.13	0.984	-0.42	-0.59	-1.42	-1.08	57.19	-108.63
27-04-91	3.13	0.985	-0.42	-0.58	-1.42	-1.08	53.04	-108.63
29-04-91	3.24	0.982	-0.42	-0.56	-1.43	-1.05	44.14	-117.28
30-04-91	3.15	0.983	-0.41	-0.58	-1.41	-1.06	53.65	-111.11
01-05-91	3.01	0.984	-0.41	-0.59	-1.41	-1.07	58.47	-112.96
03-05-91	2.88	0.985	-0.41	-0.60	-1.42	-1.07	64.24	-121.53

SPECIMEN #: 7C

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hrs. curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: anode - 7/16 in. (11.1 mm)
cathode - 1-3/16 in. (30.2 mm)
Starting Date: March 19, 1991
Ending Date: May 3, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			CATHODE		ANODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	CATHODE	ANODE
20-03-91	0.92	0.995	1.18	1.02	0.18	0.80	173.91	-673.91
21-03-91	0.84	0.995	1.18	1.01	0.18	0.68	202.38	-591.67
22-03-91	1.02	0.995	1.20	1.00	0.20	0.79	198.04	-579.41
23-03-91	0.86	0.995	1.18	1.02	0.18	0.71	186.05	-620.93
25-03-91	3.41	0.982	1.37	0.94	0.34	0.82	127.57	-140.76
26-03-91	3.77	0.980	1.37	0.90	0.34	0.84	124.14	-131.30
27-03-91	4.21	0.977	1.37	0.89	0.35	0.86	114.49	-120.67
28-03-91	4.92	0.974	1.36	0.84	0.36	0.87	104.88	-104.27
29-03-91	4.78	0.975	1.34	0.86	0.34	0.82	101.26	-100.84
30-03-91	4.85	0.974	1.33	0.84	0.32	0.82	100.82	-102.68
01-04-91	5.24	0.972	1.28	0.80	0.28	0.81	91.41	-102.29
02-04-91	5.48	0.970	1.26	0.78	0.26	0.84	87.77	-106.02
03-04-91	5.79	0.968	1.25	0.76	0.24	0.87	85.49	-107.60
04-04-91	5.91	0.968	1.24	0.74	0.23	0.87	84.26	-109.14
05-04-91	6.14	0.967	1.22	0.73	0.22	0.88	79.15	-107.49
06-04-91	6.37	0.965	1.21	0.73	0.20	0.88	75.82	-106.12
08-04-91	6.93	0.963	1.19	0.69	0.18	1.02	72.73	-120.63
09-04-91	7.55	0.959	1.19	0.67	0.18	1.03	69.27	-112.05
10-04-91	7.03	0.962	1.17	0.68	0.17	0.98	69.42	-114.94
11-04-91	6.44	0.965	1.16	0.70	0.15	0.94	72.05	-122.52
12-04-91	6.54	0.965	1.15	0.68	0.14	0.95	71.41	-122.94
13-04-91	6.75	0.963	1.15	0.68	0.15	0.98	69.78	-122.96
15-04-91	7.11	0.960	1.16	0.68	0.15	1.00	68.21	-119.55
16-04-91	7.53	0.958	1.16	0.67	0.15	1.02	64.94	-115.14
17-04-91	7.33	0.958	1.14	0.65	0.13	1.04	66.85	-124.28
18-04-91	7.05	0.962	1.12	0.66	0.11	0.97	65.53	-121.99
19-04-91	7.40	0.958	1.12	0.66	0.11	1.01	62.70	-122.30
20-04-91	7.57	0.958	1.12	0.65	0.10	1.03	61.56	-123.12
22-04-91	7.70	0.957	1.12	0.66	0.10	1.02	60.39	-118.96
23-04-91	7.88	0.956	1.12	0.65	0.11	1.01	59.64	-114.09
24-04-91	8.00	0.956	1.12	0.65	0.12	1.01	58.50	-111.88
26-04-91	8.37	0.955	1.12	0.65	0.11	1.02	55.68	-108.36
27-04-91	8.26	0.956	1.08	0.65	0.07	1.00	52.42	-112.23
29-04-91	6.92	0.963	1.08	0.62	0.06	0.95	65.90	-128.47
30-04-91	7.46	0.959	1.07	0.64	0.06	0.94	57.91	-119.03
01-05-91	7.81	0.956	1.06	0.65	0.05	0.94	52.62	-113.70
03-05-91	8.38	0.955	1.07	0.64	0.07	1.03	51.31	-115.04

SPECIMEN #: 7D

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hrs curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear cover: anode = 2.0 in. (50.8 mm)
cathode = 1-3/16 in. (30.2 mm)
Starting Date: March 19, 1991
Ending Date: May 3, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE		ANODE	CATHODE
			ON	OFF	ON	OFF		
20-03-91	0.36	0.997	0.17	-0.54	-0.83	-0.76	1961.11	-188.89
21-03-91	0.24	0.997	0.09	-0.55	-0.91	-0.78	2633.33	-545.83
22-03-91	0.20	0.998	0.06	-0.48	-0.94	-0.82	2670.00	-590.00
23-03-91	0.24	0.998	0.01	-0.52	-1.00	-0.89	2179.17	-433.33
25-03-91	0.13	0.998	-0.00	-0.41	-1.00	-0.91	3169.23	-684.62
26-03-91	0.11	0.999	0.04	-0.40	-0.96	-0.86	3990.91	-845.45
27-03-91	0.12	0.999	0.06	-0.40	-0.94	-0.84	3875.00	-808.33
28-03-91	0.11	0.999	0.08	-0.41	-0.92	-0.83	4463.64	-818.18
29-03-91	0.10	0.999	0.14	-0.38	-0.86	-0.80	5180.00	-590.00
30-03-91	0.08	0.999	0.21	-0.37	-0.79	-0.74	7237.50	-625.00
01-04-91	0.08	0.999	0.20	-0.37	-0.80	-0.74	7087.50	-762.50
02-04-91	0.08	0.999	0.19	-0.37	-0.81	-0.74	7050.00	-812.50
03-04-91	0.08	0.999	0.19	-0.37	-0.81	-0.74	6937.50	-875.00
04-04-91	0.08	0.999	0.19	-0.35	-0.81	-0.74	6762.50	-850.00
05-04-91	0.08	0.999	0.16	-0.36	-0.83	-0.77	6512.50	-825.00
06-04-91	0.09	0.999	0.14	-0.36	-0.86	-0.79	5544.44	-788.89
08-04-91	0.09	0.998	0.01	-0.36	-0.99	-0.94	4111.11	-577.78
09-04-91	0.08	0.999	0.05	-0.36	-0.95	-0.89	5000.00	-825.00
10-04-91	0.08	0.999	0.17	-0.35	-0.83	-0.78	6487.50	-600.00
11-04-91	0.08	0.999	0.22	-0.37	-0.78	-0.73	7350.00	-575.00
12-04-91	0.07	0.999	0.21	-0.34	-0.80	-0.74	7857.14	-742.86
13-04-91	0.07	0.999	0.26	-0.34	-0.75	-0.74	8585.71	-71.43
15-04-91	0.07	0.999	0.31	-0.34	-0.69	-0.74	9285.71	685.71
16-04-91	0.06	0.999	0.37	-0.34	-0.63	-0.73	11816.67	1716.67
17-04-91	0.07	0.999	0.40	-0.33	-0.60	-0.46	10510.00	-1957.14
18-04-91	0.07	0.999	0.37	-0.34	-0.63	-0.48	10057.14	-2214.29
19-04-91	0.07	0.999	0.40	-0.33	-0.62	-0.48	10485.71	-2028.57
20-04-91	0.06	0.999	0.40	-0.33	-0.61	-0.46	12133.33	-2466.67
22-04-91	0.06	0.999	0.39	-0.32	-0.60	-0.46	11966.67	-2333.33
23-04-91	0.06	0.999	0.40	-0.33	-0.60	-0.47	12066.67	-2166.67
24-04-91	0.07	0.999	0.40	-0.32	-0.60	-0.47	10300.00	-1914.29
26-04-91	0.07	0.999	0.40	-0.32	-0.60	-0.47	10300.00	-1857.14
27-04-91	0.06	0.999	0.37	-0.33	-0.63	-0.46	11683.33	-2833.33
29-04-91	0.06	0.999	0.05	-0.33	-0.96	-0.90	6300.00	-850.00
30-04-91	0.06	0.999	0.07	-0.34	-0.93	-0.87	6833.33	-900.00
01-05-91	0.06	0.999	0.10	-0.34	-0.90	-0.84	7300.00	-900.00
03-05-91	0.05	0.999	0.18	-0.32	-0.82	-0.76	10140.00	-1080.00

SPECIMEN #: 7D

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hrs curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: anode - 2.0 in. (50.8 mm)
cathode - 1-3/16 in. (30.2 mm)
Starting Date: March 19, 1991
Ending Date: May 3, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

DATE (D-M-Y)	I (mA)	Volt (V)	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			CATHODE		ANODE			
			ON	OFF	ON	OFF	CATHODE	ANODE
20-03-91	0.23	0.998	1.03	1.03	0.04	0.33	21.74	-1300.00
21-03-91	0.53	0.997	1.03	1.00	0.03	0.66	66.04	-1179.25
22-03-91	0.48	0.997	1.02	0.99	0.02	0.67	45.83	-1350.00
23-03-91	0.54	0.996	1.17	1.08	0.17	0.66	164.81	-911.11
25-03-91	0.93	0.995	1.15	0.99	0.14	0.73	168.82	-631.18
26-03-91	0.80	0.995	1.13	0.99	0.13	0.68	180.00	-688.75
27-03-91	0.75	0.996	1.12	0.99	0.12	0.65	181.33	-702.67
28-03-91	0.64	0.996	1.11	0.99	0.11	0.63	192.19	-809.38
29-03-91	0.56	0.997	1.06	0.95	0.06	0.49	196.43	-762.50
30-03-91	0.43	0.997	1.00	0.92	0.00	0.37	193.02	-858.14
01-04-91	0.36	0.997	0.98	0.90	-0.02	0.36	213.89	-1061.11
02-04-91	0.36	0.998	0.98	0.91	-0.02	0.36	202.78	-1058.33
03-04-91	0.36	0.998	0.98	0.91	-0.02	0.36	194.44	-1058.33
04-04-91	0.37	0.998	0.99	0.92	-0.01	0.37	202.70	-1010.81
05-04-91	0.37	0.998	1.00	0.92	-0.00	0.39	194.59	-1054.05
06-04-91	0.38	0.998	1.00	0.93	0.00	0.42	184.21	-1097.37
08-04-91	0.45	0.997	1.06	0.96	0.05	0.53	204.44	-1057.78
09-04-91	0.53	0.997	1.07	0.97	0.07	0.53	205.66	-858.49
10-04-91	0.39	0.997	1.04	0.91	0.03	0.49	335.90	-1194.87
11-04-91	0.27	0.998	0.98	0.86	-0.02	0.46	429.63	-1770.37
12-04-91	0.29	0.998	0.97	0.84	-0.03	0.41	448.28	-1500.00
13-04-91	0.28	0.998	0.94	0.80	-0.05	0.34	500.00	-1407.14
15-04-91	0.29	0.998	0.89	0.76	-0.09	0.30	455.17	-1341.38
16-04-91	0.28	0.998	0.83	0.72	-0.12	0.21	417.86	-1171.43
17-04-91	0.29	0.997	0.88	0.66	-0.12	0.24	758.62	-1244.83
18-04-91	0.22	0.998	0.88	0.72	-0.12	0.21	745.45	-1490.91
19-04-91	0.23	0.998	0.88	0.71	-0.13	0.22	730.43	-1482.61
20-04-91	0.24	0.998	0.88	0.71	-0.13	0.22	725.00	-1458.33
22-04-91	0.24	0.998	0.87	0.70	-0.13	0.22	712.50	-1454.17
23-04-91	0.23	0.998	0.87	0.71	-0.13	0.21	700.00	-1508.70
24-04-91	0.22	0.998	0.86	0.71	-0.13	0.21	695.45	-1545.45
26-04-91	0.23	0.998	0.87	0.72	-0.13	0.20	652.17	-1434.78
27-04-91	0.23	0.999	0.88	0.73	-0.12	0.19	669.57	-1347.83
29-04-91	0.25	0.999	0.88	0.84	-0.10	0.54	152.00	-2548.00
30-04-91	0.31	0.998	0.98	0.89	-0.01	0.46	293.55	-1519.35
01-05-91	0.34	0.997	1.06	0.94	0.06	0.35	352.94	-844.12
03-05-91	0.64	0.998	0.99	0.81	-0.00	0.35	290.63	-551.56

SPECIMEN #: 7E

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hrs curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: anode - 1-3/16 in. (30.2 mm)
cathode - 1-3/16 in. (30.2 mm)
Starting Date: March 19, 1991
Ending Date: May 3, 1991
Immersion Period: 45 days

NORMAL POLARITY
(Concrete-Embedded Anode)

DATE	I	Volt	Electrode Potentials (V)				Electrode Resistance (Ohms)	
			ANODE		CATHODE			
(D-M-Y)	(mA)	(V)	ON	OFF	ON	OFF	ANODE	CATHODE
20-03-91	0.61	0.995	-0.24	-0.64	-1.23	-1.12	642.62	-180.33
21-03-91	0.61	0.996	-0.24	-0.67	-1.22	-1.12	711.48	-163.93
22-03-91	0.57	0.996	-0.23	-0.65	-1.20	-1.12	743.86	-140.35
23-03-91	0.36	0.998	-0.20	-0.55	-1.20	-1.12	983.33	-222.22
25-03-91	0.36	0.997	-0.22	-0.52	-1.21	-1.11	847.22	-277.78
26-03-91	0.30	0.997	-0.21	-0.49	-1.20	-1.10	956.67	-333.33
27-03-91	0.31	0.996	-0.21	-0.55	-1.19	-1.10	1106.45	-290.32
28-03-91	0.30	0.996	-0.21	-0.58	-1.18	-1.10	1253.33	-266.67
29-03-91	0.24	0.998	-0.20	-0.47	-1.18	-1.11	1129.17	-291.67
30-03-91	0.20	0.999	-0.18	-0.47	-1.18	-1.09	1455.00	-450.00
01-04-91	0.17	0.998	-0.18	-0.45	-1.17	-1.10	1594.12	-411.76
02-04-91	0.17	0.998	-0.18	-0.46	-1.17	-1.11	1605.88	-352.94
03-04-91	0.16	0.999	-0.18	-0.46	-1.17	-1.10	1725.00	-437.50
04-04-91	0.16	0.999	-0.18	-0.41	-1.17	-1.07	1418.75	-625.00
05-04-91	0.20	0.998	-0.18	-0.44	-1.17	-1.09	1285.00	-400.00
06-04-91	0.24	0.997	-0.18	-0.47	-1.18	-1.10	1208.33	-333.33
08-04-91	0.25	0.996	-0.20	-0.48	-1.18	-1.11	1140.00	-280.00
09-04-91	0.25	0.996	-0.19	-0.48	-1.18	-1.10	1164.00	-320.00
10-04-91	0.22	0.997	-0.19	-0.45	-1.17	-1.09	1218.18	-363.64
11-04-91	0.20	0.998	-0.18	-0.55	-1.17	-1.08	1815.00	-450.00
12-04-91	0.21	0.998	-0.18	-0.46	-1.17	-1.08	1300.00	-428.57
13-04-91	0.25	0.998	-0.19	-0.49	-1.17	-1.09	1204.00	-320.00
15-04-91	0.29	0.997	-0.19	-0.49	-1.18	-1.10	1044.83	-275.86
16-04-91	0.28	0.997	-0.19	-0.51	-1.18	-1.11	1128.57	-250.00
17-04-91	0.22	0.997	-0.19	-0.49	-1.18	-1.10	1337.84	-360.36
18-04-91	0.25	0.997	-0.19	-0.52	-1.18	-1.10	1300.00	-320.00
19-04-91	0.25	0.997	-0.19	-0.52	-1.18	-1.10	1336.00	-320.00
20-04-91	0.26	0.997	-0.19	-0.52	-1.18	-1.10	1284.62	-307.69
22-04-91	0.26	0.997	-0.19	-0.53	-1.18	-1.11	1280.77	-269.23
23-04-91	0.25	0.997	-0.19	-0.53	-1.18	-1.11	1356.00	-280.00
24-04-91	0.24	0.998	-0.20	-0.53	-1.18	-1.10	1412.50	-333.33
26-04-91	0.23	0.998	-0.20	-0.53	-1.18	-1.11	1452.17	-304.35
27-04-91	0.25	0.999	-0.21	-0.56	-1.20	-1.11	1384.00	-360.00
29-04-91	0.19	0.999	-0.19	-0.46	-1.18	-1.12	1384.21	-315.79
30-04-91	0.18	0.998	-0.19	-0.47	-1.17	-1.10	1572.22	-388.89
01-05-91	0.16	0.997	-0.18	-0.48	-1.17	-1.08	1900.00	-562.50
03-05-91	0.13	0.999	-0.15	-0.42	-1.16	-1.05	2030.77	-846.15

SPECIMEN #: 7E

VARIABLES:
Impressed Voltage: 1.0 V
Distance Between Electrodes: 4 in. (101.6 mm)
Water-Cement Ratio: 0.45 (24 hrs curing)
Electrolyte Solution: 3.5% NaCl
Electrodes: Non-Epoxy No.15
Clear Cover: anode - 1-3/16 in. (30.2 mm)
cathode - 1-3/16 in. (30.2 mm)
Starting Date: March 19, 1991
Ending Date: May 3, 1991
Immersion Period: 45 days

REVERSED POLARITY
(Concrete-Embedded Cathode)

			Electrode Potentials (V)				Electrode Resistance (Ohms)	
DATE (D-M-Y)	I (mA)	Volt (V)	CATHODE		ANODE			
			ON	OFF	ON	OFF	CATHODE	ANODE
20-03-91	1.11	0.993	1.24	1.08	0.23	0.85	144.14	-565.77
21-03-91	1.31	0.993	1.24	1.05	0.22	0.79	145.04	-434.35
22-03-91	1.85	0.989	1.31	1.04	0.29	0.83	145.95	-293.51
23-03-91	1.13	0.995	1.30	1.05	0.29	0.74	221.24	-404.42
25-03-91	3.59	0.979	1.40	0.98	0.40	0.87	116.71	-130.36
26-03-91	3.50	0.979	1.40	1.00	0.41	0.86	115.14	-129.14
27-03-91	3.38	0.980	1.41	1.00	0.41	0.85	121.30	-130.47
28-03-91	3.28	0.981	1.42	1.02	0.42	0.85	121.95	-130.18
29-03-91	3.13	0.982	1.42	1.01	0.41	0.81	130.99	-126.84
30-03-91	3.03	0.984	1.42	1.03	0.42	0.81	128.71	-128.38
01-04-91	2.92	0.985	1.43	1.04	0.43	0.82	133.56	-131.51
02-04-91	2.86	0.985	1.43	1.04	0.43	0.81	136.36	-132.17
03-04-91	2.81	0.985	1.43	1.04	0.43	0.81	138.79	-132.38
04-04-91	2.98	0.984	1.41	1.00	0.40	0.8[illegible]	138.26	-132.21
05-04-91	2.87	0.984	1.41	1.00	0.41	0.80	142.86	-137.63
06-04-91	2.78	0.985	1.42	1.02	0.41	0.81	143.88	-142.45
08-04-91	3.20	0.980	1.44	1.01	0.44	0.83	134.37	-123.44
09-04-91	3.25	0.980	1.44	1.00	0.44	0.83	135.38	-119.08
10-04-91	3.30	0.980	1.42	1.00	0.37	0.81	127.27	-132.73
11-04-91	3.25	0.981	1.43	1.01	0.28	0.79	129.23	-157.23
12-04-91	1.72	0.991	1.43	1.01	0.33	0.79	244.19	-272.09
13-04-91	2.01	0.989	1.43	1.00	0.37	0.80	213.93	-211.94
15-04-91	2.38	0.986	1.43	1.00	0.40	0.81	181.51	-173.53
16-04-91	2.75	0.983	1.43	1.00	0.42	0.83	158.18	-145.82
17-04-91	3.07	0.983	1.44	1.00	0.43	0.87	143.65	-141.37
18-04-91	2.63	0.985	1.42	1.00	0.42	0.83	159.70	-156.27
19-04-91	2.55	0.986	1.42	1.00	0.42	0.82	164.71	-159.22
20-04-91	2.41	0.986	1.43	1.00	0.41	0.82	179.67	-168.05
22-04-91	2.33	0.987	1.43	1.01	0.41	0.81	180.26	-173.39
23-04-91	2.18	0.988	1.44	1.02	0.41	0.81	192.66	-185.32
24-04-91	2.22	0.987	1.42	1.03	0.40	0.81	175.68	-183.78
26-04-91	2.27	0.987	1.43	1.03	0.40	0.80	176.21	-178.41
27-04-91	2.62	0.986	1.40	0.97	0.39	0.80	164.50	-159.54
29-04-91	2.52	0.985	1.41	1.00	0.41	0.80	162.70	-154.37
30-04-91	2.02	0.987	1.38	1.03	0.38	0.78	173.27	-197.52
01-05-91	1.62	0.989	1.35	1.05	0.35	0.74	185.19	-245.68
03-05-91	3.54	0.982	1.37	0.90	0.37	0.79	133.90	-120.62