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PERFORMANCE EVALUATION OF CORROSION INHIBITORS AND GALVANIZED STEEL IN CONCRETE EXPOSURE SPECIMENS

JERZY ZEMAJTIS
Research Associate
Virginia Polytechnic Institute
and State University

RICHARD E. WEYERS
Professor
Virginia Polytechnic Institute
and State University

MICHAEL M. SPRINKEL
Research Manager
Virginia Transportation Research Council

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Authors:
Mr. Jerzy Zemajtis, Dr. Richard E. Weyers, Mr. Michael Sprinkel

Performing Organization Name and Address:

Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903

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Virginia Department of Transportation
1401 E. Broad Street
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Abstract

Corrosion inhibitor admixtures (CIA) and galvanized reinforcing steel (GS) are used for the corrosion protection for reinforced concrete bridges. The results of a 3.5-year evaluation of exposure specimens containing CIA from three different manufacturers and GS are presented. The specimens were built to simulate four exposure conditions typical for concrete bridges located in the coastal region or inland where deicing salts are used. The exposure conditions were Horizontal, Vertical, Tidal, and Immersed Zones. The specimens were kept inside the laboratory and were exposed to weekly ponding cycles of 6% sodium chloride solution by weight.

The methods used to assess the condition of the specimens included chloride concentration measurements, corrosion potentials, and corrosion rates. Additionally, visual observations were performed for identification of rust stains and cracking on concrete surfaces.

The results of chloride testing indicate that the amount of chlorides present at the bar level is more than sufficient to initiate corrosion. Chloride and rapid permeability data indicate no significant difference either in a rate of chloride ingress or in the diffusion coefficients for concretes with and without CIA.

Corrosion potentials were the most negative for the Bare Steel (BS) specimen prepared with the Armatec 2000 corrosion inhibitor and generally indicated a 90% probability of active corrosion. Corrosion potentials were similar for the two BS control specimens and the BS specimen prepared with Rheocrete 222 and generally indicated an uncertain probability of corrosion. Corrosion potentials were the least negative for the BS specimen prepared with DCI-S corrosion inhibitor and generally indicated a 90% probability of no corrosion.

Rate of corrosion measurements were the highest for the BS control specimens and the one prepared with A2000 and the most recent data suggest corrosion damage in 2 to 10 years. Although early rate of corrosion measurements were higher or about the same as for BS control specimens, recent measurements were slightly lower for the specimen prepared with Rheocrete 222 and suggest corrosion damage in 10 to 15 years. Rate of corrosion measurements were consistently the lowest for the BS specimens prepared with DCI-S and indicate corrosion damage is expected in 10 to 15 years.

The corrosion potential and rate of corrosion data indicate that DCI-S is the only CIA evaluated that clearly provides some level of corrosion protection.

A direct comparison of the GS specimens to the BS specimens is not possible because the measured potential refers to the zinc oxide and not to the steel. Nevertheless, the potential data agree with the chloride and permeability data, as well as with the visual observations, and indicate the damaging effect of a high concentration of chloride ions on the GS. At low and moderate chloride exposures, however, GS does provide corrosion protection.

Recommendations are to continue monitoring until sufficient cracking has occurred in all specimens to provide for making a better estimate of the service lives of CIA and GS used in the construction of concrete bridge components in Virginia. The specimens with CIA and one control (continuous reinforcement in the legs) should be taken to the Hampton Road North Tunnel Island and placed in the brackish water to a depth of the Immersed Zone at low tide for further exposure to chloride. The specimens with GS and the other control (non-continuous reinforcement in the legs) should remain in an outdoor exposure in Southwest Virginia like the Civil Engineering Materials Research Laboratory in Blacksburg, Virginia.

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Jerzy Zemajtis, Research Associate
Charles E. Via Department of Civil Engineering
Virginia Polytechnic Institute and State University

Richard E. Weyers, Professor
Charles E. Via Department of Civil Engineering
Virginia Polytechnic Institute and State University

Michael M. Sprinkel, Research Manager
Virginia Transportation Research Council

Project Monitors
Michael Sprinkel, Virginia Transportation Research Council

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Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

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ABSTRACT

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Keywords: bridge, concrete, corrosion, corrosion inhibitors, galvanized steel, reinforcing steel

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Jerzy Zemajtis, Research Associate
Charles E. Via Department of Civil Engineering
Virginia Polytechnic Institute and State University

Richard E. Weyers, Professor
Charles E. Via Department of Civil Engineering
Virginia Polytechnic Institute and State University

Michael M. Sprinkel, Research Manager
Virginia Transportation Research Council

INTRODUCTION

Presently, the extent of the rapid deterioration of reinforced concrete bridges from chloride ion induced corrosion is well known. During the early recognition stages of the cause, process and severity of the concrete bridge deterioration problem in the United States, a multitude of corrosion abatement techniques were developed for existing and newly constructed bridges. Epoxy-coated reinforcing steel (ECR) and corrosion inhibiting admixtures (CIA) are two techniques developed to extend the service life of newly constructed concrete bridge components. ECR, presently, is the most used corrosion protection method for concrete bridges in the United States. CIA have been used for over 20 years but significantly less frequent than ECR and in Virginia primarily in precast-prestressed members.

Until 1986 when Florida reported that the Long Key Bridge showed signs of corrosion only 6 years after construction, the corrosion protection effectiveness of ECR remained unquestioned. Since the Florida reported findings, 12 field studies have been conducted on the corrosion protection effectiveness of ECR (1). Conclusions have been mixed, from satisfactory corrosion protection performance to date for bridge decks to poor performance in substructures with predictions that ECR will not provide long-term (50 years) of corrosion protection performance for substructures or decks.[1] The reason for the mixed conclusions of the performance of ECR included limited or inappropriate evaluation methods which always accompany a lack of knowledge of the cause(s) of failure and subjectively defined failure criteria. From studies where care and appropriate evaluation methods and failure criteria have been employed, the conclusions are that ECR will not provide 50 years of corrosion free protection for steel in concrete bridge components.[2, 3] More recent studies, including one in Virginia, support the earlier conclusions that ECR will not provide long term corrosion protection performance.[4, 5] As a result of these recent findings on the limited effectiveness of ECR, more interest has been developed in the effectiveness of CIA.

Thus, the Virginia Department of Transportation initiated a corrosion protection performance effectiveness study for newly constructed concrete bridges. The protection systems included in the study are ECR (present and new coatings), galvanized reinforcing steel (GS), three commercial CIA, low permeable concretes, and two dual corrosion protection systems (a CIA and ECR and a CIA and low permeable concrete). Evaluation of the corrosion protection effectiveness was assessed in both a simulated concrete pore water solution and in concrete exposure specimens. A field study on ECR was also included. The field study bridges were 3, 8 year old substructures in a marine environment and 21 bridge decks, ranging in age from 2 to 20 years, in a deicer salt environment. This report presents the results of the evaluation of CIA and GS in concrete exposure specimens.

PURPOSE & SCOPE

The purpose of this study was fourfold:

1. To access the corrosion protection effectiveness of three commercial CIA for concrete.
2. To provide a corrosion protection comparison base for CIA in concrete with the concrete pore water solution test procedure.
3. To provide well characterized specimens for long term corrosion protection performance evaluation for CIA.
4. To access the corrosion protection effectiveness of GS in concrete.

The study was limited to the CIA presently used in prestressed members in Virginia, DCI-S, and two other commercial products, Armatec 2000 (A2000) and Rheocrete 222 (R222), being marketed as CIA for reinforced concrete at the time this study was initiated. In addition, GS as a corrosion protection method was also included in this study.

METHODS & MATERIALS

Specimen Design

To assess the performance of the reinforcing steel in concrete with CIA, three specimens with

DCI-S, Rheocrete 222, Armatec 2000, and two control specimens, with no CIA were cast. Also a specimen with GS and A4 concrete was fabricated. The constant parameter for these specimens was a 0.45 water to cement ratio. In addition to the six specimens, one specimen with GS and a w/c ratio of 0.71 was cast, for a total of seven specimens. All specimens had 25 mm reinforcing cover depth and were exposed to a 6%, by weight, sodium chloride wetting solution. Each specimen, as shown in Figure 1, is 1.72 m high with horizontal dimensions of 1.12 m by 1.12 m, and was designed to simulate four exposure conditions: wetted deck surface (Horizontal Zone), wetted vertical surfaces of bridge members (Vertical Zone), tidal zone (Tidal Zone), and immersed zone (Immersed Zone). The Immersed Zone covered an area from the bottom of specimens' legs to the height of 305 mm. The Tidal Zone was from 305 mm to 610 mm from the bottom of specimens' legs. A vertical surface area above 610 mm from the bottom of a specimen corresponded to the Vertical Zone, and the Horizontal Zone was the top surface area of the specimen.

The specimens differed by the following parameters (see Table 1):

- type of the reinforcing steel: BS (specimens BS-1, BS-2, DCI, R222, A2000), GS (specimens GS-1 and GS-11)
- configuration of the reinforcing steel (RS) in specimen's legs: type I - RS electrically disconnected in both legs, type II - RS electrically connected in both legs (same bars for Vertical, Tidal, and Immersed Zones), type III - RS electrically disconnected in the right leg and RS electrically connected in the left leg (same bars for Vertical, Tidal, and Immersed Zones)
- concrete type: Virginia Department of Transportation (A4) concrete with w/c = 0.45, A4 concretes with various CIA, or concrete with w/c > 0.7

Specimens were cast in steel forms, which were carefully cleaned and oiled with a form release agent before each concrete placement. Specimens were wet cured in forms for seven days. After taking them out of the forms, specimens were wrapped with wet burlap and covered with plastic for additional 21 days of wet curing. After 28 days of wet curing, specimens were air-dried in the laboratory for a minimum of 30 days. During that time the specimens were prepared for wet-dry cycles. All bar ends protruding from specimen legs in the lower part of the legs (610 mm from the bottom) were protected with plastic tubing, stoppers, and silicone rubber against contact with wetting solution. Plexiglass dikes were assembled and adhered to the horizontal surface with silicone rubber to provide the ponding dike for the horizontal surface and to uniformly wet the legs of the specimens. Each specimen was placed into a 710 mm deep high-density polyethylene (HDPE) tank and exposed to wet-dry cycles.

Experimental Plan

Specimens were kept indoors and exposed to wet-dry cycles. Each cycle was one week in duration and was divided into two stages. The specimens were paired so when the wetting solution was at high tide level (610 mm from the bottom of a specimen) for the first specimen, the second specimen had wetting solution at low tide level (water level at 305 mm from the bottom of a specimen). When the water was at low tide position, wetting solution was pumped to the top of a specimen, thus wetting specimen surfaces in the Horizontal and Vertical Zones. At the same time surfaces in the Tidal Zone were allowed to air dry. While first specimen from the pair had wetting solution at the low tide level, the other specimen had water at the high level position, thus the Tidal Zone and the Immersed Zone areas were covered with NaCl solution, and the Horizontal and Vertical Zones of that specimen were allowed to air dry. Since there was an odd number of specimens, wetting solution from one specimen was pumped to external containers, so that the high tide - low tide levels could easily be adjusted.

Horizontal, Vertical, and Tidal Zones were subjected to wetting for an average of 3.5 days in a week and to air drying also for an average of 3.5 days in a week. Immersed Zone was subjected to wetting solution for 7 days a week. The wetting solution used in the study was 6% sodium chloride by weight.

After approximately 1.5 years of wet-dry cycles, the specimens were removed from the tanks and moved outdoors.

Evaluation Methods

The objective of the testing program was to investigate three commercial CIA and GS as corrosion protection systems and evaluate their performance in reference to BS control specimens. Methods used to assess performance included chloride diffusion rates, corrosion potentials, and corrosion rates measurements. Additionally, visual observations were performed for identification of rust stains and cracking on concrete surfaces.

Chloride diffusion was monitored by collecting concrete powder samples at three depths: 13 mm, 25 mm, and 38 mm after 33 weeks, one year, and 1.5 years of exposure. In order not to significantly damage the specimens, samples collected at 33 weeks and 1 year, were obtained from small concrete blocks, 300 mm by 300 mm by 130 mm, placed in the Tidal and Immersed Zones. These blocks were cast from the same batch of concrete as the specimens, cured in the same conditions, and placed into the HDPE tanks at the same time as the specimens. After 1.5 years of ponding, chloride samples were collected from all four exposure zones of the specimens. In addition to the chloride samples from the three above mentioned depths, a sample from the depth of 51 mm was collected in the Horizontal Zone.

Corrosion potential measurements in the Horizontal Zone were taken on a monthly basis and were recorded at 12 locations: 4 bars, 3 locations each. For Vertical, Tidal, and Immersed Zones, corrosion potentials were recorded at 9 locations: 3 bars, 3 locations each, for each zone and for each leg of the specimen. Total number of corrosion potential measurement locations was 66, including 12 in the Horizontal Zone, 9 in the Vertical Zone Left Leg, 9 in the Tidal Zone Left Leg, 9 in the Immersed Zone Left Leg, 9 in the Vertical Zone Right Leg, 9 in the Tidal Zone

Right Leg, and 9 in the Immersed Zone Right Leg.

Corrosion rates were measured at three locations for each exposure zone and each leg, for a total of 21 different locations per specimen. See Figure 2 for a measurement location plan for Horizontal Zone and Vertical, Tidal, and Immersed Zones on the specimen's right leg. Measurement locations on the specimen's left leg were the same as on the right leg.

Chlorides

Chloride content is a common technique to determine the possibility of corrosion activity. It is generally known that once the concentration of chloride ions reaches the corrosion threshold level, the higher the chloride the higher the probability of active corrosion. Table 2 provides guidelines for interpretation of chloride content measurements.[6]

Samples for chloride concentration were collected as pulverized concrete at three or four average depths. The collection apparatus used an impact drill with 29 mm diameter bit, 2.3 times the maximum aggregate size, connected to a vacuum collection unit.[7] The concrete powder was collected in a coffee filter, which was then stored in a plastic container until chemical analysis (chloride ion concentration determination) was performed. A sample set was taken from the blocks for each concrete type and for two exposure conditions, Tidal and Immersed Zones, after 33 weeks and 1 year of exposure. A sample was taken from specimens for all exposure conditions after 1.5 years. Each sample set consisted of chloride samples from the following depths: 13 mm - from 6 to 19 mm, 25 mm - from 19 to 32 mm, 38 mm - from 32 to 44 mm. A sample was taken at a fourth depth, 51 mm - from 44 to 57 mm in the Horizontal Zone, at 1.5 years.

Due to high variability of chloride content close to the surface, powdered concrete sample from the top 6 mm was discarded. Background chloride content measurements were performed by sampling concrete cylinders that were made with the compressive strength cylinders.

Measurements of chloride content were carried out according to the ASTM C 114-88.[8] A titration method is used to determine the quantity of acid soluble chlorides in the concrete digestion solution. A simple formula transfers the amount of milliliters of titration solution into chloride ion concentration expressed in kg/m^3 of concrete.

Corrosion Potentials

Corrosion potentials non-destructively identify the probability of active corrosion. The method uses a copper-copper sulfate half-cell electrode (CSE) that is connected to the voltmeter and then to the reinforcing steel. According to the ASTM C 876-80 the more negative the voltmeter reading, the greater the probability of active corrosion.[9] Table 3 presents the relationship of the potential readings versus probability of corrosion for bare reinforcing steel. Note, that the interpretation of the potential readings refers to BS only and not to GS.

The locations for potential measurements for the specimens are shown in Figure 2.

Corrosion Rates

The linear polarization technique is a non-destructive method for assessing the instantaneous corrosion current density. Corrosion current density is directly proportional to the instantaneous rate of metal loss. Often the corrosion current density is referred to as the corrosion rate. Several devices, based on the linear polarization method, can be used to determine the corrosion current density of steel in concrete. One of the most common is the 3LP device. Corrosion current density measurements are very susceptible to variable field conditions: concrete temperature, moisture, and oxygen content. The manufacturer's interpretation of measured corrosion current density (rate) is given in Table 4. The locations of the 3LP measurements are presented in Figure 2.

Materials

Bare Steel

BS reinforcement was used for fabrication of specimens with CIA and controls. All BS was in the form of #5 (D = 16 mm) bars, Grade 60, and came from one heat. Physical and chemical properties of BS, based on mill certificates, are presented in Table 5.

Galvanized Steel

Two specimens, GS-1 and GS-11, were fabricated with #5 (D = 16 mm) GS reinforcement, class 50. The source of GS was Metalplate Galvanizing Inc. from Birmingham , AL. No additional data on the GS was available.

Concrete

Concrete, designated as Virginia A4, was used for two control specimens, BS-1 and BS-2, and two specimens with GS, GS-1 and GS-11. Concretes, with the addition of DCI-S, Rheocrete 222, and Armatec 2000 corrosion inhibitors, were used for specimens DCI, R222, and A2000, respectively. Water to cement (w/c) ratio of 0.45, together with the amounts of cement and coarse aggregate equal to 377 and 867 kg/m^3 of concrete respectively were kept constant for all mixtures. Concrete mixture proportions are presented in Table 6 (except for the A4 concrete that was accidentally batched with a water to cementitious ratio of 0.71, used for specimen GS-11).

Type I/II cement was used for all concrete mixtures. Its density was 3.15 g/cm^3 and was certified to meet ASTM C-150-92, AASHO M-85-88, and Federal SS-C-1960 Specifications. Chemical and physical test data are provided in Table 7.

Coarse aggregate used for concrete mixtures was #78 stone with unit weight of 96.7. Its density was 2.75 g/cm^3 and absorption was measured to be 0.66%. Natural sand, with fineness modulus (FM) of 2.7, 2.66 g/cm^3 density, and 0.84% absorption, was used as fine aggregate. Daravair-M air entraining admixture was used for all mixtures in the amount of 65 ml/100 kg of cement. In addition to Daravair-M, MB-VR air entraining admixture, in the amount of 65 ml/100 kg of cement, was used in concrete for R222 specimen. Water reducing admixture was necessary to keep the w/c ratio unchanged and to provide adequate workability during the placing of the concrete in the forms. The high range water reducer WRDA-19 was used with concretes for BS-1, BS-2, GS-1, GS-11, and DCI specimens, while Rheobuild 1000 was used for R222 and A2000 specimens.

The concrete was batched in 2.4 cubic meter batches at a local ready mix concrete plant, mixed and transported to the laboratory. About 0.78 m^3 of concrete was used in the casting of a specimen. Manufacturers' representatives for the R222 and A2000 CIA assisted in adjusting batch weights, verified batch weights and approved the concrete batching, mixing, transporting and placing procedures. Manufacturers' representatives for the DCI-S admixture were not present during any of the specimen fabrication procedures.

Slump, air content, concrete temperature, and concrete density (unit weight) were recorded before concrete placement. Results of these tests are presented in Table 8. While placing concrete, several 100 by 200 mm cylinders were made for compressive strength and rapid chloride permeability tests. Compressive strength was measured after 3, 7, 28, 56 days and 1 year of wet curing. Cylinders for rapid chloride permeability tests were sent to the Virginia Transportation Research Council (VTRC), Charlottesville, VA for testing. The tests were performed, according to ASTM C 1202, at 28 days and 1 year of wet curing.[10] The compressive strength and rapid chloride permeability tests results are presented in Tables 9 and 10, respectively.

RESULTS

Corrosion Potentials

Specimens were monitored with the half-cell potential measurements in the Horizontal and Vertical Zones. The potential data collected in the Horizontal Zone are presented in Figures 3-9, for specimens BS-1, BS-2, DCI, R222, A2000, GS-1, and GS-11, respectively. In the interest of brevity, only the Horizontal Zone (Deck) potential and corrosion rate data is presented in the text of this report. Average values for potentials recorded for the horizontal deck and the left and right legs of the specimens are appended to the report. In general, the potentials are similar for the legs and the deck.

Note: each curve in Figures 3-9 represents an average of three readings taken from one reinforcing steel bar.

Corrosion Rates

A relationship of corrosion rates (i_{corr}) versus time for the two control specimens, BS-1 and BS-2, with BS bars is presented in Figures 10 and 11 for the Horizontal Zone. Readings collected after 74 and 80 weeks of exposure were made while the specimens were still indoors and the ponding was in progress. Readings after 83 weeks of exposure were made indoors immediately after the ponding was discontinued. Readings at 97th week of exposure and later were taken after the specimens were moved outdoors. Corrosion rates for the specimens with CIA, DCI, R222, and A2000, were collected in the Horizontal Zone after 65 weeks of exposure. Corrosion rate data for these specimens is presented in Figures 12-14 for the Horizontal Zone. Readings collected after 65 and 71 weeks of exposure were made while the specimens were still indoors and the ponding was in progress. Readings after 74 weeks of exposure were made indoors immediately after the ponding was discontinued. Readings at 88th week of exposure and later were taken after the specimens were moved outdoors.

Chlorides

Chloride concentrations were determined for all concrete types used for specimen fabrication. Concrete powder samples were collected from three depths for all exposure zones, except for the Horizontal Zone at 1.5 years, for which samples were collected from four depths. Chloride concentrations, for Horizontal, Vertical, Tidal, and Immersed Zones, versus depth are presented in Figures 15-22. Values for the A4 concrete used in the controls and the GS-1 specimens were averaged.

Rapid Concrete Chloride Permeability

The rapid permeability was measured on cylinders of all concrete types according to ASTM C-1202.[10] The measurements were taken after 28 days and 1 year of wet curing. The data from these measurements are presented in Figure 23 for 28 days and Figure 24 for 1 year.

Visual Observations

A crack survey was performed after approximately four months of outdoor exposure. Visually observed cracks and rust stains, in the BS-1, BS-2, DCI, R222, A2000, GS-1, and GS-11 specimens, are presented in Figures 25-31, respectively.

DISCUSSION

Corrosion Potentials, Horizontal Zone

As shown in Figures 3 and 4, corrosion potentials in the Horizontal Zone for the two control specimens were in the range from -170 mV to -278 mV, with the exceptions of bar No. 4 of specimen BS-1 and two sets of readings that were taken at two and four months after the specimens were moved outdoors. Potentials recorded on bar No. 4, BS-1 specimen, started at -261 mV at 18th week of exposure and stayed in the -242 mV to -269 mV range till the 37th week of exposure. After 37 weeks of ponding, potentials decreased to -305 mV and stayed close to -

300 mV reaching -326 mV after 80 weeks of ponding. Once the specimens were moved outdoors, potentials for specimen BS-1 increased to the range of -103 mV to -142 mV, after 105 weeks of exposure. For the second control specimen, BS-2, potential values also increased but to a lesser extent, and after 98 weeks of exposure were in the range from -165 mV to -172 mV for bars No. 1, 2, and 3, and -203 mV for bar No. 4. After 106 weeks of exposure potentials for BS-2 specimen were close, for all four bars, to an average of -220 mV. After four months of being outdoors, the corrosion potentials have again become significantly more negative, -240 to -290 mV for BS+1 and -390 to -460 mV for BS-2.

As seen in Figures 5-7, corrosion potentials measured in the Horizontal Zone while the specimens were housed inside the laboratory, for DCI, R222, and A2000 specimens, varied from -106 mV to -227 mV, from -263 mV to -369 mV, and from -248 mV to -403 mV, respectively. Potentials for both, DCI and A2000, specimens were decreasing in time, however, the potentials for A2000 specimen were much more negative than for DCI specimen, see Figures 5 and 7. This trend was not observed for R222 specimen, Figure 6. Even though its potentials were not changing in time to the same degree as for DCI and A2000 specimens, the values were 1.5 to 2.5 times more negative than the values recorded on DCI specimen, and similar to the values observed on A2000 specimen. After the specimens were moved outdoors, potentials increased for DCI, R222, and A2000 specimens and after 95 weeks of total exposure average potentials were -108 mV, -123 mV, and -297 mV, respectively. Since the 95th week measurement outdoors, the potentials for the DCI, R222, and A2000 specimens have again become more negative, -150 to -210 mV, -200 to -250 mV, -360 to -450 mV for the DCI, R222, and A2000 specimens, respectively, at the last reading time.

Potentials recorded in the Horizontal Zone of specimens with galvanized steel, GS-1 and GS-11, are presented in Figures 8 and 9, respectively. For both specimens, while inside the laboratory, potentials became less negative in time, with little variation between the bars. Average potentials measured after 7 weeks of ponding were -403 mV, for the GS-1 specimen, and -806 mV for the GS-11 specimen. After 72 weeks of ponding, average potentials were -275 mV and -581 mV for GS-1 and GS-11 specimens, respectively. The most negative values for specimens GS-1 and GS-11 were -447 mV after 9 weeks of ponding and -830 mV after 16 weeks of ponding, respectively. Once the specimens were moved outdoors, potentials became more negative and then less negative for specimen GS-1 and less negative for GS-11, see Figures 8 and 9.

Corrosion potentials observed in the Horizontal Zone of BS-1 and BS-2 specimens suggest possibility of an active corrosion process development during indoor exposure. A shift towards more negative potentials was observed after 40 weeks of ponding for all bars in the Horizontal Zone of both control specimens, see Figures 3 and 4. It is apparent that bar No. 4, BS-1 specimen, is leaning more towards an active corrosion region, with the lowest measured potential of -326 mV, than any other bar. Corrosion potentials observed in the Horizontal Zone of the DCI specimen were significantly less negative than controls indicating no corrosion activity. Two other specimens with corrosion inhibitors, R222 and A2000, however, had more negative potentials than the control specimens. It suggests a high probability of an active stage of corrosion for these two specimens. Besides, the potential data for A2000 specimen is more variable than it is for the R222 specimen indicating various stages of corrosion on different bars.

Another phenomenon was observed while measuring potentials after few weeks of outdoor exposure. The potential values in the Horizontal Zone of all specimens, except GS-1, increased significantly, especially for all bars in the BS-1, DCI, and R222 specimens, see Figures 3-9. A possible explanation is the fact that the specimens, after being moved outdoors, have dried out and a possible corrosion process taking place has been reduced. It is expected that once the moisture content of the concrete decks rises to a certain level, potentials will become more negative again and corrosion process will accelerate, as indeed subsequent measurements so indicate.

Potentials recorded in the GS-1 and GS-11 specimens were significantly more negative than the controls or specimens with CIA. A direct comparison is not possible because the measured potential refers to the zinc oxide and not to the steel. However, more negative potentials were recorded on the GS-11 specimen than on the GS-1 specimen. It appears that the zinc oxide of the bars in the GS-11 specimen corroded faster than in the GS-1 specimen. This would agree with the chloride and permeability data, and indicate damaging effect of chloride ions on the galvanized steel.

Corrosion Rates

Corrosion rates in the Horizontal Zone, Figures 10 and 11, were similar for both control specimens and were decreasing in time. After 105 weeks of exposure the average corrosion rates for BS-1 and BS-2 were relative constant at about 1.2 $\mu A/cm^2$ and 2 $\mu A/cm^2$ respectively. This corrosion rate behavior is typical, a very high spike in corrosion rate initially after the onset of corrosion followed by a decreasing corrosion rate to a near steady-state rate.

Corrosion rates in the Horizontal Zone, while the specimens were housed indoors, ranged from 4.60 $\mu A/cm^2$ to 5.58 $\mu A/cm^2$ for R222 specimen, from 6.11 $\mu A/cm^2$ to 7.54 $\mu A/cm^2$ for A2000 specimen, and from 2.82 $\mu A/cm^2$ to 3.83 $\mu A/cm^2$ for DCI specimen, see Figures 12-14. After the specimens were moved outdoors, corrosion rates initially decreased to 2.63 $\mu A/cm^2$ for R222 specimen, 2.01 $\mu A/cm^2$ for A2000 specimen, and 0.93 $\mu A/cm^2$ for DCI specimen. Since that time, the R222 corrosion rate has continued to decrease to about 0.9 $\mu A/cm^2$, the A2000 corrosion rate increased to about 3 $\mu A/cm^2$ and then returned to 2 $\mu A/cm^2$, and the DCI corrosion rate has continued to decrease to about 0.5 $\mu A/cm^2$. These rates indicate corrosion damage is possible in 2 to 15 years.

The corrosion rate results indicate that control specimens were in an active region of corrosion when they were kept indoors, since the corrosion rates were higher than 2 $\mu A/cm^2$, see Figures 10 and 11. The data from the Horizontal Zone agree with potential data, indicating a reduction in corrosion activity when the specimens were moved outdoors. While indoors, the R222 and A2000 specimens were corroding more than the controls, and the DCI specimen about the same as the controls, see figures 12-14.

Later age rate of corrosion measurements were the highest for the BS control specimens and the one prepared with A2000 and suggest corrosion damage in 2 to 10 years. Although early rate of corrosion measurements were higher or about the same as for BS control specimens, recent measurements were slightly lower for the specimen prepared with Rheocrete 222 and suggest corrosion damage in 10 to 15 years. Rate of corrosion measurements were consistently the lowest for the BS specimens prepared with DCI-S and indicate corrosion damage is expected in 10 to 15 years.

The corrosion potential and rate of corrosion data indicate that DCI-S is the only CIA evaluated that clearly provides some level of corrosion protection.

Chlorides

Chloride concentrations in blocks measured after 33 weeks of ponding are presented in Figure 15, for the Tidal Zone, and in Figure 16, for the Immersed Zone. Chloride concentrations in blocks measured after one year of ponding are presented in Figure 17, for the Tidal Zone, and in Figure 18, for the Immersed Zone. Chloride concentrations in specimens measured after 1.5 years of ponding are presented in Figures 19-22, for the Horizontal, Vertical, Tidal, and Immersed Zones, respectively.

Chloride concentration threshold of 0.71 kg/m^3 of concrete was reached at the bar depth, 25 mm, between 33 weeks and 1 year of ponding for controls, GS-1, DCI, and R222 specimens in all exposure zones, and for A2000 specimen in Horizontal, Vertical, and Tidal Zones.[8] Chloride concentration threshold at the bar depth, 25 mm, was reached by A2000 specimen in the Immersed Zone and GS-11 specimen in all exposure zones before 33 weeks of ponding. Chloride concentration measured from samples collected after 1 year of ponding were higher for all concrete types (DCI, R222, A2000, and GS-11) when compared to A4 concrete (controls and GS-1), see Figures 17 and 18. After 1.5 years of ponding, the highest concentration of chlorides, at the bar depth, were observed in the Horizontal and Vertical Zones, and the lowest in the Tidal and Immersed Zones, see Figures 19-22.

Once, the chloride ion concentrations were measured, diffusion constants were calculated for all concrete types. The calculations were performed in accordance to Fick's second low of diffusion with a boundary condition of surface concentration, C_0, being dependent on square root of time ($C_0 = k\sqrt{t}$). The solution is in the form of an equation:[11]

$$C_{(x,t)} = k\sqrt{t}\,[e^{-x^2/4D_c t} - \frac{x\sqrt{\pi}}{2\sqrt{D_c t}}\,(1 - erf\frac{x}{2\sqrt{D_c t}})]$$

where $C_{(x,t)}$ - chloride ion concentration at depth x after time t [kg/m^3 of concrete]
x - sample depth [mm]

t - time of exposure [years]
D_c - diffusion coefficient [mm^2/year]
erf - error function

After 1.5 years of indoor exposure, diffusion coefficients were 138, 199, 141, and 187 mm^2/year for A4 concrete, DCI, R222, and A2000 specimens, respectively. Control specimens and the GS-1 specimen were all cast with the A4 concrete. Diffusion constant for the GS-11 specimen was calculated to be 2510 mm^2/year.

Rapid Concrete Chloride Permeability

The rapid permeability was measured on cylinders of all concrete types after 28 days and 1 year of moist curing, see Figures 23 and 24, respectively. The rapid permeability values were the highest for the GS-11 specimen, w/c = 0.71. Even after 1 year of moist curing, the value was 4999 Coulombs, which is regarded as very high. This can be explained by a continuous pore system which resulted from high water to cement ratio. The second highest value was observed in the concrete with the DCI-S corrosion inhibitor. Its value was about two times that of controls after 28 days of wet curing and about 50% more than the controls after 1 year. The explanation may be the accelerating action of this product on cement hydration. In result, larger crystals are developed and permeability is increased. The rapid permeability results for the two other corrosion inhibitors were slightly higher than the controls, see Figures 23, 24 and Table 10.

The results of chloride testing indicate that the amount of chlorides present at the bar level is more than sufficient for corrosion to occur. Chloride concentration data agree with the rapid permeability test, see Table 10. After one year of ponding, the lowest chloride level and permeability were observed in the control and GS-1 specimens (A4 concrete), higher values were observed in specimens with CIA, and the highest in the GS-11 specimen. After 1.5 years of ponding, chloride concentrations in the GS-11 specimen were significantly higher than in any other specimen, see Figures 19-22. Chloride concentrations in the specimens with CIA were all similar to each other and to controls. For specimens with CIA, there appears to be no significant difference in a rate of chloride ingress in comparison to the controls. Also the diffusion constants were not significantly different from the control, even though they were higher.

High concentration level of chlorides in the GS-11 specimen is certainly attributed to the high permeability caused by the high water/cement ratio equal to 0.71. Calculated diffusion constant was more than 20 times larger than any of the other specimens. Due to high concentration of chlorides at the bar depth, it was anticipated that the GS-11 specimen would be the first to crack, and it did shortly after being moved outdoors.

Visual Observations

Figures 25-31 present visually observed cracks and rust stains in the BS-1, BS-2, DCI, R222, A2000, GS-1, and GS-11 specimens, after approximately four months of outdoor exposure. As shown, most of cracking had occurred in the Horizontal and Vertical Zones and over the bars that were not included in the corrosion condition assessment. For the BS-1 specimen one crack in the

Horizontal Zone was found, see Figure 25. The crack with a rust spot was first observed after 54 weeks of exposure over the bar No. 4a, between points 4 and 8. Five smaller cracks were found in the Vertical Zone, four of which were on the left leg and one on the right leg, see Figure 25. In the left leg, one crack was over the top mat reinforcing bar, two cracks over the bar No. 1a and one crack over the bar No. 1. In addition to the two cracks over the bar No. 1a, relatively large rust stains were also observed. The crack in the right leg was observed in the upper right corner. It was the only crack progressing vertically and also the shortest crack of all cracks found in the BS-1 specimen. As shown in Figure 26, several cracks were found in the Horizontal Zone, as well as in the legs of the BS-2 specimen. The two cracks in the Horizontal Zone were found over the side bars, 1a and 4a. The bar No. 1a also caused cracking in the right leg, and the bar No. 4a in the left leg. These cracks appeared in the upper parts of the specimen's legs. Two rust spots were found in the lower part of the specimen: one over the bar No. 1 in the Tidal Zone, the other one was on the boundary between the Tidal and Immersed Zones, see Figure 26. In addition, two structural cracks were formed while the specimen was being removed from the steel forms. These cracks progressed through the whole thickness of each leg. The structural crack in the left leg occurred in the vicinity of the bar No. 1a, while the crack in the right leg close to the bar from the bottom mat of the deck reinforcement. There were only two cracks and four rust spots in the DCI specimen, see Figure 27. These two cracks were found in the upper right corner of the right leg, over the bar from the top mat of deck reinforcement. As presented in Figure 27, the rust spots were observed in each upper corner of specimen's legs. Cracks in the R222 specimen occurred in the deck and the upper part of both legs, see Figure 28. Seven cracks that were found in the Horizontal Zone occurred over the bars No. 1a, 1, 3a, 4, and 4a. Cracking in the right leg occurred only over the bar from the top mat of deck reinforcement. Cracking in the left leg occurred over the bars from the top and bottom mats of deck reinforcement. A structural crack, caused by specimen's removal from the forms, occurred in the left leg just below the bar from the bottom mat of deck's reinforcement. In addition to cracking, four rust spots were observed in the left leg, see Figure 28. As for the A2000 specimen, cracks were found in the upper parts of both legs, and cracks and a rust spot in the deck, see Figure 29. Cracking in the left leg occurred in the Vertical Zone over the bars No. 2a and 3. Cracking in the right leg occurred only over the bar from the top mat of deck reinforcement. Cracks in the Horizontal Zone occurred over the bars No. 1a, 1, 2a, and 4a. The rust spot was observed close to the crack found over the bar No. 2a. The GS-1 specimen had one structural crack in the left leg, just below the bar from the deck bottom mat, see Figure 30. No cracks due to corrosion were found at the time of investigation. For the GS-11 specimen cracks were observed over almost every bar in each exposure zone, see Figure 31. In addition to the cracks progressing over the bars, there were two cracks in the right leg and one in the left leg that were perpendicular to the main reinforcing steel. The crack in the left leg extended from the bar No. 2a to the bar No. 3. The two cracks in the right leg were 3-4 times longer and extended from the bar No. 1a to the bar No. 2b and from the bar No. 1 to the bar No. 3a. No cracks were observed in the Tidal Zone of the right leg, bar No. 3 in the Tidal Zone of the left leg, bars from the top mat of deck reinforcement in both legs, and bar No. 2a in the Horizontal Zone.

Before exposure to sodium chloride solution, all structural cracks were filled with silicone and a duct tape was applied over the crack to minimize the influence of these cracks to corrosion development. These cracks appeared to have no influence on the corrosion development on the bars in the vicinity of the these cracks indicating that the silicone and duct tape protection was adequate.

The cracking, other than structural, appeared to be related to the reinforcing steel corrosion. The bars No. 1a and No. 4a in the Horizontal Zone and being corner bars at the Horizontal and Vertical interaction zones were expected to corrode first since they were exposed to more severe condition than any other bar. The chlorides diffused from the top, 25 mm of the cover depth in the Horizontal Zone, and from the side, 25 mm cover depth in the leg. This behavior was observed in all specimens with an exception of the GS-1 specimen that did not have any cracks at the time of evaluation.

The largest number of cracks and the highest severity was observed in the GS-11 specimen. The cracks were found in all exposure zones, except the Tidal Zone in the right leg. This specimen was the only one with a high water-to-cement ratio, 0.71, and consequently the highest chloride concentrations at the bar depth. Since the GS-1 specimen did now exhibit any cracking, it was concluded that galvanized steel can provide corrosion protection, at low and moderate chloride exposures.

From the specimens with CIA, the DCI specimen looked best since rust spots and cracks appeared only over the bars that had double exposure of chlorides. Also, the cracks were shorter than the ones observed in the R222, A2000, or control specimens. The R222, A2000, and control specimens had similar degree of visual damage, however, more cracks were found in the Horizontal Zone of the R222 and A2000 specimens than in the controls. It appears that these corrosion inhibitors were not slowing the development of corrosion, but rather accelerating it, especially since the total exposure time of R222 and A2000 specimens was shorter than the controls.

It is believed that some of the rust stains and cracking found on the specimens' surfaces were caused by the corrosion of the steel ties that must have changed their positions during concrete placement and vibration resulting in a shallower cover depth than the 25 mm for the reinforcing steel. This was confirmed by the cover depth check with a rebar locator device. The BS-2 and A2000 were the specimens that were affected. In case of the BS-2 specimen there were three locations with a cover depth lower than 25 mm, and all of them were in the right leg. A 22 mm cover was found in the location of the rust spot in the Vertical Zone. Also, a 22 mm cover was found in the location of a crack, in the middle of leg's width, that was associated with the deck top mat bar that is in the right leg face. A cover of 23 mm was observed in the location of the rust spot in the Tidal Zone. As for the A2000 specimen, a cover depth of 17 mm was found in the Vertical Zone of the left leg in the location of a crack and a rust spot that occurred over the bar No. 2a.

CONCLUSIONS

Based on the potential and corrosion rate data, as well as visual observations, two CIA, Rheocrete 222 and Armatec 2000 (R222 and A2000 specimens), appear to provide little to no corrosion inhibition, while DCI-S corrosion inhibitor (DCI specimen) increases the chloride corrosion threshold limit in concrete. These results confirm the results and conclusions of the companion study on CIA in simulated concrete pore solutions.[11] Also, GS is providing corrosion protection in A4 concrete.

RECOMMENDATIONS

It is recommended that annual monitoring of the specimens be continued until more cracking has occurred on all specimens in all exposure zones in order to estimate the service extension provided by CIA and GS used in the construction of concrete bridge components in Virginia. Also, DCI-S should remain as the only approved CIA for use in Virginia at this time.

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7. SHRP-S / FR-92-110, *Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion*, Volume 8: Procedure Manual, 1992.
8. ASTM C-114-88 *Standard Test Methods for Chemical Analysis of Hydraulic Cement, Section 19: Chloride (Reference Test Method)*
9. ASTM C 876-80 *Standard Test Method for Half Cell Potentials of Reinforcing Steel in Concrete*
10. ASTM C 1202, *Standard Test Method for Electrical Indication of Concrete's Ability to resist Chloride Ion Penetration*
11. Pyc, W., R.E. Weyers, M. Sprinkel, "Corrosion Protection Performance of Corrosion Inhibitors and Epoxy-Coated Reinforcing Steel in a Simulated Concrete Pore Water Solution, " Virginia Transportation Research Council, Charlottesville, VA, VTRC 98-R42, June 1998.

Table 1. Specimen Configuration.

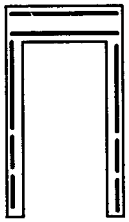
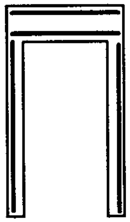
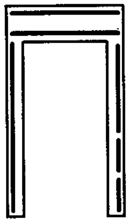
Specimen Legs' Reinforcement	A4 Concrete No Corrosion Inhibitor		A4 Concrete with Corrosion Inhibitor		
			DCI-S	Rheocrete 222	Armatec 2000
	Bare Steel	Galvanized Steel	Bare Steel	Bare Steel	Bare Steel
Type I 	BS-1 (Control 1)				
Type II 	BS-2 (Control 2)				
Type III 		GS-1 GS-11	DCI	R222	A2000

Table 2. Recommended Action for Chloride Content Measurements.

Chloride Concentration	Recommendation
< 0.59 kg/m^3	leave intact
$0.59 - 1.19$ kg/m^3	questionable area
> 1.19 kg/m^3	remove concrete below bar level or replace entire section

Table 3. ASTM C-876 Interpretation of Potential Readings.

Voltmeter Reading	Interpretation
more than -200 mV	90% probability of no corrosion
from -200 mV to -350 mV	uncertain
less than -350 mV	90% probability of active corrosion

Table 4. Manufacturer's Data Interpretation for 3LP Device.

i_{corr}	Interpretation
$< 0.21\ \mu A/cm^2$	no damage expected
$0.21 - 1.07\ \mu A/cm^2$	damage possible in 10-15 years
$1.07 - 10.7\ \mu A/cm^2$	damage possible in 2-10 years
$> 10.7\ \mu A/cm^2$	damage possible in less than 2 years

Table 5. Physical and Chemical Properties of Bare Steel.

Physical Properties		Chemical Properties	
Yield Point [MPa]	425 - 473	C [%]	0.38 - 0.43
Tensile Strength [MPa]	645 - 703	Mn [%]	0.83 - 1.00
% Elongation [200 mm]	10	P [%]	0.01
		S [%]	0.03 - 0.05

Table 6. Concrete Mixtures.

Concrete	A4	DCI	R222	A2000
Ingredients [kg/m^3 of concrete]				
Cement	377	377	377	377
#78 Coarse Aggregate	867	867	867	867
Fine Aggregate	864	856	864	864
Water	170	153	170	170
Corrosion Inhibitor [l/m^3 of concrete]:				
DCI-S	-	20	-	-
Rheocrete 222	-	-	5.0	-
Armatec 2000	-	-	-	2.5
Admixtures [ml/100 kg of cement]:				
HRWR: WRDA-19	1215, 914	782	-	-
HRWR: Rheobuild 1000	-	-	780	792
AEA: Daravair-M	72, 69	69	69	52
AEA: MB-VR	-	-	69	-

Table 7. Cement Properties (as Provided by the Manufacturer).

Chemical Test Data		Physical Test Data	
SiO_2	22.1	Fineness - Blaine	3760
Al_2O_3	4.29	Fineness - Wagner	2212
Fe_2O_3	2.83	Autoclave Expansion	0.05
CaO	63.4	Initial Set (H:min.)	2:25
MgO	2.86	Final Set (H:min.)	3:35
SO_3	2.23	Vicat (min.)	95
Total Alkalies	0.62	Air Content (Mortar)	6.6
Insoluble Residue	---	Compressive Strength [MPa]	
Ignition Loss	1.1	1 day	15.0
C_3S	51.3	3 day	27.4
C_3A	6.58	7 day	35.5

Table 8. Fresh Concrete Properties.

Specimen	Water/Cement Ratio	Slump [mm]	Air [%]	Temperature [C]	Density [g/cm^3]
BS-1	0.46	191	6.2	25	2.34
BS-2	0.44	203	5.5	26	2.34
DCI	0.45	152	5.4	26	2.33
R222	0.44	178	4.7	22	2.36
A2000	0.44	152	5.2	25	2.33
GS-1	0.44	203	8.0	18	2.29
GS-11	0.71	152	7.4	22	2.25

Table 9. Compressive Strengths.

Specimen	Average Compressive Strength (Mpa)				
	3 days	7 days	28 days	56 days	1 year
BS-1	39	48	58	62	72
BS-2	35	40	48	54	63
DCI	31	36	49	52	60
R222	29	36	41	44	54
A2000	29	34	45	47	58
GS-1	36	39	44	50	59
GS-11	11	15	21	21	22

Table 10. Rapid Concrete Chloride Permeability.

Specimen	Water/Cement Ratio	Permeability [Coulomb] 28 days	Permeability [Coulomb] 1 year
BS-1	0.46	3049	1816
BS-2	0.44	3120	2048
DCI	0.45	6413	3002
R222	0.44	3595	2384
A2000	0.44	3236	2516
GS-1	0.44	2958	1209
GS-11	0.71	8818	4999

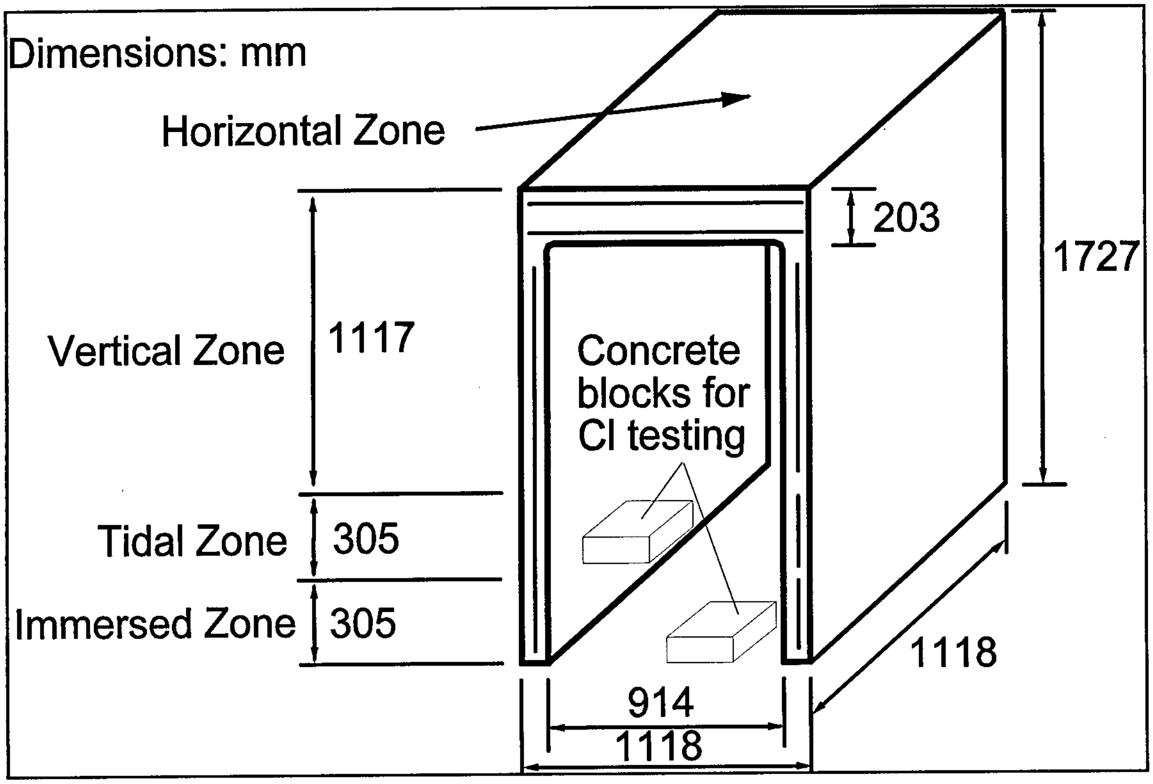


Figure 1. Specimen Configuration.

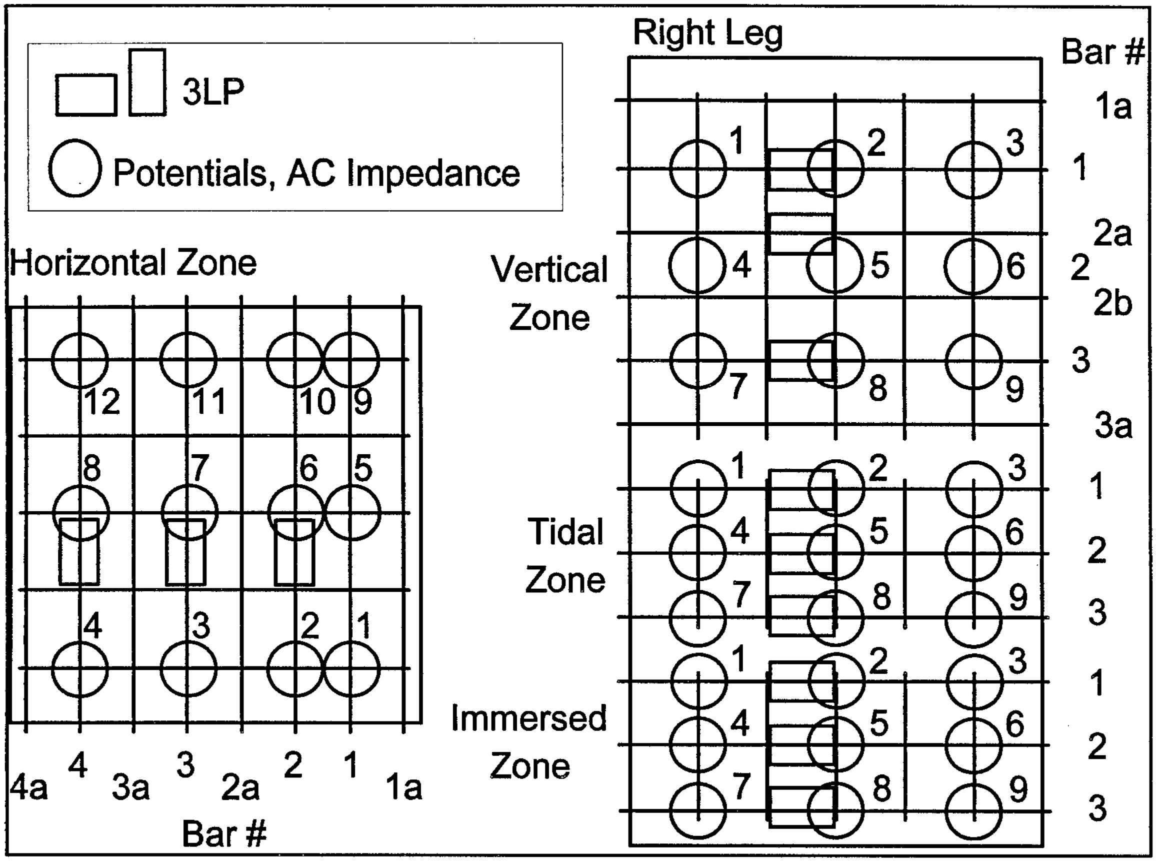


Figure 2. Measurement Plan.

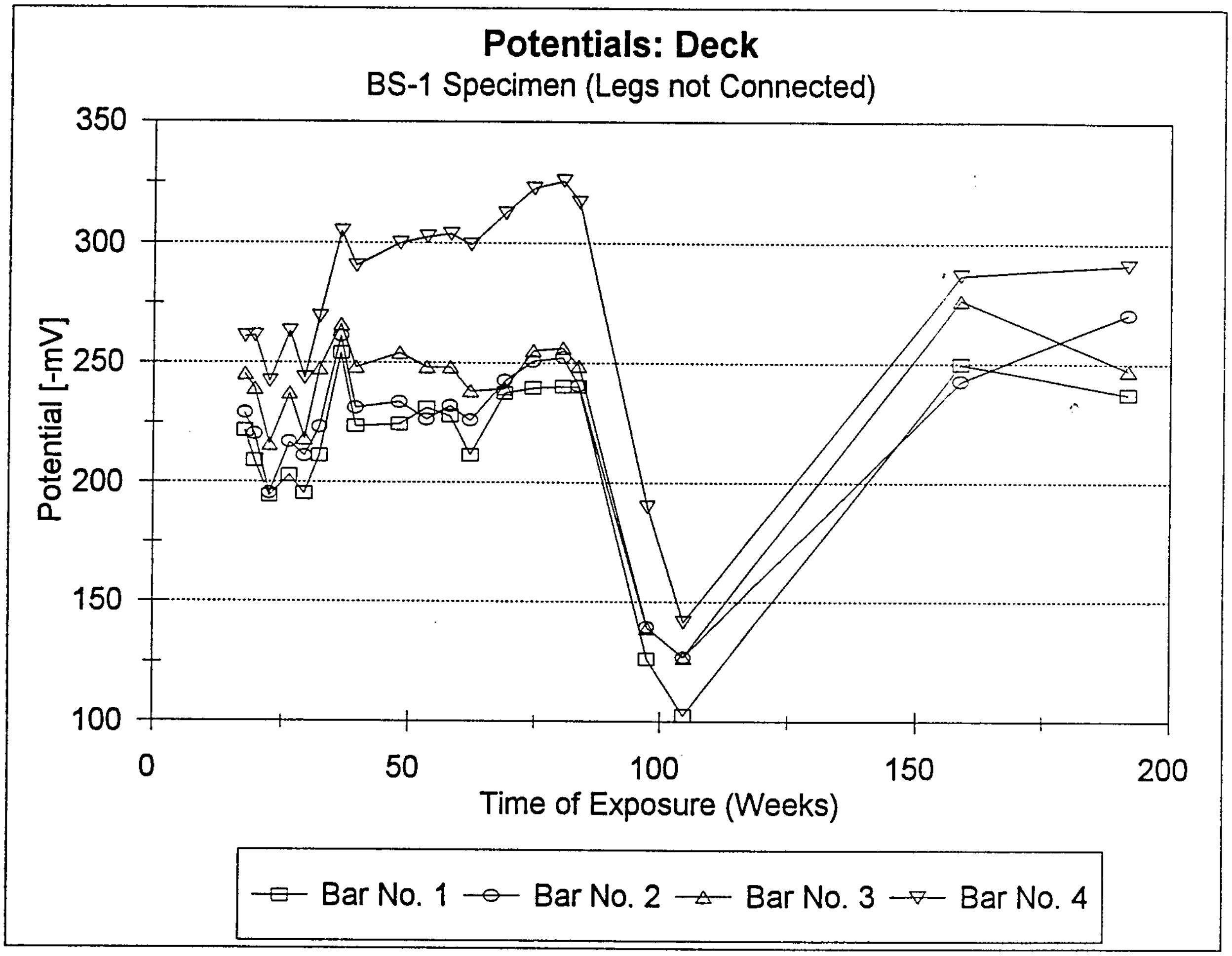


Figure 3. Corrosion Potentials in the Horizontal Zone, BS-1 Specimen (Control 1).

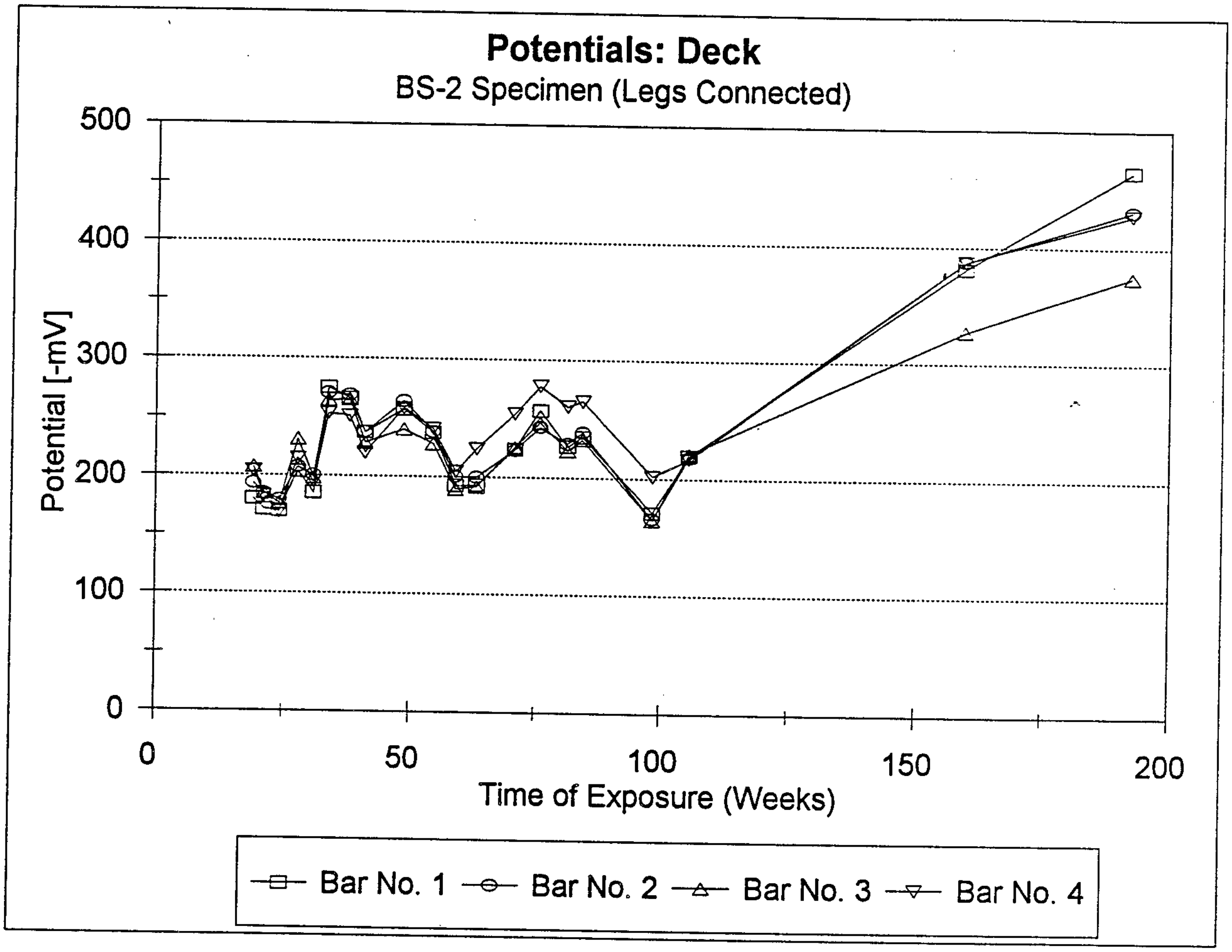


Figure 4. Corrosion Potentials in the Horizontal Zone, BS-2 Specimen (Control 2).

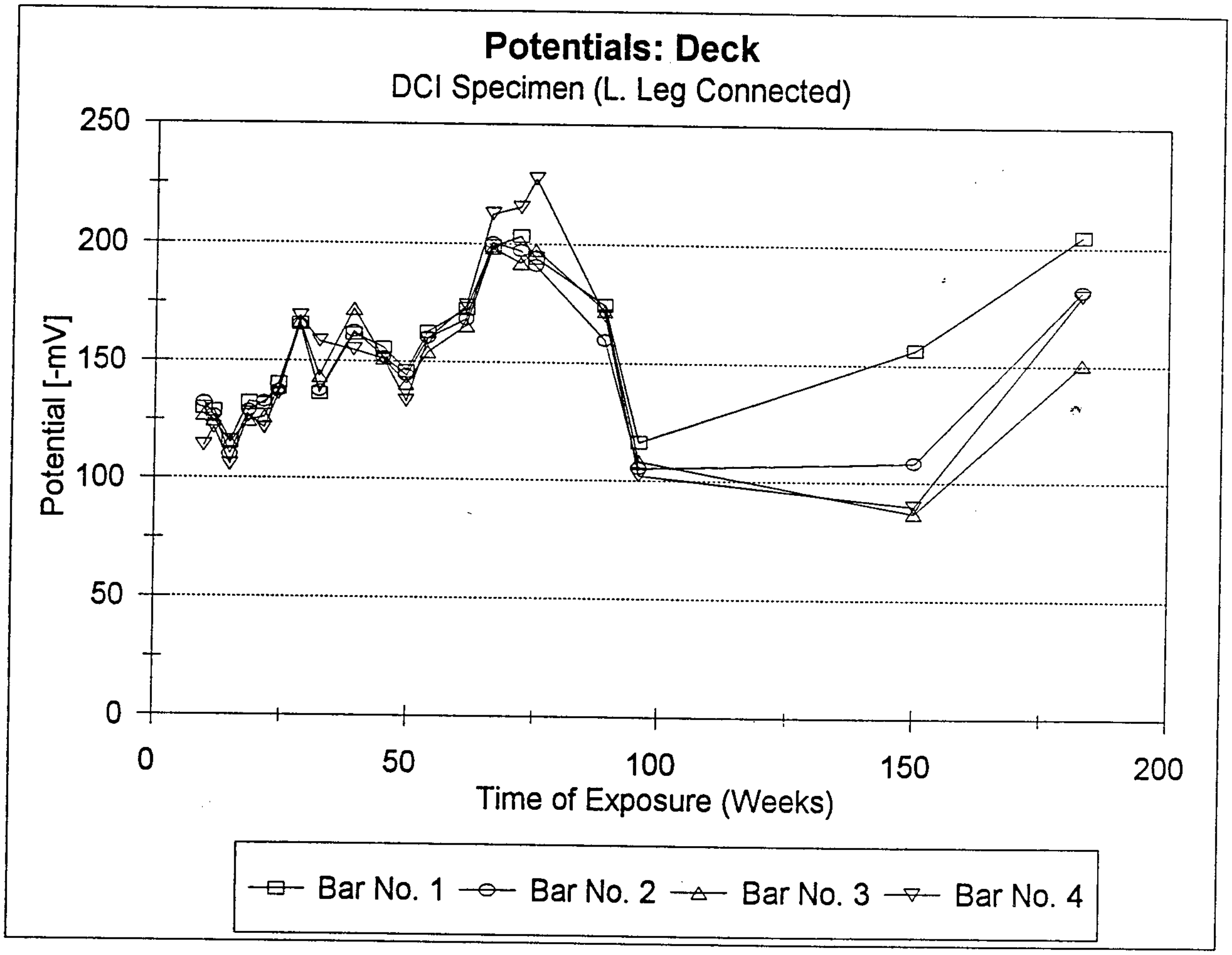


Figure 5. Corrosion Potentials in the Horizontal Zone, DCI Specimen.

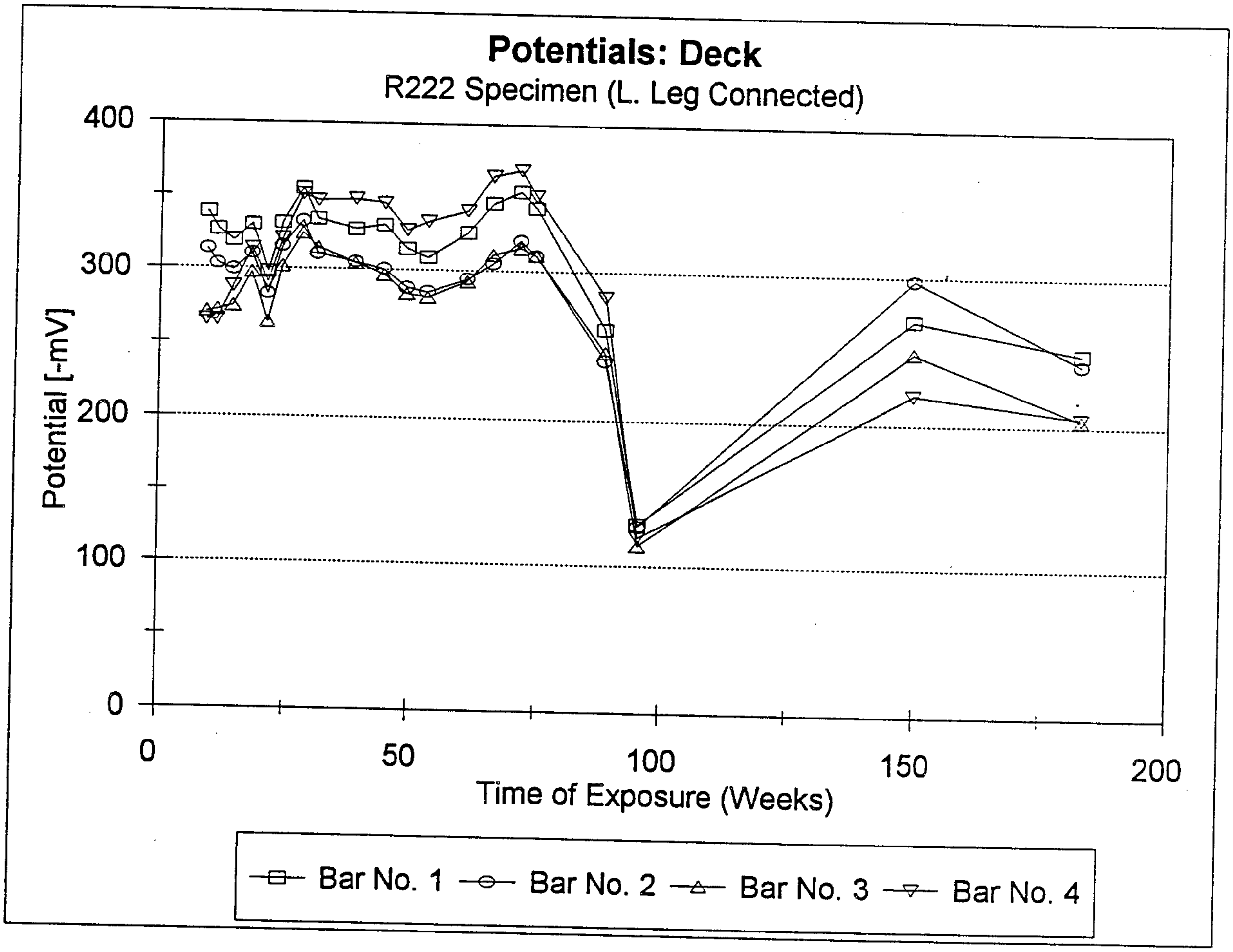


Figure 6. Corrosion Potentials in the Horizontal Zone, R222 Specimen.

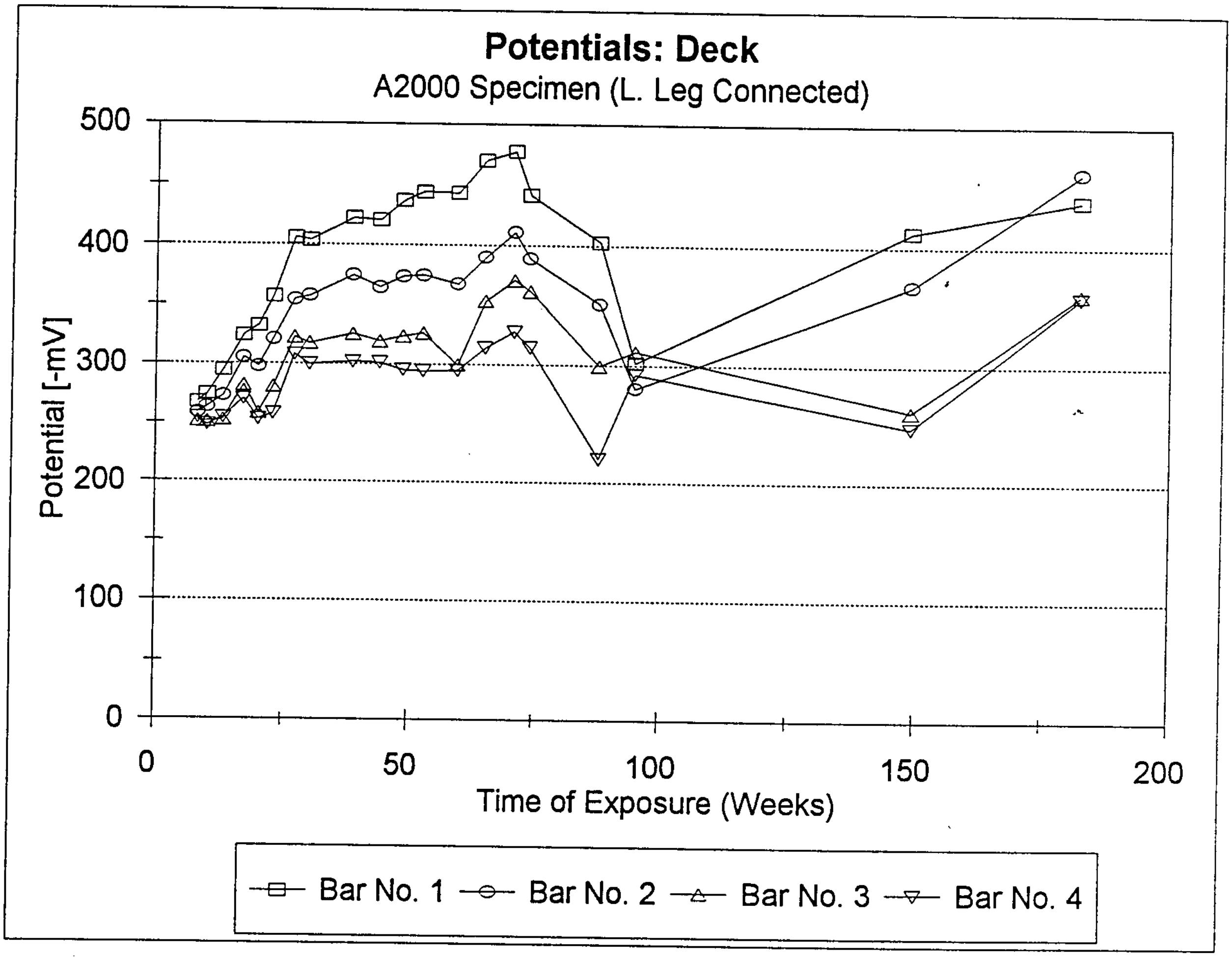


Figure 7. Corrosion Potentials in the Horizontal Zone, A2000 Specimen.

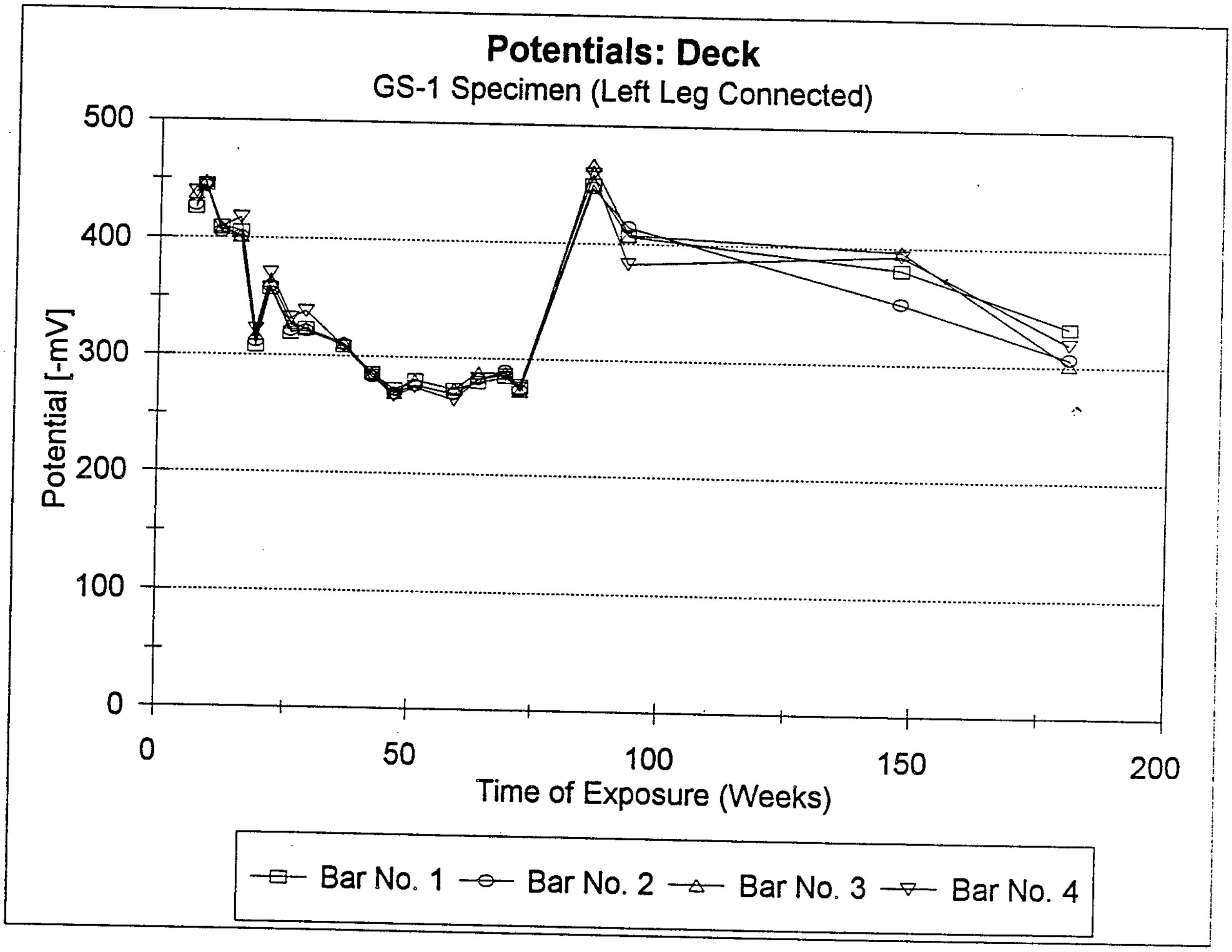


Figure 8. Corrosion Potentials in the Horizontal Zone, GS-1 Specimen.

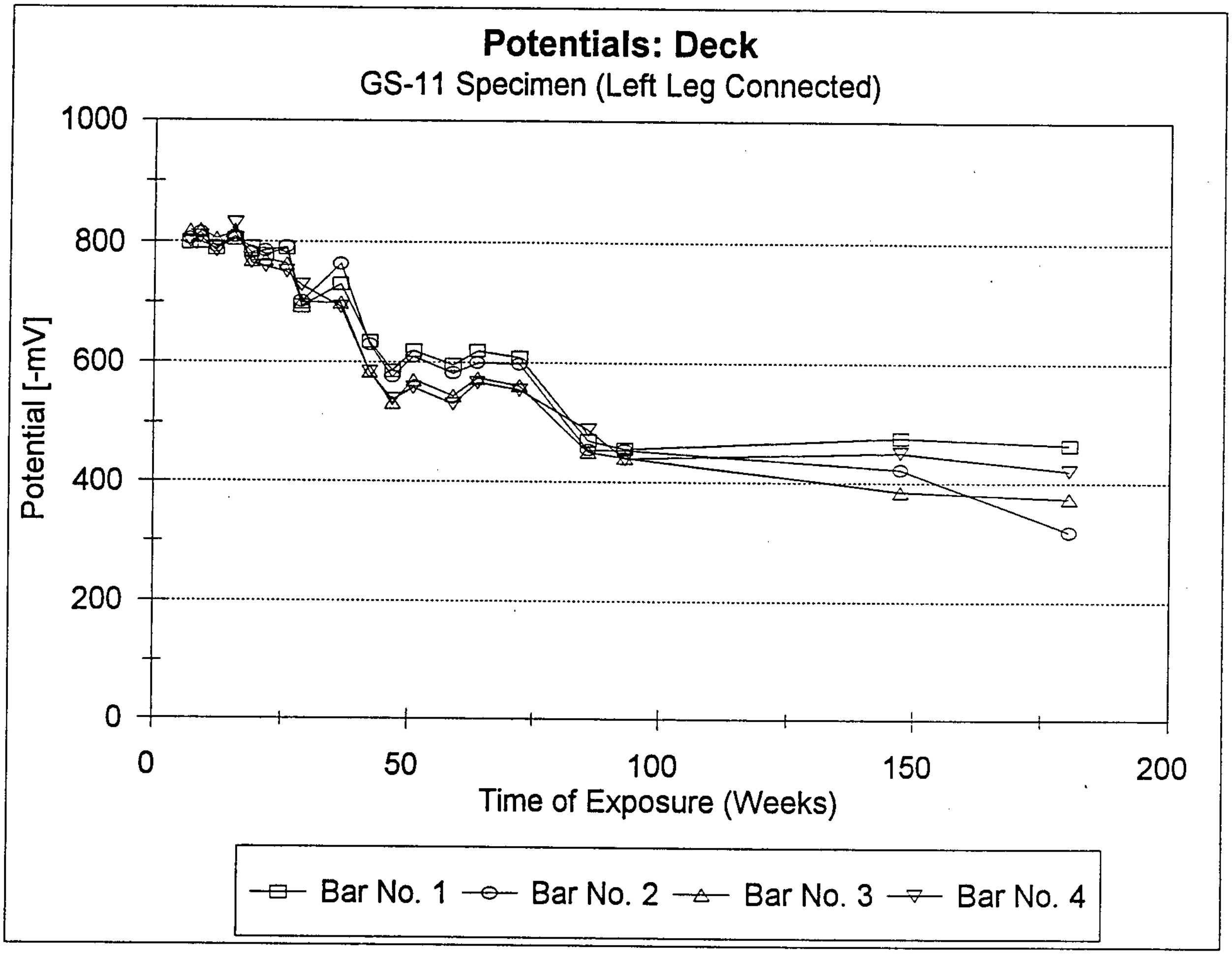


Figure 9. Corrosion Potentials in the Horizontal Zone, GS-11 Specimen.

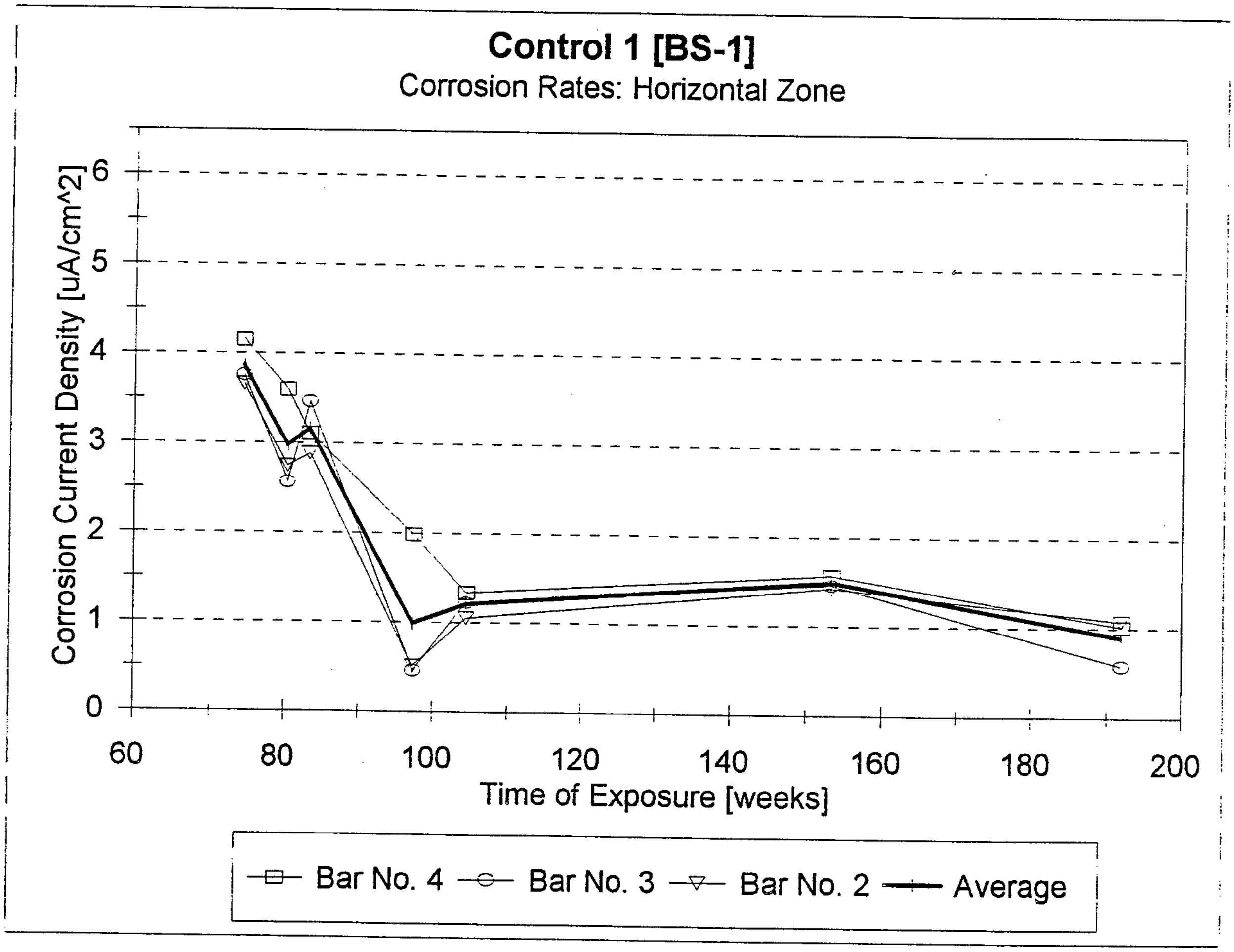


Figure 10. Corrosion Rates in the Horizontal Zone, BS-1 Specimen.

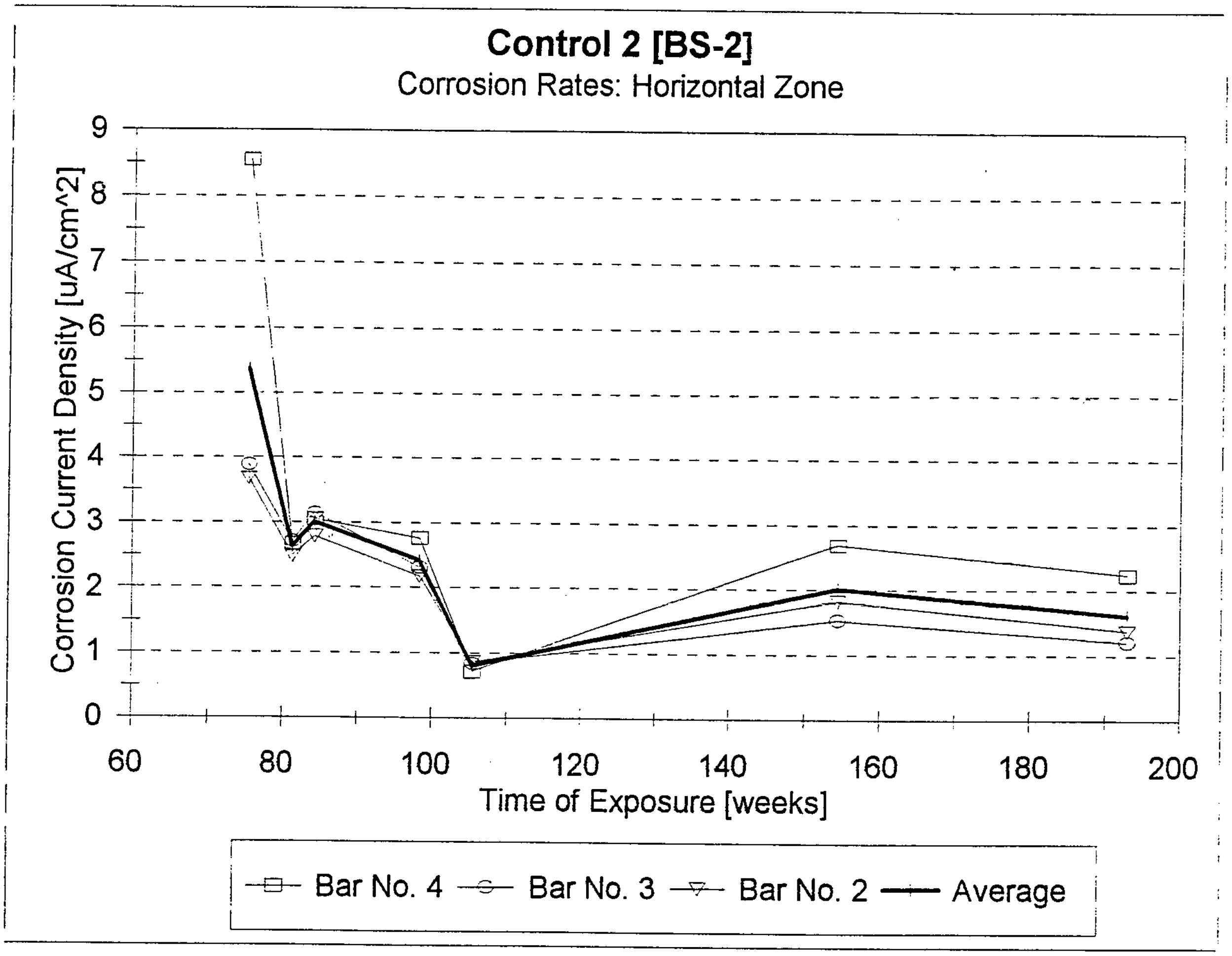


Figure 11. Corrosion Rates in the Horizontal Zone, BS-2 Specimen.

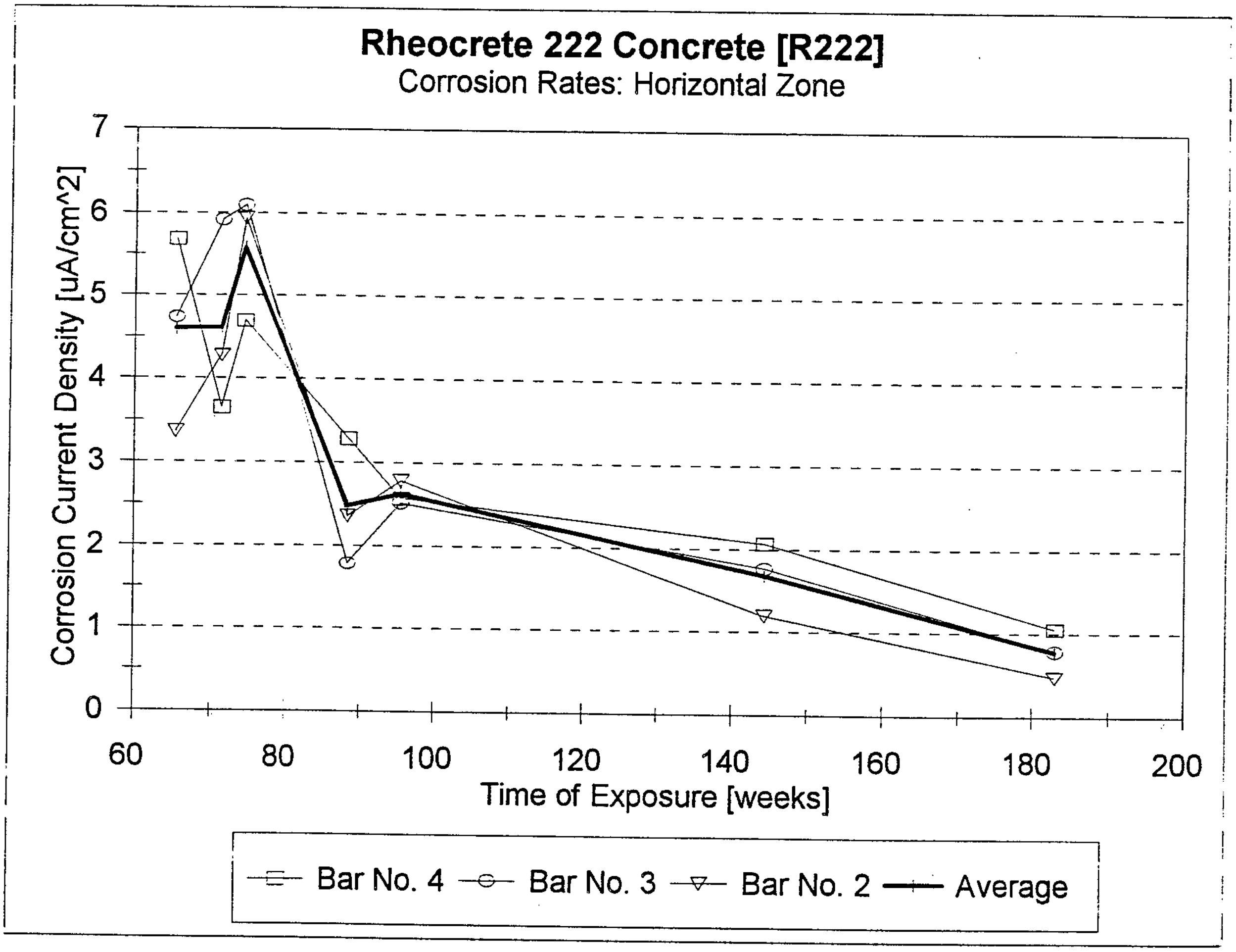


Figure 12. Corrosion Rates in the Horizontal Zone, R222 Specimen.

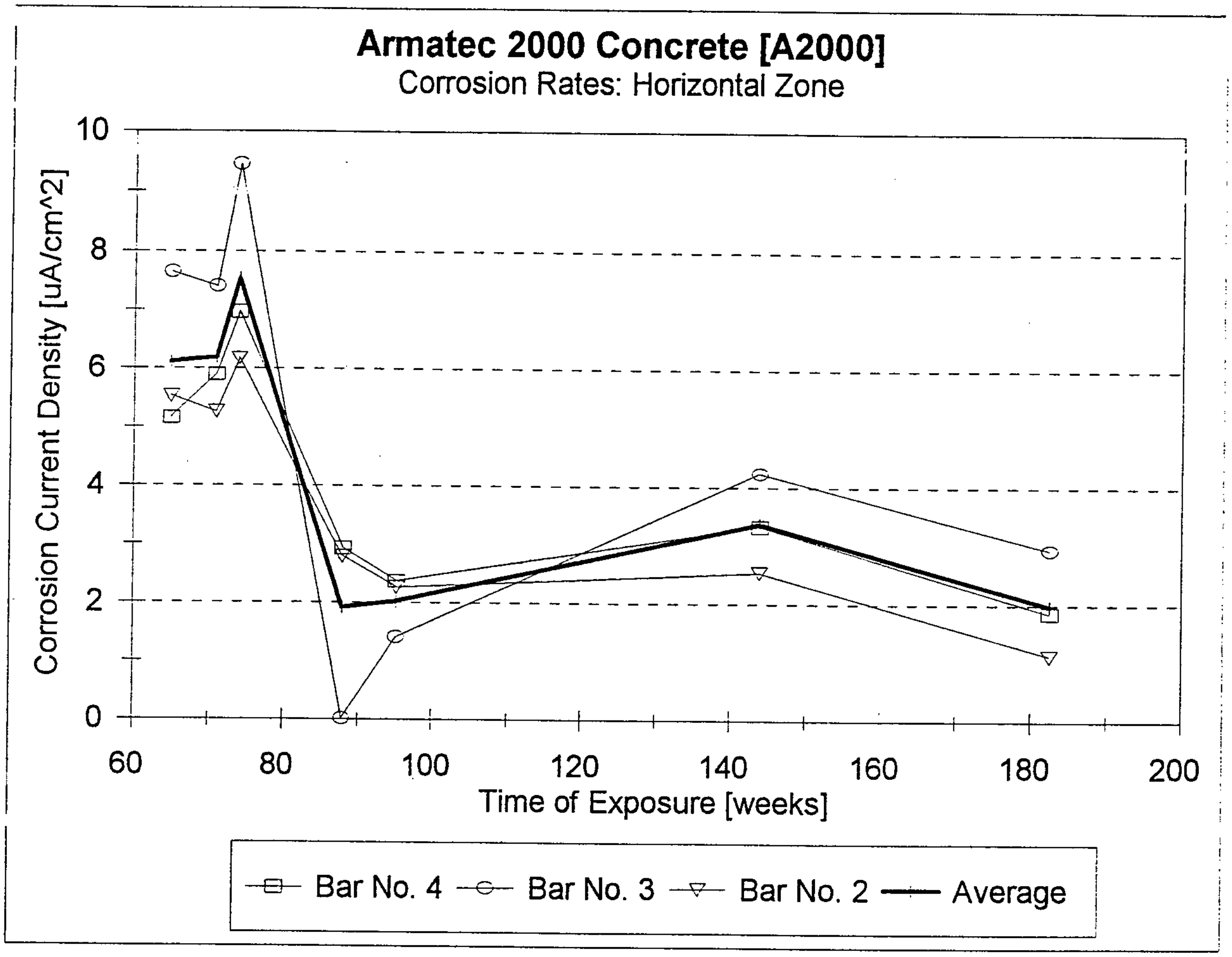


Figure 13. Corrosion Rates in the Horizontal Zone, A2000 Specimen.

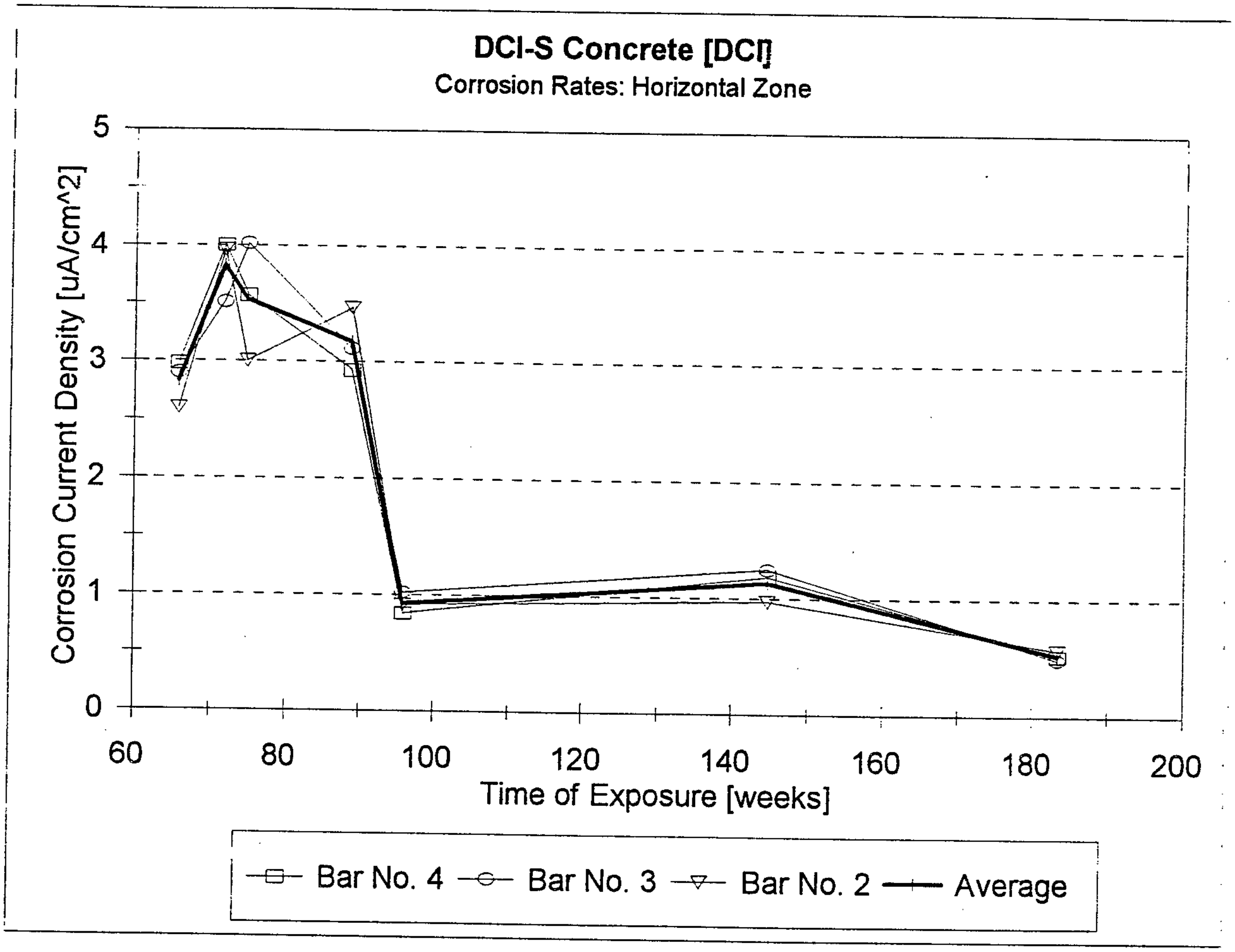


Figure 14. Corrosion Rates in the Horizontal Zone, DCI Specimen.

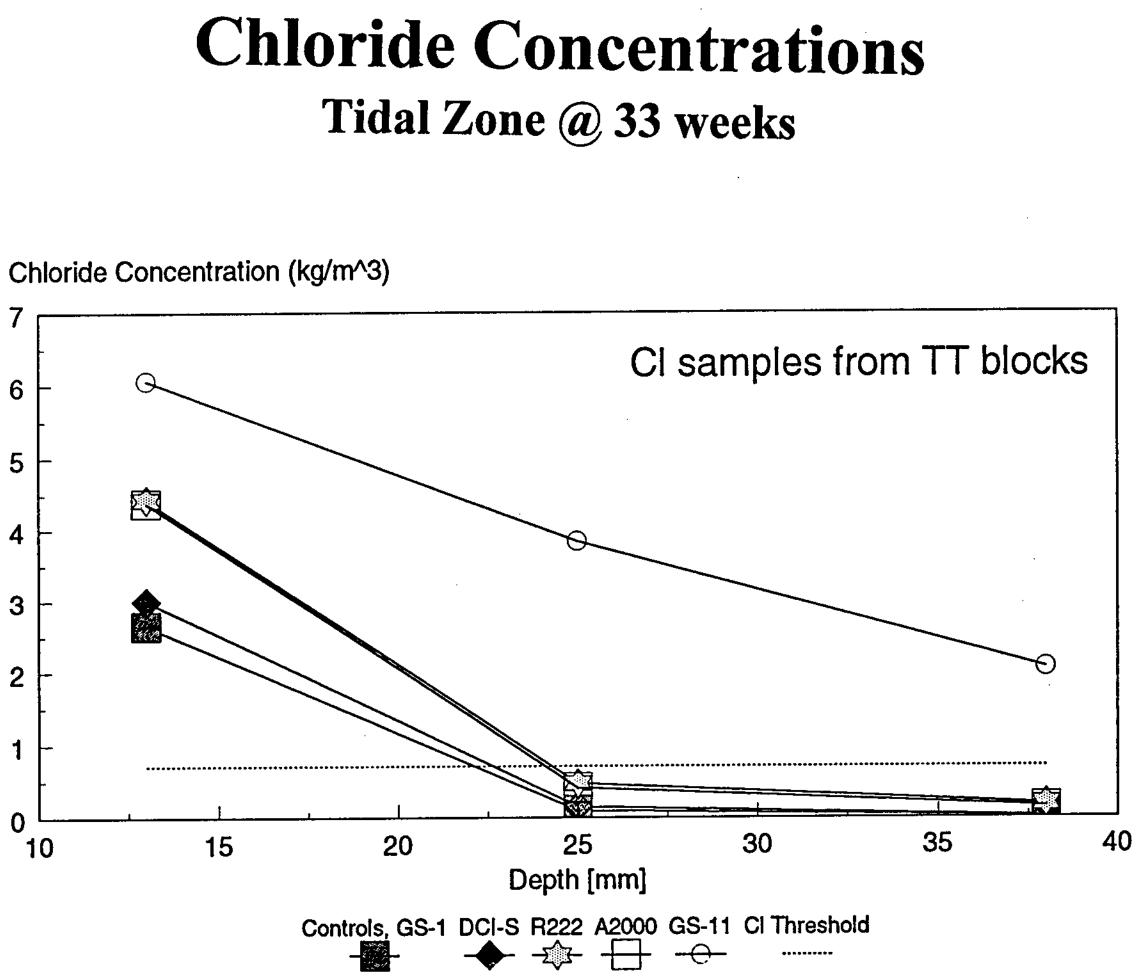


Figure 15. Chloride Concentrations at 33 Weeks, Tidal Zone

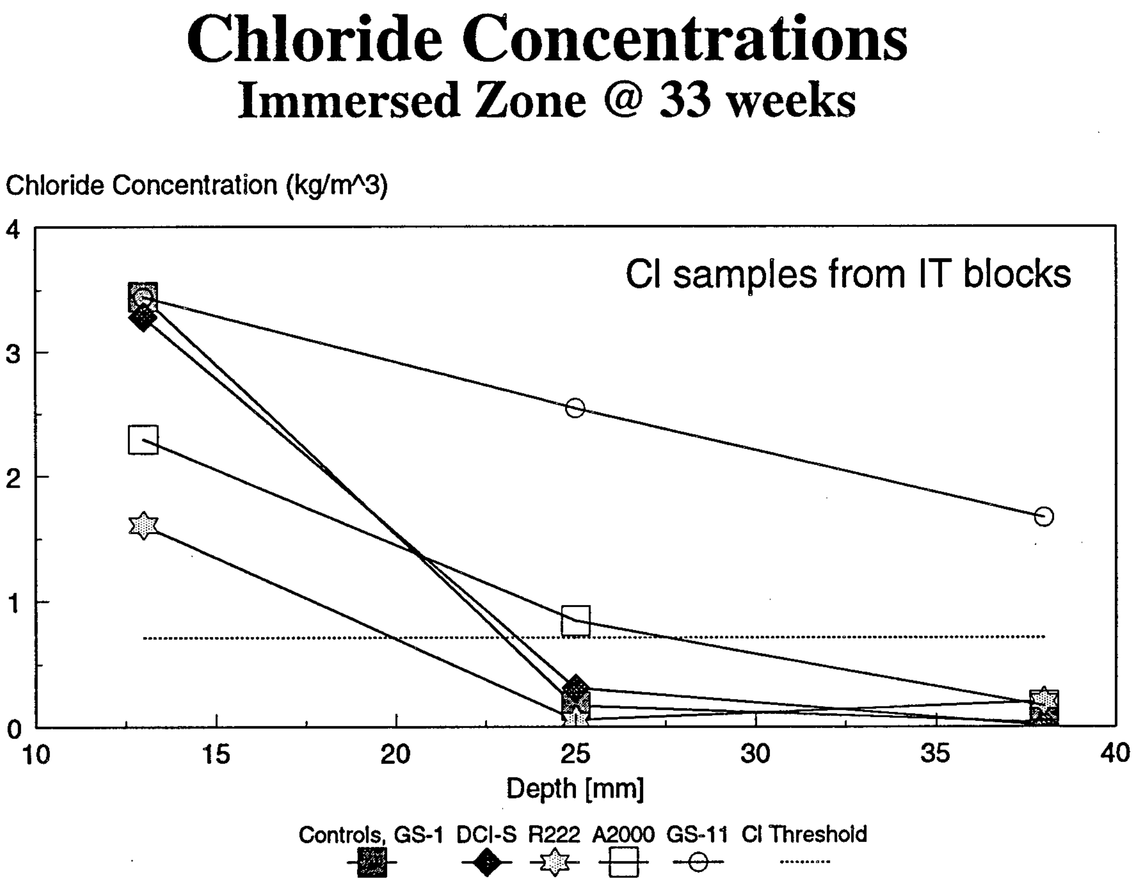


Figure 16. Chloride Concentrations at 33 Weeks, Immersed Zone.

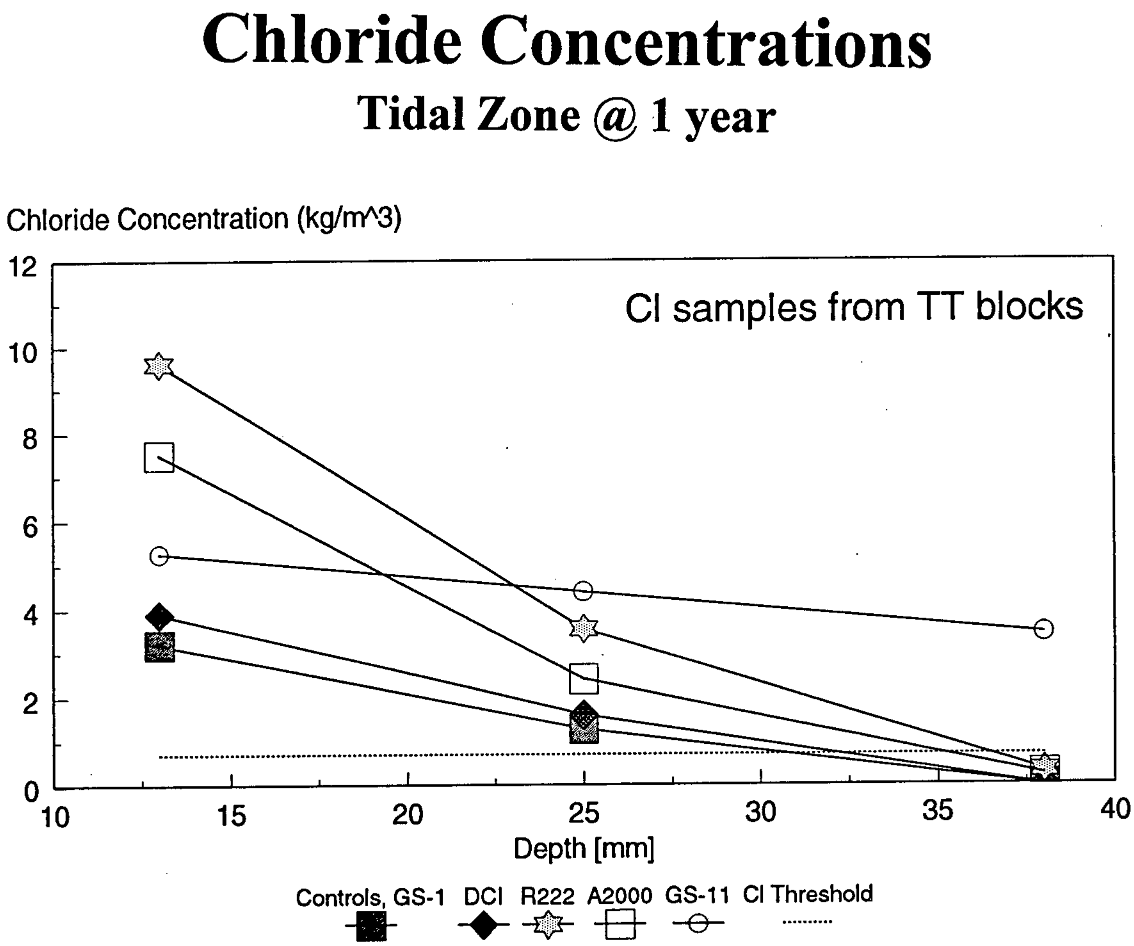


Figure 17. Chloride Concentrations at 1 Year, Tidal Zone

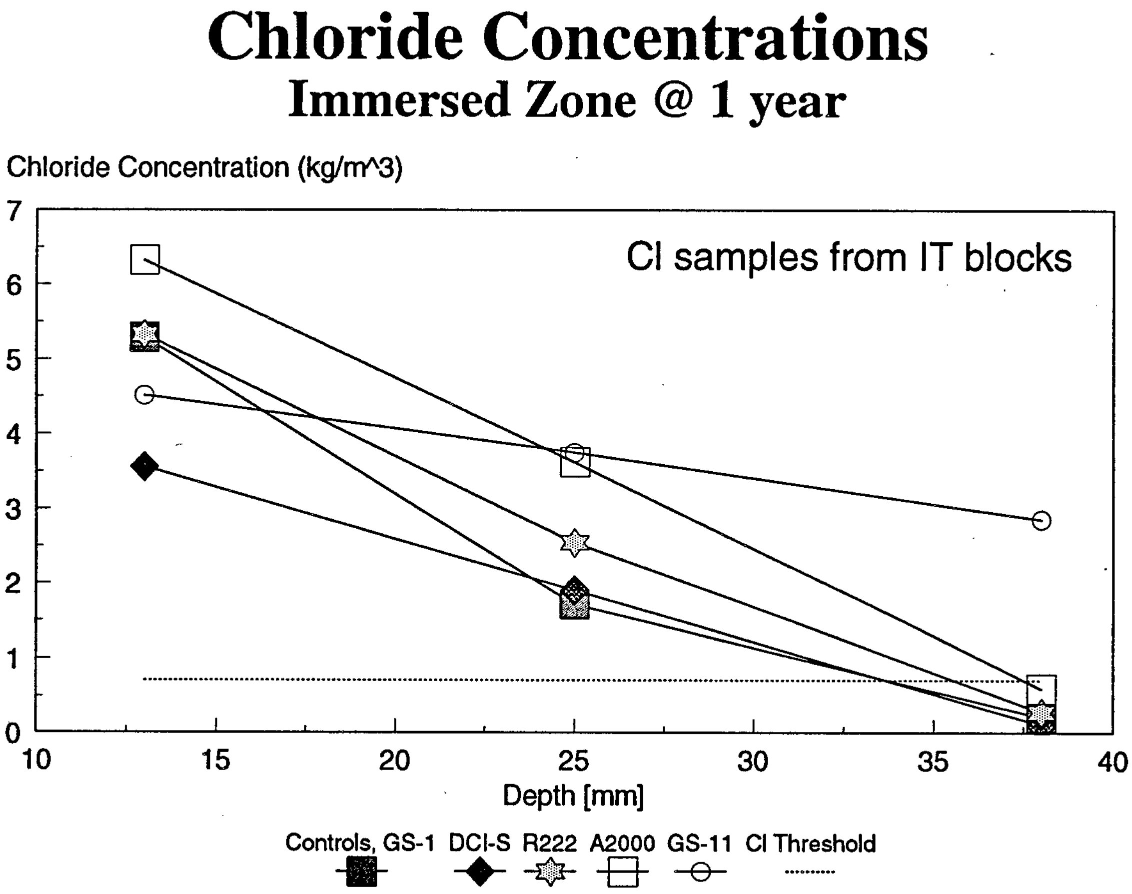


Figure 18. Chloride Concentrations at 1 Year, Immersed Zone.

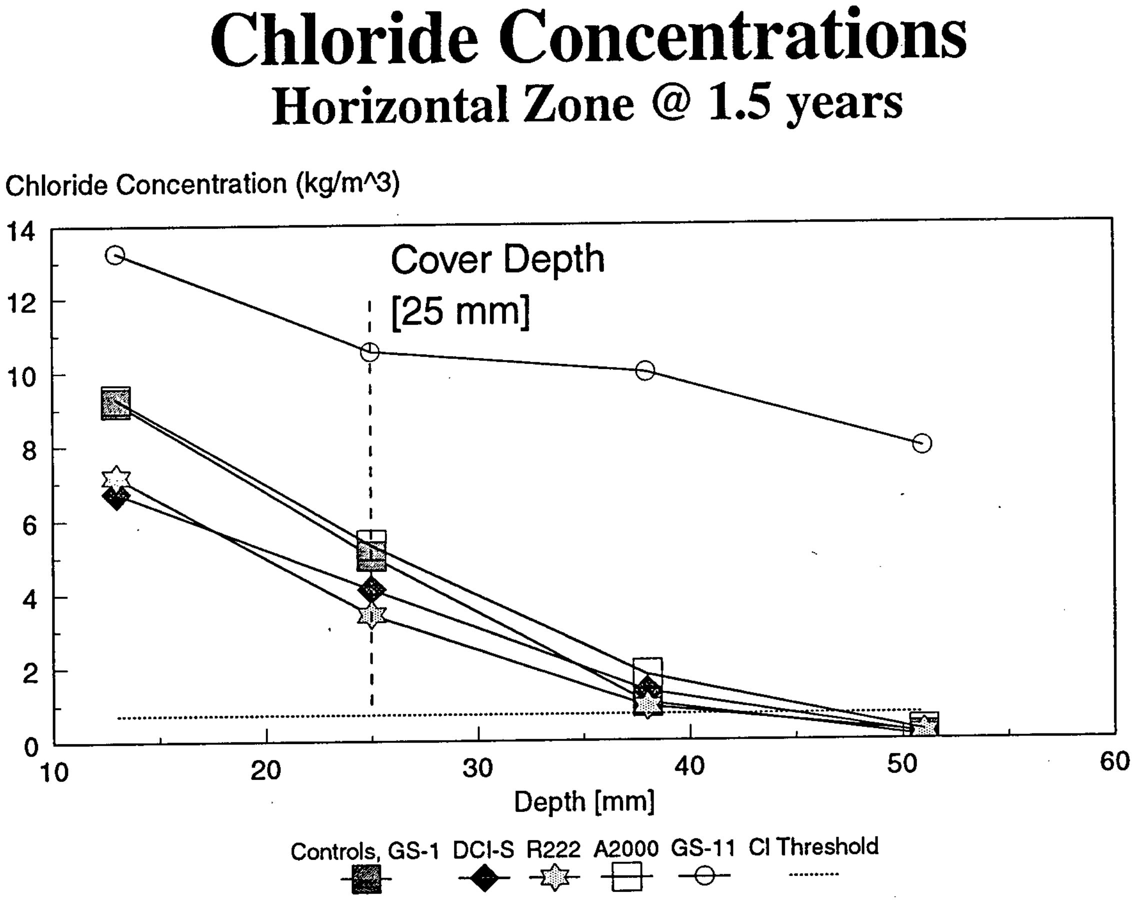


Figure 19. Chloride Concentrations at 1.5 Year, Horizontal Zone.

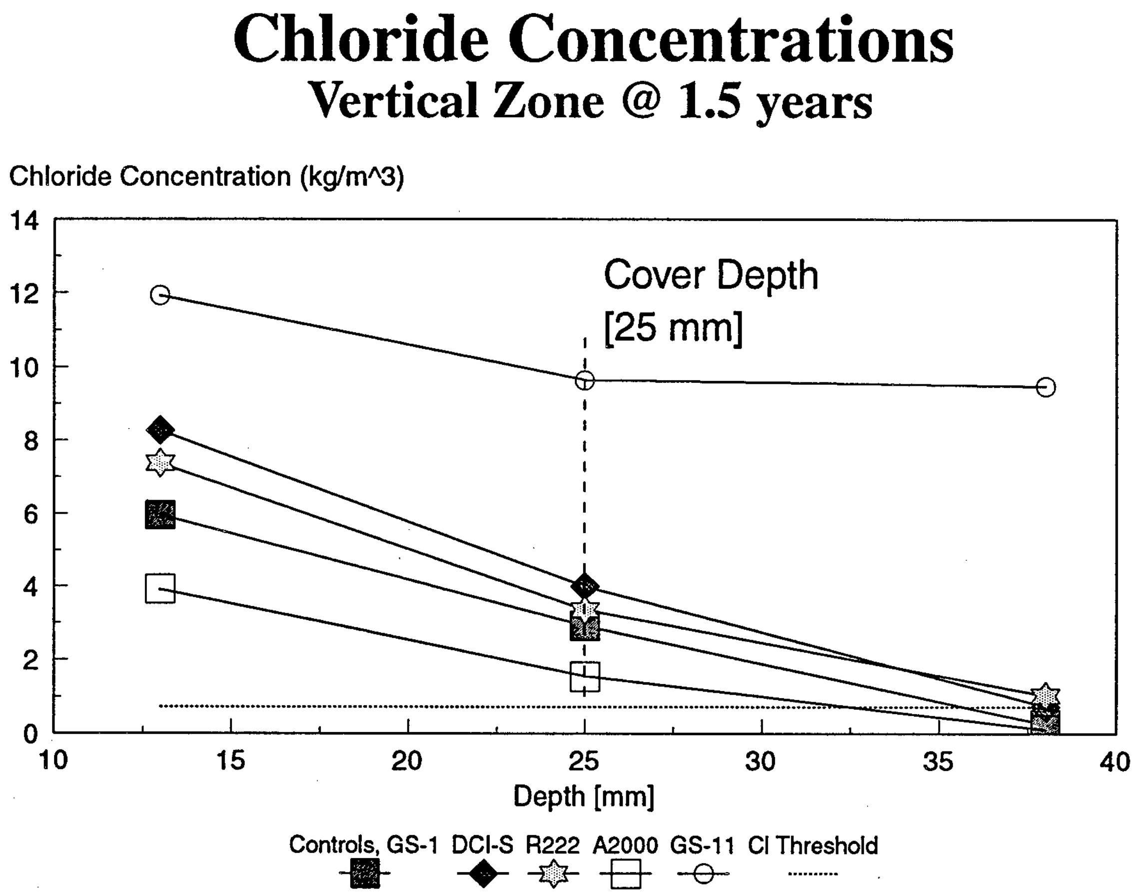


Figure 20. Chloride Concentrations at 1.5 Year, Vertical Zone.

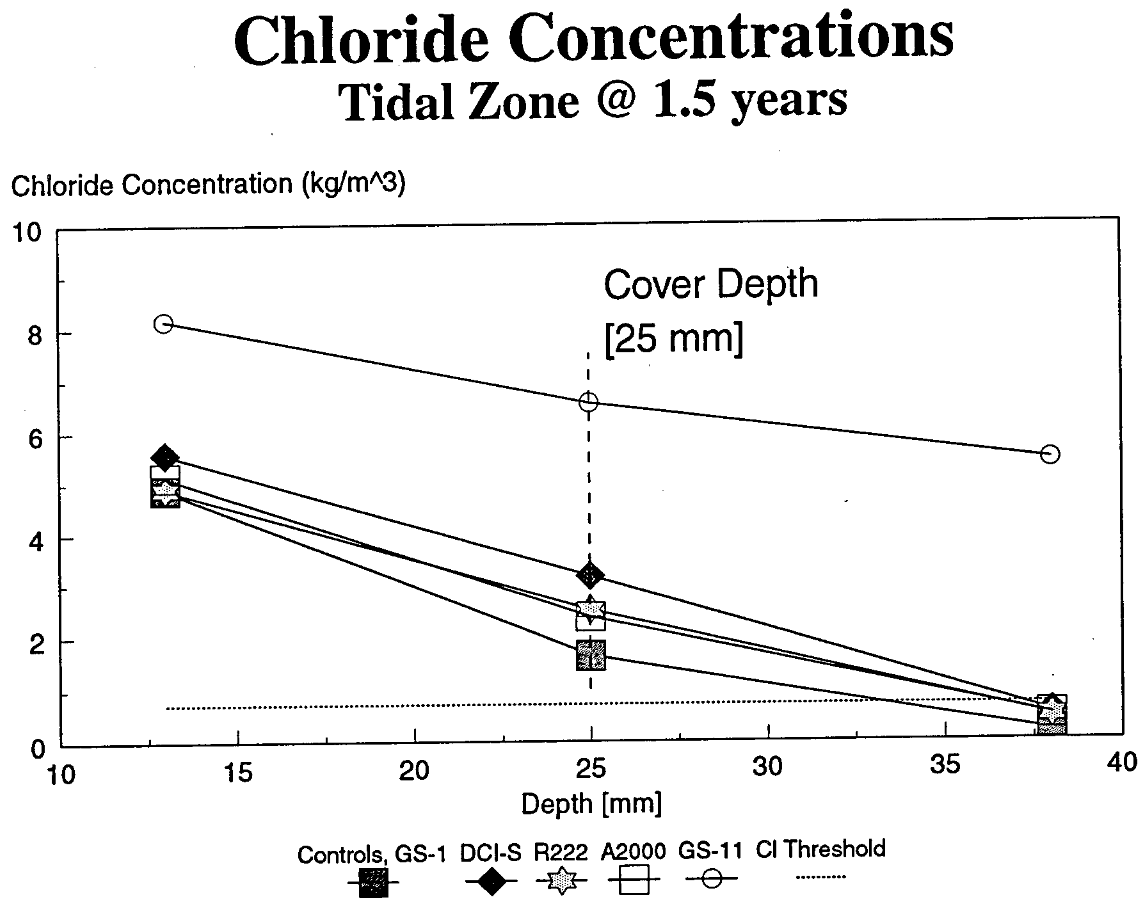


Figure 21. Chloride Concentrations at 1.5 Year, Tidal Zone.

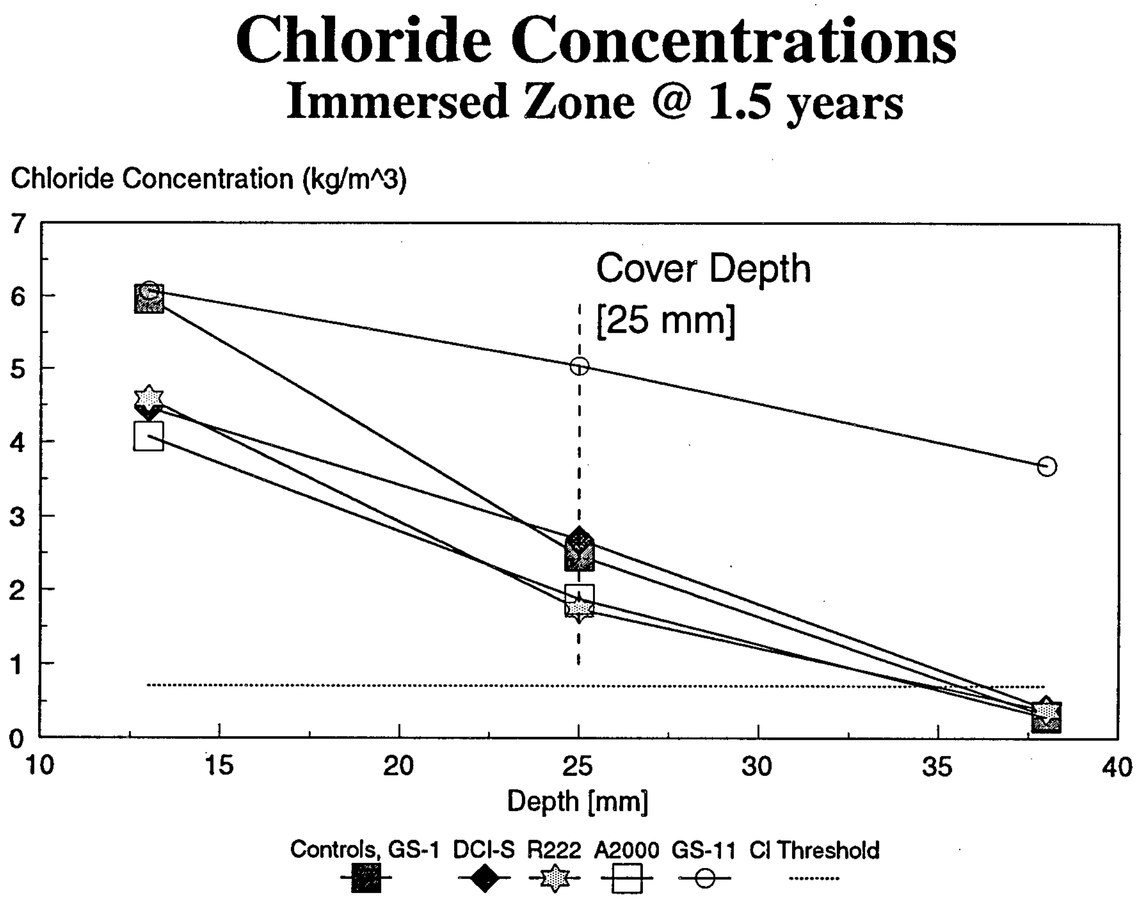


Figure 22. Chloride Concentrations at 1.5 Year, Immersed Zone.

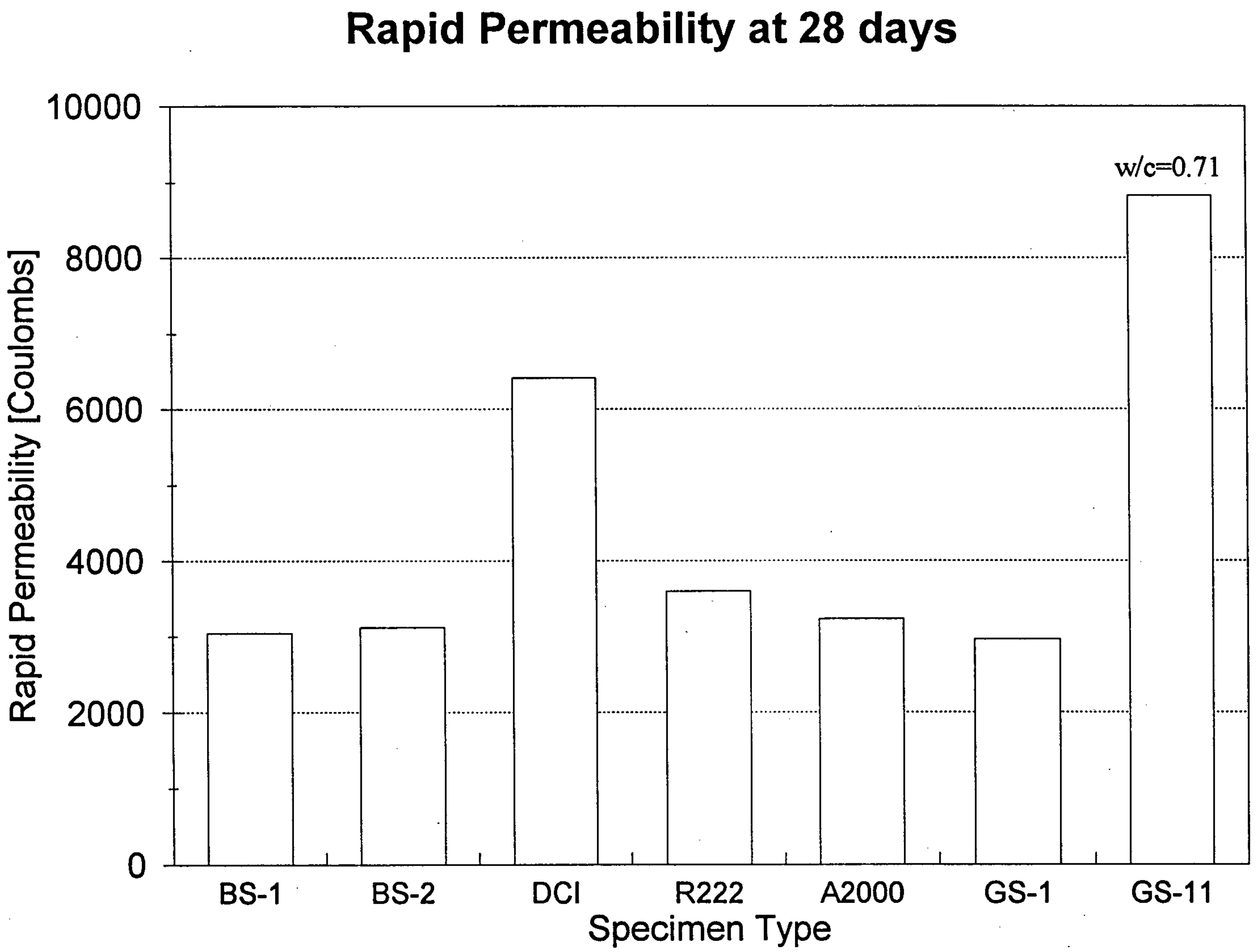


Figure 23. Rapid Concrete Chloride Permeability at 28 Days.

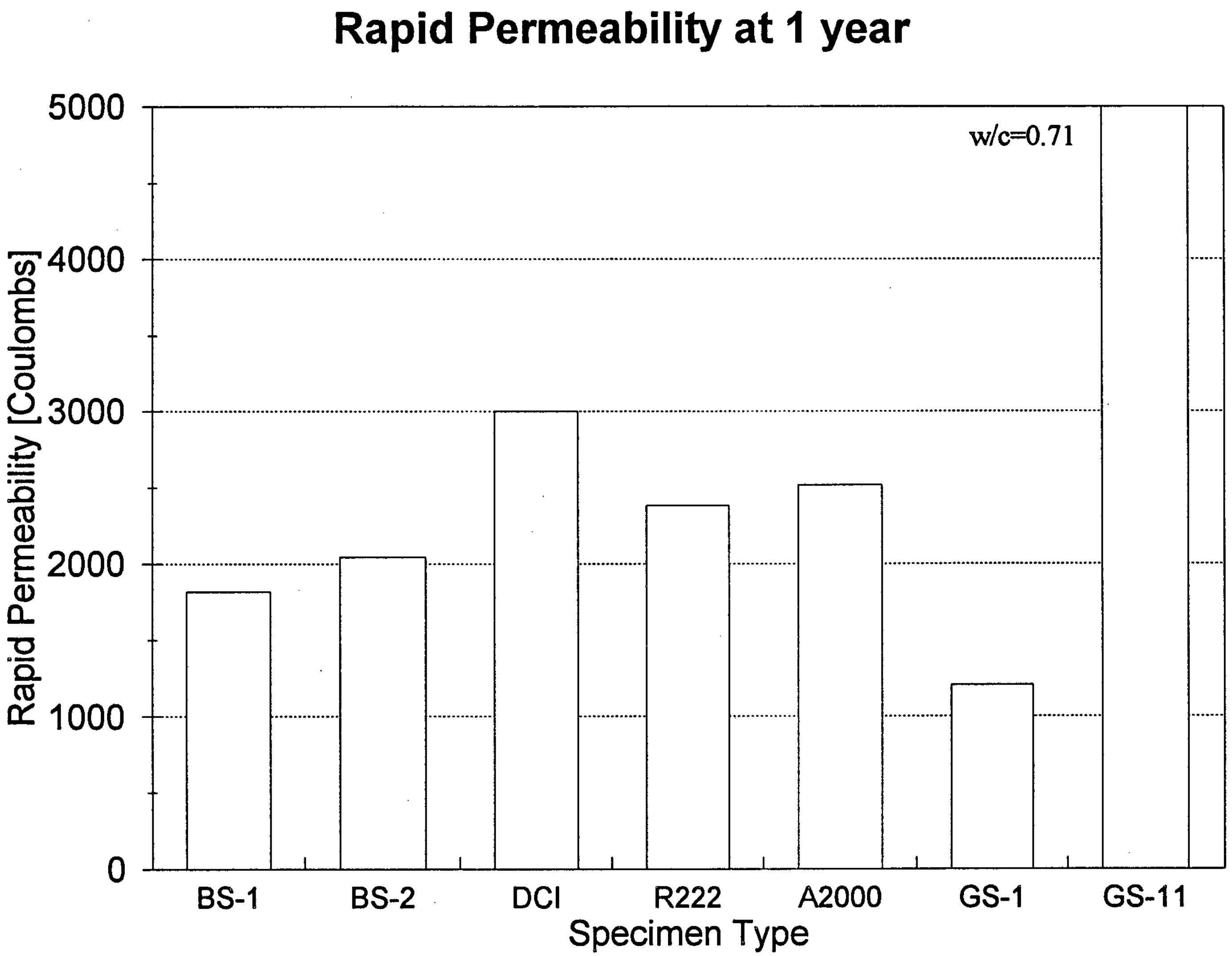


Figure 24. Rapid Concrete Chloride Permeability at 1 Year.

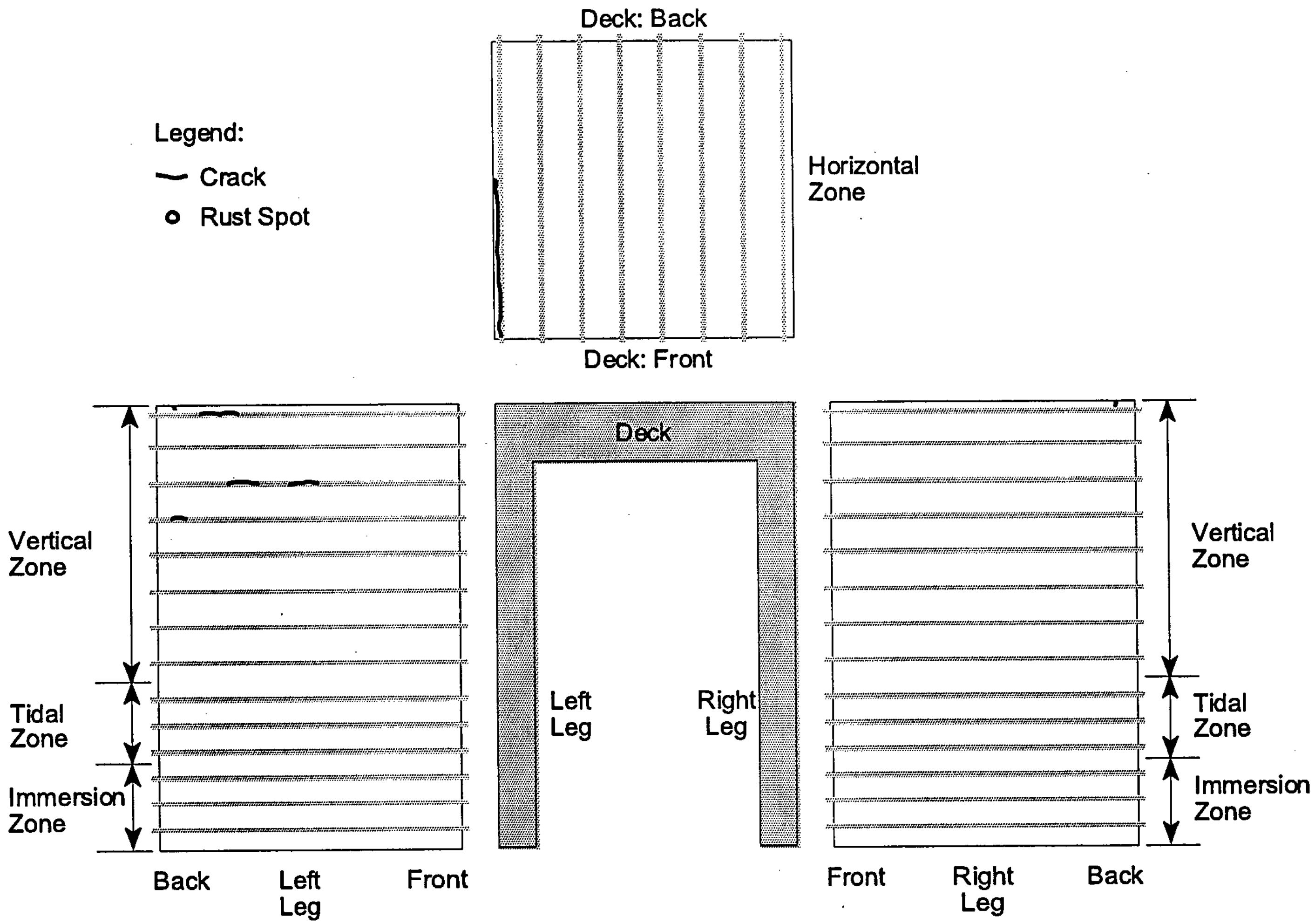


Figure 25. Visual Observations: October 1996. Cracking and Rust Spots in the BS-1 Specimen.

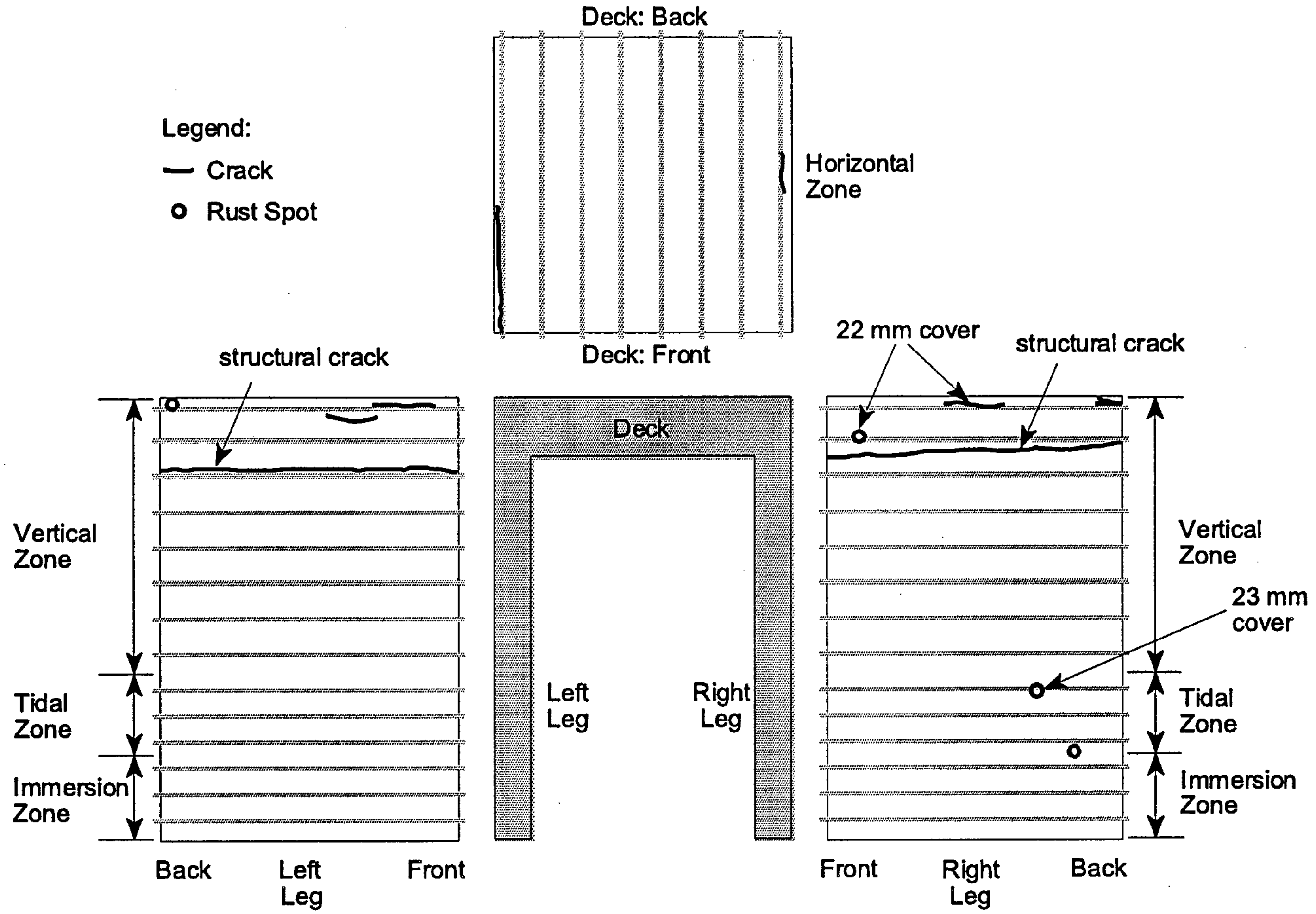


Figure 26. Visual Observations: October 1996. Cracking and Rust Spots in the BS-2 Specimen.

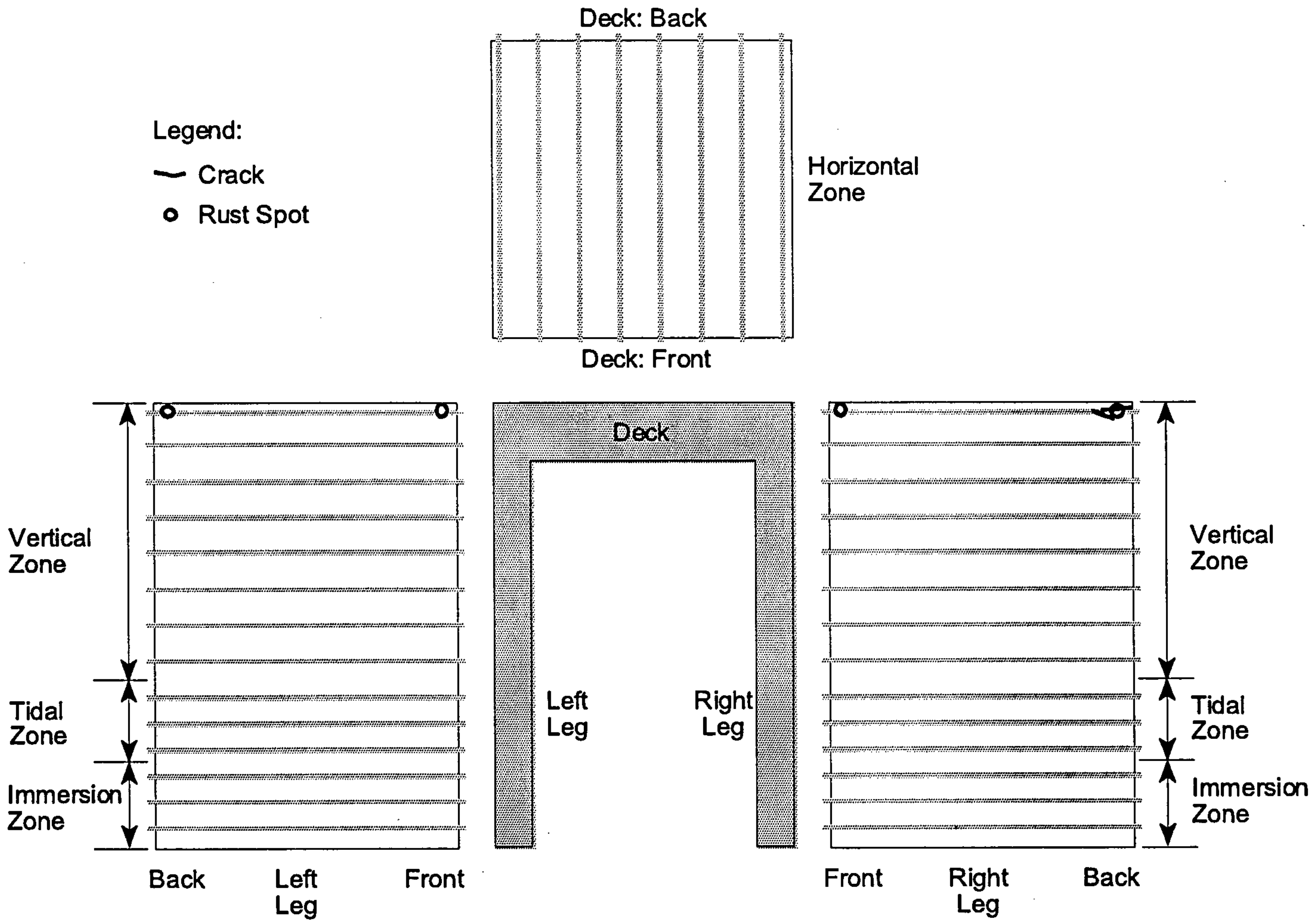


Figure 27. Visual Observations: October 1996. Cracking and Rust Spots in the DCI Specimen.

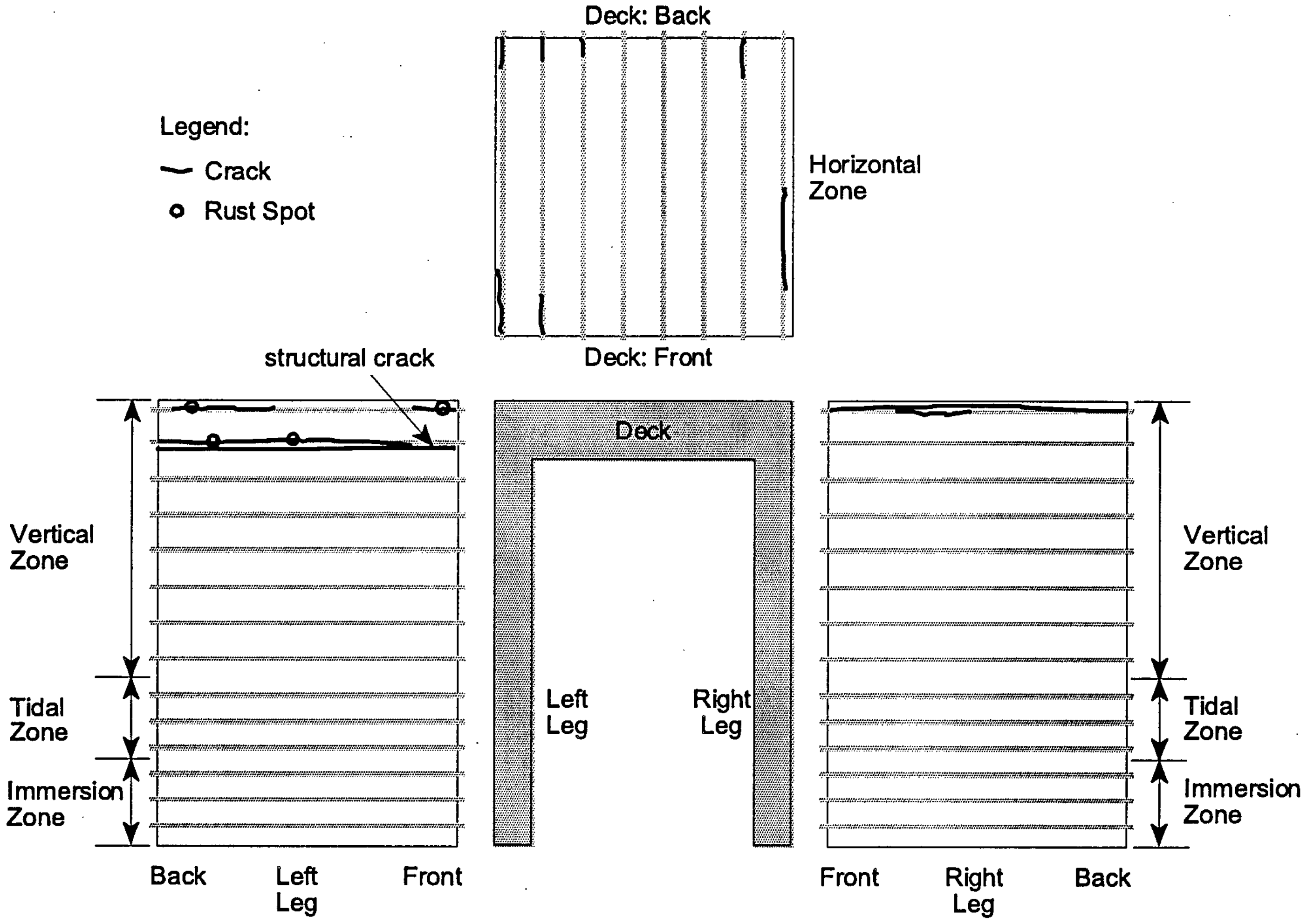


Figure 28. Visual Observations: October 1996. Cracking and Rust Spots in the R222 Specimen.

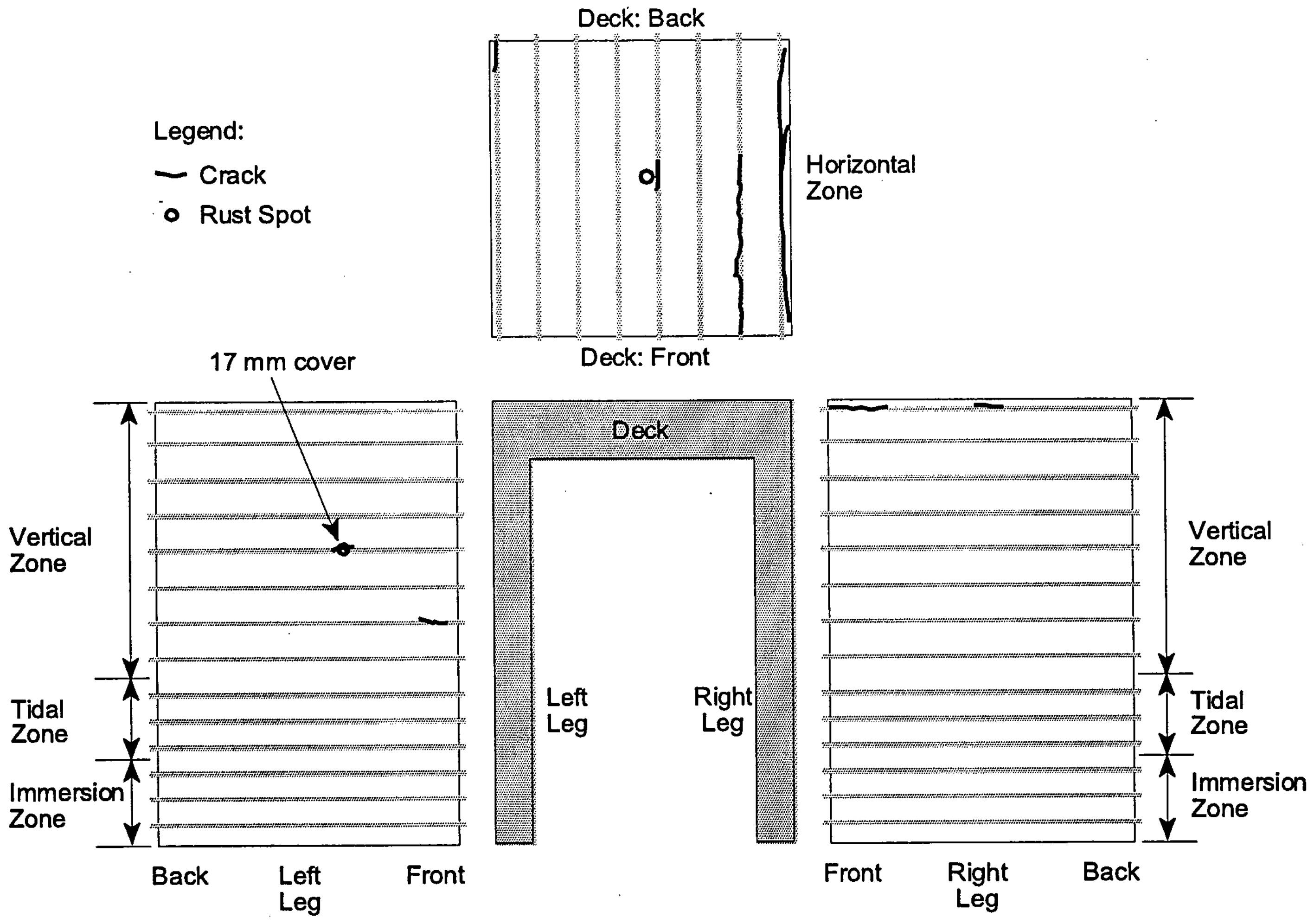


Figure 29. Visual Observations: October 1996. Cracking and Rust Spots in the A2000 Specimen.

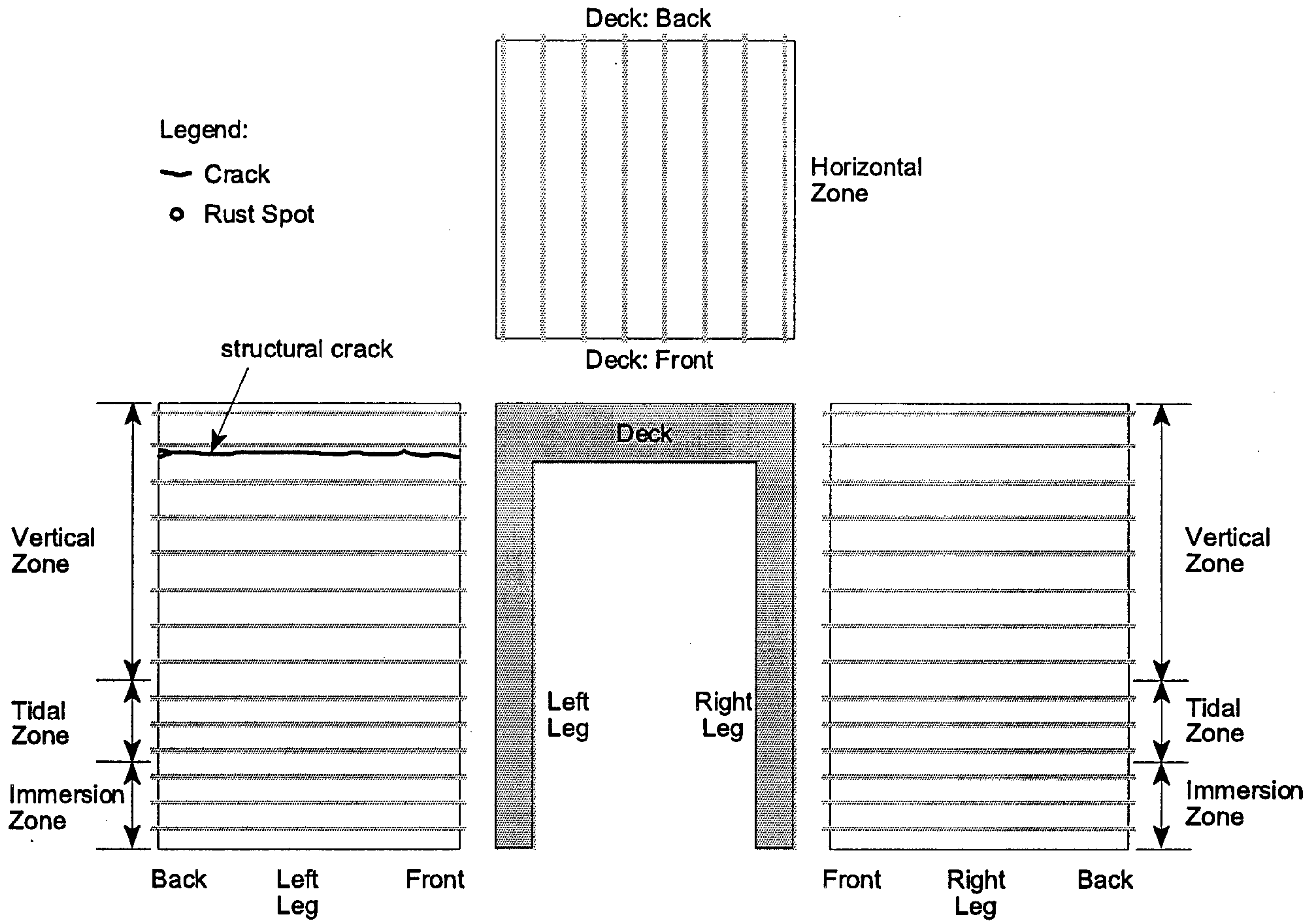


Figure 30. Visual Observations: October 1996. Cracking and Rust Spots in the GS-1 Specimen.

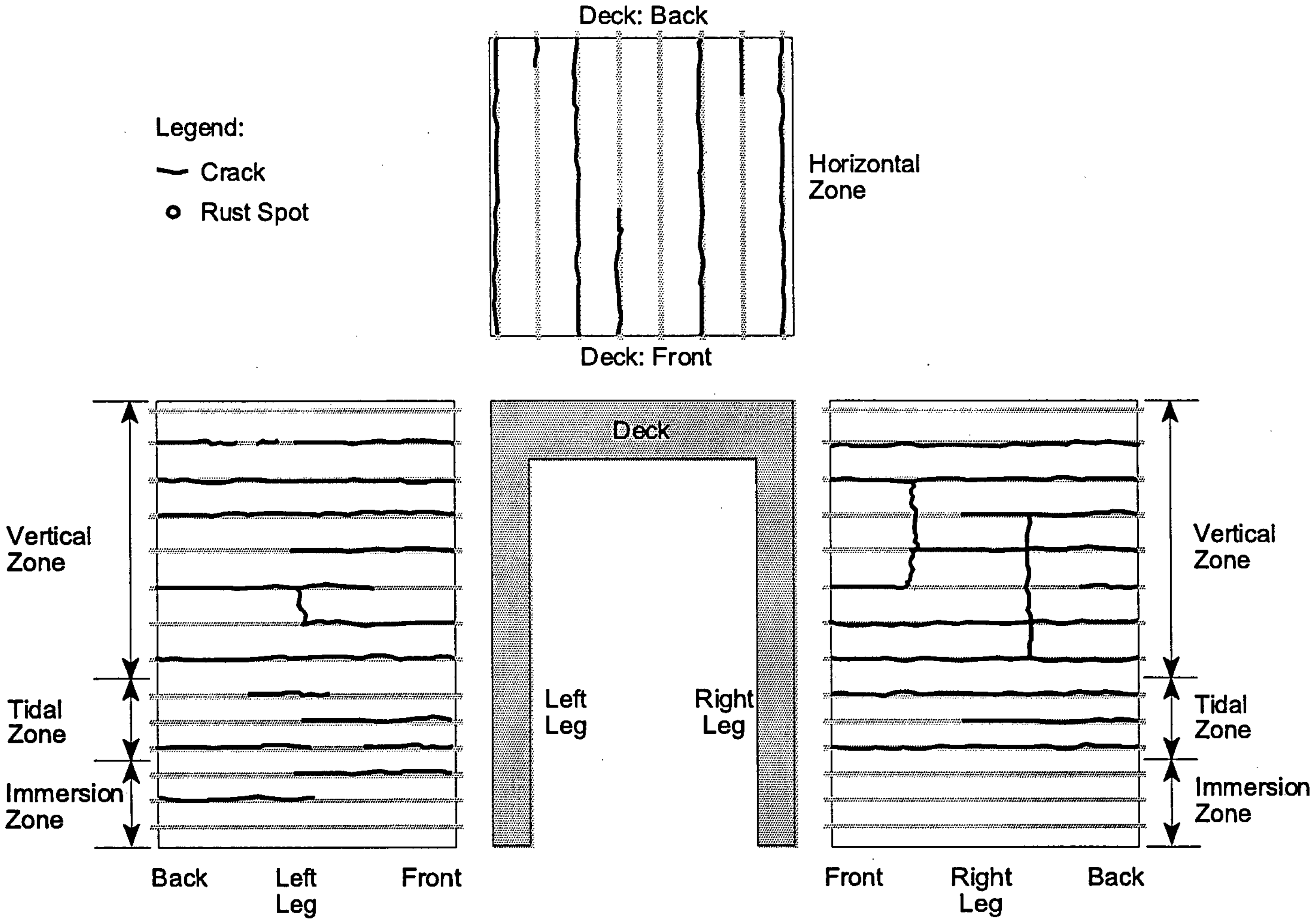
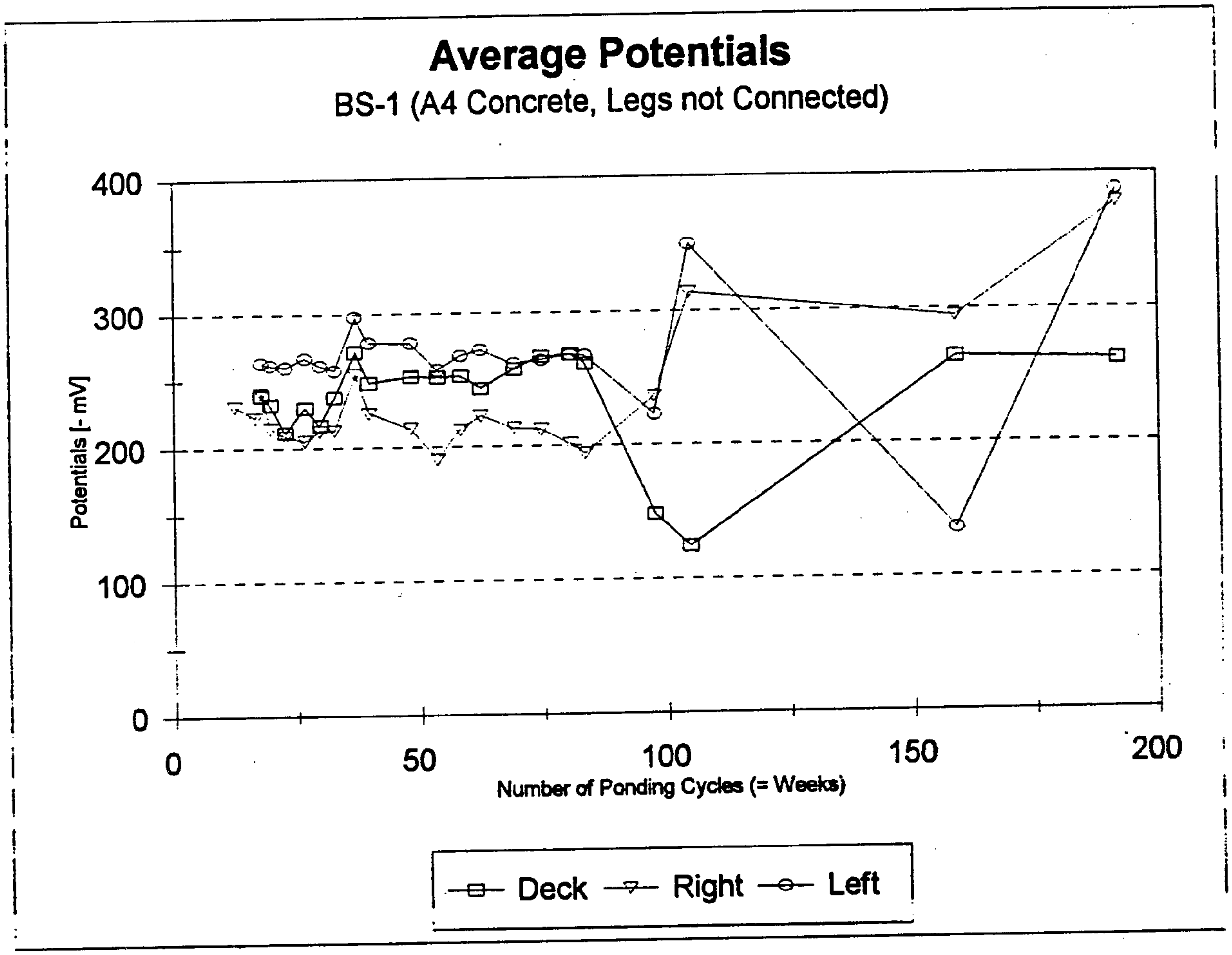


Figure 31. Visual Observations: October 1996. Cracking and Rust Spots in the GS-11 Specimen.

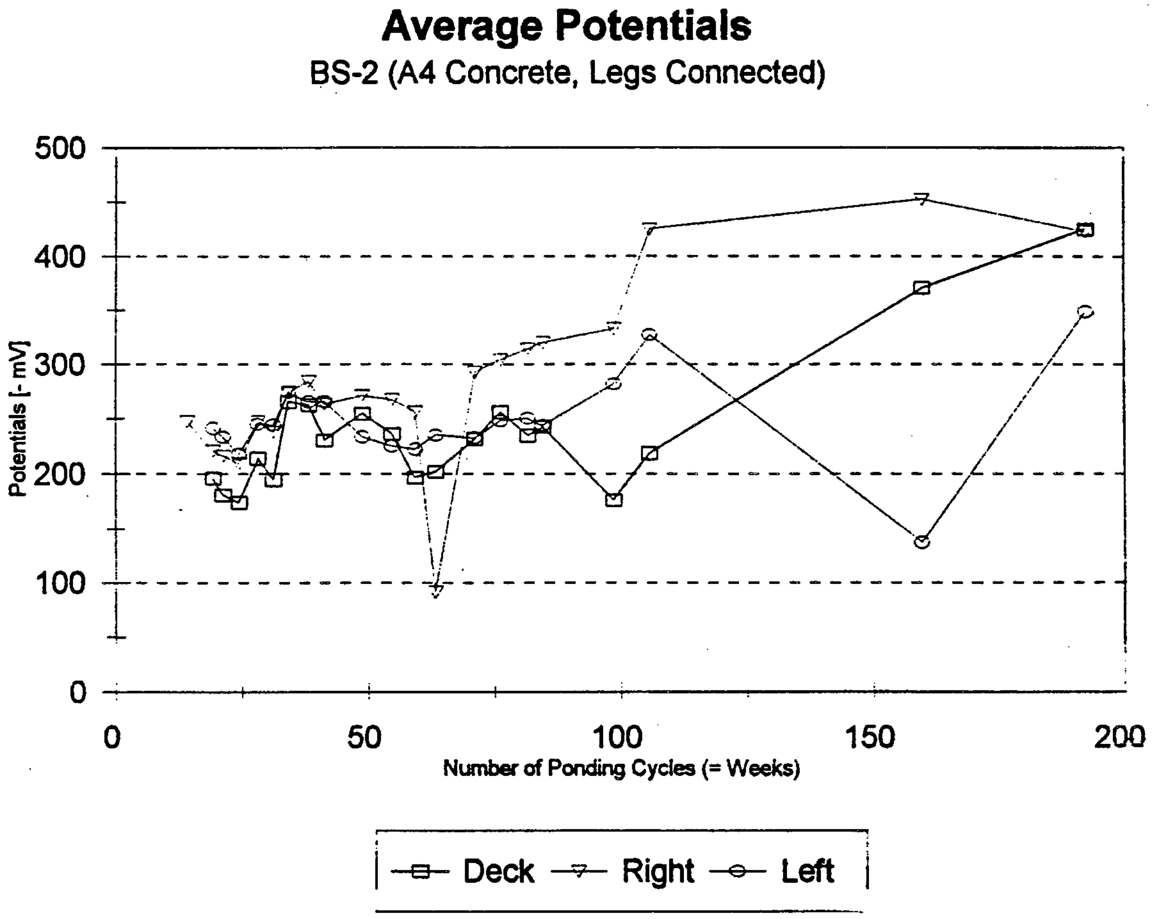
APPENDIX

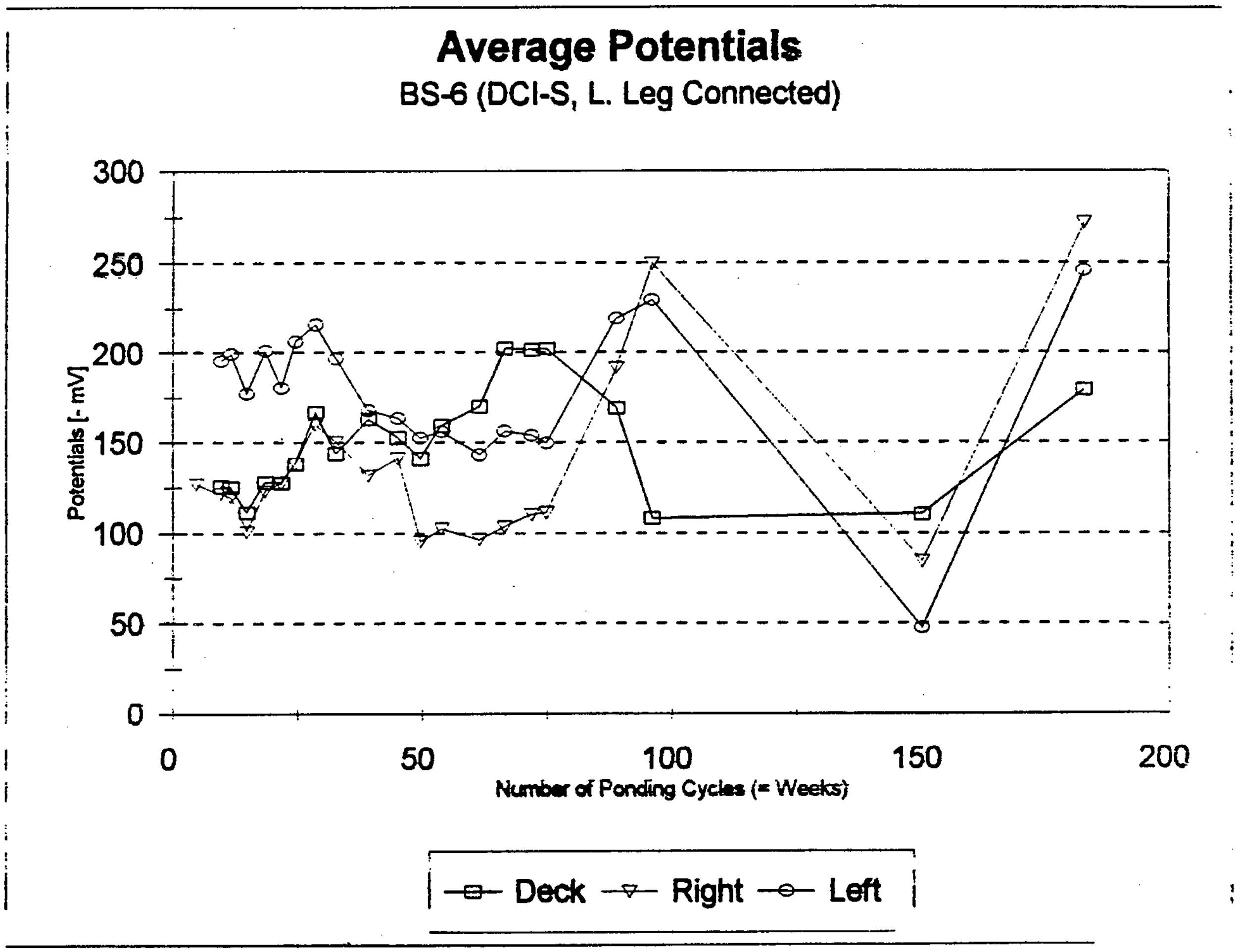
Average Corrosion Potentials for the Deck and Left and Right Legs of Specimens.

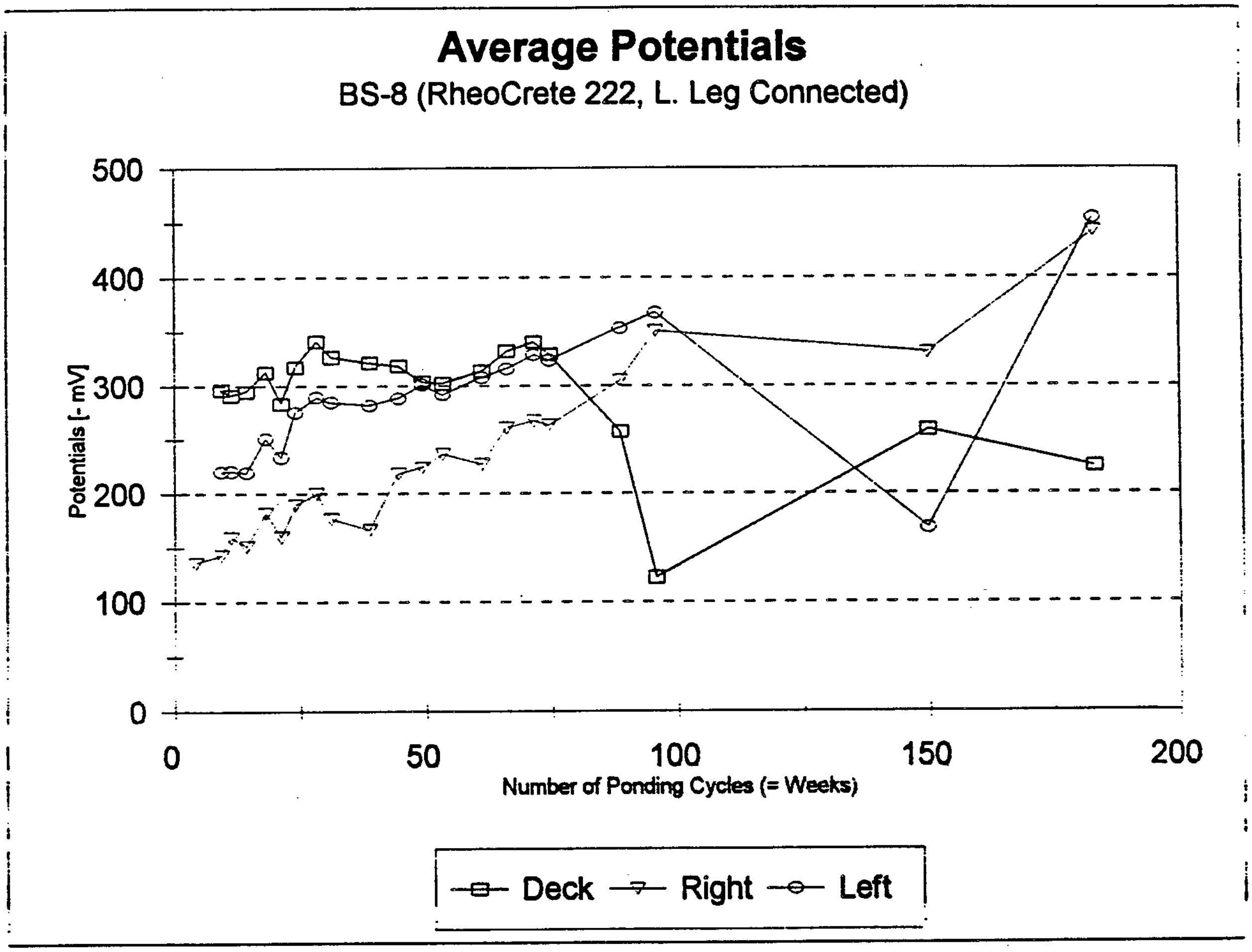


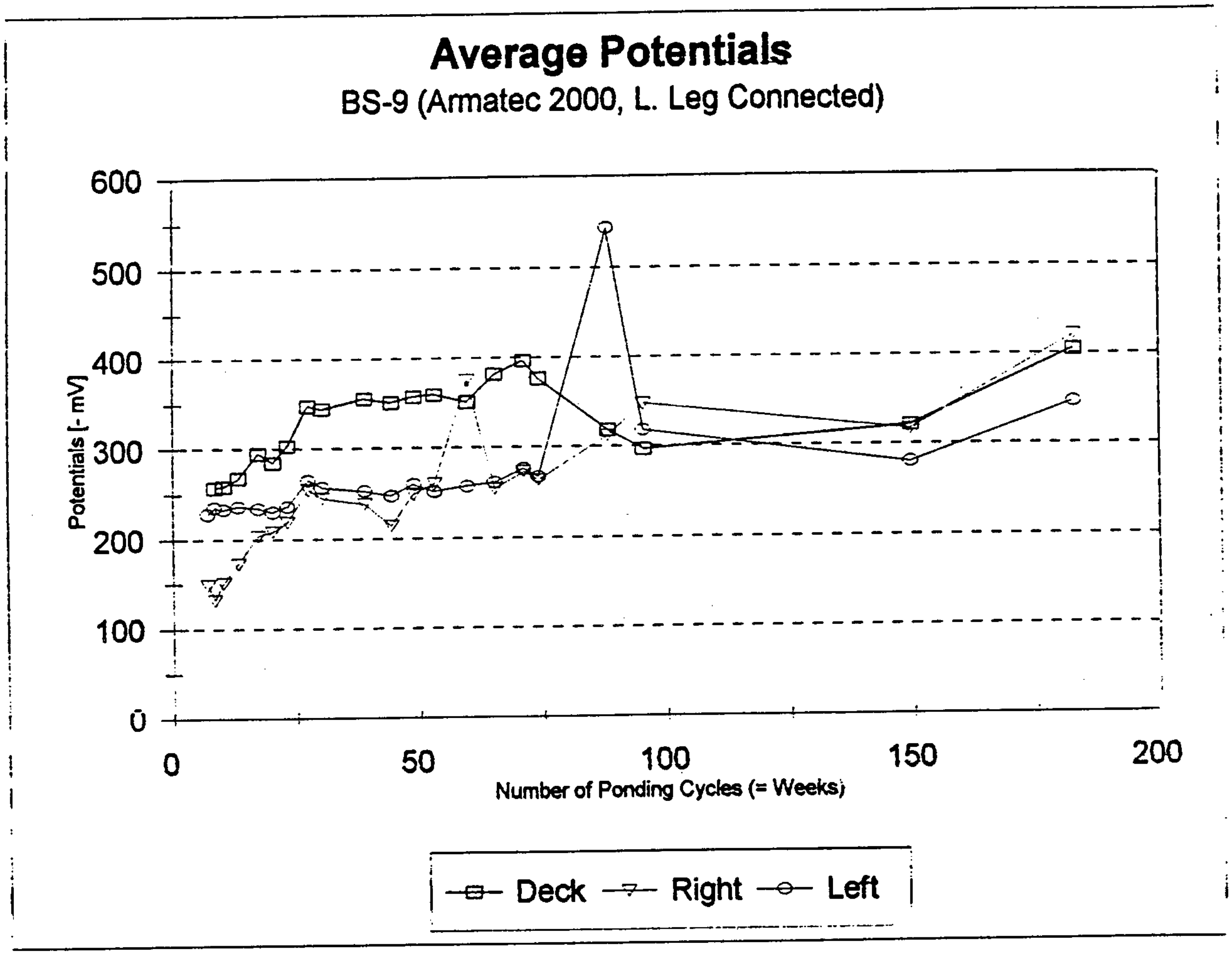
Average Potentials

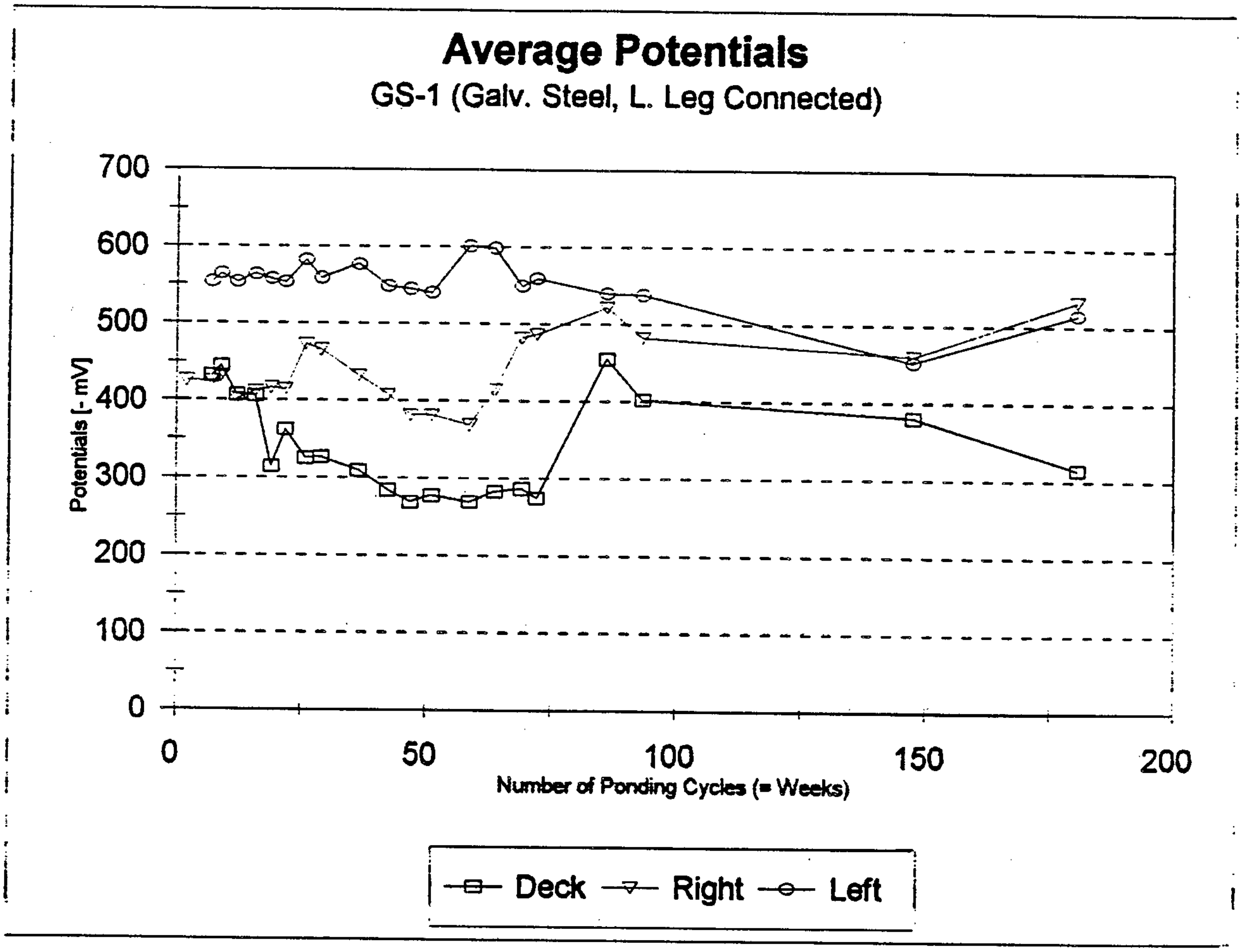
BS-1 (A4 Concrete, Legs not Connected)

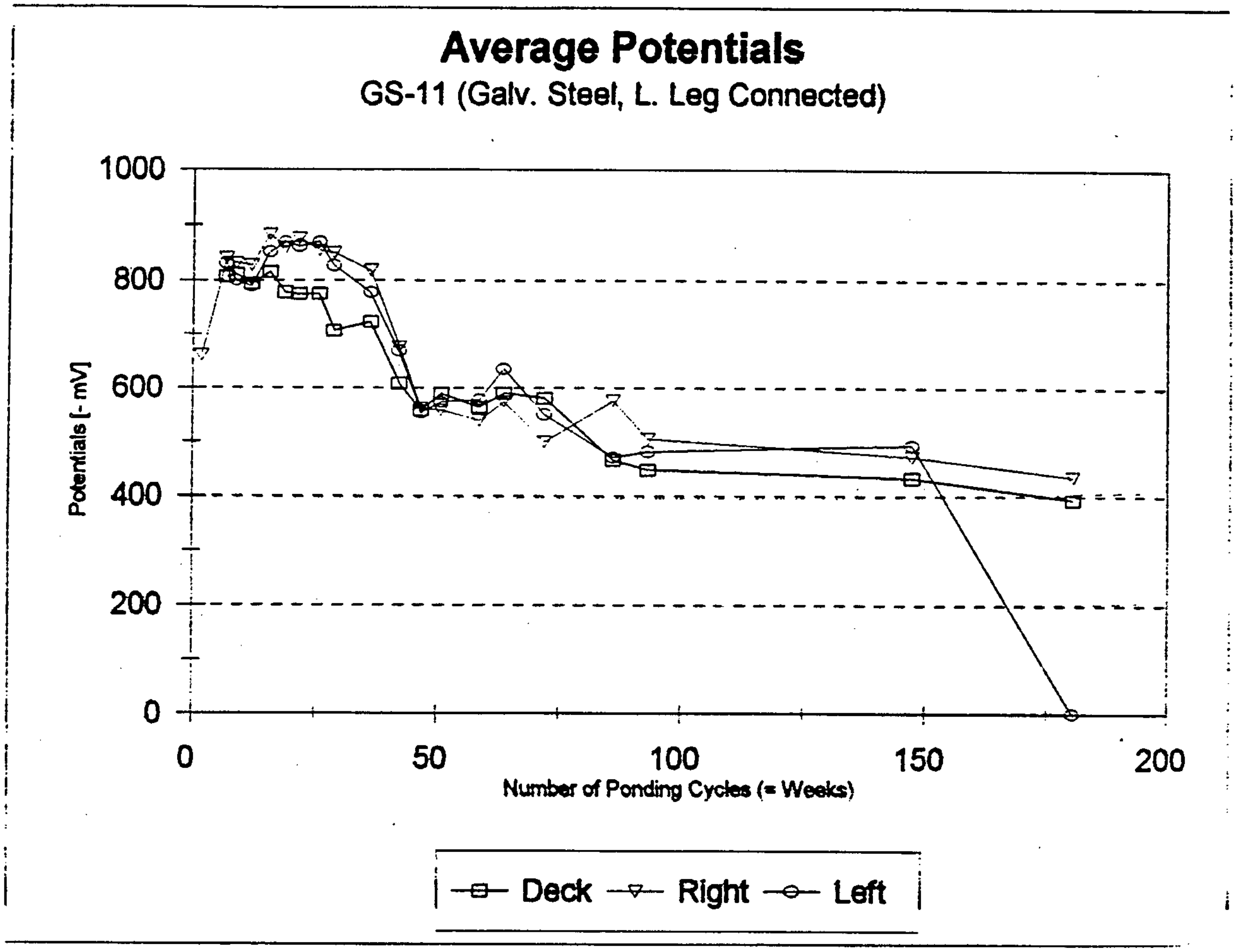

Average Potentials
BS-2 (A4 Concrete, Legs Connected)
Potentials [- mV]
500
400
300
200
100
0
0
50
100
150
200
Number of Ponding Cycles (= Weeks)
Deck
Right
Left


Average Potentials
BS-6 (DCI-S, L. Leg Connected)
Potentials [- mV]
300
250
200
150
100
50
0
0
50
100
150
200
Number of Ponding Cycles (= Weeks)
Deck
Right
Left


Average Potentials
BS-8 (RheoCrete 222, L. Leg Connected)
500
400
300
200
100
0
Potentials [- mV]
0
50
100
150
200
Number of Ponding Cycles (= Weeks)
Deck
Right
Left


Average Potentials
BS-9 (Armatec 2000, L. Leg Connected)
600
500
400
300
200
100
0
Potentials [- mV]
0
50
100
150
200
Number of Ponding Cycles (= Weeks)
Deck
Right
Left


Average Potentials
GS-1 (Galv. Steel, L. Leg Connected)
Potentials [- mV]
700
600
500
400
300
200
100
0
0
50
100
150
200
Number of Ponding Cycles (= Weeks)
Deck
Right
Left


Average Potentials
GS-11 (Galv. Steel, L. Leg Connected)
1000
800
600
400
200
0
Potentials [- mV]
0
50
100
150
200
Number of Ponding Cycles (= Weeks)
Deck
Right
Left