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DEPARTMENT OF PUBLIC WORKS
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CAUSES OF CORROSION OF REINFORCING STEEL IN SAN MATEO-HAYWARD BRIDGE

Part II

55-10

IV-SM,Ala-105-B,A

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MATERIALS & RESEARCH DEPARTMENT

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State of California
Department of Public Works
Division of Highways
Materials and Research Department

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(Part II)

31 p. tables, exhibits

Mr. F. W. Panhorst
Assistant State Highway Engineer
Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is:

PART II

of a report covering

CAUSES OF CORROSION OF REINFORCING STEEL

in

SAN MATEO-HAYWARD BRIDGE

IV-SM,ALA-105-B,A

Study made by.....Structural Materials Section
Under general direction of.....J. L. Beaton
Report prepared by.....R. F. Stratfull

Very truly yours,

F. N. Hveem

F. N. Hveem
Materials and Research Engr.

cc: Withycombe
Hellesoe
Wood
Jahlstrom
Tremper
Ivy

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I. FOREWORD

This is Part II of a report of the cause of corrosion of the reinforcing steel in the San Mateo-Hayward Bridge.

Part I Plan Lib. does not have dealt with the physical and chemical properties of the concrete and was conducted by the Technical Section of the Materials and Research Department. Part I also covered the historical facts concerning the bridge. Therefore, these background items are touched upon only as needed in this report.

This report, Part II, presents data on the electrochemical nature of the corrosion of the reinforcing steel and was conducted by the Structural Materials Section of the Materials and Research Department.

As stated in Part I of this investigation, the immediate purpose was to conduct pilot studies that would be of assistance in determining whether or not more complete investigations would be warranted. These studies indicated that further investigations would be warranted, and such studies are now underway.

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II. SUMMARY

The corrosion of the reinforcing steel, which is accompanied by concrete spalling, has been a major maintenance problem on the San Mateo-Hayward Bridge starting approximately seven (7) years after the bridge was constructed in 1928-29 and continuing to the present, 1955.

The appearance of the reinforcing steel, when cleaned of rust, indicates that the corrosion attack is not normal atmospheric corrosion. There are deep corrosion pits, some of which are 3/16" deep, in the main reinforcing steel in the beams. Also portions of many 3/8" diameter stirrup bars are almost completely disintegrated. This is the type of corrosion attack normally expected, when the currents causing corrosion are attacking a small anodic area.

In three laboratory experiments, corrosion cells were made by connecting steel electrodes to the surfaces of concrete samples obtained from the bridge. Voltages and electrical currents which were measured in these cells showed that concrete could function as an electrolyte and thereby create a corrosion cell.

A concrete core obtained from the deck of the bridge had two separate embedded bars of reinforcing steel. When the two bars of reinforcing steel were connected by a conductor through a microammeter, an electrical current flow was measured. This indicates that a corrosion cell entirely within the concrete structure is possible.

Normal concrete should be alkaline, with a pH of about 12.5 to 13. The average pH of the visually "air dry" concrete samples obtained from the bridge was 8.9 on the surface adjacent to the reinforcing steel at the cathodic areas and 7.9 adjacent to the steel at the anodic areas. The numerical pH values obtained from these samples were secured as an indication of the possibility of differences in the alkalinity of the concrete, and are not necessarily true pH values. A more complete study will have to be made to determine the true alkalinity of the concrete in the San Mateo-Hayward Bridge.

Measurements were made of the specific electrical resistance of concrete samples taken from the bridge. These measurements indicated that the electrical resistance of the concrete samples is approximately equal to certain sandy loam and clay soils.

Electrical potentials were obtained on the surfaces of the concrete in portions of four spans on the bridge. These electrical measurements indicated that corrosion currents are generally flowing from corroding anodic areas in the beams to non-corroding cathodic areas in the deck.

Tests were made to determine if stray electrical currents were causing the corrosion of the reinforcing steel. Electrical potential measurements were made on the surface of the bay and land. The measurements indicated that no stray electrical current was either entering or leaving the structure.

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At one span, electrical potentials indicated that corrosion currents were flowing within a beam from a section of reinforcing steel embedded in the original concrete to reinforcing steel embedded in shotcrete placed as a repair. The measurements indicated that the steel in the concrete is anodic to that in the shotcrete and therefore is subject to corrosion.

As examples for correlation to the concrete piles of the bridge, electrical potential measurements were made on three abandoned reinforced concrete piles. Two of the piles were rejected from use on the 1-1/2 year old P.G.&E. transmission line adjacent and parallel to the bridge. The piles had their original wooden driving cushions in place and were lying in tidal water. Electrical potential measurements indicated that a corrosion cell was formed between the steel embedded in concrete and the steel embedded in the wooden driving cushion. When the wooden driving cushion was removed, it was found that some of the 1" diameter steel bars in the cushion had lost up to 75% of their original cross-section within 1-1/2 years.

Electrical potential measurements were made on a rejected San Mateo Bridge reinforced concrete pile lying in tidal water. The reinforcing steel of the pile was corroding and the concrete was spalling. The potential measurements indicated that there were anodic and cathodic areas within this pile which were separated by distances of 1 to 5 feet. The present appearance of the cracks in this pile is similar to those in the piles in place in the structure.

The absorption of sea salts by the concrete apparently is a major cause of corrosion in the San Mateo-Hayward Bridge. As indicated in Part I, the salts tend to lower the pH of the concrete thus making the steel more vulnerable to corrosive attack. Because of this effect, and an accompanying lowering of electrical resistance, corrosion cells are more readily formed. The cells are probably set up by differences in alkalinity from point to point due to unequal distribution of salts. However, these cells could also be caused to function by differential aeration of the steel in areas of nearly equal but sufficient chloride concentration to destroy the inhibiting effect of the concrete.

As the corrosion of the reinforcing steel in the San Mateo-Hayward Bridge is due to a corrosion cell with the anodic and cathodic areas separated by distances of approximately two to ten feet, it appears that neutralization of this effect might be secured by means of cathodic protection to prevent further corrosion of the reinforcing steel. However, the effect of the electrical currents used in cathodic protection on the chemical stability of the concrete is not entirely known and must be further investigated.

These pilot studies have formed the basis for recommendations for future work which appear on page 20.

The conclusions from these pilot studies appear on page 21.

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III. CORROSION HISTORY

After the San Mateo-Hayward Bridge had been opened to traffic for about 7 years, cracks in the piles, caps and beams were repaired with shotcrete. It was stated that the reason for this repair was that cracks were occurring in the concrete and that the steel was corroding. The bridge was built in 1928-29.

Approximately 9 years after the completion of the original repair project, another repair project was commenced.

A recent preliminary survey of the existing condition of the bridge indicated that nearly every span has indications of steel corrosion as evidenced by the concrete cracking or by repairs to the structure.

A. Nature of the Deterioration.

The physical appearance of the cracks in the concrete of the piles, caps and beams is adequately described in Part I of this investigation and will not be repeated except as necessary.

The rust on the reinforcing steel is usually one of two types: the first type is similar in appearance to the typical heavy, stratified flake type rust found in marine atmospheric exposure. The second type of rust is not as dense as the "normal" type of atmospheric rust. This rust is a dark reddish brown and has streaks of green and black through it. When this type of rust is exposed, an acidic odor is perceived. The surface appearance of the reinforcing steel, when cleaned of both types of rust, is much more deeply pitted than is ordinarily found under atmospheric conditions.

Portions of the stirrup bars, in some cases, are almost completely destroyed by corrosion, the rust being as described above.

It is incidental to the main study of this structure, but of interest to note, that the steel bolts, which hold the electrical insulators for the wires of the abandoned lighting system, are severely corroded where they are exposed to the atmosphere. However, it is an exceptional circumstance to find the concrete cracked at the embedded bolts. These bolts are located on the underneath surface of the deck about one foot in from the outside edge of the deck. This appears to support in a small way the preliminary conclusion that the corrosion of the reinforcing steel of this structure was not due to atmospheric attack of any consequence.

Exhibits 1 to 5 inclusive, which are in the Appendix, depict the corrosion problem at the San Mateo-Hayward Bridge.

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IV. THEORY OF CORROSION

The aspect of chemical action and reaction in the electrochemical process of corrosion is adequately described in Part I of this report.

This part of the report is primarily concerned with the electrical aspect of corrosion.

It is a well accepted fact that the corrosion process involves the flow of electrical currents as well as a chemical action. The electrical current produced during corrosion can be measured. Not only can the magnitude of the current be measured, but the location of the anodic and cathodic areas producing these currents can be electrically located.

In accordance with this theory, as the corrosion of the reinforcing steel in the San Mateo-Hayward Bridge is occurring, an electrical current is flowing from the corroding anodic reinforcing steel to the non-corroding cathodic reinforcing steel through an electrolyte of concrete.

The following definitions concerning corrosion have been taken from Uhlig's Corrosion Handbook:

1. Differential Aeration Cell.

   This type of corrosion cell occurs when differences in air, or oxygen, concentration in the electrolyte at one of two electrodes of the same metal cause an electrical corrosion current to flow between the electrodes.

2. Concentration Cell.

   This type of corrosion cell occurs when an unequal concentration of an electrolyte at the anode and the cathode causes an electrical current to flow between the electrodes.

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V. INVESTIGATIONS

A. Laboratory Studies.

Complete details of the methods used in the laboratory studies are in the Appendix along with the results. The following is a resumé of the laboratory studies:

1. Electrical corrosion currents induced by concrete and steel.

Four experiments were performed during the laboratory studies to ascertain if concrete could be an electrolyte, and if moisture or chemical differences in concrete could cause a corrosion current to flow between steel electrodes contacting concrete.

Additional experiments were performed to ascertain if there are differences in alkalinity of the concrete causing anodic and cathodic areas. Also, the specific electrical resistance of the concrete was determined under various moisture conditions.

EXPERIMENT #1.

Steel electrodes were clamped to opposite surfaces of concrete samples. All current flow was measured and tabulated. The steel electrodes were then reversed in position to ascertain whether the concrete or the steel electrodes were the major influence in determining the direction of current flow.

In all cases electrical measurements indicated an electrical current was flowing between the steel electrodes in intimate contact with the concrete samples. In only 1 out of the 8 samples the direction of the current flow reversed when the electrodes were reversed in position. In the remaining cases the electrode contacting the concrete surface normally exposed to the atmosphere was anodic to the surface that was not normally exposed to the atmosphere. The concrete acted as an electrolyte and influenced the direction of current flow.

EXPERIMENT #2.

In this experiment the concrete samples were used in pairs. The surfaces of the concrete originally exposed to the atmosphere were butted together and steel electrodes were contacted to the surfaces of the concrete originally not exposed to the atmosphere.

In all cases an electrical current flow was indicated by measurements to be flowing between the steel electrodes. In 4 out of 12 cases the direction of the current flow reversed when the electrodes were reversed in position.

In 6 different couples between the steel electrodes contacting originally "anodic and cathodic" specimens, 4 couples indicated that the "anodic" concrete retained its "status quo" when coupled to "cathodic" concrete.

This experiment also indicated that the concrete could act as an electrolyte.

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EXPERIMENT #3.

In this experiment a concrete deck core (which was sheared through during removal at 2 places) was used to ascertain if current would flow when steel electrodes were contacted to the concrete surfaces.

The steel electrode which contacted the atmospheric surface of the concrete was anodic even when contacted to the normally sheltered surface.

The concrete acted as an electrolyte and also influenced the direction of current flow.

EXPERIMENT #4.

In this experiment a concrete core, with two electrically disconnected steel reinforcing bars, was obtained from the deck of the bridge.

A microammeter was electrically connected to the steel reinforcing bars under two conditions: (1) the core was visually atmospheric dry; and (2) the concrete core was moistened to a damp appearance.

Condition 1 -- atmospheric dry: The microammeter indicated that a current flow of 0.7 microamperes was flowing between the bars. The steel bar nearest the deck was anodic to the bar more deeply imbedded.

Condition 2 -- Concrete core moistened to a damp appearance. A maximum current flow of 10 microamperes was measured. The steel bar nearest the deck was anodic to the steel bar more deeply imbedded.

This experiment indicated that it is possible for corrosion cells to function in the deck of the bridge.

EXPERIMENT #5.

This experiment was performed to determine if there is a possibility that differences in alkalinity in the cathodic and anodic areas of the concrete are causing the corrosion of the steel.

A few drops of tap water, pH 8.3 were placed on visually atmospheric dry concrete.

The pH measurements indicated that the concrete at cathodic areas was more alkaline than the concrete at anodic areas. However, the numerical results of this experiment may not have indicated the true pH of the concrete tested.

The measurements indicated that further work should be performed on the alkalinity of concrete in anodic and cathodic areas.

EXPERIMENT #6.

In the previous experiments the concrete samples obtained from the bridge indicated that they could influence the direction of

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current flow, as well as act as an electrolyte. In this experiment, it was decided to measure the specific electrical resistance of the concrete under three conditions: (1) Visually atmospheric dry, (2) immediately after being soaked in tap water for 48 hours, and (3) one hour after removal from the soaking bath.

The measurements indicated that the specific electrical resistance of concrete in a wet or damp condition was from ten to thirty times more conductive of electricity than concrete in an atmospheric dry condition. Under all moisture conditions the concrete sample which was taken from a cathodic area on the bridge had a greater electrical resistance than the concrete samples taken from anodic areas.

Further work should be performed to determine if there is a relationship between specific electrical resistance of concrete and corrosion of reinforcing steel.

B. Field Studies.

1. Potential Survey of Span #408.

An electrical potential field survey was made of beam #S-1 between bents #408 and 409.

When making potential measurements, apparently the simplest method would be to contact the electrolyte with a steel bar or copper wire. However, when a steel bar or copper wire is used to measure potentials of a corroding structure, the potential of the steel bar or copper wire to the electrolyte at the point of measurement is variable. The erratic potentials of a steel bar or copper wire to the electrolyte are caused by variations in chemical content, aeration, and many other factors in the electrolyte. For this reason a standard reference cell is used to make a potential measurement.

The field measurements made, as a part of this report, were made by using a copper sulfate half cell. This reference cell has a relatively constant potential of +0.316 volts referred to a normal hydrogen electrode. With commercial materials this reference cell can be reproduced to within ±.006 volts.

The copper sulfate half cell consists of a copper electrode immersed in a saturated solution of copper sulfate. When making potential measurements, the voltmeter is connected to the electrolyte through a "bridge" of copper sulfate solution.

A sketch of the copper sulfate half cells, as well as the method of making electrical connections, is shown on Exhibit 6, which is in the Appendix.

This survey indicated that there was an electrical current flowing in the concrete. This electrical current was flowing from corroding areas in the beams to the deck area. The current flow was located by potential measurements. There

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was excellent correlation between the indicated anodic corrosion areas located by potential measurements during the survey and actual corroding reinforcing steel which was exposed at these areas. (Note: The field notes of this survey were destroyed in the laboratory fire of March 1954).

2. Potential Survey of Span #385.

A supplementary potential survey was made of beams #S-1, S-2 and N-2 between bents #385 and 386.

The equipotential "contours" of these beams are depicted on Exhibits 7, 8 and 9. Charts 1, 2 and 3 respectively, which are in the Appendix. In this survey, as in the previous survey, there was excellent correlation between the potential measurements and actual areas of corrosion of the reinforcing steel.

The fundamental purpose of these two surveys was to establish a correlation between variations in electrical potential measurements taken on the surface of the concrete and actual areas of corrosion, on the reinforcing steel as exposed by chipping off the concrete. The correlation was excellent.

The measurements were taken by grounding a voltmeter to the reinforcing steel and using a copper sulfate half cell to make the voltage measurements on the surface of the concrete. A potentiometer voltmeter was used to measure the magnitudes of the voltages.

3. Potential Survey, Span #512.

An additional potential survey was made of the northerly 1/2 of the structure between bents #512 and #513 to locate the cathodes and the anodes. From this survey equal voltage lines were drawn on a scale model of the bridge.

Exhibit 10, which consists of photographs of the scale model of the north 1/2 of the bent #512, are included in the Appendix. On this model the dashed lines are cathodic voltages, and the solid lines are anodic voltages.

In this survey there was excellent correlation between the anodic voltages and areas of corrosion of the reinforcing steel. There was also excellent correlation in this survey, as well as in previous surveys, between the anodic voltages and the concrete cracks caused by the corrosion of the reinforcing steel.

As indicated by the equipotential contour lines drawn on the bridge model shown in the Appendix, the cathodic areas causing the corrosion of the steel in the beams, are in the deck area.

The cathodic areas for the caps and piles are in the diaphragms and caps. The electrical measurements indicate that the corrosion attacking the reinforcing steel has anodes and cathodes spaced at distances of two to ten feet.

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4. Potential Survey, Span #25.

A series of potential measurements were made on beam #S-2, and are plotted on Exhibit 11, Chart 4, in the Appendix. This beam was repaired with shotcrete approximately 3 years ago. The potential measurements indicated that corrosion was occurring in the bottom section of the beam approximately 1' east of the cap of bent #25.

The cathodic area was located at the bottom of the same beam #S-2, approximately 11' east of the cap of bent #25. The cathodic area was located within the area repaired by shotcrete while the anodic, or corroding area, was located in an area of original concrete. The voltage gradient measured on the surface of the concrete between the anodic and cathodic areas was 0.42 volts. A horizontal crack in the concrete approximately 1' long was located in the anodic area. The steel was not exposed at this location.

5. Potential Survey, Abandoned San Mateo Bridge Pile (Pile A).

A potential survey was made on a rejected reinforced concrete pile abandoned during the construction of the San Mateo-Hayward Bridge. This pile, called Pile A, was located approximately 25' north of the west end of the bridge and was in the tidal water zone. The concrete in the pile was cracked in the same typical manner as the piles in the structure. The cracks were longitudinal, and the steel was corroded.

Potential measurements were made on the top face of the pile. These measurements drawn to equipotential contours are shown on Exhibit 12, Chart 5 in the Appendix. The potential measurements on this pile indicate that the corrosion of the steel is caused by a corrosion cell with the anodes and cathodes separated by distances of one or more feet. The corrosion products of the steel are causing the cracking and spalling of the concrete. Indirect evidence of corrosion products causing concrete to crack is shown on Exhibit 5 in the Appendix.

6. Potential Survey, Abandoned P. G. & E. Pile (Pile B).

Corrosion tests were performed on a reinforced concrete pile, approximately 1-1/2 years old. This pile, designated Pile B, was located approximately 200' south of the west end of the bridge, and was in the tidal water zone.

There was no cracking or spalling of the concrete. The pile had the original wooden driving cushion attached to the head of the pile.

The equipotential contours of Pile B (Exhibit 13, Chart 6 in the Appendix) indicated an anodic area within the wooden driving cushion, and a cathodic area approximately 6' distant and located in the area of concrete-imbedded steel.

When the wooden driving cushion was removed, it was disclosed that some of the 1" diameter reinforcing steel bars within the wooden driving cushion had lost up to 1/2 of their original metal.

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The steel which extended outside of the driving cushion, so that the corrosion attack was due to the atmosphere and alternate sea water immersion, was badly rusted. This rust was the typical stratified flake type, accompanied with the usual sea water organisms found on steel in atmospheric marine environment. A typical example of the reinforcing steel corrosion is shown in Exhibit 1 in the Appendix.

As the wooden driving cushion was obviously more porous and less alkaline than the concrete, it was decided to investigate the possibility of a corrosion cell being caused by steel imbedded in concrete and steel immersed in a saline electrolyte.

EXPERIMENT #7.

A. Purpose.

To determine if a corrosion cell would function when there is a different electrolyte at each electrode.

B. Method.

A steel bar was placed on cotton saturated with sodium chloride and sea water in a previously cathodic area on top of Pile B. The steel bar was then electrically connected to the reinforcing steel embedded in the concrete pile.

Electrical potentials were measured on the surface of the concrete pile before and after the steel bar was placed on the pile.

The voltage measurements were made by placing a reference copper sulfate half cell at a remote distance from the pile. A second copper sulfate half cell was used to measure the voltages on the concrete surface.

C. Equipment and Materials.

The equipment used was two copper sulfate half cells and a high impedance vacuum tube voltmeter.

The materials used were a steel bar, sodium chloride and an existing reinforced concrete pile.

D. Results of the Experiment.

The experiment indicated that a corrosion cell will function when steel embedded in concrete is electrically connected to steel that is in contact with sodium chloride. The steel bar in contact with sodium chloride immediately became an anode to the concrete embedded reinforcing steel. This is illustrated by the potential measurements of the current flow on Exhibit 13, Chart 6, in the Appendix. The voltage between the reinforcing steel in concrete and the steel bar in sodium chloride was 0.48 volts.

7. Potential Survey, Abandoned P. G. & E. Pile (Pile C).

Corrosion tests were also performed on another abandoned P. G. & E. reinforced concrete pile approximately 1-1/2 years old. This pile, designated Pile C, was located approximately 250' south of the west end of the bridge and was in the tidal water zone.

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There was no cracking or spalling of the concrete. The pile had the original wooden driving cushion attached to the head of the pile.

The reinforcing steel extended through the wooden driving cushion into the atmosphere.

Electrical potential measurements were obtained by two methods. One method was to electrically ground the voltmeter to one of the reinforcing steel bars, and a copper sulfate half cell was used to measure the voltages. The second method was to ground the voltmeter to a copper sulfate half cell which contacted the soil at a remote distance from the pile. Voltage measurements were then measured by using another copper sulfate half cell to contact the surface of the pile. The measurements are depicted on Exhibit 14, Chart 7, in the Appendix.

Both methods of measuring voltage gradients on the surface of the pile indicated an anode within the wooden driving cushion, and a cathode within the pile.

The wooden driving cushion was stripped from the pile and the condition of the exposed reinforcing steel was observed. One of the steel reinforcing bars within the wooden driving cushion had lost more than 75% of its original cross-section.

The corrosion products of the steel within the driving cushion were black in color, and were not solidified. This indicated that there was insufficient atmospheric oxygen to oxidize the corrosion products to the reddish brown appearance of common rust. Under certain conditions, oxygen is not necessary for corrosion to proceed. [20, 21, 22, 27]

Normally the rate of corrosion is dependent upon the removal of the hydrogen film at the cathode. This can be accomplished by oxygen combining with the cathodic hydrogen film and forming water, or by hydrogen evolution, or by other chemicals reacting with the hydrogen film. As the corrosion takes place at the anode, it is only necessary for the cathode to be exposed to some type of hydrogen film removal process.

The corrosion rate of a corrosion cell with an anode in an oxygen free electrolyte and a cathode in a hydrogen removing or oxygen saturated electrolyte will normally depend upon the solubility, removal, or inhibiting effects of the corrosion products.

In the above discussed pile, the section of reinforcing steel which was exposed to alternate immersion and atmosphere exposure had heavy-stratified red rust. The metal loss of the steel was the normal amount to be expected in such an exposure of alternate sea water immersion.

The general field appearance of the abandoned piles is shown on Exhibit 15, in the Appendix.

8. Tests for stray electrical direct currents.

Potential measurements were made on the earth's surface away from the west end of the bridges for a distance of 1100 feet.

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Potential measurements were made every 50 feet. The measurements did not indicate a potential gradient to or from the bridge.

Potential measurements were made on the earth's surface during the opening and closing of the lift span, and no fluctuation of the earth's potential to two copper sulfate half cells was observed.

At span #512 on the bridge, potential measurements were made on the surface of the bay for a distance of 400' away from, and north of, the bridge. This was accomplished by floating a copper sulfate half cell, by means of wooden floats, with the tide water. Another copper sulfate half cell was in contact with the concrete bridge. The measurements indicated zero potential gradient on the water's surface.

The possibility of the deck, beams, caps, and piles being tied together by the reinforcing steel was checked. For this test a welding generator was employed. It was observed during the test that the deck and beams were electrically tied together. However, the reinforcing steel in the piles and caps was not designed to be electrically connected to the deck and beams. It was also determined that the reinforcing steel in each bent was not designed to be electrically inter-connected. The fact that it was not connected was checked at two spans only during this preliminary study and should be verified during any comprehensive study.

In view of the preceding findings, it is very improbable that a stray electrical current of any magnitude could flow through the bridge for a greater distance than one span. The potential measurements made on the bridge did not indicate the presence of stray electrical currents.

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VI. OBSERVATIONS

The measuring of potential gradients on the surface of the concrete beams indicated the areas of steel corrosion. In the areas of corrosion of the reinforcing steel, some rust was observed to be distributed in the cracks in the concrete. It was observed, during the measuring of the surface potential on the concrete, that the reproducibility of measurements varied with the moisture content of the beams. This fact was observed when over wetting of the concrete surface was required to obtain a voltage reading.

In the field checking of the possibility of stray electrical currents causing the corrosion, the State welder on the bridge was contacted. The welder's experience indicated that the bridge was not electrically connected through its length. It was his opinion that the reinforcing steel in the deck and beams was electrically tied together, and the reinforcing steel in the caps and piles was electrically tied together; but the steel in the beams and deck was not electrically connected to the steel in the piles and caps.

With the assistance of the Resident Engineer and the contractor performing the contract repair work at the San Mateo Bridge, the statements of the State employed welder were verified by test using the contractor's welding generator.

The foreman of the bridge crew on the San Mateo Bridge was then contacted. The foreman offered statements on the hardness of the concrete on the bridge. It was his opinion that the concrete is usually harder in the vicinity of cracks in the concrete. The degree of hardness of concrete is not known, but is referenced to the ease with which the concrete chipping hammers demolish the concrete. The foreman stated that on one cap on the bridge the concrete was so soft that a steel "gad" could be hand driven to a depth of 1/4 to 1/2 inch into the concrete. There was no evidence of corrosion of the reinforcing steel at the location of this "soft" concrete.

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VII. DISCUSSION

A. Theoretical Cause of the Corrosion.

The primary cause of the corrosion of the reinforcing steel of the San Mateo-Hayward Bridge is the functioning of a corrosion cell with the anodic and the cathodic areas separated by the approximate distances of two to ten feet.

The corrosion cell appears to be caused by the following factors:

1. The general concentration of chloride in the concrete has sufficiently lowered the electrical resistance of the concrete to permit current flow through the concrete.

2. The concentration of chlorides in the anodic areas is great enough to destroy the corrosion inhibiting effect of the concrete.

3. The cathodic areas are probably caused by two factors, the first factor would be the difference in alkalinity between the anodic and cathodic areas. The differences in aeration between the cathodic areas of equal alkalinity probably cause a shifting in the location of the cathodes as the moisture content of the concrete changes, but the locations of the anodic areas remain relatively constant, as these areas have a greater salt and moisture content than the cathodic areas.

B. Evidence supporting the theoretical cause of corrosion.

1. Permeation of chlorides.

   In a report by the Bureau of Standards[4], it was stated that 1/3 of one percent of sodium chloride in cement is sufficient to destroy the passivity of embedded iron.

   In tables IX and X in Part I of this study, the amount of chlorides in the concrete of the San Mateo Bridge, at an average depth of 2" from the atmospheric surface of the concrete, varies from approximately 0.05% to 0.86% of the dry weight of the mortar.

   Therefore, it appears that the percentage of chlorides in the concrete of the San Mateo Bridge is sufficient to destroy the inhibiting effect of the concrete on the steel.

2. Concrete cover over reinforcing steel.

   In a report by the Bureau of Standards[5], the minimum recommended depth of a dense concrete cover exposed to a marine environment is 2".

   Reinforcing steel has been reported[19] to corrode under 2" to 4" of concrete cover. There are many reports,[1,2,3,4,5,6,7,8,9,10,11,12,18,19,20,21,22] in the literature of the corrosion of steel embedded in concrete. The majority of the above references deal with the corrosion of reinforcing steel due

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to impressed or stray electrical currents and are but indirectly of use in this study. References 3,5,12,19, 20,21 and 22 deal with "local" causes and are more directly related.

The depth of concrete cover over the outer reinforcing steel bars in the San Mateo Bridge varied from 1-1/2" to 3" in depth and averages 2".

3. Corrosion Cells and Alkalinity.

Generally, an electrolyte is more alkaline at the cathode 3,4,6,13,18,20,21,22. and less alkaline at the anode 13,15,20,21,22,26.

Corrosion cells can be caused by difference in alkalinity 3,18,20,21,22 and are described in the literature. The pH measurements of the concrete samples from the San Mateo Bridge had a higher indicated pH value at the cathodes than at the anodes.

4. Specific Electrical Resistance.

As the corrosion of steel is an electrochemical action, the rate, and sometimes the probability of corrosion, is a function of the electrical resistance of the electrolyte 3,20,21,22,24. It has been previously reported [12] that cement mortar when wet has about the same electrical resistance as many soils.

The specific electrical resistance of the concrete in the San Mateo Bridge is within the range of a reported corrosive soil [27].

5. Corrosion Cells with Concrete as an Electrolyte.

The results of the experiments of this report clearly indicate that a corrosion cell could be made with steel in contact with concrete samples obtained from the San Mateo Bridge.

6. Corrosion Cell on an Abandoned San Mateo Bridge Pile.

Exhibit 12, Chart 5, of this report, clearly indicates that a corrosion cell is causing the corrosion of the steel in this abandoned reinforced concrete pile (Pile A).

The voltage measurements located the non-corroding cathodic areas and the anodic corroding areas. The concrete in the pile was cracked, and the steel was rusted in the areas the potential measurements indicated to be anodic.

7. Galvanic Corrosion Cell on Abandoned P. G. & E. Reinforced Concrete Piles.

The potential measurements on piles B and C, Exhibits 13 and 14, Charts 6 and 7 respectively, indicated that an anodic corrosion area was located in the wooden driving

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cushion of these piles. The potential measurements indicated the cathode was located on the steel within the pile at a distance of approximately 7' from the anode.

With the subsequent removal of the wooden driving cushion, severe corrosion of the reinforcing steel was observed to have taken place. The sections of the reinforcing bars which projected beyond the wooden driving cushion, and were subject to atmospheric and alternate sea water immersion, were rusted to the extent that would be normally expected in approximately 1-1/2 years of exposure time.

The subsequent experiment of placing a steel bar in intimate contact with concentrated sodium chloride, on top of Pile B, indicated that a corrosion cell could be caused by the steel in the concrete acting as a cathode, and the steel bar on top of the pile in the concentrated sodium chloride acting as an anode.

8. Potential Measurements on the San Mateo Bridge.

All of the potential measurements taken on the San Mateo Bridge indicated that a current flow caused by a corrosion cell is the cause of the reinforcing steel corrosion.

The potential measurements taken at span #512, indicated that the steel which has the greatest height above the water, and the greatest depth of concrete cover will tend to be cathodic to the steel which has less height above the water and less concrete cover for the heights above water observed.

The cathodic areas for the caps and piles are in the diaphragms and caps. Insufficient potential measurements were taken in the piles to establish if there were cathodic or anodic areas below the high tide level.

9. Effect of Present Repair Methods.

In Part I of this study it was established that the shotcrete used in previous repair projects on the bridge is approximately equal to the shotcrete now being used for repairs. It has been reported that corrosion of the reinforcing steel has occurred in previously shotcrete repaired sections.

The potential survey of the shotcrete repaired beam #S-2 at span #25, Exhibit 11, Chart 4, indicates that shotcrete coated steel is cathodic to non-shotcrete coated steel. This is logical since the two types of concrete may form two differing electrolytes so that any non-shotcrete coated steel adjoining a repaired section of steel may suffer a concentration cell type of corrosion attack, as soon as the electrical conductivity of the shotcrete is sufficiently low enough to permit current flow.

Under the present corrosion conditions of the bridge structure there is a possibility that the shotcrete method of repair may accelerate or focus a corrosion attack on previously non-

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corroding steel. The tendency for this corrosion attack will be to concentrate on the steel near the junction of the shotcrete and original concrete.

10. Effect of Corrosion Currents on Concrete.

With a cathodic electrode embedded in concrete and voltages ranging from 15 to 200 volts, numerous investigators [1,4,6,9] have observed a loss of concrete bond strength at the cathode when sodium chloride is present. A cause of concrete softening has been shown [1,4,6,9] to be the result of the migration of alkali ions to the cathodic electrode.

The migration of ions in an electrolyte with current flow have been adequately described in the literature [1,4,6,9,13,14,15,16,17,27,28]. In general it has been reported that the cathode becomes alkaline [1,4,6,9,15,26] and the anode becomes less alkaline or acidic [12,13,15,20,21,22].

In one case [13] with a current flow of 200 microamperes between electrodes in a solution of 0.002N Na_2Co_3 + 100 ppm KCl, the concentration of chlorides in the electrolyte at the anode increased 400% within 72 hours.

As the literature gives evidence of ion flow in an electrolyte with current flow, extreme care must be exercised if an external current, such as cathodic protection, is applied to the bridge to prevent further corrosion.

11. Aeration and Cathodic Areas.

When electrical potentials were being obtained on the structure, it was noted that minor shifts in potentials altered the locations of the cathodic areas. As it was obvious that there were humidity changes during the days, the changes in the potentials could be the result of either of two factors: (1) the high electrical contact resistance of the half cells caused an error in the recorded potentials, or (2) the location of the cathodic areas changed as the moisture content of the concrete changed.

The measured electrical contact resistance of the half cells has varied from approximately 1,000 to 100,000 ohms. The input impedance of the voltmeter is 50,000,000 ohms per volt. Therefore, any error introduced into the measurements by electrical contact resistance of the half cells would be approximately 0.2% or less.

In determining whether aeration had any effect on the corrosion cells, a very limited study was made on one beam on the bridge. A potential survey was initially made on a beam and an anodic area was located. The concrete at this anodic area was cracked and beginning to spall. The concrete was forced off and the exposed steel was found to be corroded.

Potential measurements were again made and the anodic area became cathodic to adjacent concrete imbedded steel.

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This observed phenomenon may indicate that when sufficient salts have permeated the concrete, the corrosion cells in the bridge can be caused by differential aeration as well as the chemical content of the concrete.

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VIII. RECOMMENDATIONS

This study, while limited in extent, indicates that the corrosion of the reinforcing steel in this structure is probably caused by a concentration type of corrosion cell. However, before definite reommendations can be made as to the method of correcting this condition by the use of cathodic protection, it is recommended that the following information be obtained:

1. The relative magnitude of corrosion current flow in the corrosion cells through the bridge should be determined.

2. Concrete samples should be taken from several anodic and cathodic areas on the bridge and analyzed for strength and chemical content.

3. A study of the chemicals found in the concrete of the San Mateo-Hayward Bridge and the minimum concentration of such chemicals which can cause an electrolyte concentration type of corrosion cell in the concrete should be made.

4. A study of chemical ion migration under various electrical current densities in concrete and in aqueous solutions should be undertaken.

5. A study of the variations of the moisture content in the concrete on the bridge should be undertaken so that duplication of field conditions for further studies can be made in the laboratory.

6. Studies of the effect of applying a dielectric, such as paints, to the reinforcing steel at the time of repair should be made.

7. Further laboratory and field study should be undertaken to determine a practical method of neutralizing the electrical corrosion currents of the reinforcing steel. It appears that the most economical method of doing this will be by cathodic protection. However, further study should be made to determine the effect of cathodic protection currents on the strength and chemical composition of concrete taken from the San Mateo-Hayward Bridge.

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IX. CONCLUSIONS.

The corrosion of the reinforcing steel of the San Mateo Hayward Bridge is an electrochemical action. The primary cause of the corrosion appears to be differences in the chemical composition within the concrete.

Limited tests seem to indicate that shotcrete encased steel may in time act as a cathode to the adjacent steel still embedded in the original concrete of the structure. This means that corrosion of the steel might be accelerated in all areas where a difference in chemical composition exists between the old and the new shell of the protecting concrete. In order to make sure that the repairs are permanent we should at least demonstrate on a laboratory basis that whatever corrective measures are employed will not be subject to the same changes that have occurred in the old concrete and that the protective measures will not create conditions that will speed up corrosion in the adjacent areas.

The reinforcing steel can be protected from additional corrosion by impressed currents, i.e., cathodic protection. However, the effect of an impressed current on the chemical composition of the concrete is not entirely known. There is some evidence that it could be detrimental to the chemical stability of the concrete. Therefore, further studies should be undertaken concerning the effect of the corrosion currents on the concrete of the San Mateo Bridge.

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XI. APPENDIX

Investigations

Exhibits, 1 through 15

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INVESTIGATIONS

A. Laboratory Studies

1. Electrical Corrosion Currents induced by Concrete and Steel.

Experiment No. 1.

a. Purpose.

The purpose of this experiment was to determine if steel electrodes contacting the surface of concrete could cause an electrical corrosion current to flow.

b. Method.

The steel electrodes were clamped to the opposite faces of the concrete samples.

The half cell potential of each steel electrode was measured against a calomel half cell. Then, the half cell voltage difference of the steel electrodes was checked by connecting the electrodes through the voltmeter. After the voltage difference of the steel electrodes was established, the electrodes were coupled through the microammeter. The current flow through the microammeter was recorded as well as the final combined half cell potential of the electrode couple.

The electrodes were then reversed in position and the aforementioned procedure was repeated. The reversal of electrode position was done to evaluate the differences in the concrete or differences in the steel electrodes that caused the current flow.

c. Equipment and Materials:

The equipment used was a 50 megohm input impedance vacuum tube voltmeter, a microammeter with a full scale deflection of 16 microamperes and two steel electrodes, approximately 1/16" x 2" x 4" mild steel.

The materials used were four concrete samples taken from anodic corrosion areas, and one taken from a non-corroding cathodic area of the beams. The beam concrete samples were taken from 2 beams in span #512. The laboratory designation and the field location of the beam samples are as follows:

Concrete Sample No.	Remarks
1.	Taken from the southerly bottom corner of beam #N-1, and approximately 8' westerly from the cap of bent

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#513. At the location of this sample on the beam, an anodic voltage of 0.32 volts was measured on the surface of the concrete. The reinforcing steel at this location was corroding and the concrete was cracked.

2. This sample was taken from the southerly bottom corner of beam #N-2, and approximately 3' easterly of bent #512. At the location of this sample on the beam an anodic voltage of 0.20 volts was measured on the surface of the concrete. The reinforcing steel at this location was corroding and the concrete was cracked.

3. This sample was taken from the southerly bottom corner of beam #N-2, approximately 10' easterly from the cap of bent #512. A cathodic voltage of 0.06 volts was measured on the surface of the concrete at this location in the field. No cracks in the concrete or corrosion of the reinforcing steel were apparent in this location.

4. This sample was taken from the southerly bottom corner of beam #N-1, approximately 5' easterly of bent #512. An anodic voltage of 0.10 volts was measured on the surface of this concrete sample in the field. The steel was corroding at this location, but no cracks in the concrete were visible.

The concrete beam samples were approximately 2" x 3" x 10". The sides of the concrete toward the centers of the beam were cut with a diamond saw to obtain smooth surfaces.

The sides of the samples were identified in the following manner:

Side	Remarks
A	Vertical and toward the center of the beam.
B	Vertical and exposed to the atmosphere.
C	Horizontal and toward the center of the beam.
D	Horizontal and exposed to the atmosphere.

d. Results of experiment.

Corrosion cells and resulting flow of current were formed when the steel electrodes were placed on opposite faces of the specimens. The numerical results of the experiment are given in Table I. The measured currents were quite small in magnitude but they indicate without doubt that cells capable of causing corrosion were formed in air-dry concrete. The cells apparently were of the "concentration cell" type and presumably resulted from unequal concentrations of sea salt. The steel electrodes that were in contact with the faces that had been in contact

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with the atmosphere in the structure were anodic to those that were placed on the sawed, inner faces of the specimens.

Experiment No. 2.

a. Purpose.

As a further check of a corrosion cell being caused by moisture or chemical differences in the concrete, the four concrete samples from the beams were checked in pairs.

b. Method.

The steel electrodes were placed on the inside vertical surface of the concrete samples (sides A). Then, the two concrete samples were butted together so that the originally atmospheric faces "B" of each sample were joined.

The half cell potentials, current measurements, and reversal of the position of the steel electrodes were done in the same manner as previously outlined in Experiment No. 1.

c. Equipment and Materials.

The equipment and materials used in this experiment are the same as used in Experiment No. 1.

d. Results of Experiment.

The numerical results of the experiment are in the Appendix and are tabulated in Table II, and demonstrate that chemical differences in concrete can apparently cause a corrosion cell to be formed. Generally the anodic samples taken from the bridge remained anodic to cathodic samples taken from the bridge.

Experiment No. 3.

a. Purpose.

The purpose of this experiment was to determine if steel electrodes in contact with concrete could cause an electrical corrosion current to flow.

b. Method.

The methods for measuring voltages and currents were identical to the procedure outlined in Experiment No. 1.

c. Equipment and Materials.

The equipment and steel electrodes were identical to those used in Experiment No. 1.

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The material used was a concrete core approximately 5" in diameter and approximately 13" long, cut from the deck of the San Mateo Bridge, and called core Sample #1. This core was located 9' westerly from the cap of bent #513 and approximately 10' northerly of the pavement-centerline of the deck.

The reinforcing steel was embedded in two locations in the core. Reinforcing bar No. 1 was embedded 5" below the deck surface, and reinforcing bar No. 2 was embedded 10" below the deck surface.

During the cutting of the core, the core sheared at the locations of the reinforcing steel. Approximately 1/2" of the concrete was abraded from the specimen at the locations of the reinforcing steel.

Two pieces of the concrete core were used in this experiment.

The bottom piece of the core was called section 1 and the middle section of the core was called section No. 2. On the bottom section, No. 1, the face of the concrete exposed to the atmosphere was called surface A. The exposed surface that sheared at the reinforcing steel was called surface B.

On the middle section, Number 2, the exposed surface of the concrete adjacent to surface B of Section 1 was called surface C. The surface of the middle section that was nearest to the deck was called surface D.

d. Results of Experiment.

The numerical results of this experiment are in the Appendix and are listed in Table III, and demonstrate that a corrosion cell can be caused by moisture or chemical differences in an apparently "air dry" concrete electrolyte.

Experiment No. 4.

a. Purpose.

To determine if a corrosion cell could function between two pieces of reinforcing steel embedded in concrete.

b. Method.

(Method 1) The concrete core was allowed to stabilize to an atmospheric dry moisture content. The two embedded bars of reinforcing steel were then electrically shorted through a microammeter and the presence of a current flow was measured.

(Method 2) The surface of the concrete was moistened with tap water until the concrete had a damp appearance.

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The reinforcing steel was then electrically connected through a microammeter and the presence of a current flow was measured.

c. Equipment and Materials.

The equipment used in this experiment was the same equipment used in Experiment No. 1.

The materials used in this experiment consisted of a 5" diameter by 9" long reinforced concrete core, designated core sample #2, cut from the deck of the San Mateo Bridge.

There were two bars of reinforcing steel in the concrete core. The upper steel bar in the deck, designated the top bar, had 2-1/2" of concrete cover from the deck surface to the top of the bar. The other steel reinforcing bar, designated the bottom bar, had 3" of concrete cover from the deck surface to the top of the reinforcing bar.

The location of this core cut from the deck of the bridge was: at span #512, approximately 15' easterly of the east face of the cap at bent #512 and 2' northerly of the centerline of the deck pavement. A cathodic voltage of 0.29 volts was measured at this location.

d. Results of Experiment.

(Method 1) Concrete core atmospheric dry.

A current flow of 0.7 microamperes was measured flowing between the two steel reinforcing bars when electrically connected through the microammeter. The top reinforcing bar was cathodic, and the bottom bar was anodic.

(Method 2) Concrete core moistened to a damp appearance.

A maximum current flow of 10 microamperes was measured flowing between the two steel bars when electrically connected through the microammeter. The top reinforcing bar was still cathodic and the bottom bar was anodic.

In both methods of this experiment, a corrosion cell was created by electrically connecting the concrete embedded reinforcing steel.

Experiment No. 5.

a. Purpose.

To determine if the pH of the concrete could be measured on the surface of visually atmospheric dry concrete samples and to determine if there were variations in

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the alkalinity of the concrete at cathodic and anodic areas.

b. Method.

A calomel half cell was placed upon a moistened cotton contact on the visually atmospheric dry concrete samples. Then a few drops of tap water, pH 8.3, were placed at each point of measurement. A pH reading was recorded as soon as the reading became stable.

c. Equipment and Materials.

The equipment used was a Beckman pH meter, model N, glass pH electrode and calomel 1/2 cell.

The materials used in this experiment were the four concrete samples taken from the beams and core sample number one taken from the deck of the San Mateo Bridge.

d. Results of Experiment.

Each surface of the several concrete samples was rechecked for an average of four times for pH measurements so as to investigate the connection between pH and the differences in polarity of the corrosion cell. The pH measurements are listed in Table IV in the Appendix. The concrete which was adjacent to the reinforcing steel had an average pH of 7.9 at the anodic areas and a pH of 8.5 at the cathodic areas.

As the moisture content and other variables of the concrete samples were unknown and were not controlled, the numerical results of the experiment may not indicate true pH measurements.

Experiment No. 6.

a. Purpose of Experiment.

The purpose of this experiment was to determine the specific electrical resistance of the concrete samples obtained from the San Mateo Bridge.

b. Method.

Pieces of wet paper were placed against the surface of the concrete to act as an electrical contact sheet. Then two copper electrodes were placed against the electrical contact sheets followed by a sheet of masonite to act as a dielectric. This sandwich was held together with clamps.

A direct electrical current was alternated between the copper electrodes which contacted the concrete samples.

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Voltage drops across the specimens were measured by means of two calomel half cells.

The specific electrical resistance was determined under three conditions: atmospheric dry; immediately after being soaked in tap water for 48 hours; and 1 hour after removal from the soaking bath.

The specific electrical resistance of the tap water used to moisten the concrete samples was 5900 ohm centimeter cube.

c. Equipment and Materials.

The equipment used was a 50 megohm input impedance vacuum tube voltmeter; a microammeter and a direct current source with a reversing switch.

The materials used were all the concrete specimens described in the previous experiments.

d. Results of the experiment.

The specific electrical resistances of the concrete samples were sufficiently low to allow corrosion to function with the anodic and cathodic areas separated by as much as the entire span length.

The specific electrical resistances of the concrete samples had a magnitude of 270,000 to 666,000 ohms per centimeter cube when they were atmospheric dry; a specific resistance of 38,600 to 51,600 ohms per centimeter cube when wet; and a specific resistance of 21,600 to 44,200 ohms per centimeter cube when they were damp in appearance.

The specific electrical resistances of the samples are listed in Table V, which is in the Appendix.

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Experiment #1

TABLE I

Electrical Currents Induced with Steel

Electrodes on a single concrete sample

COUPLED SURFACES						COUPLED SURFACES				
Sample	A *Voltage	B *Voltage	Current uA	*** Result *Voltage	Anode Side	C *Voltage	D *Voltage	Current uA	*** Result *Voltage	Anode (Side)
1	.25	.35	1.1	.33	B	.33	.38	0.7	.37	D
**1 Reversed	.26	.40	2.6	.35	B	.39	.40	0.3	.395	D
2	.41	.39	0.9	.40	A	.32	.40	0.9	.36	D
**2 Reversed	.40	.44	2.4	.38	B	.34	.47	1.8	.41	D
3	.41	.36	0.6	.40	A	.27	.42	1.1	.39	D
**3 Reversed	.31	.38	0.3	.35	B	.25	.45	1.7	.43	D
4	.42	.47	0.4	.38	B	.40	.44	0.1	.43	D
**4 Reversed	.41	.47	0.6	.45	B	.36	.50	2.0	.47	D
Average	.36	.41	1.1	.38	B	.33	.43	1.1	.41	D

*Voltage is average 1/2 cell potential of steel electrodes placed on the surface of the concrete
**Reversed is when steel electrodes are in reversed position
*** Resultant voltage is the half cell potential of electrically coupled steel electrodes with current flow to a calomel half cell, and indicates whether the corrosion cell is under anodic or cathodic control.

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Experiment #2

TABLE II

Electrical Currents Induced with Steel

Electrodes and Combining Concrete Samples

ELECTRODES DIRECT					ELECTRODES REVERSED			
Combined Samples	* Voltage	uA Current	**Result *Voltage	Anode	* Voltage	uA Current	**Result *Voltage	Anode
1 2	.42 .44	0.1	.43	2	.47 .30	0.5	.34	1
1 3	.37 .38	0.1	.38	3	.44 .30	0.3	.43	1
1 4	.29 .43	1.8	.36	4	.41 .46	0.2	.41	4
2 3	.30 .37	1.3	.35	3	.41 .32	1.7	.40	2
2 4	.41 .45	0.2	.42	4	.43 .40	0.1	.41	2
3 4	.36 .40	0.4	.395	4	.36 .46	1.4	.41	4

*Voltage is the average 1/2 cell potential of the steel electrode to a calomel 1/2 cell
**Resultant voltage is the half cell potential of electrically coupled steel electrodes with current flow to a calomel half cell, and indicates whether the corrosion cell is under anodic or cathodic control.

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Experiment #3

TABLE III

Electrical Current Induced with Steel

Electrodes and 2 sections of deck core Sample Number 1

	Bottom Section No. 1					Middle Section No. 2				
	Coupled Surface					Coupled Surface				
	A Voltage	B Voltage	Current uA	Result Voltage	Anode Side	C Voltage	D Voltage	Current uA	Result Voltage	Anode Side
Electrodes Direct	.43	.15	1.3	.42	A	.34	.36	0.6	.37	D
Electrodes Reversed	.39	.19	5.8	.36	A	.40	.49	0.5	.46	D
Average	.41	.17	3.6	.39	A	.37	.43	0.55	.42	D

*Voltage is the 1/2 cell potential of the steel electrodes to a calomel 1/2 cell

**Result voltage is the half cell potential of electrically coupled steel electrodes, with current flow, to a calomel half cell, and indicates whether the corrosion cell is under anodic or cathodic control.

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Experiment #5

TABLE IV

pH of Concrete Samples

		Beam Samples					Core Sample			
		Sample Surfaces					Sample Surfaces			
Sample No.		A	B	C	D	**Steel	A	B **Steel	C ** Steel	D
#1	Max.	7.6	6.8	11.7	6.9	7.9				
	Min.	6.1	6.6	7.5	6.6	6.1				
	Avg.	7.2	6.6	7.9	6.9	6.8				
#2	Max.	8.5	7.0	9.0	7.9	8.6				
	Min.	8.0	6.6	8.3	7.6	8.1				
	Avg.	8.2	7.0	8.6	7.8	8.3				
#3	Max.	8.7	7.3	7.5	7.0	8.5				
	Min.	7.1	6.9	6.6	6.4	7.0				
	Avg.	8.3	7.3	6.9	6.5	7.7				
#4	Max.	8.9	8.4	8.7	7.0	8.9				
	Min.	7.9	7.1	7.5	6.4	8.0				
	Avg.	8.3	7.8	8.0	6.6	8.6				
Core #1	Max.						7.9	9.6	11.8	10.9
	Min.						6.9	7.9	8.8	8.6
	Avg.						7.5	8.7	9.1	8.8

*Beam Surface
B--Side exposed to atmosphere and was vertical on bridge
D--Side exposed to atmosphere and was horizontal

**Steel
Surface of Concrete sample formerly contacting reinforcing steel

Note: Water used to wet surface of concrete sample had a pH of 8.3

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Experiment No. 6

Table V

Specific Electrical Resistance

of Concrete

in ohms per centimeter cube

Sample Condition	Beam Sample No.				Deck Core No.	
	1	2	3	4	1	2
Atmospheric Dry	270,000	571,000	666,000	616,000	450,000	466,000
Wet	43,400	38,600	51,600	41,500		
Damp	21,600	35,700	44,200	29,200		

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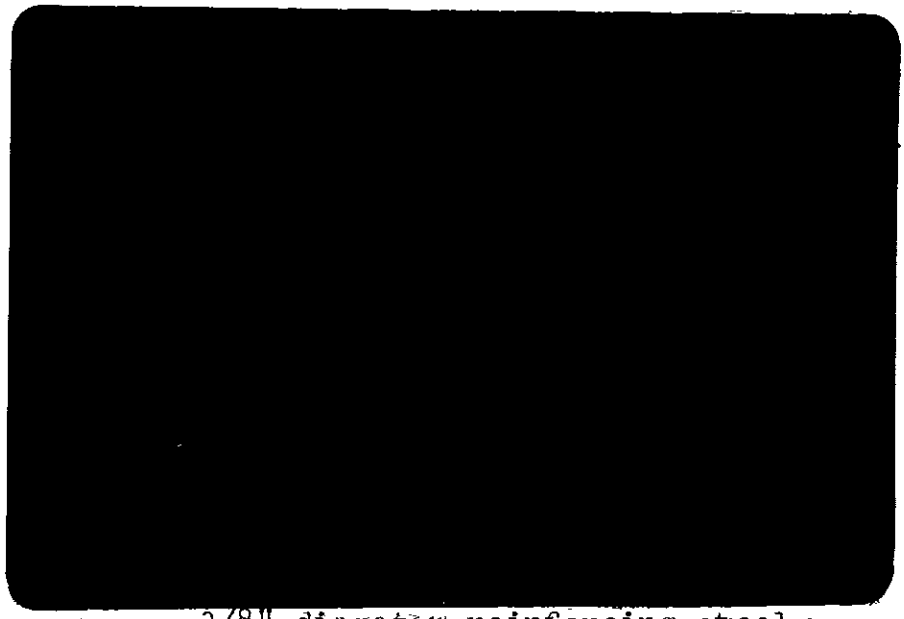
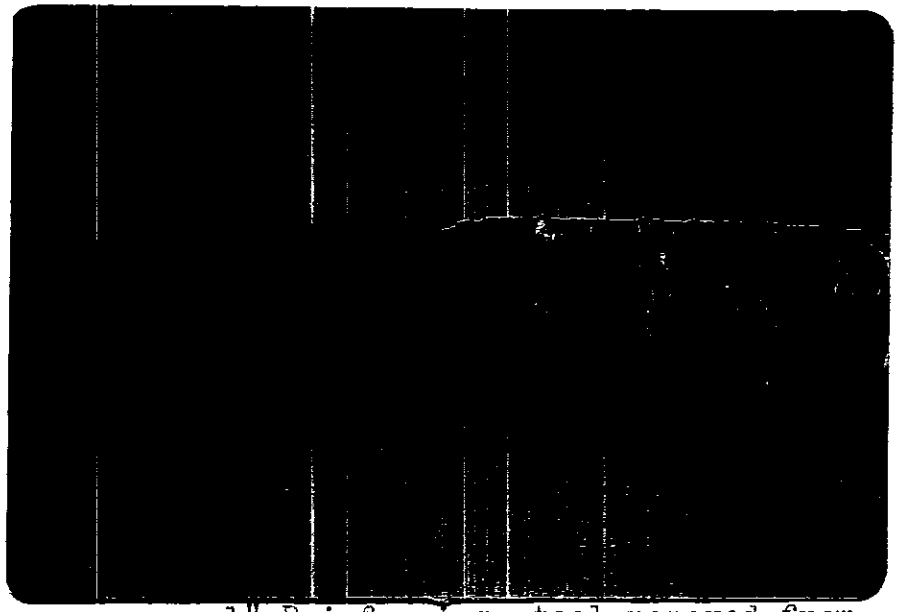
Exhibit 1



3/8" diameter reinforcing steel bars removed from San Mateo Hayward Bridge



1" Reinforcing steel removed from abandoned pile in tidal water. Pitted area was within wooden driving cushion. Note sea water organisms where steel projected beyond wooden driving cushion. Exposure was approximately 1 1/2 years.

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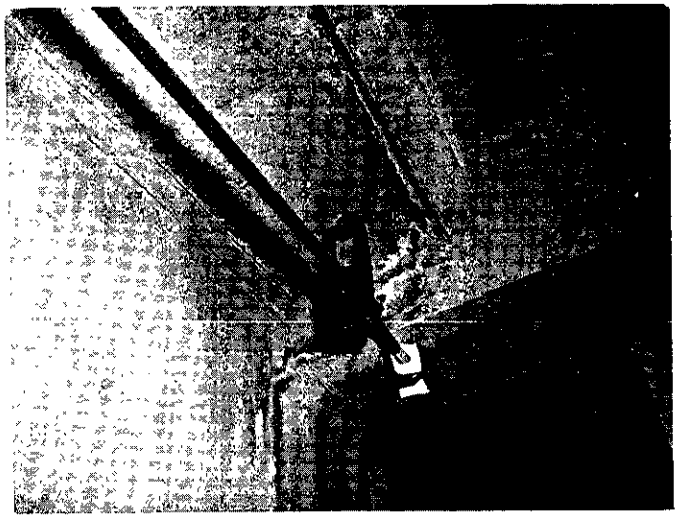
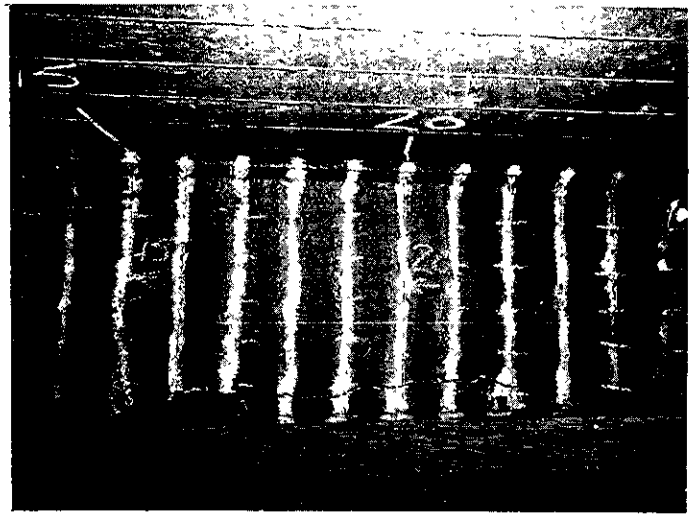
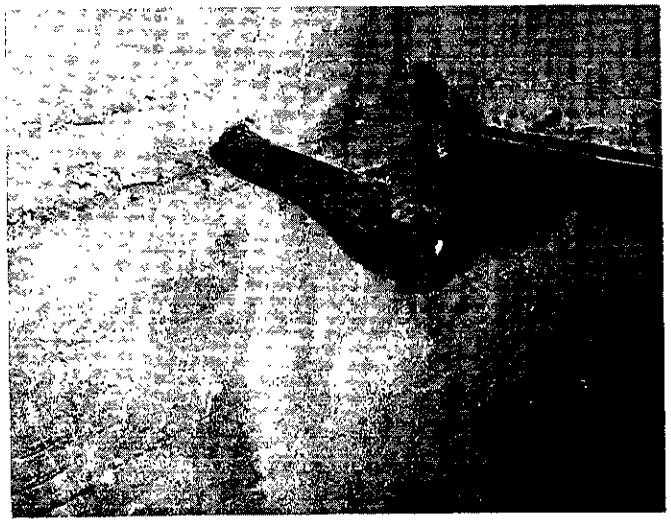
Exhibit 2



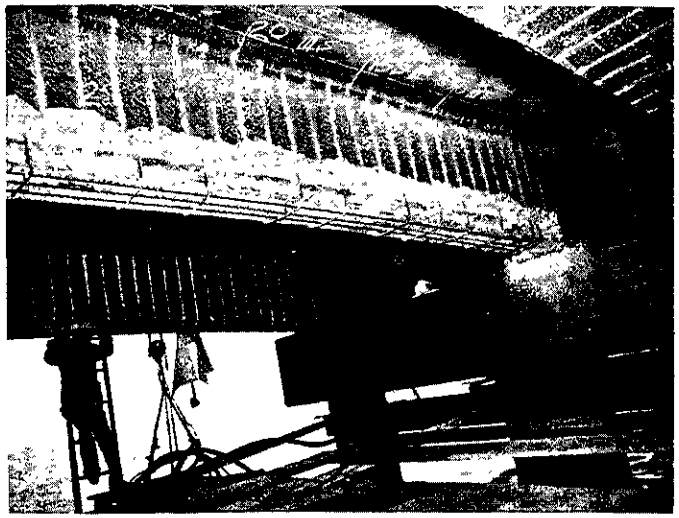
Steel support for insulator of abandoned lighting cable on underside of deck. Note corrosion of steel supports.



Typical appearance of cracked concrete in bottom of beams. Distance between vertical sandblast lines = 0' - 5" ±



Typical appearance of steel conduit (use unknown) remaining in diaphragm.



Beam ready for sandblasting.

Exhibit 3

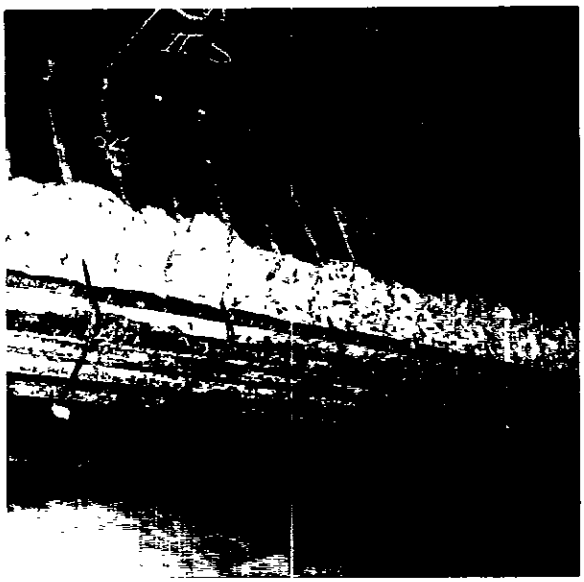


Photo 1

Photo 2

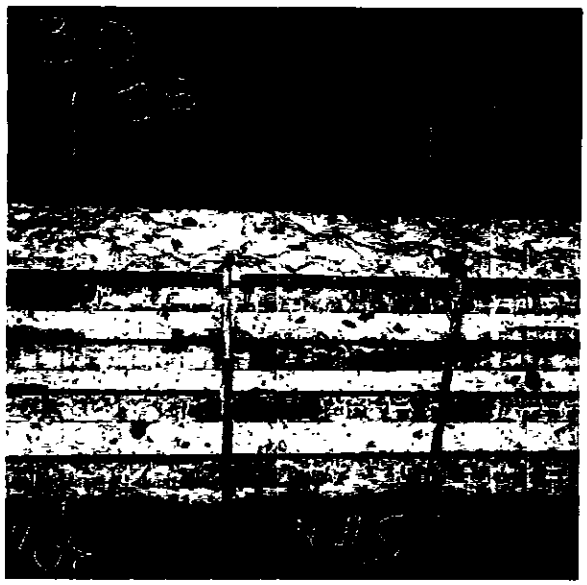


Photo 3

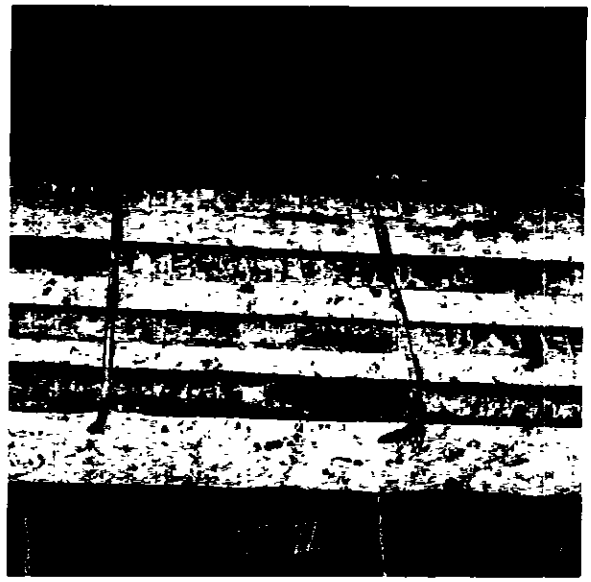


Photo 4

Looking upward at typical corrosion attack of reinforcing steel in the bottom of Beam S-1, Span #385. These photos are typical of the corrosion of the reinforcing steel in the bottom of beams.

Vertical lines in photo 1 are concrete exposed by sand blasting of asphalt coating. Horizontal distance between lines = 0'5" ±.

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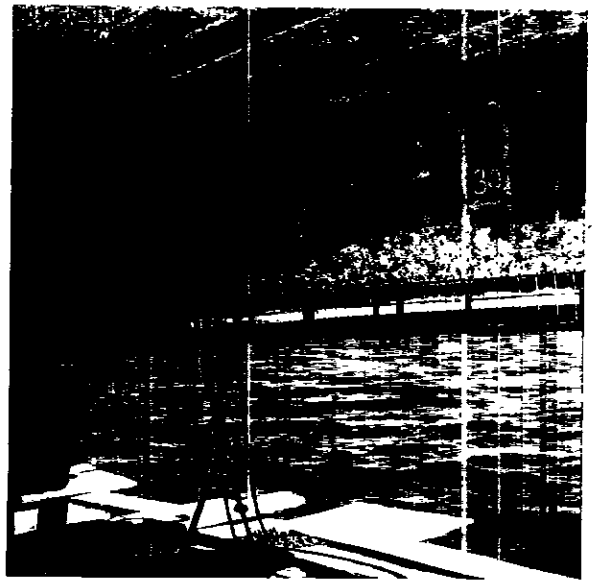
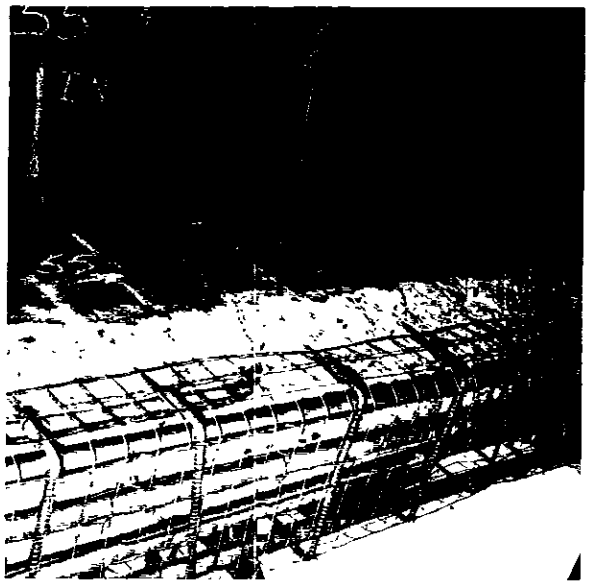
Exhibit 4

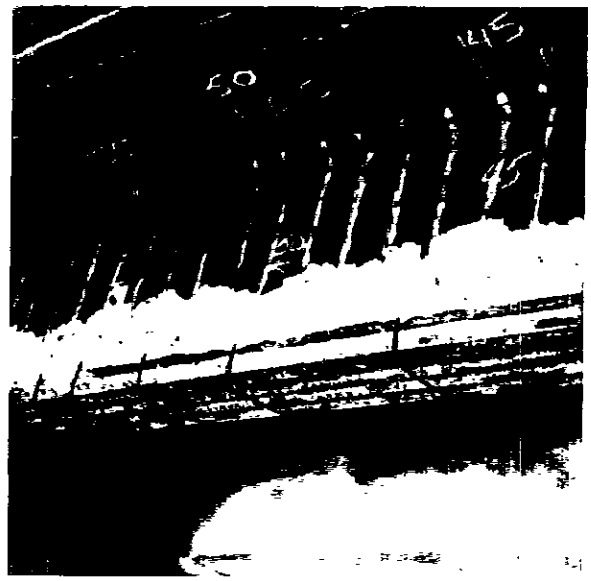


Steel sand blasted and wire reinforcing in place prior to placing shotcrete.

Concrete chipped exposing steel in cap (lower left) prior to sand blasting. Note rusting.



Steel sand blasted and wire reinforcing in place prior to placing shotcrete. Chalk marks on reinforcing steel are the locations of corrosion pits. Notice replaced stirrup bars.



Beam in foreground ready for sandblasting. Note corrosion areas. Beam in background has been repaired and coated with shotcrete.

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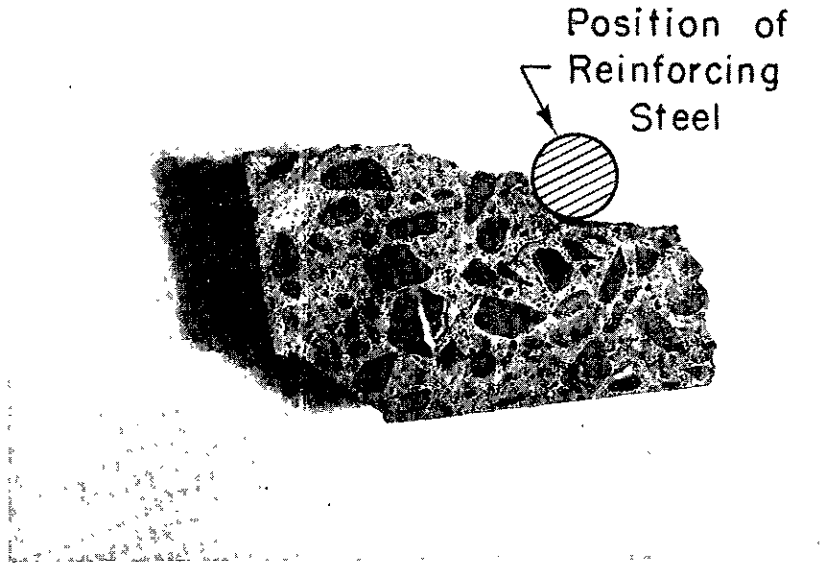
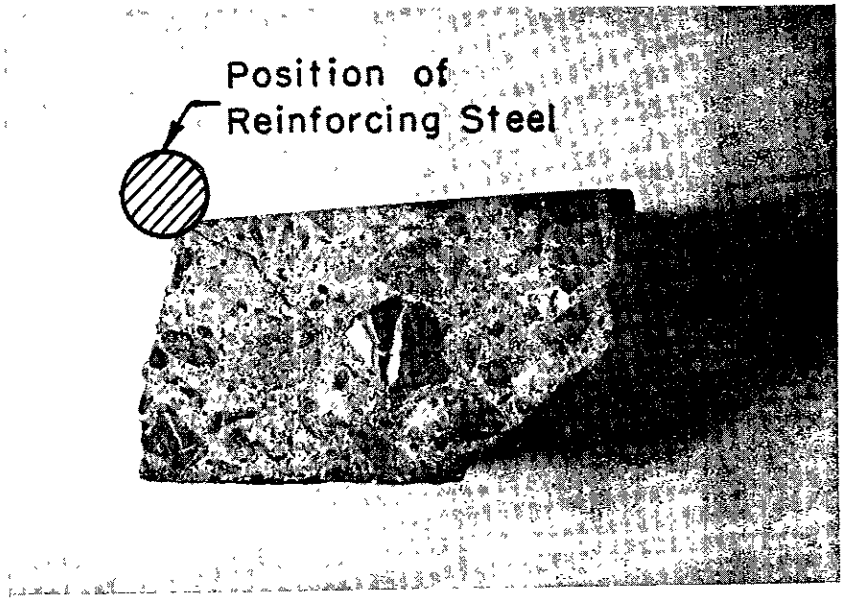
Exhibit 5



Concrete beam sample obtained from area of steel corrosion and concrete spalling. Note crack in concrete which started at the location of steel contact and has not reached the outside surface of the concrete.



Concrete beam sample obtained from area of steel corrosion and concrete spalling. Note crack in concrete which started at the location of steel contact but has not reached the outside surface of the concrete.

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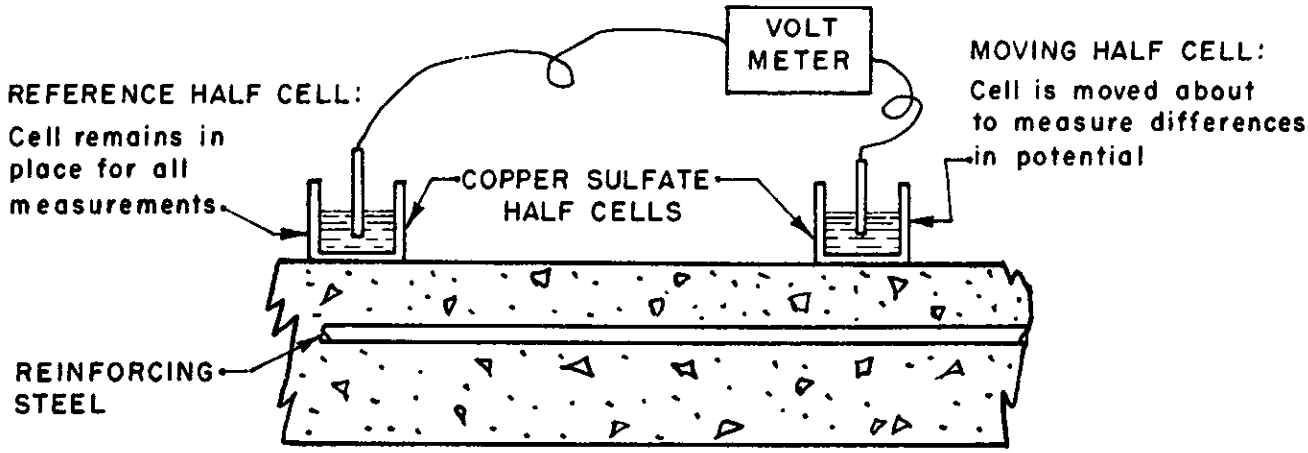
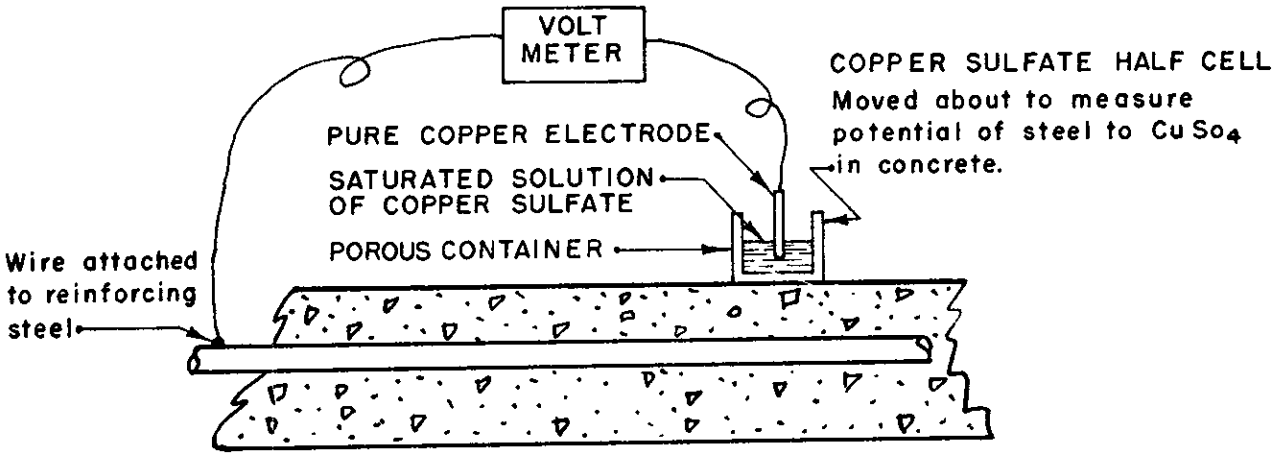
Exhibit 6



Method for making electrical surface potential gradients.



Method for making electrical surface potential measurements using embedded steel and $CuSo_4$ halfcell.

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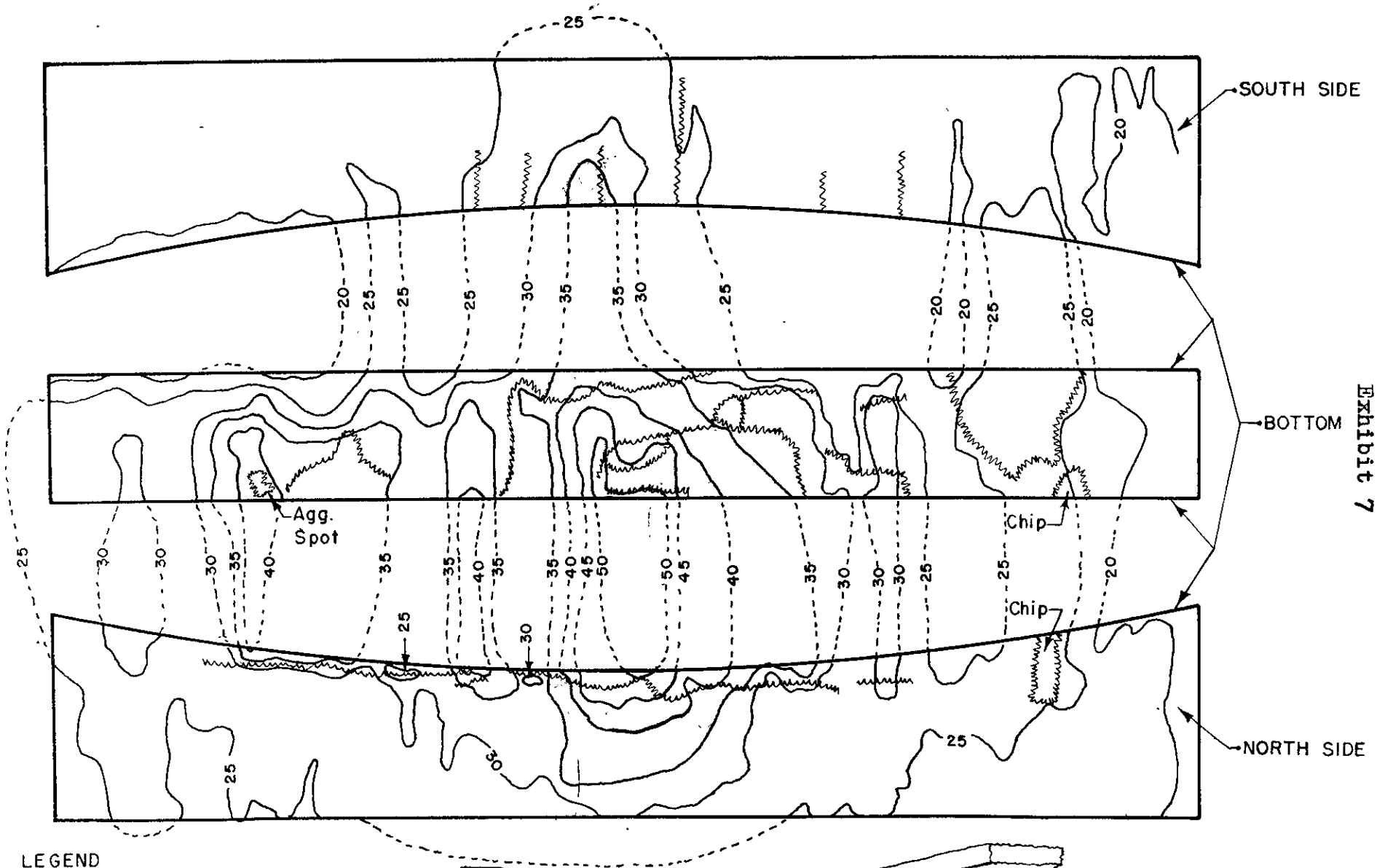
CHART I
Equipotential Contours of

CALIFORNIA DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPARTMENT

BEAM S-I BETWEEN BENTS #385 & #386



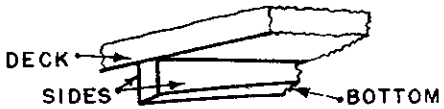
LEGEND

Cracks in Concrete

NOTE: Potentials Are Steel to Cu Cu So4

Anodic

Cathodic



TO ACCOMPANY REPORT
DATED JULY, 1955

Exhibit 7

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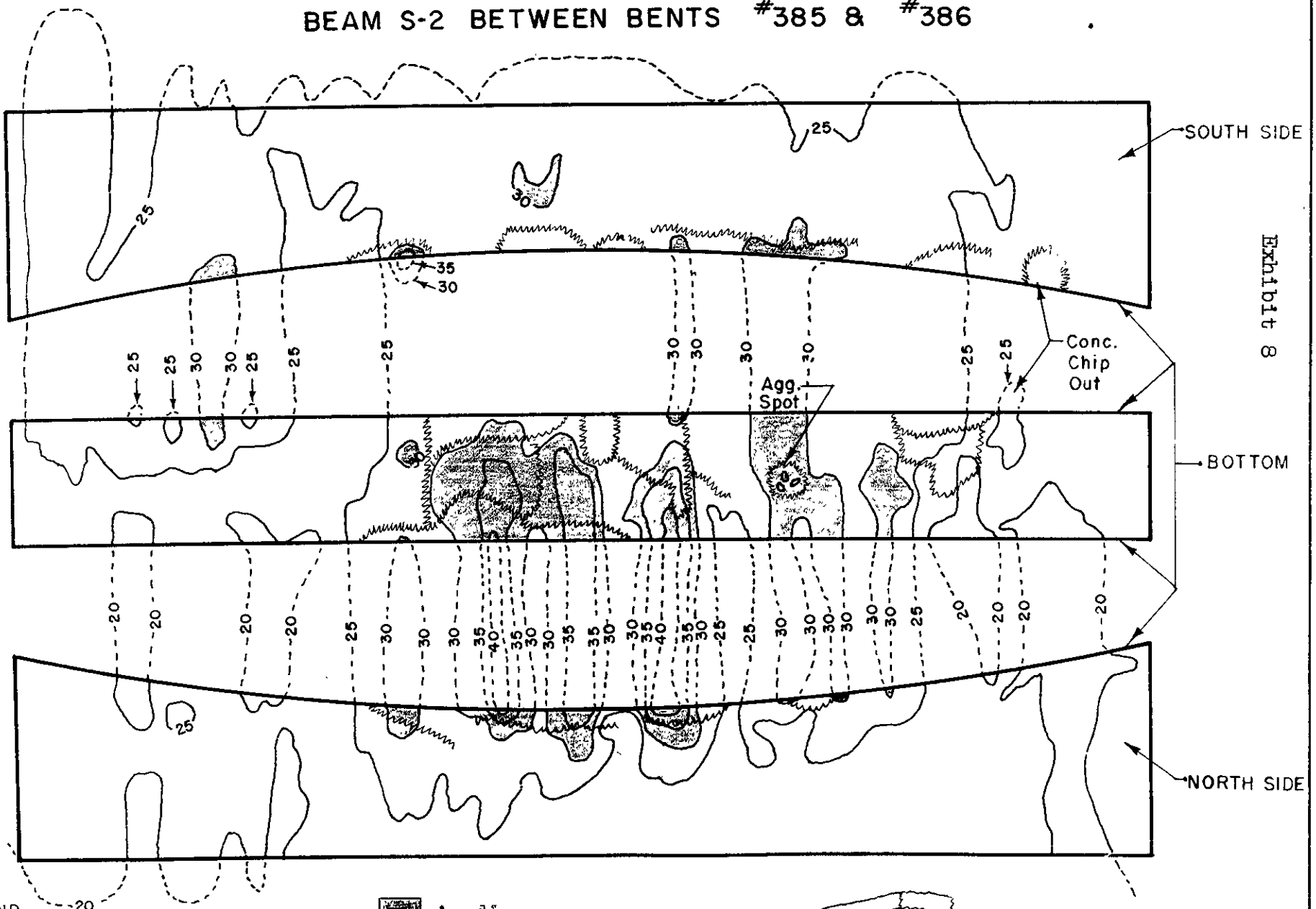
CALIFORNIA DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPARTMENT

CHART 2
Equipotential Contours of
BEAM S-2 BETWEEN BENTS #385 & #386



LEGEND
Cracks in Concrete.
NOTE: Potentials Are Steel to $CuCuSo_4$

Anodic
Cathodic

TO ACCOMPANY REPORT
DATED JULY, 1955

Exhibit 8

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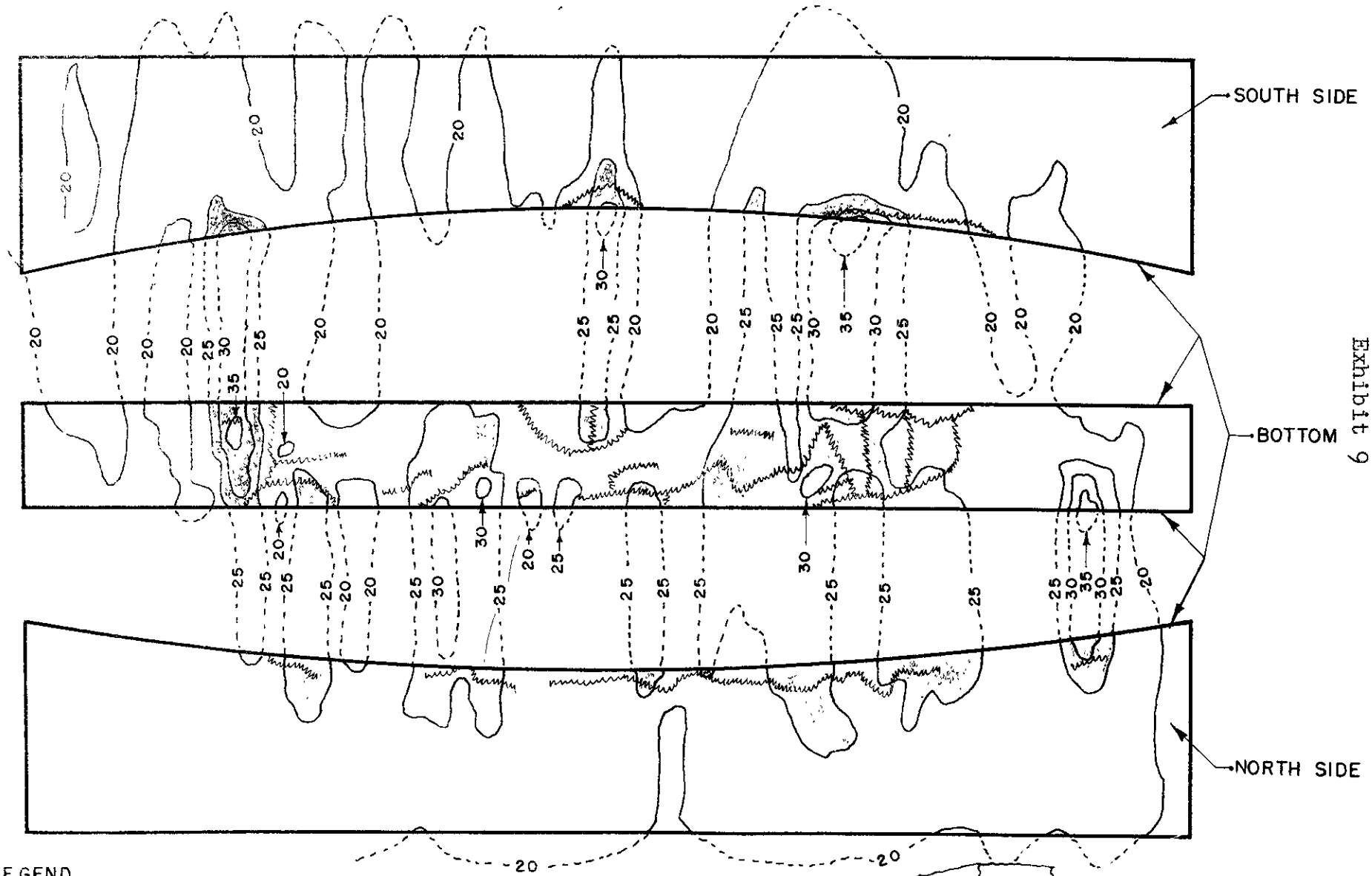
CALIFORNIA DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPARTMENT

CHART 3
Equipotential Contours of
BEAM N-2 BETWEEN BENTS #385 & #386



LEGEND
Cracks in Concrete
NOTE. Potentials Are Steel to $CuCuSO_4$
Anodic
Cathodic

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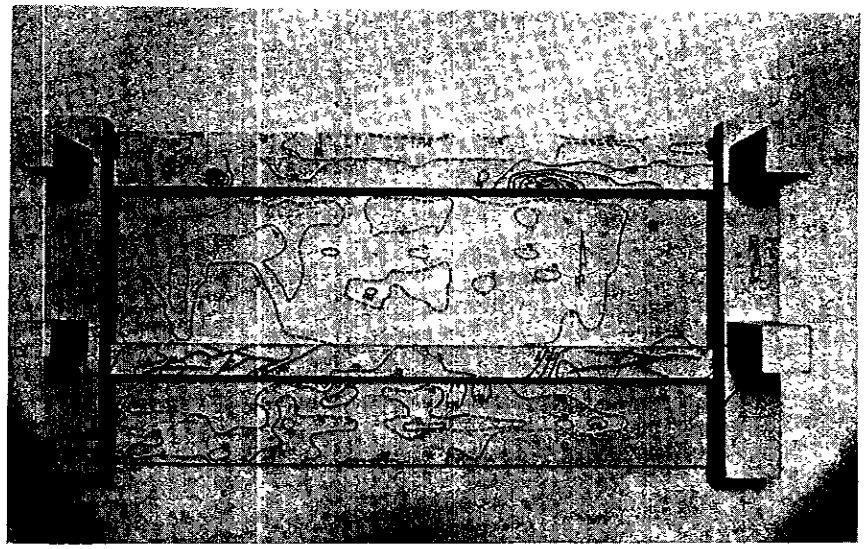
Exhibit 9

Exhibit 10

San Mateo - Hayward Bridge

Model of bridge span showing corrosion current contours



Equipotential contours plotted on under surface of scale model of left half of span 512.

----- lines are cathodic (non-corroding) voltages.
_____ lines are anodic (corroding) voltages.
~~~~ lines are cracks in concrete.

Note that the cathodic areas are located in the deck, and the anodes are located in the bottom of the beams.

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~~~~

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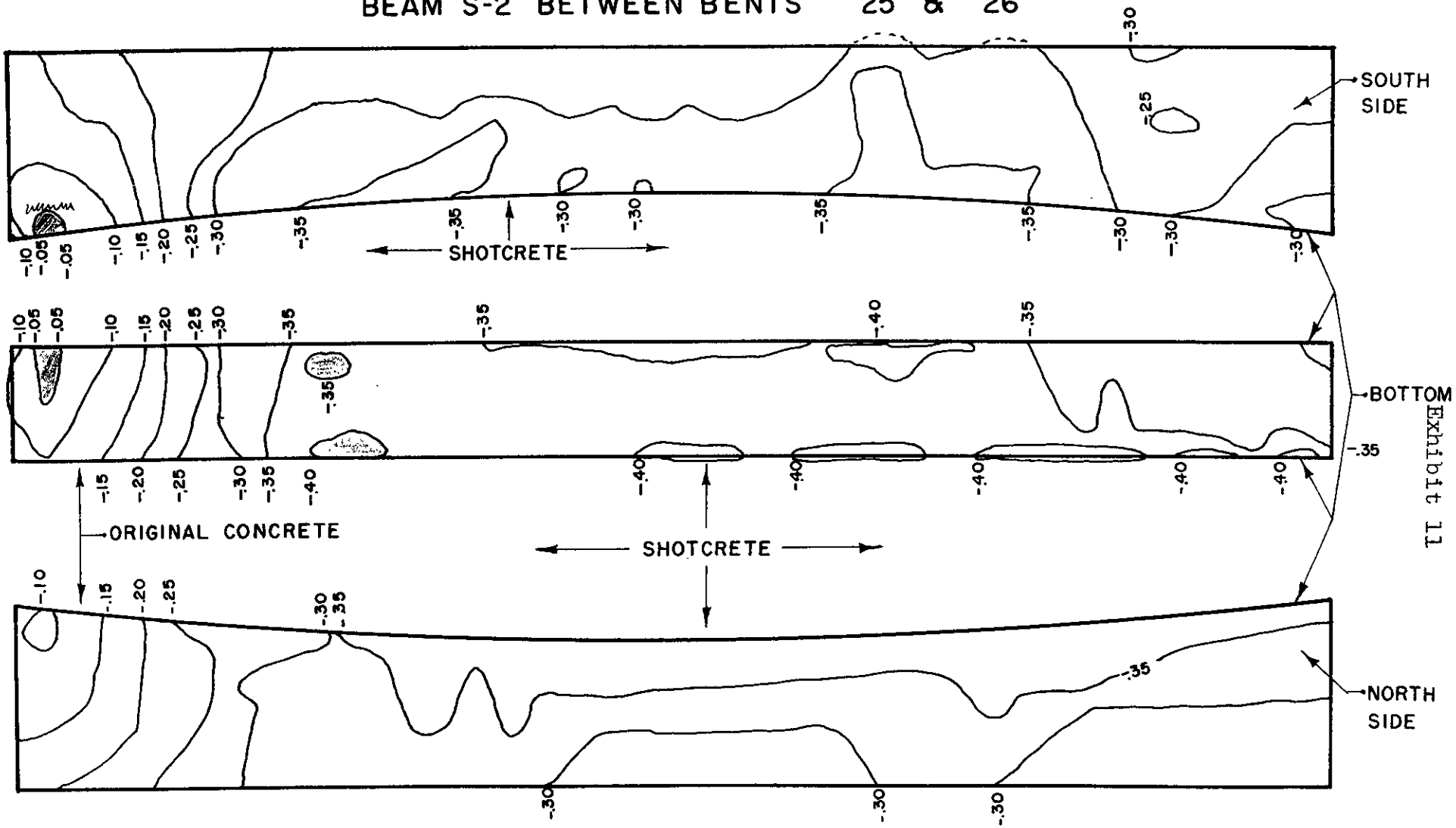
CHART 4
Equipotential Contours of
BEAM S-2 BETWEEN BENTS #25 & #26



NOTE:
Anode Located in Bottom Layer of Reinforcing Steel.

Potentials are Cu Cu So_4 on Concrete to a Reference Cu Cu So_4 on Soil at a remote distance.

LEGEND
Cracks in Concrete
Anodic Area
Cathodic Area

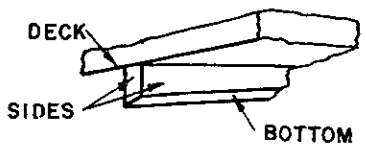


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Exhibit 11

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CHART 5
Equipotential Contours

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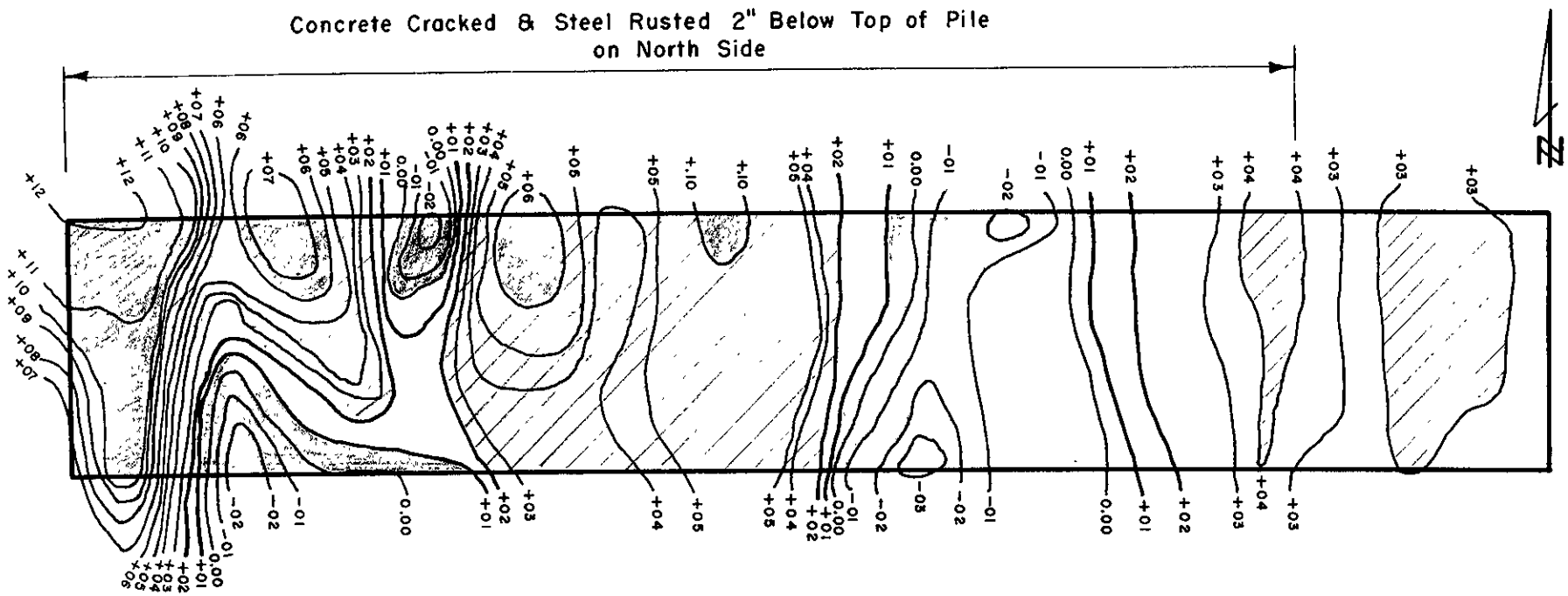
MATERIALS & RESEARCH DEPARTMENT

PILE A

Abandoned R.C. Pile From Construction of San Mateo-Hayward Bridge



Note: Potentials are to $CuCuSo_4$ on concrete to a reference $CuCuSo_4$ on soil at a remote distance.

(+) Voltages are anodic.

(−) Voltages are cathodic

Scale 1" = 4' long. 1" = 1' lat.

Anodic Area

Severely Anodic Area

Cathodic Area

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Exhibit 12

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CHART 6

Equipotential Contours on

TOP SURFACE OF PILE "B"

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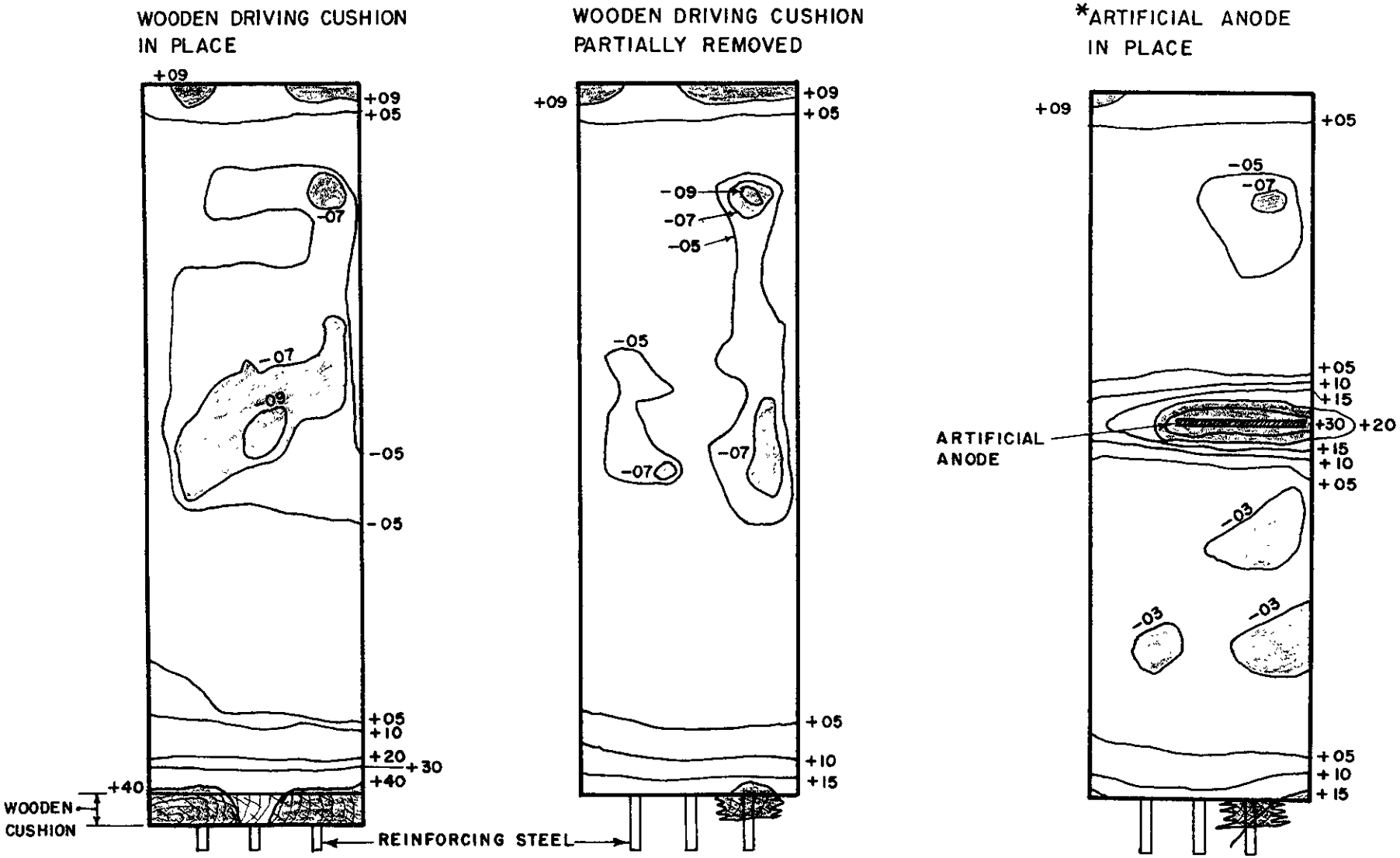
MATERIALS & RESEARCH DEPARTMENT



Scale: 1" = 3' Long. 1" = 1' Lat.

Note: Pile B is an abonded P.G. & E., R.C. Pile, $1\frac{1}{2}$ years old. Voltages obtained with a Cu Cu So_4 half cell, and referenced to a remote Cu Cu So_4 half cell on soil.

* Artificial Anode is a steel bar in Na Cl atop of R.C. Pile, and electrically connected to reinforcing steel.

Anode (+) Voltage

Cathode (-) Voltage

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Exhibit 13

CHART 7
Equipotential Contours of
PILE "C"

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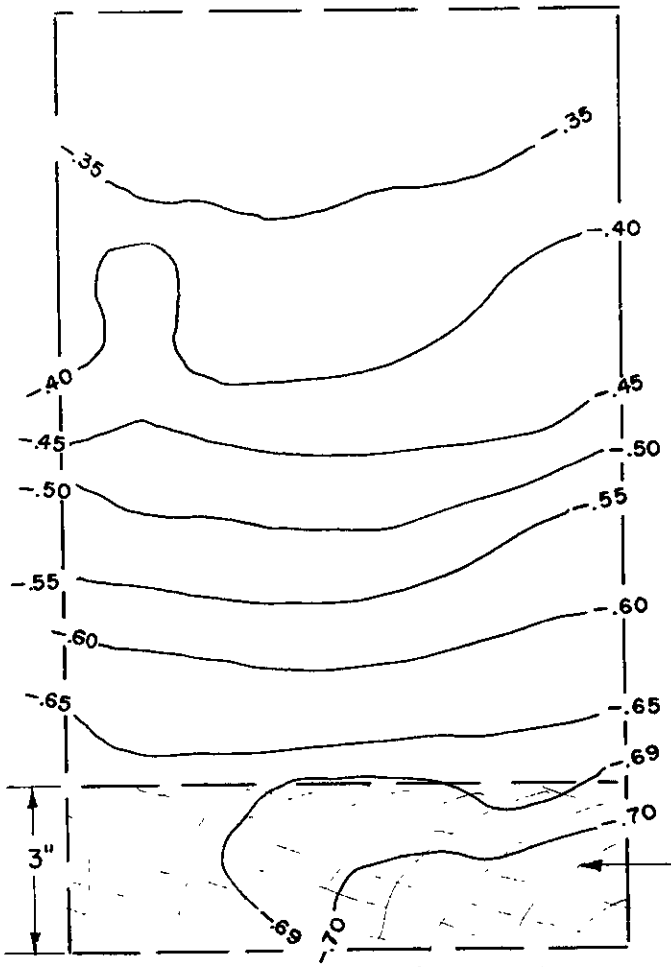
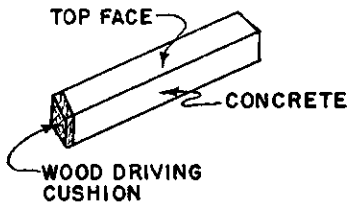
MATERIALS & RESEARCH DEPARTMENT

Top Face Pile "C"
Equipotential gradient of "Natural" currents flowing in reinforced concrete pile.



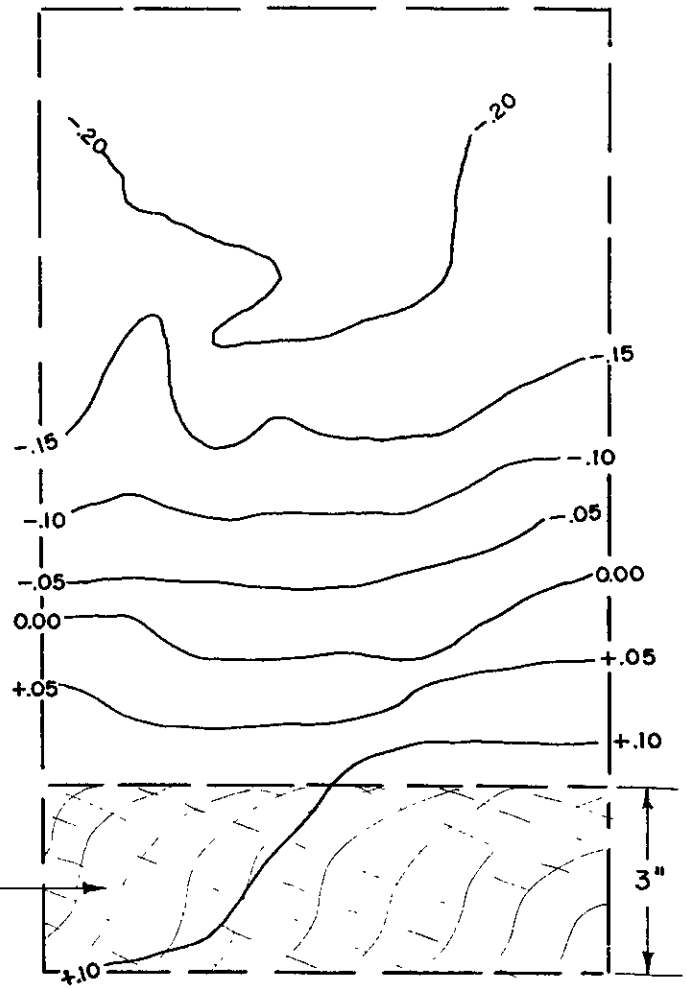
Reference is reinforcing steel bar.
(+) Voltages are anodic.
(−) Voltages are cathodic.



Approx. Scale.
Long. Scale 1" = 2'
Lat. Scale 1" = 6"
Above scale for concrete section only.

WOOD DRIVING CUSHION

Equipotential gradient of "Natural" currents flowing in reinforced concrete pile.



Reference is remote Cu Cu So_4 half cell.

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Exhibit 14

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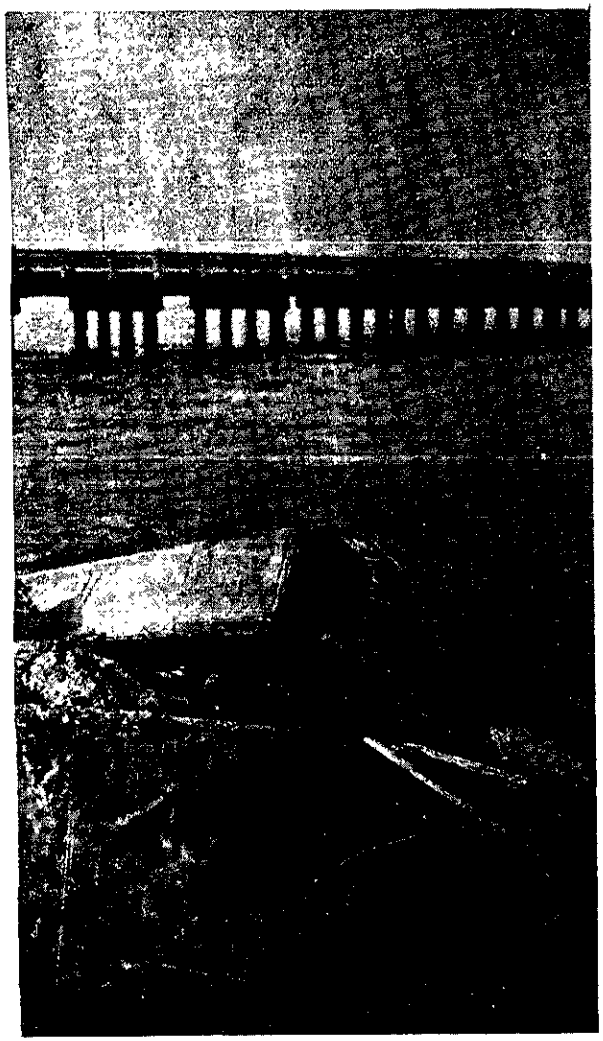
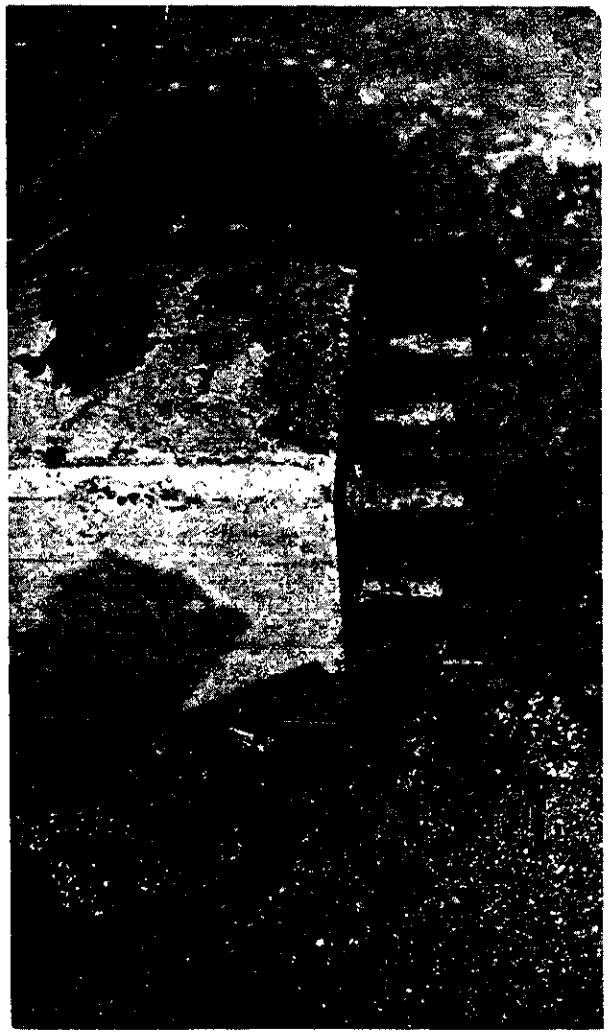


Rejected and abandoned P.G.&E. piles with wooden driving cushion in place.



Wooden driving cushion removed, revealing severe corrosion of steel formerly within cushion.

Exhibit 15