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16. ABSTRACT

This report presents field and laboratory studies relating to monitoring techniques, materials, and instrumentation used on reinforced concrete bridge decks under cathodic protection. It provides follow-up data on Sly Park Bridge, the first known deck to be placed under experimental cathodic protection, first reported in 1974.

Effects of concrete temperature and moisture changes on potential measurements are documented and discussed. Use of an oscilloscope voltmeter, to avoid turning off the cathodic protection current is presented. Use of corrosometer probes, and isolated reinforcing bars as current and corrosion monitors is discussed. Impressed current anode data are presented. An attempt to develop a conductive concrete overlay using 100% coke as the aggregate is documented.

High-silicon iron anodes were inspected after five years intermittent operation, and were found to be performing very well in a conductive layer of coke and asphaltic binder. Inspections and brief studies of mild steel, platinum coated, and copper anodes are also reported.

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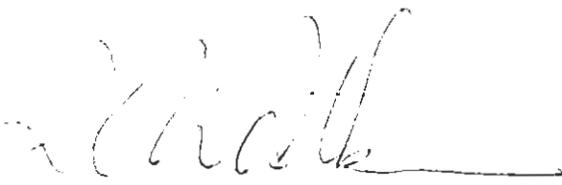
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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

CATHODIC PROTECTION STUDIES
ON REINFORCED CONCRETE

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CONVERSION FACTORS

English to Metric System (SI) of Measurement

| <u>Quantity</u> | <u>English unit</u> | <u>Multiply by</u> | <u>To get metric equivalent</u> |
|--------------------------|---|------------------------------|--|
| Length | inches (in) or (") | 25.40 .02540 | millimetres (mm) metres (m) |
| | feet (ft) or (') | .3048 | metres (m) |
| | miles (mi) | 1.609 | kilometres (km) |
| Area | square inches (in ²) | 6.432 x 10 ⁻⁴ | square metres (m ²) |
| | square feet (ft ²) | .09290 | square metres (m ²) |
| | acres | .4047 | hectares (ha) |
| Volume | gallons (gal) | 3.785 | litres (l) |
| | cubic feet (ft ³) | .02832 | cubic metres (m ³) |
| | cubic yards (yd ³) | .7646 | cubic metres (m ³) |
| Volume/Time | | | |
| (Flow) | cubic feet per second (ft ³ /s) | 28.317 | litres per second (l/s) |
| | gallons per minute (gal/min) | .06309 | litres per second (l/s) |
| Mass | pounds (lb) | .4536 | kilograms (kg) |
| Velocity | miles per hour (mph) | .4470 | metres per second (m/s) |
| | feet per second (fps) | .3048 | metres per second (m/s) |
| Acceleration | feet per second squared (ft/s ²) | .3048 | metres per second squared (m/s ²) |
| | acceleration due to force of gravity (G) | 9.807 | metres per second squared (m/s ²) |
| Weight Density | pounds per cubic (lb/ft ³) | 16.02 | kilograms per cubic metre (kg/m ³) |
| Force | pounds (lbs) | 4.448 | newtons (N) |
| | kips (1000 lbs) | 4448 | newtons (N) |
| Thermal Energy | British thermal unit (BTU) | 1055 | joules (J) |
| Mechanical Energy | foot-pounds (ft-lb) | 1.356 | joules (J) |
| | foot-kips (ft-k) | 1356 | joules (J) |
| Bending Moment or Torque | inch-pounds (ft-lbs) | .1130 | newton-metres (Nm) |
| | foot-pounds (ft-lbs) | 1.356 | newton-metres (Nm) |
| Pressure | pounds per square inch (psi) | 6895 | pascals (Pa) |
| | pounds per square foot (psf) | 47.88 | pascals (Pa) |
| Stress Intensity | kips per square inch square root inch (ksi / √in) | 1.0988 | mega pascals square root metre (MPa √m) |
| | pounds per square inch square root inch (psi / √in) | 1.0988 | kilo pascals square root metre (kPa √m) |
| Plane Angle | degrees (°) | 0.0175 | radians (rad) |
| Temperature | degrees fahrenheit (F) | $\frac{t_F - 32}{1.8} = t_C$ | degrees celsius (°C) |

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INTRODUCTION

A mounting problem confronting the maintenance of U.S. roads is bridge deck deterioration, manifested in the form of spalls at the riding surface. This damage is often caused by marine or de-icing salts penetrating the concrete and corroding the reinforcing steel. The resulting corrosion products create internal stresses which eventually lead to cracks and spalling of the deck.

One method of controlling corrosion of salt-contaminated bridge decks is the application of cathodic protection to the reinforcing steel. This method, widely used in underwater, pipeline, and underground utility protection, was first developed and adapted for bridge decks on an experimental basis by California in 1973 and the initial findings reported in 1974 (25).

This project was designed to build on the initial development, refine methods, materials, and techniques, and provide operational guidelines for the public agencies which were beginning to apply cathodic protection on their structures.

One main aim of this project was to determine the levels of cathodic protection currently required to arrest corrosion of the reinforcement. This information is required for designing future systems, which must strike a balance between the obvious effects of insufficient protection, and damage by hydrogen evolution caused by "overprotection".

Another aim was to study the characteristics of alternative conductive deck overlays, composed of portland cement concrete using coke as the aggregate. (The original overlay consisted of asphaltic concrete using coke, followed by a normal AC wearing course because the conductive overlay lacked cohesion and durability.)

An additional aim was to evaluate alternative materials to be used as current distribution anodes, and test their performance and suitability for use on bridge deck protection systems.

CONCLUSIONS

Impressed-current cathodic protection is a successful method of halting corrosion-caused damage to reinforced concrete bridge decks. In its present form, this method requires a two-layer deck overlay, the lower layer being a conductive aggregate asphalt concrete, and the upper a conventional asphalt concrete wearing course. The two-layer system is limited to structures capable of supporting the additional dead load, and to areas where the extra moisture retained by the lower layer would not increase freeze-thaw damage. Ongoing experimental work and currently marketed proprietary systems are aimed at removing or reducing the drawbacks of the overlays.

Measurement of electrochemical potentials between the reinforcing steel and standard electrodes is useful in performing initial deck surveys, to determine relative areas of corrosion activity. This allows strategic placement of monitoring instruments in the event cathodic protection is applied.

Oscilloscopes can be of benefit in measuring polarized potentials on decks under cathodic protection, when this protection is impressed by means of unfiltered rectifiers. Using an oscilloscope eliminates influencing the actual electrochemical process being measured - whereas the conventional voltmeter method in common use may adversely influence measured values, due to the depolarization that occurs when the current must be momentarily interrupted. The adverse effect of these interruptions is cumulative, and creates difficulties when a large number of readings are being taken, such as on a deck survey. Regardless of the method used, however, measurement of polarized potentials do not provide reliable indications as

to whether the steel is adequately protected from corrosion. The variable moisture level and oxygen content of concrete has a significant effect on such potential values, and thus potential data require careful interpretation.

Corrosometer probes, strategically placed, appear to be the best available indicators that the protection level is sufficient, with potential measurements being used to insure against disbonding due to excessive voltages. Experience with corrosion probes indicates that, although many behave as expected, others permanently cease to corrode after initial CP application, pointing to a need for further studies to improve their embedment method.

An experimental deck conductive overlay consisting of portland cement concrete with coke used as aggregate was unsuccessful, primarily because the mix required excessive cement, which in turn caused excessive shrinkage cracking. Additional work is required to perfect a suitable conductive PCC overlay.

A study of alternative anodes for cathodic protection indicated that, although noble metal coatings are very efficient, the high-silicon iron anodes used on bridge decks are performing very well in a conductive layer consisting of coke and asphaltic binder.

IMPLEMENTATION

The results of this study will be implemented by incorporating pertinent findings into the plans and specifications for future projects involving cathodic protection (CP) systems. Specifically, the design of corrosion monitoring and control systems will take into account voltage, current density, anode materials, probe design and performance criteria necessary for distribution of the protective current and the durability of the overlays. The most reliable and accurate methods of monitoring CP systems as developed by this project will be used.

CHAPTER 1. Field Studies on the Sly Park Bridge

During the first three years of operation of the Sly Park Bridge cathodic protection (CP) system, the adequacy of protection was determined by corrosometer probes installed on the deck (25) and by periodic deck potential surveys using standard copper-copper sulfate electrodes (CSE). In the absence of a proven criterion for reinforced concrete bridge decks, a range of electrochemical potentials (-0.85 volts to -1.10 volts) between the reinforcing steel and the CSE was adopted as indicating adequate protection. These values were well-established in pipeline CP technology, the former being one of several criteria (15), and the latter being a limiting value in excess of which hydrogen evolution might tend to cause disbondment between steel and concrete. (See Appendix A, History of the Sly Park Cathodic Protection, and Appendix C, Instruments and Equipment Used on Sly Park and Laboratory Studies.)

Initial Studies

The potential survey measurements were taken with the CSE in contact with the riding surface of the bridge, which was a standard asphaltic concrete (AC) over the conductive layer, which in turn rested on the structural concrete deck. These measurements indicated that nearly all the cathodically protected top mat of reinforcing was polarized to a potential of -0.85 volts vs CSE. It was thus assumed that, since the -0.85 volt criterion was being met, full protection was being provided to the structure.

At that point in time, additional studies indicated that the potential measurement technique used during the first

three years was in error. The conductive coke layer assumed an electrochemical potential of its own as a result of current flow, and was adversely influencing the measurements between the steel and the CSE.

In order to eliminate the interference, it became necessary to place the CSE in contact with the concrete deck, and isolate it from the conductive overlay. This resulted in the installation of permanent potential-measurement locations on the original concrete deck surface. Each location was composed of three different trial systems of achieving the desirable contact between the CSE and the deck (Figures 1-1, 1-2). Eventually, the 1.5 inch hole system was judged most convenient and reliable.

Measurements taken using the revised technique indicated an average potential of -0.76 volts with the CP system on, and -0.60 volts vs CSE with the system off. The adopted criterion (-0.85 to -1.10 volts vs CSE) was not being met. The question remained, however, whether or not the level of protection was adequate.

Throughout this initial three year period, readings from the installed corrosometer probes indicated that they were not corroding. (Nine probes were originally installed, two of which were damaged during installation. It should be added that, unexplainably, three of the remaining probes have not corroded to date, as can be indicated by electrical measurements.) To test the reliability of this criterion for adequate protection, the CP current was stopped on two separate occasions. Several corrosometer probes began to corrode upon the cessation of the CP current. It was expected that the residual polarization caused by three years of protection would

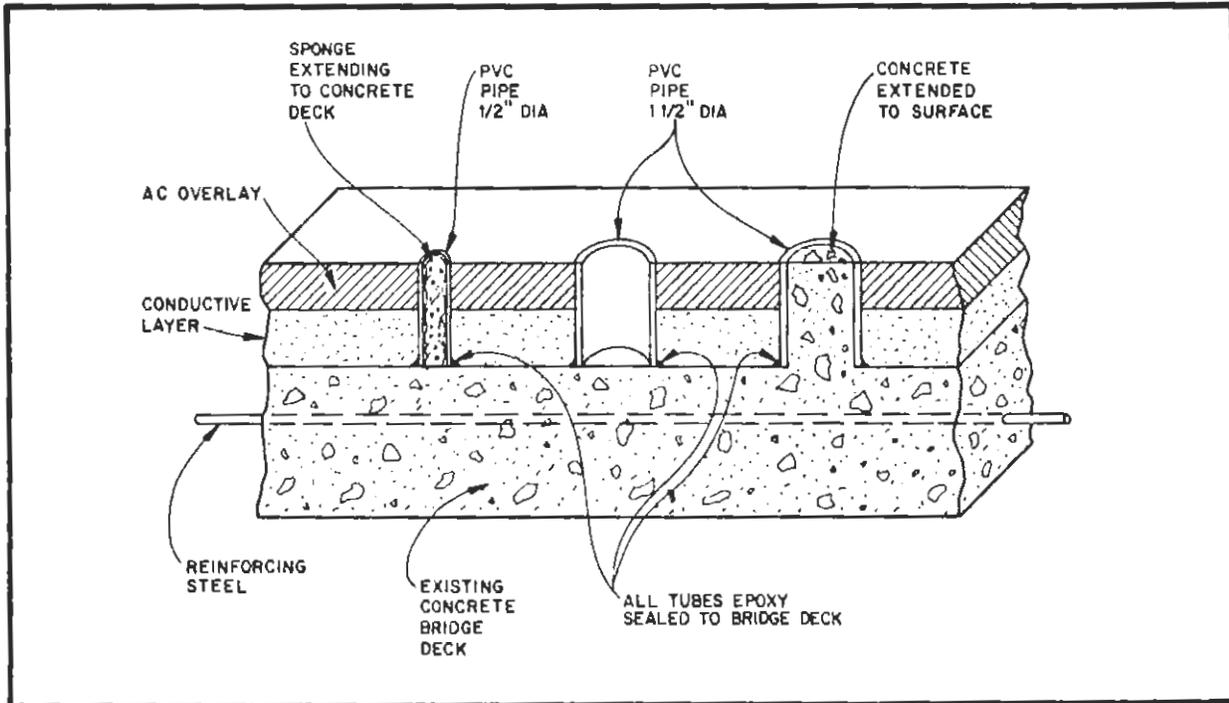


Figure 1-1. Sly Park Bridge CSE Access Locations



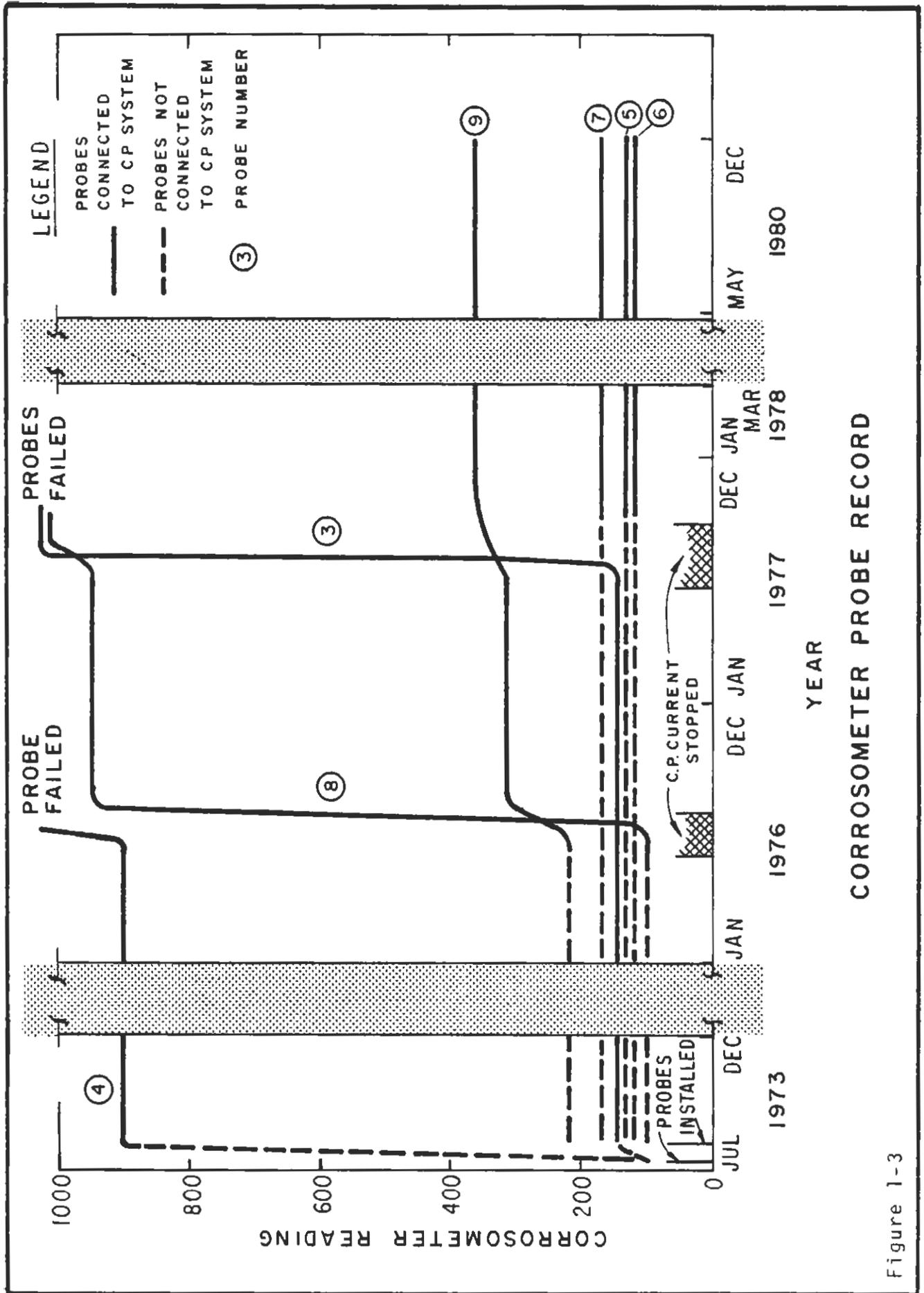
Figure 1-2. Deck Riding Surface with CSE in Place for Potential Measurements.

delay the onset of corrosion for several months, but the polarization decay took only a few weeks (see Figure 1-3). The onset of corrosion also indicated that embedded steel was apparently being fully protected at potential levels less negative than -0.85 volt vs CSE, and that this criterion was unnecessarily conservative, and even unattainable under certain conditions such as high concrete resistance.

Potential Measurements Using an Oscilloscope

The rapid polarization decay exhibited by the corrosometer probes was reflected by potential measurements between the reinforcement and CSE. It was found that, following the application of CP current for a period of 3 minutes, polarization decay periods of about 2.5 hours were required to return the steel vs CSE potentials to their original values. In a similar fashion, 20 minute CP current applications required about 20 hours for this de-polarization. Thus, a rough rule of thumb required an hour of recovery for each minute of interruption of current when "instant-off" readings were to be taken. This phenomenon does not have an adverse effect in cathodic protection per se, but does create difficulties in monitoring; measurements using the "instant-off" method are not repeatable within a practical length of time. In making a survey of bridge deck potentials, the CP current must be interrupted several times, and thus excessively long delays between measurements are required for confident results. In practice, a compromise is struck between measurement accuracy and available time limits.

In an effort to circumvent this difficulty, a method was developed (in 1976) that permitted the measurement of potentials "an instant after the CP current was interrupted"

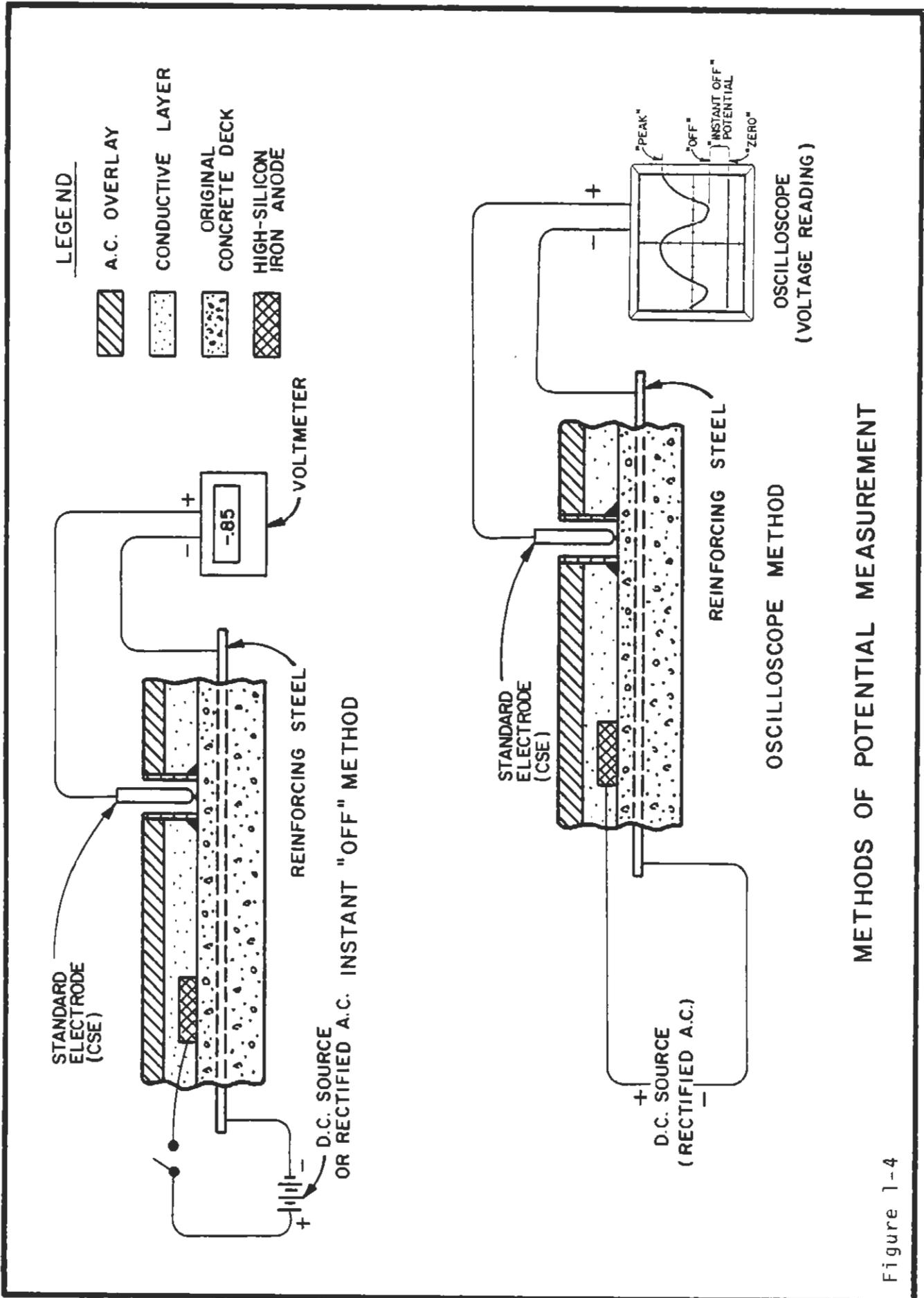


CORROSOMETER PROBE RECORD

Figure 1-3

(instant-off) without actually interrupting the system. It was noted that, since impressed current CP systems usually employ unfiltered full wave rectifiers, the driving voltage is not constant, but varies from some given value to zero, 120 times per second. The impressed current exhibits similar behavior, and also periodically returns to zero (except for some capacitance effects between the reinforcing steel and the conductive layer). Assuming that, for all practical purposes, the CP current is automatically "turned off" at every half cycle of the rectifier output, reading the potential of the steel vs CSE at that instant would provide "instant-off" values without actual disruption of the system. This can be accomplished by substituting oscilloscope for the standard voltmeter normally used for potential measurements (see Figure 1-4). A high input impedance (10 megohm) oscilloscope was used on Sly Park measurements and was found to provide easily read, stable potential values.

A comparison test was run on the Sly Park CP system using the two methods of potential measurement. Steel vs CSE potential measurements were taken and "instant-off" values were established at various locations using the oscilloscope method, and then the same locations were measured with a digital voltmeter and actual ultra-brief interruptions of the CP current. Table 1-1 indicates that the oscilloscope method compares favorably with the voltmeter/current interruption method.



METHODS OF POTENTIAL MEASUREMENT

Figure 1-4

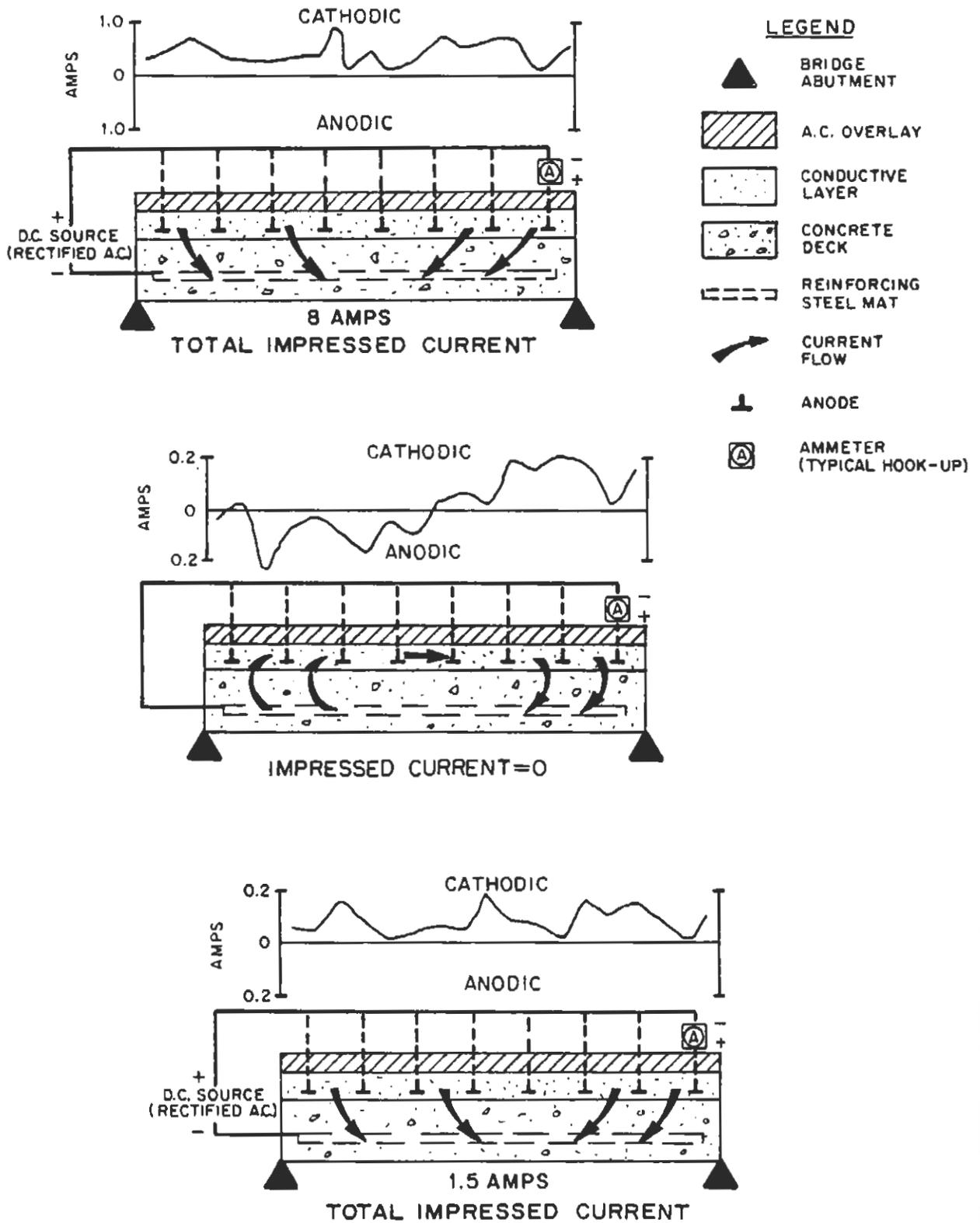
Table 1-1. Comparative Steel vs CSE Potential Measurements-
Oscilloscope vs "Instant-Off" Voltmeter Methods

| Location of CSE Contact on Bridge Deck (see Fig. A-3) | Potential vs CSE, Volts | |
|--|-------------------------|---------------------------------------|
| | Oscilloscope Method | Voltmeter With Current Interrupter |
| B-25.5 | -0.480 | -0.470 |
| B-22.5 | -0.580 | -0.579 |
| B-19.5 | -0.460 | -0.505 |
| B-15.5 | -0.630 | -0.617 |
| B-12.5 | -0.720 | -0.686 |
| B- 7.5 | -0.730 | -0.664 |
| Means | -0.600 | -0.587 |

CP Current Distribution

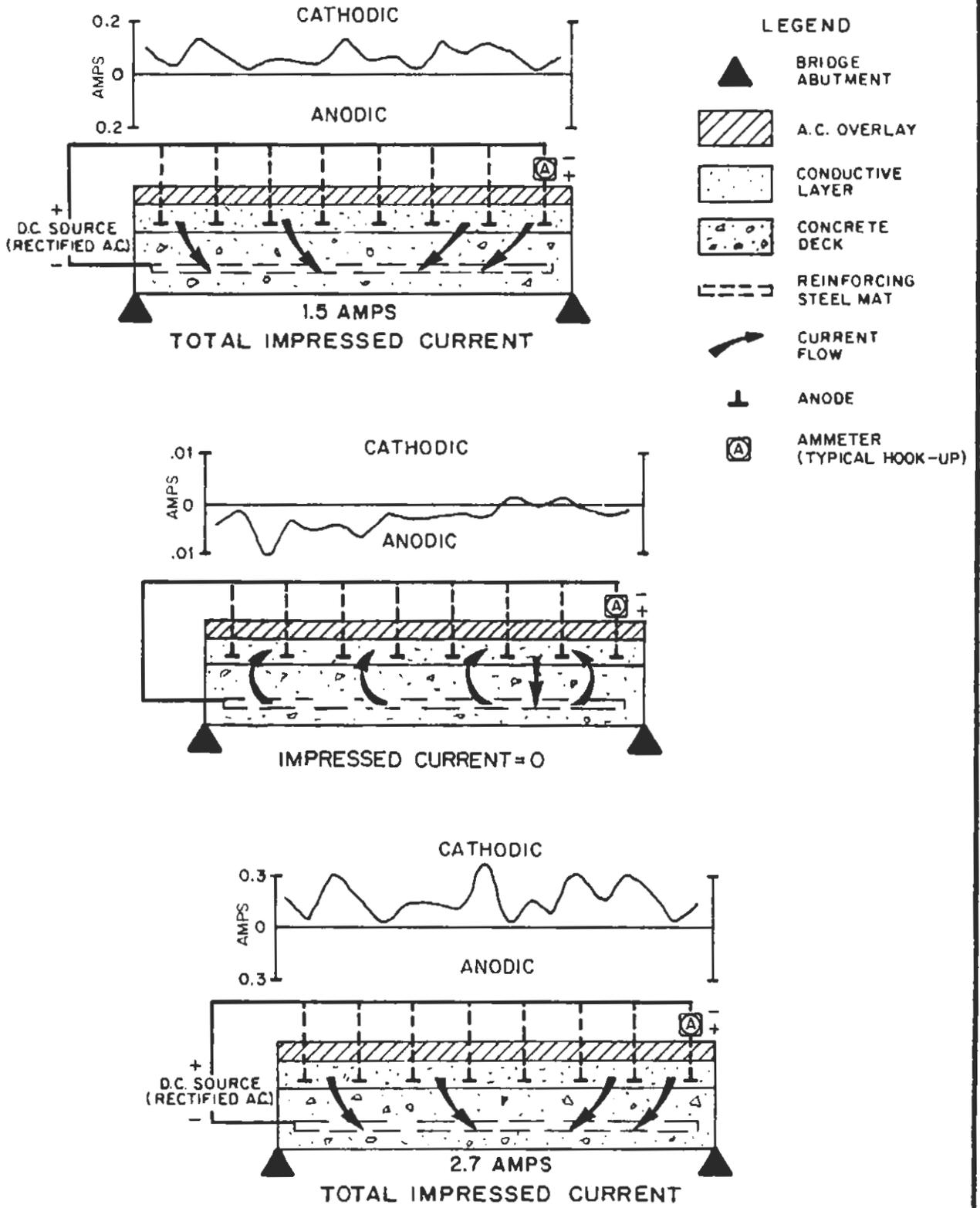
The distribution of CP current is not uniform throughout the top reinforcing mat. Local differences in the conductivity of the concrete cover, resulting from variable density, cracks, and salt contamination create preferential paths for current flow. The amount of moisture in the concrete, as well as temperature, play a significant part in affecting concrete conductivity. Since moisture and temperature vary seasonally, current flow measurements, both galvanic and CP, were made between the reinforcing steel and all operating anodes at Sly Park Bridge. One series of measurements was made during dry, warm summer conditions and another during wet, cold winter conditions (see Figures 1-5 and 1-6).

Initial measurements were conducted in summer, after 2.5 years of CP under a total impressed current of 8 amperes. All anodes were discharging current to the deck, but in differing quantities, as expected. The CP current was



SCHEMATIC
CURRENT FLOW WITHIN SLY PARK BRIDGE
DRY SUMMER CONDITIONS

Figure 1-5



**SCHEMATIC
CURRENT FLOW WITHIN SLY PARK BRIDGE
WET WINTER CONDITIONS**

Figure 1-6

then stopped, and similar readings were taken the following day. These measurements indicated that about half the deck area tested had become anodic, and was discharging current. Polarization (E-Log I) measurements were then performed, in order to determine the total current requirements for cathodic protection as recommended by the National Association of Corrosion Engineers (NACE). (See Chapter 2 for discussion of criteria.) Based on the E-Log I test results, a total CP current of 1.5 amperes was then impressed on the bridge, and the current discharge by each anode again measured. It was found that this level of current was sufficient to arrest the reverse discharge.

During the following winter, the same series of tests was repeated under wet concrete conditions. The CP current had remained at a nominal 1.5 amperes, and its distribution to each anode was again found to be unequal, but remarkably similar to the summer readings. When the CP current was stopped, however, measurements indicated that nearly all the reinforcement in the deck area tested had become anodic, and was discharging current. The level of reverse current flow was very low, despite the low resistance of the moist concrete. Polarization measurements that followed indicated a requirement of 2.7 amperes CP current, which was then impressed on the bridge. This level of current arrested the reverse discharge, and distributed itself preferentially among the anodes.

Isolated Bar

Measuring the CP current flow to each anode provides a general indication of the distribution of protection, but is, at best, an indirect method. The ideal measurement would be that of

current flow at the level of the reinforcing steel. A technique was developed to provide such measurements, by isolating a small segment of the steel, and measuring the CP current flow to it exclusively.

Since the reinforcing mat is usually interconnected, isolated bars were not encountered. One method of providing such a bar would be to install it at the steel mat level and backfill the necessary cavity with an appropriate mortar. Another method would be to somehow isolate an existing bar without disturbing the concrete matrix around it.

The latter method, as developed at Sly Park Bridge, involved using a concrete saw to cut into the concrete and sever a bar at two places, about 5 inches apart (see Figure 1-7). Bars from the lower steel mat were used because the deck soffit provided convenient and safe access. (Performing the experiment on the upper mat would have involved removal of portions of the AC overlay and conductive layer, which would have necessitated traffic control, lane closures, and accompanying costs and danger.)

The two ends of the severed segment were sealed with epoxy, and the sawcuts filled with epoxy putty. To provide electrical connections, small holes were drilled into the concrete and partially through the bar, and steel pins were then driven in. Instrumentation was then connected to the pins. Four such isolated bars were thus created, two at each end of the bridge, their actual location being dictated by easy access to the soffit near the abutments.

With the CP system in operation, the quantity of current reaching the isolated bars was measured by connecting a

LEGEND

-  A.C. OVERLAY
-  ORIGINAL CONCRETE DECK
-  CONDUCTIVE LAYER
-  HIGH-SILICON IRON ANODE

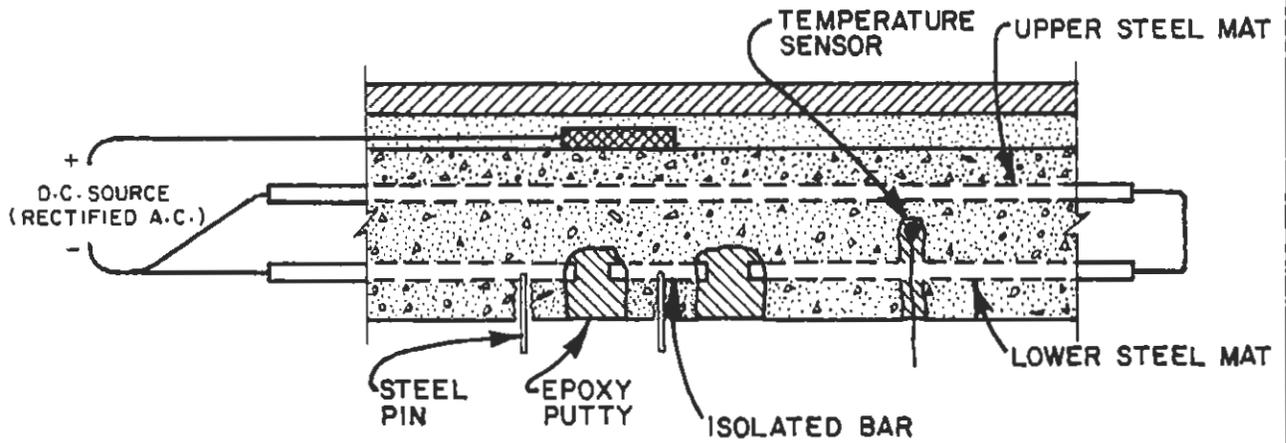


Figure 1-7

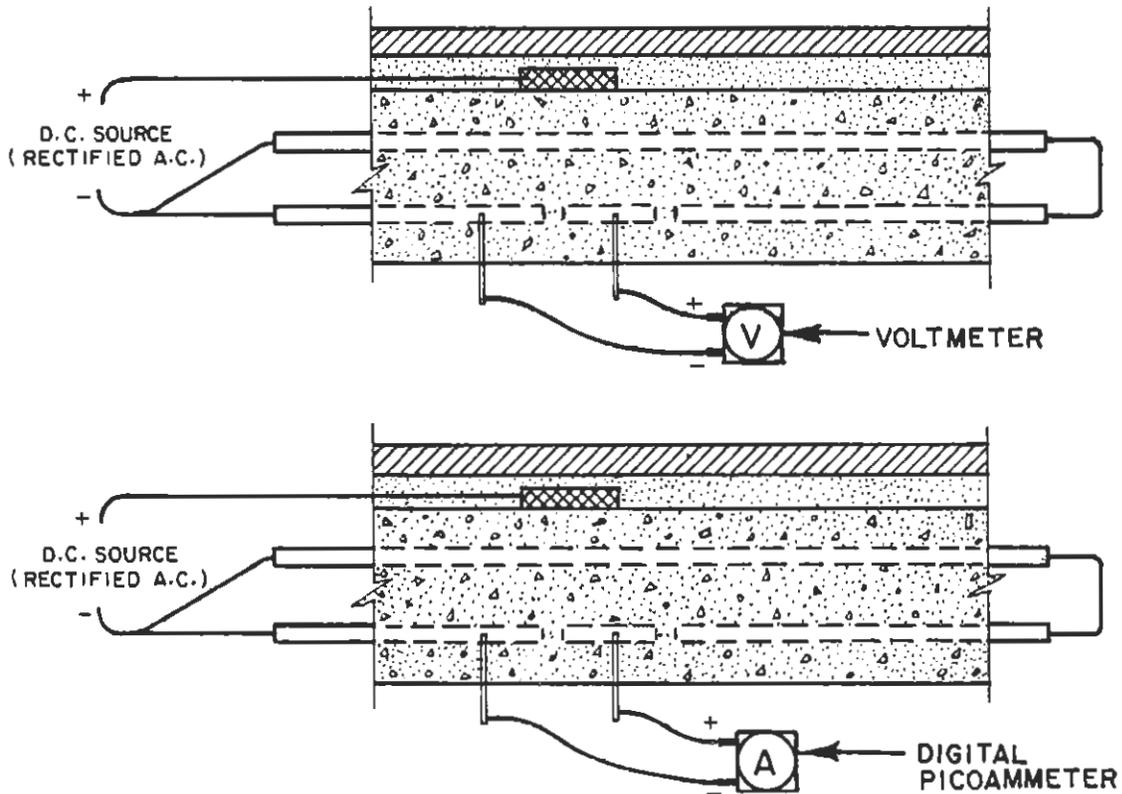


Figure 1-8

digital picoammeter in series between the segments and the negative pole of the DC source (see Figure 1-8). Since the size and length of the segments were known, current density could be calculated, in terms of milliamperes per square foot of steel area. It should be noted that the instrument used was capable of measuring only the DC portion of the current flow, when, in fact, this current consisted of both DC and AC segments, the latter due to capacitance effects. The ideal instrument for such measurements should have the ability to measure the combined DC plus AC flow.

The isolated bars would also act as substitute electrodes, allowing measurements of potential changes in the adjacent steel caused by cathodic protection. The steel mat, being connected to the CP circuit and receiving current, normally changed its potential to more negative values, whereas the unconnected segment would not be affected (barring possible stray current effects). Using a high impedance voltmeter, the potential difference between the two was measured. This value is a direct effect of cathodic protection, and its magnitude could be compared with commonly-used criteria for adequacy of protection (15).

Table 1-2 presents typical values obtained during a summer morning: air temperature 62°F, concrete temperature 48°F. It was intended that wet winter readings would also be taken using this method, but other operations (22) damaged several anodes and changed the mixture of the conductive layer in certain areas. This precluded meaningful comparison of seasonal fluctuation.

Table 1-2. Results of Isolated Bar Measurements

| <u>Location</u> | <u>Bar Length, Inches</u> | <u>Steel Surface Area, ft²</u> | <u>Impressed Current Density, ma/ft² of Steel</u> | <u>Potential Isolated Bar vs Steel Mat Under CP, Volts</u> |
|-----------------|-------------------------------|---|--|--|
| A West End | 4 | 0.0546 | 0.24 | +0.396 |
| B West End | 5 | 0.0682 | 0.46 | +0.465 |
| C East End | 7 | 0.0954 | 1.09 | +0.406 |
| D East End | 7 | 0.0954 | <u>0.40</u> | <u>+0.410</u> |
| Means | | | 0.55 | +0.464 |

CHAPTER 2. Polarization (E-Log I) Measurements on Bridge Decks Under Cathodic Protection

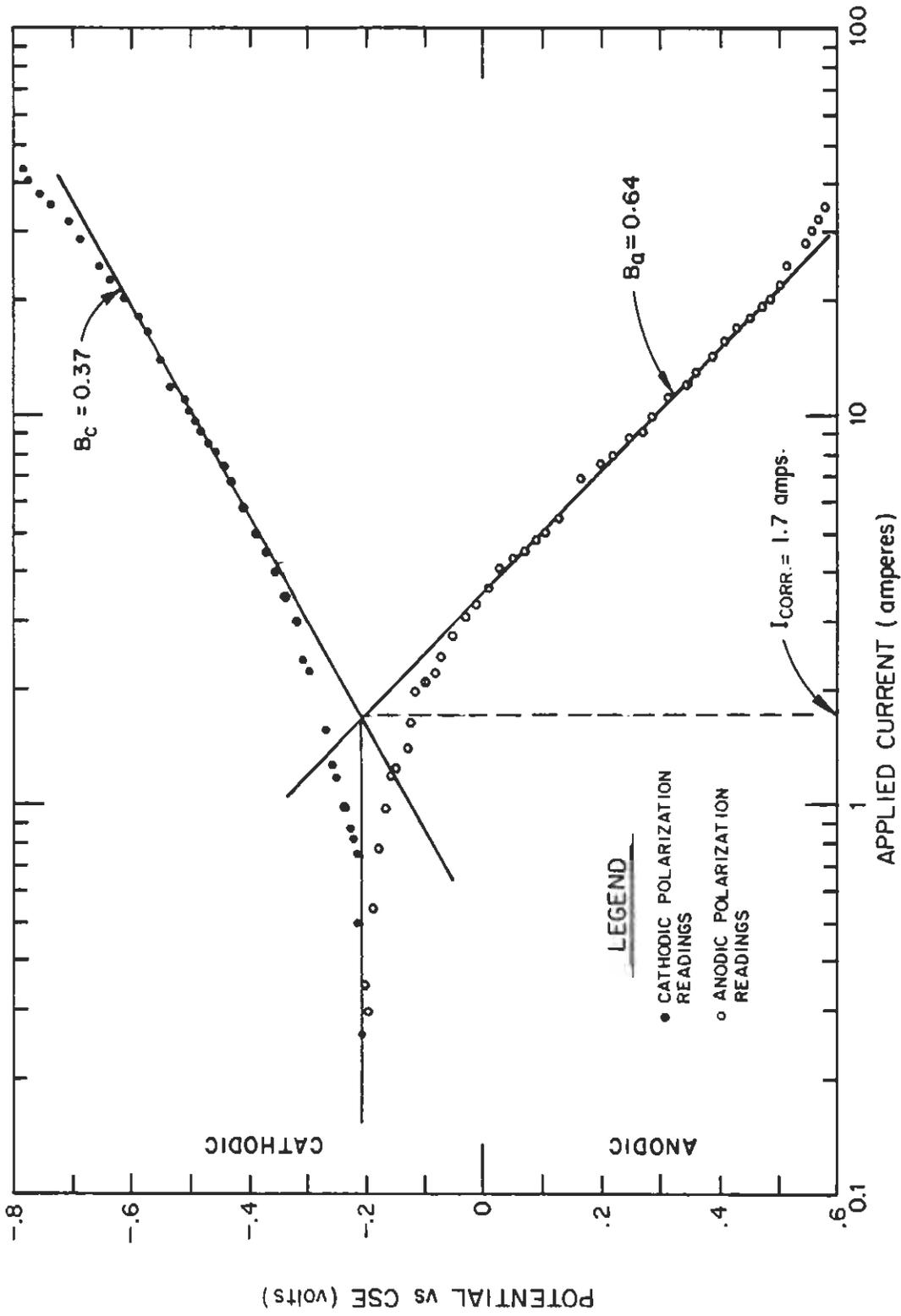
A review of cathodic protection criteria was conducted, in order to determine their applicability to bridge deck work. The most universally accepted value is the -0.85 volts vs CSE for buried steel pipelines. In addition, the National Association of Corrosion Engineers (NACE) has recommended shifts in potential of -0.30 volts with CP current off, and -0.10 volts polarization decay measured after the initial voltage shift occurs (due to interruption of the CP current), or a voltage at least as negative as that originally established as the beginning of the Tafel segment of the E-Log I curve (19) (24). Morgan (18) indicates that complete protection is achieved by the application of the current value indicated at the point where the E-Log I curve becomes a straight line. Hausmann's work (10) indicates protection is achieved at potentials of -0.50 and -0.71 volts vs CSE for uncorroded and corroded steel, respectively, and a shift of 0.40 volts vs CSE to protect against possible stray current interference, (which is unlikely to occur in bridge decks). Robinson (23) rejects the -0.85 volt criterion for steel in concrete and also recommends -0.50 and -0.71 volts vs CSE for uncorroded and corroding steel in chloride-contaminated concrete.

It should be noted that most of the above criteria were recommended for buried or submerged reinforced concrete pipeline and thus had limited application for bridge deck CP. (More recently, criteria for reinforced concrete decks have been published (5) but were not available at the time of testing.)

In order to obtain CP criteria specifically for bridge decks, polarization (E-Log I) tests were conducted on Sly Park and three other bridges in California. All four decks had been under CP prior to the tests, which made them less than ideal candidates, due to the inevitable influence of residual polarization on the resulting measurements. Nevertheless, these were the only decks available, so the residual effects were minimized by stopping the CP current and allowing the steel to de-polarize for a period of 24 hours prior to testing.

Figure 2-1 illustrates a typical plot of data from the E-Log I test and the subsequent analysis. The anodic and cathodic field test data are shown, along with the Tafel slopes drawn to best fit plotted points.

One limitation of the E-Log I tests on the four structures was the capacity of their Direct Current (DC) power supplies and/or the size of the conductors leading to the anodes. It was intended that the test results be compared using six differing criteria, three relying on achievement of a given potential vs CSE and the other three upon achievement of current levels, as proposed by NACE (19), Morgan (18) and Tomashov (27). The limitations mentioned above precluded reaching the -0.85 volt level at Sly Park and the Tomashov criterion for the other three structures. Table 2-1 and Figure 2-2 present the values of CP current required for each structure under the six different criteria, converted to values of current per unit area of bridge deck surface.



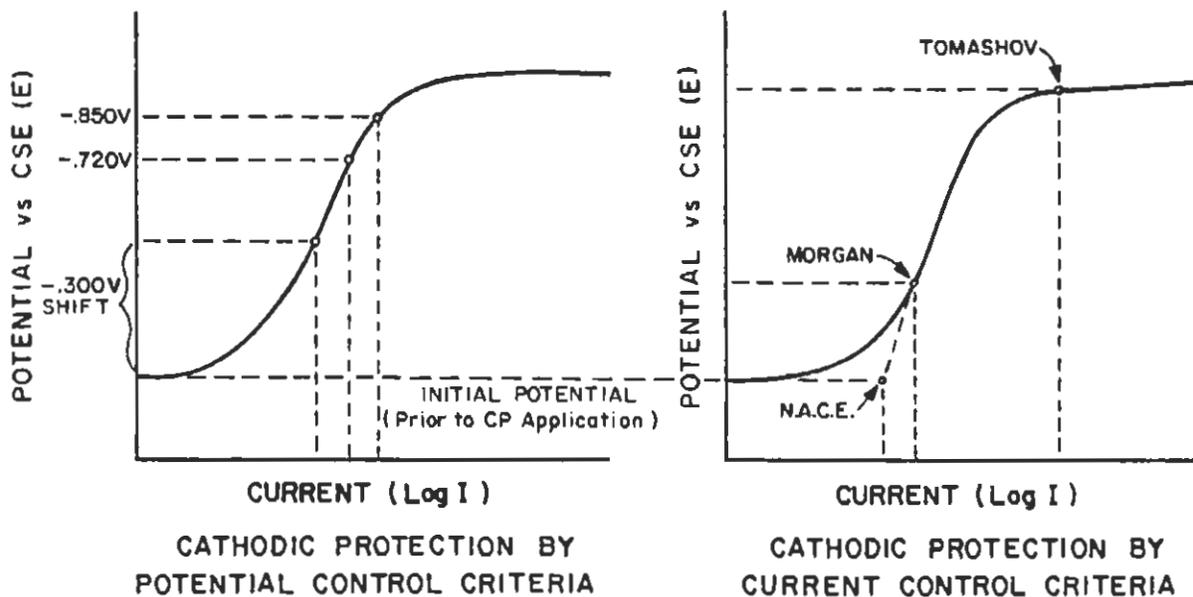
TYPICAL SLY PARK BRIDGE E-LOG I DATA PLOT

Figure 2-1

TABLE 2-1. CURRENT REQUIREMENTS FOR INITIAL CATHODIC PROTECTION

| BRIDGE | POTENTIAL vs CSE CONTROL CRITERIA | | | CURRENT CONTROL CRITERIA | | |
|------------------------|-----------------------------------|--------|---------|--------------------------|--------|----------|
| | -.300 V SHIFT | -.710V | -.850 V | N.A.C.E. | MORGAN | TOMASHOV |
| SLY PARK | 3.03 | 9.85 | 25.8+ | 0.50 | 1.40 | 12.12 |
| UPPER SALT CREEK (LT.) | 1.21 | 2.12 | 3.13 | 1.56 | 3.13 | 4.50 |
| UPPER SALT CREEK (RT.) | 0.54 | 1.28 | 1.75 | 1.12 | 3.64 | 4.50 |
| O'BRIEN (RT) | 0.89 | 1.43 | 1.79 | 1.20 | 3.00 | 3.80 |
| AVERAGE | 1.42 | 3.67 | 8.12 | 1.10 | 2.79 | 6.23 |

Note: Values are expressed in ma/ft² of bridge deck required to attain the above cathodic protection criteria.



COMPARISON OF DESIGN CRITERIA FOR CATHODIC PROTECTION OF REINFORCED CONCRETE BRIDGE DECKS

Figure 2-2

CHAPTER 3. Laboratory Studies on Steel Embedded in Concrete

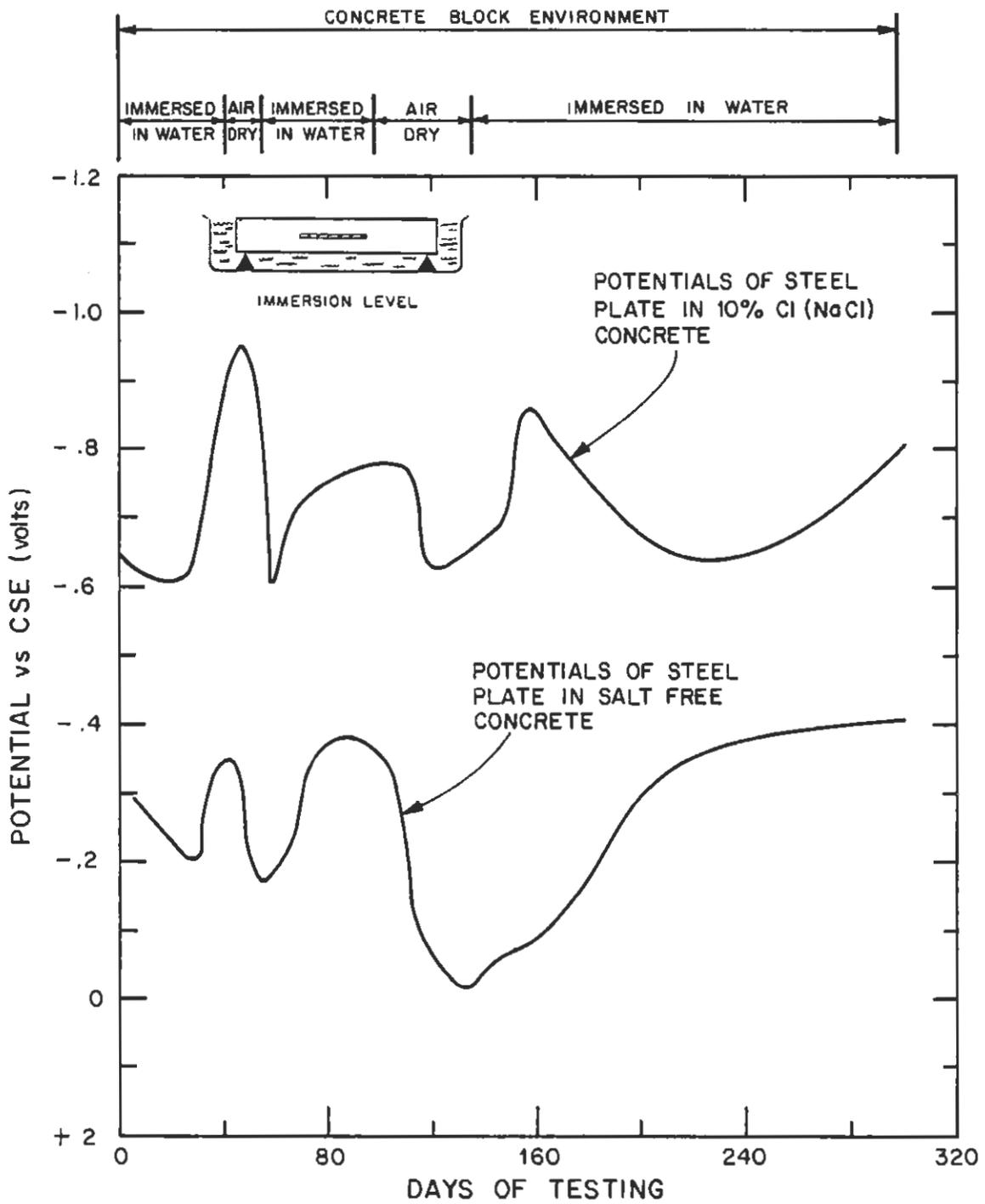
One significant problem involving field studies on bridge decks is that the concrete temperature, humidity, and local chloride ion concentration are very difficult to obtain, and impossible to repeat, due to the uncontrollable environment. The effect of these factors is profound, and, along with other difficulties, tends to make potential measurements of reinforcing steel vs CSE unreliable. Stratfull also suggests these potentials are influenced by the quantity of oxygen available around the steel, which in turn is influenced by the degree of moisture saturation of concrete (26).

In order to study the effect of environmental factors under controlled conditions, a series of laboratory tests was conducted to determine their effect in both the galvanic corrosion and behavior under cathodic protection, on steel embedded in concrete.

Galvanic Corrosion Studies

A total of six concrete blocks, 12 in. by 6 in. by 2 in. were cast, three of which were conventional mix and the other three containing salt (NACE). The quantity of the salt used was such that the resulting chloride ion content was 10% of the cement content by weight. Each block contained an embedded steel plate.

After curing, the blocks were individually subjected to a cyclical environment of alternate partial immersion in tap water and air drying at laboratory air for a period of approximately 10 months. Potentials of the embedded steel vs CSE were measured during this period (see Figure 3-1). As



CORROSION POTENTIALS
STEEL IN SALTY AND SALT-FREE CONCRETE

Figure 3-1

expected, steel in salty concrete registered considerably more negative values than its salt-free counterparts. It was also evident that moisture content had a profound influence in the potential values measured on both types of blocks. Increases in water content (or, stated differently, reductions in the air content) tended to change the potentials by several hundred millivolts towards more negative values.

Following the isolated test period, pairs of blocks, one salty and one salt-free, were placed in the same electrolyte, and the two embedded steel plates were electrically connected. This set-up simulated conditions existing on actual bridge decks, where portions of the upper reinforcement are in contact with salt-laden concrete, the lower reinforcement is in contact with comparatively salt-free concrete, and both mats are electrically connected through contact with truss bars.

The actual set-up consisted of placing the two blocks into a plastic pan, filling the area around them with coke, and connecting the two wires leading to the embedded steel. A 10 ohm resistor was placed in series with the resulting cell to allow measurement of the galvanic current by measuring potential drop, and periodic measurements of the steel potentials vs CSE were taken on both blocks (see Figure 3-2).

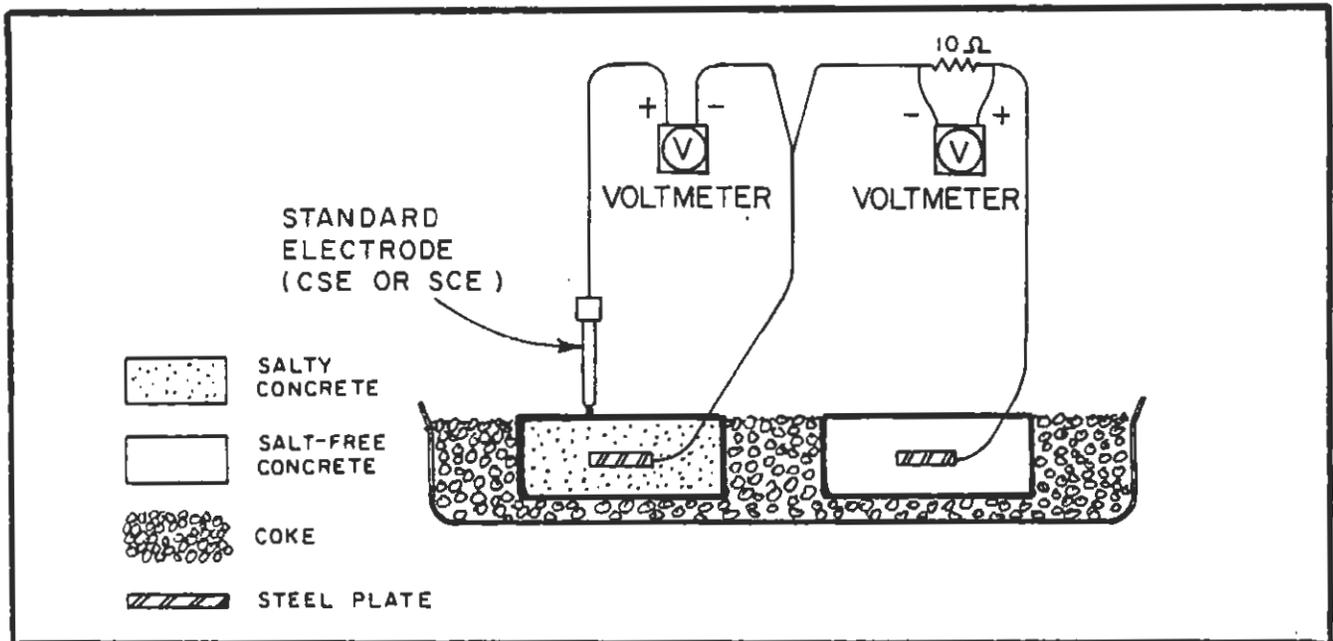


Figure 3-2. Schematic: Galvanic Corrosion Measurements, Steel in Salty and Salt-Free Concrete.

The air-dry weight of the coke fill was measured, and used as a basis for adding moisture to the electrolyte. During the subsequent 170 days, the moisture content of the coke was increased in eight increments, from 5% to 70% of the original weight of the coke. A sealed plastic cover minimized evaporation.

Resistance measurements of the electrolyte, taken between the two embedded steel plates decreased to a constant range between 200 and 300 ohms early in the test, indicating saturated concrete conditions.

Initial potential measurements indicated a 0.3 volt difference between the two plates, which was gradually reduced by polarization to about 0.08 volts, as galvanic current was allowed to flow through the electrolyte. At the same time,

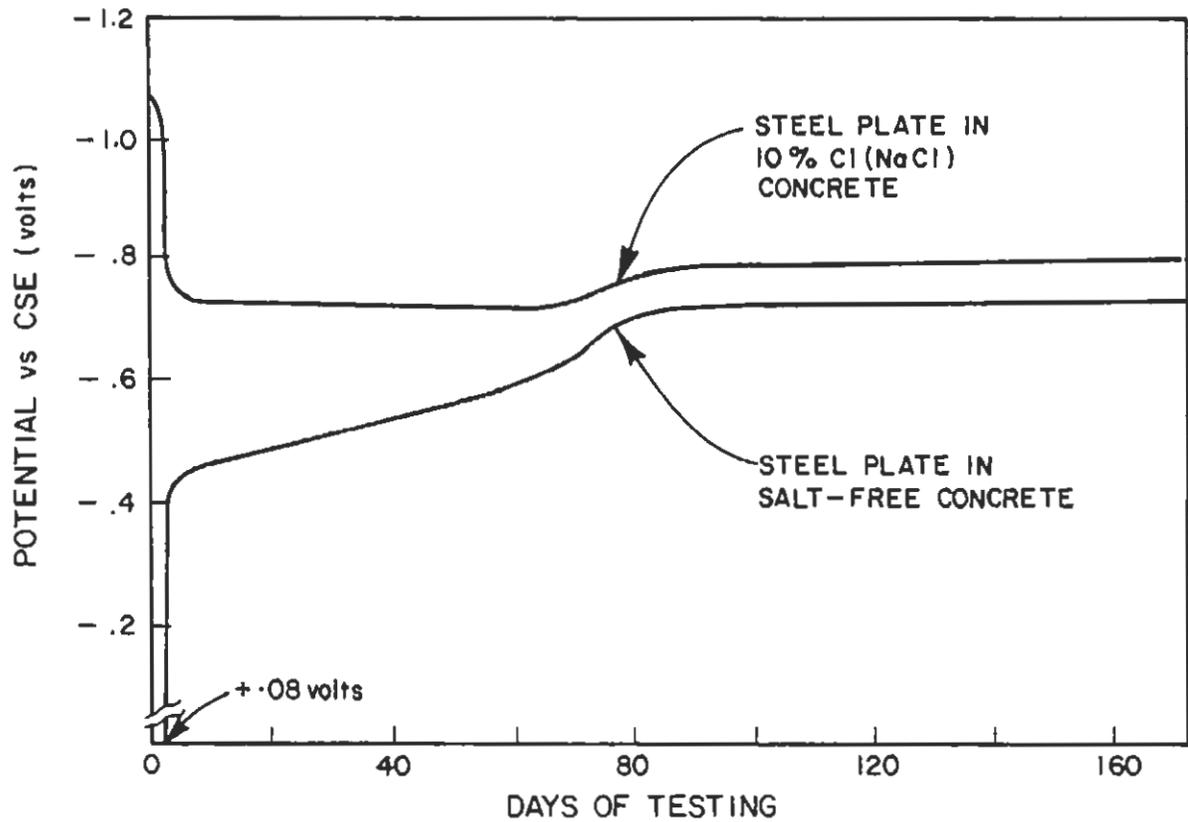
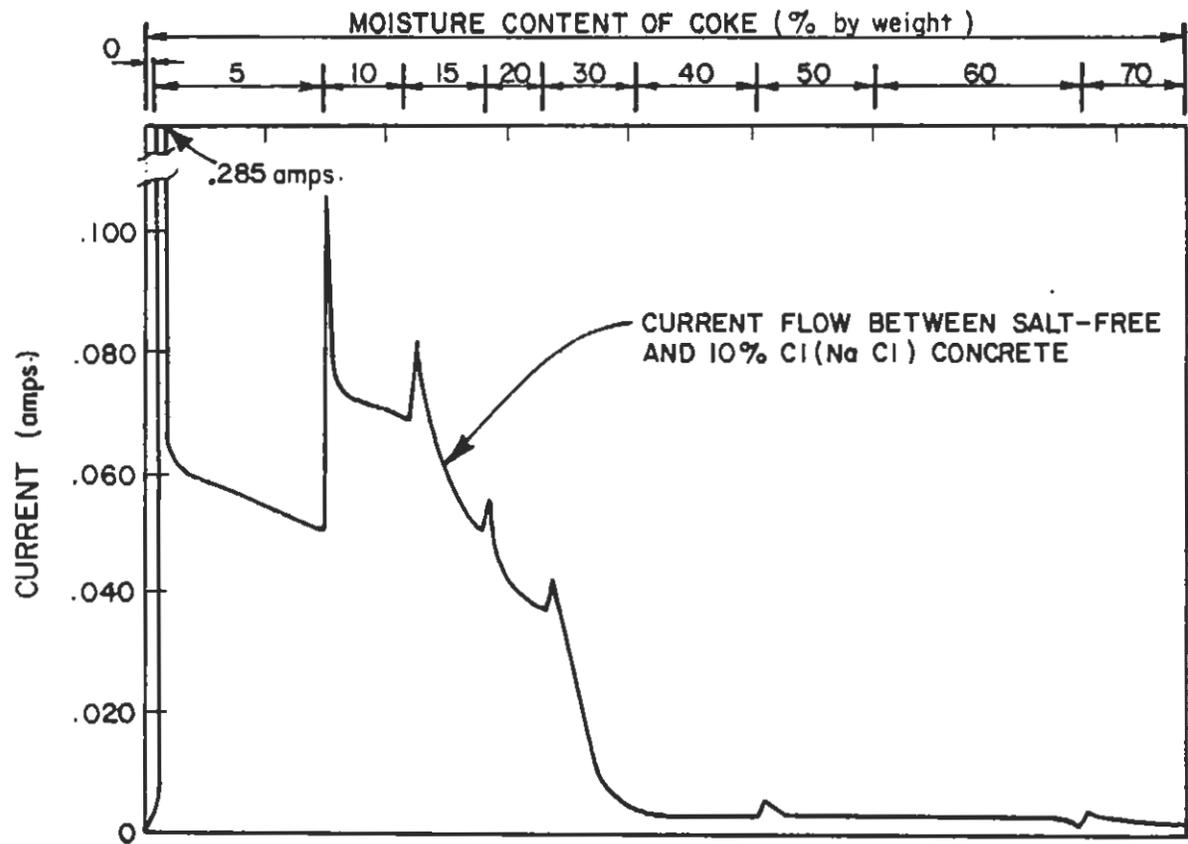
current flow, which initially was measured at 285 micro-amperes, also declined (see Figure 3-3). Addition of water at each moisture level increment tended to temporarily reduce the electrolyte resistance, which resulted in sharp temporary increases in current flow, while the potentials remained generally unaffected. Testing was ended when the potential difference and current flow became low enough where the electrolyte resistance became the major controlling factor in the galvanic reactions.

These galvanic studies demonstrated the extreme variations in measured properties associated with salt vs salt-free concrete, and tended to emphasize the difficulty of attempting to control CP systems using potentials of embedded steel vs CSE or similar electrodes.

Cathodic Protection Studies

In order to study the effects of CP under controlled conditions, a total of seven concrete blocks with embedded steel plates were cast and cured. Each specimen combined salt-free and salty concrete in one monolithic block. This was achieved by casting the salt-free portion, allowing it to set for one hour, and then carefully placing the salty concrete against it. The salty concrete contained 10% chloride ions by weight of cement.

A platinum-coated steel wire was embedded along the interface of the two mixes, to act as an impressed-current anode. A small steel plate was embedded into the salt-free portion, and a corrosometer probe was embedded into the salty portion.



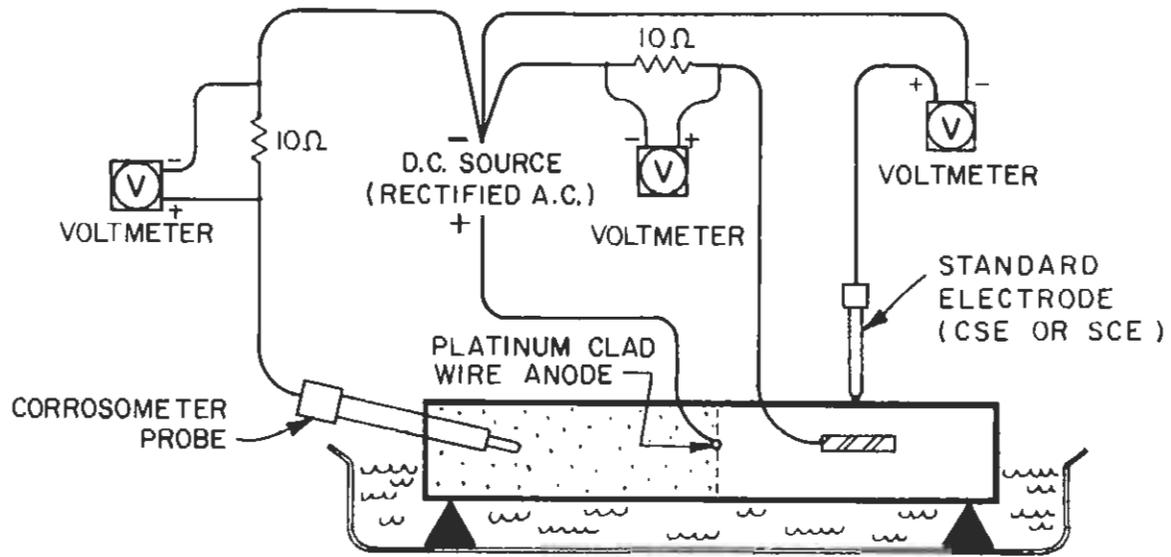
TYPICAL GALVANIC CORROSION MEASUREMENTS
 STEEL IN SALTY & SALT-FREE CONCRETE AS AFFECTED BY MOISTURE

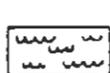
Figure 3-3

These specimens, measuring approximately 12 in. by 6 in. by 2 in. were cast with the two portions side-by-side, so that both could be immersed simultaneously in water (see Figure 3-4).

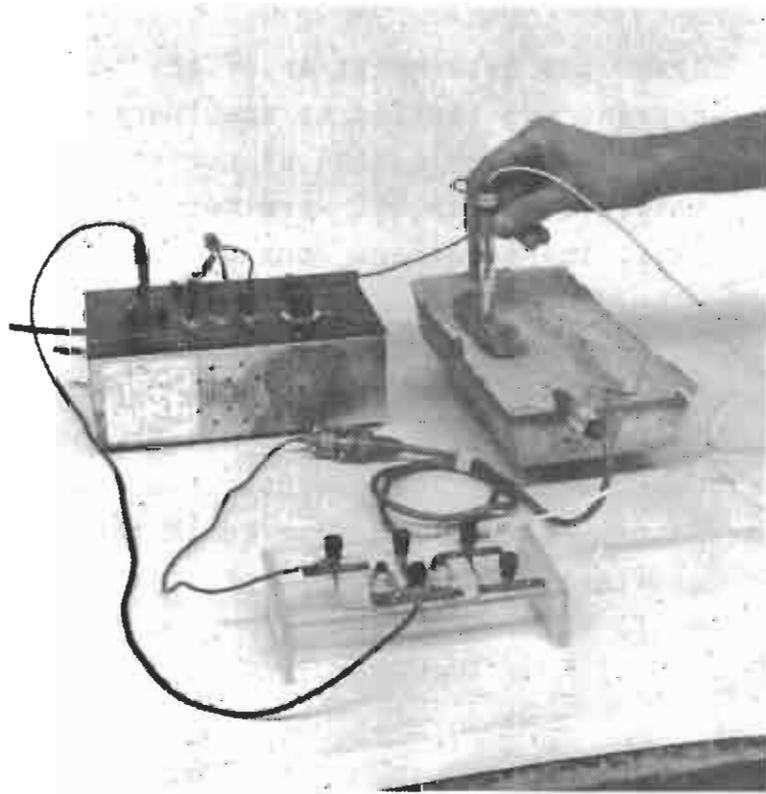
Following curing (107 days in 95% relative humidity), representative specimens containing steel in both salt and salt-free portions were subjected to polarization (E-Log I) tests to determine the amount of impressed current required for cathodic protection. Typical results, presented in Figure 3-5, indicated that an impressed current of 0.0335 milliamperes would be sufficient to stop corrosion of the steel in salty concrete, according to NACE criteria (see Chapter 2). This testing was conducted with specimens saturated by immersion in water.

After the determination of the corrosion current, this current was applied to specimens for 700 days, during which time the distribution of current and potentials of embedded metal vs CSE or SCE were monitored. During the first 560 days, the specimens were allowed to dry in laboratory air (68-72°F, 45-50% relative humidity), in order to determine the effect of drying on these measurements. At that time, the specimens were partially immersed in water to increase their moisture content, followed by cycles of drying and re-immersion. Throughout this time, the level of cathodic protection current applied to the specimens was kept constant. Figure 3-6 depicts a specimen during its immersed cycle.



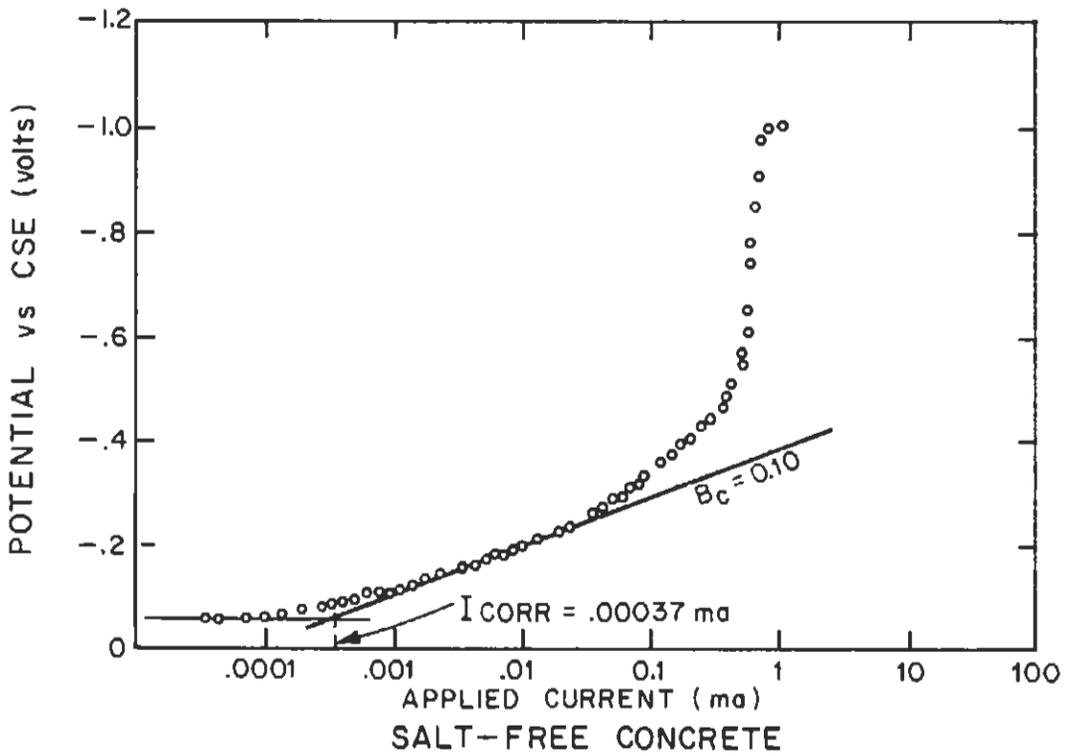
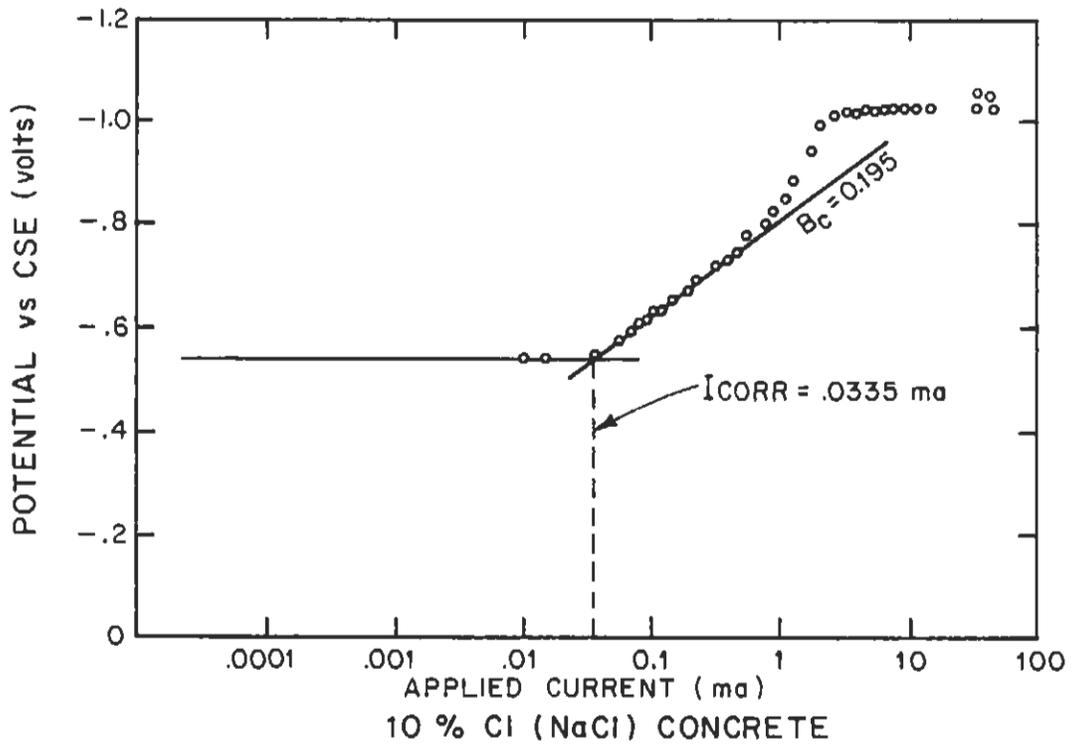
-  SALTY CONCRETE
-  SALT-FREE CONCRETE
-  TAP WATER
-  STEEL PLATE

SCHEMATIC



LABORATORY TEST SPECIMEN

Figure 3-4



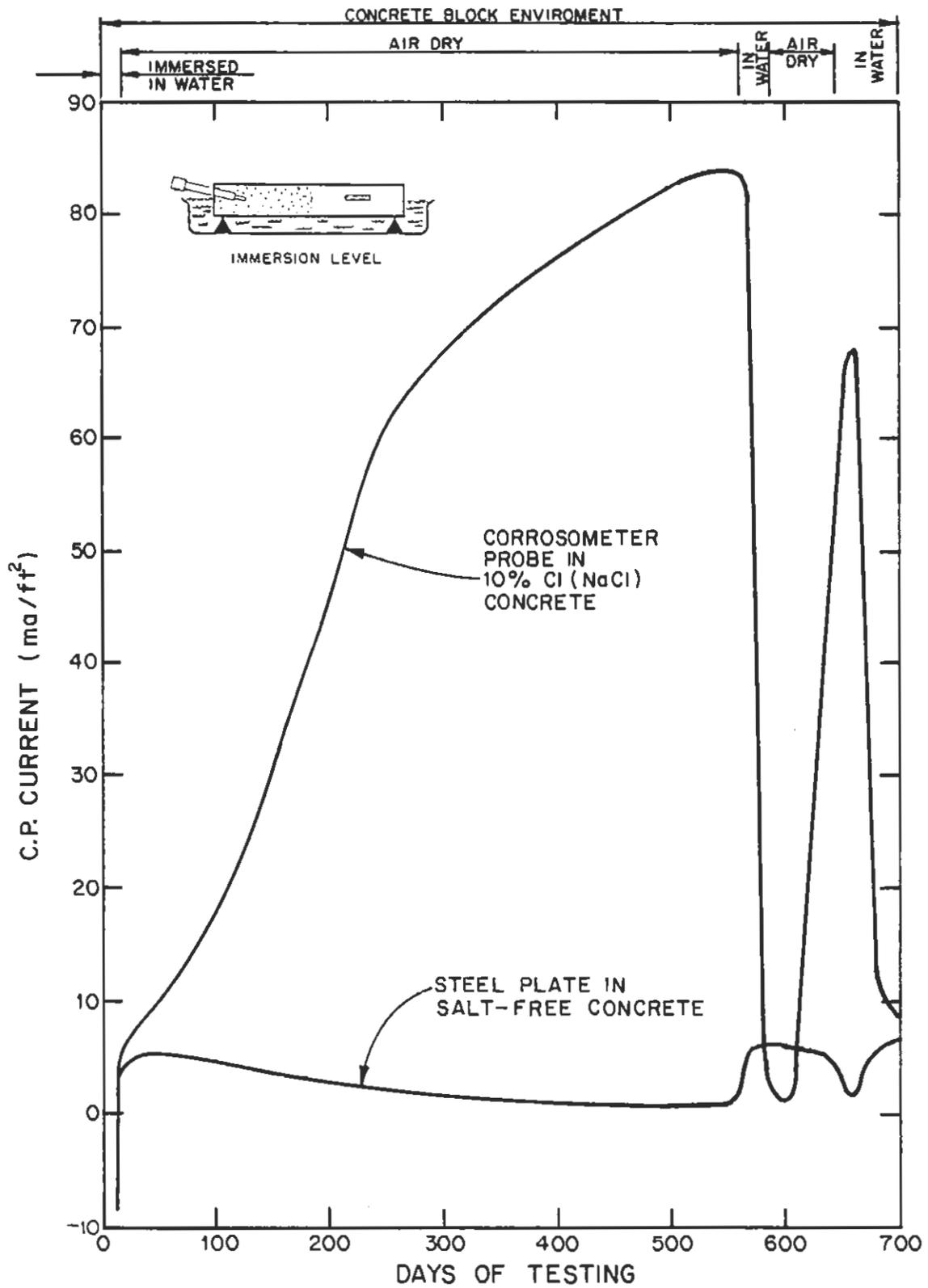
TYPICAL CATHODIC POLARIZATION
SATURATED CONCRETE

Figure 3-5



Figure 3-6. CP Current Being Applied to Partially Immersed Concrete Specimen.

The distribution of CP current between the salt-free and salty concrete segments was dramatically influenced by moisture. Figure 3-7 presents the typical share of current received by a corrosometer probe in salty concrete and the share received by the steel plate in salt-free concrete, in terms of current density (milliamperes per surface area in contact with the electrolyte). When the concrete was saturated, the current distribution was essentially the same - however, when the concrete contained lesser quantities of moisture, CP current was preferentially directed to the salty areas. This was due to the moisture-retentive properties of chloride ions, which created an electrolyte having significantly less resistance to current flow than the drying concrete. These laboratory tests substantiated the logical expectation that CP current tends to flow preferentially to



DISTRIBUTION OF CP ON SALTY AND SALT-FREE CONCRETE

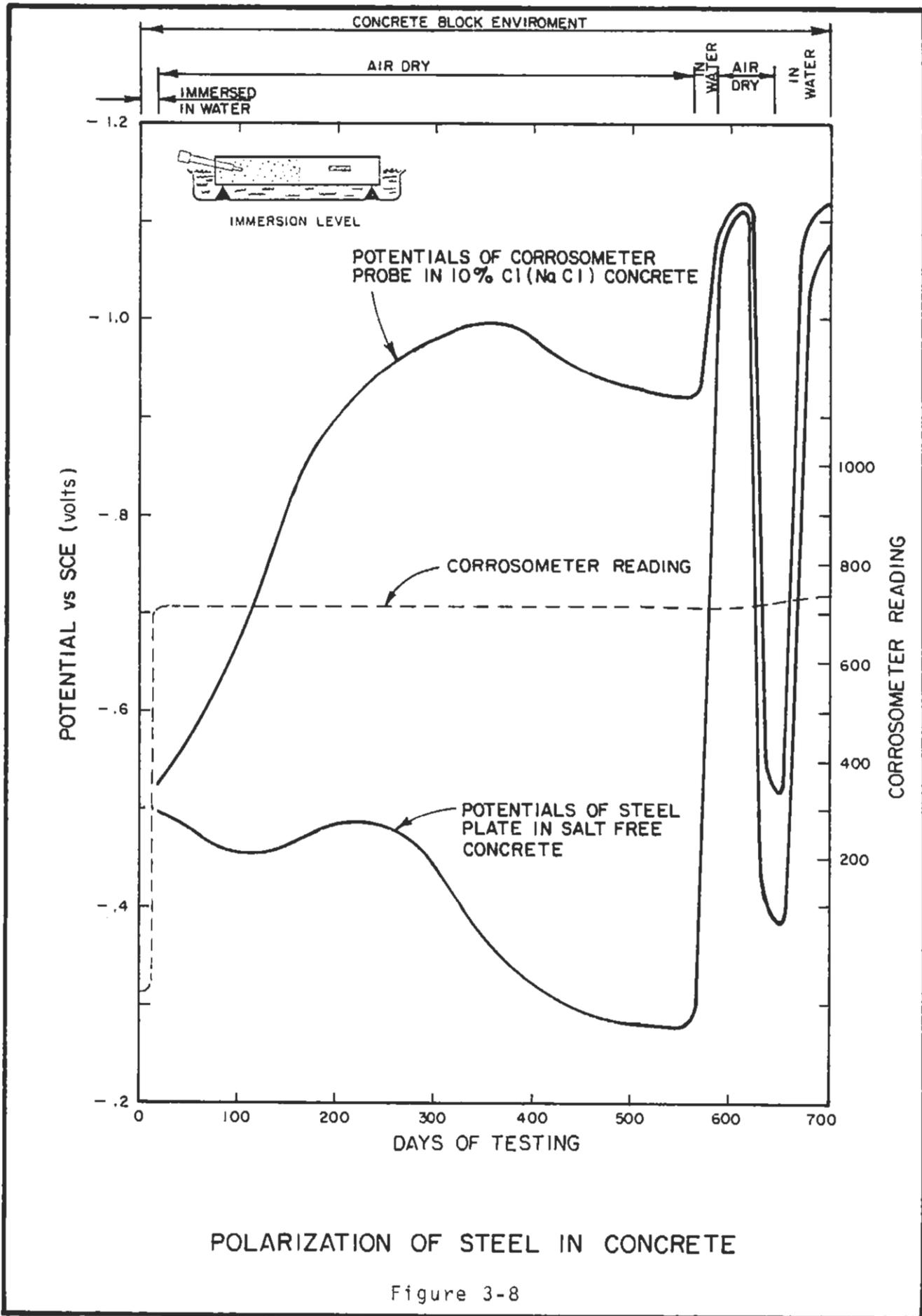
Figure 3-7

the areas where it is most needed. Furthermore, since bridge deck concrete would be expected to be neither totally dry nor fully saturated, and have a non-uniform chloride content, the CP current distribution would behave in a similar - and beneficial - fashion as on the laboratory specimens.

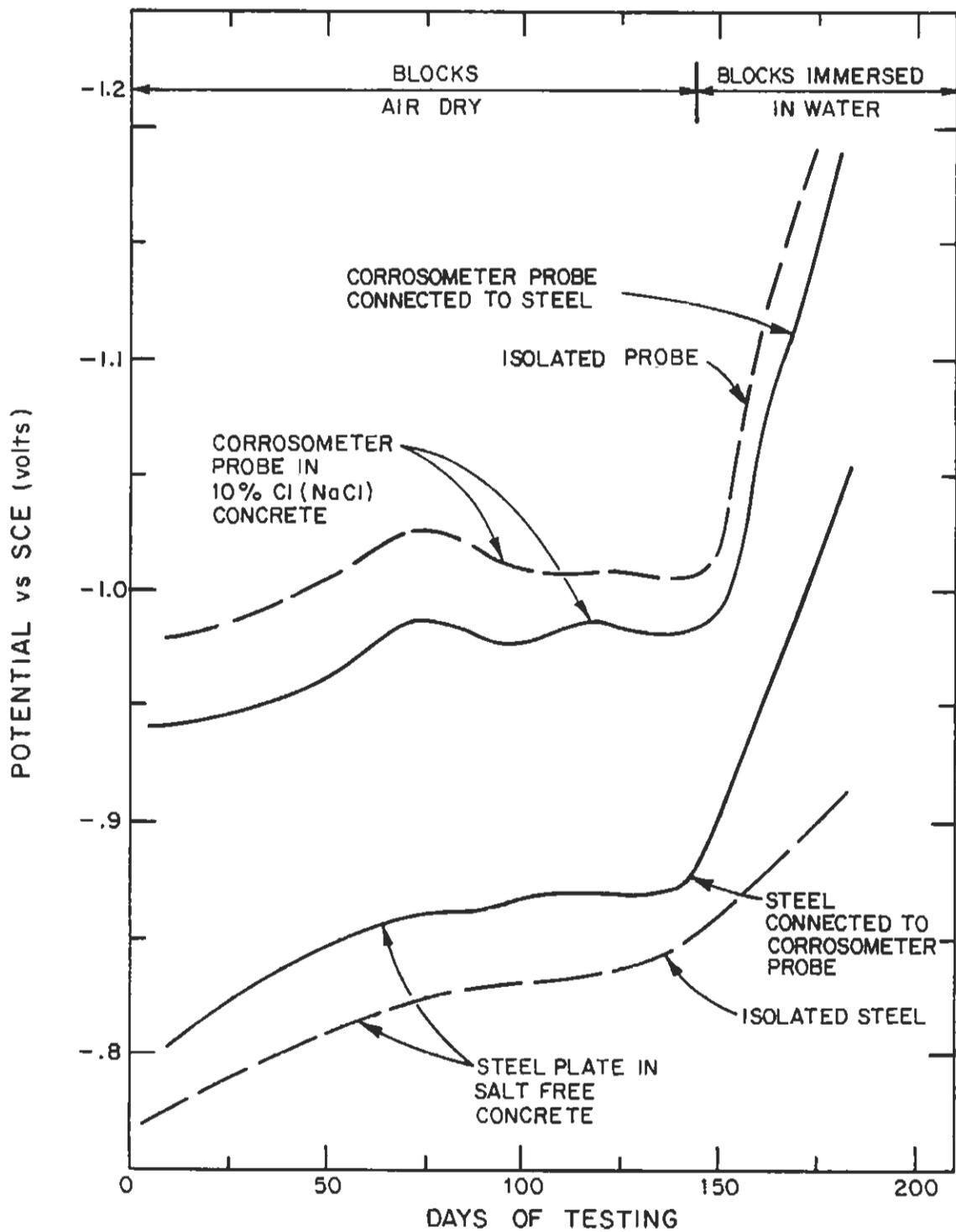
Potential measurements between the embedded metals (steel, and corrosometer alloy) vs a SCE indicated that, as the CP current density preferentially increased in the salty environment, the readings moved toward more negative values for metals embedded in those areas (see Figure 3-8). Conversely, as the concrete density was reduced in the salt-free environment, readings of metals embedded therein moved toward more positive values. When the specimens were saturated, the corresponding values became quite similar, often exhibiting less than 100 millivolts difference. At the same time, corrosometer readings indicated that the 0.34 milliamperes total CP current was effectively arresting corrosion of the probes in salty environment.

These values indicate that, unless a method is devised to measure and map the local moisture content of a bridge deck, individual potential measurements vs standard electrodes are extremely difficult to interpret - on the other hand, corrosometer probe readings can provide useful information as to whether or not sufficient CP current is being applied at specific locations.

An additional test was conducted on a composite specimen to determine the change in potentials when the embedded metals were electrically connected. On typical bridge decks, the upper reinforcing mat would be surrounded by more salty



concrete than the bottom mat, and both would be electrically connected by truss bars. While a constant CP current was being applied, potentials vs SCE were measured with the embedded metals connected and unconnected. Figure 3-9 presents the values obtained which indicate that, as galvanic current was allowed to flow between the steel plate and the corrosometer probe, the resulting polarization brought the potential difference between them closer by approximately 100 millivolts. It should be noted that the alloy used in the corrosometer probes (Magma Corp. 8001) represents ASTM 1010 mild steel, which is galvanically slightly more anodic to the ASTM A-36 steel plates used in these tests.



POLARIZATION POTENTIAL COMPARISON

Figure 3-9

CHAPTER 4. Alternative Conductive Overlay

Coke-asphalt conductive overlays have proven to be quite efficient in distributing impressed CP current on bridge decks. They do, however, have drawbacks. The coke particles which compose a significant portion of the aggregate are relatively weak and friable, and the resulting coke-asphalt mix cannot be adequately compacted to withstand traffic. An additional overlay of a conventional AC wearing course is necessary. This is reflected in installation costs and in additional dead load on the structures under protection. Another potential drawback is that the relatively loose conductive layer retains considerable moisture which, although enhancing its electrical properties, may accelerate freeze-thaw damage to the concrete deck.

As an alternative to the coke-AC plus AC wearing course system, a single overlay consisting of a conductive portland cement concrete (CPCC) would offer potential reductions in costs, dead load, and freeze-thaw damage. To this end, laboratory studies and a brief field study were made to develop data on CPCC characteristics and suitability as an alternative conductive overlay. A report by the U.S. Bureau of Reclamation, concerning mortars with coke breeze as aggregate provided some basis for optimism (13).

Laboratory Studies

Initial test mixes of CPCC were tried, using various combinations of coke aggregate with normal cement factors (5 to 7 sacks per cubic yard). Such mixes were unsatisfactory because they were excessively harsh and had poor workability.

Workable mixes were obtained only when the cement factors exceeded 10 sacks per cubic yard.

A total of four mix designs were prepared and batched, using nominal 10 sack cement factors and varying proportions of coke/conventional aggregates. Air entrainment was also used as an additional variable. A conventional aggregate mix was included as the control as presented in Table 4-1.

Table 4-1. Conductive Portland Cement Concrete Design Mix Variables.

| Design Mix | No. of Batches | Nominal Cement Factor Sacks/cu yd | Nominal Aggregate Proportions | | Nominal Air Entraining % |
|------------|----------------|-----------------------------------|-------------------------------|----------|--------------------------|
| | | | % Coke | % Normal | |
| 100C-0A | 3 | 10 | 100 | 0 | --- |
| 100C-6A | 3 | 10 | 100 | 0 | 6 |
| 70C-0A | 3 | 10 | 70 | 30 | --- |
| 70C-6A | 3 | 10 | 70 | 30 | 6 |
| Control | 1 | 7 | 0 | 100 | --- |

Some difficulty was encountered in material preparation, batching, and mixing, due to the significant difference in specific gravities and water absorption of the two aggregates: normal aggregate specific gravity and absorption average 2.7 and 2%, respectively, compared with coke values of 1.04 and 14%+. Special handling of the coke was required, to insure full saturation prior to mixing, otherwise individual particles tend to float to the top of the mix under normal vibratory consolidation. They would also act as sponges, if dry, and absorb all the mixing water. The coke was immersed in water for 24 hours, drained for 4 hours, mixed thoroughly, the moisture content was determined, and then batched into the mix.

Mixing followed established laboratory procedure - 3 minutes mixing, 3 minutes resting, and 2 minutes of remixing. Several tests were then performed on the fresh mix, as presented in Table 4-2. Because of the low specific gravity of the coke, air content was measured by the volumetric method rather than the pressure method, which is intended for concrete made with denser aggregates.

Table 4-2. Results of Tests on Fresh Concrete

| <u>Design Mix</u> | <u>No. of Batches</u> | <u>Average Slump^a Inches</u> | <u>Average Cement Content Sacks/C.Y.</u> | <u>Average Water/ Cement Ratio</u> | <u>Average Air Content^b %</u> |
|-------------------|-----------------------|---|--|--|--|
| 100C-0A | 3 | 2.3 | 10.3 | .41 | 2.7 |
| 100C-6A | 3 | 2.7 | 10.3 | .36 | 5.9 |
| 70C-0A | 3 | 2.7 | 10.3 | .41 | 2.8 |
| 70C-6A | 3 | 3.2 | 10.3 | .40 | 5.5 |
| Control | 1 | 2.5 | 7.0 | .52 | 1.9 |

a. As per ASTM C 143-74

b. As per Calif. Test 543

The various concrete mixes were cast into specimens of appropriate configurations for testing of various physical parameters. Table 4-3 presents the results of the physical testing of the concrete specimens.

The results of compressive strength testing indicate that the mixes containing entrained air have lower strengths than those without; and the mixes with 100% coke aggregate have lower strengths than the mixes with 70% coke aggregate, as expected. However, the differences were not major and all compared quite favorably to the control.

| DESIGN MIX | COMPRESSIVE STRENGTH ^(a) (psi) | | | SPLITTING TENSILE STRENGTH ^(b) (psi) | 28 DAY BOND STRENGTH ^(f) (psi) |
|------------|--|--------|--------|--|--|
| | 7 DAY | 28 DAY | 90 DAY | | |
| 100c-0A | 3900 | 5160 | 6060 | 565 | No Test |
| 100c-6A | 3870 | 4870 | 5500 | 515 ^(g) | 330 |
| 70c-0A | 4420 | 5850 | 6620 | 630 | No Test |
| 70c-6A | 3950 | 5650 | 6060 | 575 ^(g) | 250 |
| Control | 4230 | 5790 | 6670 | No Test | 225 |

| DESIGN MIX | RELATIVE DRYING SHRINKAGE % ^(c) | | | | FREEZE-THAW ^(d) | | ABRASION ^(e) % WEIGHT LOSS | | |
|------------|--|--------|--------|--------|----------------------------|--|--|--------|---------|
| | 7 DAY | 14 DAY | 28 DAY | 90 DAY | PERMANENT CHANGE (in) | MAXIMUM DILATION (10 ⁻⁶ in/in) | 20 SEC | 60 SEC | 180 SEC |
| | | | | | | | | | |
| 100c-0A | .024 | .040 | .063 | .106 | .0436 | 300+ | 0.21 | 0.57 | 1.26 |
| 100c-6A | .028 | .045 | .069 | .112 | .0006 | 7 | 0.24 | 0.50 | 1.13 |
| 70c-0A | .030 | .043 | .065 | .100 | .0325 | 300+ | 0.16 | 0.49 | 1.04 |
| 70c-6A | .033 | .049 | .071 | .101 | .0002 | 7 | 0.17 | 0.41 | 1.03 |
| Control | .015 | .026 | .038 | .055 | .0003 | 6 | 0.14 | 0.47 | 0.91 |

- a. - Calif. Test 521
- b. - ASTM C496-71
- c. - Calif. Test 537 Modified
- d. - Calif. Test 528 Modified
- e. - Calif. Test 360 Modified
- f. - Calif. Test 420 Modified
- g. - Calculated Values

Table 4-3
**PHYSICAL PROPERTIES
OF COKE AGGREGATE PORTLAND CEMENT CONCRETE
(AVERAGE VALUES)**

There was little variation in drying shrinkage values between the four trial mixes. Those mixes which contained entrained air exhibited values slightly larger than mixes without entrained air.

In general, the trial mixes exhibited about twice the shrinkage recorded for the control mix. Although such values are considered high (Caltrans has no specification that limits drying shrinkage), aggregates that produce greater shrinkage values have been successfully used in the past.

Results of the freeze-thaw testing strongly indicate that CPCPC using coke aggregate must be air-entrained in order to provide freeze-thaw resistance. Other than the permanent change in length for mix 100C-6A, the air-entrained mixes exhibit values that comply with California Test 528 requirements for maximum dilation (0.00005 in. per in.) and permanent change in length (0.00045 inches in a 7.5 inch gage length).

Results of abrasion testing indicated that the trial mixes abraded more rapidly than the control mix and the mix containing 100% coke aggregate abraded more readily than the mix containing 70% coke aggregate. Due to the low specific gravity of the coke aggregate, abrasion losses are listed as a percentage of specimen weight. This allows a meaningful comparison of the trial mixes with the control mix.

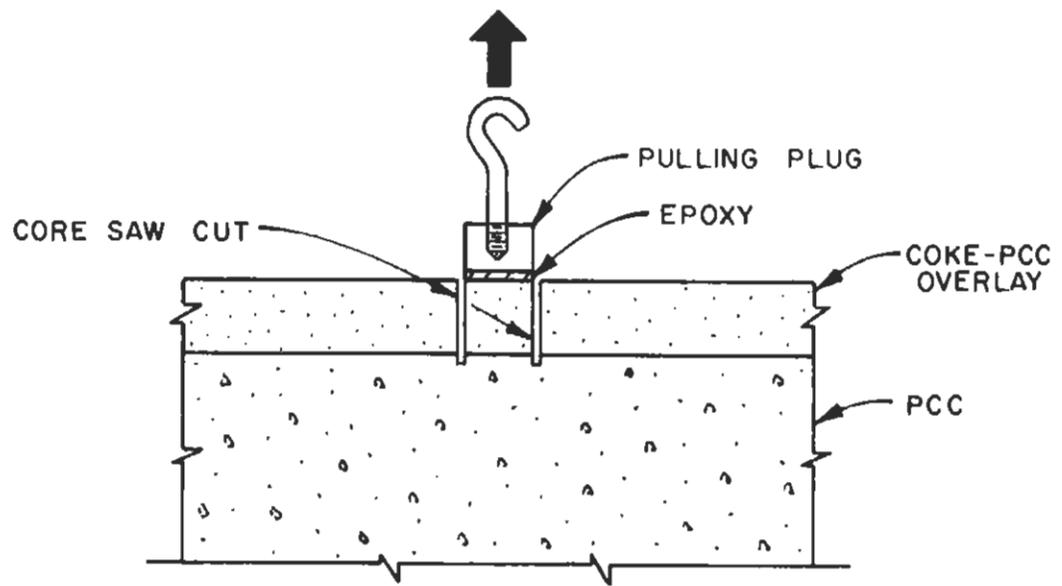
Splitting tensile strength tests were conducted on freeze-thaw cylinders representing both non-entrained air mixes. The resulting strengths were then multiplied by an appropriate factor to obtain estimates of the splitting tensile

strength for the air-entrained mixes. The factors are a ratio of the 90-day compressive strength for entrained air and non-entrained air mixes. The resulting values comply with the splitting tensile strength requirement (360 psi) of Section 89-1.02, January 1978 California Standard Specifications, for lightweight concrete of comparable compressive strength.

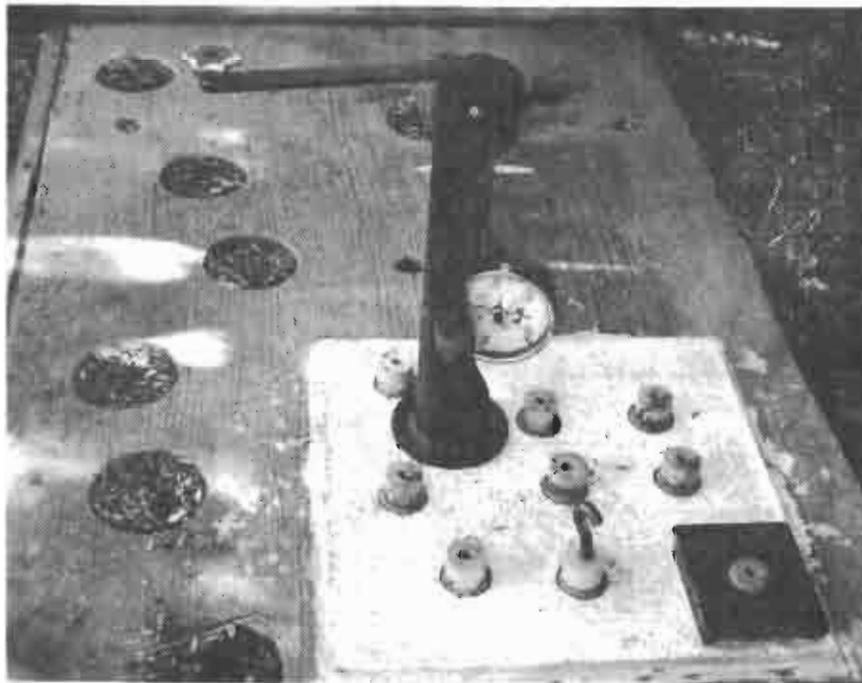
Table 4-3 also contains the results of a study to evaluate the bond strength between an existing concrete bridge deck and a CPCC overlay. Concrete test blocks (12 in. x 12 in. x 3 in.) were overlaid with two inches of 70% and 100% CPCC and then cured in 95% relative humidity for the 28-day test period. Tensile pull tests were then performed (see Figure 4-1). The results of these tests seemed quite promising with average values of 250 and 330 psi. It has been reported (14) that a bond strength as low as 40 psi may be adequate for an overlay.

An inspection of the data contained in these tables indicates that, in general, CPCC compared quite favorably with the control or with specification requirements for PCC, with the exception of drying shrinkage. The drying shrinkage for these relatively harsh mixes is high. The abrasion test results indicate that CPCC may require some protection or reinforcement if it is to successfully withstand normal traffic.

In addition to the physical tests, specimens were prepared and subjected to electrochemical tests to determine their conductive properties. Measurement of electrical resistivity was conducted by the Wenner 4-pin method, using a soil resistivity meter and a specially-constructed laboratory apparatus (see Figure 4-2).

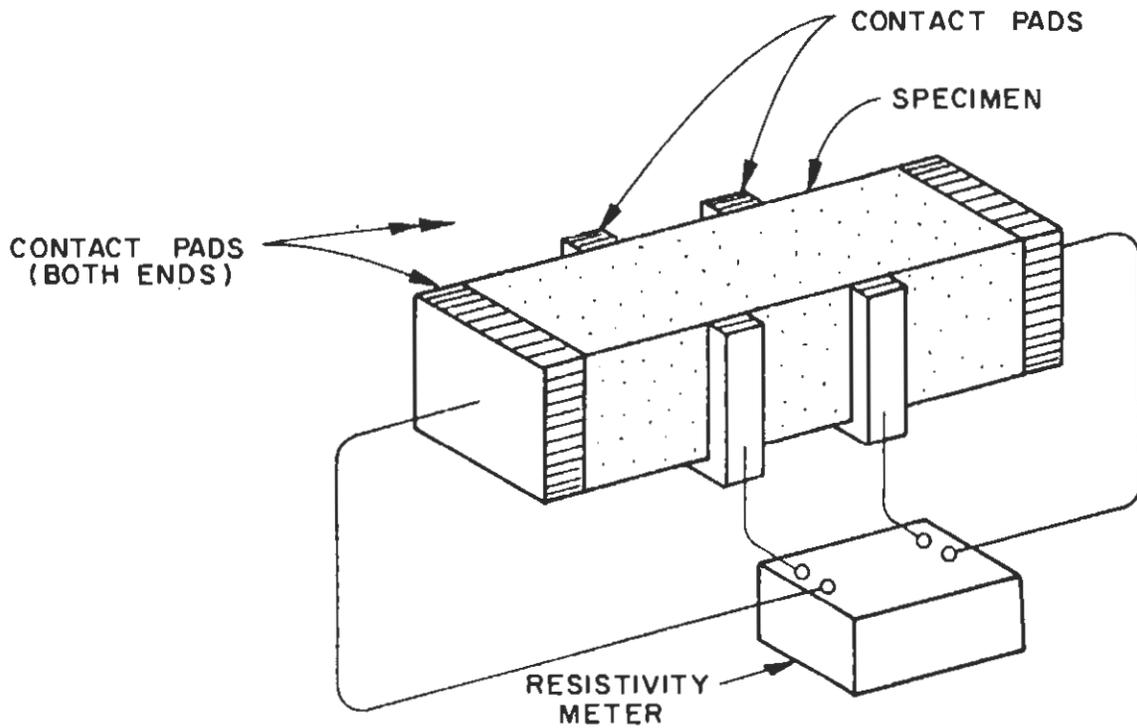


TYPICAL SECTION

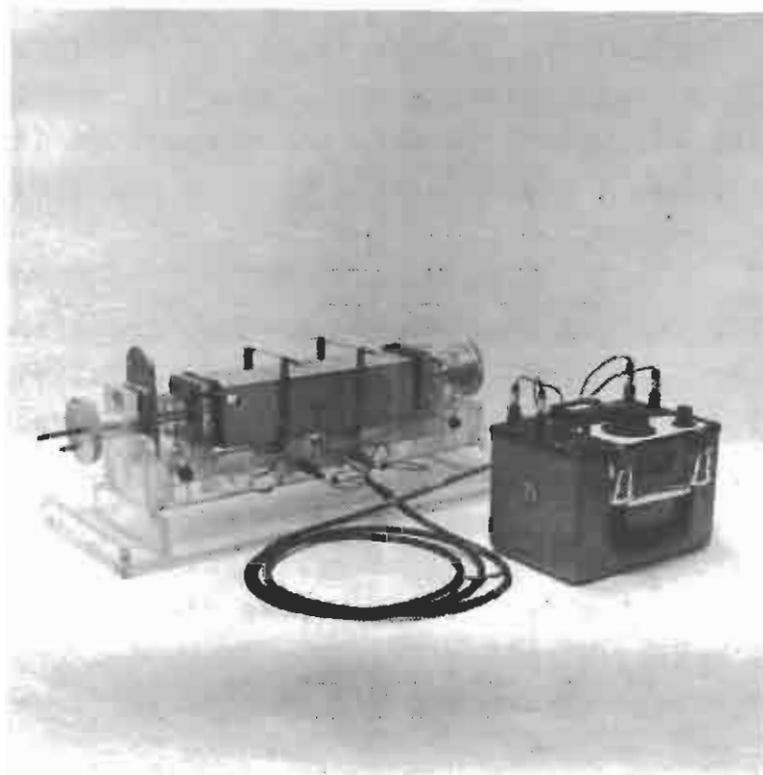


TENSILE PULL TEST

Figure 4-1



SCHEMATIC



RESISTIVITY MEASUREMENTS - LABORATORY METHOD

Figure 4-2

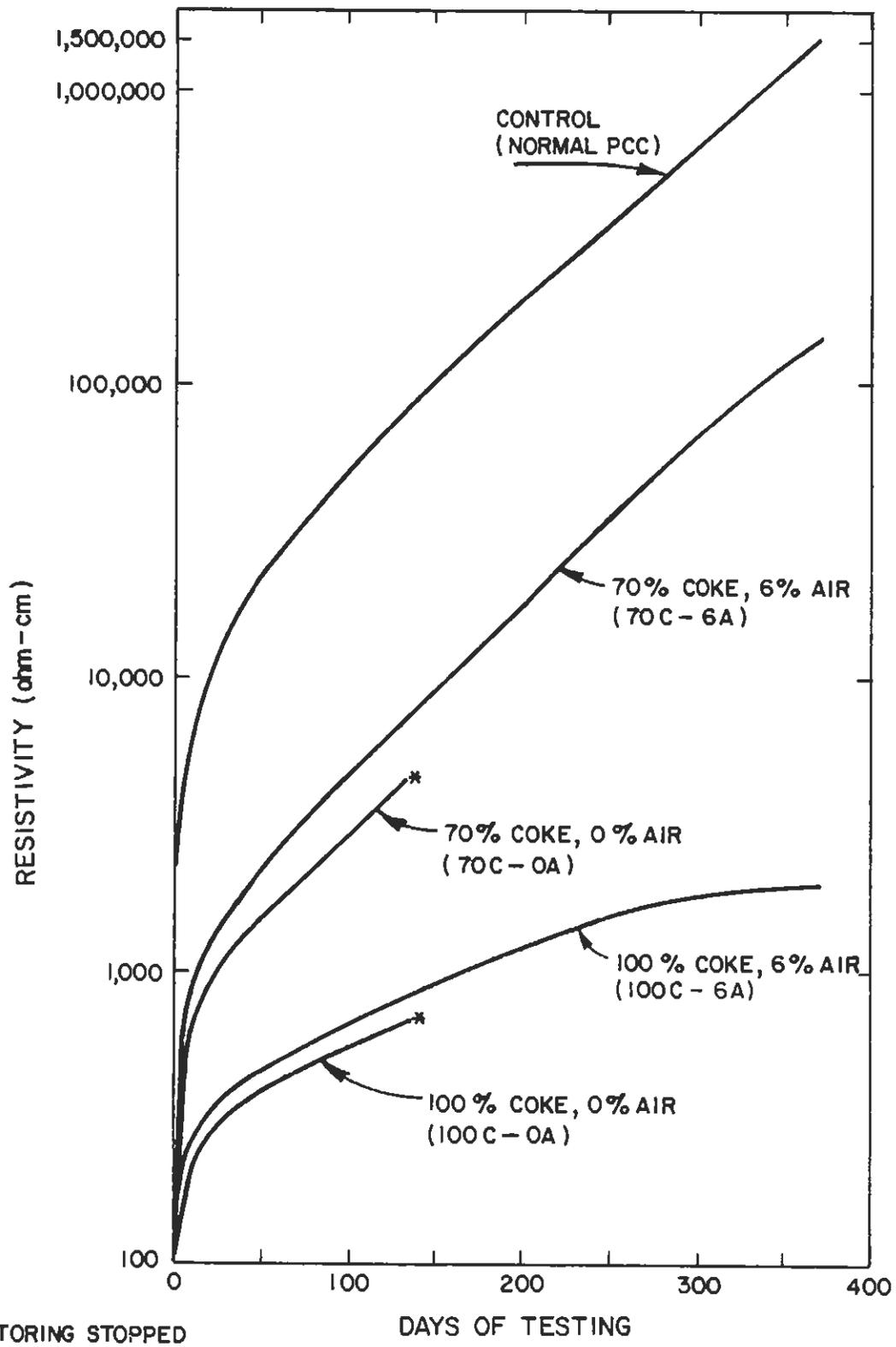
The original resistivity measurements were conducted after the specimens were removed from cure, at 72°F under saturated-surface dry conditions, and frozen, at -13°F. Table 4-4 presents the average values obtained from the 12 specimens containing coke aggregate.

Table 4-4. Average Initial Resistivity of CPCC Specimens

| <u>Design Mix</u> | <u>No. of Specimens</u> | <u>Resistivity, ohm-centimetres</u> | |
|-------------------|-------------------------|-------------------------------------|--------------------------|
| | | <u>Frozen (-13°F)</u> | <u>Room Temp. (72°F)</u> |
| 100C-0A | 3 | 6300 | 420 |
| 100C-6A | 3 | 400 | 170 |
| 70C-0A | 3 | 5600 | 740 |
| 70C-6A | 3 | 3300 | 800 |
| Control | Not measured | --- | --- |

These resistivity specimens were monitored for approximately one year, while allowed to dry in the laboratory (68-72°F, 45-50% relative humidity). Monitoring of two groups of three specimens, 100C-0A and 70C-0A was discontinued after approximately five months, because identical mix specimens had failed the freeze-thaw tests. The measurements, presented in Figure 4-3, indicate that the proportion of coke in the aggregate has a significant effect on the conductivity of the mature concrete.

Following the one year drying period, these specimens were tested to determine the variation in resistivity they would exhibit during a hot summer day, with temperatures ranging from 70°F± to 120°F±. The testing consisted of placing the specimens in a 120°F oven for two hours, followed by cooling in the laboratory for 22 hours. Since no moisture was added, the result was a cumulative drying effect which created a general increase in resistance. Table 4-5 presents average typical measurements obtained in this test, which demonstrate



* MONITORING STOPPED
 (DUPLICATE SPECIMENS
 FAILED FREEZE-THAW
 TEST).

RESISTIVITY MEASUREMENTS OF
 COKE-CONCRETE TEST MIXES

Figure 4-3

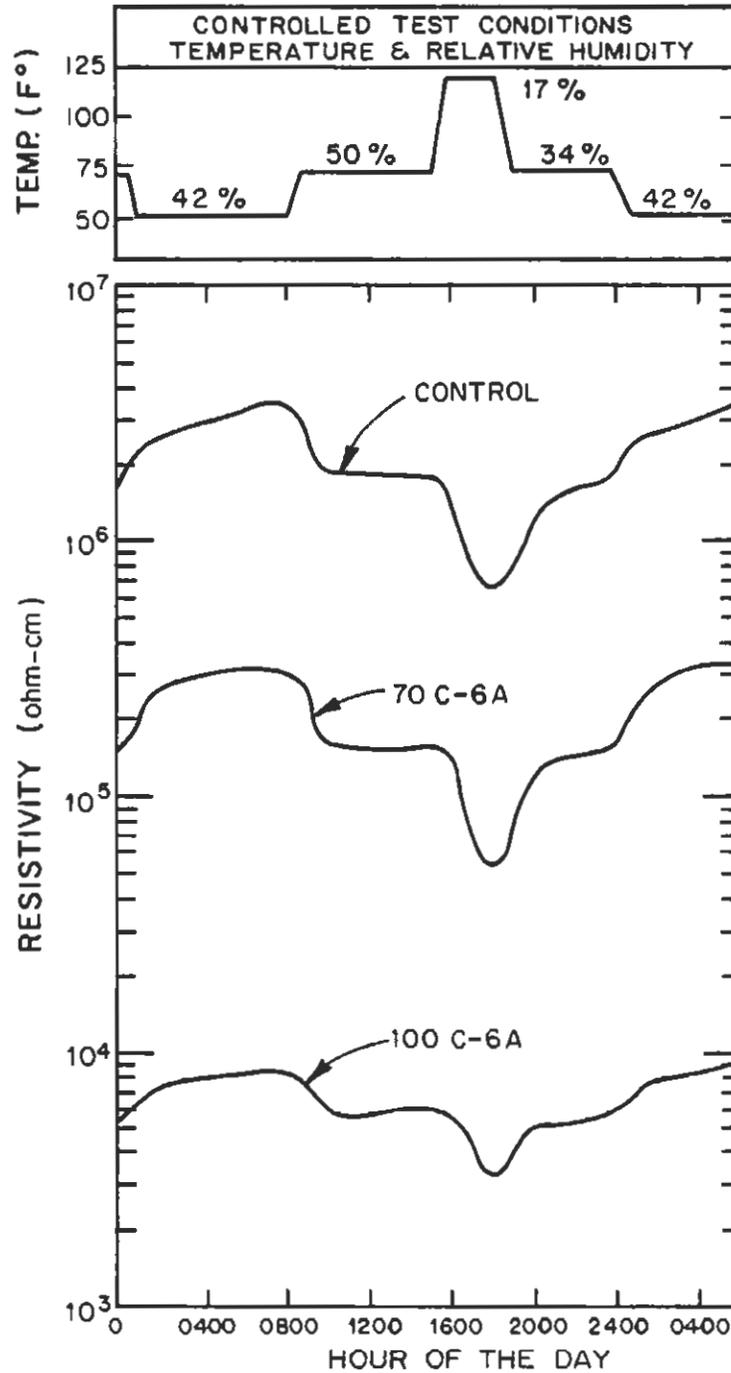
the very large change in concrete resistivity due to temperature variation, the 100% coke CPCC specimens showing the least amount of change.

Table 4-5. Change in Resistivity of CPCC With 24-Hour Cyclic Temperature Changes

| Design Mix | No. of Specimens | Typical Resistivity, ohm-centimetres | | Average | Change + From Average |
|------------|------------------|--------------------------------------|---------|-----------|--------------------------|
| | | 72°F | 120°F | | |
| 100C-6A | 3 | 5,300 | 2,800 | 4,100 | +31% |
| 70C-6A | 3 | 142,000 | 45,000 | 93,500 | +52% |
| Control | 1 | 1,600,000 | 500,000 | 1,050,000 | +52% |

A concurrent study involved placing specimens in an environmental chamber, where predetermined temperature and relative humidity changes were programmed to simulate a Northern California 24-hour climatic cycle. The resulting measurements, presented in Figure 4-4, also indicated that temperature and humidity influence concrete resistivity, with the 100% coke CPCC specimens being the least affected.

| SPECIMEN COMPOSITION | | | | | |
|----------------------|--------------------|-------------|------------|------|-----------------------|
| SPECIMEN | NOMINAL CEM. FACT. | MIXTURE (%) | | | PERCENT ENTRAINED AIR |
| | | COKE | CONC. AGG. | SAND | |
| 100 C-6A | 10 | 100 | 0 | 0 | 6 |
| 70 C-6A | 10 | 70 | 0 | 30 | 6 |
| CONTROL | 7 | 0 | 70 | 30 | 0 |



TYPICAL DAILY CHANGE OF RESISTIVITY
IN CONCRETE

Figure 4-4

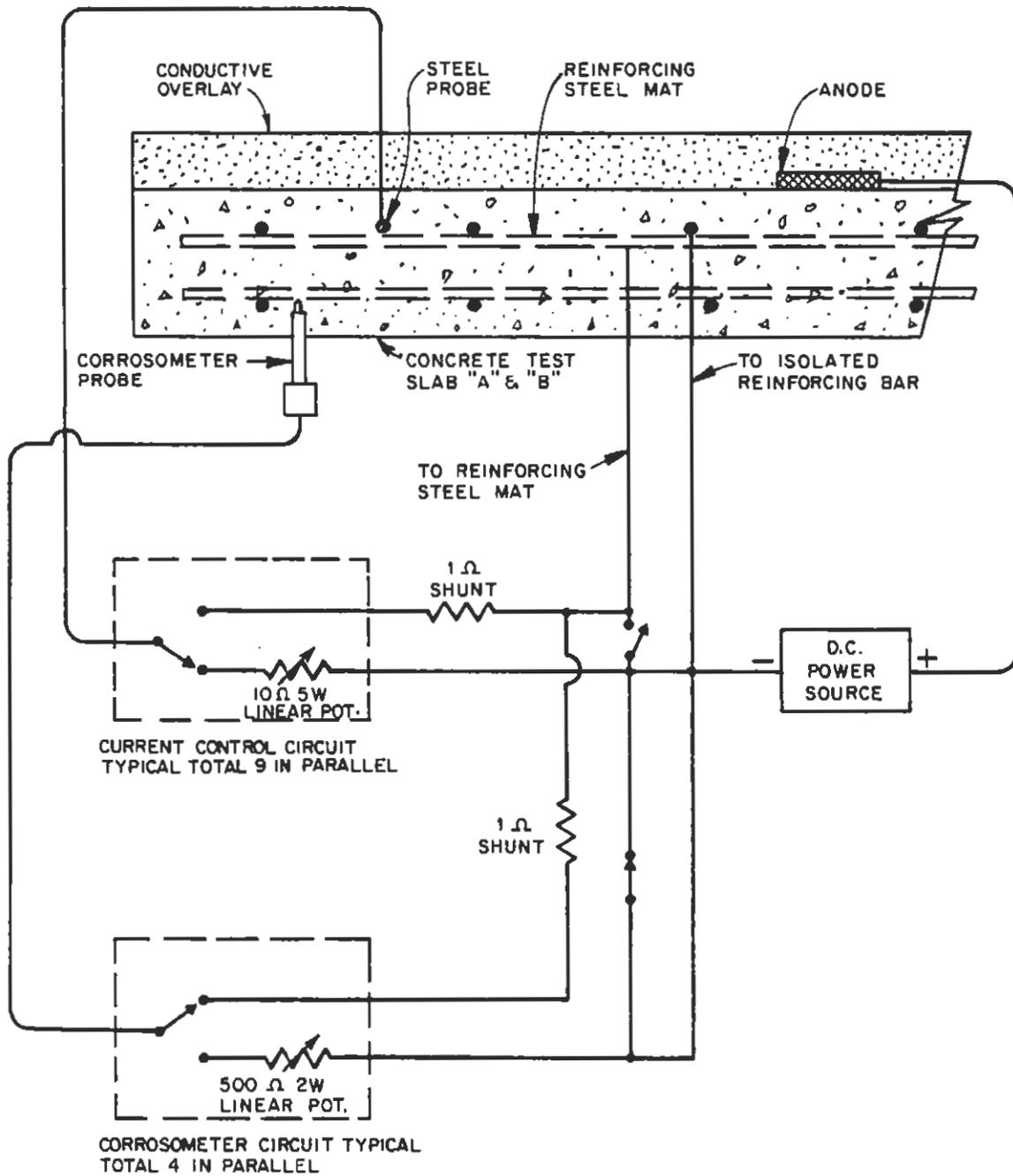
Application of CPCC on Test Slabs

After gaining experience by performing trial mixing and applications over existing concrete slabs-on-grade, a two inch thick, CPCC overlay was placed on two reinforced concrete slabs, measuring 6 ft by 7 ft, which contained corrosive levels of chlorides (see Appendix B, History of Three Test Slabs). The overlay contained aggregate consisting of 100% coke.

A cathodic protection system was set-up for application to the two slabs, along with data acquisition instrumentation including installation of corrosometer probes, cast in salty mortar and embedded into the concrete (see Figure 4-5). A special temporary CP system was used to protect each of these probes from its fresh, salty environment.

A neat portland cement paste bonding layer (consisting of 0.45 lb water per 1.0 lb cement) was mixed and spread by hand over the completely dry slab surfaces. The CPCC was then placed over this bonding layer and finished by hand. Chlorinated rubber curing compound was applied to the finished surfaces, followed by wet curing mats.

Prior to mixing, the coke aggregate was soaked in water for 24 hours, followed by draining for four hours. Mixing was performed in a 3.5 cubic foot portable mixer according to California Test 530 in several batches, and the CPCC was placed before the bonding layer could dry out. The time elapsed between completion of finishing and the application of the curing compound was between one and two hours. In retrospect, this delay was too long, and at the time of application, shrinkage cracks were beginning to appear on



**SCHEMATIC DIAGRAM
TEST SLAB DATA ACQUISITION SYSTEM**

Figure 4-5

the first slab overlaid, i.e., two hours after finishing. Saturated cotton curing mats were placed over both slabs two hours after the application of the curing compound, and kept wet for seven days.

Concrete mix design data, and test results on both the fresh and mature CPCC are presented in Table 4-6.

Table 4-6. Properties of CPCC Overlay on Test Slabs

| | |
|-------------------------------|----------|
| Coke Aggregate Portion | 100% |
| Cement Content, Sacks/cu yd | 11.7 |
| Water/Cement Ratio | 0.40 |
| Slump | 5 inches |
| Air Content | 6.5% |
| Compressive Strength (28-day) | 6480 psi |
| Shrinkage (14-day) | 0.04% |

An inspection of the mature overlays indicates that this mix was unsatisfactory. The excessive cement content and delay in application of curing compound resulted in considerable shrinkage cracking, which is more prominent on the first slab to receive the overlay. Figure 4-6 gives an overall view of the test slabs with instrumentation installed, just prior to placing the overlay.

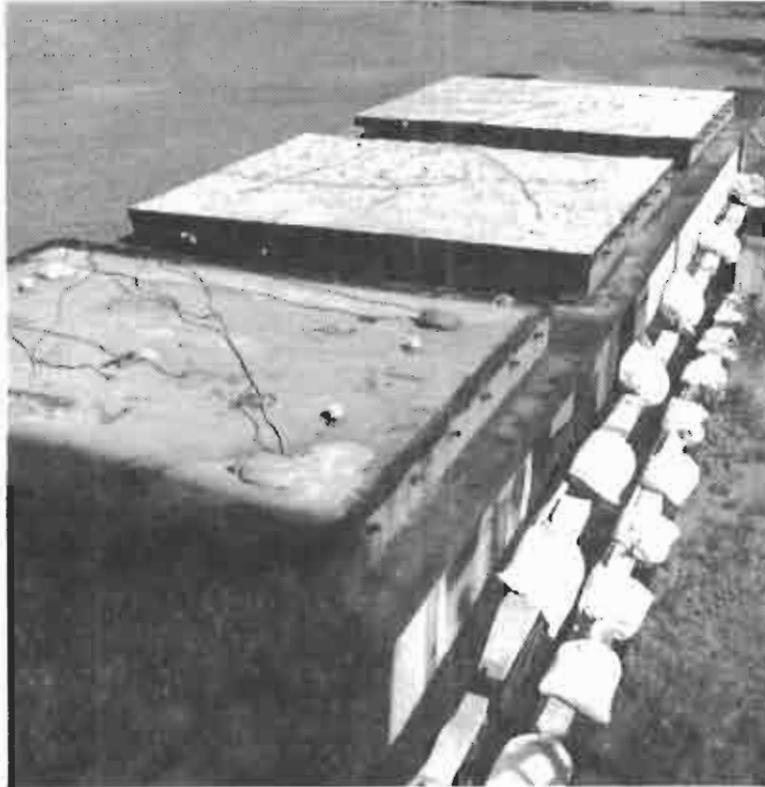


Figure 4-6. View of Three Reinforced Concrete Test Slabs Used in CPCC Overlay Study.

Chain dragging the mature overlay surfaces indicated good bond between the original deck and overlay. The planned application of cathodic protection, and subsequent data acquisition, however, were cancelled.

Although this particular CPCC overlay was unsuccessful, the experience gained, along with information presented by Ellis and Colson (5) and others, will help bring further research to a satisfactory conclusion.

CHAPTER 5. Alternative Anodes for Impressed Current CP

In an impressed-current cathodic protection system, the current is transmitted to the electrolyte by means of an electrode, commonly referred to as an "anode". Almost any conductive substance can be used as an anode, but all tend to be consumed (corrode) as they discharge current. In practice, selection is limited to a few materials which have a low consumption rate, and thus a long useful life. Such materials include graphite, high-silicon iron, precious metals such as platinum, rhodium, palladium and ruthenium and their alloys. Occasionally, iron and steel have been used as anodes.

High-Silicon Iron Anodes

Anodes used on the Sly Park Bridge installation consisted of cast high-silicon iron discs, 10 in. diameter by 1.25 in. thick. Rectangular shapes, 24 in. by 4 in. by 1.25 in. of the same material were used in other field installations (see Figure 5-1).

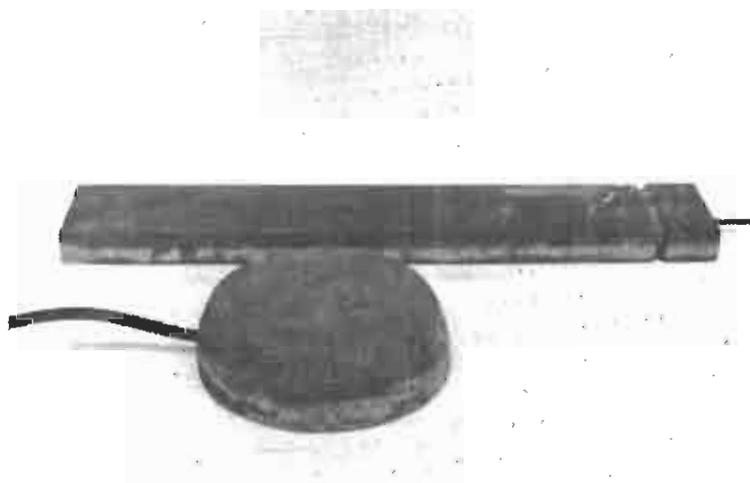


Figure 5-1. High-Silicon Iron Anodes

Since high-silicon iron is a brittle material, it must be handled with the care required of a ceramic, rather than a metal. Original installation consisted of bonding the anodes to the concrete deck with epoxy, and taking special care to prevent damage to them and their wire leads when placing the conductive overlay and AC wearing course. An improved method used by Fromm (8) consists of recessing the anodes and wires flush into the deck. This method minimizes potential damage from subsequent overlay repairs.

A common method of extending the useful life of anodes used in underground cathodic protection is to surround the impressed-current anode with a backfill consisting primarily of (conductive) coke. This results in transfer of a portion of the current to the coke through direct contact, making the coke perform the actual discharge into the electrolyte (concrete). Since anode consumption occurs only at the point of current discharge, a portion of the degradation is thus transferred to the coke, saving the anode.

Bridge deck CP systems using coke-AC as a conductive layer provide similar direct contact to the anodes, so their consumption rate would be expected to be lower than normal. To study this effect, two anodes were uncovered and inspected after five years of intermittent operation at Sly Park Bridge, at locations C-6 and C-27 (see Appendix A, Figure A-3). A review of the records indicated that the actual operating time for these anodes was 2.8 years, at currents ranging from 0.04 to 1.68 amperes.

Initial observations indicated that little or no degradation of the anodes had occurred (see Figure 5-2). The original epoxy layer connecting the anodes to the deck, and intended to act as an electrical insulator had deteriorated to the form of a brittle, leathery consistency, and lacked bond to either concrete or anode (see Figure 5-3).

One of the two exposed anodes was removed from the deck, cleaned, and weighed, to determine its consumption rate. It was found that 0.4 lb was missing from the original weight of 29.0 lbs. The total current discharged by this anode was 1.43 ampere-years, providing an observed consumption rate of 0.3 lb/ampere-year. The theoretical consumption rate for this material was 0.5 lb/ampere-year, indicating that the coke-AC layer was reducing the consumption by 40%. This indicates that even at an extremely high current level of 2 amperes, a 29 lb anode would last 48 years, and, at more realistic current levels, would far outlast the useful life of the protected structure.

In addition to determining the consumption rate, the condition of the electric cable-to-anode connection was inspected, since this is a common area of trouble. After removal of the epoxy sealing material, no sign of distress could be detected.

Steel Anodes

Steel plate anodes were installed on other bridge decks in California, using the same conductive overlay as in Sly Park. They consisted of ASTM A-36 mild steel, made in long strips. Their excessive length caused considerable problems in installation, and subsequent problems due to thermal expansion



Figure 5-2. High-Silicon Iron Anode Exposed After Five Years Service.

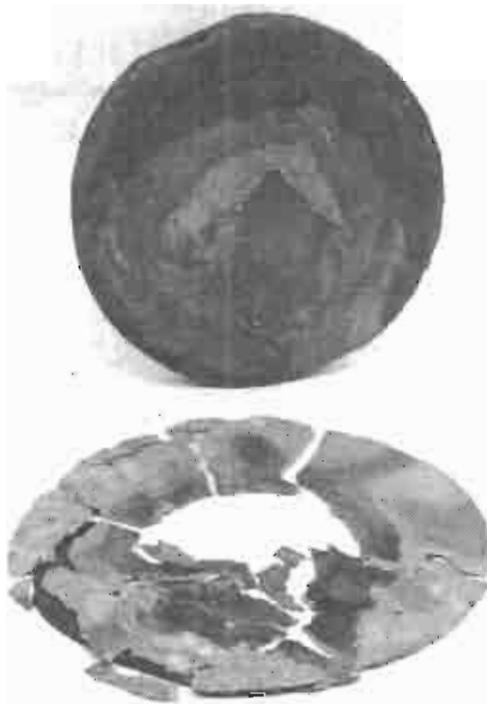


Figure 5-3. Underside of Anode and Brittle Epoxy Bonding Layer After Five Years Service.

and contraction, and associated disbonding, caused their eventual removal. Visual inspection of two of these strips, one 122 ft by 8 in. by 0.25 in. and the other 119 ft by 8 in. by 0.25 in., indicated some pitting had taken place, but the overall consumption had been relatively minor. Unfortunately, original weight records were not available for weight loss determinations.

One strip had been in place for approximately 3.7 years, and operated at an average of 3.5 amperes for a total of 13.0 ampere-years. The other strip had operated for approximately 2.7 years at circa 3.5 amperes for a total of 7.1 ampere-years. Theoretical consumption rate for steel is 20 lb/ampere-year, so projecting the high-silicon iron data would reduce this value to 12 lb/ampere-year.

Even based on incomplete weight loss information, an estimate of the steel consumption rate can be made. Their estimated original combined weight, based on their given dimensions, was 1640 lb. The two strips had discharged a total of 20.1 ampere-years of current. At 12 lb/ampere-year, they would be expected to lose, collectively, 241 lb of weight, which would indicate a 15% loss. Visual observation of these strips was somewhat cursory, but the loss was estimated as half that amount, or 6 lb/ampere-year.

Platinum-Coated Anodes

During the laboratory testing phase of this project (see Chapter 3), cathodic protection was impressed upon steel embedded in concrete by use of platinum coated wire anodes. The wire used consisted of a steel core coated with platinum, and had a diameter of 0.0307 inches. One such

anode has provided over 2.5 years of continuous service, totalling 0.015 ampere-years at a current density of 0.7 ampere per square foot of its surface area. In comparison, it can be estimated that 115 equivalent steel wires would have been consumed while providing the same service. A similar concrete specimen was broken after 1.25 years under the same CP levels, and revealed that the platinum surface of the wire was bright and did not exhibit any visible signs of distress.

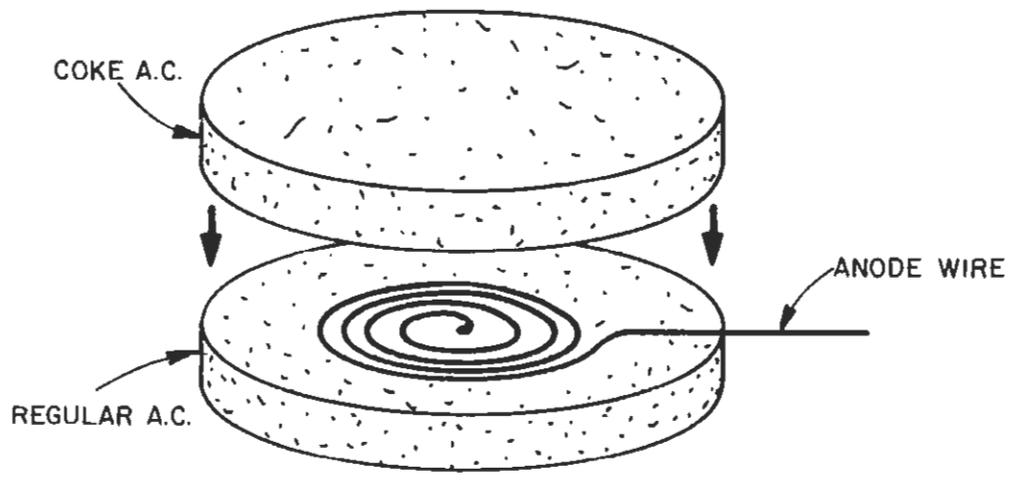
Modern platinum-coated anodes use highly inert metals, such as titanium, niobium, and tantalum as substrates, (30) and are available in wire, clad sheet, and expanded sheet configurations.

Platinum-coated wire anodes, suitably embedded in grooves cut into the concrete surface, are currently being offered in commercial CP applications.

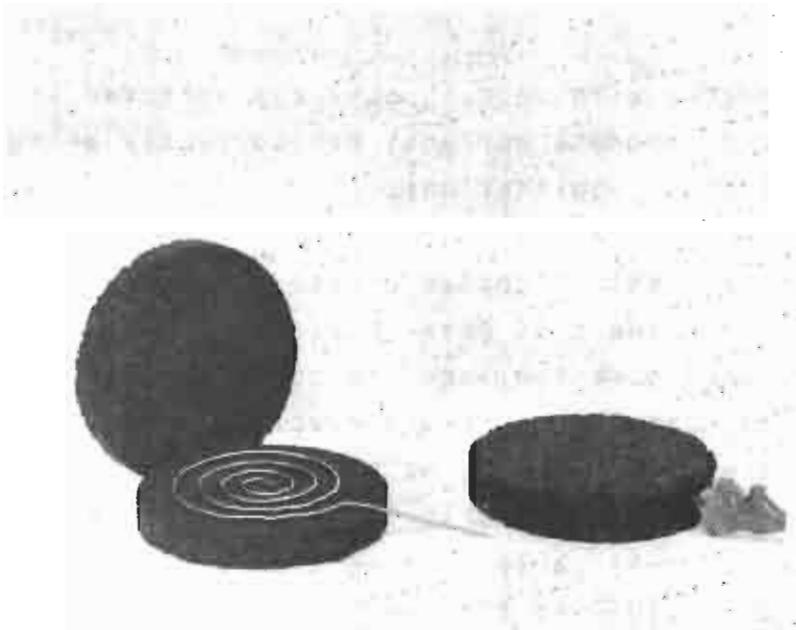
Two types of platinum-coated anodes were designed for use with the CP on the CPCC (see Chapter 4). One was an expanded sheet configuration, and the other consisted of a coiled wire, sandwiched in a conductive medium consisting of coke fines with asphalt as a binder (see Figure 5-4). Both types were successfully installed, but, as reported in Chapter 4, this particular testing program was not carried out, due to failure of the conductive overlay.

Copper Anodes

Copper has a theoretical consumption rate of 46 lbs per ampere-year, and is clearly not suitable as a permanent anode. It is, however, inexpensive and thus suitable for



TYPICAL DETAIL



SANDWICH-TYPE ANODE

Figure 5-4

short-term field studies. In the process of evaluating the electrochemical properties of air-blown mortar, bare 12 gauge copper wire was fastened to a reinforced concrete surface with tape, and covered with an air-blown CPCC mortar overlay. Cathodic protection was applied for approximately one year, at which point the wire was completely consumed directly below a shrinkage crack, and exhibited similar distress throughout its length. It is speculated that, had it been in contact with coke or a similar conductive medium, its life would have been considerably extended.

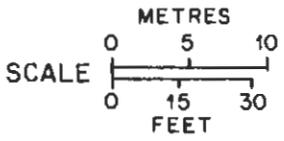
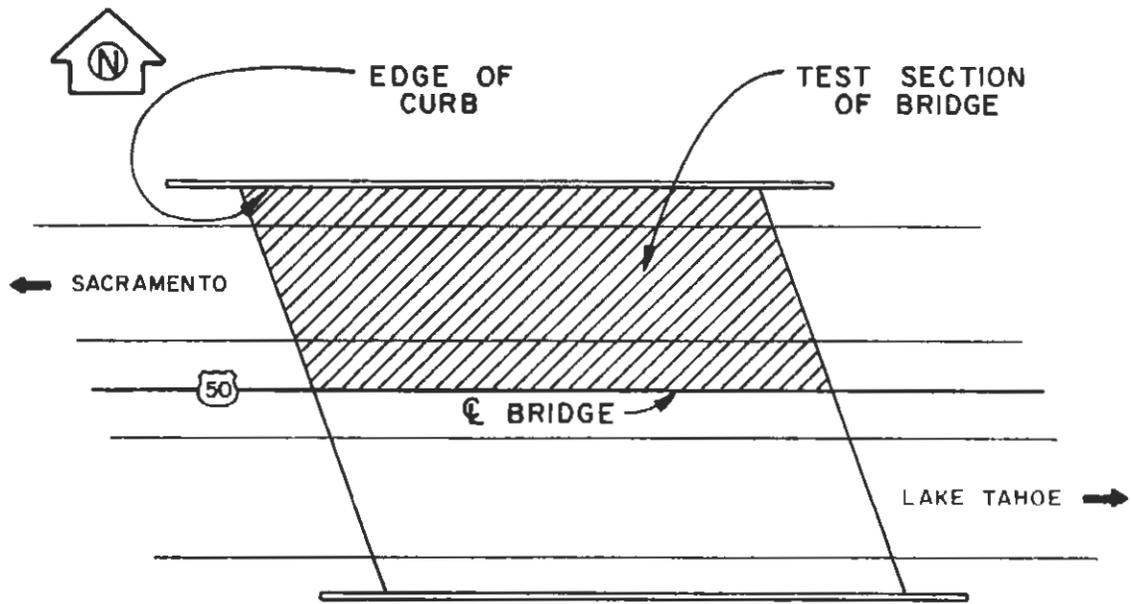
APPENDIX A

HISTORY OF SLY PARK CATHODIC PROTECTION

The Sly Park structure is a continuous three-span reinforced concrete T-beam bridge 86 ft wide and 100 ft long that was completed in 1964. Deck design specified concrete with a cement factor of seven sacks per cu yd and 1-1/2 in. of cover over the top reinforcing steel mat. It is located on U.S. 50 at an elevation of 4,000 ft and carries two lanes each of eastbound and westbound traffic (see Figure A-1). The average annual precipitation at Sly Park is 42 in. (including 18 in. of snow) with an annual temperature range of 15 to 105°F. By 1972, corrosion had caused spalling of the deck concrete, so repair and overlay were scheduled for 1973. An April 1972 deck survey indicated that about 2% of the deck was delaminated, corrosive potentials were measured over 53% of the deck area, and the average concrete chloride content at a depth of 1 to 2 in. was 3.5 lb per cu yd. Fourteen months later, a subsequent deck survey indicated that the delaminated area had increased from 2 to 12% and the area of corrosive potentials from 53 to 72%.

During 1973, the south half (eastbound lanes) of the bridge was repaired by removing deteriorated concrete, patching with epoxy mortar, placing a fabric-coal tar emulsion membrane, and paving with a 3 in. AC overlay.

In June 1973, a cathodic protection system was installed on the north half (westbound lanes) of the structure (25). In general, this consisted of the injection of a styrene or methyl-methacrylate monomer plus catalyst or epoxy to rebond



PLAN VIEW



SLY PARK BRIDGE LOCATION MAP

Figure A-1

the delaminated areas (see Figure A-2), placing of impressed-current anodes, applying a coke AC electrically conductive overlay, and paving with a 3 in. AC overlay.

The conductive overlay was an asphalt concrete consisting of 3/8 in. maximum size coke aggregate, complying with grading requirements of Section 39-2.02 of the 1973 California Standard Specifications and 15% of 85-100 penetration paving asphalt (equivalent to AR-4000). Prior to placing the coke AC, the bridge deck surface was primed with an SS-1 asphalt emulsion tack coat applied at a rate of 0.05 gal per sq yd. The variable (2.5, 3.0 and 3.5 in. uncompacted thicknesses) coke AC layer was overlaid with normal AC to a combined thickness of 5 inches.

High-silicon cast iron anodes, 1.25 in. thick by 10 in. diameter and weighing on the average 29 lbs, were fastened directly to the deck with epoxy. The anodes were placed on 12 ft centers (see Figure A-3) on each of the three lines that delineate the two traffic lanes. Anodes were connected to 3 ohm, 5 watt, wire-wound resistors that allowed control of the amount of direct current flowing to individual anodes. Any combination or pattern of anodes utilizing from 1 to 33 anodes could be used to provide cathodic protection. Anode consumption rate was initially estimated to be approximately 0.5 lb per ampere-year. (The actual consumption rate for one anode that was removed in 1979 after 1.43 ampere-year of operation was calculated to be 0.28 lb per ampere-year.)

Initially, direct current was supplied to the anodes by standard automobile type batteries. After about two months,

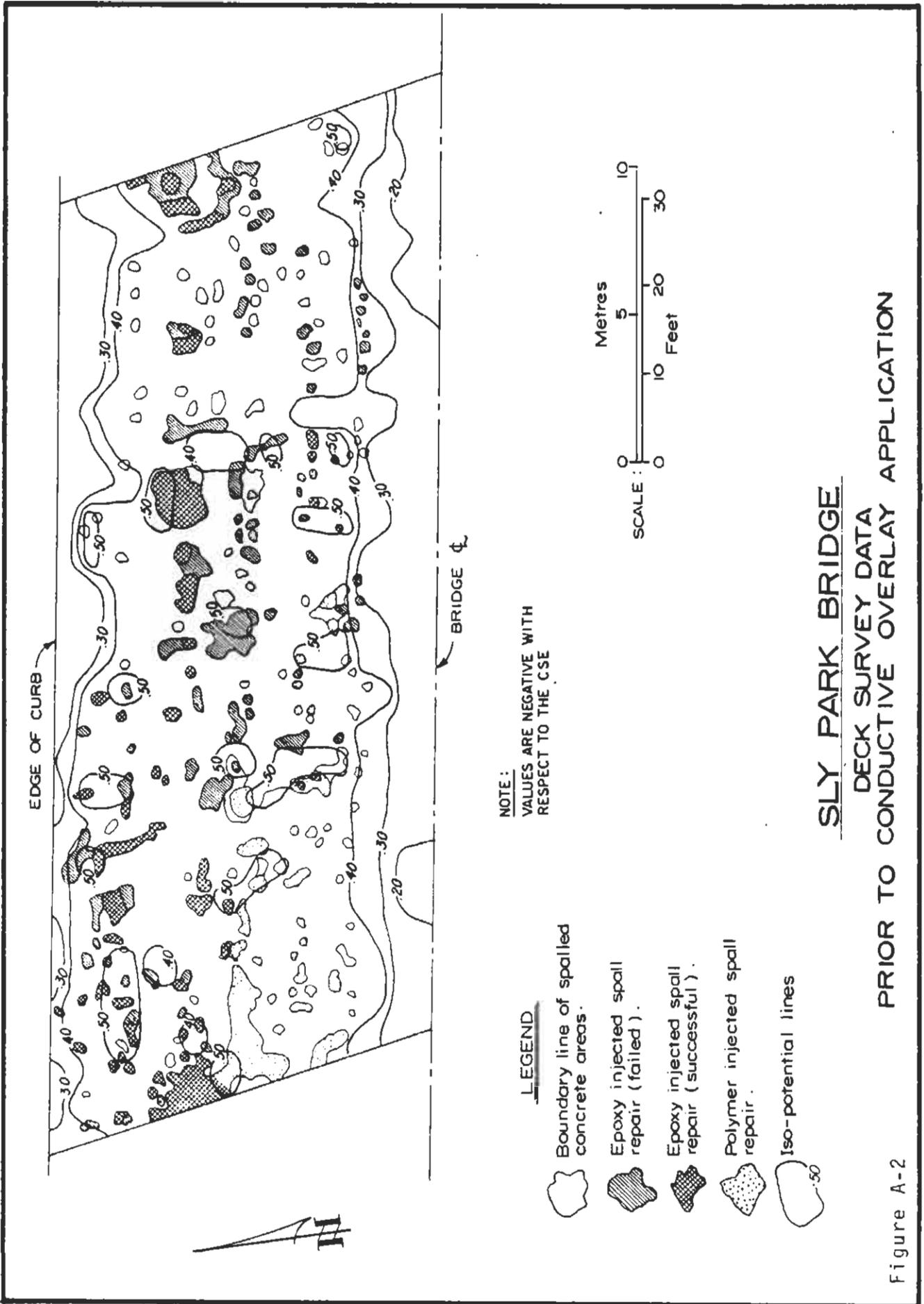
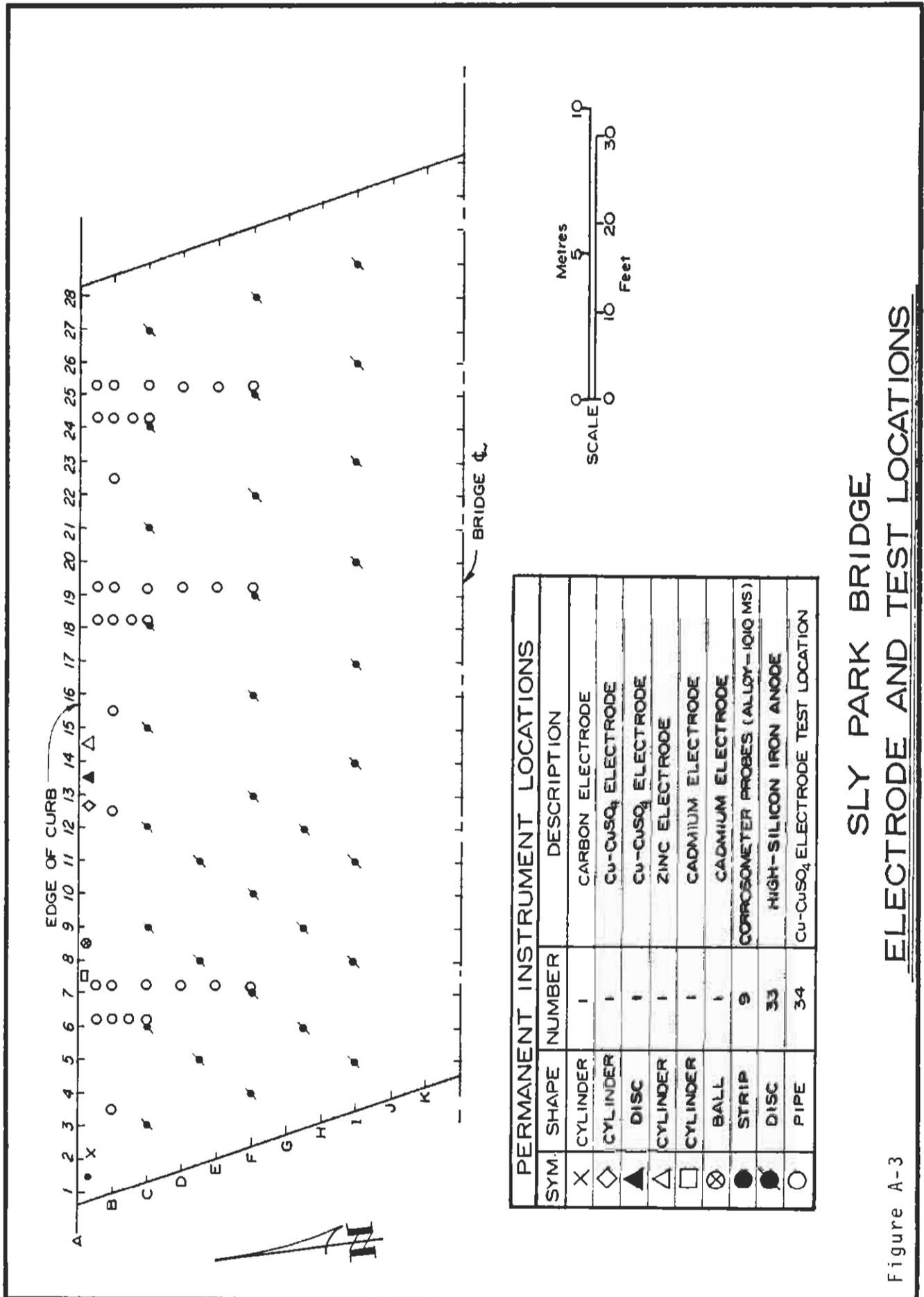


Figure A-2



| PERMANENT INSTRUMENT LOCATIONS | | DESCRIPTION | |
|--------------------------------|----------|-------------|--|
| SYM. | SHAPE | NUMBER | DESCRIPTION |
| X | CYLINDER | 1 | CARBON ELECTRODE |
| ◇ | CYLINDER | 1 | Cu-CuSO ₄ ELECTRODE |
| ▲ | DISC | 1 | Cu-CuSO ₄ ELECTRODE |
| △ | CYLINDER | 1 | ZINC ELECTRODE |
| □ | CYLINDER | 1 | CADMIUM ELECTRODE |
| ⊗ | BALL | 1 | CADMIUM ELECTRODE |
| ● | STRIP | 9 | CORROSION PROBE'S (ALLOY-1010 MS) |
| ● | DISC | 33 | HIGH-SILICON IRON ANODE |
| ○ | PIPE | 34 | Cu-CuSO ₄ ELECTRODE TEST LOCATION |

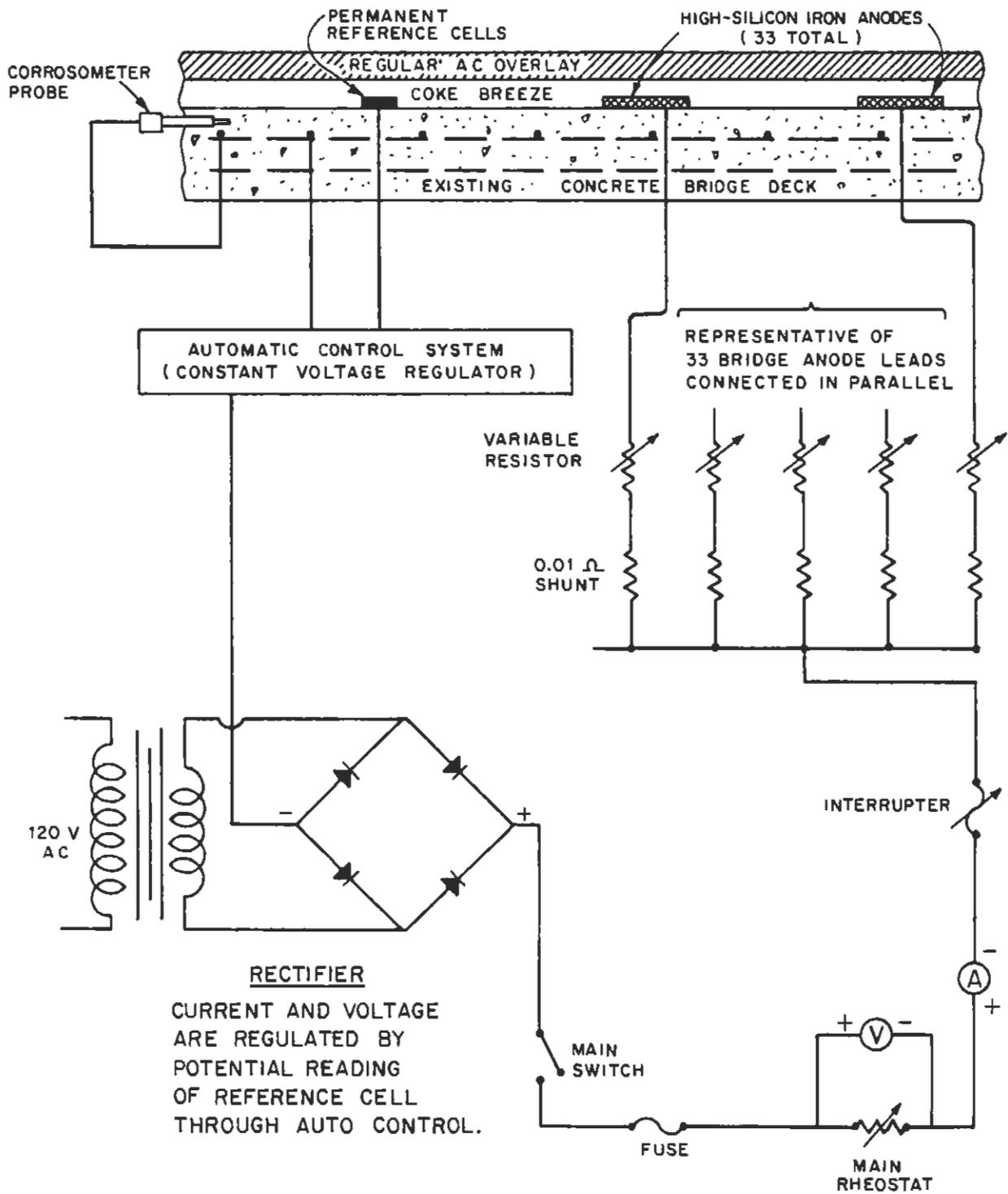
SLY PARK BRIDGE
ELECTRODE AND TEST LOCATIONS

Figure A-3

the battery operation was replaced by a constant-potential rectifier. The rectifier output was controlled either manually or automatically by means of a permanent reference cell installed on the bridge deck. Several additional electrodes, of varying materials and shapes were also installed (see Figure A-3). At present, a constant-current rectifier is being used to provide the desired current to the anodes. Schematic diagrams (Figures A-4 and A-5) of the cathodic protection system illustrate the major changes that have been employed during the first seven years of operation.

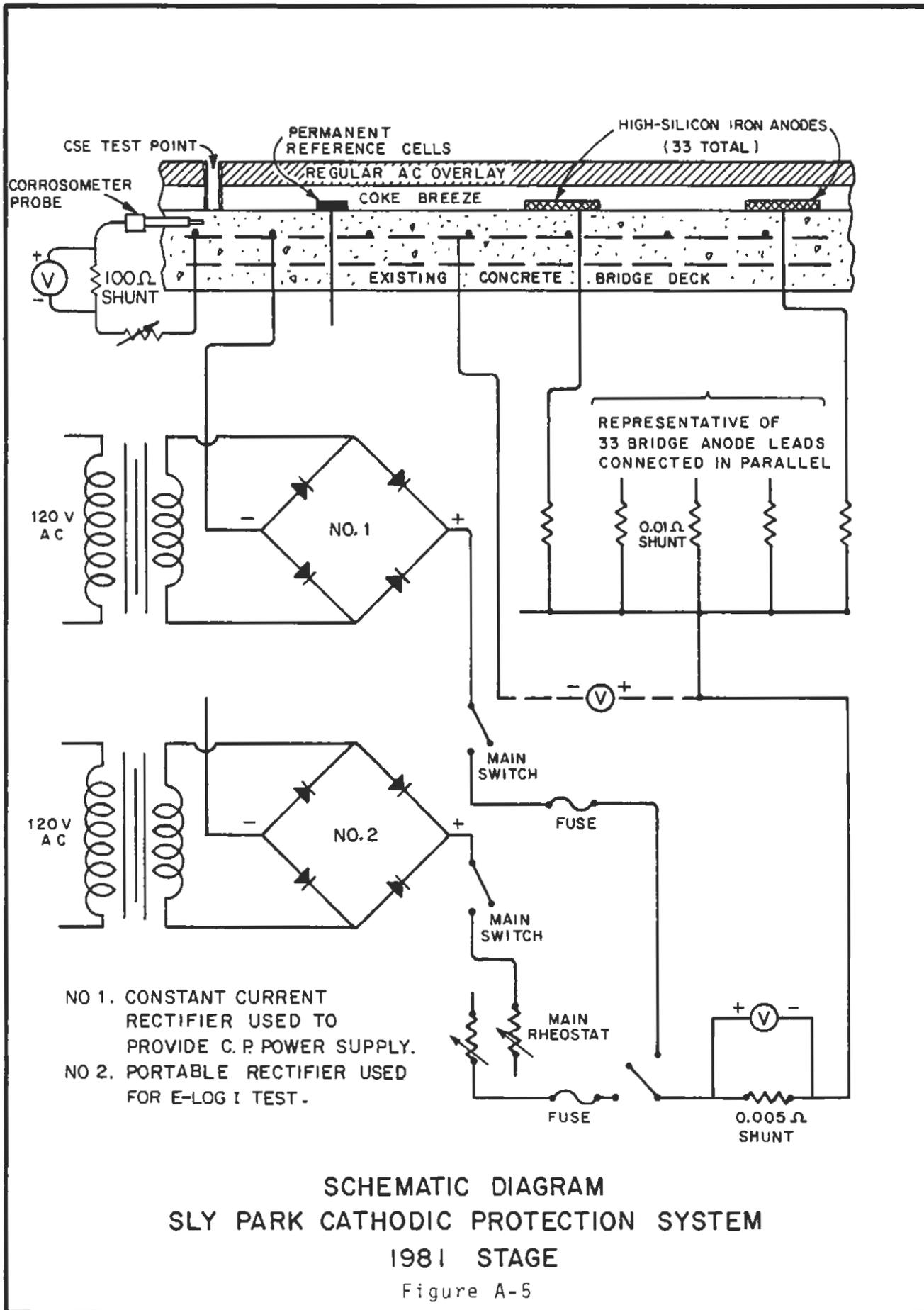
Figures A-6 and A-7 illustrate the polarization of the deck reinforcing steel that took place during the first two years of cathodic protection. It should be noted that these measurements were made with the reference cell placed on the AC surface that had been wetted with a water-wetting agent mixture. (This technique was subsequently found to be inaccurate due to adverse influence of the conductive layer.) The potentials were measured with a digital multimeter and a current interrupter that automatically interrupted the current each minute for a 20 second interval.

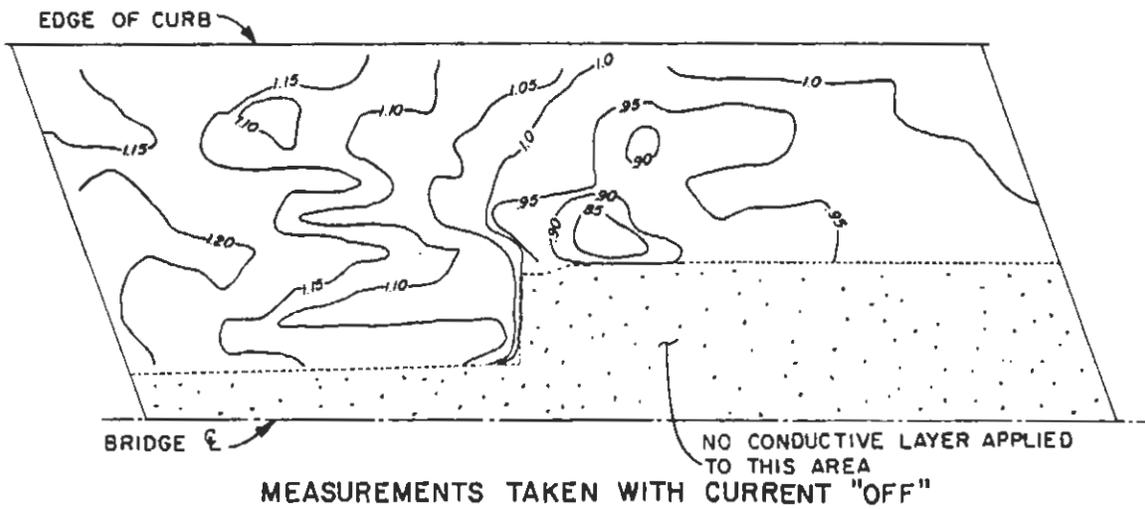
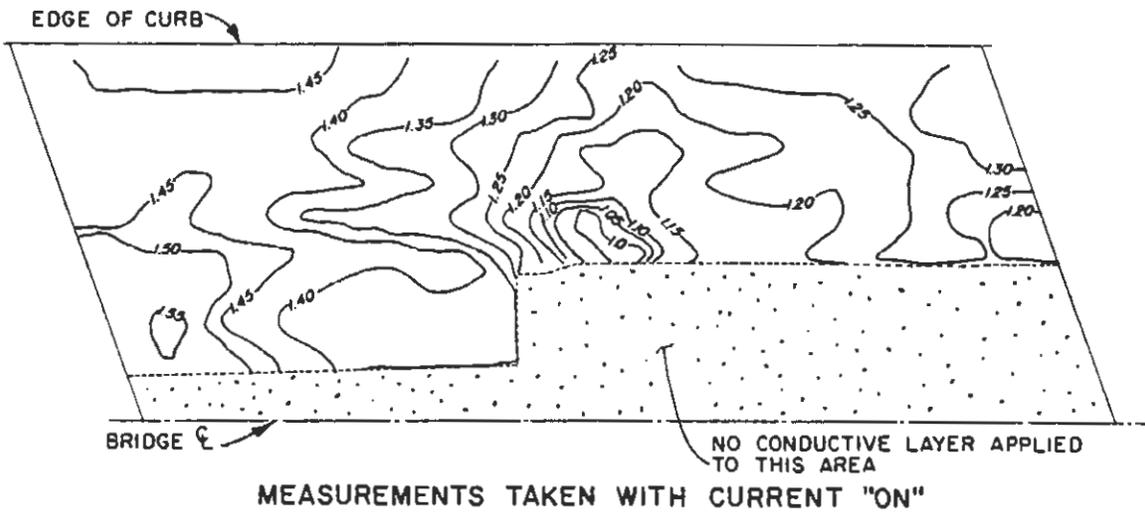
Cathodic protection has been applied to the Sly Park Bridge deck for seven years. The effectiveness of protection has been verified by means of corrosometer (resistance) probes. The probes were installed on the bridge deck encased in concrete that contained 10% Cl^- (as NaCl) by weight of cement. It is assumed that a cathodic protection level that has arrested corrosion of the probes will also arrest corrosion of the embedded reinforcing steel.



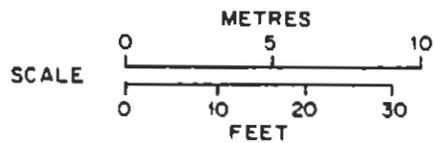
SCHMATIC DIAGRAM
 SLY PARK CATHODIC PROTECTION SYSTEM
 EARLY STAGE

Figure A-4



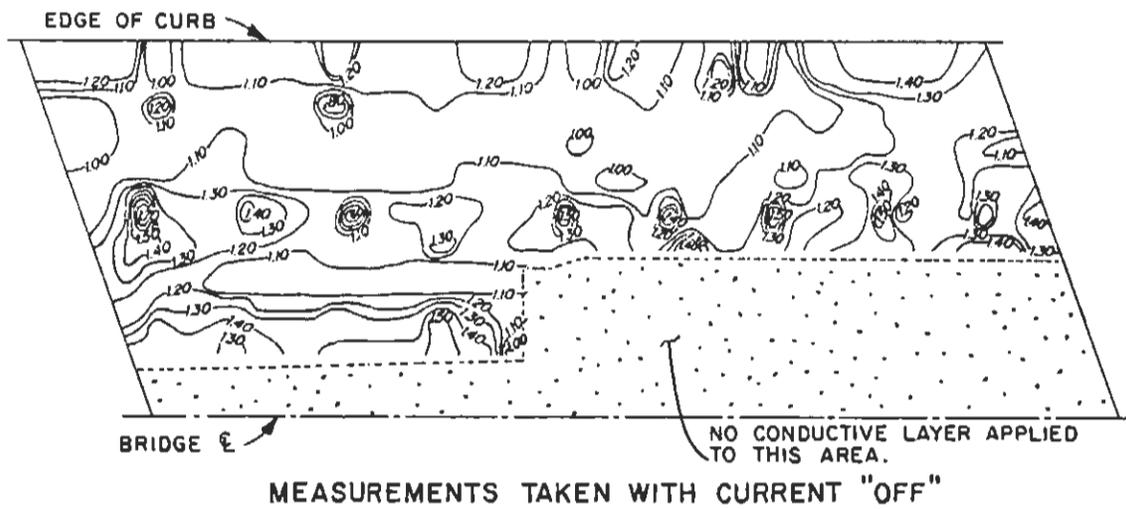
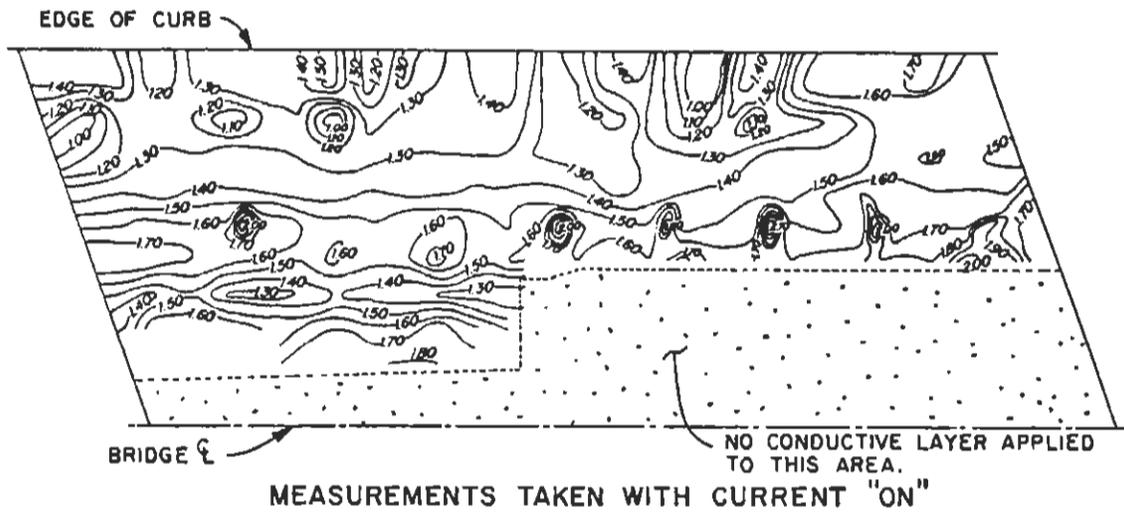


NOTE:
VALUES ARE NEGATIVE WITH
RESPECT TO THE CSE

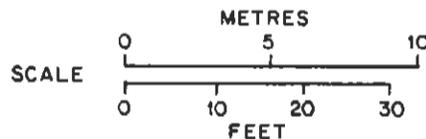


SLY PARK BRIDGE
CSE ISO-POTENTIAL LINES
JULY 1973

Figure A-6



NOTE:
VALUES ARE NEGATIVE WITH
RESPECT TO THE CSE



SLY PARK BRIDGE
CSE ISO-POTENTIAL LINES
MAY 1975

Figure A-7

During November 1976, approximately 35% of the soffit area of the east half of the bridge was painted with chlorinated rubber curing compound. It was theorized that sealing the soffit surface would reduce moisture loss and increase concrete moisture content. This increase in moisture content would be accompanied by a decrease in concrete resistivity which would be indicated by more negative deck potentials for the east half of the bridge.

Potentials vs CSE taken during the subsequent four month period did show the expected change, but it was difficult to determine whether the major cause was the soffit painting or the winter rains.

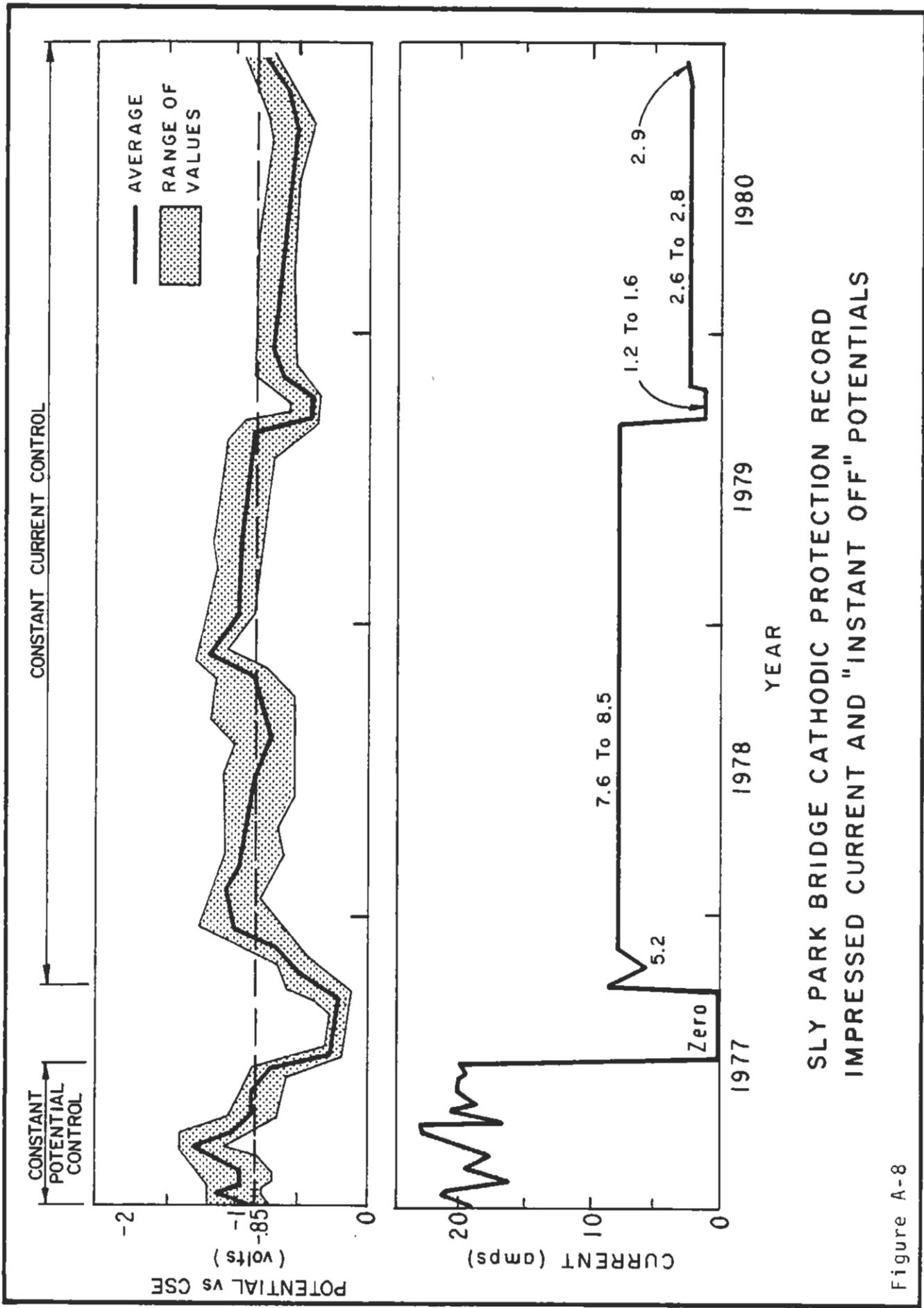
Further indication that the cathodic protection has arrested steel corrosion was provided by an October 1977 inspection of areas of the original deck. Detailed information concerning the inspection is reported by Poppe and Jurach (22), but, in general, the inspection disclosed that:

1. Corrosion continued in the portion of the deck (eastbound lanes) not receiving cathodic protection. Approximately 15% of the inspected area had delaminated since the 1973 deck repair.
2. Little or no new corrosion-related distress was observed in the area under cathodic protection. Delamination noted in this inspection was associated with delaminated areas that were injected with epoxy in 1973. It is theorized that the epoxy (a dielectric) layer prevented the underlying steel from receiving the protective current and, thus, allowed corrosion to continue.

These findings are essentially the same as those determined from the inspection of Ontario's Duffin Creek Bridge in 1977 (8).

At present, cathodic protection is maintained at Sly Park Bridge with impressed voltages between 1.6 and 1.8 volts and a constant current of 2.7 ± 0.2 amperes. This current is equivalent to 0.0008 ampere per square foot of deck or approximately 0.0016 ampere per square foot of reinforcing steel area in the top mat.

A record of the impressed-current CP at Sly Park for the last four years is presented in Figure A-8.



SLY PARK BRIDGE CATHODIC PROTECTION RECORD
 IMPRESSED CURRENT AND "INSTANT OFF" POTENTIALS

Figure A-8

APPENDIX B

HISTORY OF THREE TEST SLABS

In connection with a previous project concerned with bridge deck corrosion, three identical full-scale reinforced concrete slabs were cast on March 19, 1971. The mature concrete was contaminated by ponding saline water on the slab surfaces. Conditions within the slabs were monitored by means of potential and resistivity measurements, corrosion meter (resistance) probes, and chloride analysis of concrete samples. The testing program was terminated when corrosion-caused distress allowed ponded water to escape under the confining surface berms. During the entire testing period, each slab was protected by a waterproof cover.

The three 6 ft by 7 ft by 5-5/8 in. reinforced concrete slabs were cast, cured, and placed on beam supports. Design of the slabs was governed by the requirements for a 6 ft effective span as listed on Sheet 4-1 (June 1969) of the California Department of Transportation Bridge Planning and Design Manual. Reinforcing consists of transverse #5 bars on 11 in. centers, longitudinal #4 bars on 18 in. centers, and transverse #5 truss bars on 11 in. centers. The lower mat of reinforcing steel is the same as the top mat, but it is spaced slightly off-center as is normal in bridge construction practice.

One electrically isolated reinforcing bar is located in the top mat. In addition, each slab contains 24 isolated electrodes, 0.25 inch diameter by 3 inches long. Six electrodes are located at each of the cover depths of 1, 2, 3, and 4 in. Two electrodes were mounted in a plastic pipe

mount which was force-fit into a 1/2 in. deep hole in the bottom form. Figure B-2 shows one electrode mount attached to the bottom form and a second mount laid on the steel to show the details.

The concrete aggregate was 3/4 in. maximum size with gradation in compliance with the 1970 California Standard Specifications. Design cement factor was six sacks of cement per cubic yard and the concrete was vibrated into place with normal vibration techniques. Kelly ball penetration of the fresh concrete was 1-1/4 in. while the slump was 2-1/2 in.

After the slabs were cast, they were cured by the water method for 28 days. This was followed by a drying period of approximately six months. Wood and plastic berms to hold ponded water were installed on each slab. Then a solution composed of 8.6 lbs of sodium chloride and 12 gallons of water was poured onto each slab surface. No further additions of salt were made, but periodically water was applied. To prevent any loss of salt due to overflow during rainy weather, the slabs were protected by waterproof covers.

Water that was ponded on the slab surfaces either evaporated or was absorbed by the concrete. After the slab surfaces became dry, they were again flooded with water as cycling continued. In general, the slabs would be flooded for about one week and allowed to dry for about two weeks. Potential measurements between the steel and a CSE were made prior to the addition of salt and the initial application of water. Potentials indicating active corrosion were detected about ten days after ponding began.

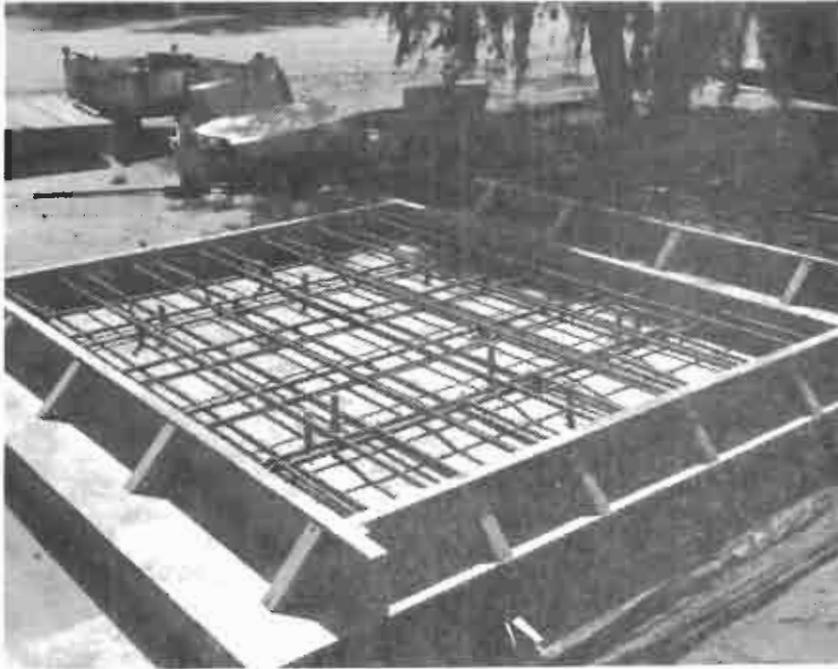


Figure B-1. Simulated Bridge Decks Prior to Concrete Placement.

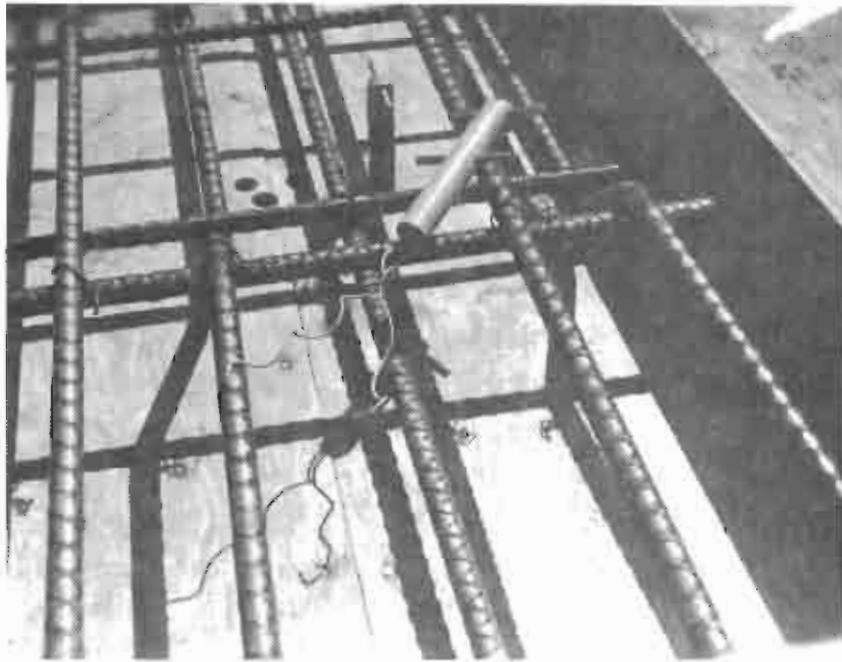


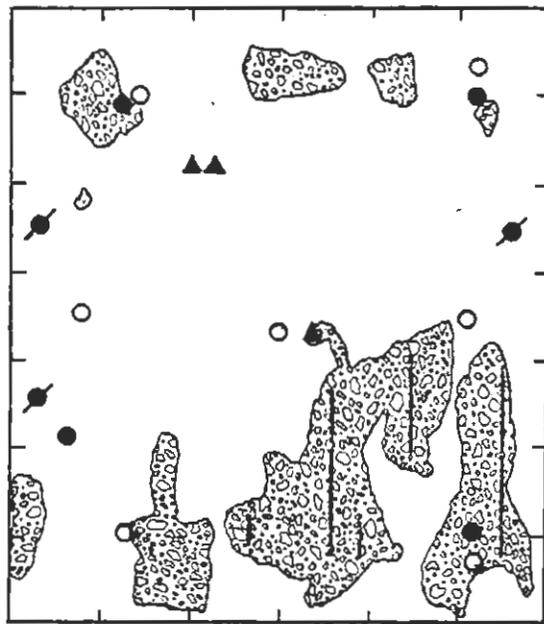
Figure B-2. Close-up of Reinforcing and Electrode (Removed From Position for Better View).

Ponding was discontinued after approximately 2.5 years when concrete cracking became significant enough to allow the water to leak under the berms and down the slab ends. Shortly before leakage occurred, some delamination was detected by chaining. Chloride contents were determined for each slab with the average values for the three slabs as follows:

| Depth | 0-1" | 1"-2" | 2"-3" | 3"-4" | 4"-5" |
|--|------|-------|-------|-------|-------|
| CL ⁻ Content-lb/yd ³ | 9 | 6 | 4 | 2 | 1 |

Figure B-3 shows the extent of the unsound and delaminated concrete that was removed from each slab. Concrete removed from these areas was replaced with "Set 45" brand magnesium phosphate concrete. Before the conductive overlays were placed on Slabs A and B, additional instrumentation was installed in each slab. This included permanent locations for measuring potential, current probes, corrosometer probes and temperature sensors.

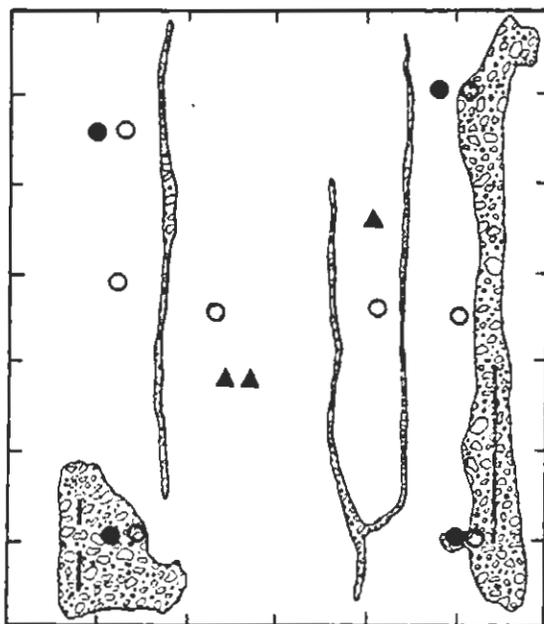
These test slabs were used in the evaluation of coke aggregate portland cement concrete. Other than having a relatively low moisture content (due to being under a protective cover for approximately nine years), and not having been subjected to traffic, the slabs were quite similar to bridge decks that have been heavily treated with deicing salts or solutions. All three slabs were repaired by standard maintenance procedures and two had experimental anodes and a conductive overlay applied to the top surface. At present, the slabs are being monitored and will subsequently be used in further study of bridge deck repair and protection methods and materials.



SLAB A



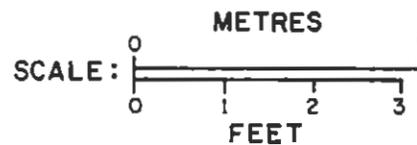
SLAB B



SLAB C

LEGEND

- SHORT ISOLATED BARS
- CORROSOMETER PROBES
- ▲ TEMPERATURE SENSORS
- ⦿ IMPRESSED CURRENT ANODES
-  DELAMINATED CONCRETE SHOWING EXPOSED RE-INFORCING STEEL



PLAN OF THREE TEST SLABS
INSTRUMENT LOCATIONS AND DISTRESSED AREAS

Figure B-3

APPENDIX C

INSTRUMENTS AND EQUIPMENT USED ON SLY PARK AND
LABORATORY STUDIES

| <u>Description</u> | <u>Month/Year In Use</u> |
|---|---|
| <u>A. Power Sources:</u> | |
| Automobile Battery | 6/73 to 9/73 |
| "CATHGARD" Auto-Constant Voltage Control Rectifier-24 volt/12 amp | 10/73 to 4/76, 6/77 to 11/77 |
| Portable "Harco" #3-9 Regular Full-Wave Rectifier-24 volt/20 amp | 4/76 to 6/77 |
| "Goodall" Constant Current Control Rectifier-8 volt/8 amp | 11/77 to Present |
| Diversifield Chemical Corp. Type "T" Field Test Rectifier PVTWSA 48 Volt/22 Amp | 11/76 to 8/77 (Used For Periodic E-Log I Test Only) |
| Diversifield Chemical Corp. Type "T" Field Test Rectifier PVTWSA 24 Volt/44 Amp | 11/76 to 8/77 (Used For Periodic E-Log I Test Only) |
| <u>B. Potential Measurements:</u> | |
| Interrupter: Cathodic Protection Service, Houston. BETA Model #1 | 6/73 to 9/73 |
| Current Interrupter, Farwest C1-50-50 Amp | 10/73 to 10/76 |
| Dynamic Voltmeter #252 | 4/73 to 7/73 |
| Hewlett-Packard Null Voltmeter #419 | 4/73 to 1/74 |
| Fluke Digital Multimeter Model 8000 | 1/74 to 10/79 |
| Hewlett-Packard Oscilloscope Model 120B | 4/74 to 3/77 |
| Tektronix Model 213 Oscilloscope w/Digital Multimeter | 3/77 to Present |
| Hewlett-Packard Digital Multimeter 3465B | 5/78 to Present |
| Hewlett-Packard Digital Multimeter 3466A w/True RMS Function | 10/79 to Present |

- C. Resistance and/or Resistivity Measurements:
- | | |
|--|-----------------|
| James R-Meter Model C-4952 | 4/73 to Present |
| James G. Biddle "Megger" Ground Tester | 4/73 to 3/77 |
| Nilsson Soil Resistance Meter Model 400 | 3/77 to Present |
- D. Current Measurements:
- | | |
|---|-----------------|
| Sensitive Research D.C. Milliammeter Model "S" | 4/73 to 3/77 |
| Sensitive Research Zero-Ammeter Model ZR | 4/73 to 3/77 |
| Keithley Picoammeter Model 480-1788 | 6/79 to Present |
- E. Supplementary Measurements:
- | | |
|---|-----------------|
| Crest Instrument Co. Corrosometer Model CK | 6/73 to 6/77 |
| Rohrback Instruments Corrosometer Model CK-3 | 6/77 to Present |
| Magma Corp. Corrosometer Probe Alloy No. 8001 w/Element Form W40 | 6/73 to Present |
| Texas Instrument Multipoint Recorder FMWSE6C | 11/73 to 5/75 |

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