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Measuring the Corrosion Rate of Reinforcing Steel Concrete - Final Report

E. Escalante, E. Whitenton, F. Qiu

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Metallurgy Division
Gaithersburg, MD 20899

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

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Measuring the Rate of Corrosion of Reinforcing Steel in Concrete
Final Report

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ABSTRACT

This report describes a three phase study directed at developing a portable system for measuring the corrosion of steel in concrete bridge decks. A small, portable computer system is used to control the measurement of polarization resistance of steel in concrete, and using current interruption, iR error is eliminated. During the first two phases, the system hardware and software were constructed, then measurements were made on small steel specimens in concrete cylinders in a laboratory controlled environment. The results of the weight losses calculated from the electrochemical measurement are compared to gravimetrically determined weight losses. In the third phase, the same portable system was used to measure the corrosion of three bridge decks in Frederick County MD, over a four month period. The results of these field measurements and the problems encountered are discussed.

INTRODUCTION

It is now well recognized that steel in concrete will corrode under certain conditions (1-3), and many studies have been directed at identifying the factors that influence this deterioration (4-8). An early review of the literature revealed a dearth of information in this area (9). A means of measuring the corrosion rate of steel in concrete would be extremely useful for many applications, and several laboratories, including the National Bureau of Standards (NBS), have devoted time to developing some understanding of how this measurement can be made in a nondestructive manner (10-12).

The ability to measure the corrosion rate of steel in concrete is useful for several reasons. First, a better understanding of the corrosion processes in concrete could be developed by making controlled changes in the concrete (oxygen, chloride, pH, moisture) and observing the effects on corrosion rate. Secondly, the performance of corrosion control systems could be monitored as a function of time, and thus, the effectiveness of overlays, reinforcing steel coatings, corrosion inhibitors, and cathodic protection could be measured and evaluated.

Recent advances in computer technology have led to commercially available, portable, battery operated computers and accessories that give us the capability of extending laboratory techniques to field measurements. The object of this study is to take a step in this direction.

BACKGROUND

In 1978, an effort was initiated at NBS to develop an understanding of the conditions and processes that control or effect the corrosion of steel in concrete. As a result, three reports have been issued (9,13,14). The first report was a literature survey covering the period from 1964 to 1978 in which 394 references were cited (9). Examination of this literature revealed that much of the effort had been concentrated in learning about the role of the chloride ion and the concrete mixture design on the corrosion process. Only one reference considered the effect of oxygen, and none were found on the corrosion of steel in an alkaline environment. On the basis of these findings, a study seeking to learn more about the interaction of oxygen, pH, and chloride was started. In addition, preliminary efforts were directed at developing a nondestructive, electrochemical technique for measuring the corrosion of steel in concrete. The results of this initial study are described in the second report (13). The third report considered the problem of current distribution during the polarization process, and included our first attempt at controlling the measurement with a microprocessor system (14).

This report describes our most recent effort at applying a useful laboratory technique to a field situation, and can be broken down into three major phases as follows:

1) Design and assembly of the microcomputer-controlled corrosion measuring system,

2) Testing of the microcomputer-controlled device under laboratory controlled conditions, and

3) Testing the microcomputer-controlled device in the field.

The general format of this report will be developed around these topics.

APPROACH

Judging from our early studies, it became apparent that there were two major obstacles to measuring the corrosion rate of steel in concrete, namely: (a) determining the area of the steel being polarized during the measurement, and (b) compensating for iR error, an error arising when potential measurements are made in the presence of an electric current in a resistive medium. Knowledge about current distribution during a measurement on a bridge deck is important for the simple reason that only a very small area of the steel in the bridge deck is polarized at a time, and this area must be known so that a corrosion rate may be calculated. Anticipating this problem earlier in the project, a study was initiated as previously described (14). This study indicated that current distribution in concrete is very limited and is concentrated to the immediate vicinity of the source of current, the counter electrode (CE). Thus, by knowing the location and size of the steel in the region of the CE of a given size, the area of the steel rebar being polarized can be determined. Elimination of iR error was accomplished through the use of a current interrupt technique whereby the potential of the steel is measured while current is zero (15,16).

Preliminary studies using manually controlled equipment indicated that the corrosion of steel in concrete, also referred to as the working electrode (WE), can be measured by polarization techniques (13,14). However, the procedure is very slow and tedious, and not at all suited for field measurements. Furthermore, iR compensation is always difficult and, at times, questionable with these manually controlled methods. The use of portable computer equipment opens new avenues to the application of laboratory methods to field measurements especially where a resistive medium may be encountered. The remainder of this report is a description of the operation of such a computer-controlled system and the results obtained in the laboratory and in the field.

System Description

The computer controlled device operates by modulating the current applied to the electrodes so as to maintain a potential (E) difference between the WE and the reference electrode (REF), Ew - Er, which is 10 mV less than the same potential difference at open circuit (o.c.):

$$(Ew - Er) - (Ew - Er)o.c. = -10 \text{ mV} = \Delta E$$

The reading, however, is taken during a brief period while the current is interrupted, so that the potential due to the iR drop is absent, but soon enough after the interruption of the current that the potential due to polarization of the WE has not yet decayed significantly. The entire process occurs as follows. Initially, during the "setting" portion of the measurement, the current is gradually increased or decreased depending on whether ΔE is smaller or larger than -10 mV. Once the desired value of ΔE is reached, it is maintained for 3.5 min, during the "holding" portion of the measurement. The duty cycle is 2.2 s with the current on and 0.4 s with the current off. The sampling of the voltage occurs approximately 75 ms after current interruption. The error in the voltage reading introduced by its decay during 75 ms is of the order of 5% if the decay constant of the electrode potential (assuming an RC parallel circuit) were of the order of 1 s. This, for instance, could be given by a polarization of 10^5 ohm cm^2 and a capacitance of 10 uF/cm^2. This is a conservative approximation of error since transport processes in concrete are likely to be very slow, and the decay constants observed experimentally are much longer than 1 s.

Figure 1 is a schematic diagram showing the relationship of the three electrodes, the current control switches, and the power supply. The details of the operation of the computer controlled system are as follows. First, the three potentials V1, V2, and V3 are measured in the open circuit condition. A voltage, V, equal and opposite to V1 is then applied by the power supply. Switch, S1, in series with a 4.7 k ohms resistor, closes and the applied current, I2, through the circuit is determined by measuring V2 across a 100 ohm resistor (I2 = V2/100). The power supply voltage, V, is then adjusted to make I2 equal to zero so that applied current at the start of the measurement is zero. This current zeroing process is repeated more accurately when the second switch, S2, is closed. The entire current zeroing procedure occurs in less than 10 s and prepares the system for the polarization measurement.

There are two stages to the measurement as described earlier, the initial "setting" stage when the WE is polarized to -10 mV and the "holding" stage when the WE is maintained at -10 mV while the data are collected. During the "setting" period, the power supply voltage, V, is increased in small increments (28 mV during the first 5 mV of ΔE and 1.4 mV as it approaches ΔE) until ΔE = -10 mV as measured at V3. This "setting" period can vary in length from a few seconds to a maximum of 5 minutes, depending on the amount of current necessary to polarize the WE. If the WE cannot reach a ΔE of -10 mV within 5 minutes, then the system is programmed to accept the ΔE reached at the end of the 5 minute period, a rare occurrence. Once ΔE = -10 mV or the 5 minute maximum is reached, the system goes into the "holding" stage where ΔE is held constant and the WE potential, V3, is measured during every "current off" cycle and the applied current, I2, is determined during the "current on "cycle.

All data taken during the "holding" period are stored on the cassette mass memory, and each file is identified by name, date, and time. Table 1 is a typical printer listing from the computer memory displaying, on the first four groups of data, the potential between the WE and the CE, V1, the applied current, I2, the potential between the WE and the REF, V3, and elapsed time, in seconds, after each set of measurements during a run. The fifth and sixth groups of data are the minimum, maximum, average, standard deviation, and number of readings for the WE potential, V3, and the polarizing current, I2, respectively. The polarization resistance is then calculated from these data and listed as shown.

The voltage and current signals were independently monitored with a digital oscilloscope during a measurement period giving us a visual record of the progress of the measurement sequence. This record can be saved in the memory of the oscilloscope for later analysis. Furthermore, the recorded trace can be expanded in the X or Y axis for close examination of any portion of the trace. The following figures, generated using this capability, illustrate some of the details of the measurement. Figures 2 and 3 are magnified portions of the measurement sequence shown in its entirety in Figure 4. Figure 2a is a recording of the potential of a steel rod in concrete during the on-off cycling of the current. The schematic representation of the recording in Figure 2b identifies the significant portions of the trace. The corresponding trace for current is shown in Figure 3a illustrating the "current on" and "current off" characteristics as a function of time. The idealized trace of the current is shown in Figure 3b. A typical trace of an entire polarization measurement, from which 2a and 3a were taken, is shown in Figure 4a, and illustrates the two important regions of the measurement, the "setting" and the "holding" portions. Figure 4b identifies the regions of this trace.

To evaluate the computer system's ability to eliminate iR error, a circuit simulating the WE, CE, and REF in a concrete environment, was constructed as illustrated in Figure 5. The resistive R component (not shown) in iR was added in series with the WE. Using known values of resistance for R in the range from from 1 to 5000 ohms, it was determined that 95% of the iR error is eliminated throughout the resistance range as shown in Figure 6. The straight line represents 100% elimination of iR and the six data points are the values eliminated by the computer system and almost lay on the plot of ideal correction for R.

The calculation of polarization resistance, corrosion rate, and weight loss are described in Appendix A. The computer system hardware and a listing of the program that controlled the measurement are shown in Appendix B. Except for the custom digital to analog converter board (Custom D/A Board), all hardware is commercially available. The program is fully documented with remark statements identifying the major routines and subsets of these routines.

LABORATORY MEASUREMENTS

Procedure - Laboratory

Cleaned and weighed steel rods 1.3 cm (0.5 in) in diameter and 15.2 cm (6 in) long encased in small cylindrical concrete cylinders 5 cm (2 in) in diameter and 15.2 cm (6 in) long as shown in Figure 7 were used for laboratory measurements. Two concrete mixes were used: one chloride free and one with chloride added as described in Table 2. After casting in molds, the concrete was mechanically vibrated to remove large air bubbles. Approximately 24 h later, the specimens were removed from the molds, and the protruding steel rod and the top surface of the concrete were coated with a primer and a rubber based coating. This was followed by immersing the specimens in either a simulated pore solution (0.6 M KOH, 0.2 M NaOH, and 0.001 M $Ca(OH)_2$), a sodium chloride saturated pore solution or a pure sodium chloride saturated solution (17). The surface area of steel imbedded in the concrete was approximately 62 cm^2 (9.6 in^2).

In an effort to stimulate oxygen diffusion and, thereby, accelerate the corrosion process, some of the specimens were immersed in their respective solution for only two hours per day and allowed to air dry the remaining 22 h. The rest of the specimens were kept continuously immersed to reduce oxygen diffusion. The specimens and conditions of immersion are shown in Table 3. The solutions were contained in 2 liter stainless steel containers which also served as counter electrodes for the laboratory polarization measurements. Saturated calomel electrodes were used as reference. The period of exposure for these specimens was approximately 115 to 148 days, and measurements were made on each specimen once a day, 5 days per week.

At the end of the exposure period, the cylindrical specimens were removed from their environment and the imbedded steel rods immediately extracted from the concrete by breaking up the concrete cylinders. The rods were then cleaned in Clark's solution prior to weighing for determination of weight loss as described in ASTM Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens (G1-81).

Results and Discussion - Laboratory

As an example of the results obtained on a day to day basis, the calculated corrosion rates of three specimens (#1, #3, and #7) are plotted as a function of time and illustrated in Figure 8. Specimen #1 was not expected to corrode since it was exposed to chloride-free conditions, however, some corrosion was expected on specimen #3 since it was cast in chloride-free concrete, but immersed into a solution containing chloride. Specimen #7 was exposed to the highest concentration of chloride with chloride in the concrete mix and in the immersion solution. Hence, specimen #7, was expected to undergo the most severe corrosion of the three illustrated. All three were maintained in conditions of alternate immersion to increase oxygen availability.

There were extensive fluctuations in the corrosion rate during the first few days, but after this initial period, the conditions stabilized. These data indicate that specimen #7 did exhibit the highest corrosion attack, and specimen #1 the least corrosion attack. Furthermore, the data also show that the corrosion rate of specimen #3 was between #1 and #7, as expected.

A test of these results was made by gravimetrically measuring the weight loss of steel for each rod as previously described and comparing this actual weight loss with the weight loss calculated from the electrochemical data. This comparison is shown in Table 4 where the twelve specimens are ranked by order of increasing gravimetric weight loss. Also listed is the corresponding average of the polarization resistance and the calculated weight loss during the period of exposure. Indeed, these data show that specimen #7 did experience the most weight loss, specimen #1 the least weight loss, and specimen #3 a weight loss in between specimens #1 and #7, as predicted by the electrochemical measurements. This listing shows an agreement between the gravimetrically determined weight loss and the calculated weight loss over the entire range encountered. A more graphic view of this relationship is shown in Figure 9 which displays a plot of gravimetric weight loss versus calculated weight loss. In general, the calculated weight loss data underestimated the actual weight loss.

The anodic and cathodic Tafel slopes were assumed to both equal 150 mV for the calculations of weight loss, and these values were picked on the basis of preliminary Tafel slope measurements made on steel in concrete indicating that both slopes were higher than those normally encountered in solutions. These same measurements further indicated that the anodic Tafel slope is larger than the cathodic slope. It is conceivable that these unusually high Tafel slopes result from the physical characteristics of concrete (voids in a matrix of concrete, sand and stone) where transport and diffusion processes can be expected to be very slow compared to those in solutions.

FIELD MEASUREMENTS

Procedure - Field

Though the problems encountered in the field measurements were completely different to those in the laboratory, in essence, the measurement and approach to obtaining the data were very similar. These similarities include the use of the same equipment programmed as previously described. Furthermore, the current and potential ranges encountered in both cases were of the same order of magnitude. The differences, on the other hand, were mostly mechanical. For example, the configuration of the electrodes in the field was as illustrated in Figure 10 showing the use of a Cu/$CuSO_4$ reference electrode, a lead (Pb) ring for a counter electrode, and the steel reinforcing bar (rebar) in the concrete bridge deck as the working electrode. Note that the CE and the REF are on a wetted absorbent material (towel or sponge) and are supported by a clear plastic holder that facilitates alignment of the electrodes. The wetting agent used on the absorbent material is a solution of 1% liquid detergent in tap water which helped wet the concrete and dispersed the oil film on the surface of the bridge deck. Scrubbing with a wire brush proved useful in some cases where the concrete was heavily encrusted with soil. Another difference was the manner in which the connection was made to the WE. To be assured of good electrical contact to the rebar, a small 15 x 15 cm (6 x 6 in) portion of the concrete over the rebar was removed on each span of the bridge deck. The location of the exposed rebar was chosen to minimize maintenence problems during the several months of the measurements. These rebar contact points were located off the traffic lanes on the centerline separating oncoming traffic. Measurements made on sections of bridge decks early in the program revealed that the grid of rebar in a bridge deck is electrically continuous, and making a contact anywhere on this grid provides electrical contact to the entire grid. Thus, measurements could be made on all lanes of traffic from one rebar contact point. The one difference that generated the most serious problems was the electronic equipment damage resulting from mechanical vibration generated during transportation between the laboratory and the field. Vibration caused breakage of wires resulting in equipment failure at inopportune moments. This destructive effect was reduced by carefully packing the equipment in shock absorbing foam material during transit. Cable and contact continuity had to be checked constantly. Using the dummy cell shown earlier in Figure 5, the equipment and cables were checked before and after every series of measurements.

Three bridges located in Frederick County, MD, were chosen for the study on the basis of age, known history, and condition. Thus, bridge number 10029 was a 54 year old structure with fine cracks scattered over the surface of the deck, but otherwise in good condition. Bridge number 10100, along a major interchange, was 17 years old and appeared to be in excellent condition. The newest bridge, number 10059, was 13 years old and also in good condition, but cracks are beginning to appear along the rebar positions. Deicing salts for snow removal are used on all three bridges.

Three measurents were made on each bridge span every two weeks over a four month period during the summer. The location of each measurement was permanently marked on the bridge deck surface so that the measurements could be repeated at the same location each time.

Results and Discussion - Field

The first 90 days of the four month period were spent in improving the equipment and developing our ability to make the measurements in the field. One problem encountered, not yet mentioned, was that of electrical noise in the measurement, and unfortunately, eliminating this interference was a time consuming process. The noise can be placed in three categories and listed in order of discovery and elimination. First, there was interference from alternating current (a.c.) sources; second, we had interference from our gasoline motor driven a. c. generator used to power the digital oscilloscope monitoring the measurements; and finally, we discovered interference from current generated by the corrosion of the counter electrode. The first problem, a. c. interference, was relatively easy to eliminate through shielding of all cables. However it was several weeks after starting the measurements that the second problem, effects of the generator, were discovered. This interference took the form of direct current (d. c.) coming through the power line and a. c. voltage spikes at random times that caused strange things to happen to the data. After extensive filtering attempts, changes in configuration of the equipment, and much time, it was finally decided that removing the offending generator was the best alternative, and a battery powered oscilloscope was used for monitoring instead. The third problem was the irreproducibility of the WE potential. Investigation revealed that localized corrosion of the steel counter electrode plate on the detergent wetted towel was generating an electric current that affected the potential measurement. By trial and error it was discovered that a lead (Pb) CE reduced the effect to a tolerable level.

After this initial period, measurements were continued, and the resulting data are displayed in Table 5. As this Table reveals, data were collected on three dates, October 8, October 23, and November 6. It was possible to make measurements on bridge number 10029 on only one occasion during this period because of weather constraints. Data for two positions on bridge number 10100 are missing because of problems (e.g. electrical continuity) that developed during those measurements. The results show that the 54-year old bridge, number 10029, on the average exhibited the lowest average corrosion rate (0.5 MDD) of the three bridges. The 17 year old bridge, number 10100, had an average corrosion rate of 1.1 MDD, and the 13 year old bridge, number 10059, exhibited the highest average corrosion rate of 1.9 MDD (Milligrams per square Decimeter per Day).

It is difficult to assess the reliability or accuracy of these data obtained through these preliminary field measurements. We hesitated to carry out a coring examination of the rebar because of the destructive nature of this action and the very limited amount of data collected. However, the results can be compared to the visual appearence of the bridge deck surface in the immediate vicinity of the measurement. On this basis we can make the following observations. Visual examination of the surfaces of the bridge decks revealed the following. The 54-year old bridge, though it has suffered wear and tear through the years, is in surprisingly good condition with small cracks randomly scattered over the surface of the deck. The 17 year old bridge appears to be relatively crack-free with little evidence of wear to the original surface, and is judged to be in good condition. The 12 year old bridge, in general, looks good, but a close examination of the surface reveals cracking of the concrete above and in line with many of the rebar. This crack alignment is not evident on the other two bridges. Thus, the visual appearance of the bridge deck surfaces tends to support the electrochemical data. In spite of this apparent agreement between the electrochemical measurements and the visual appearance of the bridge deck, we are reluctant to place much meaning to the results because of the very limited amount of useful data obtained. Nevertheless, the exercise of making this corrosion measurement in the field was very valuable in providing information on the problems encountered.

SUMMARY

In order to evaluate the effectiveness of bridge deck protection systems and gain a better understanding of corrosion processes in concrete, a fast, reliable, nondestructive means of measuring the corrosion of steel in concrete is needed. In an effort to meet this need, NBS undertook a study of the application of an electrochemical technique to measure the corrosion of steel in concrete. Using a portable computer as a basis for control of the measurment, a procedure was developed that applied the polarization resistance technique and current interruption to the measurement. Through this approach, measurements of corrosion of steel in concrete were carried out in the laboratory indicating that there is a relationshop between the polarizatuon resistance measured and the corrosion observed. This same approach was then applied to the measurement of corrosion of steel rebar in a bridge deck. After overcoming many problems of mechanical breakdown of the equipment and electrical interference, the measurement was successfully carried out on three bridges in Frederick County, MD. This preliminary venture into field measurements indicated that the corrosion measurement can be performed, and furthermore, revealed many of the obstacles that can be expected.

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TABLE 1

Information Printed During Polarization Measurement

Specimen ID
Date
Time

Open Circuit Measurement at t=0 :
- WE Potential, V3
- Current, I2
- WE-CE Potential, V1
- Time

Closed Circuit Measurement after Current Zeroing:
- WE Potential, V3
- Current, I2
- WE-CE Potential, V1
- Time, s

First Measurement During "Holding":
- WE Potential, V3
- Current, I2
- WE-CE Potential, V1
- Time, s

Last Measurement During "Holding":
- WE Potential, V3
- Current, I2
- WE-CE Potential, V1
- Time, s

Summary of WE Potential During "Holding":
- Minimum V3
- Maximum V3
- Average V3
- Standard Deviation V3
- Number of Readings

Summary of Applied Current During "Holding":
- Minimum I2
- Maximum I2
- Average I2
- Standard Deviation I2
- Number of Readings

Polarization Resistance, ohms

$$(V3_{Avg.} - V3\ )_{O.C.} / \ I2_{Avg.}$$

TABLE 2

Composition of Concrete Mixes
(Weight Ratio of Components to Cement)

	Without Chloride	With Chloride
Cement	1	1
Sand	1.7	1.5
Pea Gravel	2.5	2.3
Sodium Chloride	none	0.06
Water	0.5	0.4

TABLE 3

CONDITIONS OF EXPOSURE

SPEC NO	TYPE OF IMMERSION	CONDITION
1	ALTERNATE	Cl FREE CONCRETE Cl FREE PORE SOLUTION
2	CONTINUOUS	Cl FREE CONCRETE Cl FREE PORE SOLUTION
3	ALTERNATE	Cl FREE CONCRETE Cl IN PORE SOLUTION
4	CONTINUOUS	Cl FREE CONCRETE Cl IN PORE SOLUTION
5	CONTINUOUS	Cl IN CONCRETE Cl IN PORE SOLUTION
6	CONTINUOUS	Cl IN CONCRETE Cl IN PORE SOLUTION
7	ALTERNATE	Cl IN CONCRETE Cl IN PORE SOLUTION
8	ALTERNATE	Cl IN CONCRETE Cl IN PORE SOLUTION
9	CONTINUOUS	Cl IN CONCRETE Cl IN DISTILLED WATER
10	CONTINUOUS	Cl IN CONCRETE Cl IN DISTILLED WATER
11	ALTERNATE	Cl IN CONCRETE Cl IN DISTILLED WATER
12	ALTERNATE	Cl IN CONCRETE Cl IN DISTILLED WATER

TABLE 4

WEIGHT LOSS AND POLARIZATION RESISTANCE DATA

(Ba = Bc = 0.15 V)

SPEC NO.	TIME DAYS	AVG Rp OHMS	GRAVIMETRIC WT LOSS g	CALCULATED WT LOSS g	STD DEV SUM g
1	142	38042	0.0011	0.0054	0.00214
2	148	13210	0.0083	0.0235	0.01004
10	115	10307	0.0228	0.0179	0.00231
9	115	3606	0.0345	0.0326	0.00282
11	115	4740	0.0357	0.0253	0.00239
12	109	3091	0.0466	0.0348	0.00325
6	148	1556	0.1700	0.4258	0.10582
3	138	1630	0.1913	0.0970	0.01015
4	148	1919	0.2522	0.1195	0.01293
5	142	895	0.4149	0.3678	0.09256
8	148	362	0.4510	0.3650	0.02841
7	148	231	0.4771	0.5427	0.03947

TABLE 5

CALCULATED CORROSION RATE, MDD
AT SIX POSITIONS ON THREE BRIDGES

DATE	SPAN 1			SPAN 2		
	POSITION			POSITION		
	A1	A3	A4	B1	B3	B4
ROUTE 28 BRIDGE (1931) NUMBER 10029						
OCT 8	-	-	-	-	-	-
OCT 23	0.6	0.3		0.8	0.3	0.6
NOV 6	(BRIDGE UNDER WATER !!)				-	-
Average Corrosion Rate = 0.5						
ROUTE 15 BRIDGE (1968) NUMBER 10100						
OCT 8	0.4	3.2	0.5	1.3	2.6	1.7
OCT 23	0.8	0.5	1.3	1.3	1.0	0.6
NOV 6		0.8	1.0		0.9	0.2
Average Corrosion Rate = 1.1						
ROUTE 80 BRIDGE (1972) NUMBER 10059						
OCT 8	3.6	2.8	2.3			
OCT 23	3.5	1.3	1.2	0.7	0.8	2.1
NOV 6	3.1	2.1	2.6	0.6	1.2	1.0
Average Corrosion Rate = 1.9						

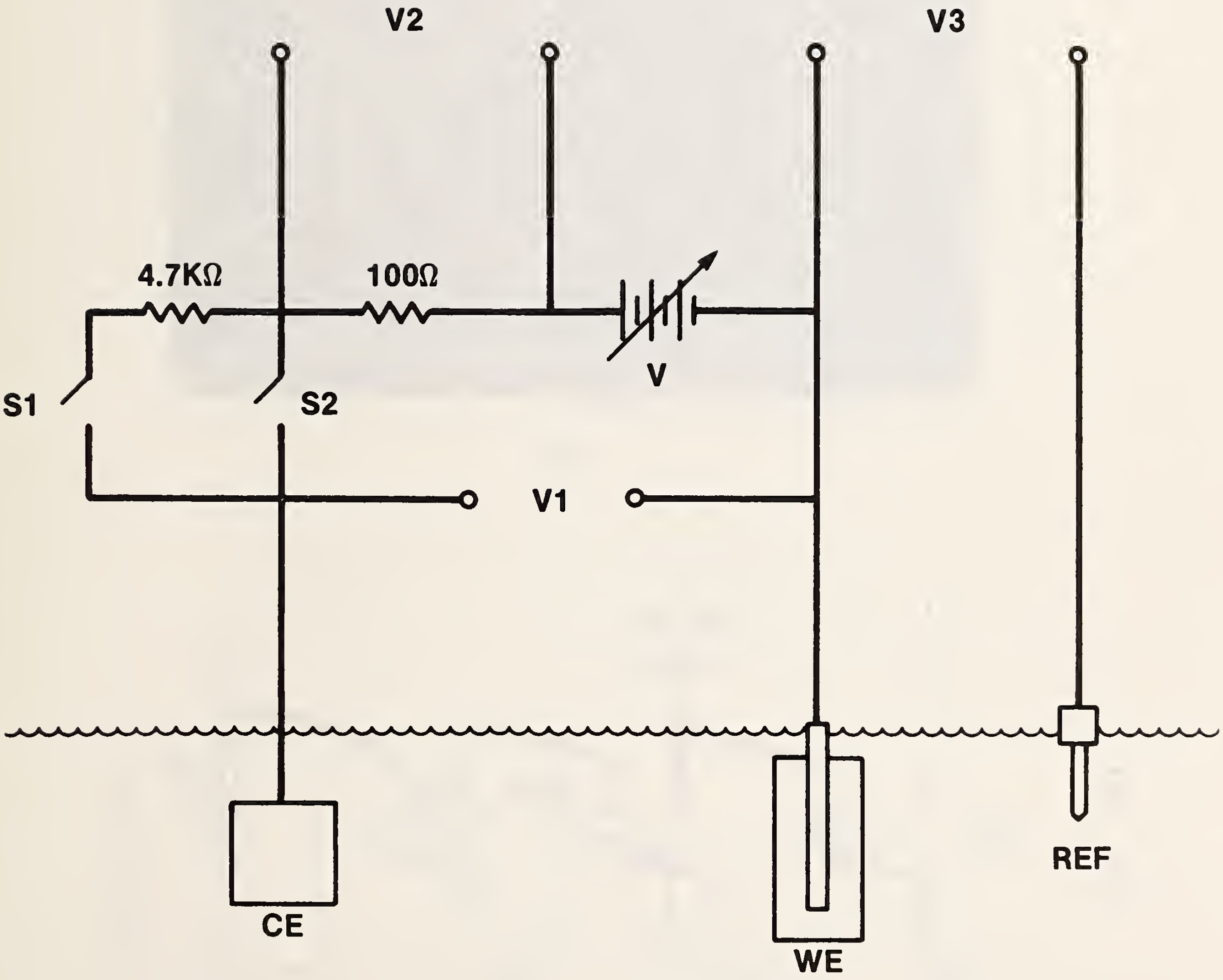
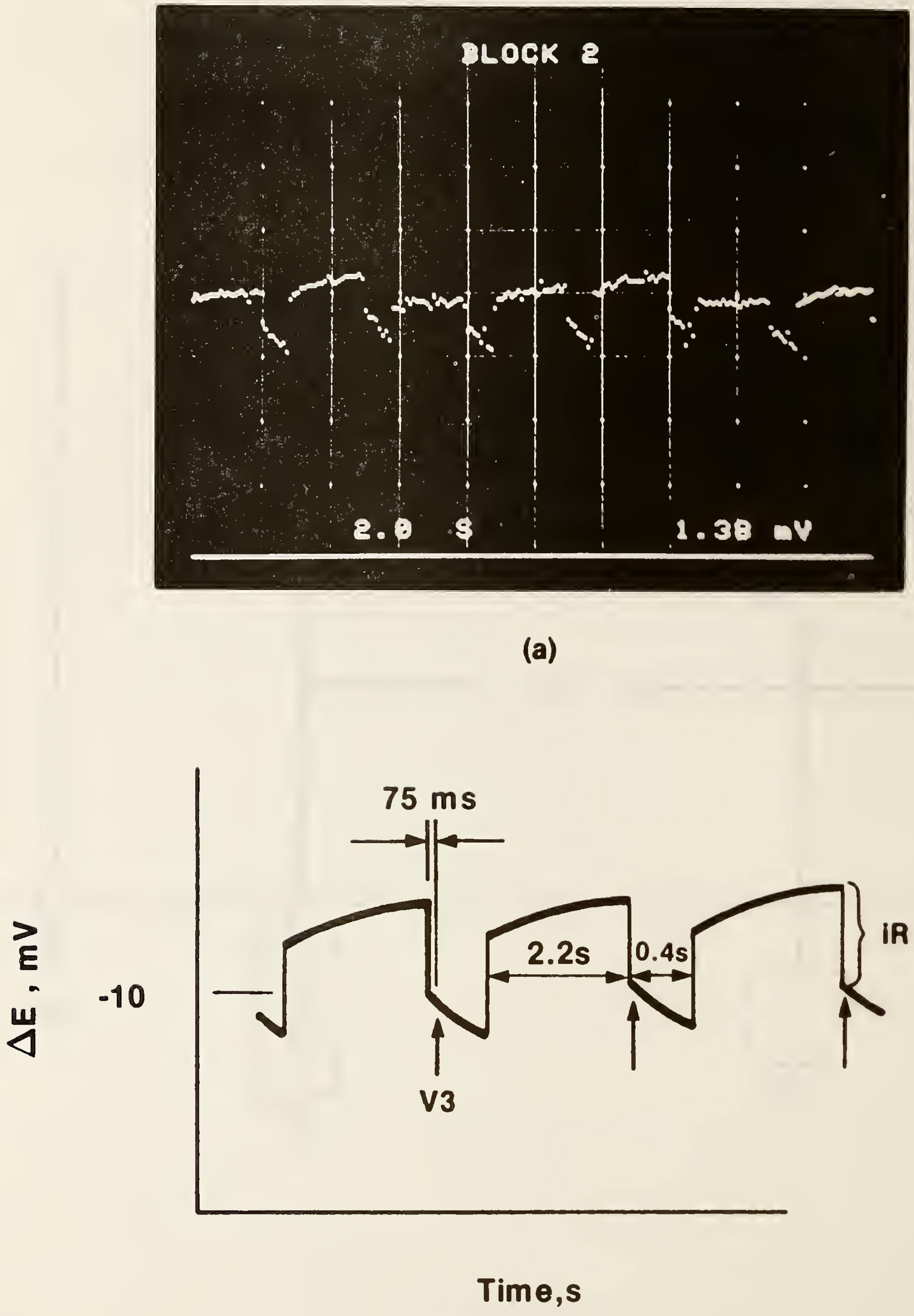


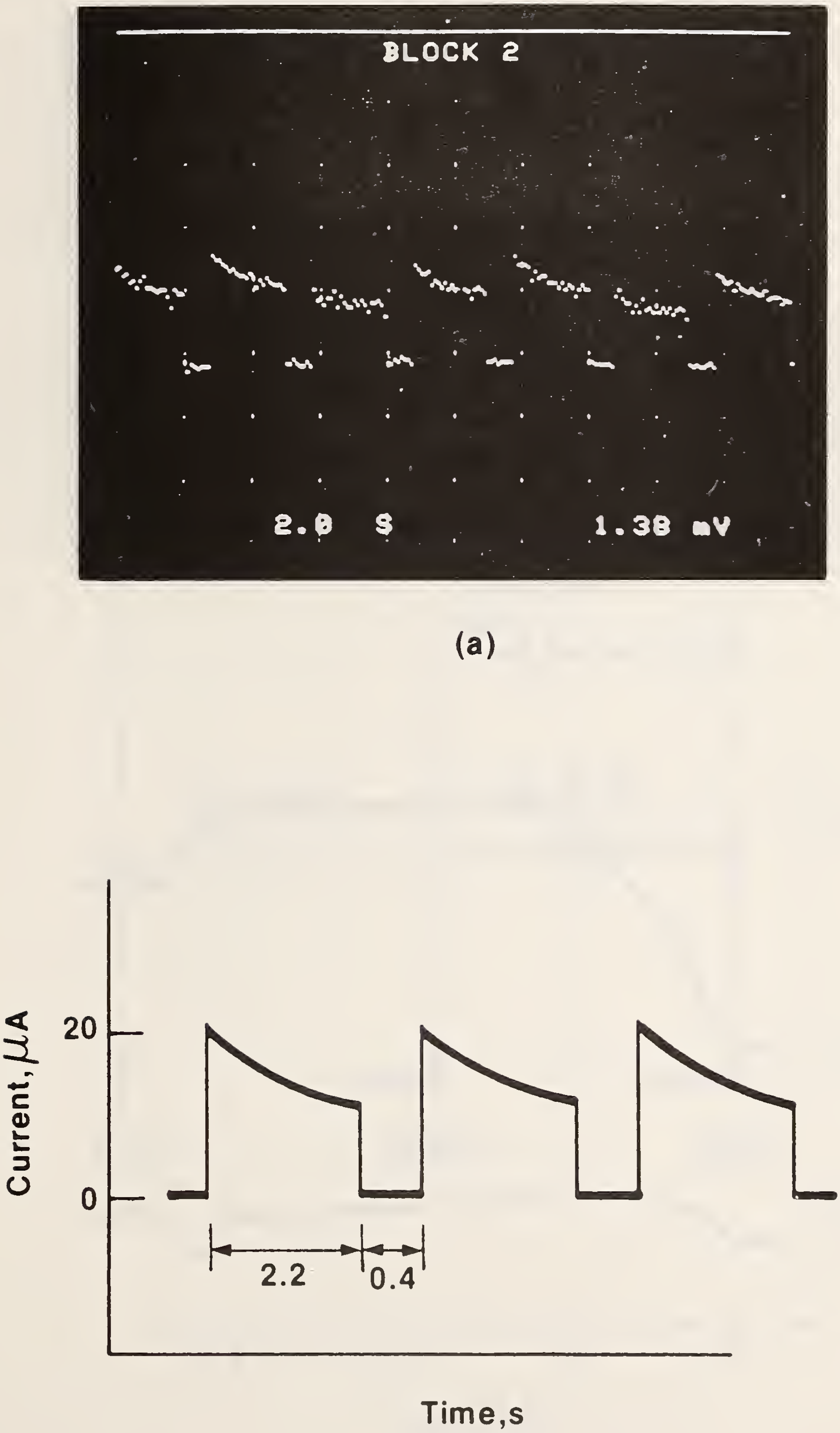
Figure 1



(a)

(b)

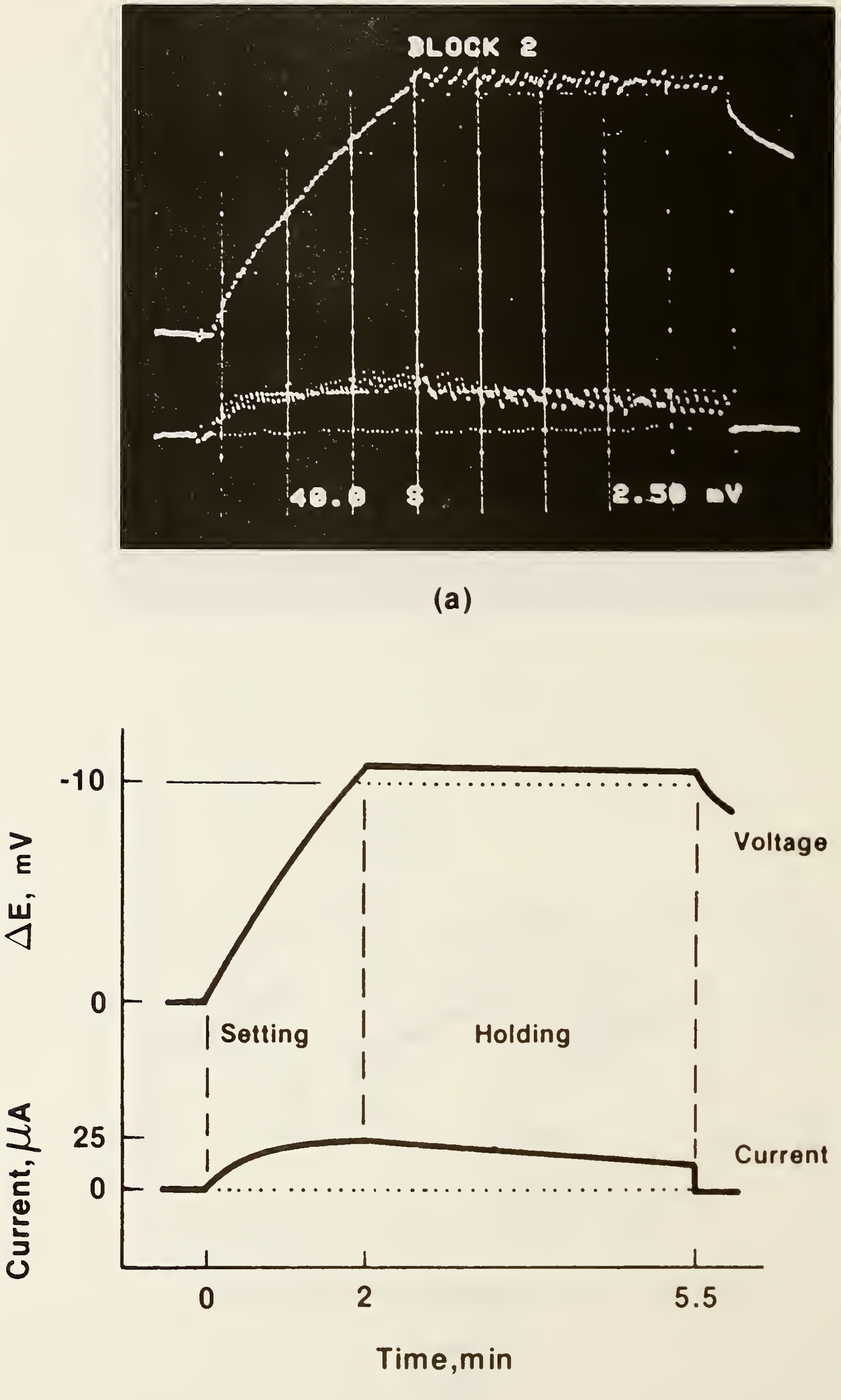
Figure 2



(a)

(b)

Figure 3


BLOCK 2
40.0 S
2.50 mV
-10
ΔE, mV
0
Voltage
Setting
Holding
25
0
Current, μA
Current
0
2
5.5
Time,min

(a)

(b)

Figure 4

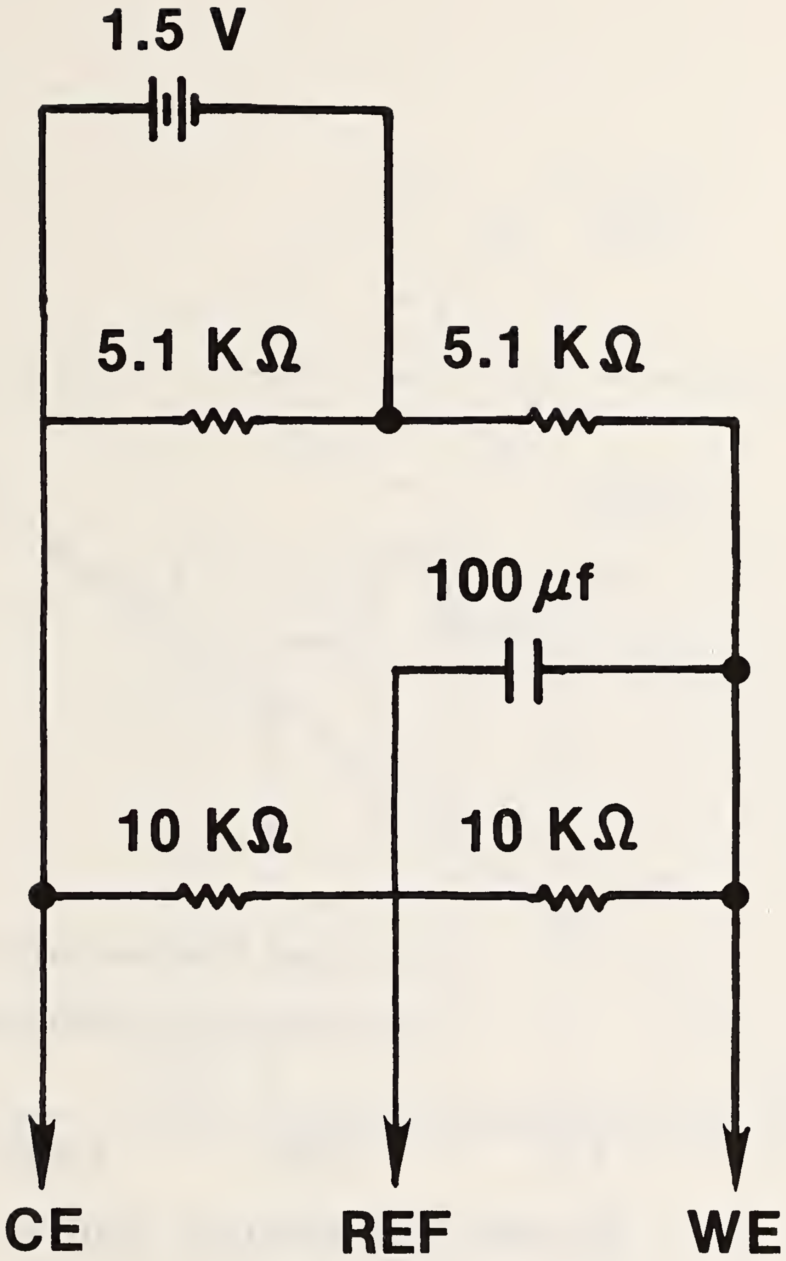


Figure 5

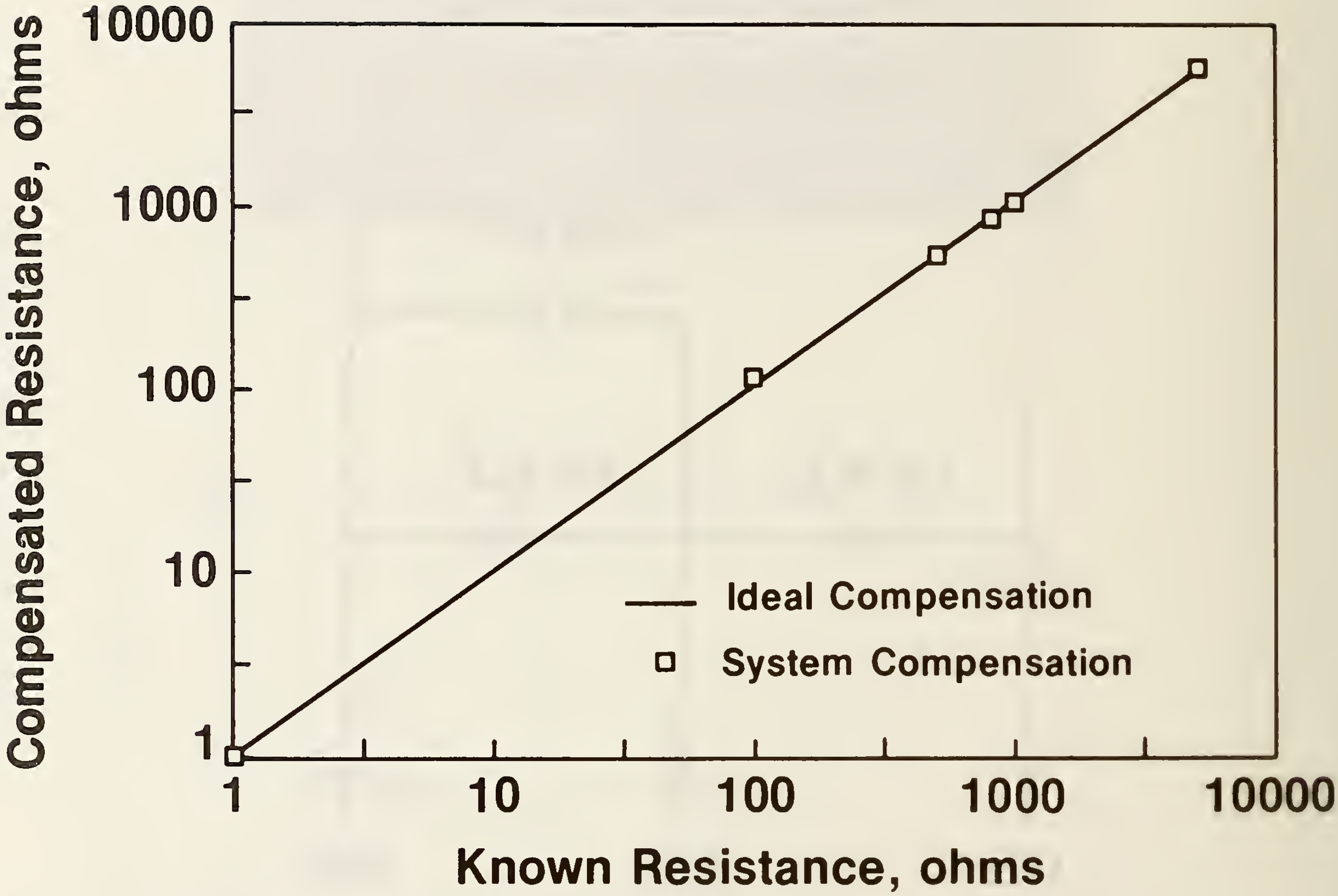

Compensated Resistance, ohms
10000
1000
100
10
1
1
10
100
1000
10000
Known Resistance, ohms
Ideal Compensation
System Compensation

Figure 6

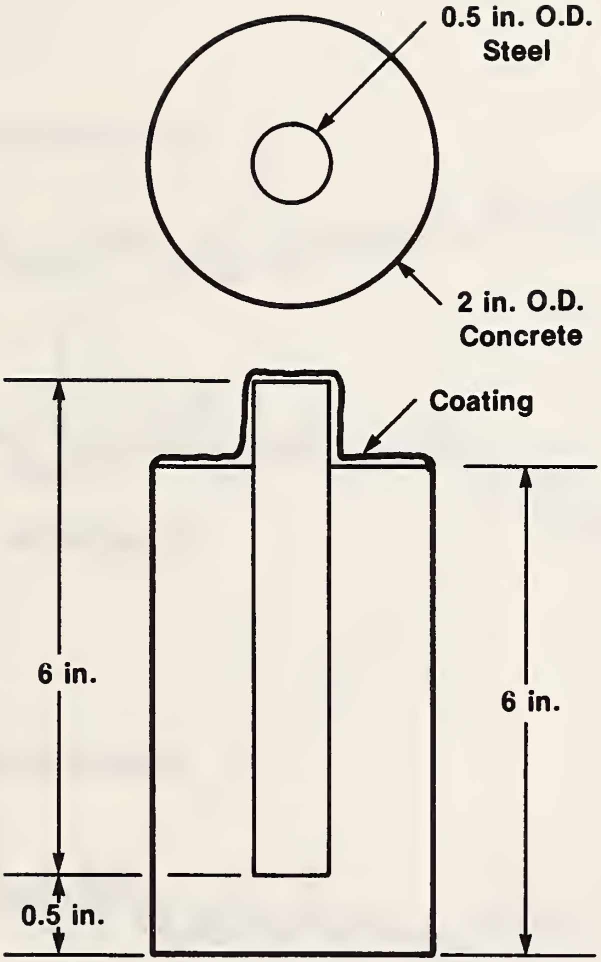


Figure 7

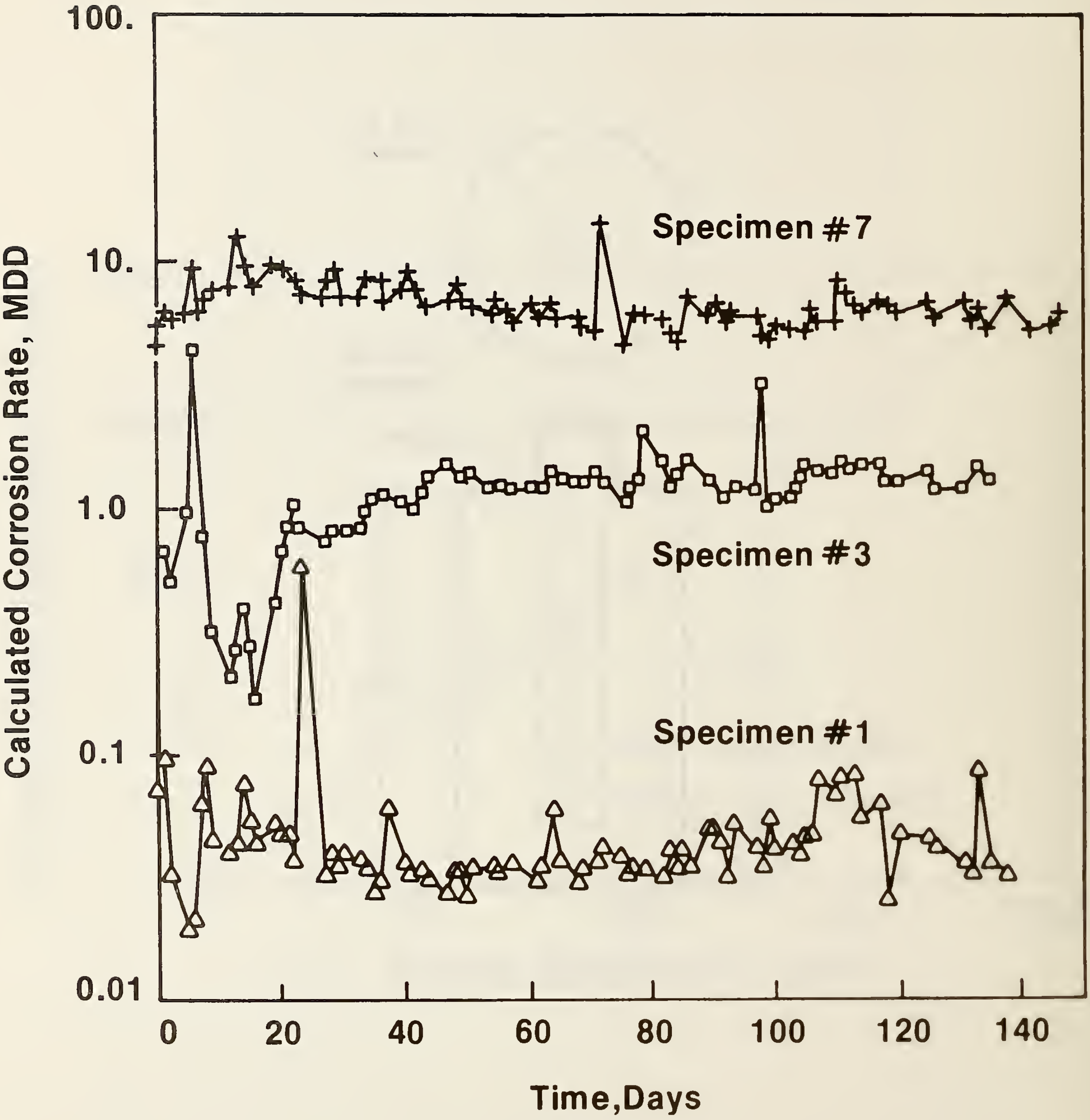

Specimen #7
Specimen #3
Specimen #1
Calculated Corrosion Rate, MDD
100.
10.
1.0
0.1
0.01
0
20
40
60
80
100
120
140
Time,Days

Figure 8

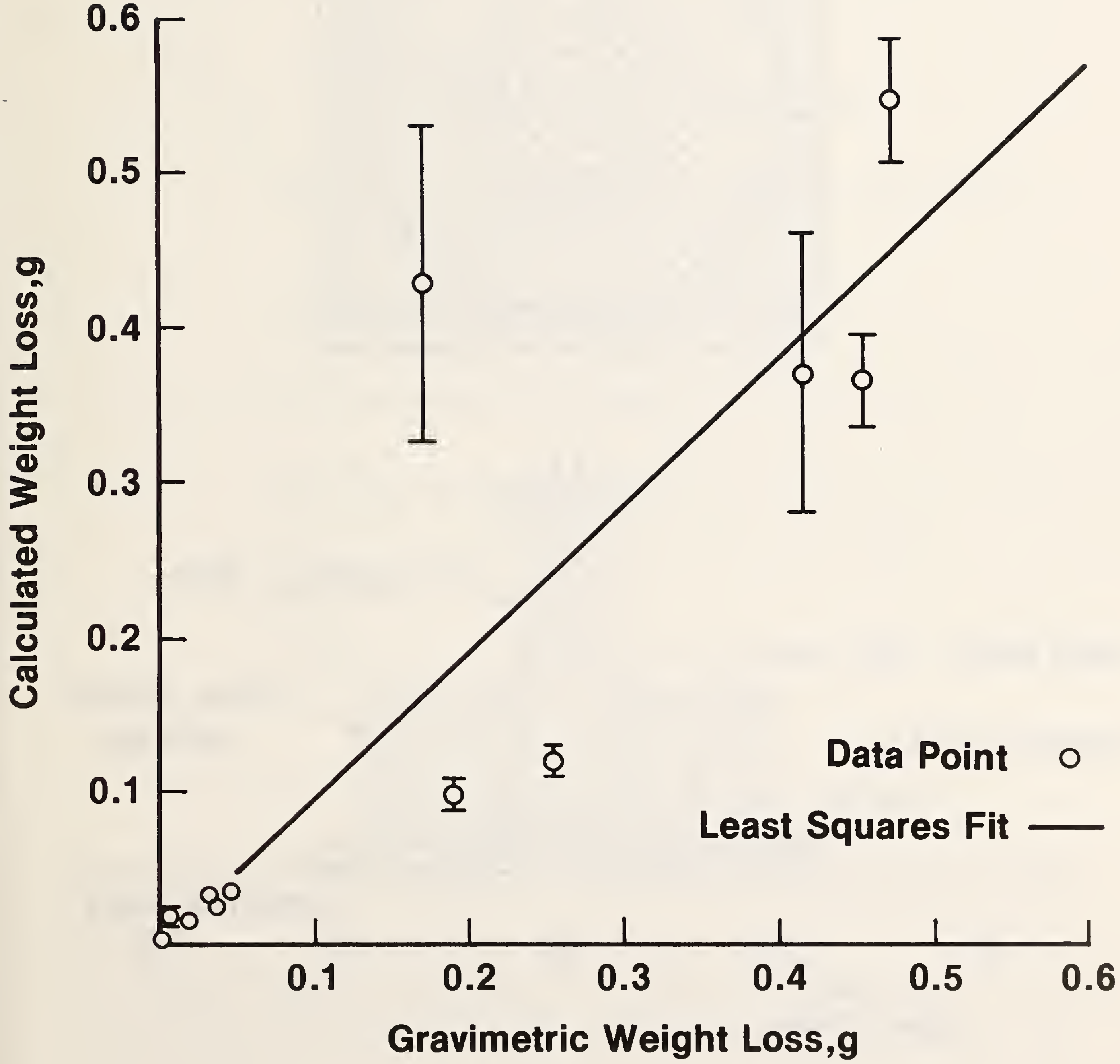

0.6
0.5
0.4
0.3
0.2
0.1
Calculated Weight Loss,g
0.1
0.2
0.3
0.4
0.5
0.6
Gravimetric Weight Loss,g
Data Point ○
Least Squares Fit

Figure 9

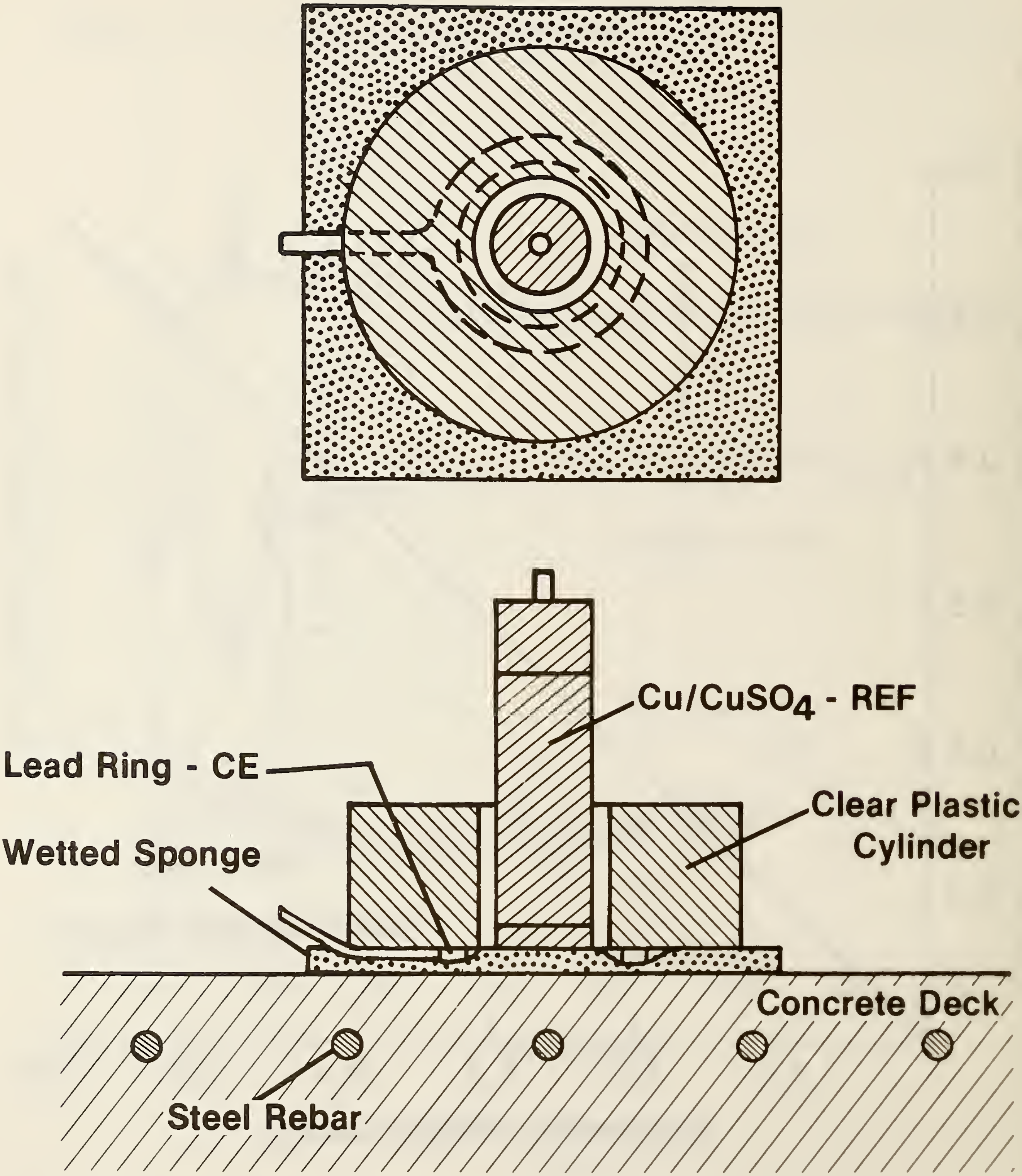

Cu/CuSO$_4$ - REF
Lead Ring - CE
Clear Plastic Cylinder
Wetted Sponge
Concrete Deck
Steel Rebar

Figure 10

APPENDIX A

Corrosion Calculations

Corrosion calculations are based on Stern and Geary's (1) equation:

$$\left.\frac{dv}{di}\right|_{i\to 0} = \frac{B_a \; B_b}{2.3026(B_a+B_c)I_{corr}}$$

where $\frac{dv}{di}$ is the slope of the polarization curve near the corrosion potential, ohms

B_a the anodic Tafel slope, V

B_c the cathodic Tafel slope, V

i_{corr} the corrosion current, A

let: $R_p = \frac{dv}{di}$

where R_p is polarization resistance, ohms

then: $$i_{corr} = \frac{B_a \; B_c}{2.3026(B_a+B_c)R_p} \qquad \text{(equation 1)}$$

Assuming $B_a = B_c = 0.15$ V,

then: $$i_{corr} = \frac{0.03257}{R_p} \qquad \text{(equation 2)}$$

where i_{corr} is the corrosion current, A

Polarization Resistance, R_p , is calculated from the values obtained during a measurement sequence.

$$R_p = \frac{(V3_{avg.} - V3_{o.c.})}{I2_{avg.}} \qquad \text{(equation 3)}$$

where $V3_{o.c.}$ the open circuit potential (at t=0) of the working electrode, V

$V3_{avg.}$ is the average polarized potential of WE during the "holding" period, V

$I2_{avg.}$ is the average current applied to the WE during the "holding" period.

R_p represents a period of 3.5 min ("holding" period) when the polarization data are collected, but it is assumed that this value of

R_p also represents the entire period, t, between measurements (e.g. 24, 48, 72 hrs, etc.). This assumption allows the calculation of weight loss for the entire time of exposure of the WE. Using Faraday's law (2):

$$W = kti_{corr} \qquad \text{(equation 4)}$$

where W is weight loss, the amount of metal reacted, g
t the time period of corrosion, s
k the electrochemical constant, g/C (grams/coulomb)

For Fe -- $Fe^{\pm\pm} + 2\,\overline{e}$; $k = 2.8938 x 10^{-4}$ g/C

Combining equations 1 and 4:

$$W = \frac{B_a\ B_c\ kt}{2.3026(B_a + B_c)R_p}$$

substituting: $$W = \frac{0.15(0.15)(2.8938\times10^{-4})t}{2.3026(0.15 + 0.15)R_p}$$

$$W = \frac{9.4257\times10^{-6}\ t}{R_p} \qquad \text{(equation 5)}$$

Total weight loss, W_{total}, is the sum of all the "daily" weight losses, W_{daily}, calculated from $R_{p(daily)}$

$$W_{total} = \sum_{0}^{t_{total}} \frac{9.426\times10^{-6}\ t_{daily}}{R_{p(daily)}}$$

The term "daily" is used loosely since t_{daily} can also represent a two-day weekend when measurements were not performed.

If we know the area of the working electrode being polarized, corrosion rate, MDD, can be calculated.

$$MDD = \frac{W}{A_{WE}t}$$

where: A is the area of the working electrode, dm^2
t the period of exposure, d

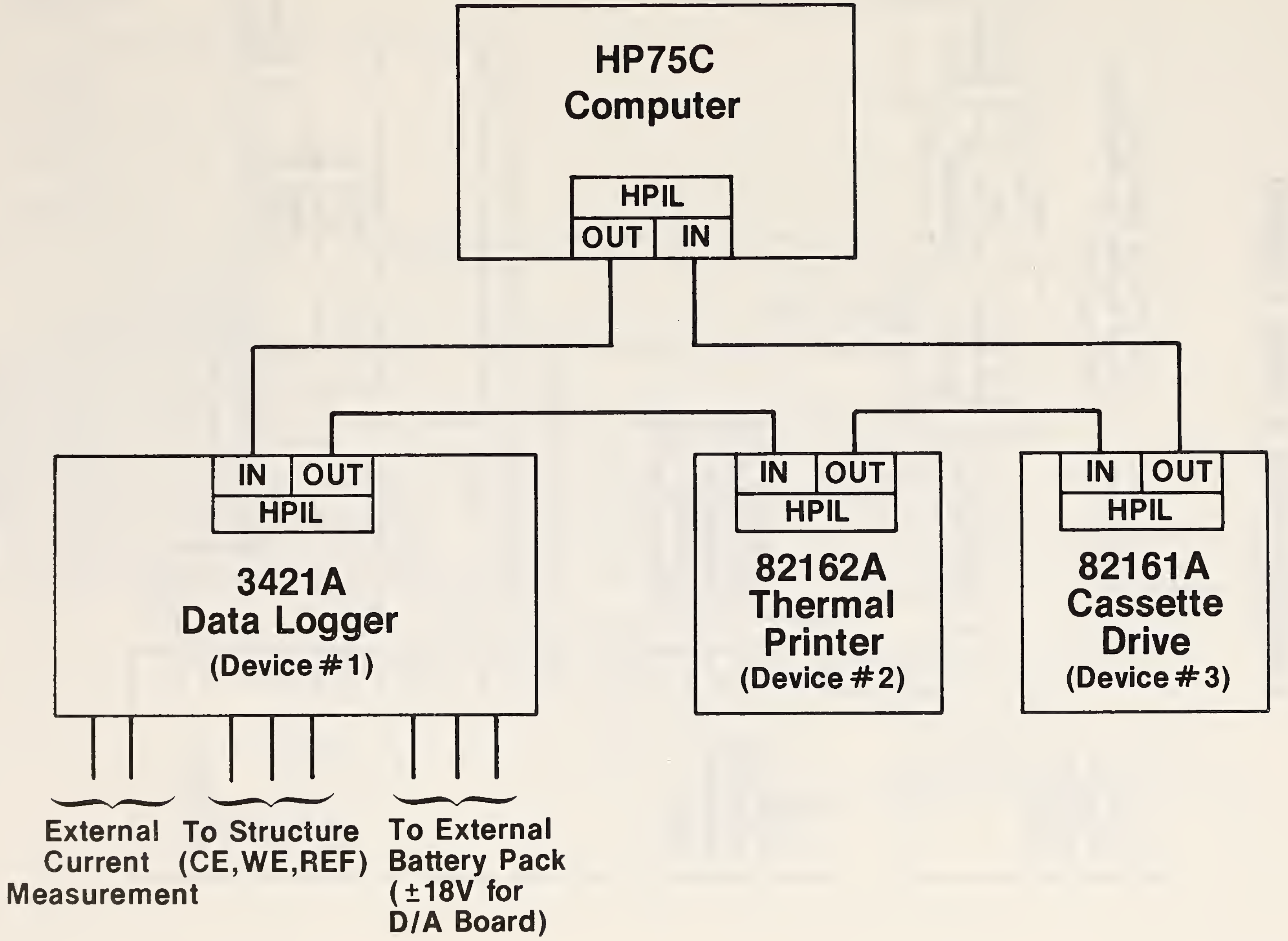
Calculations of corrosion rates on the bridge decks were based on an area of rebar of 60.3 sq.cm which is twice the area of projection from a 6 cm (2.5 in) diameter CE on a 1.6 cm (5/8 in) rebar with a 5 cm (2 in) concrete cover. The time period was 30 days, the period of the final measurements.

REFERENCES

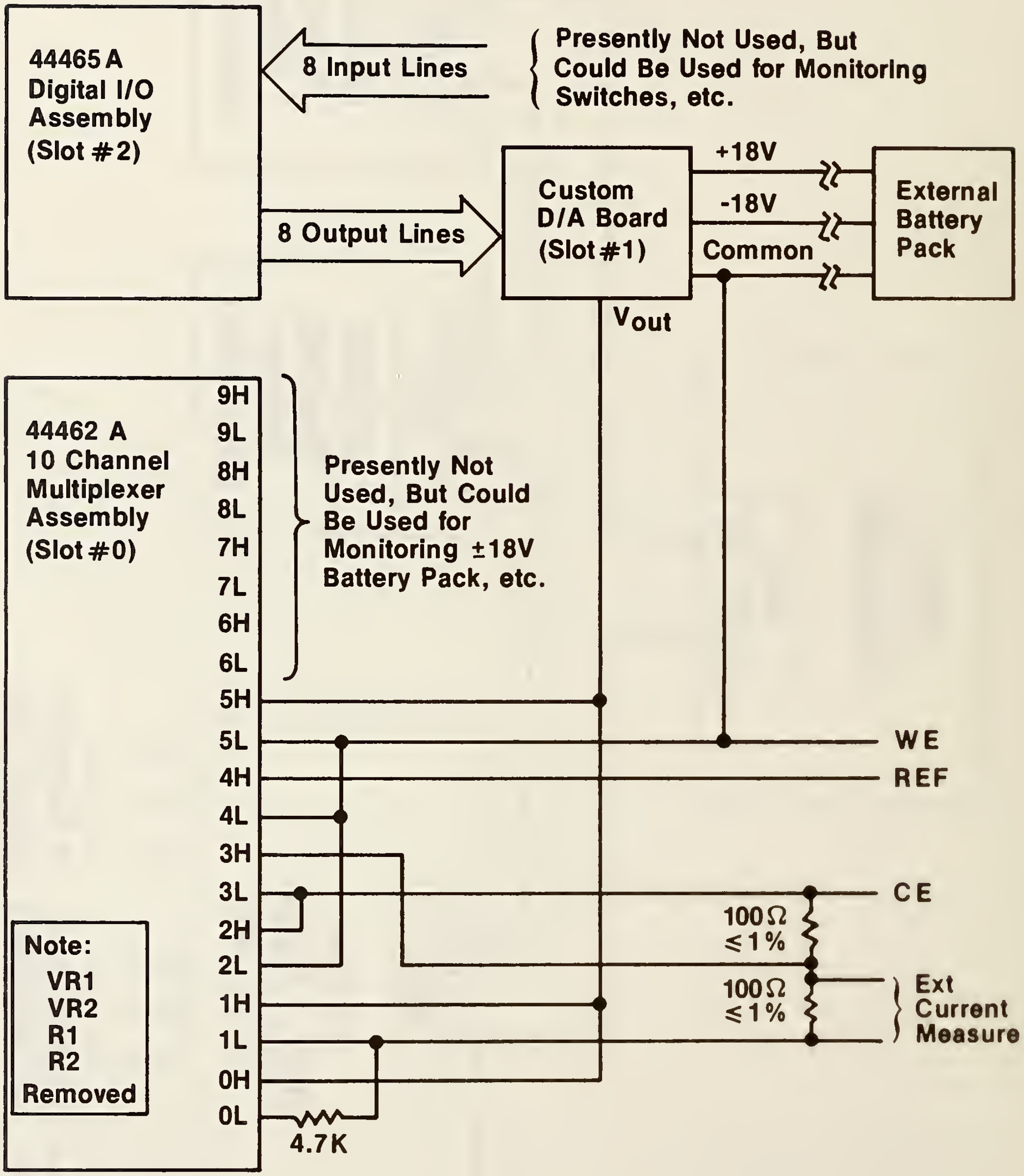
1. Stern, M. and Geary, A. L., Electrochemical Polarization, A Theoretical Analysis of the Shape of {olarization Curves, J Electrochemical Society, 104, 1, p56-63, 1957.

2. Uhlig, H. H. and Revie, R. W., Corrosion and Corrosion Control, third edition, Joln Wiley and Sons, N. Y., 1985.

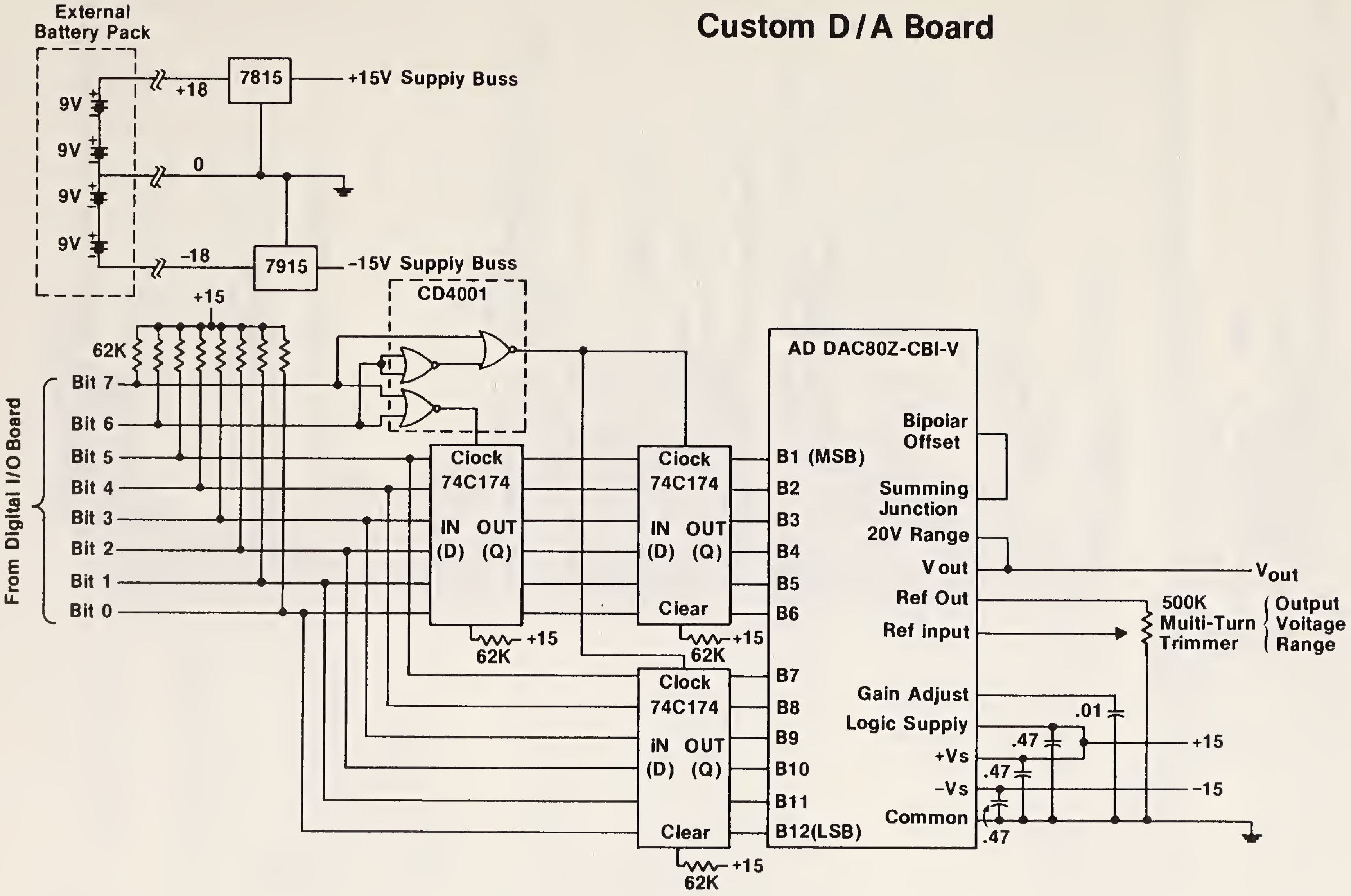
Over view of System



Detail of 3421A Data Logger



Custom D/A Board



APPENDIX B4

```
10 ! ************************* POTENTIAL TEST *******************************
20 !                          ERIC P WHITENTON
30 !                    NATIONAL BUREAU OF STANDARDS
40 !                            MARCH 1986
50 !                    DOCUMENTED VERSION OF 'COR6'
60 !
70 !
80 ! ***************************** SET UP ***********************************
90 DISP 'SETTING UP COMPUTER'
100 OPTION BASE 1
110 GOSUB 3920 !           HPIL CONFIGURATION
120 DIM E$[2] !            CARRIAGE RETURN / LINE FEED
130 E$=CHR$(13)&CHR$(10)
140 DIM F$[20] !           CASSETTE FILE NAME
150 DIM D(4,4) !           DATA ARRAY FOR WHOLE TEST
160 !                      D(1,*)-V1
170 !                      D(2,*)-I2
180 !                      D(3,*)-V3
190 !                      D(4,*)-TIME
200 !                      D(*,1)-OPEN CIRCUIT
210 !                      D(*,2)-INITIAL
220 !                      D(*,3)-SET
230 !                      D(*,4)-FINAL
240 P=0 !                  D(*,P) FOR SUBROUTINE 'READALL'
250 M=0 !                  MODE FOR SUBROUTINE 'READALL'
260 DIM C$[6] !            CARD FOR D/A (REALLY DIGITAL I/O BOARD DRIVING D/A)
270 C$=';WRT2,'
280 B=0 !                  BINARY VALUE OF v, THE D/A VOLTAGE
290 B0,B1,B2=0 !           TEMP BINARY VALUES
300 P1=0 !                 BINARY TO VOLT SLOPE FOR v
310 P2=0 !                 BINARY TO VOLT INTERCEPT FOR v
320 S=0 !                  ERROR STATUS
330 DIM S(10) !            COUNTER FOR EACH TYPE OF ERROR
340 E=-1 !                 ERROR LOCATION
350 T=0 !                  TARGET VOLTAGE FOR V3
360 D=.01 !                ATTEMPTED DELTA VOLTAGE FOR V3
370 K1=.5 @ K2=20 !        USED IN SUBROUTINE SET V3 -
380 !                        WHILE SETTING V3, IF THE PRESENT V3 IS MORE THAN
390 !                        D*K1 AWAY FROM T, THEN CHANGE B BY K2 UNITS,
400 !                        ELSE CHANGE B BY 1 UNIT
410 T1,T2=0 !              TEMP TIMES
420 C1,C2=0 !              TEMP COUNTERS
430 F1,F2,F3,F4=0 !        TEMP FLAGS
440 Q0,Q1,Q2,Q3,Q4=0 !     TEMP VAR
450 Q5,Q6,Q7,Q8,Q9=0 !     TEMP VAR
460 DIM Q$[100] !          TEMP STRING
470 DIM Q1$[30],Q2$[30] !  TEMP STRING
480 R2=100 !               VALUE OF RESISTOR USED TO MEASURE I2
490 Z2=0 !                 I2 ZERO
500 Z4=0 !                 TIME ZERO
510 DIM V(5),I(5) !        STATS FOR V3,I2 DURING HOLD
520 !                      (1)-MIN
530 !                      (2)-MAX
540 !                      (3)-AVE
550 !                      (4)-STD
560 !                      (5)-# PTS
570 !                      FILE ASSIGNMENTS
580 !                        IF F$<>"NO" THEN
590 !                          #1-A BASIC FILE CALLED 'TTTT' FOR DATA WHILE
600 !                             WHILE HOLDING V3
```

```
610 !                           #2-A TEXT FILE CALLED F$ GENERATED FROM FILE
620 !                              #1 WHEN TEST IS OVER
630 !                           AT END OF TEST FILE #2 IS COPIED ONTO CASSETTE
640 !                              AND BOTH FILE #1 & #2 ARE ERASED IN MEMORY.
650 !                              IF YOU STOP THE PROGRAM EARLY, THEN ONE OR
660 !                              BOTH OF THE FILES MAY BE LEFT IN MEMORY AND
670 !                              EVENTUALLY HAVE TO BE PURGED.
680 !                    ******************** MAIN PROGRAM ********************
690 FOR C2=1 TO 4 !                           CLEAR ARRAYS
700 FOR C1=1 TO 4 @ D(C1,C2)=0 @ NEXT C1
710 NEXT C2
720 FOR C1=1 TO 5 @ V(C1),I(C1)=0 @ NEXT C1
730 GOSUB 3420 !                              CLEAR ERROR
740 GOSUB 3480 !                              INITIALIZE DATA LOGGER
750 GOSUB 3720 !                              CALIBRATE D/A & SET P1,P2
760 IF S<>0 THEN E=0 @ GOSUB 1860 @ GOTO 740
770 SENDIO ':DL','UNL,LAD#','F1RA1Z1N4'&E$ ! SET UP VOLTMETER
780 !                                         CONNECT WIRES TO STRUCTURE
790 DISP "CONNECT WIRES" @ BEEP 280,1 @ Q$=KEY$
800 IF KEY$='' THEN GOTO 800
810 ON ERROR GOTO 810 !                       GET FILE NAME FOR HOLD V3 DATA
820 BEEP 280,1 @ INPUT 'enter cassette file name or NO  ';F$
830 IF F$<>"NO" THEN ASSIGN # 2 TO F$,TEXT
840 OFF ERROR
850 IF F$<>"NO" THEN PRINT F$
860 PRINT DATE$ @ PRINT TIME$ !               PRINT DATE,TIME
870 Z2=0 @ Z2=FNB @ Z4=TIME !                 SET ZEROES
880 P=1 @ M=0 @ GOSUB 3000 !                  READALL
890 IF S<>0 THEN E=1 @ GOSUB 1860 @ GOTO 880
900 B=INT(P1*D(1,1)+P2+.5) @ GOSUB 3340 !     SETv, SO v CLOSE TO V1
910 IF S<>0 THEN E=2 @ GOSUB 1860 @ GOTO 900
920 GOSUB 3560 !                              CLOSE S1,CONNECTING D/A,THRU RES.
930 IF S<>0 THEN GOSUB 1860 @ GOTO 920
940 T1=120 @ GOSUB 2120 !                     ZEROI FOR A MAX OF T1 SECONDS
950 IF S<>0 THEN E=3 @ GOSUB 1860 @ GOTO 940
960 GOSUB 3600 !                              CLOSE S2,CONNECTING D/A,NO RES.
970 IF S<>0 THEN GOSUB 1860 @ GOTO 960
980 GOSUB 3640 !                              OPEN  S1, DONT NEED ANY MORE
990 IF S<>0 THEN GOSUB 1860 @ GOTO 980
1000 T1=120 @ GOSUB 2120 !                    ZEROI FOR A MAX OF T1 SECONDS
1010 IF S<>0 THEN E=4 @ GOSUB 1860 @ GOTO 1000
1020 P=2 @ M=1 @ GOSUB 3000 !                 READALL
1030 IF S<>0 THEN E=5 @ GOSUB 1860 @ GOTO 1020
1040 T=D(3,1)+D !                             TARGET VOLTAGE FOR V3
1050 PRINT
1060 PRINT 'TARGET VOLTAGE'
1070 PRINT T
1080 PRINT
1090 T1=300 @ T2=3 @ GOSUB 2330 !             SET V3 FOR T1 SECONDS,
1100 !                                        WITH T2 SECOND TEST-ADJUST CYCLES
1110 IF S<>0 THEN E=6 @ GOSUB 1860 @ GOTO 1040
1120 P=3 @ M=1 @ GOSUB 3000 !                 READALL
1130 IF S<>0 THEN E=7 @ GOSUB 1860 @ GOTO 1120
1140 T1=180 @ T2=3 @ GOSUB 2630 !             HOLD V3 FOR T1 SECONDS,
1150 !                                        WITH T2 SECOND TEST-ADJUST CYCLES
1160 IF S<>0 THEN E=8 @ GOSUB 1860 @ GOTO 1140
1170 P=4 @ M=1 @ GOSUB 3000 !                 READALL
1180 IF S<>0 THEN E=9 @ GOSUB 1860 @ GOTO 1170
1190 GOSUB 3480 !                             INITIALIZE DATA LOGGER
1200 IF S<>0 THEN E=10 @ GOSUB 1860 @ GOTO 1190
```

```
1210 GOSUB 1570 !                            PRINT RESULTS
1220 IF F$="NO" THEN GOTO 1370 !             IF F$<>'NO' THEN CONVERT TEMP
1230 !                                       FILE TO LOTUS .PRN FILE AND
1240 !                                       SAVE ON CASSETTE
1250 DELAY 0
1260 READ # 1,1 ; Q1
1270 FOR Q2=1 TO Q1
1280 READ # 1,10*Q2 ; Q3,Q4,Q5
1290 Q$=FNS$(Q3,8,10)&FNS$(Q4,2,10)&FNS$(Q5,3,10)
1300 DISP Q$ @ PRINT # 2,Q2 ; Q$
1310 NEXT Q2
1320 DELAY 1 @ PURGE 'TTTT' @ Q$=F$
1330 DISP 'PUTTING DATA ON CASSETTE' @ ON ERROR GOTO 1750
1340 COPY F$ TO Q$&':CA'
1350 OFF ERROR
1360 PURGE F$
1370 DISP "DONE" @ BEEP 280,1 @ Q$=KEY$ !     DONE
1380 FOR C1=1 TO 5 @ PRINT @ NEXT C1
1390 IF KEY$='' THEN GOTO 1390
1400 GOTO 680 !                              LOOP BACK FOR ANOTHER TEST
1410 END
1420 !
1430 ! **************************** ROUTINES *********************************
1440 !
1450 ! *** CENTER NUMBER IN STRING ***  A FUNCTION
1460 ! Q6 IS NUMBER TO PUT IN STRING
1470 ! Q7 IS LOCATION OF DECIMAL POINT
1480 ! Q8 IS STRING WIDTH
1490 ! MODIFIES Q1$,Q2$,Q0,Q9
1500 DEF FNS$(Q6,Q7,Q8)
1510 Q1$[1,Q8]=" " @ Q9=10^(Q8-Q7) @ Q2$=STR$(INT(.49+Q6*Q9)/Q9)
1520 Q9=POS(Q2$,".") @ Q0=LEN(Q2$) @ IF Q9=0 THEN Q9=Q0
1530 Q9=Q7-Q9+1 @ IF Q9>0 THEN Q1$[Q9,Q9+Q0-1]=Q2$
1540 FNS$=Q1$
1550 END DEF
1560 !
1570 ! *** PRINT RESULTS ***  A SUBROUTINE
1580 ! VIEWS D(*,*),V(*),I(*)
1590 ! MODIFIES C1,C2,Q1,Q2
1600 DISP 'PRINTING RESULTS'
1610 PRINT
1620 FOR C2=1 TO 4
1630 FOR C1=1 TO 4 @ PRINT D(C1,C2) @ NEXT C1
1640 PRINT
1650 NEXT C2
1660 FOR C1=1 TO 5 @ PRINT V(C1) @ NEXT C1
1670 PRINT
1680 FOR C1=1 TO 5 @ PRINT I(C1) @ NEXT C1
1690 PRINT @ PRINT "COR. RES. IN OHMS"
1700 IF I(3)=INF OR V(3)=INF THEN PRINT "NOT COMPUTABLE" @ GOTO 1730
1710 Q1=I(3)-D(2,1) @ Q2=D(3,1)-V(3)
1720 IF Q1=0 THEN PRINT SGN(Q2)*INF ELSE PRINT Q2/Q1
1730 RETURN
1740 !
1750 ! *** CASSETTE ERROR ***  NOT A SUBROUTINE - EXITS WITH A GOTO
1760 ! MODIFIES Q$
1770 ! CALLS HPIL CONFIGURATION
1780 PRINT @ PRINT 'CASSETTE ERROR'
1790 PRINT 'TRY AGAIN' @ PRINT
1800 INPUT 'enter cassette file name  ';Q$
```

```
1810 GOSUB 3920 ! HPIL CONFIGURATION
1820 IF Q$="NO" THEN GOTO 1350
1830 PRINT 'NEW FILE NAME' @ PRINT Q$ @ PRINT
1840 GOTO 1330
1850 !
1860 ! ***ERROR ROUTINE***  NOT ALWAYS A SUBROUTINE - EXITS WITH EITHER A
1870 !                      POP,GOTO OR A RETURN
1880 ! MANY OF THE VALUES OF S(*) LEFT UNDEFINED FOR FUTURE EXPANSION
1890 ! MODIFIES S,S(*),E,Q0
1900 ! CALLS CLEAR ERROR, INITIALIZE DATA LOGGER
1910 IF S(5) THEN PRINT "SOFTWARE TIME OUT (";S(5);")"
1920 IF S(6) THEN PRINT "DELAY BETWEEN READINGS TO SHORT (";S(6);")"
1930 IF S(7) THEN PRINT "DATA LOGGER ERROR (";S(7);")"
1940 PRINT "LAST ERROR"
1950 IF E=0 THEN PRINT "WHILE SETTING UP FOR TEST"
1960 IF E=1 THEN PRINT "WHILE READING OPEN CIRCUIT VALUES"
1970 IF E=2 THEN PRINT "WHILE SETTING INITIAL V1"
1980 IF E=3 THEN PRINT "WHILE COURSE ZEROING I2"
1990 IF E=4 THEN PRINT "WHILE FINE ZEROING I2"
2000 IF E=5 THEN PRINT "WHILE READING INITIAL VALUES"
2010 IF E=6 THEN PRINT "WHILE SETTING V3"
2020 IF E=7 THEN PRINT "WHILE READING SET VALUES"
2030 IF E=8 THEN PRINT "WHILE HOLDING V3"
2040 IF E=9 THEN PRINT "WHILE READING FINAL VALUES"
2050 IF E=10 THEN PRINT "AFTER TEST OVER"
2060 Q0=0 @ INPUT "(1) AGAIN / END (2)     ";Q0
2070 DISP
2080 IF Q0=1 THEN GOSUB 3410 @ RETURN
2090 IF Q0=2 THEN GOSUB 3480 @ GOSUB 3410 @ POP @ GOTO 1210
2100 GOTO 2060
2110 !
2120 ! *** ZEROI ***  A SUBROUTINE
2130 ! VIEWS T1
2140 ! MODIFIES Q1,Q2,Q3,Q4,F1,F2,F3,F4,S,S(5),B
2150 ! CALLS FNB,SETv
2160 DISP 'ZEROING I2'
2170 Q1=S ! SAVE OLD STATUS
2180 Q2=0 ! PRESENT I2
2190 F1=0 @ F2=10 @ F3=20 ! OVER/UNDER ZERO FLAGS
2200 Q3=TIME ! START TIME
2210 ! LOOP
2220 Q4=Q2 ! LAST I2
2230 Q2=FNB ! PRESENT I2
2240 IF S<>Q1 THEN RETURN
2250 F4=F3 @ F3=F2 @ F2=F1 @ F1=SGN(Q2)
2260 IF F1=0 THEN RETURN
2270 IF F4=F2 AND F3=F1 AND ABS(Q2)<=ABS(Q4) AND F1<>F2 AND F3<>F4 THEN RETURN
2280 IF TIME-Q3>=T1 THEN S=S+1 @ S(5)=S(5)+1 @ RETURN
2290 B=B+F1 @ GOSUB 3340 ! SETv
2300 IF S<>Q1 THEN RETURN
2310 GOTO 2210
2320 !
2330 ! *** SET V3 ***  A SUBROUTINE
2340 ! VIEWS D,T1,T2,K1,K2
2350 ! MODIFIES Q1,Q2,Q3,Q4,F1,F2,F4,T,B,S,S(6)
2360 ! CALLS OPEN S2,CLOSE S2,FNC,SETv
2370 DISP 'SETTING V3'
2380 Q1=S ! SAVE OLD STATUS
2390 Q2=TIME ! START TIME
2400 Q3=TIME ! NEXT TIME
```

```
2410 F4=0 ! REACHED TARGET FLAG
2420 GOSUB 3680 ! OPEN S2
2430 F1,F2=SGN(FNC-T)
2440 GOSUB 3340 ! CLOSE S2
2450 IF S<>Q1 THEN RETURN
2460 ! LOOP
2470 IF F1<>F2 AND F4=0 THEN F4=1 @ PRINT "TARGET REACHED" @ PRINT TIME$ @ PRIN
2480 IF TIME-Q2<T1 THEN GOTO 2510
2490 IF F4=0 THEN T=FNC @ PRINT "NEW TARGET" @ PRINT T @ PRINT
2500 RETURN
2510 F2=F1
2520 GOSUB 3680 ! OPEN S2
2530 Q4=FNC-T @ F1=SGN(Q4)
2540 IF ABS(Q4)>K1*D THEN B=B+K2*F1 ELSE B=B+F1
2550 GOSUB 3340 ! SET v
2560 GOSUB 3600 ! CLOSE S2
2570 IF S<>Q1 THEN RETURN
2580 Q3=Q3+T2 ! NEXT TIME
2590 IF TIME>Q3 THEN S=S+1 @ S(6)=S(6)+1 @ RETURN
2600 IF TIME<Q3 THEN GOTO 2600
2610 GOTO 2460
2620 !
2630 ! *** HOLD V3 ***  A SUBROUTINE
2640 ! VIEWS T,T1,T2,F$
2650 ! MODIFIES FILE #1,Q1,Q3,Q4,Q5,Q6,Q7,B,S,S(6),V(*),I(*)
2660 ! CALLS OPEN S2,CLOSE S2,SETv,FNC,FNB
2670 DISP 'HOLDING V3'
2680 IF F$<>"NO" THEN ASSIGN # 1 TO 'TTTT',BASIC
2690 Q1=S ! SAVE OLD STATUS
2700 V(1)=INF @ V(2)=-INF @ V(3)=0 @ V(4)=0 @ V(5)=0
2710 I(1)=INF @ I(2)=-INF @ I(3)=0 @ I(4)=0 @ I(5)=0
2720 Q3=TIME ! START TIME
2730 Q4=TIME ! NEXT TIME
2740 ! LOOP
2750 Q5=FNB @ Q7=B
2760 GOSUB 3680 ! OPEN S2
2770 Q6=FNC
2780 B=B+SGN(Q6-T) @ GOSUB 3340 ! SETv
2790 GOSUB 3600 ! CLOSE S2
2800 IF S<>Q1 THEN GOTO 2910
2810 I(1)=MIN(I(1),Q5) @ I(2)=MAX(I(2),Q5)
2820 I(3)=I(3)+Q5 @ I(4)=I(4)+Q5^2 @ I(5)=I(5)+1
2830 V(1)=MIN(V(1),Q6) @ V(2)=MAX(V(2),Q6)
2840 V(3)=V(3)+Q6 @ V(4)=V(4)+Q6^2 @ V(5)=V(5)+1
2850 IF F$<>"NO" THEN PRINT # 1,1 ; I(5) @ PRINT # 1,10*I(5) ; Q7,Q5,Q6
2860 IF TIME-Q3>=T1 THEN GOTO 2910
2870 Q4=Q4+T2
2880 IF TIME>Q4 THEN S=S+1 @ S(6)=S(6)+1 @ GOTO 2910
2890 IF TIME<Q4 THEN GOTO 2890
2900 GOTO 2740
2910 ! COMPUTE STATS & RETURN
2920 Q3=I(3) @ Q4=I(4) @ Q5=I(5)
2930 IF Q5>=1 THEN I(3)=Q3/Q5 ELSE I(3)=INF
2940 IF Q5>=2 THEN I(4)=((Q5*Q4-Q3*Q3)/(Q5*(Q5-1)))^.5 ELSE I(4)=INF
2950 Q3=V(3) @ Q4=V(4) @ Q5=V(5)
2960 IF Q5>=1 THEN V(3)=Q3/Q5 ELSE V(3)=INF
2970 IF Q5>=2 THEN V(4)=((Q5*Q4-Q3*Q3)/(Q5*(Q5-1)))^.5 ELSE V(4)=INF
2980 RETURN
2990 !
3000 ! *** READ ALL ***   A SUBROUTINE
```

```
3010 ! VIEWS Z4,M,P
3020 ! MODIFIES D(*,P)
3030 ! CALLS FNA,FNB,FNC,OPEN S2,CLOSE S2
3040 DISP 'READING V1,I2,V3,TIME'
3050 D(1,P)=FNA
3060 D(2,P)=FNB
3070 D(4,P)=TIME-Z4
3080 IF M=1 THEN GOSUB 3680 ! OPEN S2
3090 D(3,P)=FNC
3100 IF M=1 THEN GOSUB 3600 ! CLOSE S2
3110 RETURN
3120 !
3130 ! *** READ V1 ***  A FUNCTION
3140 ! VIEWS E$
3150 DEF FNA
3160 SENDIO ':DL','UNL,LAD#','CLS2;T2'&E$
3170 FNA=-VAL(ENTIO$(':DL','UNL,TAD#,SDA'))
3180 END DEF
3190 !
3200 ! *** READ I2 ***  A FUNCTION
3210 ! VIEWS E$,R2,Z2
3220 DEF FNB
3230 SENDIO ':DL','UNL,LAD#','CLS3;T2'&E$
3240 FNB=VAL(ENTIO$(':DL','UNL,TAD#,SDA'))/R2-Z2
3250 END DEF
3260 !
3270 ! *** READ V3 ***  A FUNCTION
3280 ! VIEWS E$
3290 DEF FNC
3300 SENDIO ':DL','UNL,LAD#','CLS4;T2'&E$
3310 FNC=VAL(ENTIO$(':DL','UNL,TAD#,SDA'))
3320 END DEF
3330 !
3340 ! *** SETv ***  A SUBROUTINE   VIEWS C$,E$   MODIFIES B,B0,B1,B2,Q$
3350 IF B<0 THEN B=0
3360 IF B>4095 THEN B=4095
3370 B0=4095-B @ B2=B0 DIV 64 @ B1=MOD(B0,64)
3380 Q$=C$[2,6]&STR$(B2+64)&C$&STR$(B2+192)&C$&STR$(B1)&C$&STR$(B1+128)&C$&'0'&
$
3390 SENDIO ':DL','UNL,LAD#',Q$
3400 RETURN
3410 !
3420 ! *** CLEAR ERROR ***  A SUBROUTINE
3430 ! MODIFIES C1,S(*),S,E
3440 FOR C1=1 TO 10 @ S(C1)=0 @ NEXT C1
3450 S=0 @ E=-1
3460 RETURN
3470 !
3480 ! *** INITIALIZE DATA LOGGER ***  A SUBROUTINE
3490 ! MODIFIES Q$,S,S(7)
3500 DISP 'CLEARING DATA LOGGER'
3510 CLEAR ':DL' @ WAIT 2 ! CLEAR DATA LOGGER
3520 Q$=ENTIO$(':DL','UNL,TAD#,SST') ! READ STATUS
3530 IF NUM(Q$)<>1 THEN S=S+1 @ S(7)=S(7)+1 ! IF STATUS NOT 1 THEN ERROR
3540 RETURN
3550 !
3560 ! *** CLOSE S1 ***  A SUBROUTINE   VIEWS E$
3570 SENDIO ':DL','UNL,LAD#','CLS0'&E$
3580 RETURN
3590 !
```

```
3600 ! *** CLOSE S2 ***  A SUBROUTINE   VIEWS E$
3610 SENDIO ':DL','UNL,LAD#','CLS1'&E$
3620 RETURN
3630 !
3640 ! *** OPEN S1 ***  A SUBROUTINE   VIEWS E$
3650 SENDIO ':DL','UNL,LAD#','OPN0'&E$
3660 RETURN
3670 !
3680 ! *** OPEN S2 ***  A SUBROUTINE   VIEWS E$
3690 SENDIO ':DL','UNL,LAD#','OPN1'&E$
3700 RETURN
3710 !
3720 ! *** CALIBRATE D/A & SET P1,P2 ***  A SUBROUTINE
3730 ! VIEWS E$
3740 ! MODIFIES Q1,Q2,Q$,B,P1,P2
3750 ! CALLS OPEN S1,OPEN S2,SETv
3760 DISP 'CALIBRATING D/A'
3770 Q$=KEY$
3780 GOSUB 3640 @ GOSUB 3680 ! OPEN S1,S2
3790 B=4095 @ GOSUB 3340 ! SETv
3800 SENDIO ':DL','UNL,LAD#','CLS5;T2'&E$ ! READ D/A OUTPUT (v)
3810 Q1=-VAL(ENTIO$(':DL','UNL,TAD#,SDA'))
3820 IF ABS(Q1)<.1 THEN DISP 'TURN D/A ON' @ BEEP 560,.02 @ WAIT 1 @ GOTO 3790
3830 B=0 @ GOSUB 3340 ! SETv
3840 SENDIO ':DL','UNL,LAD#','CLS5;T2'&E$ ! READ D/A OUTPUT (v)
3850 Q2=-VAL(ENTIO$(':DL','UNL,TAD#,SDA'))
3860 P1=4095/(Q1-Q2) @ P2=-Q2*P1
3870 Q$=KEY$
3880 DISP 'TOTAL RANGE IS ';ABS(Q1-Q2)
3890 IF Q$='' THEN GOTO 3790
3900 RETURN
3910 !
3920 ! *** HPIL CONFIGURATION ***
3930 ASSIGN IO ':DL,:PR,:CA'
3940 PRINTER IS ':PR'
3950 RETURN
```

APPENDIX C1

Technical Report Documentation Page

1. Report No.
FHWA/RD-86/

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Measuring the Rate of Corrosion of Reinforcing Steel in Concrete--Final Report

5. Report Date
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6. Performing Organization Code
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7. Author(s)
E. Escalante, E. Whitenton, F. Qiu

8. Performing Organization Report No.
NBSIR 86-3456

9. Performing Organization Name and Address
National Bureau of Standards
Gaithersburg, MD 20899

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11. Contract or Grant No.
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Federal Highway Administration
McLean, Virginia

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Final

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15. Supplementary Notes
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16. Abstract

This report describes a two phase study directed at developing a portable system for measuring the corrosion of steel in concrete bridge decks. A small, portable computer system is used to control the measurement of polarization resistance of steel in concrete, and using current interruption, iR compensation is accomplished. During the development stage, measurements were made on small specimens in a laboratory controlled environment, and the results of the calculated weight loss measurements based on the electrochemical measurement are compared to gravimentrically determined weight loss. In the second phase, the portable system was used to measure the corrosion of three bridge decks in Frederick Country, Maryland, over a four month period. The results of these field measurements and the problems encountered are discussed.

17. Key Words
bridge deck corrosion
corrosion of steel
corrosion rate measurement
polarization resistance
steel in concrete

18. Distribution Statement

19. Security Classif. (of this report)

20. Security Classif. (of this page)

21. No. of Pages

22. Price

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APPENDIX C2

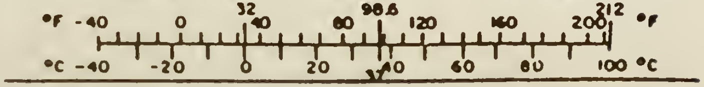
METRIC CONVERSION FACTORS

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
In	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons(2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares(10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	8.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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5. AUTHOR(S)

E. Escalante, E. Whitenton, F. Qiu

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McLean, Virginia

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FHWA Contract Manager: Y. P. Virmani

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This report describes a two phase study directed at developing a portable system for measuring the corrosion of steel in concrete bridge decks. A small, portable computer system is used to control the measurement of polarization resistance of steel in concrete, and using current interruption, iR compensation is accomplished. During the development stage, measurements were made on small specimens in a laboratory controlled environment, and the results of the calculated weight loss measurements based on the electrochemical measurement are compared to gravimentrically determined weight loss. In the second phase, the portable system was used to measure the corrosion of three bridge decks in Frederick Country, Maryland, over a four month period. The results of these field measurements and the problems encountered are discussed.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

bridge deck corrosion; corrosion of steel; corrosion rate measurement; polarization resistance; steel in concrete.

13. AVAILABILITY

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