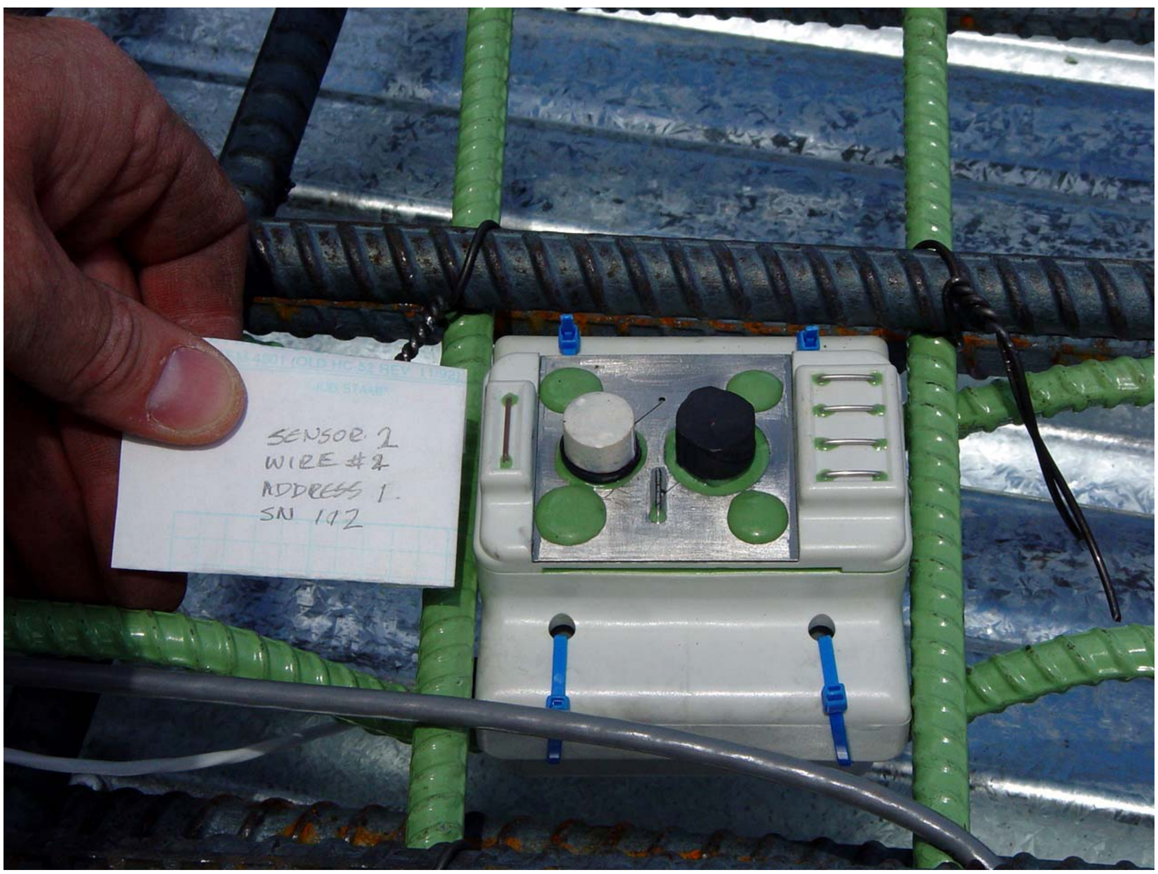
STATE OF CALIFORNIA
DEPARTMENT of TRANSPORTATION

MATERIALS ENGINEERING AND TESTING SERVICES

OFFICE OF TESTING AND TECHNOLOGY SERVICES
CORROSION TECHNOLOGY BRANCH

5900 Folsom Boulevard
Sacramento, California 95819

EVALUATION OF THE VTI ECI-1 CORROSION MONITORING DEVICE



January 2006

STATE OF CALIFORNIA
DEPARTMENT of TRANSPORTATION

MATERIALS ENGINEERING AND TESTING SERVICES

OFFICE OF TESTING AND TECHNOLOGY SERVICES
CORROSION TECHNOLOGY BRANCH

5900 Folsom Boulevard
Sacramento, California 95819

EVALUATION OF THE VTI ECI-1 EMBEDDED CORROSION INSTRUMENT

Principle Investigator .... Rob Reis, P.E. – Corrosion Specialist
Senior Materials & Research Engineer
Corrosion Technology Branch
Materials Engineering and Testing Services
Division of Engineering Services

Robert A. Reis

Co-Principle Investigator .. Malinda Gallaher - Transportation Engineer
Infrastructure Methods Advancement Branch
Office of Materials and Infrastructure
Division of Research and Innovation

Malinda Gallaher

Project Support .... Robert Meline, P.E. – Senior Transportation Engineer
Chief, Infrastructure Methods Advancement Branch
Office of Materials and Infrastructure
Division of Research and Innovation

Robert Meline

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FHWA/CA/TL-2003/07/ECI-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of the VTI ECI-1 Embedded Corrosion Instrument		5. Report Date January 2006 6. Performing Organization Code
7. Authors Robert A. Reis, Malinda Gallaher		8. Performing Organization Report No.
9. Performing Organization Name and Address Materials Engineering and Testing Services 5900 Folsom Blvd. Sacramento, California 95819-0128		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address California Department of Transportation Sacramento, California 95814		13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

This project was completed in cooperation with FHWA as a result of work on Federal Aid Program Number S 00 IR 001 under the Innovative Bridge Research and Construction Program. http://ibrc.fhwa.dot.gov/

16. Abstract

This report describes an evaluation performed by the California Department of Transportation (Department) of the ECI-1 Embedded Corrosion Instrument, developed by Virginia Technologies, Incorporated (VTI).

The ECI-1 Embedded Corrosion Instrument was designed to several parameters related to corrosion of reinforcement in concrete. These parameters include chloride ion sensing, concrete resistivity, linear polarization resistance (LPR), corrosion potential, and concrete temperature. These measurements can allow corrosion engineers to monitor corrosion activity within reinforced concrete in a non-destructive manner.

Four ECI-1 devices were evaluated in laboratory experiments in mortar samples. Chlorides were introduced using an external power supply to accelerate the ingress of chlorides from ponding solution into the mortar matrix. Corrosion parameters were obtained using the ECI-1 devices and an external potentiostat for comparison. The results of the laboratory evaluation are presented in this report.

In addition to the laboratory study, four ECI-1 devices were installed in a bridge deck located in Northern California. The bridge deck is subjected to deicing salt applications during winter snow periods and will be used to evaluate the long-term (10 to 12-years) performance of the ECI-1 devices. The installation procedures and preliminary data for these devices are presented in this report.

17. Key Words ECI-1, Embedded Corrosion Instrument, Chloride, Linear Polarization Resistance, LPR, Concrete, Sensor, SDI-12		18. Distribution Statement No Restriction. This document is available to the public through the National Technical Information Service, Springfield, VA 22161
19. Security Clasif. (of this report) Unclassified	20. Security Clasif. (of this page) Unclassified	21. No. of Pages 58

DS-TL-1242 (Rev. 6/76)

LIST OF FIGURES

INTRODUCTION

Corrosion of reinforced concrete structures due to chlorides can result in increased maintenance costs and may reduce the design life of a structure. Existing methods for inspecting and monitoring structures for corrosion related damage, such as visual inspections, chaining/sounding for unsound concrete, and coring to determine the depth of chloride ingress are labor intensive, and often expose work crews to hazardous working conditions in and around traffic lanes. Alternative methods of health monitoring of structures for corrosion-induced damage are needed. A number of devices have been or are being developed to perform health monitoring related to corrosion in reinforced concrete. Virginia Technologies, Incorporated (VTI) has developed, and is currently marketing one device, the ECI-1 Embedded Corrosion Instrument, to monitor the rate of chloride ingress and progression of corrosion in reinforced concrete. The device is capable of performing a variety of measurements including electrical potential, linear polarization resistance (LPR), chloride ion sensing, and resistivity measurements. These measurements can allow corrosion engineers to monitor corrosion activity within reinforced concrete in a non-destructive manner.

This report describes an evaluation performed by the California Department of Transportation (Department) of four ECI-1 devices embedded in laboratory mortar samples. In addition, this report documents the installation of four ECI-1 devices in a bridge deck and presents preliminary field operation data for these devices.

OBJECTIVE

The objective of this research was to monitor the ECI-1 devices in a cement-based matrix to evaluate the effectiveness of the ECI-1 in signaling corrosion activity as measured by the devices sensor parameters of chloride sensing, concrete resistivity measurement, and linear polarization measurement capability. The main thrust of this evaluation was performed in a laboratory on sensors embedded in a cement-mortar matrix. Additional testing was initiated on four ECI-1 devices that were placed into a bridge deck during a deck reconstruction project.

BACKGROUND

Corrosion of reinforcing steel in concrete occurs in the presence of chlorides, moisture and oxygen. The ECI-1 device was developed by VTI to monitor several parameters related to corrosion of reinforcing steel. These parameters include corrosion rate measurements using the linear polarization resistance (LPR) method, open circuit potential (OCP), concrete resistivity, and chloride ion concentration. In addition to these measurements, the ECI-1 device also measures concrete temperature.

Linear Polarization Resistance (LPR)

The polarization resistance (R_p) of a corroding electrode is defined as the slope of a potential versus current density at a current (i) equal to 0 (ASTM G 59-03). Since polarization resistance is a function of electrical potential and charge current flow, it may be used to provide useful information regarding the corrosion rate of steel over time. The term "linear polarization" refers to the concept of determining the best fit straight line to a set of data points (potential versus current) within a small deviation (typically ±20mV) around the corrosion potential that defines the polarization resistance as the slope of the best fit line to the potential versus current plot.

The corrosion rate of an electrode can be obtained from the LPR measurement using a procedure based on the Stern-Geary equation (ASTM G59-97) with some assumptions regarding corrosion kinetics occurring at and around the material being studied (in this case the sample of carbon steel surrounded by cementitious material).

The corrosion rate (measured by the corrosion current I_{corr}) is calculated from R_p as follows:

$$\mathbf{I_{corr} = \frac{B}{R_p}}$$

where **B** is the **Stern-Geary constant** that can be obtained as follows:

$$\mathbf{B = \frac{\beta_a \cdot \beta_c}{2.303(\beta_a + \beta_c)}}$$

and $\boldsymbol{\beta_a}$ and $\boldsymbol{\beta_c}$ are the **anodic** and **cathodic Tafel constants, respectively**.

The Stern-Geary equation indicates that the corrosion rate is inversely proportional to the polarization resistance. Values of B have been reported to range from 26 mV to 52 mV depending on whether the steel is corroding or non-corroding (Broomfield 1997).

It is important to recognize that R_p measurements and I_{corr} calculations can be useful in comparing the relative performance of materials and in studying the long-term performance even if precise corrosion rates cannot be obtained. For example, for reinforcing steel embedded in concrete, determining the exact corrosion rate may not be as important as knowing when a significant change, such as a breakdown in the passive film layer, has occurred.

Open Circuit Potential Measurements
Monitoring the open circuit potential is necessary when performing LPR measurements. In addition, tracking electrical potential over time can also give an indication as to when corrosion has initiated.

Chloride Concentration
The chloride concentration (threshold) needed to initiate corrosion is dependant on a number of factors including moisture content, oxygen availability, and temperature. Typical chloride corrosion threshold values for non-saturated concrete are reported to be about 0.2% to 0.4 % of chloride ion by weight of cement. Although the exact mechanisms of chloride induced corrosion of steel in concrete are not fully understood, it is generally believed that chloride ions incorporate into the passive film on reinforcing steel, replacing some of the oxygen, and increasing the conductivity and solubility of the film (Liu, 1996).

Concrete Resistivity
Bulk concrete resistivity decreases as concrete absorbs moisture and chlorides (Liu, 1996). As the concrete resistivity decreases, ionic flow through the concrete is easier, resulting in higher rates of chemical reactions and increased corrosion rates.

Temperature
Corrosion rates of materials increases as temperature increases, since chemical reactions occur at higher rates with increased temperature.

Combined monitoring of the parameters noted above can give an indication of the relative condition of reinforcing steel over time.

Laboratory testing of the ECI-1 monitoring device was needed to evaluate the effectiveness in signaling corrosion activity accurately and to evaluate the durability of the device in concrete.

ECI-1 SENSOR DESCRIPTION

As previously noted, the ECI-1, Embedded Corrosion Instrument was developed by VTI as a device designed to perform corrosion-related measurements in concrete. The device is relatively small, occupying a space of only about 80 mm by 100 mm (Figure 1).

The ECI-1 device contains an array of five sensors used to perform corrosion-related measurements.

LPR measurements are performed using a carbon steel working electrode fabricated from a small section of steel reinforcing bar, a stainless steel counter electrode, and a manganese dioxide (MnO_2) reference electrode. A silver/silver chloride (Ag/AgCl) ion specific electrode (ISE) is used in combination with the MnO_2 reference electrode as a chloride sensing unit. Changes in electrode potential between the two electrodes may be used to signal a change in chloride concentration. An array of four, parallel, stainless steel wires provide discreet resistivity measurements based on the Wenner 4-pin measurement technique (ASTM G 57). All electrodes are surface mounted at or near the top of the device to provide a measurement plane that can be directed to the area of interest (e.g., the surface of a bridge deck or toward the exterior wall of a concrete column). In addition to the surface mounted electrodes described above, a solid state temperature sensing device in the unit provides temperature readings of the surrounding concrete.

A microcontroller within the polymer body of the ECI-1 sequences all of the sensor measurements, stores and processes individual measurements related to the LPR measurement (outputting a single final measurement result), and controls/allows data acquisition through digital-to-analog (DAC) and analog-to-digital (ADC) converters . The microcontroller is also used to assign a unique data address to the device, and to control the power sequencing of the device when used alone or in combination with other ECI-1 devices. Communication and power to the device is provided through an SDI-12 communications link. Additional information regarding the ECI-1 device may be located at the following web link: http://www.vatechnologies.com/eciIndex.htm

An external datalogger is used to control the frequency of data acquisition to store data for future retrieval.

EXPERIMENTAL DESIGN

Laboratory Testing

Four ECI-1 devices were evaluated in the laboratory. The devices were cast into mortar using forms fabricated from Schedule 40 PVC. Figure 2 shows a photo of the forms used to house the ECI-1 device and mortar during testing. These forms were easy to construct and provided stable platforms to contain the ECI-1 devices and additional electrodes used in this evaluation. Figure 3 shows an additional photo of the PVC forms and the ECI-1 devices prior to placing mortar.

A mortar mix with a ratio of 1 part by mass water, 2 parts by mass cement, and 4.5 parts by mass sand was used for the evaluation. This mix provided a workable mortar that could be placed into the molds and consolidated with minimal vibration using a vibration table and three lifts of mortar. Samples were prepared in accordance with ASTM Designation: C192, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. The ECI-1 devices were placed into the molds to provide a mortar cover of approximately 25 mm over the working electrode.

Figures 4 through 8 show photos of the PVC assembly and mortar mixing/placing operations. Each sample was identified with an "address" (name) identification used by the SDI communications.

All samples were cured in a moisture fog room for a period of 28 days prior to initiating the testing as shown in Figure 9.

In order to evaluate the ability of the ECI-1 devices to detect changes in the mortar as chloride concentrations increased over time, chlorides were artificially drawn into the mortar matrix using the external power supply and anode/cathode arrangement shown in Figures 10 through 12. With this arrangement, chlorides from a 3.5 % by mass sodium chloride solution held in the reservoir at the top of the sample mold were drawn into the mortar matrix. The power supply potential was set at 20 Volts, and applied for an initial 12-hour cycle. After a rest period of a minimum of 48-hours, electrochemical corrosion measurements were obtained. This sequence was repeated once, and then the power cycle increments were decreased to 6-hours, with a continued 48-hour minimum rest periods between electrochemical measurements. The 6-hour power cycles were continued with 48-hour minimum rest cycles prior to performing electrochemical tests until the corrosion current density of each sample approached $10\mu A/cm^2$, based on a surface area of 6.967 cm^2 supplied by VTI. Additional information regarding the testing sequence is provided in Appendix B.

The ECI-1 devices are typically supplied with leads for SDI communication. For this evaluation, two of the four ECI-1 devices were also supplied with additional test leads (breakout leads) that provided direct access to the ECI-1 working electrode, reference electrode and counter electrode. This was provided so that a direct comparison could be made between the measured data of the ECI-1 and data obtained from external electrochemical testing equipment. In addition to the breakout leads, two Chromel D (chromium-nickel alloy) wires were added to the sample molds used to hold the ECI-1 devices and the mortar matrix as an additional reference and counter electrode.

When a sample reached a corrosion current approached $10\mu A/cm^2$, testing was terminated, and the sample was sectioned to observe and document the condition of the working electrode, and to obtain the chloride concentration of the mortar adjacent to the working electrode. The molds were sectioned by making saw-cuts around the perimeter of the molds to a depth of approximately 25 mm at the split between the lower and upper half of the mold. This location was near the top surface of the working electrode. A nylon mesh inserted in the mold during fabrication between the lower and upper half of the mold (in addition to the saw cut after testing) facilitated splitting of the sample at or near the surface of the working electrode by providing a break line. The break line allowed the samples to be split apart with the working electrode imprint directly exposed on one-half of the sample. Chloride sampling was achieved using a profile grinder to obtain a small amount of mortar from at the location of the working electrode imprint in the mortar.

Chloride sampling was performed using a Germann Instruments profile grinder. Mortar powder samples were carefully obtained from the working electrode imprint area left in the mortar section contained in the upper half of the sample mold after dismantling. Chloride analysis was performed using CTM 404.

Field Testing

To evaluate the long-term (10-year or more) performance of the ECI-1 devices in actual concrete, four ECI-1 devices were installed in a replacement bridge deck on The Sacramento River Bridge at Antlers located on Interstate 5 in Shasta County at Lake Shasta, SHA-02-005-R040.16, Bridge Number 06-0089. The bridge is often referred to as the "Antlers Bridge", due to it's proximity to the nearby town of Antlers. It was selected since the deck is subjected to deicing salt applications during winter snow periods. The entire bridge is scheduled for replacement within 10 to 12 years. However, the deck was being replaced under a repair contract (EA: 02-0C8704) since it was severely deteriorated due to corrosion (spalling) and cracking. The deck replacement was considered to be a temporary measure. As such, the typical construction practices of using mineral admixture concrete and epoxy-coated reinforcement were not employed. In addition, stay-in-place deck forms were allowed.

For long-term installations, VTI recommended that the ECI-1 devices collect data no more than once every 2 weeks to minimize damage to the working electrode (personal communication, May 17, 2004) that could occur due to repeated LPR measurements. For the Antlers bridge deck installation, three of the ECI-1 devices, Addresses 0, 1 and 2, collect data twice a month. Since Address A, is collecting data twice a day, only the resistivity and temperature measurements are relevant.

The data collection program for the field datalogger was originally configured to collect data simultaneously from all ECI-1 units. However, this configuration resulted in an erroneous spike in data for the Address A unit during each collection cycle. The data collection configuration was changed to sequential (with each unit completing its measurement cycle prior to the next unit initiating a measurement) in June 05. This change in data collection sequence seems to have eliminated the spike in data collection for Address A.

Figures 13 through 17 show the Antlers Bridge, placement of the ECI-1 devices in the Southbound No. 2 Lane, and a schematic drawing indicating the location of the ECI-1 devices.

A datalogging system with a cellular phone unit was added to the installation to allow for remote access monitoring. The ECI-1 devices, datalogger, and cellular phone unit are powered by a solar power panel mounted on the bridge. A gel-cell battery is used to store power from the solar panel. Figures 18 through 23 show the datalogger system and solar panel installed at the site.

Two programs were developed to control the collection of data at the Antlers Bridge site. The first program collects solar panel voltage output and battery charge as well as data from the ECI-1 Address A device. Data from this program is collected twice daily (once at 12:00 AM and once at 12:00 PM). The second program reads data from ECI-1 Devices, Addresses 0, 1 and 2 on a schedule of twice a month. Additional information about remote access to the datalogger and its software and hardware is listed in Appendices C through E.

TEST RESULTS AND DISCUSSION

Linear Polarization Testing

The results of the laboratory LPR testing are presented in Figures 24 through 27. These figures illustrate the results of LPR measurements using a comparison of corrosion current (I_{corr}), calculated using a working electrode area of 6.967 cm^2 (provided by VTI) and an assumed B value of 26 mV (corresponding to β_a and β_c values equal to 120 mV per decade).

As previously mentioned chromel wire electrodes were used in addition to the ECI-1 mounted electrodes for comparison LPR measurements. In addition, LPR measurements were performed using the on-board ECI-1 measurement capability and an external potentiostat (PAR 273A), also for comparison where breakout leads were available (ECI-1 devices 2 and 3).

LPR measurements performed using the PAR 273A for ECI-1 devices 2 and 3 were in good agreement with measurements obtained using the on-board LPR measurement capabilities of the ECI-1 (Figure 27). As expected, high polarization resistance readings were obtained during the initial stages of the testing. As chloride levels at the surface of the working electrode increased, corrosion activity increased as evident by the decrease in polarization resistance and corresponding increase in corrosion current (I_{corr}).

An increase in corrosion current for ECI-1 devices, Address 1, 2, and 3 occurred after about 120 to 130 hours of accelerated chloride ponding, with additional significant increases in corrosion current occurring at or beyond about 170 to 180 hours.

LPR measurements obtained on Address 0 indicated an increased level of corrosion current (Figure 24) much sooner, at about only 40 hours of accelerated ponding, relative to the other ECI-1 devices. It is not clear why this occurred. However, it is possible that the sample may have been compromised during fabrication, although this was not readily apparent.

Open circuit potential (OCP) measurements for the lab samples are shown in Figure 28. In general, OCP measurements were consistent with LPR measurements for the ECI-1 devices. OCP measurements for Address 0 indicated increasingly corrosive potentials soon after accelerated ponding was initiated (at or about 40 hours). OCP potentials for the remaining ECI-1 devices dropped significantly at later stages of accelerated ponding, corresponding to decreases in LPR values (increases in corrosion current).

The counter electrode and reference electrode configuration of the ECI-1 devices showed good stability during the duration of the laboratory testing, and were consistent with data obtained using the external chromel wire electrodes installed in the sample molds for comparison.

LPR measurements for the ECI-1 devices installed at the Antlers Bridge have so far indicated "out of range" values, and are not able to be reported at this time. The new concrete deck at the Antlers Bridge has been in-service for less than 1-year and is not yet expected to show signs of significant chloride intrusion. As such, out of range polarization readings are expected due to the relatively high resistance of the new deck concrete.

Electrochemical Impedance Spectroscopy (EIS) Testing

Polarization resistance was periodically measured for the two lab samples with breakout leads at later stages of the evaluation using Electrochemical Impedance Spectroscopy (EIS) testing. The excitation platform consisted of an alternating sinusoidal waveform with an amplitude of 10 mV, applied with respect to OCP over a frequency range of 10 kHz to 100 mHz. The equipment used included the use of a Solartron Frequency Response Analyzer in conjunction with a PAR 273A Potentiostat.

The results of the EIS measurements (shown in Figure 29) show a similar trend to that of the LPR testing, with a decrease in polarization resistance over time as would be expected with increased corrosion activity. Calculated I_{corr} values were slightly lower than the values obtained using the LPR method, but were on the same order of magnitude.

Resistivity Measurements

Resistivity measurements for the four laboratory ECI-1 devices are presented in Figure 30. The ECI-1 device reports a resistivity value in ohm-cm. Based on information from the ECI-1 website, the values are obtained using an array of four-parallel stainless steel wires. Typically, concrete resistivity will change depending on the localized presence of moisture and chlorides. This has been demonstrated by studies of electrochemical chloride extraction (ECE) techniques where external power sources were used to move chlorides through concrete samples (Sharp et al, 2002). Typical trends are that bulk concrete resistivity decreases with increased moisture and chloride concentration. The ECI-1 device does not measure the bulk resistivity. Instead, a discreet or "apparent localized resistivity" measurement is obtained within a specific zone of influence around a four-pin array mounted on the top of the ECI-1 device. Resistivity measurements showed some instability for each of the four ECI-1 devices included in this study. However, the general trend showed an increase in localized resistivity as measured by each device.

A possible explanation for the observed increase in apparent localized resistivity relates to the ionic conductivity of the dominant species present in the pore water solution surrounding the 4-pin resistivity array at the time of measurement. In concrete (or mortar) without the presence of chlorides, the pore water solution contains an abundance of hydroxyl ions. As chlorides migrate into the concrete, the displacement of hydroxyl ions could lead to an increase in localized resistivity since the ionic conductivity (reciprocal of resistivity) of the hydroxyl ion is greater than that of the chloride ion.

Discreet localized resistivity measurements such as obtained by the ECI-1 device may not be of great benefit. It may be of more interest to know the overall bulk resistivity of a concrete matrix when considering corrosion activity in concrete structures. There was no observance of a sharp change in apparent localized resistivity that coincided with the increase in corrosion activity as evident by LPR measurements or OCP measurements for any of the ECI-1 samples.

The results of the resistivity measurements collected from the four ECI-1 devices installed at the Antlers Bridge are shown in Figure 31. The measurements are not stable and are not providing any useful information regarding the concrete resistivity at this time.

Chloride Sensor Measurements

Chloride potential data for the four lab ECI-1 devices are presented in Figure 32. Information provided by VTI regarding the ECI-1 chloride sensor indicates that the chloride data is obtained as a potential measurement between the on-board Ag/AgCl ion specific electrode (ISE) and the MnO_2 reference electrode. In concept, the electrical potential between the two electrodes will change as the chloride concentration in the surrounding concrete changes. Based on a discussion provided on VTI's website, normal operation of the ECI-1 device provides for a numeric value reported as three specific values (1 = high Cl^- concentration, 2 = moderate Cl^- concentration, 3 = low Cl^- concentration). For this study, the devices were configured to report the actual voltage differential between the two electrodes. This was done to allow data collection for calibration future planned calibration testing.

Chloride voltage potentials for all devices were fairly consistent. As ponding time increased, the voltage decreased. During the earlier stage of testing, some of the chloride measurements were unstable. Research done at University of Virginia showed that the Ag/AgCl sensor is erratic at low chloride concentrations (Presuel-Moreno, 2005). A calibration factor correlating the chloride voltage with chloride concentration was not determined in the above-mentioned study. Future work is needed to study the long-term performance of these electrodes in cementitious based material and to develop calibration curves to correlate the voltage readings with actual chloride concentrations.

Chloride sensor data obtained from the ECI-1 devices installed at the Antlers Bridge is shown in Figure 33. There is no clear interpretation of the field data at this time. The bridge deck was recently constructed (May/June 2004), and no salting has occurred to date.

Temperature Measurements

Temperature measurements were logged by the ECI-1 devices for all laboratory samples and are shown in Figure 34. Temperature measurements were stable and consistent for all ECI-1 devices.

Field temperature measurements are presented in Figure 35. The measurements are consistent with temperature variations at the project site, and are nearly identical for each ECI-1 device.

Forensic Evaluation of Test Samples

Figures 36 through 41 show photos of the ECI-1 samples after they were sectioned, and prior to chloride sampling. Corrosion products were visible on the working electrodes of all samples.

Chloride data obtained by profile grinding of the mortar adjacent to the working electrode surface indicated that chloride thresholds had been exceeded. For all samples, chloride concentrations near the working electrode surface exceeded 3% by mass of cement. These values were well beyond the 0.2% by mass required for corrosion initiation, and were consistent with observed corrosion observed on surfaces of the working electrodes of each ECI-1 device.

CONCLUSIONS

The following conclusions are based on the laboratory and field evaluation of the VTI, ECI-1 devices included in this study.

- Linear polarization resistance (LPR) measurements conducted using the ECI-1 devices were consistent with LPR measurements performed using external electrochemical testing equipment.
- LPR measurements conducted using the auxiliary electrodes introduced in the mortar molds were consistent with results obtained using the ECI-1 supplied electrodes.
- LPR measurements gave a reasonable indication of corrosion activity of the working electrodes as verified by visual observations of the working electrodes at the completion of the electrochemical testing.
- The four-pin resistivity measurements showed increasing values with time. It may be more appropriate to refer to the resistivity measurement as an "apparent localized resistivity" to distinguish the value from a typical "bulk resistivity" measurement. The bulk resistivity of concrete/mortar typically decreases with increased moisture and chlorides. The observed decrease in localized resistivity may be attributed to the displacement of hydroxyl ions by chloride ions in the pore water in the vicinity of the four-pin resistivity array of the ECI-1 device.
- Although there was a trend of increasing localized resistivity for all ECI-1 devices, there was no observance of a sharp change in apparent localized resistivity that coincided with the increase in corrosion activity as evident by LPR measurements or OCP measurements for any of the ECI-1 samples.
- Potential measurements (Ag/AgCl ion specific electrode versus MnO_2) reference electrode measurements were consistent for all ECI-1 devices. Overall, there was a slight negative trend in voltage. The correlation between the voltage and chloride concentration has not been determined by other research.

RECOMMENDATIONS

Based on the findings of this study, the authors have the following recommendations:

1. Continue monitoring the ECI-1 devices installed at the Sacramento River Bridge at Antlers (Antlers Bridge) site. Monitoring the devices will provide useful information regarding the long-term durability of the ECI-1 sensor package in an actual concrete service environment.
2. Monitor the development/refinement of chloride and resistivity sensors such as used on the ECI-1 devices. The authors recognize that additional work is needed to improve the reliability of embeddable sensors for chloride and resistivity measurements.

REFERENCES

1. ASTM Designation: C192-05, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory", American Society of Testing and Materials (ASTM) International, Conshohocken, PA.
2. ASTM Designation: G 57-01, "Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method", American Society of Testing and Materials (ASTM) International, Conshohocken, PA.
3. ASTM Designation: G-59-03, "Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements", American Society of Testing and Materials (ASTM) International, Conshohocken, PA.
4. Broomfield, J., *Corrosion of Steel in Concrete: Understanding, investigation and Repair*, 1st Ed., 1997.
5. Fontana, Mars G., and N.D. Green., *Corrosion Engineering*, 2nd Ed., McGraw Hill, Inc., New York, 1978.
6. Gopalakrishnan, Radhakrishna, Pillai., "Accelerated Quantification of Critical Parameters for Predicting the Service Life and Life Cycle Costs of Chloride-Laden Reinforced Concrete Structures," M.S.Thesis, Office of Graduate Studies of Texas A&M University., 2003.
7. Kelly, R.G., J. Yuan, S.H. Joanes, W/Wang, K. Hudson, A. Sime, O. Schneider, G.G. Clemema., "Embeddable Sensor for Corrosion Measurement," SPIE Conference, Newport Beach, March 1999.
8. Liu, Y., "Modeling the Time –to-Corrosion Cracking of the Cover Concrete in Chloride Contaminated Reinforced Concrete Structures," PhD Dissertation, Charles E. Via Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA., 1996.
9. Princeton Applied Research (PAR) Application Note Corr-4: Electrochemistry and Corrosion Overview and techniques, Electrochemical Instruments Division, PAR, Oak Ridge, TN.
10. Princeton Applied Research (PAR) Technical Note 101: Potential Error Correction (iR Compensation), Electrochemical Instruments Division, PAR, Oak Ridge, TN.
11. Ramniceanu, Andrei., "Correlation of Measurements and Bridge Conditions with NBIS Deck Rating," M.S. Thesis, Department of Civil and Environmental Engineering, University of Virginia Polytechnic Institute and State University, 2004.
12. Sharp, Stephen R., Gary G. Clemena, Y. Paul Virmani, Glenn F. Stoner., Robert G. Kelly., "Electrochemical Chloride Extraction Influence of Concrete Surface on Treatment," FHWA-RD-02-107, Virginia Transportation Research Council., September 9, 2002.
13. Presuel-Moreno, Francisco J., "Investigation to Characterize/Calibrate Chloride Sensor by Using Ag/AgCl Electrode," University of Virginia, 2005.

APPENDIX A (FIGURES)

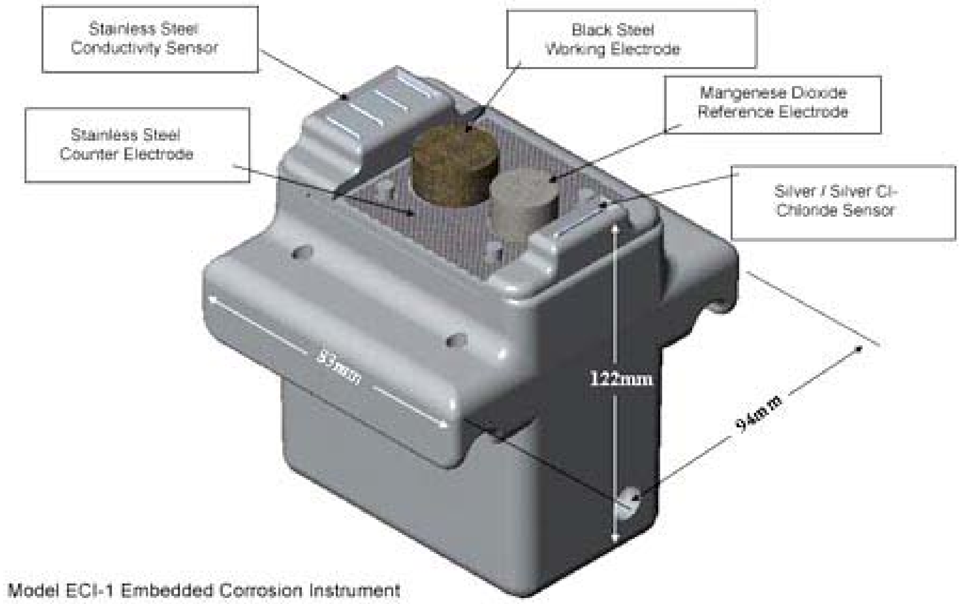


Figure 1 Schematic of VTI, ECI-1 Embedded Corrosion Instrument showing the placement of the LPR sensors, conductivity sensor and silver/silver chloride sensor. (Photo provided by VTI)

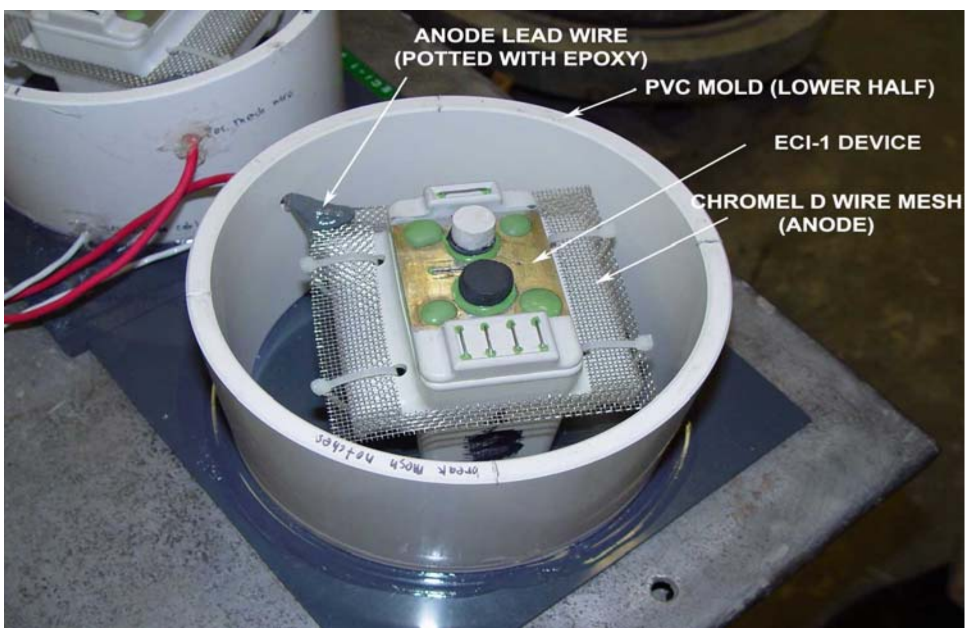


Figure 2 Lower half of PVC mold with ECI-1 device prior to placing mortar. This ECI-1 device was not fitted with breakout leads to the working electrode, counter electrode and reference electrode components of the ECI-1 device.

Figure 3 Molds with ECI-1 devices prior to placing mortar. The white coiled cable is the standard SDI communication cable supplied with the ECI-1 devices. The non-white leads shown coiled on the table are the breakout leads that connect to electrodes of two of the ECI-1 devices.

Figure 4 Paddle mixer used for mixing mortar. Remaining water is being added.

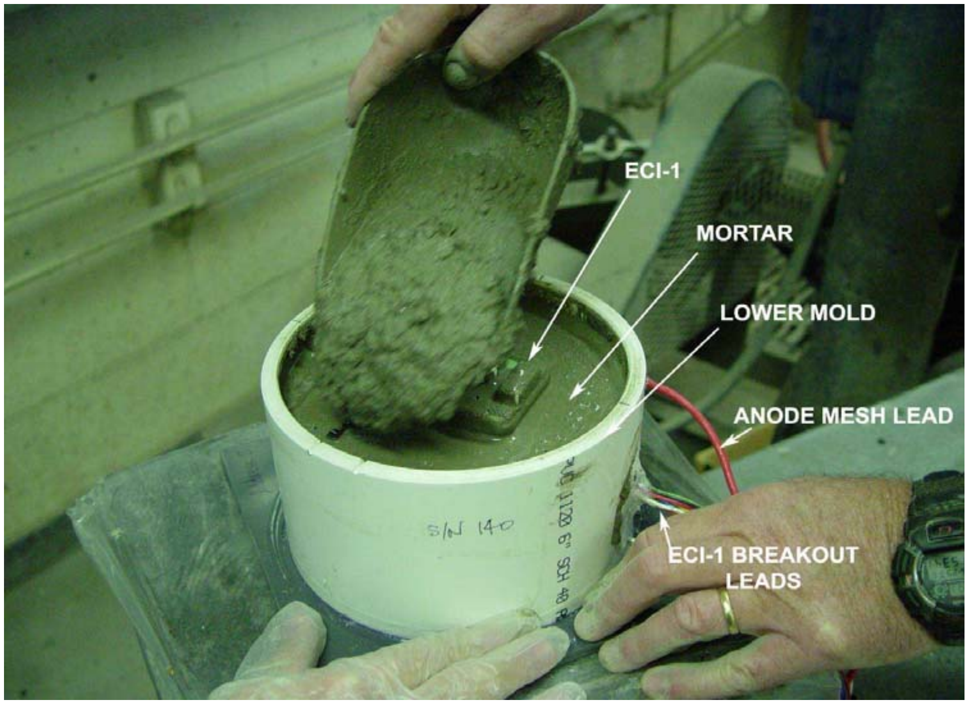


Figure 5 Placing mortar in lower PVC mold. A vibratory table was used to consolidate the mortar during placement.

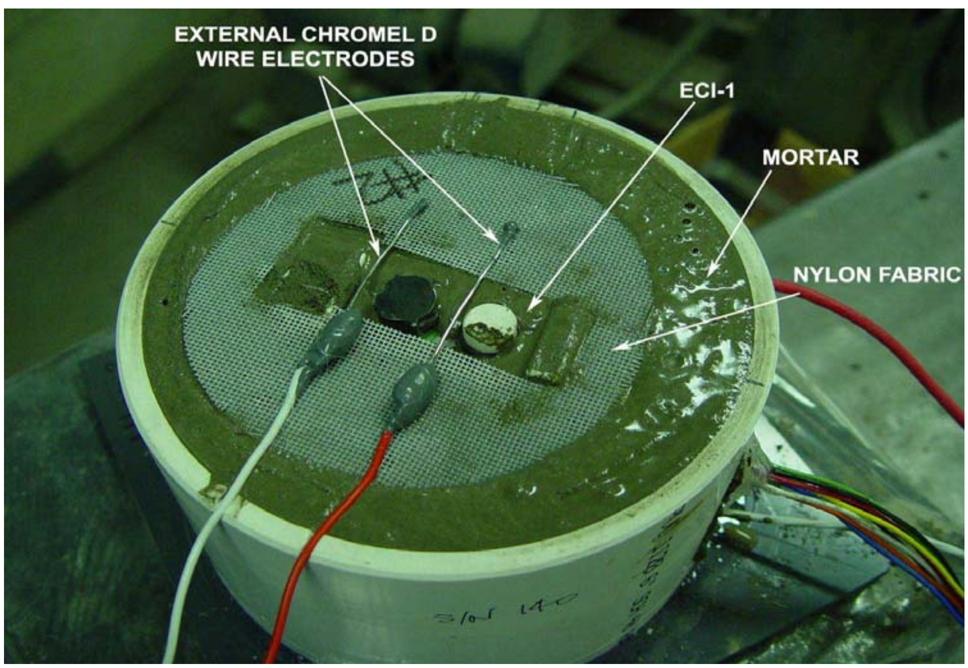


Figure 6 Lower mold has been filled. At this point in the assembly process, a nylon mesh has been added and two external Chromel D wire electrodes have been placed. The nylon mesh acted as a support for the electrodes (to maintain the electrodes at or near the surface of the working electrode) and as a natural break when the sample was later dismantled.

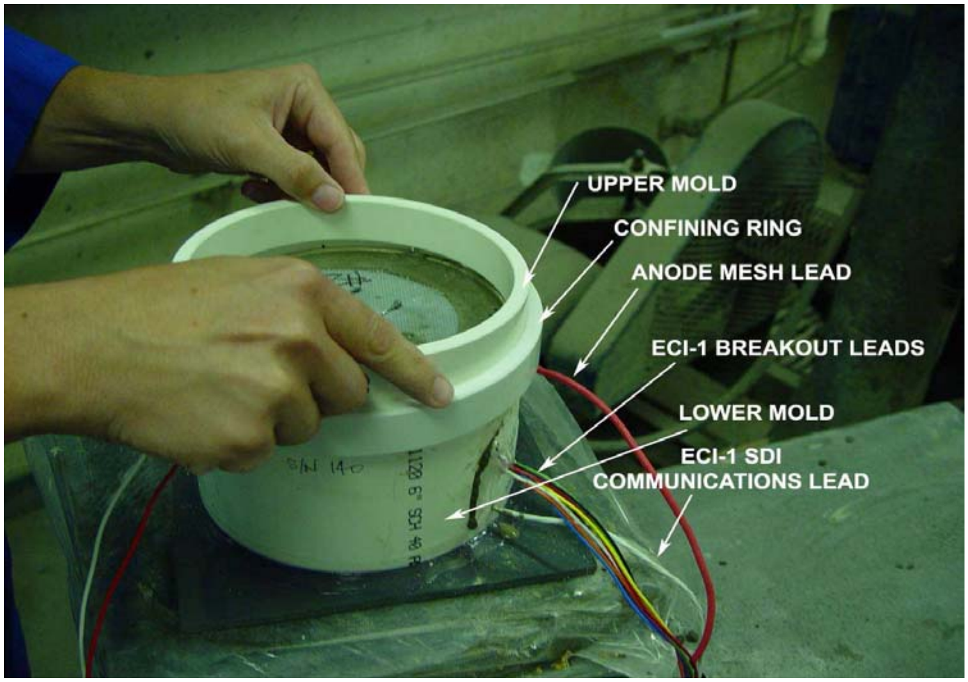


Figure 7 Here the upper mold section of the form is being added. The form was divided into sections to aid disassembly after testing. The confining ring was used to keep the two halves of the form together.

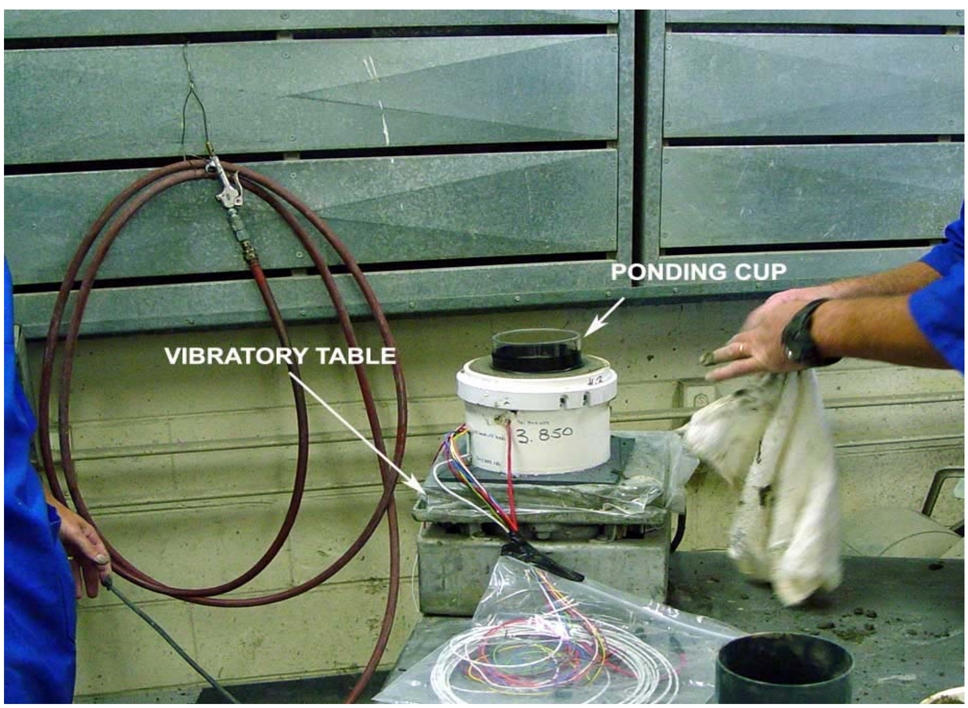


Figure 8 The ponding cup shown in the photo was added by gently pressing a clear plastic tube into the surface of the mortar approximately ¼ inch. The tube was marked with tape and an O-ring was added to the lower half to facilitate a water-tight seal prior to inserting it into the mortar.

Figure 9 Lab samples curing in a moisture fog room. All samples were cured for 28 days prior to testing.

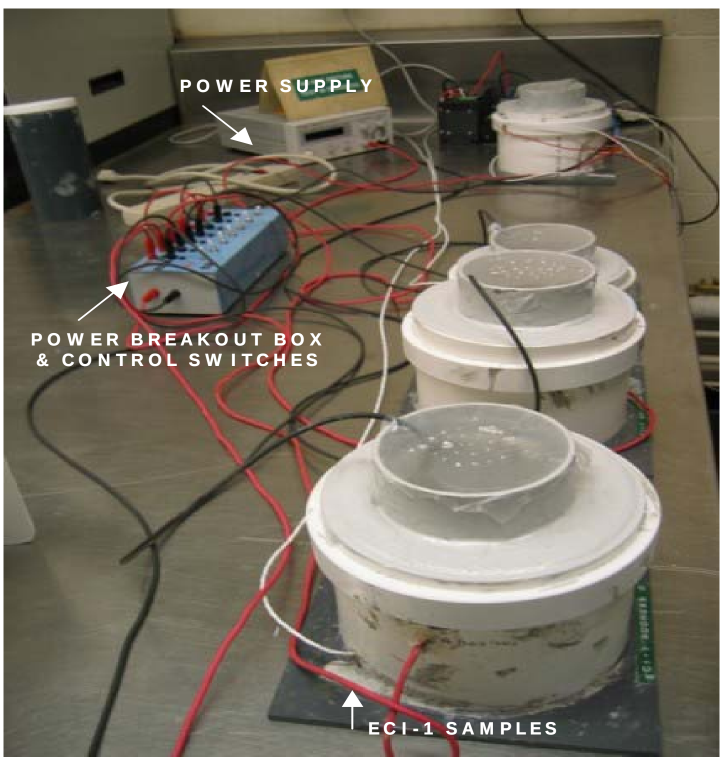


Figure 10 Lab set-up showing samples being ponded. The ponding cups were covered with Parafilm (wax paper) to minimize evaporation of the ponding solution. Epoxy was also added to prevent leakage of the ponding solution.

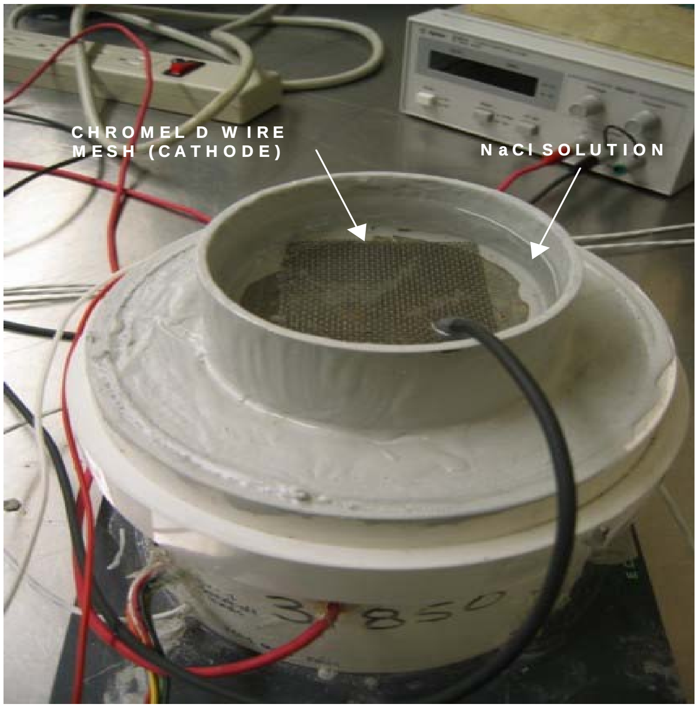


Figure 11 Individual ECI-1 sample being ponded. The NaCl solution was changed every week or as needed to maintain pH and chloride level of the ponding solution.

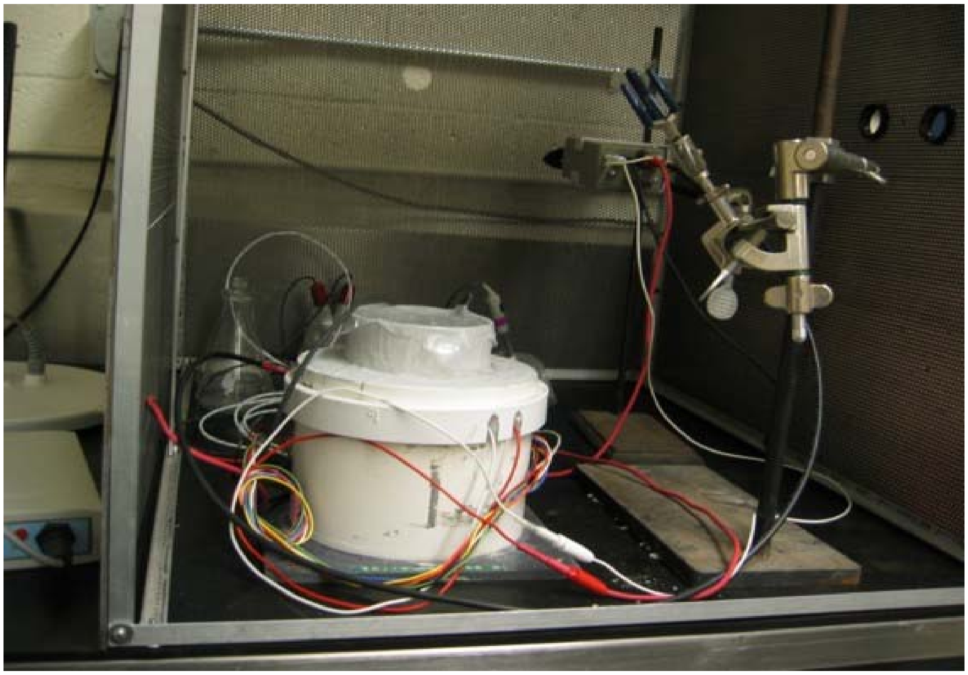


Figure 12 Lab samples were placed in a Faraday cage grounded cage to minimize electrical interference during LPR and AC impedance testing.

Figure 13 Aerial photo of the Sacramento River Bridge (Antlers Bridge) located in Shasta County (at Lake Shasta) in Northern California. This site was selected for the ECI-1 field installation site.

Figure 14 Antlers Bridge in Shasta County. The reinforced concrete deck is subjected to deicing salts during the winter months. The deck was being replaced due to corrosion and corrosion related spalling. The ECI-1 devices were installed into the deck replacement.

Figure 15 Antlers Bridge. View of Southbound No. 2 lane. Plain (uncoated) reinforcement and stay-in-place deck forms were used for the deck replacement. Plain reinforcement and stay-in-place forms are not typically used in areas where deicing salts are applied. However, these options were allowed, since it is anticipated that the entire bridge will be replaced within 10 to 12 years. The cones in were placed over the ECI-1 units to mark their position prior to concrete placement.

Figure 16 ECI-1 installed at Antler's bridge in Shasta County, CA. Epoxy-coated reinforcement was used to hold the ECI-1 in place. As previously noted, plain (uncoated) reinforcement and stay-in-place deck forms are not typically used in areas where deicing salt is applied. However, these options were allowed, since it is anticipated that the entire bridge will be replaced within 10 to 12 years.

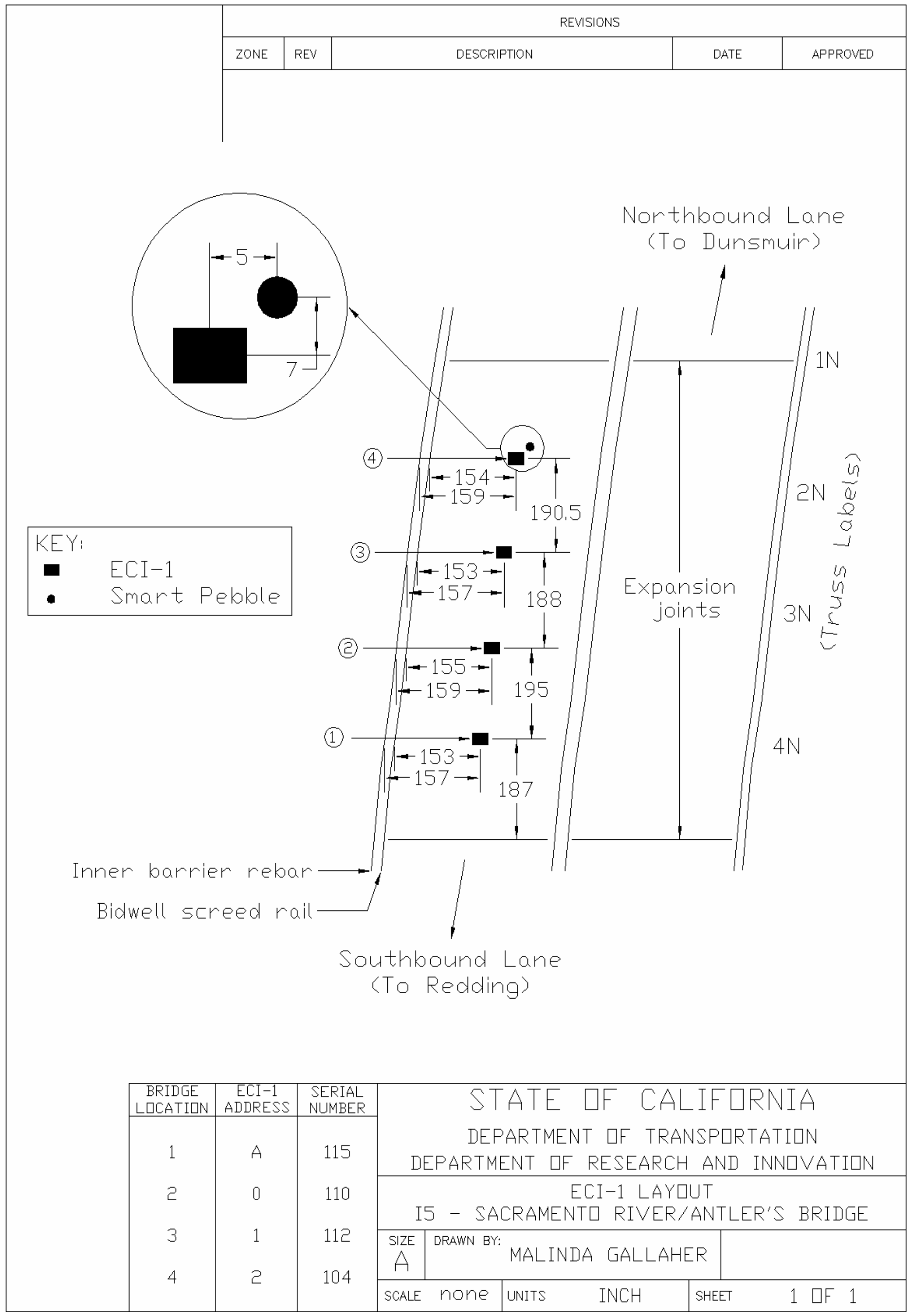
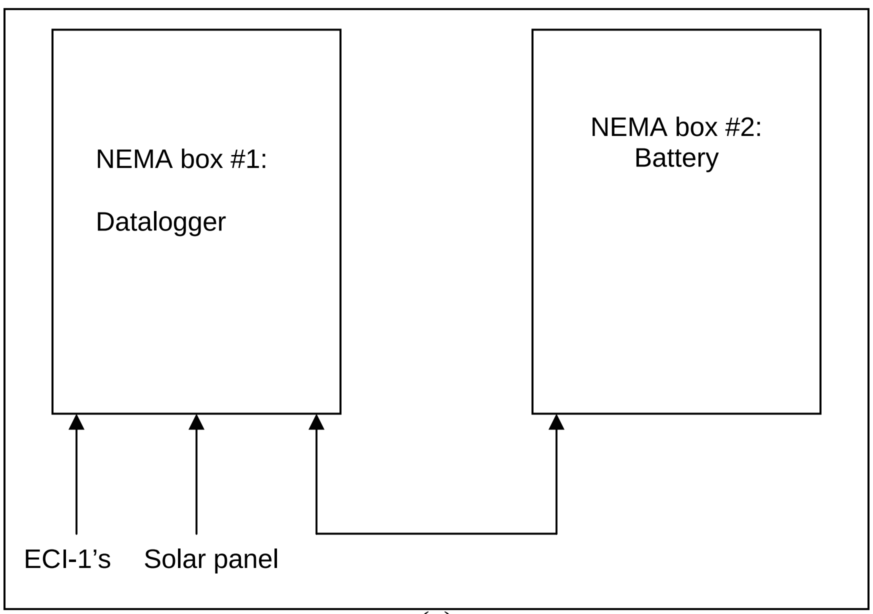


Figure 17 Diagram showing the location of the ECI-1 devices in the Antlers Bridge deck. The deck replacement was performed under Contract 02-0C8704. The Bridge is located in Shasta County on Interstate 5 in District 2.

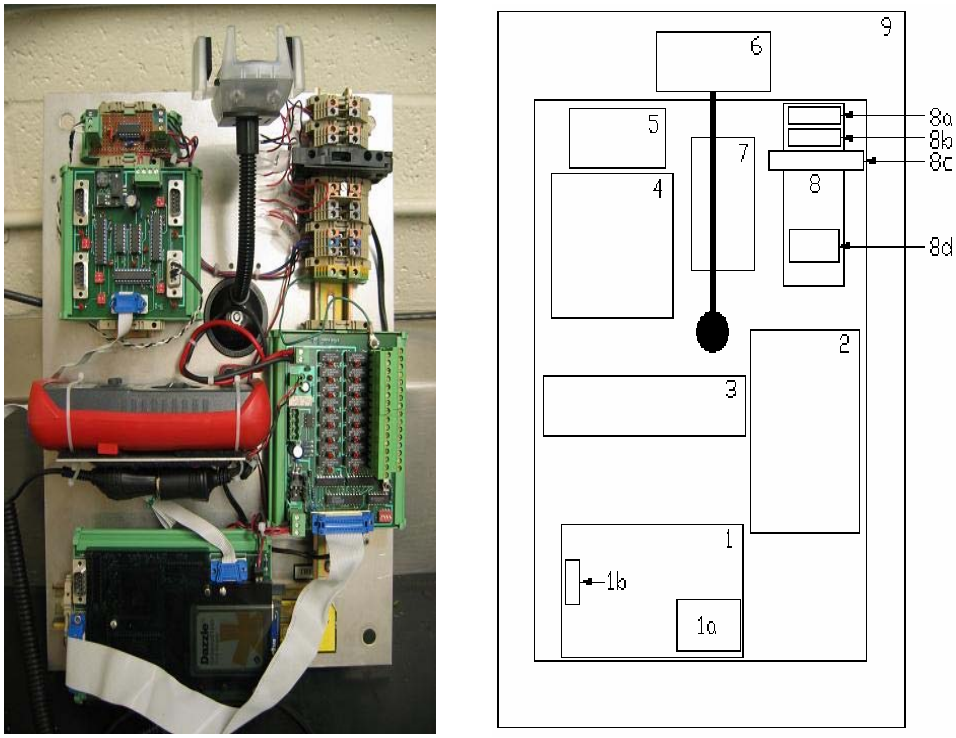
(a)

(b)



(c)

Figure 18 **(a)** Datalogger used to record readings from the ECI-1 devices installed at the Antlers Bridge. **(b)** Battery that supplies power to the datalogger and ECI-1 devices. Both the datalogger and battery are mounted below the bridge in an access compartment near the bridge catwalk. Voltage in the battery is maintained by a solar panel mounted off the side of the bridge. **(c)** Schematic layout of the datalogger and battery box.



(a) **(b)**

Figure 19 (a) Close-up of datalogger. (b) Schematic representation of datalogger.

Item #	Description	Notes
1	Datalogger	Assembled by Environmental Data Systems (edsc@bellsouth.net)
1a	Compact Flash card	64 MB
1b	Serial port	Direct serial connection
2	Relay board	Environmental Data Systems
3	Voltmeter	
4	Device control board	
5	SDI-12 conversion board	
6	Cell phone holder	Holds Kyocera 2325
7	Solar charge controller	Specialty Concepts, Inc – Automatic Sequencing Charger (www.specialityconcepts.com)
8	Power ports	Environmental Data Systems
8a	Solar panel port	
8b	Battery port	
8c	Fuse	
8d	Port to VTI DL-10 breakout board	
9	Mounting board	

Figure 20 Description for the schematic shown in Figure 19 (b).

Figure 21 Photo of catwalk and utility box below the bridge deck. The datalogger is housed in the utility box. The solar panel is installed directly above the utility box on the side of the bridge.

Figure 22 Close-up of solar panel mounting rack. The rack was installed on the outside railing out of the view of moving traffic, and in a location on the bridge to maximize daylight exposure. .

Figure 23 Solar panel (view from bridge deck).

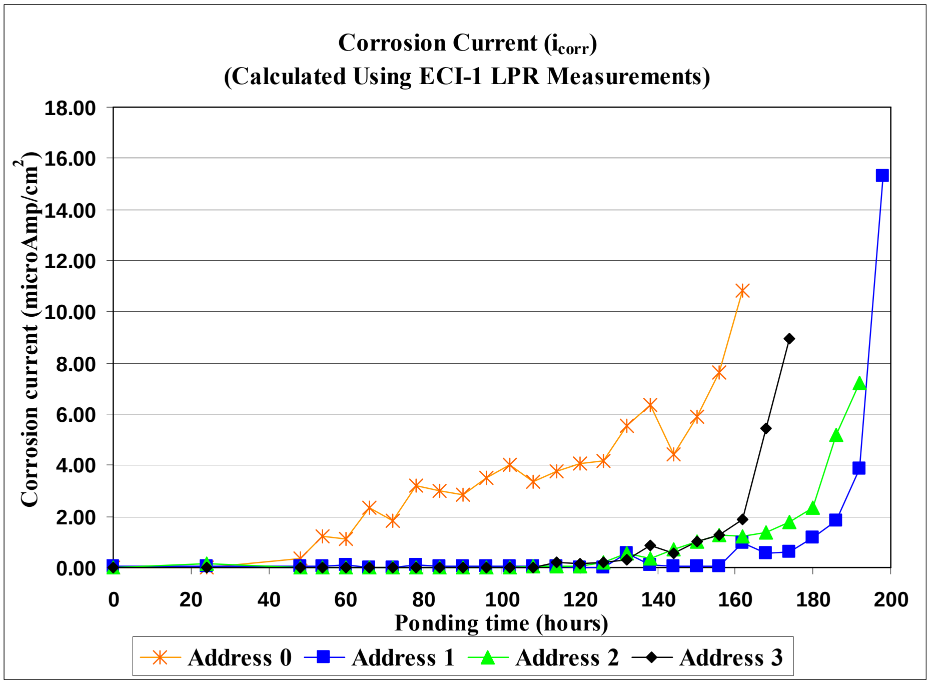


Figure 24 Corrosion currents measured using the internal LPR measurement capability of the ECI-1 devices (lab samples) with their electrodes. As was previously discussed, chloride ingress was controlled using an external power supply. The ponding time in hours represents the cumulative time that of power on cycle that was achieved prior to obtaining each LPR data point.

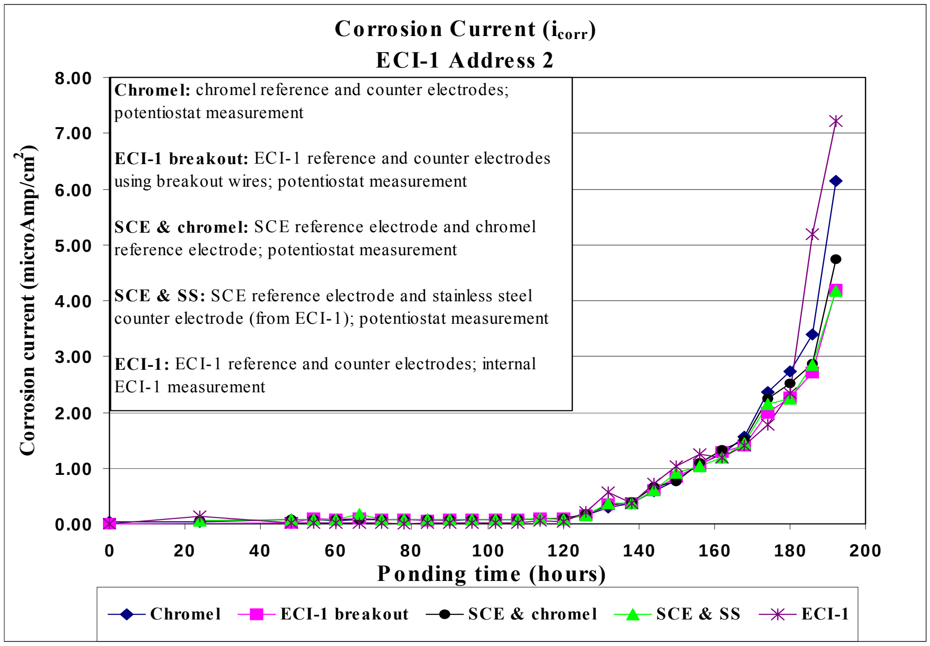


Figure 25 Corrosion currents for Address 2 (lab sample) , measured using the breakout electrodes (wire leads provided by VTI with direct access to the ECI-1 electrodes) and additional electrodes placed in the mortar samples. Measurements were consistent between each set of electrodes.

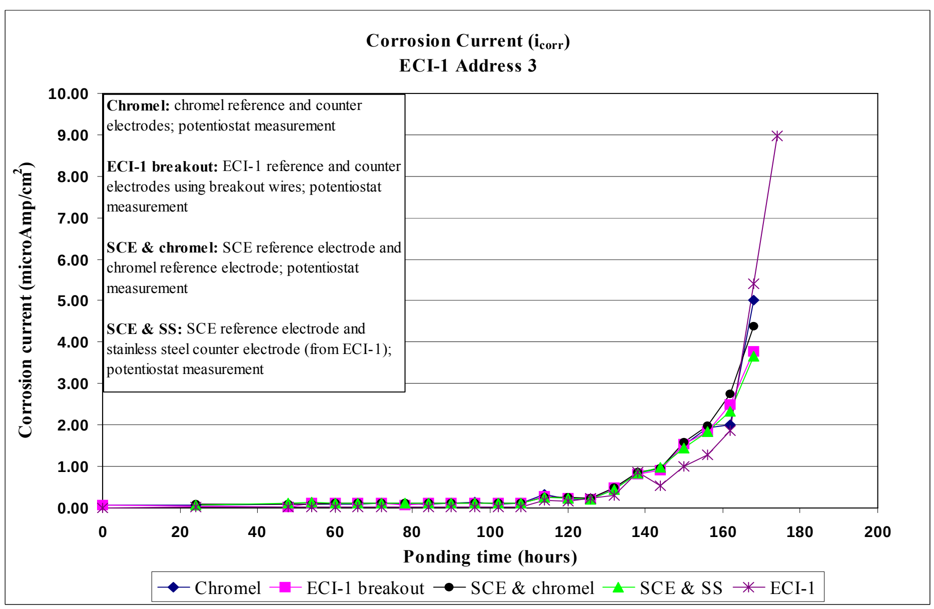


Figure 26 Corrosion currents for Address 3 (lab sample), measured using the breakout electrodes (wire leads provided by VTI with direct access to the ECI-1 electrodes) and additional electrodes placed in the mortar samples. Measurements were consistent between each set of electrodes.

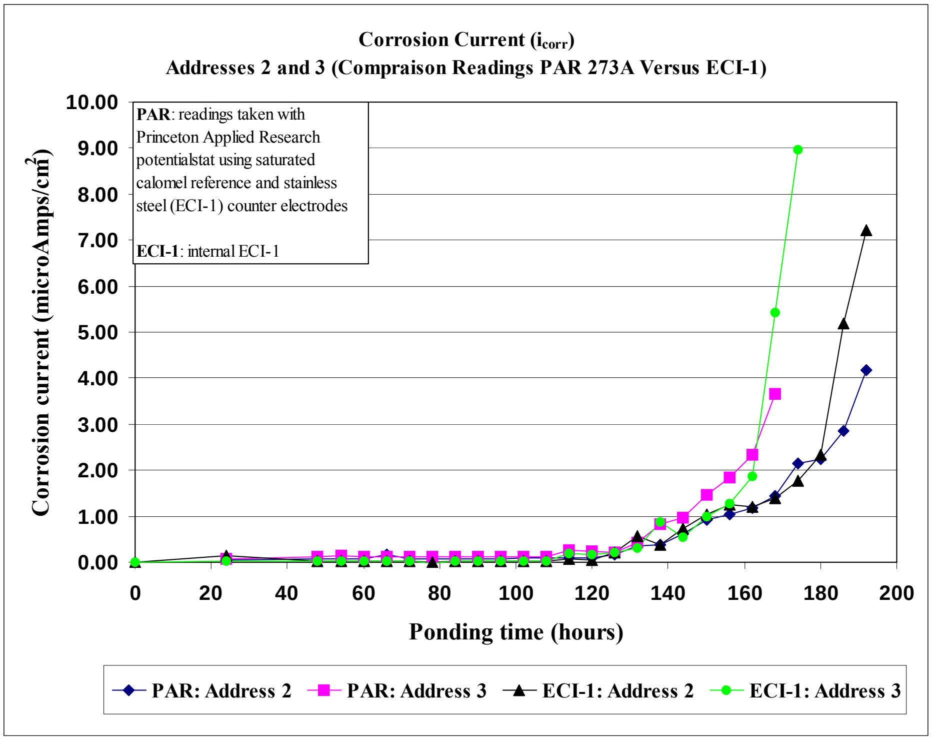


Figure 27 Comparison of LPR (calculated I_{corr}) readings using a PAR 273A Potentiostat and the ECI-1 LPR capabilities for Address 2 and 3 (lab samples).

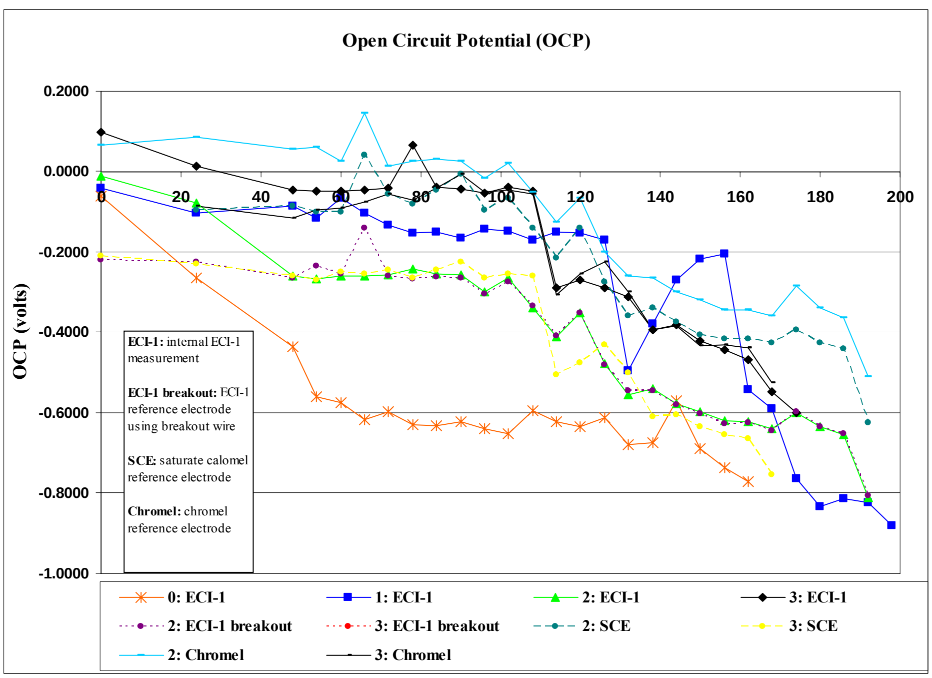


Figure 28 Open circuit potential measurements obtained using a range of electrodes. The numbers represent the Address ID for each sample.

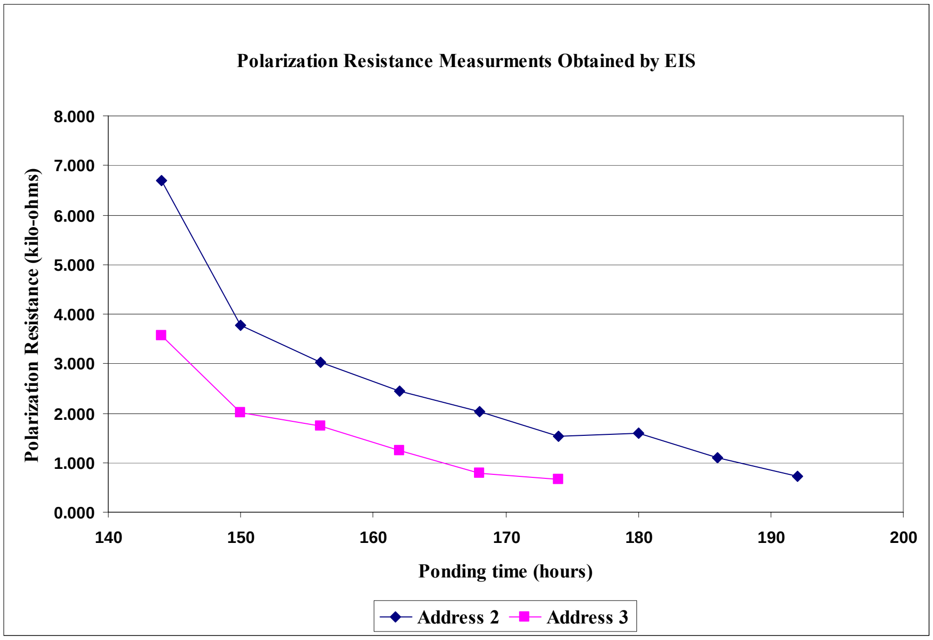


Figure 29 Polarization resistance measurements obtained using a Solartron Frequency Response Analyzer in conjunction with a PAR 273A Potentiostat for lab samples, Address 2 and 3.

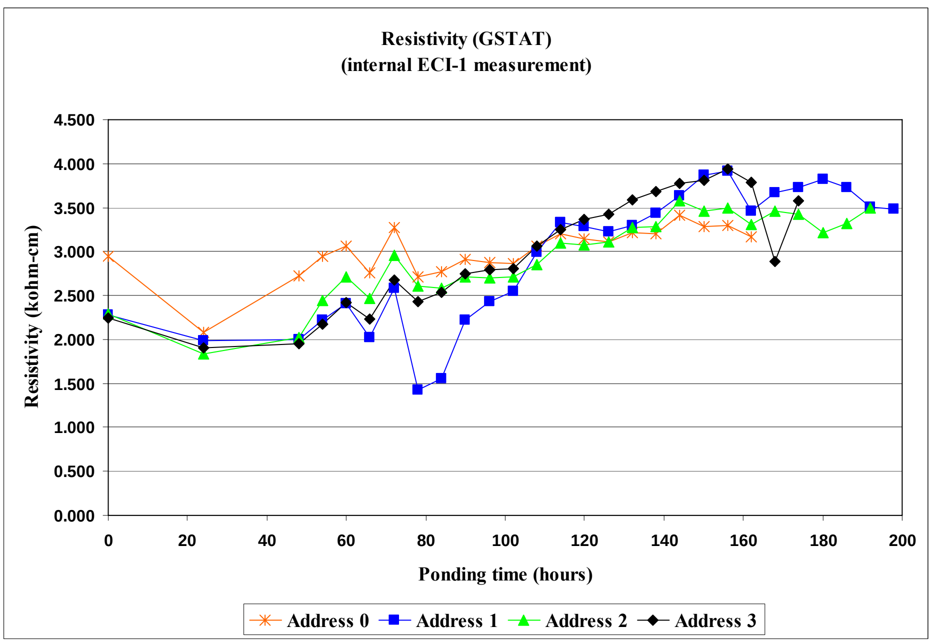


Figure 30 Resistivity measurements obtained using the 4-pin array on the ECI-1 devices (lab samples).

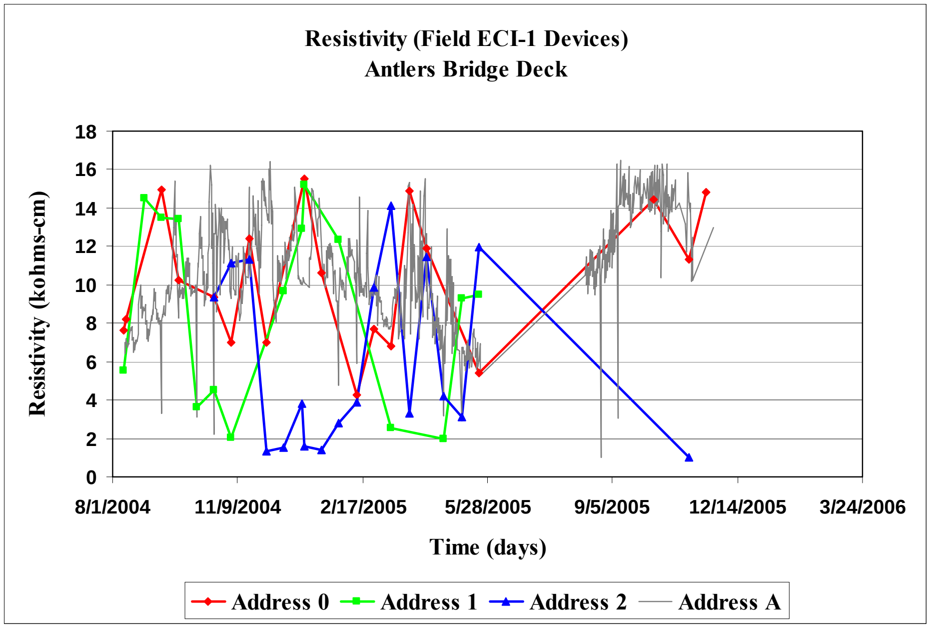


Figure 31 Resistivity measurements obtained using the 4-pin array on the ECI-1 devices installed at the Antlers Bridge. These values appear to be quite unstable compared to the laboratory cast samples.

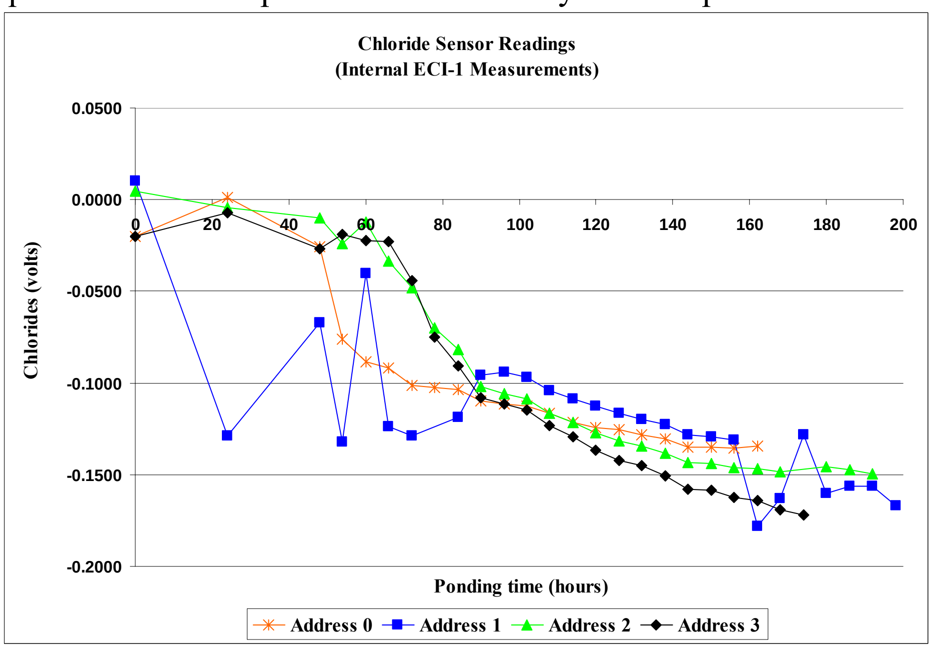


Figure 32 Chloride sensor data obtained from the ECI-1 devices (lab samples). The chloride sensor readings show a drop in measured voltage at about the 60-hour accelerated ponding exposure time. This did not appear to coincide with corrosion activity as measured by LPR.

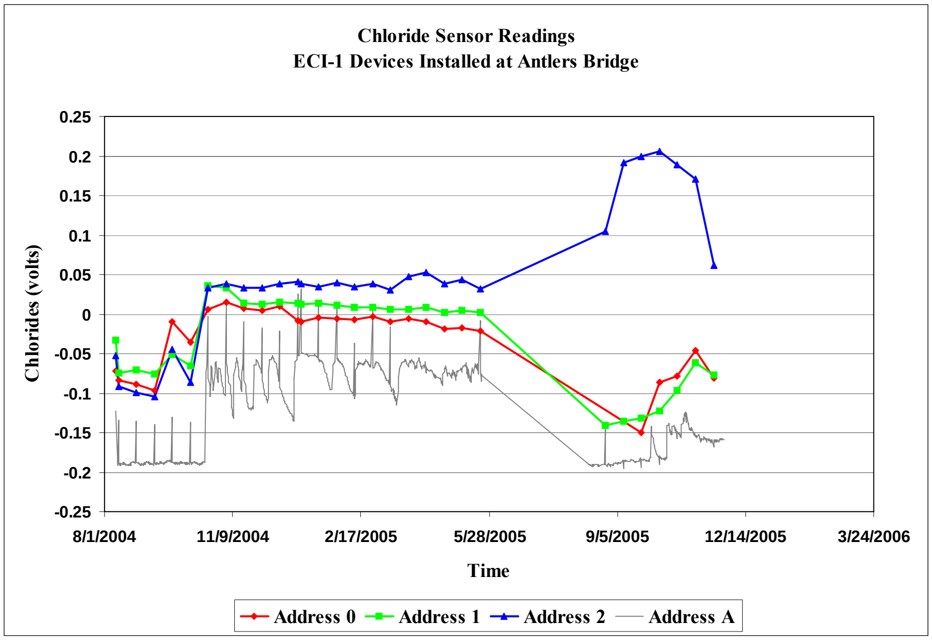


Figure 33 Chloride sensor data obtained from the ECI-1 devices installed at the Antlers Bridge. No clear interpretation of this data is available. The bridge deck was recently constructed (May/June 2004), and no salting has occurred to date. Some field data was lost between 5/28/05 and 9/5/05 due to technical difficulty with programming operations of the datalogger at the site.

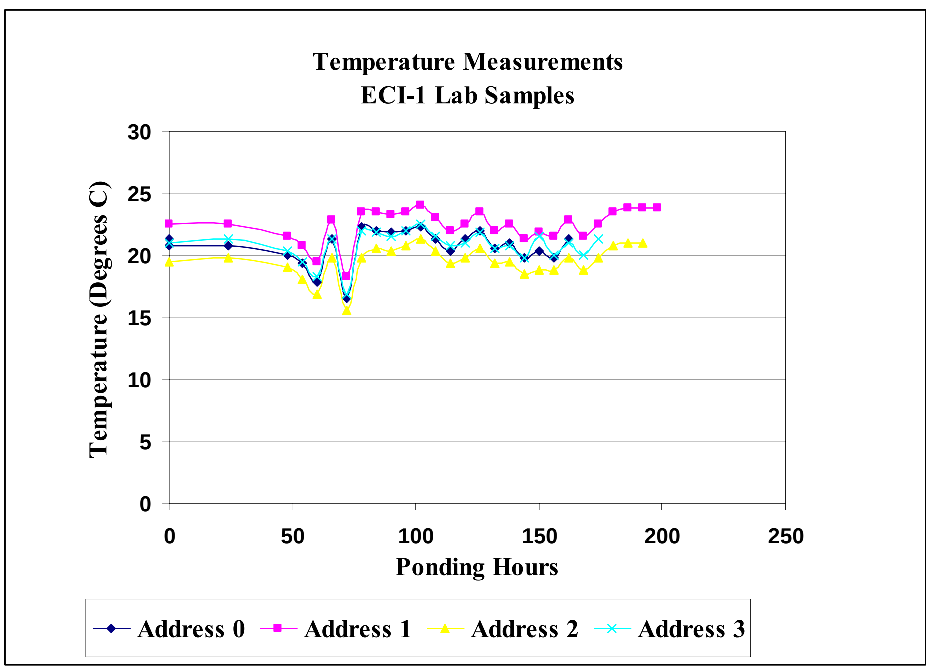


Figure 34 Temperature measurements obtained from the lab samples.

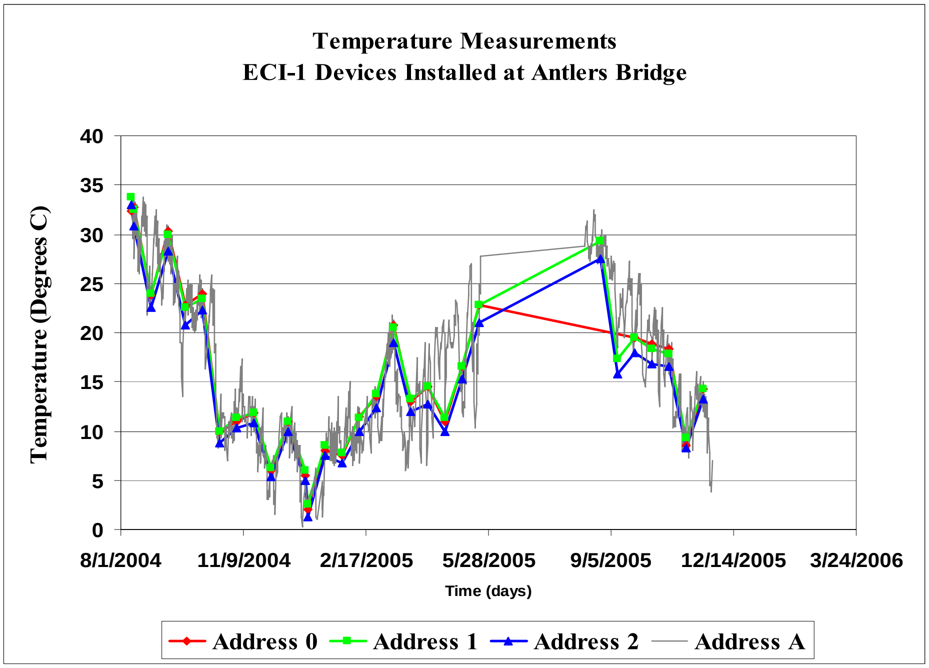


Figure 35 Temperature measurements obtained from the ECI-1 devices installed at the Antlers Bridge. The measurements are consistent with temperature variations at the project site, and are nearly identical for each ECI-1 device. Some field data was lost between 5/28/05 and 9/5/05 due to technical difficulty with programming operations of the datalogger at the site.

Figure 36 Top view of test sample after the ponding cup and upper half of the test mold have been removed. Corrosion products were visible in the mortar adjacent to the working electrode.

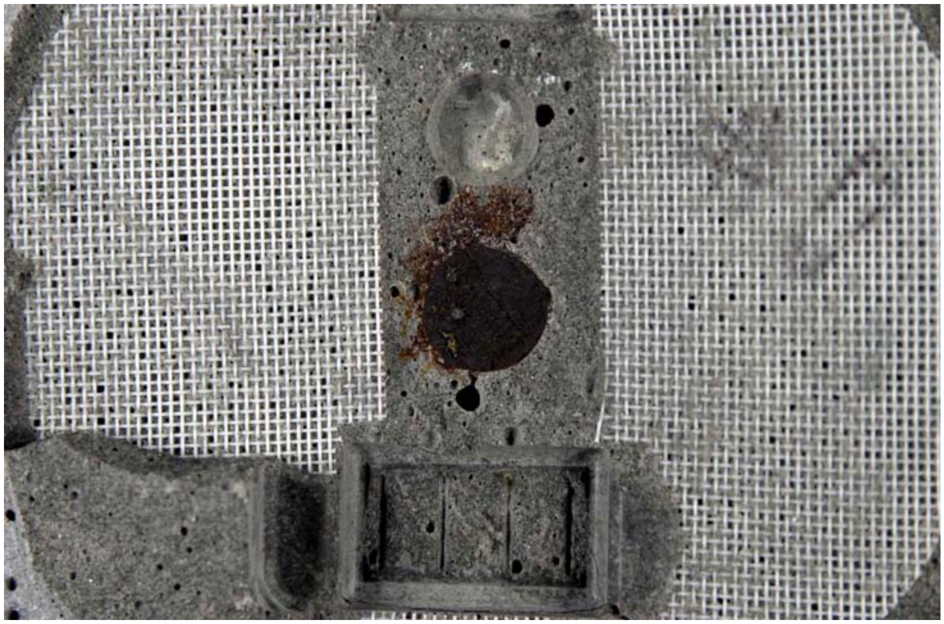


Figure 37 View of upper half of same sample as shown in Figure 36. This photo shows the nylon mesh that facilitated breaking the sample at the surface of the working electrode. The powder sample for the chloride analyses was obtained from an area around the working electrode imprint approximately 2 mm in depth and 25 mm in diameter.

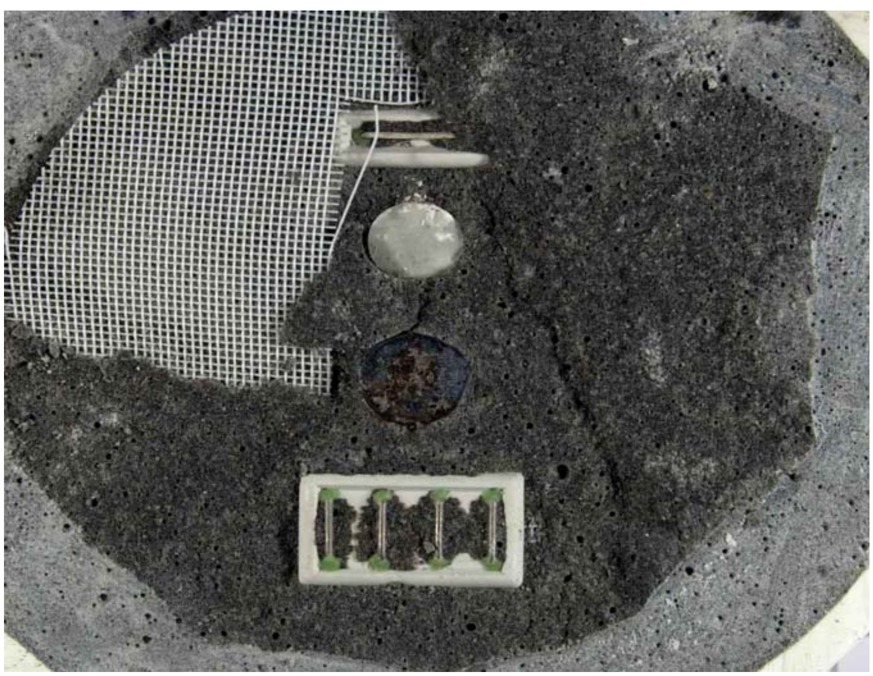


Figure 38 Top view of test sample after the ponding cup and upper half of the test mold have been removed. Some corrosion products were visible on the working electrode surface.

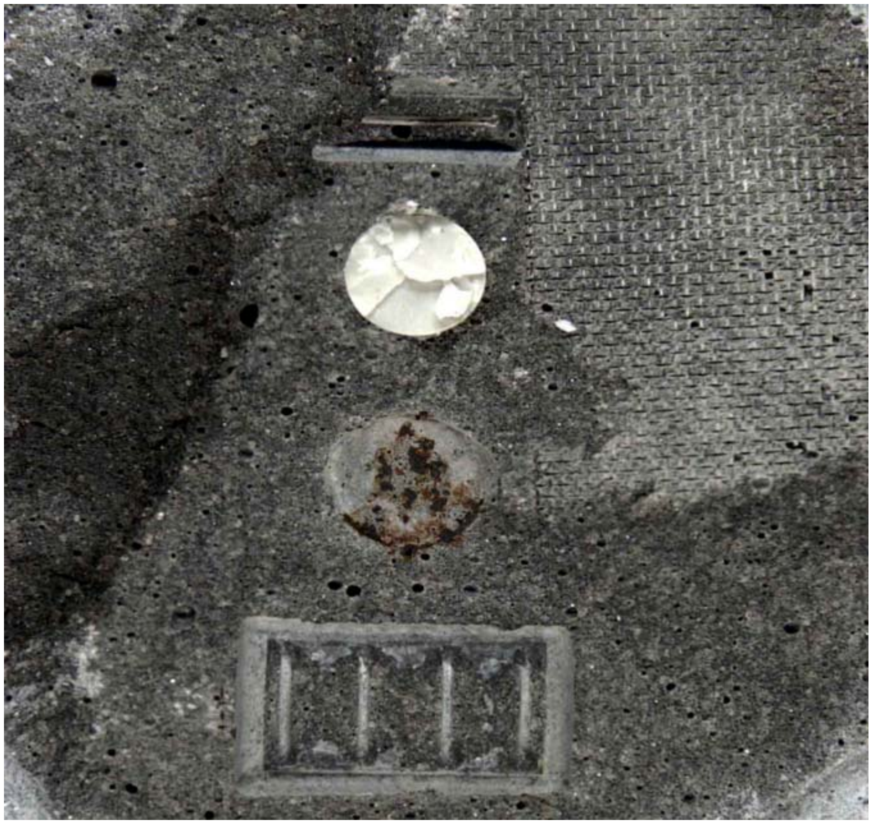


Figure 39 View of upper half of same sample as shown in Figure 38. Corrosion products were visible in the mortar where the working electrode imprint is.

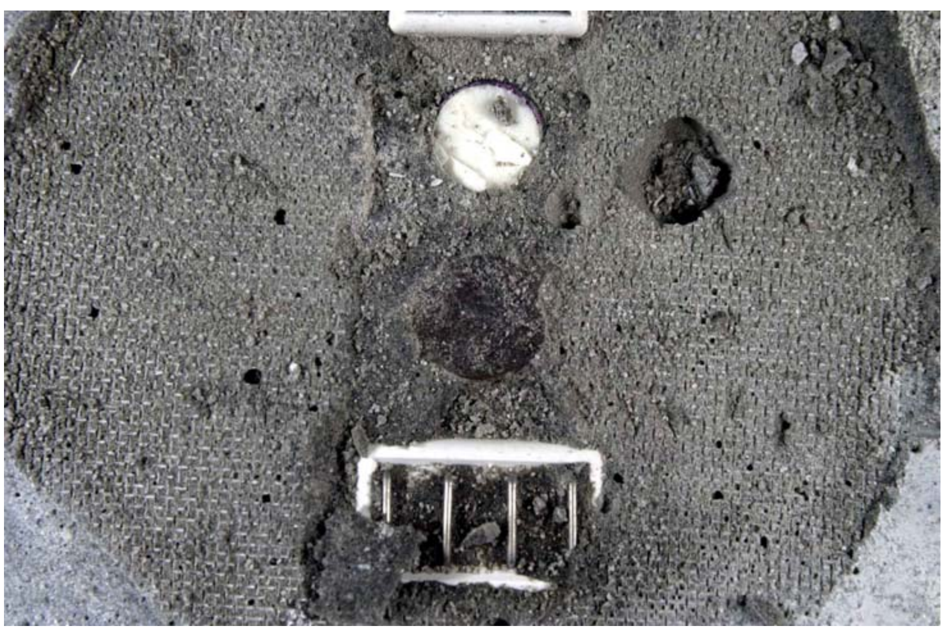


Figure 40 Top view of test sample after the ponding cup and upper half of the test mold have been removed. Some corrosion products were visible on the working electrode surface.

Figure 41 View of upper half of same sample as shown in Figure 38. Corrosion products were minimal in the mortar surrounding the working electrode.

APPENDIX B
(Lab Testing Procedure)

The test sequence discussed previously in this report is outlined here to provide a better explanation of the steps used in this evaluation.

ECI-1 Sample with breakout leads

1. Collect data from ECI-1's using Campbell Scientific datalogger.
2. Initiate accelerated ponding with an externally applied DC potential of 20 volts using the following procedure:
   - Apply the 20 volt DC potential for a 12-hour power cycle period. Disconnect the applied potential after the 12-hour period.
   - Let the sample remain undisturbed for a minimum of 48-hours.
   - Perform step 1.
   - If the corrosion current is less than 10μA/cm^2, continue accelerated ponding with an additional 12-hour power cycle period, and repeat step 1.
   - If the corrosion current is greater than or equal to 10μA/cm^2, discontinue testing; otherwise apply the 20 volt DC potential for a 6-hour time increment. Disconnect the applied potential after the 6-hour time period.
   - Let the sample remain undisturbed for a minimum of 48 hours.
   - Repeat step 1 and 6-hour power cycles with 48-hour minimum rest periods until corrosion currents reach approximately 10 μA/cm^2 at which time the test is terminated
3. Change NaCl solution if needed (approx. every week).
4. Perform a forensic examination of the sample. Evaluate the corrosion of the working electrode. Section the sample to obtain the chloride content at the depth of the working electrode.

ECI-1 Sample without accessible electrode leads.

1. Collect data from ECI-1's using Campbell Scientific datalogger.
2. Wait 24 hours (minimum).
3. Measure Open Circuit Potential (OCP) and perform Linear Polarization Resistance (LPR) measurement of the ECI-1 Working Electrode (WE) using the accessible test leads using external potentiostat.
4. Measure the OCP and perform the LPR measurement of the ECI-1 WE using the embedded chromel reference and counter electrodes using external potentiostat.
5. Measure the OCP and perform the LPR measurement using the ECI-1 WE, a saturated calomel electrode (SCE) for reference, and ECI-1's counter electrode with an external potentiostat. (SCE was placed in ponding cup.)

6. Measure the OCP and perform the LPR measurement using the ECI-1 WE, SCE for reference, and the chromel counter electrode with an external potentiostat.
7. Initiate accelerated ponding with an externally applied DC potential of 20 volts using the following procedure:
   - Apply the 20 volt DC potential for a 12-hour power cycle period. Disconnect the applied potential after the 12-hour period.
   - Let the sample remain undisturbed for a minimum of 48-hours.
   - Perform steps 1 through 6 above.
   - If the corrosion current is less than $10 \mu A/cm^2$, continue accelerated ponding with an additional 12-hour power cycle period, and repeat steps 1-6 above.
   - If the corrosion current is greater than or equal to $10 \mu A/cm^2$, discontinue testing; otherwise apply the 20 volt DC potential for a 6-hour time increment. Disconnect the applied potential after the 6-hour time period.
   - Let the sample remain undisturbed for a minimum of 48 hours.
   - Repeat steps 1 through 6 above and 6-hour power cycles with 48-hour minimum rest periods and electrochemical measurements until corrosion currents reach approximately $10 \mu A/cm^2$ at which time the test is terminated
8. Change NaCl solution if needed (approx. every week).
9. Perform a forensic examination of the sample. Evaluate the corrosion of working electrode. Section the sample to obtain the chloride content at the depth of the working electrode.

APPENDIX C
(Data Collection/Viewing)

Instructions for Remote Collection of Field Data

Data is stored on a 64 MB Compact Flash card in files corresponding to the ECI-1 address, month, and year. The file format is ECIxmmyy, where x is the ECI-1 address, mm is the month, and yy is the year. For example, an ECI-1 with address A that is collecting data in January 2005 would have the file name ECIA0105.txt. A new file is created every month.

NOTE:
Data cannot be collected from 11 AM – 1 PM and 11 PM – 1 AM (PST). During this time, the datalogger is in a measurement cycle and should not be disturbed.

1. Open HyperTerminal.
2. Dial Antlers bridge number including area code. (Add 9 if dialing for within Caltrans.)
3. Type “0123” and press enter after the menu loads for the c-prompt.
4. Type “dir” for a listing of all files on datalogger.
5. Type “scopy /s *filename*.txt” at the c-prompt.
6. Select **Transfer** from the menu bar.
7. Scroll down and select **Receive File**.
8. Click on the **Browse** button to change the target folder.
9. Select **1KXmodem** protocol.
10. Click on the **Receive** button.
11. Enter in a filename. It does not have to be the same as the original file.
12. Select the **OK** button to initiate transfer.
13. Repeat steps 5 – 12 for other files (if desired).

Viewing Collected Data

1. Open Microsoft Excel.
2. Open a data file (with .txt extension). The Text Import Wizard will appear.
3. Select **Delimited**.
4. Click on the **Next** button.
5. Select **Comma** under Delimiters.
6. Click the **Finish** button.

The column headings are (from left to right): collection date, collection time, ECI-1 address, chlorides, resistivity (GSTAT), linear polarization resistance (LPR or PSTAT), temperature, and open circuit potential (OCP).

APPENDIX D
(EDS Datalogger Operating Instructions)

VTI.EXE is a program designed to connect SDI-12 devices to the CPM8x8 data logging system. This version of the program is designed to control the VTI ECI-1 device.

Command line interface:

The VTI.EXE program accepts the following command line arguments. Instructions in the command line cause a certain function to be performed and then the program exits back to the operating system. This mode of operation is used by the data logging system to automatically record data.

/r:A This causes the CPM8x8 logger to read the ECI-1 device at address A where A is the numbers 0 through 9 and the uppercase letters A through Z. The device triggers a reading, waits 15 minutes, reads the ECI-1 and writes the data to the CompacFlash card. The data will appear on the card in a text file with the following name:

ECIAMMYY.TXT

Where

ECI = Indicates data is from ECI-1 device
A = ECI device address
MM = Month data was recorded 01 – 12
YY = Year data was recorded 04 = 2004

The logger will automatically create a monthly data file for each of the ECI-1 devices connected to the logger. The logger reads the date from the internal real time clock, and looks for a file on the card with the name as described above. If the logger finds a file for the unit address that matches the current month and year, the new data is appended to the end of the file. If no file is found the logger creates a new file named as above and writes the data.

/t:A This command causes the ECI-1device A to trigger a reading. If a reading is currently underway, the ECI-1 stops the current reading. Refer to the ECI-1 manual for more information.

/d:A This causes the ECI-1 to record data as in the /r: command. This command reads and records data from the ECI-1 immediately without triggering a reading or waiting for the measurement to complete. This command is used after issuing the /t: command and waiting the required period. Refer to the ECI-1 manual for more information.

Manual mode:

The manual mode of operation provides a direct interface for operating and setting up the ECI-1. Manual operation is performed by connecting the CPM8x8 logger to a PC running terminal emulation software such as HyperTerminal.

When the program is started the logger shows the program main menu as follows:

VTI ECI-1 Command Interface
Environmental Data Systems Inc.

MENU
[1] = Setup ECI-1
[2] = Get ECI-1 Data
[3] = Scan SDI-12 Bus
Press number in brackets then Enter to select command.
Press Esc to exit.

Entering the number 1 2 or 3 then pressing the Enter key selects that command. Pressing the Esc key returns to the operating system.

[1] Setup ECI-1

Before the ECI –1 units can be used in a network environment each unit must be assigned a unique address. The SDI-12 standard allows 36 addresses. The address is a single character and includes the digits 0 – 9 and the letters A – Z. When setting up the ECI – 1, each unit connected to the logger should be assigned a consecutive address starting at 0. When the command is selected the following appears:

This command is used to get and / or change the ECI1 SDI-12 Bus address.

There must be ONLY ONE ECI1 UNIT connected to the SDI-12 bus.
Press Enter to continue or Esc to exit.

To use this command there must be ONLY ONE ECI1 UNIT connected to the SDI-12 bus.

When Enter is pressed, the logger checks for a connected ECI-1 device at each address. If a device is found the following is displayed:

Current ECI Address is A

Where A is the current device address. If no device is found, the logger displays:

No Response from ECI1

and returns to the main menu. The logger will then prompt for the new address:

Enter new address: (0 - 9) (A - Z) :

Enter the new device address. The logger will respond with:

ECI Address changed to A

Where A is the new device address.

[2] Get ECI-1 Data

This command will trigger a reading on the selected ECI-1 device, wait the appropriate time, then display the data on the screen. When the command is selected, the logger will display:

Enter ECI-1 Address(s) (0 - 9) (A - Z) then press Enter.

More than one address can be entered at a time without spaces or other characters in between. For example to read units 0 1 and 2 you would enter:

012{Enter}

After entering the address, the logger will display:

Sending Command to Address: A

The logger will then display the ECI-1 response (see ECI –1 manual)

Address A Response: [cmdstr]

This is repeated for each address entered.

The logger then displays a count-down timer for the 910 second measurement cycle of the ECI-1.

DELAY TIME: 910 SECONDS

When the delay timer reaches zero the logger reads and displays the data from each ECI-1 on the screen. The data will also be stored on the logger memory card as described in the /r: command above. Press any key to return to the main menu.

[3] Scan SDI-12 Bus

This command will scan all 36 SDI-12 addresses to determine if a device is connected. If a device is found the logger shows:

Found Address: A ID:[idstr]

Where A is the device address and [idstr] is the device ID string as defined by the SDI-12 standard. Note this command will identify ALL SDI-12 devices and not only the ECI-1.

APPENDIX E
EDS Datalogger Software Information

FILES ON THE MEMORY CARD

The memory card must contain the program LOG.EXE for the logger to operate. This program is not found on new memory cards and must be copied from the users computer to the logger memory card. Other programs and files may be necessary to allow operations such as FAX transmission and custom configuration of logger parameters. Collected data is stored on the memory card in a text file that is automatically created and maintained by the logger.

The following files and programs must be copied to the memory card by the operator for
operation of the logger. Some programs are required for logger operations, while other files are for optional functions. Each program and file is listed below.

1. **LOG.EXE (REQUIRED):** This is the main logging program and MUST be on all memory cards inserted into the DAC computer. This is the only program file required for basic logging operation.
2. **ENCODE.EXE and FAX.EXE (OPTIONAL):** These program files are used to send FAX reports of the collected data. These files are required on the disk ONLY if the FAX / MODEM module is connected and FAX reports are desired.
3. **SETUP.TXT (OPTIONAL):** This file provides custom configuration information for the data logger. By using this file, the operator can provide custom names for each channel as well as designate a channel to read voltage, current , or ON / OFF potentials. This file also stores the FAX numbers and times for automatic FAX reporting. More on this is found in the section CUSTOMIZING THE LOGGER SOFTWARE.

FILES CREATED BY THE LOGGER

In addition to the files listed above, the logger automatically creates files for use by the software. These files are listed below. Unless noted otherwise, these files can be ignored by the user.

1. **LOG.DAT:** This is where the logger stores the collected data. If this file does not exist on the memory card, the logger will create it. Otherwise the logger will append new data to the end of the existing LOG.DAT file.
2. **SETUP.LDT:** This file stores the loggers operating parameters. These include the number and type of channels, channel names, recording interval and other data. This file is created and maintained by the loggers software and can not be directly modified by the user. If this file is not found on the logger memory card during the power up boot process, or if the file is

found to be corrupted, the logger will create a new SETUP.LDT file based on the number of relay cards connected and the information found in the optional SETUP.TXT file.

3. **FAXDATA.TXT:** This file is created by the logger software for reports and faxes. Not used by operator.
4. **FAX.$$$:** Encoded fax data. Used for temporary storage of FAX information. Not used by operator.

INITIAL LOGGER SETUP

The hardware for the data logger is configured as shown in the DAC DATA LOGGER HARDWARE manual. For a minimum system, a memory card with the program LOG.EXE as described above, is inserted into the DAC Controller and +12VDC power is applied to the system. During the initial startup, or if no SETUP.LDT file is found on the memory card, or if the SETUP.LDT file has become corrupted, the DAC controller sets the logging parameters to their default values and creates a new SETUP.LDT file. If the file SETUP.TXT exists on the memory card, the software uses the information in the file to customize the logger setup. More information can be found in the section CUSTOMIZING THE LOGGER SOFTWARE.

DEFAULT LOGGER CONFIGURATION

The following default values are loaded by the logger during the setup procedure. These values can be modified by the SETUP.TXT file or by direct communication with the logger.

NUMBER OF CHANNELS:	Number of relay cards connected X 16.
RECORDING INTERVAL:	1 HOUR
CHANNEL TYPE:	VOLTAGE
INTERRUPT RELAY STATUS:	ON (rectifier enabled)
FAX REPORTING:	DISABLED

RECORDING INTERVALS:

The logger records the input channels at an interval specified by the operator. The software provides 9 preset recording intervals ranging from 1 set of readings every 15 minutes to 1 set of readings every 12 hours. The readings are synchronized to midnight (00:00) and are in 24 hour format. The default interval is 1 hour, and can be set to any of the preset values by the operator via the SETUP.TXT file or by direct communication with the logger. Following is a list of the available recording intervals and times:

Recording Intervals and Times

Interval / Readings/Day	Times
1 15 minutes / 96	hh:00 hh:15 hh:30 hh:45
2. 30 Minutes / 48	hh:00 hh:30
3. 1 Hour / 24	hh:00
4. 2 Hours / 12	00:00 02:00 04:00 06:00 08:00 10:00 12:00 14:00 16:00 18:00 20:00 22:00
5. 3 Hours / 8	00:00 03:00 06:00 09:00 12:00 15:00 18:00 21:00
6. 4 Hours / 6	00:00 04:00 08:00 12:00 16:00 20:00
7. 6 Hours / 4	00:00 06:00 12:00 18:00
8. 8 Hours / 3	00:00 08:00 16:00
9. 12 Hours / 2	00:00 12:00

Notes:
1. Times are in 24 Hour format.
2. hh = Hour (00 - 24)
3. Readings are synchronized to midnight. (00:00)

The DAC Datalogging Computer stores the voltage values from each input channel and other data in a comma delimited DOS / OS2 ASCII TEXT formatted file on the loggers memory card disk drive. The file consists of consecutive lines of data stored on the disk at the record interval.

DATA FILE FORMAT

The recorded data file is an ASCII comma delimited text file with string data in quotation marks. This format is readable by most spreadsheet and word processing programs. The data file has the following format:

"date","time",first channel,,,,,last channel CR
"*date*" is the month , day and year the line of data was recorded. ("MM/DD/YY")
"*time*" is the time of day when the line of data was recorded ("HH/MM/SS")
first channel,,,,,last channel refers to the value recorded on each of the input channels .

Each reading is in VOLTS or AMPS DC (See CUSTOMIZING THE LOGGER SOFTWARE) and each value is separated by a comma(,)

CR (Carriage Return) is the end of line character. (Dec: 13 Hex: 0d)

The recorded data file is named LOG.DAT and is created automatically by the logger. If the file does not exist on the memory card, the logger creates a new file and writes the data. If the file already exists, the data is appended to the end of the file.

The recorded data is copied directly from the memory card to the users hard disk, or transmitted via the communications port.

CUSTOMIZING THE LOGGER SOFTWARE

The logger recording parameters and other configuration information can be altered from the default values (see INITIAL LOGGER SETUP section) by including a setup file on the logger's memory card. The file is a standard text file named SETUP.TXT and can be created using Windows NOTEPAD or any word processor or editor software capable of producing ASCII TEXT files.

The SETUP.TXT file instructs the logger to modify the default logging parameters. This information is used by the logger software to create the SETUP.LDT file. (see INITIAL LOGGER SETUP section).

The setup file consists of a number of commands followed by data or text. All commands MUST BE IN UPPERCASE and separated from any other text on the same line by space characters. Lines of text with no valid commands or text preceding a valid command is ignored, allowing comments and headers to be included in the file. Command data must be contained on a single line, and lines can be no longer than 128 characters.

Note that the information in SETUP.TXT is only loaded only once by the data logger when no valid SETUP.LDT file is found on the memory card disk drive. This is done so that some of the parameters can be modified by the user during direct communication with the logger. It is necessary to erase any existing SETUP.LDT file to cause the logger to reload the information stored in SETUP.TXT.

The following is a list of commands allowed in SETUP.TXT. Commands are in UPPERCASE and all commands are followed by a colon : .

NAME: _*text*

This is the name of the logger installation as displayed in the communication MAIN screen and in printed and FAX reports. This name is for user information only and has no effect on logging. _*text* indicates the name of the logger installation. The NAME: command is not included.

LOCATION: _*text*

This is the location of the logger installation as displayed in the communication MAIN screen and in printed and FAX reports. This name is for user information only and has no effect on logging. _*text* indicates the name of the logger installation. The LOCATION: command is not included.

The above commands provide information needed to identify the logger installation on printed and FAX reports. Text is limited to 40 characters. These parameters can not be modified via the communications port.

INTERVAL:HH:MM

This is the interval for recording input data. The recording interval can be set to any one of 9 preset intervals. (see RECORD INTERVAL section). HH:MM refers to the Hours and Minutes as follows:

00:15	15 minute interval.
00:30	30 minute interval
01:00	1 hour interval
02:00	2 hour interval
03:00	3 hour interval
04:00	4 hour interval
06:00	6 hour interval
08:00	8 hour interval
12:00	12 hour interval

The interval must be entered as shown above (leading zero included) and should follow the INTERVAL: command with no intervening spaces.

NOTE: The interval can be changed at any time via the communications port.

CHANNEL COMMANDS

Channel commands allow the operator to specify the number and type of input data channels displayed and recorded by the logger. Each channel can be given a unique name that will appear in the communications screen and in printed and FAX reports. By default, the logger reads and records the maximum number of channels connected to the system. This is the number of relay cards times 16.

If channel commands are used, EACH desired channel must be listed in the SETUP.TXT file. Each time a channel command is encountered, the next relay channel is assigned to that command, starting with 1. In other words, if 5 channel commands are found in the SETUP.TXT file, only the first 5 relay input channels will be displayed and recorded. In this way unused channels can be ignored. Note that input channels on the relay cards are read consecutively and channels cannot be skipped.

Following are channels command descriptions:

VOLTS:*channel_description*

Reads the input channel as VOLTS DC. *channel_description* indicates the channel description for the communications display and printed or FAX reports. *channel_description* is limited to 40 characters. This is the default value for all channels if no channel commands are entered.

AMPS:*channel_description*

Reads the input channel as AMPS DC. Reads the voltage across a shunt and displays and records the voltage divided by the shunt value. The shunt value is .01 ohms by default and can be set to other values using the SHUNT: command. *channel_description* indicates the channel description for the communications display and printed or FAX reports. *channel_description* is limited to 40 characters.

POT:*channel_description*

Used to read ON and OFF potential values. The logger selects the input channel relay and takes a reading. The logger then SETS the interrupt relay, interrupting the rectifier current, waits 1/2 (.5) second then reads the channel again. The interrupt relay is then RESET, (unless disabled by the communications port) and the rectifier current is restored. To read potential values without rectifier control, use the VOLTS: command. This command results in two readings to be displayed and recorded for one input channel. The readings are stored in the data file with the ON reading first. *channel_description* indicates the channel description for the communications display and printed or FAX reports. *channel_description* is limited to 40 characters. See the section on RECTIFIER INTERRUPT CONTROL for more information.

SHUNT:*shuntval*

Sets the shunt value for the AMPS: command. Valid values for *shuntval* are in ohms and range from .005 to 10,000 ohms. Note that this value is used for ALL channels using the AMPS command. Default value is .01 ohms. (5 A / 50 MV shunt)

FAX COMMANDS

The following commands enable and control the automatic FAX report generation. Setting these parameters enables the datalogger to send a FAX report of the input data at a preprogrammed time and day of week.

FAX#:*fax_phone_number*

Sets the phone number for the auto FAX function. This is the number the logger will call to send the FAX. The number should not contain spaces and should be entered exactly as required to dial the telephone.

FAXHOUR:*hour*

Sets the hour (1 - 24) that the logger will attempt to send the fax report. Valid values for *hour* are 1 to 24. (24 = midnight: 1 = 1 AM) Set this value to zero (0) to disable the automatic fax function.

FAXDAY:*dayofweek,dayofweek*

Sets the day(s) of week the logger will send the FAX report. The logger will send a FAX report on the day(s) selected here at the hour set with the FAXHOUR command. Day of week entries are abbreviated and are separated by commas (,). Valid entries for *dayofweek* are as follows:

mon	Monday
tues	Tuesday
wed	Wednesday
thu	Thursday
fri	Friday
sat	Saturday
sun	Sunday

EXAMPLE
FAX#:18005551212
FAXHOUR:24
FAXDAY:mon,wed,sun
The above will send a FAX report on Monday, Wednesday, and Friday at midnight to
18005551212 .

LOGGER OPERATION

When power is connected, the data logger begins to record data at the preset recording interval. The logger remains powered down (OFF) between recording operations. The DAC controllers real time clock (RTC) wakes up (turns on) the unit at the specified interval and one set of readings are recorded along with the time and date the data was recorded. The data is written to the memory card's data file and the unit returns to the low power mode.

MANUAL MODE OPERATION

Manual mode operation provides a way of checking the input data and copying the recorded data without connection to a computer.

READING THE INPUT DATA

1. Turn on the system by pressing the ON button located on the DAC controller card.

2. Press the CHANNEL button on any connected relay card. The LED on the relay card will indicate the currently selected channel. Read the value on the VOLTMETER display. Each time the CHANNEL button is pressed the channel will increment. Holding down the CHANNEL button for more than 5 seconds will cause the INTERRUPT relay to toggle.

   NOTE: The CHANNEL button will cause the logger to cycle through ALL of the available relay card channels regardless of the information stored on the SETUP.TXT files. The interrupt relay will not be activated on any channel except by holding down the button as described above.

3. If the CHANNEL button is not pressed for 20 seconds, the unit will return to the low power mode.

RETRIEVING THE RECORDED DATA

In manual mode, the DAC controller memory card is removed from the DAC controller and is inserted to the users computer or card reader. Two cards are typically used in this mode. Each card contains the necessary setup information for the logger at that location. The cards are simply swapped out in the field, and the data is later copied and analyzed at the users PC. The data file LOG.DAT can be erased if desired.

RECTIFIER INTERRUPT CONTROL

The DAC datalogging system can control 1 or more banks of rectifier interrupt relays. Each relay card controls 1 bank of interrupt relays. See the relay card data sheet for more information.

By default the interrupt relays are RESET (Rectifier ON). The relays remain in the ON condition until one of the following occurs.

A channel read occurs that has been designated as a POTENTIAL by using the POT: command in the SETUP.TXT file. The DAC controller performs the following steps during a POTENTIAL measurement.

1. Set the channel relay
2. Wait .5 seconds
3. Read the voltmeter
4. Set the Interrupt Relay (Rectifier OFF)
5. Wait .5 seconds
6. Read the voltmeter
7. Reset the Interrupt relay (Rectifier ON)

This procedure results in the logger reading a potential with the rectifier current ON and then another reading of the same potential with the rectifier OFF. The OFF reading is recorded exactly .5 seconds AFTER the rectifier is turned OFF.

The interrupt relay can be permanently set (rectifier OFF) by remote control via the communication port. When in this condition, the rectifier is OFF during both potential readings described above. (The rectifier is already OFF for the first reading and step 7 does not occur). The rectifier remains OFF until reset by remote control. See the section LOGGER REMOTE CONTROL for more information.

APPENDIX F
(EDS Datalogger Hardware Information)

A complete data logging system is formed by combining the DAC Data acquisition system controller, a voltmeter equipped with an RS232 communications port, and one or more 16 channel relay boards. Fig. 1 is a wiring diagram for a basic data logging system. Power for the voltmeter is provided by the relay board.

In operation, the DAC controller selects one of the 16 (or more) relays to connect to the voltmeter. The controller waits .5 seconds after closing the relay contact and then triggers a reading from the voltmeter. The voltmeter reading is stored on the Compact Flash memory card, along with the time and date. This is repeated for each of the connected channels.

The time interval for recording is set by the system software and ranges from 1 set of readings every 15 minutes to one set of readings every 12 hours. The system powers down between readings to conserve power for battery powered installations.

An external relay driver for rectifier interruption is provided on the relay card. Up to three latching DPDT 10A relays can be connected to each relay card. Remote control of the interrupter relay is provided by system software. The software can also interrupt the rectifier during potential measurements to provide ON and OFF potential readings.

There are several options for downloading the data stored on the memory card to the users desktop or laptop computer. In the simplest configuration, the memory card is removed from the system and inserted into the user's computer PC Card (PCMCIA) slot or into a Compact Flash card reader. The card appears as a disk drive to the users computer, and the data is simply copied to the users computer hard disk. The card is then re-inserted into the DAC controller, and logging resumes at the set interval.

The DAC controller can also be connected to the users computer via the serial RS232 port using a NULL MODEM cable. A terminal emulation program such as Windows HyperTerminal is required to access the DAC system. The DAC system provides menu driven software that allows viewing the current values of the input channels, setting the recording interval, downloading the stored data to the users computer using the XMODEM protocol, and other options.

The addition of the FAX / MODEM module and a land line or cellular telephone allows remote access to the DAC system. In addition to the options listed above, the system can send a FAX report of the input data on demand or at a preprogrammed time and date.

The software for the DAC system automatically configures itself to record voltage data from all of the connected channels. A configuration file can be created by the user to customize the logger for the particular application. More information can be found in the software section of this document.

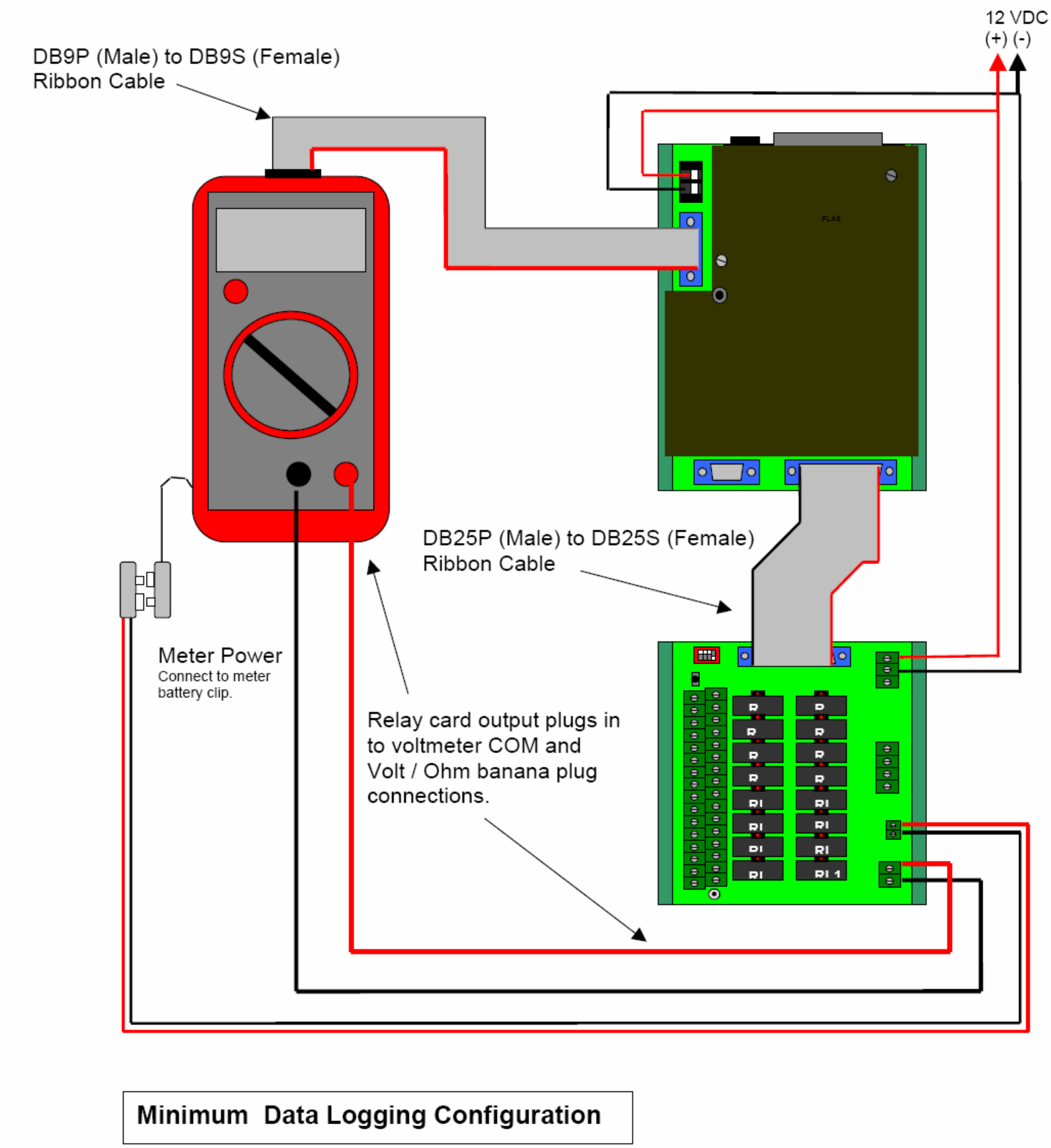


Figure 1 Datalogger wiring diagram

HARDWARE INSTALLATION

Figures 2 to 4 show most of the components required to form a 16 channel data logger. A +12VDC battery or AC power supply is required for power. Refer to the DAC controller and relay card data sheets for more information.

The DAC Controller and 16-channel relay board are mounted on 3.5mm DIN rail. The voltmeter is mounted to the panel using the holes provided in the rubber housing or by using elastic cord. A 25 pin MALE to FEMALE ribbon cable connects the relay board to the DAC parallel port. A nine pin ribbon cable connects the voltmeter to the DAC COM port 2. +12VDC power is connected to the DAC board via the 2 pin connector.

Input, output and power supply connections are made to the relay board via the pluggable terminal strips on the board. Connect the output of the relay card to the voltmeter VOLT /OHM and COMMON banana Plugs. CAUTION: Do not plug the relay board output into the AMPS or current terminals on the voltmeter. Damage to the voltmeter and relay card could result.

+9VDC power for the voltmeter is provided on the relay card via connector J4. This isolated, filtered power supply is designed specifically to power voltmeters that run on standard 9 volt batteries and should not be used for any other purpose. The voltmeter should be powered by the supply or internal batteries. Connecting the voltmeter directly to the +12VDC power will damage the voltmeter, relay card, DAC controller and any devices connected to the relay card inputs. Be careful to observe proper polarity when connecting the voltmeter power. Refer to the 16 channel relay card data sheet for more information.

Up to 4 relay cards can be connected to the DAC controller, for a total of 64 inputs. Figure 2 shows connections and DIP switch settings for multiple relay boards. A 25 pin 'daisy chain' ribbon cable connector containing 4 DB25S (female) D connectors for connection to the relay boards and 1 DB25P (male) connector for connection to the DAC controller is required. The relay board outputs are connected in parallel and plugged into the voltmeters VOLT/OHM and COMMON banana plug inputs.

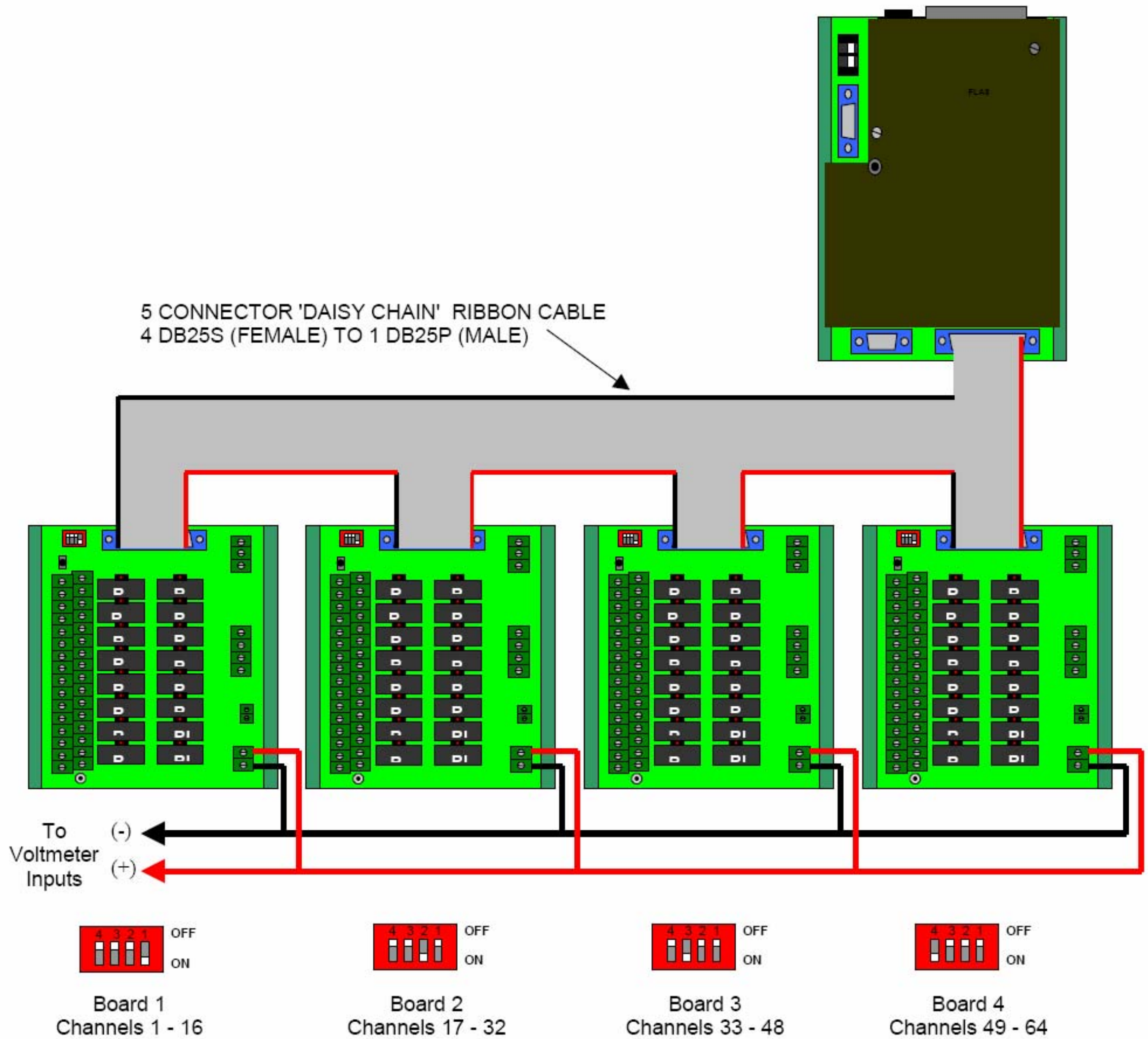


Figure 2 Datalogger connected to 4 relay boards

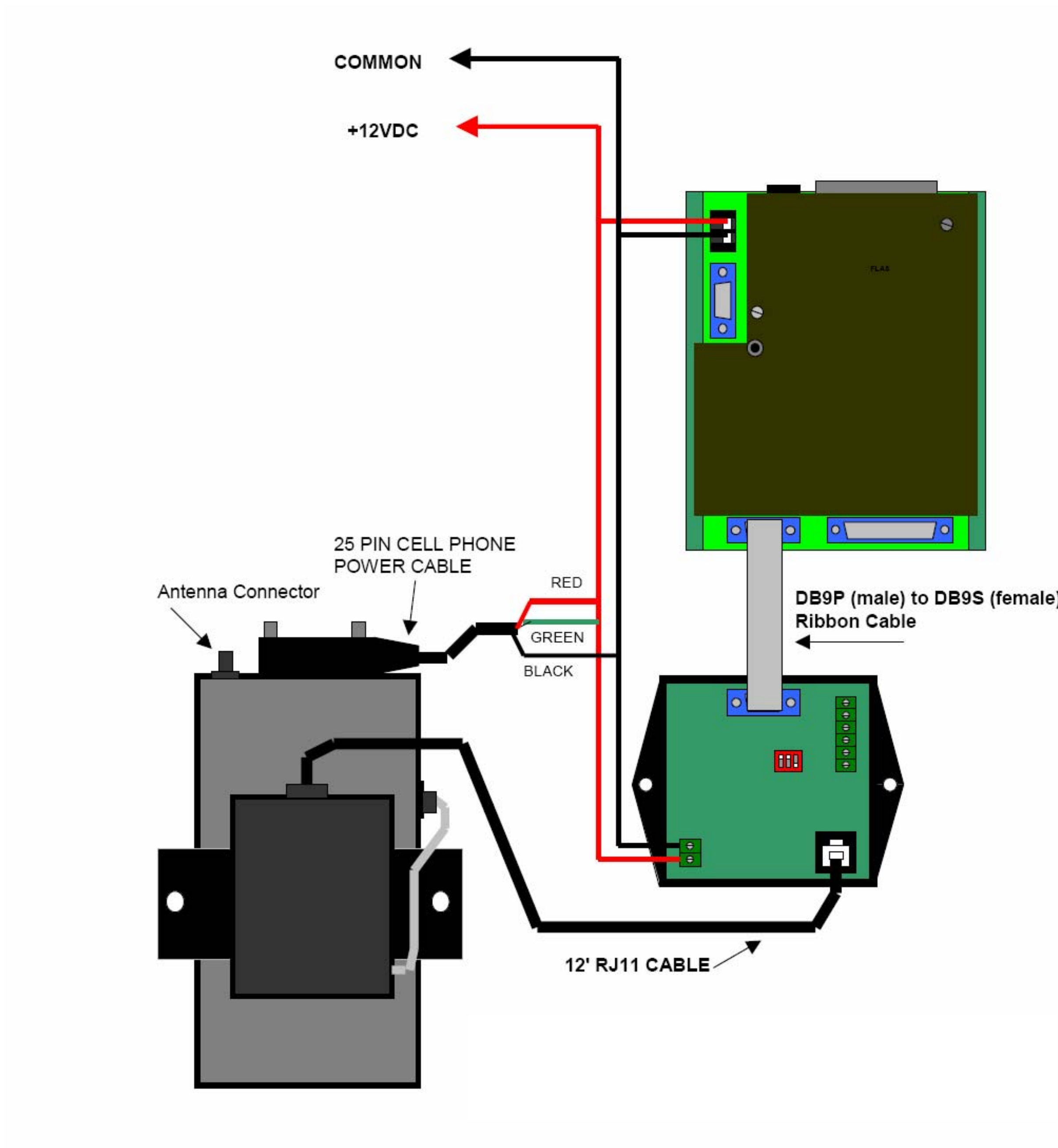


Figure 3 Modem/Cellular Telephone Wiring Diagram

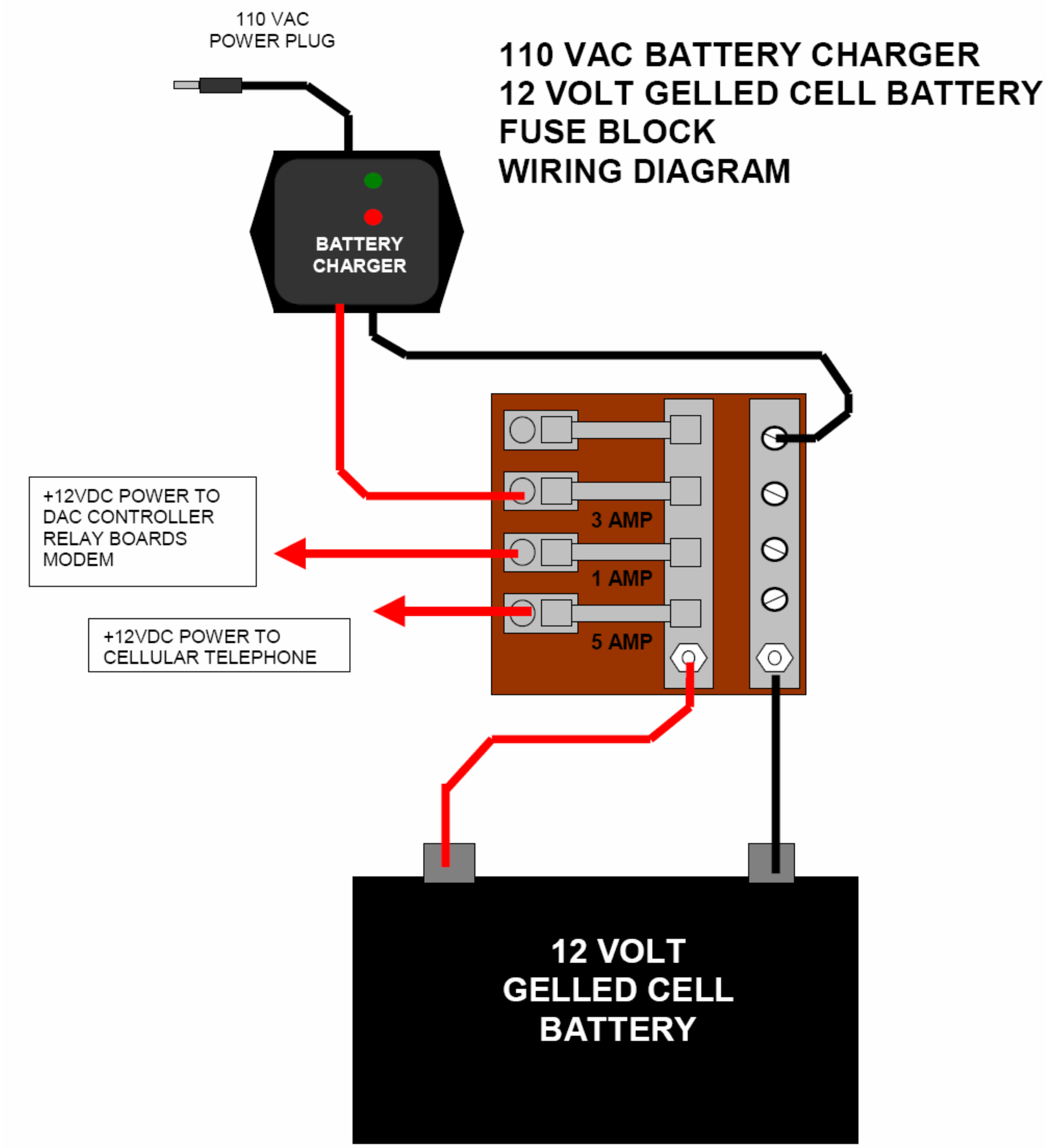


Figure 4 Power circuit diagram