FINAL CONTRACT REPORT

DEVELOPMENT OF A PROTOTYPE VERSION OF AN EMBEDDABLE CORROSIVITY MEASURING INSTRUMENT FOR REINFORCED CONCRETE

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(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

December 2002
VTRC 03-CR10

ABSTRACT

To address the problem of safely and quantifiably detecting corrosion in a cost-effective and timely manner, the University of Virginia and Virginia Technologies, Inc. have developed a remotely accessible, networked, embedded corrosion instrument. The instrument measures the corrosion rate and open circuit potential of a sample of black steel reinforcement in the concrete of interest. It does not directly measure the corrosion parameters of the nearby bars in the reinforcement network but instead measures the corrosivity of the concrete environment nearby. The instrument also measures the conductivity of the concrete, which can be used to assess the moisture content of the concrete. An onboard temperature sensor records the internal temperature of the concrete and an Ag/AgCl ion specific electrode (ISE) can detect increasing changes in chloride concentration. These measurements combined provide a fairly comprehensive snapshot of the internal electrochemical corrosivity of the structure. The instrument also contains the necessary circuitry to stimulate and measure a strain gauge external to the instrument, which can be used to measure mechanical stresses caused by the buildup of corrosion products on the reinforcement steel.

A rugged, environmentally sealed enclosure was designed and molded to provide protection for the electronics, a rigid mounting surface for the electrodes, and features for mounting the instrument to the rebar. A finite element analysis was performed for the enclosure embedded in a bridge deck to show that the Embedded Corrosion Instrument (ECI) could withstand the compressive and tensile forces encountered in the bridge without rupturing or compromising the integrity of the bridge. Successful laboratory tests of the prototype were performed that demonstrate its ability to detect changes in corrosivity, analyze them, and communicate them in a useable form to the operator.

In the spring of 2002, four instruments were installed in the 29/460 interchange near Lynchburg, Virginia. Their functionality is being monitored via a wireless cellular connection. Thus, there is no need to visit the site to collect corrosion information. The entire system is powered directly from the rechargeable battery. The solar panel is used to maintain the charge level of the battery. A single battery is being used to power all of the microinstruments installed on a bridge. The most important achievements of the project are the development, demonstration, and field installation of a microinstrument prototype that can measure multiple parameters relevant to corrosivity and communicate this information via a wireless cellular connection to a central site. Specific recommendations include continued monitoring of the instruments installed in the 29/460 interchange, and expansion of microinstrument use to long-term laboratory measurements at the Virginia Transportation Research Council in studies of inhibitors and other corrosion mitigation strategies.

INTRODUCTION

Civil structures such as bridges and dams are extremely large construction efforts costing millions to billions of dollars and spanning several years. In the United States alone, repairs for corrosion damage to federal bridges are estimated at $50 billion annually (MIT News Office, 1997). These structures are vital to commerce and the standard of living of millions of people in the United States and billions of people around the world. Worldwide estimates to repair reinforced concrete structures are $200/m^2 of exposed surface. Premature or unexpected failures of these structures are often catastrophic in terms of time, money, and lives. The high costs of corrosion due to replacement and premature failures mandate the need for integrated in-situ non-destructive testing (NDT) systems. These NDT systems should provide information based on changes in the structure's corrosion condition to effect timely maintenance interventions and to predict the remaining life of the structure.

The current methods of assessing the health of steel reinforced concrete structures rely heavily on non-quantifiable visual and sounding inspections or destructive direct examination techniques. Visual inspections and sounding of structures require a great deal of training, experience, and personnel in the field. These methods are prone to incomplete coverage because of hard to visualize and inaccessible parts of the structure and possible oversight by the inspectors. The findings of soundings and visual inspections are not easily or uniformly quantifiable and only reveal damage caused by advanced corrosion processes. Direct examination requires physical core samples from the structure under investigation and can cause permanent damage to the structure and the need to repair the sample site. Field inspections are problematic on several fronts. They require inspection personnel to be in the field, which is costly in time and resources and puts the inspectors at risk in traffic and other precarious places. Traffic lanes must be shut down while some inspections are performed, which requires even more personnel and resources. In general, these methods cannot detect the increased potential for, or the onset of, corrosion.

The original impetus for this project came from personnel from the Virginia Transportation Research Council (VTRC) and the Federal Highway Administration (FWHA) personnel who were in search of a very small, inexpensive, highly capable, corrosivity instrument that could be added to the concrete mix. The need such an instrument would address is that of providing early and spatially discrete alerts of increased corrosivity. In order to achieve such a goal, the development of a small, economical, and highly capable embeddable instrument was critical.

PURPOSE AND SCOPE

The purpose of the project was to design, develop, and implement a remotely accessible instrument for the measurement of corrosivity in reinforced concrete that could serve as a prototype. The scope of the measurements was to include polarization resistance, temperature, resistivity, open circuit potential, and chloride content. The means of remotely accessing and powering the instrument were also investigated.

METHODS AND MATERIALS

The following research tasks were performed to design, develop and test a remotely accessible, networked, embedded corrosion instrument capable of quantifiably detecting corrosion.

- Task 1. A literature review of current methods and instrumentation for corrosion detection and measurement.
- Task 2. Design and development of an embedded corrosion instrument capable of multiple measurement types.
- Task 3. Design and fabrication of test procedure and equipment.
- Task 4. Data collection and analysis.
- Task 5. Field installation and demonstration.

Corrosion Monitoring Methods

The first task in designing an embeddable instrument for corrosion detection and monitoring was a literature review. Current methods of detection and measurement of corrosion were considered in the design of the corrosion instrument.

Embedded Corrosion Instrument Design

The system block diagram of Figure 1 shows the basic components of an embeddable corrosion instrument.
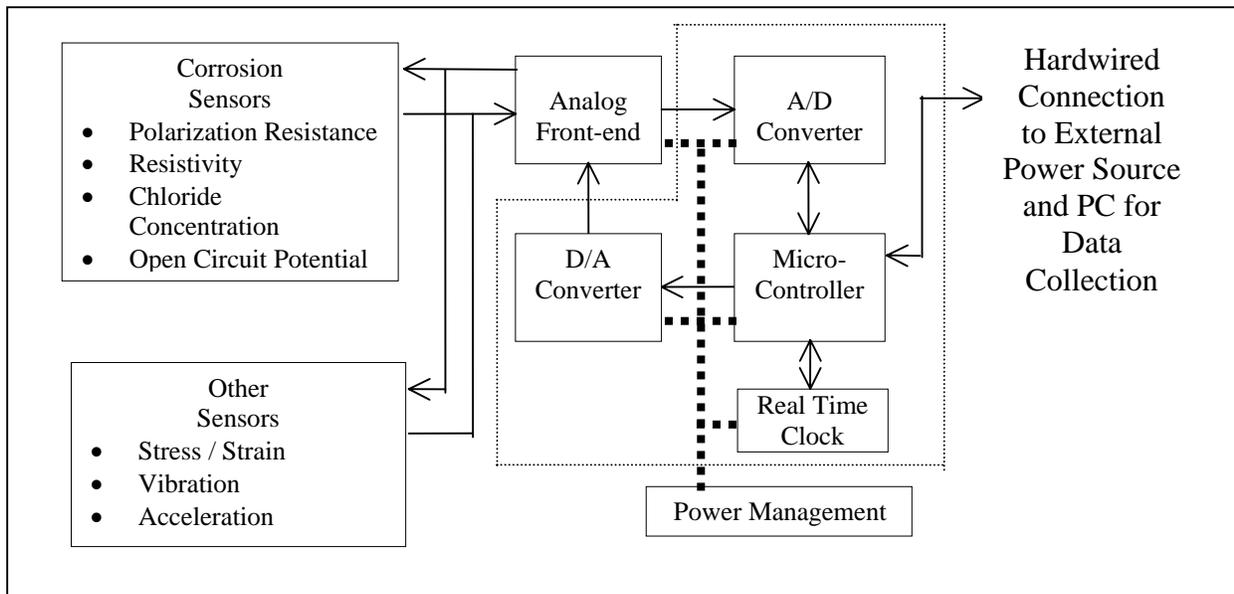

Figure 1. Block Diagram of the Corrosion Measuring Instrument.

This was used as the basis for a proof of concept prototype. The electronic circuitry and software were designed and tested to perform the measurements of chloride potential, resistivity, polarization resistance and open circuit potential. This design was used to produce a printed circuit board and embedded software that was used in the test procedure and data collection.

Test Procedure

Chloride ingress in concrete is a lengthy process in the field. To facilitate this process, two containers of 1 M NaCl solution were clamped to either side of the concrete block shown in Figures 2 and 3. Rubber O-rings (not shown) were used to provide a leak tight seal between the containers and concrete block. Pt/Nb mesh electrodes were placed in both containers to apply an electrostatic field with the polarity shown in Figure 2 to drive the Cl⁻ from left to right, toward the sensor electrode array. The chloride driving current was maintained at approximately 10 mA. The 1 M NaCl solution was changed on a regular basis to prevent the accumulation of hydroxide ions (OH⁻) during the chloride driving process.

The test apparatus shown in Figures 2 and 3 was used to test the performance of the Virginia Technologies, Inc. (VTI) Embedded Corrosion Instrument (ECI) drive and sense electronics versus the EG&G VersaStat™, a commercial laboratory grade instrument. The sensor electrode array embedded in the concrete block was used to make *in situ* measurements of chloride ion concentration (Cl⁻) and the resistivity (ρ) of the concrete as well as the polarization resistance (R_p) of an electrode made from reinforcement steel. The sensor electrode array embedded in the test block has the same geometric configuration and material composition as the electrodes to be used in the ECI prototype.
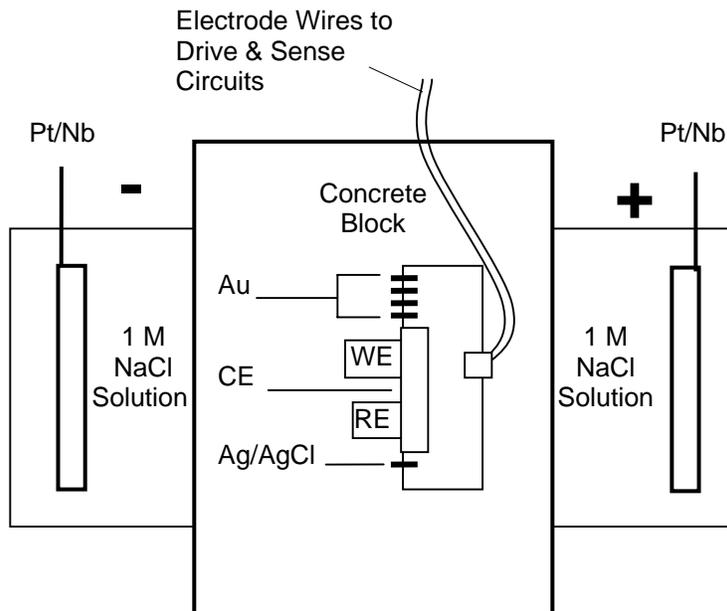

Figure 2.   Apparatus for Electrochemical Driving of Chloride into Concrete.

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Figure 3.   Photograph of Apparatus for Electrochemical Driving of Chloride into Concrete.

The concrete block was poured at the VTRC. The mix was created according to the following recipe: 20.1% (29.1 lb) Type II cement, 50.9% (73.8 lb) fine (#4 mesh) aggregate, 19.1% (27.7 lb) sand, and 9.9% (14.3 lb) water to make 1 ft^3 of mix at 145 lb/ft^3. The chloride ion concentration was measured by recording the potential of a calibrated Ag/AgCl electrode versus an MnO_2 reference electrode (RE). The resistivity of the concrete was measured with a four-pin Au probe. The working electrode (WE) of the potentiostat was a piece of reinforcement steel; the counter electrode (CE) was made of Pt/Nb mesh. The RE is shared with the chloride ion sensor. The electrodes were mounted on an acrylic plate. Insulated conductors from the sensor electrode array were run out of the concrete block to be connected to the ECI and an EG&G VersaStat™ for comparative measurements.

Data Collection

Data were collected from the test setup over a period of 75 days. Chloride ions were actively driven into the concrete toward the measurement electrodes during this time. The data are graphed and analyzed in the results section.

Field Installation and Demonstration

After the embedded instrument was designed and tested in the laboratory, it was installed on a bridge in the field. Remote collection of the data from the embedded instruments was demonstrated.

RESULTS AND DISCUSSION

Literature Review

Corrosion of Steel in Concrete

Typically, the high alkalinity of concrete (pH ~ 12.5 to 13.8) facilitates formation and maintenance of a protective, passive film on embedded steel. A low corrosion rate generally results (Jones, 1996). However, this protective film can be compromised, particularly by chlorides. Dissolved chlorides play a major role in corrosion damage to concrete because this particularly aggressive and ubiquitous species impairs passivity and increases the active corrosion rate of the carbon steel in neutral and alkaline pore waters. In addition, the resultant ferrous corrosion products form an acid solution with chloride that neutralizes the alkaline concrete environment and further enhances corrosion. There is a threshold – ~ 0.02 % (concrete wt. basis) - above which corrosion is significantly accelerated in the presence of chloride (Glass and Buenfeld, 1997). Chlorides arise from exposure of the concrete to deicing salts, marine environments, high chloride soils, and ground waters and from entrainment in raw materials. In the presence of moisture, sufficient oxygen to sustain cathodic reactions, and either carbonation or chlorides, the resultant corrosion rate can be unacceptably high.

Corrosion of steel embedded in concrete can impact structural integrity by (1) corrosion product-induced cracking and spalling of the concrete, (2) loss of load transfer (disbondment) between concrete and reinforcement, (3) overload failure of stressed tendons due to thinning by corrosion, and (4) hydrogen-induced embrittlement of pre-stressed/post-tensioned elements. Not all mechanisms are relevant to both reinforced and pre/post-stressed structures. For example, the low carbon steels used as rebar are not susceptible to embrittlement in conditions typically associated with concrete structures.

Corrosion Detection and Quantification Methods

There is a variety of techniques for detecting and characterizing corrosion in steel reinforced concrete. These are roughly divided into non-electrochemical and electrochemical techniques. Both types of techniques are useful in determining the presence and extent of corrosion and offer different advantages and drawbacks.

Non-electrochemical methods include visual inspections, soundings, direct examination, electrical resistance, and acoustic and strain measurements (Sagues, 1993). Evidence of corrosion in visual inspection is usually seen by the presence of small cracks that may or may not be accompanied by rust. These cracks are not always easily detected and may be overlooked during inspection. Generally by the time external signs are visible, the corrosion process has been active for some time. The sounding method of corrosion detection involves striking the

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concrete with a hammer, or in the case of bridge decks by dragging a heavy chain, and listening for a characteristic hollow sound, which may indicate the presence of corrosion products that have caused internal cracks and delamination of the concrete. Direct examination for the presence of corrosion can be performed by exposing the reinforcement steel and evaluating material properties such as thickness, weight loss, and corrosion pit size. The rebar can also be given a numerical descriptor based on its overall appearance. The electrical resistance of the reinforcement steel increases as the cross-sectional area decreases due to corrosion-related material loss.

Acoustic methods are available that generate multi-frequency signals, which are collected by a detector and spectrally analyzed. Distinctive defects such as internal cracking can be mapped to produce a picture of corrosion damage in the structure. Corrosion detection and measurement by acoustic methods are not widely used because the relationships between corrosion products and acoustic emissions are not well understood. The external dimensions of concrete structures can be monitored by strain gauges to detect stresses generated by the expansion of corrosion products.

Electrochemical techniques offer several methods for the detection and quantification of corrosion in steel reinforced concrete. Reinforcing steel (rebar) in concrete exhibits a corrosion potential or open circuit potential measured against a reference. As corrosion takes place and the rebar becomes active, the potential will shift and become more negative. While this open circuit potential may indicate corrosion activity, it can be affected by a variety of environmental factors and cannot be relied upon as a stand-alone means of evaluating corrosion. The resistivity of the concrete surrounding the reinforcement steel can also serve as an indication of conditions under which corrosion may or may not take place. Generally the corrosion rate is lower in concrete with higher resistivity. Water levels in the concrete are lower with higher concrete resistivity. The measurement of macrocell currents in a structure can provide a direct indication of corrosion activity. The downside of macrocell current measurement is that regions of the rebar can have anodic and cathodic reactions occurring simultaneously and can significantly underestimate the corrosion currents. Very small fluctuations in potentials due to pitting and repassivation of the rebar can be spectrally analyzed over time to infer the corrosion rate. This electrochemical noise method is difficult to utilize outside of the laboratory due to the extremely small changes in potential and the laboratory grade instruments needed to accurately measure them. Polarization resistance measurements performed in situ can provide instantaneous corrosion rates as well as measure accumulated damage over time. Small amplitude polarization scans are conducted about the local open circuit potential to determine the polarization resistance. The potential range of these scans is small in magnitude to avoid possible initiation of corrosion by driving the potential in the anodic direction. Polarization resistance measurements in concrete are subject to error from potential differences between the steel surface and the reference electrode due to the ohmic resistance of the concrete.

There is a variety of techniques currently available for the detection and measurement of corrosion. However, many of these methods are labor intensive and require technicians to be on site to perform. Several of these means of detection are qualitative and only reveal the problem once it has damaged the structure. Currently there is no single embeddable field instrument that

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incorporates linear polarization resistance, resistivity, chloride detection, temperature, and open circuit potential in a single package that requires no oversight in the field.

Corrositivity Sensing and Quantification

After curing for 2 weeks in a humidity chamber, the concrete block was connected to the NaCl containers and chloride driving at 10 mA commenced. Chloride driving was not constant in order to allow monitoring of the chloride content. The Cl$^-$ concentration at the microinstrument is shown in Figure 4 as measured with the Ag/AgCl electrode versus the MnO$_2$ reference electrode. The concentration cited (in weight %) is based on the calibration curve shown in Figure 5 for the sensor type in concrete. Although there is considerable scatter in the calibration curve, the change in the chloride content above the critical concentration for initiation of corrosion can be reasonably established. The scatter in the calibration curve is due to some failures of these early laboratory versions of the Ag/AgCl electrodes in which the leakage occurred at the electrical connection. This problem was remedied in the prototype with improved sealing. The chloride concentration at the microinstrument increased after approximately 500 h of electrochemical driving.
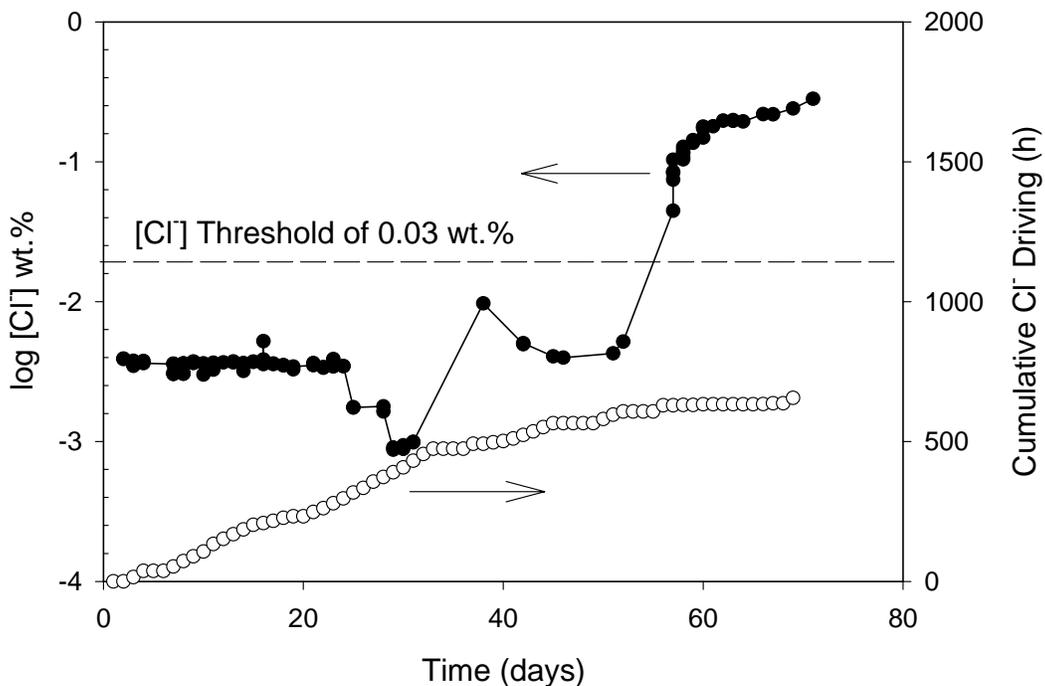

Figure 4. Chloride Concentration at the Microinstrument and Cumulative Hours of Chloride Driving vs. Time. The dotted line represents 0.02 wt.% chloride, considered the threshold concentration for corrosion of steel in concrete. The chloride concentration was based on the calibration curve line shown in Figure 5.
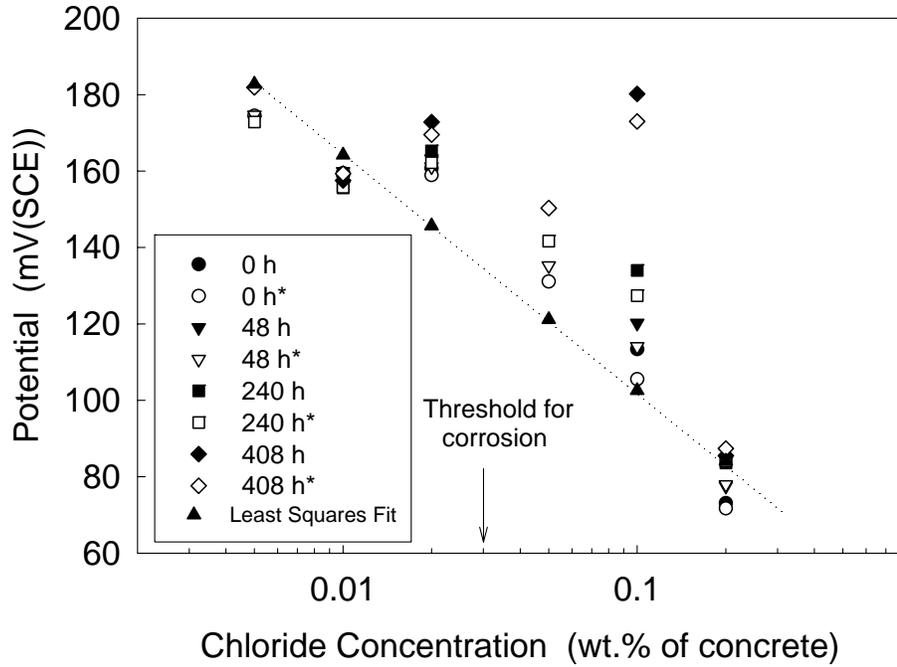
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Figure 5. Calibration Data for Separate Ag/AgCl electrodes in Concrete Made with Different Amounts of Chloride in the Mix. The 0.03 wt.% threshold concentration is also indicated. The time dependence shown is due to failures of the insulation at the electrical connections in these early prototype Ag/AgCl electrodes.
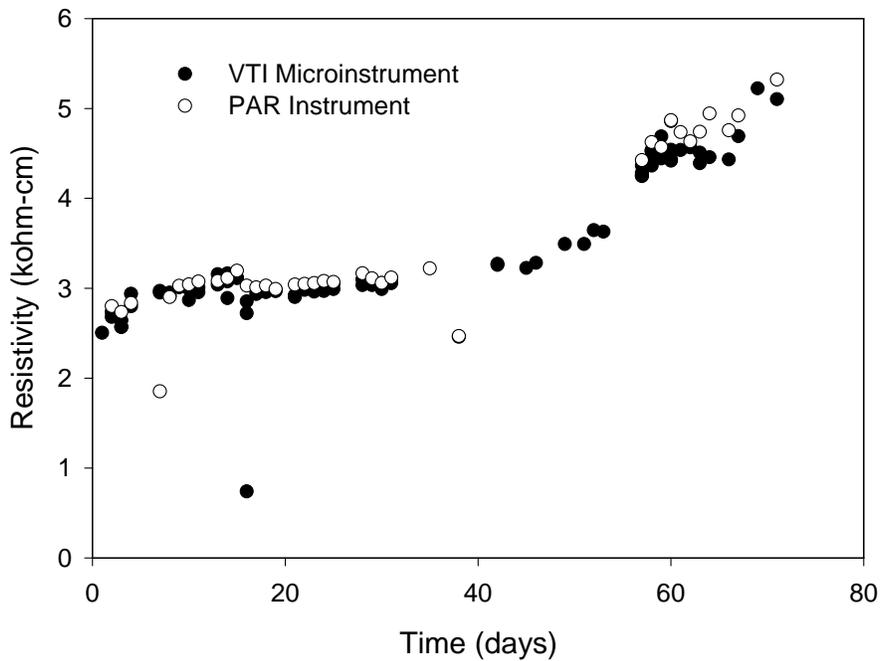

Figure 6. Resistivity of Concrete at the Microinstrument as a Function of Time. Resistivity was measured with both the VTI microinstrument and a commercial galvanostat produced by Princeton Applied Research.

As the chloride concentration at the microinstrument sensor array increased, so did the resistivity as shown in Figure 6. This effect may be due to the loss of hydroxide in the area due to its higher mobility relative to chloride. The agreement between the measurements by the VTI microinstrument (950 cm^3) and the commercial PAR instrument (costing ca. $10K and requiring about 180,000 cm^3) is excellent in general.

As the chloride concentration at the sensor array increased above the threshold concentration for corrosion, one would expect the open circuit potential of the steel to decrease and the corrosion rate (which is proportional to $1/R_p$, the inverse of the polarization resistance) to increase. Figure 7 shows this depassivation of the reinforcement steel working electrode. Data are only shown for R_p between 1 MΩ-cm^2 to 1 KΩ-cm^2, which is the operating specification of the ECI. The open circuit potential (OCP) of the steel was measured between WE and RE. The R_p data were collected with both the ECI and the EG&G VersaStat^{TM}. The steel was passive (R_p > 1 MΩ-cm^2) until Day 57 of chloride driving. The onset of corrosion in the WE corresponded to a sharp decrease in the Ag/AgCl- RE potential (indicating a large increase in chloride concentration as shown in Figure 4), and resulted in a rapidly changing OCP and $1/R_p$.
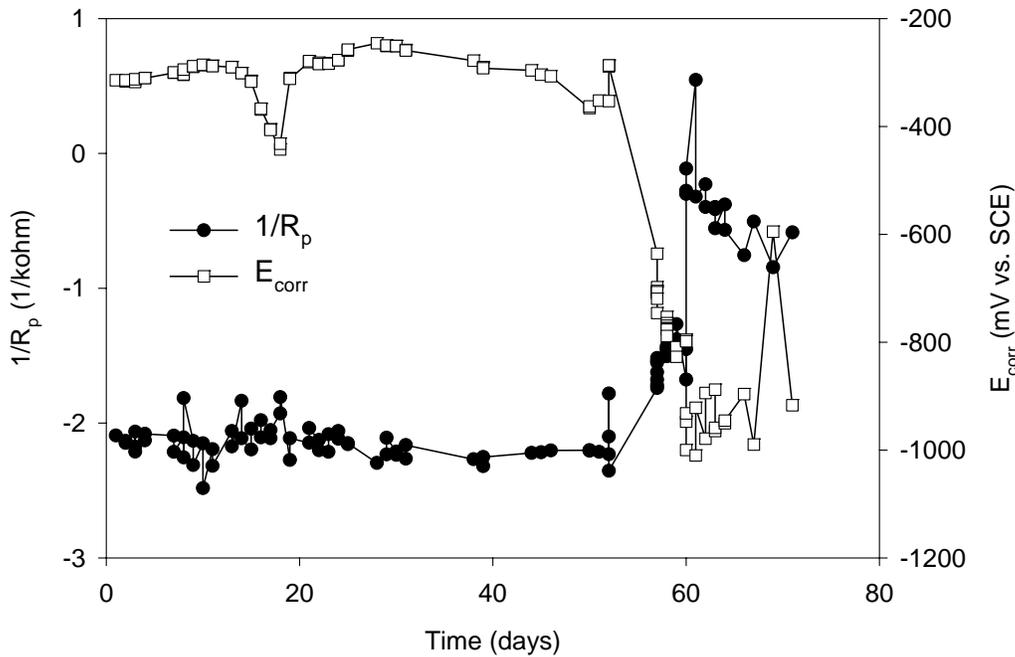

Figure 7. Corrosion Rate (Directly Proportional to the Inverse of the Polarization Resistance, $1/R_p$) and Open Circuit Corrosion Potential (E_{corr}) as a Function of Time. Note the sharp increase in corrosion rate and simultaneous decrease in the corrosion potential.

Communications

It was determined that using active RF transmission and reception are feasible from a communications perspective but not feasible due to power consumption and price. The typical "Blue Tooth" compliant RF transceiver module requires 35 milliamps during transmission. It is

important to understand that for wireless transmission to have any value, an instrument must have self-contained power. All self-contained power options have limited power capacity. Because of this limitation, the relatively high power requirements of active RF technology present a significant problem. An active RF transceiver module is also prohibitively expensive, costing approximately $100 in quantity. It is improbable that a cost-effective instrument could be built using such an expensive component.

A viable communications alternative to using an active RF transceiver is use "RF tag" technology (used in the SRI International "Smart Pebble"). RF tag devices transfer information by modulating and reflecting incoming RF energy. Since RF tags do not actually transmit, they require no internal power to operate. In addition, a small amount of power for the instrument can be derived from the incoming RF energy.

The problems associated with using RF tag technology are significant. Primarily, the amount of power that can be parasitically derived from the incoming RF energy is minute and can only be used to power a limited amount of internal circuitry to conduct a simple measurement such as chloride concentration. Measurements that require significant numerical processing such as polarization resistance require more power to perform. This required power is not available using RF tag technology. Second, RF tag technology has a limited read distance. RF tag devices embedded in a bridge deck may only have a readable distance of 3 to 6 inches. Results would be uncertain in the event that these instruments are embedded in a deep bridge deck such as the Rt. 29 bypass bridge in Lynchburg, Virginia that is 9 inches thick. In order to read these devices, a truck or van fitted with an RF tag reader and an antenna suspended 1 or 2 inches from the surface of the roadway would need to be driven over the embedded devices. This measurement process would require operator intervention on site and possibly closure of a traffic lane

The ECI-1 approach addresses each of these problems. It was determined that providing wireless power and communications for each embedded instrument was costly, technically problematic, and unnecessary. Each ECI-1 instrument is hardwired, using a 0.2-inch-diameter Teflon-jacketed cable, to a central externally mounted datalogger and communications system. The routing of the wires in the Lynchburg, Virginia installation has offered little or no problem. Wireless communications are between the externally mounted cellular data transceiver and the wireless cellular network. Corrosion data from embedded ECI-1 instruments can be evaluated remotely anywhere in the world. Perhaps most important, collecting data from ECI-1 instruments does not require any intervention on site or disruption of traffic flow.

The deliverables cited in the proposal were:

1. Design Specification
2. Five Wired Units
3. Five Wireless Units
4. Demonstration of Graphical User Interface (GUI)
5. System Demonstration.

The research efforts for this project were highly focused toward designing and building an instrument that performed to specifications during laboratory testing and was ready for field testing. It was determined that pursuing the design and construction of an instrument having the measurement capabilities of the ECI-1, and that was wireless with a self-contained power source, was outside the timeframe and funding limitations of this project.

Here is the status of the deliverables cited above:

1. Design Specification
    The ECI-1 technical specification has been completed.

2. Five Wired Units
    10 Hardwired units have been constructed.

3. Five Wireless Units
    Determined to be outside the timeframe and funding limitations of this project.

4. Demonstration of Graphical User Interface (GUI)

A basic graphical user interface is provided by the Campbell Scientific datalogger software and is ready for demonstration.

Prospects of Long-Term Stability

There are no universally accepted methods that allow accelerated testing in the laboratory to be extrapolated to field service life. Nonetheless several comments can be made in this regard. A rugged, environmentally sealed enclosure was designed and molded to provide protection for the electronics, a rigid mounting surface for the electrodes, and features for mounting the instrument to the rebar as shown in Figure 8. There should be no concern for the longevity of the conductivity electrodes and sensors. The stainless steel electrodes are not susceptible to corrosion in concrete at the levels of chloride expected. In addition, the conductivity measurement is made in such a way that the nature of the electrodes is not important. The steel working electrode should also last; it is the same material as that of the reinforcement mat. When the working electrode does *begin* to corrode, this will be used to indicate the need for the planning of mitigation measures for the bridge. Due to the relatively slow diffusion of chloride in concrete and the position of the ECI-1, the working electrode will begin to corrode (by reaching the critical chloride content) well before the reinforcing mat, leaving sufficient time to implement mitigation measures. The reference electrode is a commercial manganese dioxide electrode from the Force Institute (Denmark). It was selected for its long history of excellent performance in concrete. The specifications from the Force Institute can be found in Appendix B. The service life of the Ag/AgCl electrode is unknown at this time. Possible degradation could occur and further studies are needed. The ECI-1 shares this uncertainty with all other devices that use ion-specific electrodes for chloride in concrete. The ability to measure four other parameters is what provides the user of the ECI-1 with a more complete and robust description of the corrosion situation in the concrete
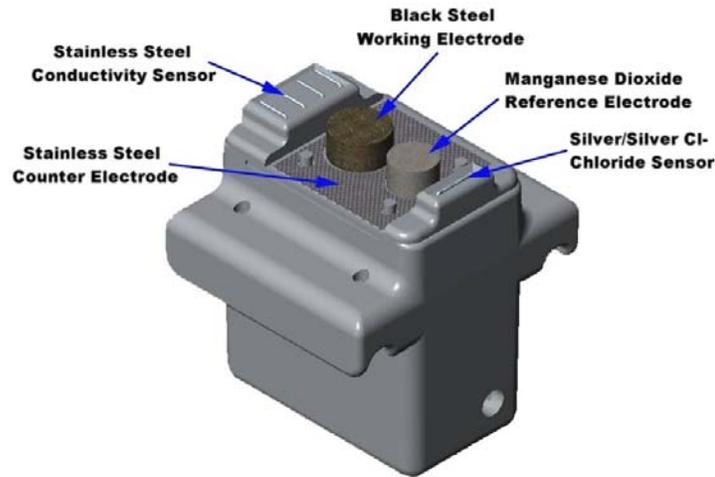
Figure 8. The ECI-1 Model with Electrodes.

Reproducibility

For the data presented, only the ECI-1 electrodes were embedded in the concrete test block. The instrument's electronics were mounted external to the block. This approach allowed us to make the required hardware and software modifications while collecting live electrode data. If the electronics were mounted in the block during testing, these refinements would not have been possible. Having the electronics connected externally to the concrete allowed the embedded electrodes to be decoupled from the ECI electronics and connected to the EG&G VersaStat™ for comparison and verification of corrosion measurements. Also, the electronics used in the ECI-1 system are specified to operate over a temperature range of -40 to +70 C. This range is much wider than any conditions that would be experienced in the field. The instrument's printed circuit board is completely potted in watertight epoxy. Any moisture that may come in contact with the instrument while embedded in concrete will not affect the electronics. If we had chosen to mount the instrument electronics in the concrete test block, it is doubtful that our results would have been any different, and we would have lost some of our testing flexibility. Of course, the ECI-1 instruments embedded in our field test site in Lynchburg Virginia include electrodes and electronics.

Repeatability data for each measurement are available but have been specifically not included in the report for clarity. The data presented in the report demonstrate that the ECI-1 can measure corrosion-related parameters over an extended range of corrosion conditions. The measurement range for each parameter is indicated on the specification sheet (Appendix A).

Note that it is not necessary to calibrate each instrument for measurement of polarization resistance, resistivity, open circuit potential, or temperature. These measurements are simply derived from the instrument's ability to measure voltage and current with good accuracy and repeatability. Data regarding long-term stability and longevity of the Ag/AgCl chloride sensor in

concrete are currently unknown. For our first field installation in Lynchburg, Virginia, the instruments have been programmed to measure the chloride electrode voltage. These voltages will be monitored over time and correlated with other measurements. Once a significant amount of field data have been collected, future instruments will be programmed to indicate three levels of chloride concentration: high, moderate, and low. These measurement bands will be wide enough so that each chloride sensor will not need to be individually calibrated. Nonetheless, individual calibration curves could be easily programmed into each instrument before shipping.

Prototypes

The current ECI-1 prototype is capable of five measurements; these include polarization resistance, open circuit potential, resistivity, chloride concentration and temperature. These electrochemical techniques (with the exception of temperature) provide direct information of internal corrosion activity. Used in combination they present a snapshot of corrosion conditions at the embedded reinforcement elements. Problems of distributed current effects and ohmic resistances in measuring polarization resistance have been overcome in the ECI-1 by use of a sacrificial working electrode and a geometry/resistivity based method of calculating and subtracting error due to ohmic resistance.

The ECI-1 provides rugged packaging for the embedded sensors and electronics necessary to protect them in concrete. An embedded instrument must be able to survive many environmental conditions such as extremes in temperature, moisture, ph ~ 13, and a variety of salts and other chemicals that may enter the structure by diffusion or were present during construction. The enclosure must be able to withstand mechanical stresses of tension and compression transferred by the surrounding concrete and steel. The enclosure also must not compromise the integrity of the structure by its placement. These factors were modeled for bridge decks and incorporated in the design of the ECI-1. These factors will be considered in the design of an enhanced embedded corrosion instrument in order to extend the use of the instrument to structures other than bridge decks.

Field Installations and Demonstration

Four of the 10 ECI-1 instruments built have been installed in the Route 460 bypass bridge in Lynchburg, Virginia. Bridge B-623 is a three-lane; 900-ft continuous span bridge reinforced with epoxy coated rebar. The instruments were placed on the lower slope of the bridge where road salt melt water is most likely to accumulate. Because the Lynchburg installation is wireless, the demonstration was held at VTI with Dr. Paul Virmani and Dr. G. G. Clemeña in attendance. The demonstration showed that from VTI in Charlottesville, Virginia, the instrumentation in the B-623 bridge in Lynchburg could be called and the requested data collected by the embedded instruments were downloaded remotely. The power for the system is provided by a solar panel charged battery. This system is shown below in Figure 9. The measurements from the ECI-1 instruments are collected daily and are graphed at VTI.

An additional six ECI-1 units were purchased and will be installed in California at a test site chosen by CalTrans this winter. VTI will install and set up the system for CalTrans.
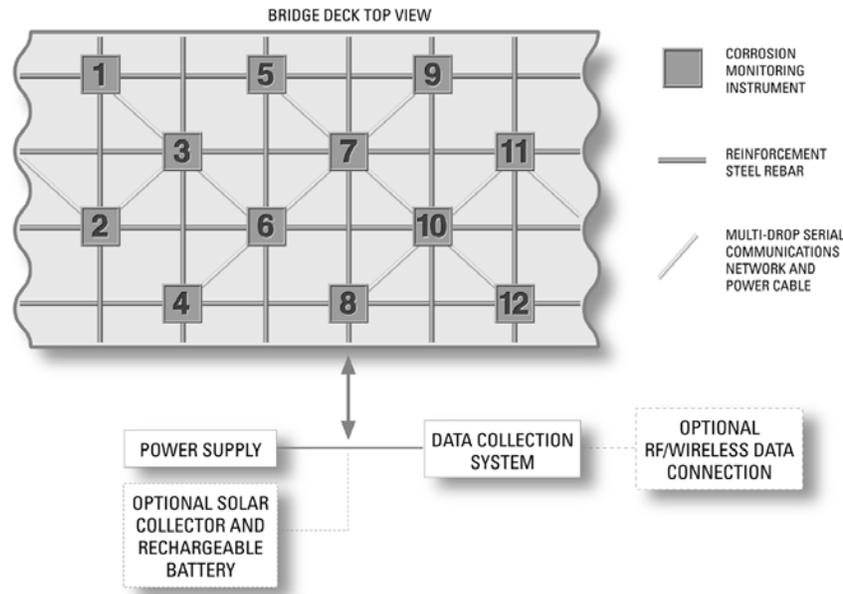
Figure 9. Bridge Corrosion Monitoring System.

CONCLUSIONS

The model ECI-1 embedded corrosion instrument provided resistivity and polarization resistance measurements comparable to those of the EG&G VersaStat™. In addition it performs Cl^- concentration measurements. The geometric configuration and material composition of the instrument electrodes in conjunction with its electronics allowed the ECI-1 to produce repeatable measurements over its specified operating range. The testing emulated a practical real-world situation where the ECI-1 was able to directly measure corrosion rates, resistivity, and increasing chloride concentration of steel rebar in concrete.

Given that the ECI-1 electronics compare favorably with the results of the laboratory instrument in the test procedure, the next step in the development of this solution is to embed fully assembled instruments in a bridge structure. At the time of this report, four instruments have been installed in the 29/460 interchange near Lynchburg, and six more are about to be installed at a test site in California for CalTrans in November.

Other practical applications of this technology can include other types of structures such as dams, spillways, and parking garages. With little or no modification, the ECI-1 can be used to monitor the internal corrosion rate of these structures. The ECI-1 can be used in ponding experiments to provide researchers with in-situ monitoring of corrosion conditions within the sample.

RECOMMENDATIONS

The instruments at the Lynchburg District site should be monitored in order to assess the continued functionality of the instruments and to gather information of the evolution of

corrosivity of the concrete at that site. These data should be collected for a minimum of 15 years, as it is not expected that large changes in corrosivity at the level of the instruments will be observed earlier. The data from the planned CalTrans installation should be compared to that from the Lynchburg site to better understand the factors that control the evolution of corrosivity.

The expansion of microinstrument use to long-term laboratory measurements at VTRC in studies of inhibitors and other corrosion mitigation strategies is also recommended. It will provide the ability to measure the effects of these strategies on not only the overall corrosivity (via the polarization resistance), but also the individual components (i.e., chloride concentration, conductivity).

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APPENDIX A: SPECIFICATIONS FOR INSTRUMENT

ECI-1 Corrosion Instrument Specifications
(U.S. Patent Pending)

Physical Dimensions -
Enclosure - 85 mm (L) x 80 mm (W) x 50 mm (H)
Enclosure and Electrodes - 107 mm (L) x 80 mm (W) x 50 mm (H)

Enclosure Material -
ABS Plastic, Epoxy Potted
Water Tight Seal

Chloride Measurement -
Range - 0.01% $\rightarrow \geq$ 1% Chloride
Electrodes (2) - Ag / AgCl (1) 15 mm (L) x 1 mm (D), MnO_2 (1)
13.5 mm (D) x 8 mm (H) (concrete)

Conductivity / Resistivity Measurement -
Range - 15,000 $\rightarrow$ 1,000 Ohm-cm
Electrodes (4) - Au (4) 8 mm (L) x 1 mm (D) spaced at 12 mm

Polarization Resistance Measurement -
Range - 1 MOhm-cm^2 $\rightarrow$ 1 KOhm-cm^2
Electrodes (3) - Pt / Nb Mesh counter electrode (1) 18 cm^2 x 1 mm thick, MnO_2 reference
electrode, Force Institute Model ERE 20, (1) 13.5 mm (D) x 8 mm (H) (concrete) shared with
Chloride measurement, Steel working electrode (1) 12.5 mm (D) x 22 mm (H)

Temperature Sensor -
Range - -55°C to +150°C

Estimated Power Requirements -
Strain Gauge Inactive - 1.5 mAmps @ 3.3 Volts < 5 mWatts
Strain Gauge (120 Ω) Active - 29 mAmps @ 3.3 Volts < 100 mWatts

Communications -
SDI-12 compatible

Strain Measurement -
Strain Gauge - supports 1 to 4 element gauges
Internal Excitation Source

Source:
Virginia Technologies, Inc.
2015 Ivy Road, Suite 423
Charlottesville, Virginia 22903

APPENDIX B: REFERENCE ELECTRODE SPECIFICATIONS

ERE 20 Embeddable Reference Electrode Specifications (from FORCE Institute)

Potential: Typical potential in saturated $Ca(OH)_2$ at 25 C is +160 mV(SCE).

Stability: At constant temperature, a single electrode will not shift more than +/- 5 mV.

Internal
Resistance: < 5000 ohm after soaking in water

Temperature
Range: Satisfactory performance for temperatures between –10 and +40 C. When frozen, false
readings can be expected, but normal performance returns when thawed.

Service Life: The half-cell is in chemical equilibrium with the surrounding environment. The
manganese oxide will be stable for a long time period. The lifetime is governed by loss of the
cell electrolyte, which has been set for several years of service.

Source:
FORCE Institute
Corrosion Department
Park Alle 345
DK-2605 Broendby, Denmark