

Coating Health Monitor (CHM)

Background

Problem

Corrosion is a wide-spread problem that affects nearly all industry and government sectors. A recent report determined that the direct cost of corrosion in the United States to be 3.1% of the Gross Domestic product (GDP).¹ This corresponds to \$300B annually or \$1000 per person. This figure includes only the *direct* costs (e.g., corrosion prevention, corrosion inspection, and replacement or refurbishment of corroded structures). The *indirect* costs (e.g., lost productivity, taxes, and overhead) were conservatively estimated to be equal to the direct costs.

In addition to the economic impact, corrosion also has other significant societal impact. Undetected or unheeded corrosion of bridges and other structures can cause catastrophic failure with loss of life. Two corrosion-induced bridge collapses, the Silver Bridge over the Ohio River and the I-95 Mianus River Bridge in Connecticut, resulted in 50 fatalities.² Several other bridges have required emergency or accelerated repairs, closure, or traffic restrictions because of corrosion to prevent additional loss of life. Aircraft are another example of undetected and repaired corrosion resulting in fatalities. According to Hoepfner,³ corrosion-related accidents resulted in 11 fatalities for the military and 70 fatalities for the civilian air fleet over a 17-year period and at least two more civilian crashes with 60 fatalities have been reported subsequently. Environmental damage caused by corrosion include the sinking of the oil tanker *Erica* off the coast of France that spilled 20,000 tons of oil over 400km of coastlines and killed 60,000 to 300,000 birds.⁴ Other oil spills arise from numerous pipeline and storage tank leaks, including the Alaska Pipeline in Prudhoe Bay. Finally, corrosion can cause a loss of readiness of equipment and vehicles that can limit the response to natural disasters or threats to national security.



Figure 1. Corroding support of a railroad bridge.

Paint coatings are the primary means of corrosion protection for most structures and they can be very effective. However, paint coatings are only temporary; they weather, absorb moisture, blister, become scratched or undergo other mechanical damage (Figure 1). Even fresh paint coatings can exhibit pinholes, holidays, or other coating defects that can adversely affect corrosion protection. Thus, there is a need for corrosion sensors to assess the health and effectiveness of paint coatings, especially on critical structures and equipment.

Although many corrosion sensors have been proposed and developed,⁵⁻¹⁵ many are not suitable for monitoring coating health. A major disadvantage of many of these, such as galvanic couple sensors and some fiber optic sensors, is that they are more properly considered corrosivity sensors; that is, they detect degradation of a sensor element and not degradation of the structure of



interest. As such, they measure only how corrosive the environment is and provide no direct information on the condition of the paint coating or the structure. Furthermore, they are consumed and have a limited lifetime and can provide no information concerning any environmental degradation prior to installation. A second disadvantage of many sensors is that they need to be embedded into the structure. This limits them to new construction and poses important issues on the effect of the sensor on structure properties and data acquisition/transfer. These sensors cannot inspect existing structures and cannot be replaced if damaged or past their useful lifetime. ElectraWatch's electrochemical impedance sensor approach has neither of these critical disadvantages. The technology is suitable for determining coating health and detection of damage under paint coatings.

Innovative Solution:

ElectraWatch's innovative coating health monitoring system (CHM) is based on electrochemical impedance spectroscopy (EIS). The system consists of a series of mini-potentiostat modules coupled to two or more tape electrodes mounted on top of the paint coating of the structure or equipment being monitored. The electrodes and modules can be coated with a topcoat if desired. They periodically report to a laptop or handheld device so that an inspector can assess the condition at each sensing point. The inspector can then determine if more detailed inspection or maintenance needs to be scheduled. Communications is implemented using the Zigbee wireless protocol. The units are battery powered an estimated battery lifetime of up to ten years, depending on the frequency of measurement and interrogation. This CHM system tracks corrosion damage from its early stages, indicates an assessment of current condition, and provides a prediction of future condition based on accelerated laboratory testing. Aside from the initial installation and eventual battery replacement for the wireless units, it requires no personnel access to the monitored locations. The CHM offers several advantages over other systems:

- It directly inspects and assesses the condition of the coating of interest. It does not involve corrosivity sensors that simply detect degradation of a sensor element.
- It is applicable for both new fabrication and retrofitting existing structures. It requires no embedded sensors that must be incorporated into a structure during manufacture or refurbishment and cannot be replaced.
- It can detect the intrusion of moisture well before any irreversible corrosion damage occurs while it is also sensitive to the growth of corrosion products during the more severe stages of damage.
- The modules monitor coating health on a programmed schedule and store the results in nonvolatile memory so that the results can be retrieved later.
- The tape sensor is flexible so that it can conform to edges, corners, and curved surfaces. It is corrosion resistant and has survived >2000 hours of alternate immersion in salt water, but can be easily replaced, if needed, or protected by paint for indefinite life.
- The area monitored by the tape sensor depends on the surface wetness so a measurement taken when the surface is wet probes a relatively large area while a measurement taken when the surface is dry is more localized around the tape. That is, the sensor monitors an area around the tape electrode and not just the protected area beneath the tape

Electrochemical impedance spectroscopy is a well-established laboratory technique known to predict materials performance,¹⁶⁻²⁰ but hitherto limited to immersion studies. The CHM extends the use of EIS to field applications and allows identical measurements to be taken under service conditions and in the laboratory. As a coating degrades, its EIS spectrum changes as shown in Figure 2.²¹⁻²⁵ The low-frequency impedance decreases by several orders of magnitude. This decrease in low-frequency impedance takes place as moisture penetrates the coating and is well before any corrosion of the substrate occurs. Thus it can give early warning of decreasing coating protectiveness so that repainting/painting or other maintenance activities can be scheduled.

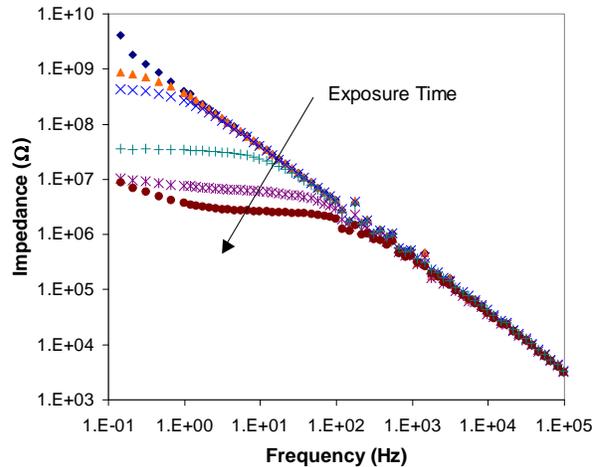


Figure 2. Magnitude of impedance of a coating versus frequency. Low frequency impedance values show good correlation with long-term exposure behavior.

Expected Significance:

Potential applications of the CHM include highways, and bridges, military and civilian land vehicles, aircraft, storage tanks, pipelines, and ships. The benefits of the assessment system will become increasingly important as these systems and structures age and are not replaced. CHM devices are strategically placed on a structure in areas that are difficult to access, monitor, and maintain. These wireless remote sensors can be read from up to 500 feet away with a laptop or PDA that displays the current condition of the coating in the area of each sensor. The CHM system can be integrated into existing Condition Based Maintenance (CBM) software or used as a stand-alone system. Benefits of a CHM system include reducing inspection costs and avoiding repainting unnecessary areas. There is also an added safety benefit associated with performing fewer inspections and painting only when necessary in areas that are difficult and dangerous to access.

Description and Selected Results

The CHM system consists of one or more sensor electrodes, a mini-potentiostat, nonvolatile memory, a wireless data transmitter, and a battery power source. It can be linked wirelessly to the control system or a computer. The CHM is sealed in a housing (except for the sensing elements) to protect the electronics from corrosion (Figure 3). The size, the wireless aspect and the low-cost are some of the attractive features of the sensor. Specifically, the CHM

- Is miniaturized to ~8-cm square, and encapsulated in a suitable material for mounting on top of a paint system
- Measures impedance at three separate frequencies, 0.2, 0.5, and 0.9 Hz
- Communicates wirelessly to a handheld device that can be easily operated and interpreted by a laboratory technician to interrogate the CHM.

A major part of the design was selection of components for low base current draw to maximize battery lifetime and the development of a micro-controller based single chip function generator for digitally synthesizing cell excitation sinusoids. The function generator chip is programmable for sine wave frequency, DC offset and amplitude and produces stable output over the specified -40°C to $+85^{\circ}\text{C}$ operating temperature range of the CHM instrument. The circuit draws extremely low active and sleep-mode currents and operates at 2.7 volts. These parameters will allow the instrument to operate over a long life from a battery source.

CHM wireless communication is accomplished using the Zigbee 802.15 compliant protocol. Each CHM module includes an on-board Zigbee transceiver module allowing the instrument to communicate with other CHM modules or a single base module using power efficient communications. The host module may be interfaced with a PDA type device or other graphical user interface with a USB port.

Software for controlling and interfacing with the prototype CHM electronic circuitry was designed and constructed in the LabVIEW Real Time environment. The LabVIEW CRio development system allows programs to be written in the graphical LabVIEW language. The software is then compiled into a form that can be downloaded into a hardware implementation in a Field Programmable Gate Array (FPGA). This hardware implementation allows the program to run in a fast real time environment with deterministic timing. The LabVIEW CRio system was used to validate the operation of software and algorithms designed to conduct EIS measurements using prototype electronic circuitry and CARC coated test panels with the tape sensors attached.

To demonstrate the CHM, several panels, covered with different paint coatings (Figure 4) were tested in the laboratory and coating degradation was tracked by the CHM. Accelerated corrosion exposure was achieved with alternate immersion (10 minutes immersion and 50 minutes atmosphere) in 3.5% NaCl solution (ASTM G44) as shown in Figure 5. The CHM was programmed and interrogated from a laptop computer in an office 40-50 feet (~15 meters) away.



Figure 3. CHM with top removed.



Figure 4. Painted panel with mounted CHM and tape electrodes.

To verify the accuracy of the CHM, comparisons were made using a commercial Gamry bench top potentiostat. The EIS measurements for the CHM and Gamry potentiostat exhibit excellent agreement over six orders of magnitude (Figure 6) for all three frequencies measured by the CHM. To put this in perspective, a good coating system would typically exhibit an impedance of $10^8 \Omega$ or higher while a poor coating system that no longer provides a barrier to the environment would typically exhibit an impedance of $10^6 \Omega$ or lower.

Examples of coatings with good and poor performance are given in Figure 7. The good coating exhibits high electrochemical impedance with very little change during the testing period. No corrosion can be seen after 36 days of testing. In contrast, although the poor coating exhibited high electrochemical impedance before testing, its impedance had dropped by three to four orders of magnitude by the first measurement period. A further check on the condition of the coating is the impedance dispersion for the three frequencies. For the good coating, the impedances remain distinct, indicating that the low-frequency impedance spectrum has capacitive behavior. (That is, the Bode log-log plot of impedance vs frequency has a negative slope as shown in Figure 2.) For the poor coating, three impedances are nearly identical, indicating resistive behavior. (That is, the Bode plot has a near zero slope also as shown in Figure 2.) Both the CHM and Gamry bench top measurements give similar results.

In a few cases, duplicate painted panels were prepared. In one case, a CHM was mounted on one panel while a nominally identical panel was tested using a free CHM. The two panels exhibited very different EIS behavior during testing (Figure 8) with one exhibiting a slow decrease in impedance and the other exhibiting a much more rapid decrease in impedance of four to five orders of magni-

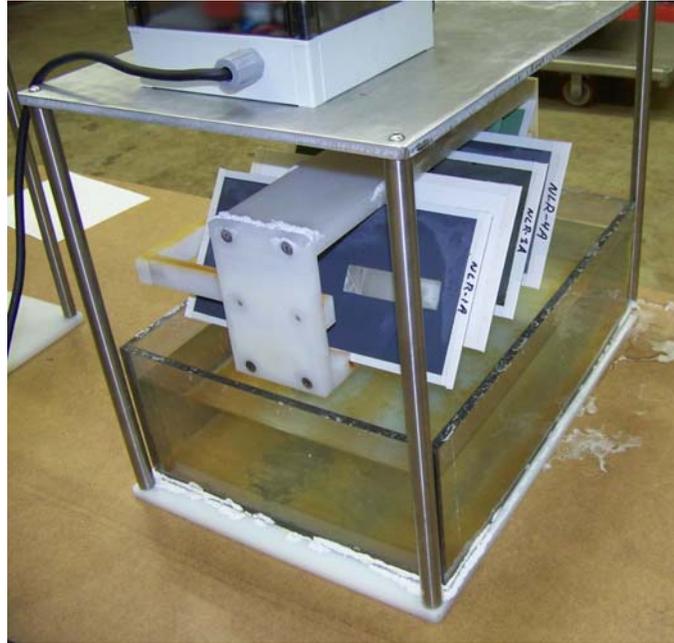


Figure 5. Panels in alternate immersion testing.

Figure 6 is a log-log plot comparing the impedance measured by a Bench Potentiostat (y-axis) against the CHM (x-axis) for several paint coatings. The plot shows a strong positive linear correlation, indicating excellent agreement between the two measurement methods. The data points are categorized by frequency: 0.9 Hz (blue diamonds), 0.5 Hz (magenta squares), and 0.2 Hz (cyan triangles). The axes range from $1.E+02$ to $1.E+10$ for both impedance and CHM values.

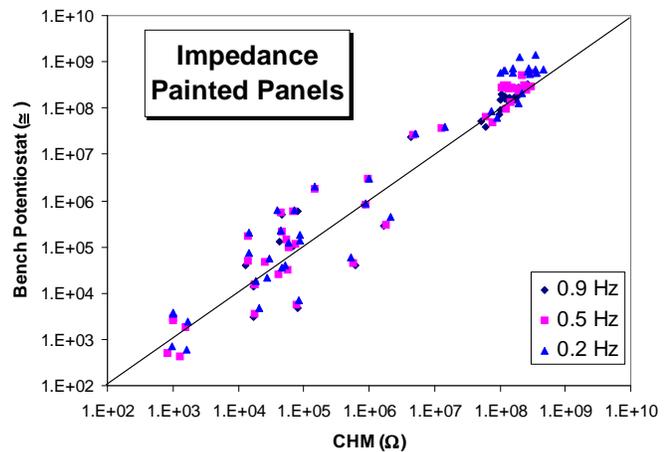


Figure 6. Comparison of results CHM and bench-top potentiostat for several paint coatings undergoing laboratory alternate immersion testing.

tude. At the end of its test (56 days), the first panel had no corrosion except at or near one corner. This corrosion appeared to originate under the tape that was intended to protect the panel edge where coating defects often occur. The second panel had a mounted CHM unit during testing. Once the CHM was removed after 31 days, corrosion was apparent that had begun at a coating defect underneath the CHM module. Here the CHM detected this defect very shortly after the alternate immersion testing began.

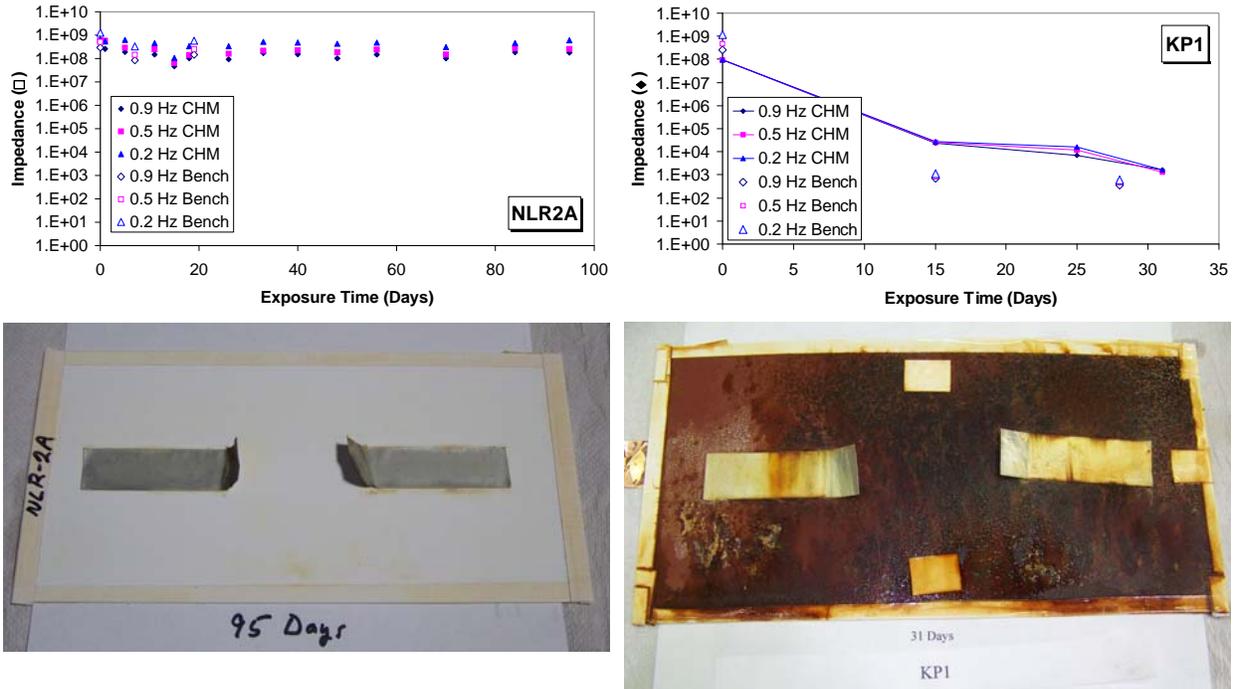


Figure 7. Examples of a good coating (left) and a poor coating (right). The good coating exhibits high electrochemical impedance with almost no change and no corrosion after 95 days. The poor coating exhibits a significant decrease in electrochemical impedance at the first measurement following commencement of testing and extensive corrosion after 31 days. The solid points are the CHM results. The open points are Gamry bench top results.

Another CHM was mounted on the frame of a pick-up truck (Figure 9). Measurements were successfully obtained over a period of several months from the truck-mounted CHM using a computer in an office across from the parking lot.

To allow the CHM measurements to be accessed and interpreted by a technician or inspector, a Graphic User Interface (GUI) was developed and is being modified based on user feedback. Figure 10 shows three screen views of the CHM GUI. The top screen allows the inspector to interrogate individual CHMs. Upon receiving this command, the CHM will transmit its stored readings to the inspector. The middle screen allows the inspector to enter identifying information about the vehicle, CHM, and the location of the CHM. The bottom screen allows the inspector to set the frequency and time for each CHM to take measurements. For example, the CHM can be set to take measurements hourly, daily, weekly, or monthly.

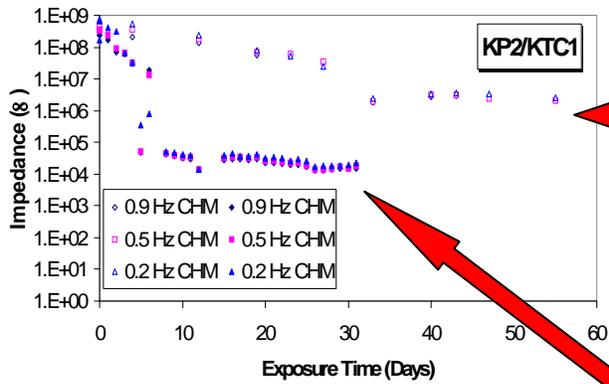


Figure 8. CHM EIS results of two nominally identical panels. One panel (top curve) exhibited a slow decrease in impedance. After 56 days, the panel (upper right) showed no corrosion except at one corner near or under the tape along the panel edge. The other panel (lower curve) exhibited a more rapid decrease in impedance. After 31 days, the panel (right) showed corrosion underneath the mounted CHM.

Figure 9. CHM mounted on the frame in a wheel well of a pick-up truck.



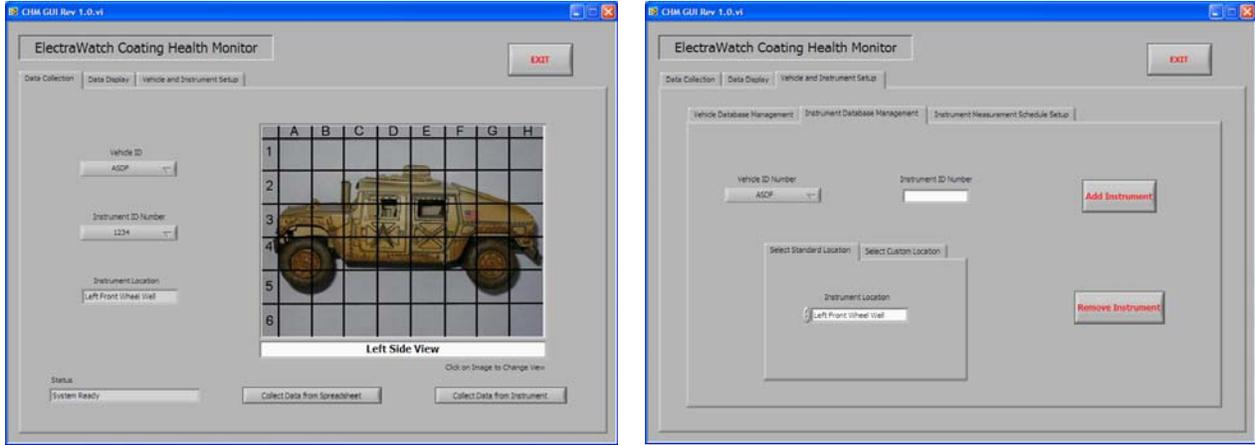


Figure 10. Different screen views of GUI.

A display screen (Figure 11) then allows the electrochemical impedance to be displayed so the inspector can determine the coating health and its rate of change. Results from two coatings are shown. The good coating exhibits little change in the electrochemical impedance while the poorer coating exhibits a decrease in its electrochemical impedance of two orders of magnitude.

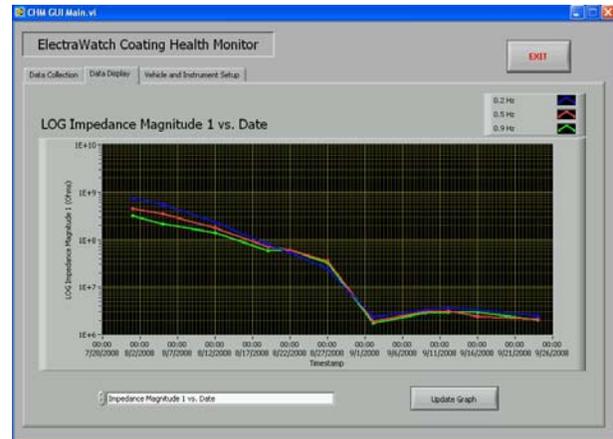
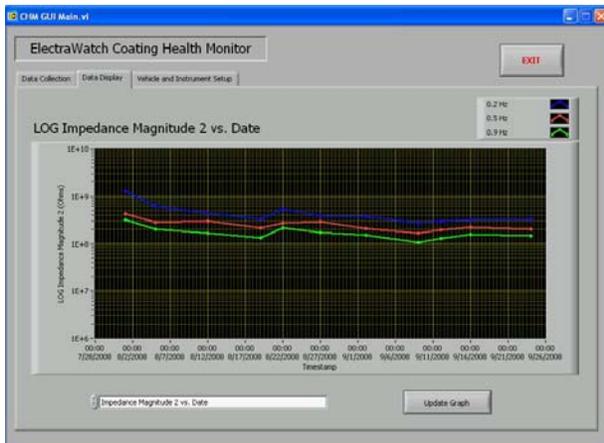
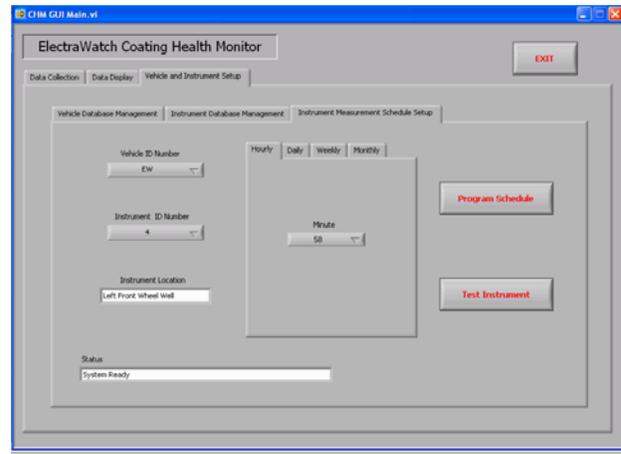


Figure 11 CHM GUI screen shots showing a good coating (left) and one that is degrading (right). Note the differences in impedance scale.

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