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Coating Health Monitoring System for Army Ground Vehicles

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ABSTRACT

A low-cost coating health monitor (corrosion sensor) is being developed for Army ground vehicles. The Coating Health Monitor or CHM is a battery-operated, wireless, miniature sensor system that uses electrochemical impedance spectroscopy (EIS) to detect degradation of the chemical agent resistant coating (CARC). It consists of a small electronics module together with a tape electrode that is mounted onto the vehicle in areas prone to corrosion. The CHM performs a three-frequency EIS measurement to determine the coating condition/protectiveness. Using a wireless handheld device or a stationary unit in a drive-in bay, a motor pool soldier or similar inspector will periodically probe the CHM(s) on a vehicle to monitor the health of the paint system. Critical sites on high-mobility, multiwheeled vehicles (HMMWVs) and other ground vehicles have been identified that are subject to corrosion and are suitable for the CHM. Different tape electrodes are being evaluated and their results compared to conventional EIS for both solventborne and waterborne CARC coatings.

Keywords: corrosion sensors, health monitor, electrochemical impedance, paint, coating

INTRODUCTION

The cost of corrosion of military vehicles and structures is significant in terms of dollars, reliability, readiness, and safety.[1] The direct cost of corrosion for the military is estimated at $20B per year – the greatest factor in lifecycle costs.[2] For the Army, the largest Operations and Maintenance cost drivers are batteries, tires, and corrosion.[3] The cost of corrosion to the Army is estimated at over $3B per year[4] with $2B being attributed to ground vehicles.[2] Another report estimated the cost of corrosion of the High Mobility Multi-purpose Wheeled Vehicle (HMMWV) alone to be $2.0-2.5B per year.[5]

Military vehicles are operated under a wide variety of environmental conditions, some of which are more corrosive than others. For example, HMMWVs operated in Hawaii are subject to hot/cold and dry/wet cycles more frequently than those in the mainland U.S. Vehicles operated in the Korean peninsula experience near-tropical climates during summer. For vehicles operating along the costal regions of the Persian Gulf and the Middle East, exposure to salt-laden water is a perennial problem. Vehicles stored in the deck of ships during transport overseas are constantly exposed to salt spray. Yet, despite the corrosion costs and the aggressive conditions to which Army vehicles can be exposed, historically, corrosion has not been a high priority and design has not always reflected good corrosion protection control practices.[6]

For example, the corrosion protection of the original HMMWVs is provided solely by the Mil-C-46164 and chemical-agent resistance coatings (CARC).[2] Unfortunately, the CARC coating is inadequate for this task as indicated by a GAO report of inspection of HMMWVs.[7] Although the most recently procured HMMWVs have improved corrosion protection, the majority of the 130,000 HMMWVs owned by the Army and the Marines rely exclusively on the paint for corrosion protection.[2]

While HMMWVs may be especially corrosion-prone, there is a need to monitor the paint coating on most, if not all, of the military's 350,000 ground and tactical vehicles to ensure that it is protecting the structure. This approach would help satisfy the Congressional mandate to reduce corrosion and its effects on military equipment.[8] Visual inspection is one way, but it is labor intensive, difficult to do for inaccessible areas, qualitative, and person-to-person dependent. A better way is low-cost corrosion sensors used by motor pool soldiers to decide if preventative maintenance needs to be scheduled. The ideal corrosion sensor for ground vehicles would:

- Directly and quantitatively monitor coating health and not merely the corrosivity of the environment. In addition to the clear benefits of directly determining coating health, this also allows a one-time measurement to assess coating condition instead of requiring two elapsed time measurements that do not take into account the initial state of the coating.
- Provide an early indication of coating degradation before structural corrosion occurs so that preventative maintenance can be scheduled before vehicle integrity is compromised.
- Be retrofittable to existing vehicles.
- Be simple enough that motor pool personnel can operate and interpret sensor readings.
- Track changes in sensor readings with time.
- Be sufficiently low cost so that several sensors can be mounted on each vehicle.
- Be robust enough to withstand the Army's operating environments.

A Coating Health Monitor or CHM is a battery-operated, wireless, miniature sensor system that is being developed to meet these properties. It is based on electrochemical impedance spectroscopy (EIS) sensor technology,[9] and an Embedded Corrosion Instrument (ECI). The CHM will take EIS measurements of coatings in the field under ambient conditions instead of the conventional laboratory approach of immersing a specimen and using remote electrodes. Traditional EIS has been correlated with long-term coating performance in a variety of environments[10-17] and is a direct, quantitative measurement of the coating protectiveness. The sensor gives identical measurements to the conventional immersion/remote electrode method. One sensor electrode acts as both the reference and counter electrodes with the substrate being the working electrode. In the case of ground vehicles, it measures the impedance of the paint. This impedance is then related to the health of the paint.

As a coating degrades, its EIS spectrum changes as shown in Figure 1.[18-22] 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 depainting/painting or other maintenance activities can be scheduled.

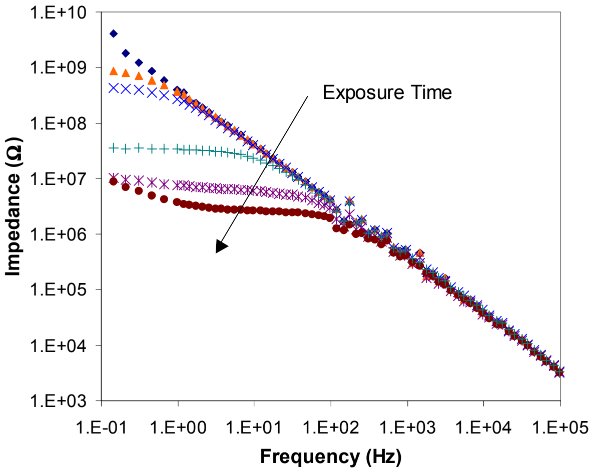


Figure 1. Magnitude of impedance of a coating versus frequency. Low frequency impedance values show good correlation with long-term exposure behavior.

The CHM electronics is a battery-operated, wireless, miniature instrument based on the ECI designed to monitor the corrosivity of concrete in bridge decks. One of the advantages of this CHM is the miniature EIS instrument that is integrated with the sensing electrode. This approach is quite unlike the most common method in which the sensing elements are electrically connected to large-size desktop EIS instruments. The desktop versions are unsuitable for permanent installation in Ground Vehicles. Besides being large in size, they are also expensive and need large power source (>10 W) to operate.

The CHM is shown schematically in Figure 2. Two tape sensor electrodes are shown. Contact to the metal substrate is provided via the two mounting screws.

Each sensor communicates wirelessly, and has an electronic ID that enables 1) the user to associate the origin of data to the sensor, and 2) use of multiple sensors in each ground vehicle. When activated, the sensor completes the measurement in about 200 seconds or less, and transmits the data to a data receiver/logger (a PDA-type device) through a wireless protocol. The receiver/logger receives and presents the user with coating impedance, temperature and the sensor ID number.

All the instrumentation, including the batteries and antennas of the CHM sensor will be housed in a plastic casing of about 5-cm-diameter and 2.5-cm-height. It will be mounted on the coating surface using two self-tapping screws. The entire unit (electronics module and electrodes) can be coated with CARC paint for camouflage and chemical agent resistance.

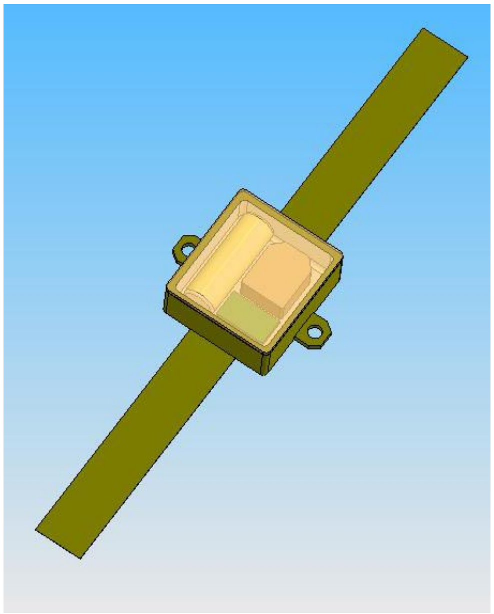
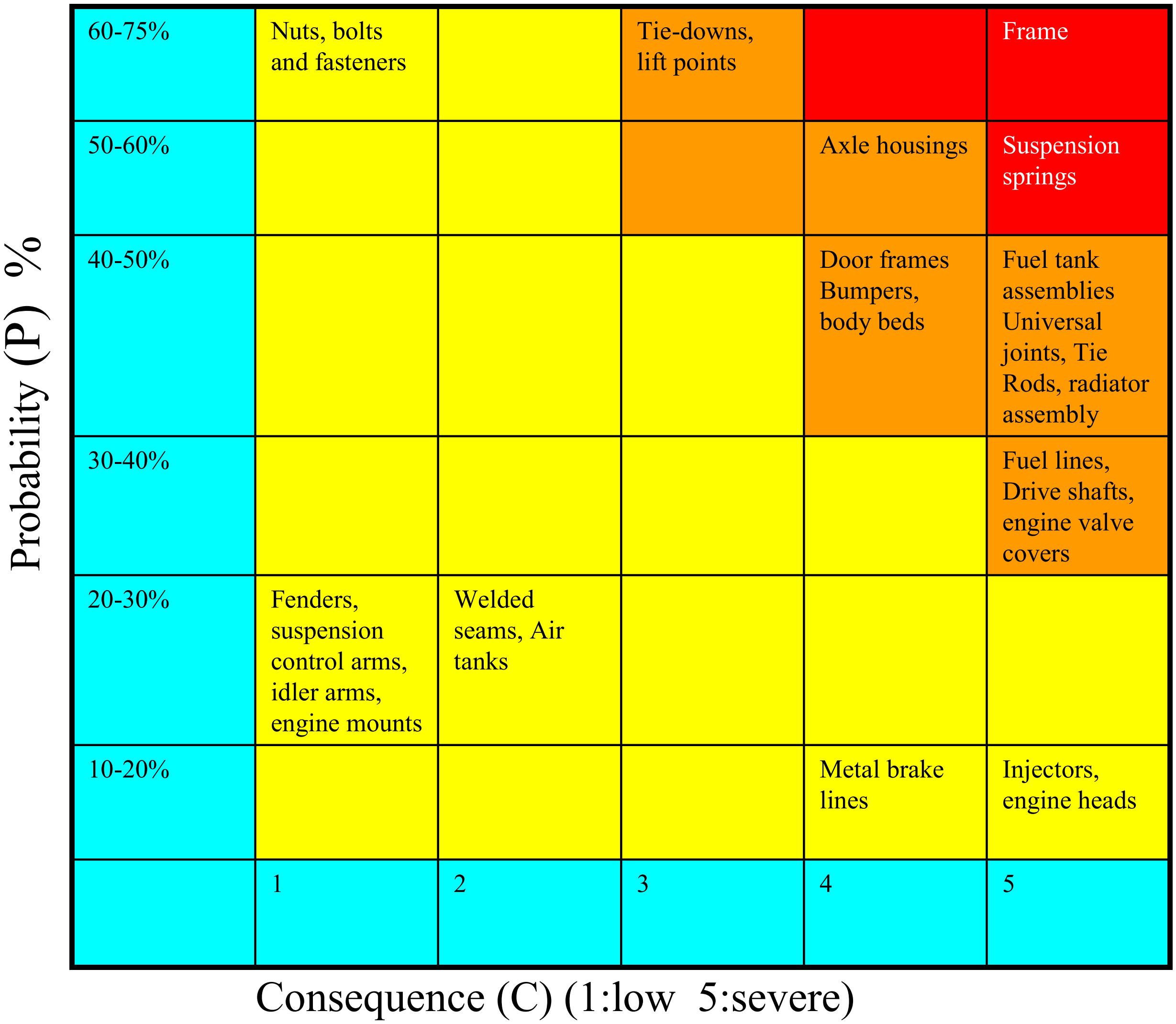


Figure 2. Schematic of the Coating Health Monitor (CHM) with two tape sensing elements.

RESULTS AND DISCUSSION

Risk Based Inspection

A *Risk Based Inspection* matrix was developed for determining the number of sensors in a vehicle. Figure 3 shows the RBI criteria based on the Corrosion in Army Vehicles Report.[2] The probability of corrosion occurrence was obtained from the report while the consequence of failure was rated from 1-5. The individual values are listed in Table 1. The product of the consequence and the probability gives the risk associated with the failure of each part. Based on threshold values, red, orange and yellow levels of risk were assigned; the components that have the highest risk are shown in the red region (upper right) while the lowest risk components are in the yellow regions (lower left). Components in the orange regions are of intermediate risk.



60-75%	Nuts, bolts and fasteners		Tie-downs, lift points		Frame
50-60%				Axle housings	Suspension springs
40-50%				Door frames Bumpers, body beds	Fuel tank assemblies Universal joints, Tie Rods, radiator assembly
30-40%					Fuel lines, Drive shafts, engine valve covers
20-30%	Fenders, suspension control arms, idler arms, engine mounts	Welded seams, Air tanks			
10-20%				Metal brake lines	Injectors, engine heads
	1	2	3	4	5

Figure 3. Risk Based Inspection criteria for CHM sensor location. Red (upper right) denotes the most critical locations based on the Probability x Consequence product; orange (middle) denotes the next most critical locations, and yellow (lower left) denotes the least crucial locations.

Table 1. Risk-Based Inspection Criteria and Sensor Suitability

Part	Likelihood of Corrosion	Consequence of Corrosion[a]	Suitability for Sensors[b]	Product (Likelihood, Consequence)	Corrosion Sensing Rating (CSR)[c]
Frame	65	5	3	325	975
Leaf Suspension Springs	55	5	3	275	825
Door Frames	45	4	3	180	540
Fuel Tank Assemblies	45	5	2	225	450
Radiator Assembly	45	5	2	225	450
Bumpers	45	3	3	135	405
Body Beds	45	3	3	135	405
Fuel Lines	35	5	2	175	350
Coil Suspension Springs	55	5	1	275	275
Universal Joints	45	5	1	225	225
Tie Rods	45	5	1	225	225
Axle Bearings	55	4	1	220	220
Tie-Downs, Lift Points	65	3	1	195	195
Drive Shafts	35	5	1	175	175
Engine Valve Covers	35	5	1	175	175
Welded Seams	25	2	3	50	150
Metal Brake Lines	15	4	2	60	120
Injectors	15	5	1	75	75
Engine Heads	15	5	1	75	75
Fenders	25	1	3	25	75
Nuts, Bolts, Fasteners	65	1	1	65	65
Suspension Control Arms	25	1	2	25	50
Engine Mounts	25	1	2	25	50
Idler Arms	25	1	1	25	25

[a] See Figure 3.

[b] 3 is most suitable; 1 is least suitable.

[c] See text.

Another important factor that influences the inspection criteria is also the ease of monitoring corrosion on a given part, *the sensor suitability*. The component surface should be conducive for placing the sensor on it. As an example, a coiled spring could be a difficult location for mounting the sensor while a leaf spring is more suitable for locating the sensor. It would also be difficult to attach sensors to rotating or very hot (engine) components. The sensor suitability index is rated from 1 to 3 and is listed in Table 1. A Corrosion Sensing Rating (CSR), defined as the product of the sensor suitability, the probability of corrosion, and the consequence of corrosion, is given in Figure 4. Based on the CSR, the following locations (and number of sensors) for installing the corrosion health monitors are proposed:

- Vehicle frame (4)
- Suspension leaf springs (4)

- Door frames (2)
- Bumpers (2)
- Body beds (1)
- Fuel tank (1).

Some of the proposed locations are shown in Figure 5. The exact placement and the packaging for the CHM are currently being developed.

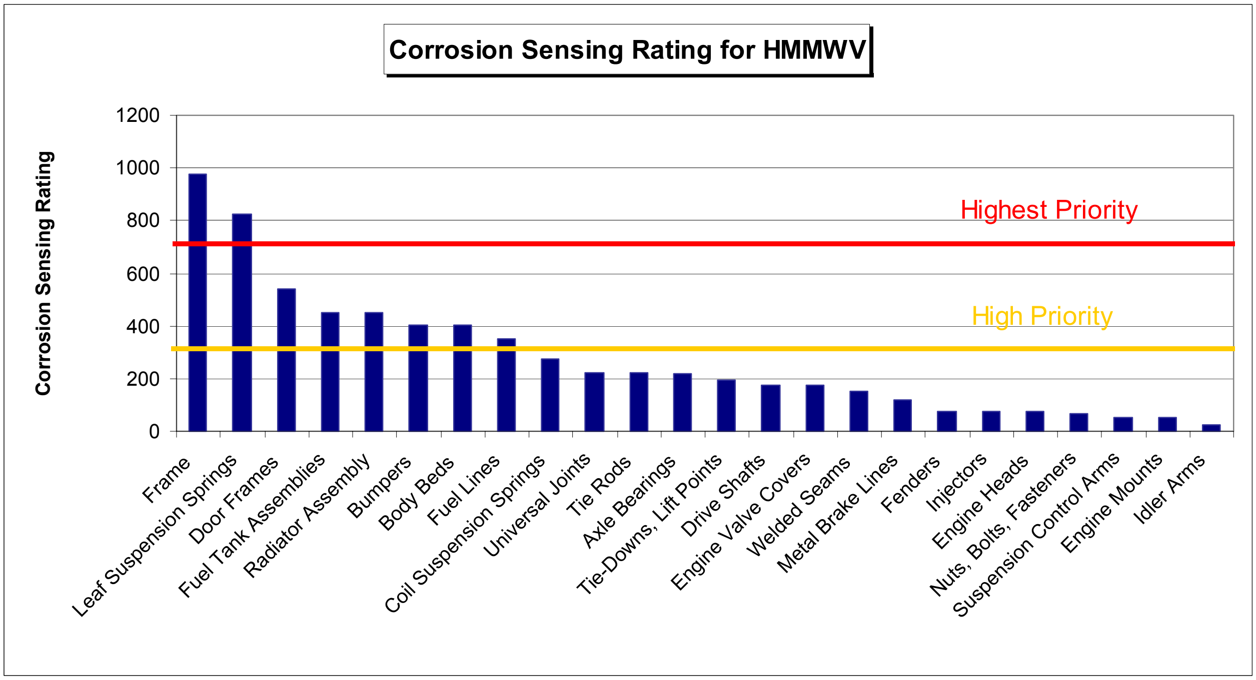


Figure 4. Corrosion sensing rating (Probability x Consequence x Sensor Suitability product) for Army ground vehicles. Components with ratings above the red line have the highest priority. Those above the orange line have high priority. The two lines are subjective but reflect reasonable priority groupings.

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Figure 5. Possible locations (light green dots) of CHM on HMMWV.

Electronics

The prototype electronic circuitry for the CHM has been designed and constructed. The design has been fully documented in schematic form and implemented a using wire-wrap type construction. Each sub-module has been tested individually for function and accuracy including A/D conversion, D/A conversion, analog switching, temperature sensing, and cell current measuring circuit (Zero Resistance Ammeter, ZRA). A major part of the design was selection of components for low base current draw to maximize battery lifetime and the development of a microcontroller 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 –40ºC to +85ºC operating temperature range of the CHM instrument. The prototype 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 (up to ten years). Figure 6 shows the prototype CHM electronics system with a CARC coated test panel with tape sensor attached.

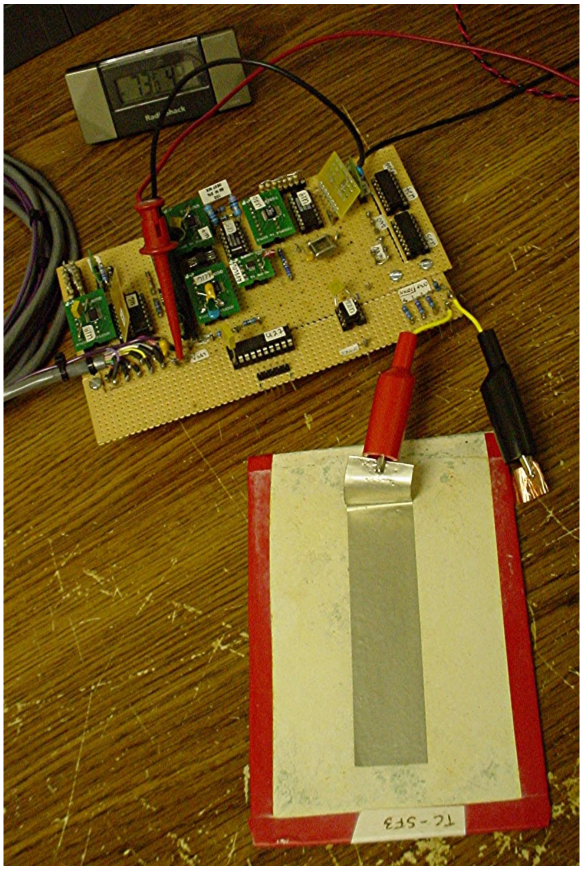

Figure 6. Prototype CHM Electronics System and Test Panel.

CHM wireless communications will be accomplished using the Zigbee 802.15 compliant protocol. Each CHM module will include an on-board Zigbee transceiver module allowing the instrument to communicate with other CHM modules (remotes) or a single base module (host) using power efficient communications. The host module may be interfaced with a PDA type device or other graphical user interface. Communications experiments were performed between two remote Zigbee modules and one host Zigbee module. The remote modules were mounted at various locations of a commercial vehicle including on top of the vehicle's muffler, in the glove box and trunk, in the engine compartment and in wheel wells. The host module was connected to a laptop computer and positioned curbside. The results of this experiment were excellent. The host module was able to communicate with the remotes in almost all mounting positions.

Prototype software for controlling and interfacing with the prototype CHM electronic circuitry has been 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 will be 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. Figure 7 shows a block diagram of the system architecture for the CHM hardware / software development environment.

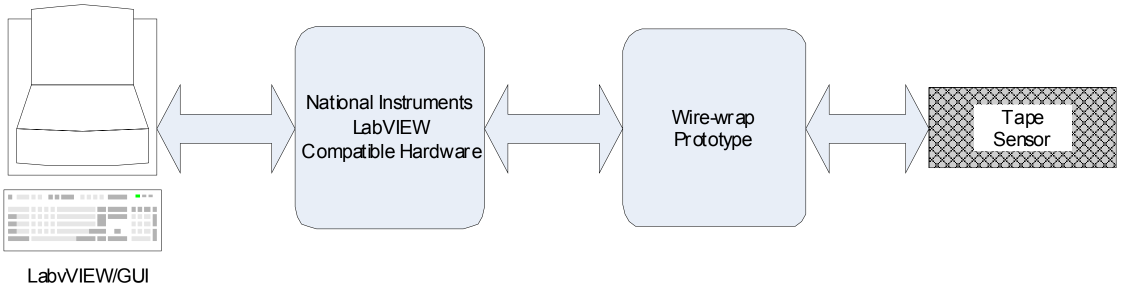

Figure 7. Prototype CHM Hardware / Software Development Environment

Panel Testing

Cold-rolled steel panels (6” x 4”, 15cm x 10cm) have been coated with the Army recommended waterborne and solventborne CARC coatings (Table 2). Panel edges were protected by adhesive tape. Both Cu and Sn/Cu sensor electrode tapes were applied to both coating systems. Half of the electrodes were coated with the CARC topcoat for chemical agent resistance and camouflage. The sensored panels are undergoing ASTM B117 Salt Fog and SAE J2334 Cyclic Test exposures. EIS measurements are being taken with a conventional potentiostat using the tape electrodes, a handheld sensor, and conventional three-electrodes in a flat cell for comparison.

Table 2. CARC Paint Systems

	Wash Primer	Primer	CARC Topcoat
Waterborne	15328	53030	64159 Type II
Solventborne	15328	53022	53039

The initial (baseline) measurements of the three different procedures are shown in Figure 8. The impedance spectra are nearly identical. Each measurement indicates a protective coating with a low-frequency impedance of $10^9 \Omega$. The low-frequency impedance measurements for the two coating systems in the two accelerated tests are given in Figure 9. The different measurements track well. The conventional data show the most variability from one measurement to another. Because these measurements were the first ones taken, this variability is associated with differenced in surface wetness that affect the detectability of coating defects away from the flat cell or sensor footprint. The observation that the tape electrodes provide similar measurements

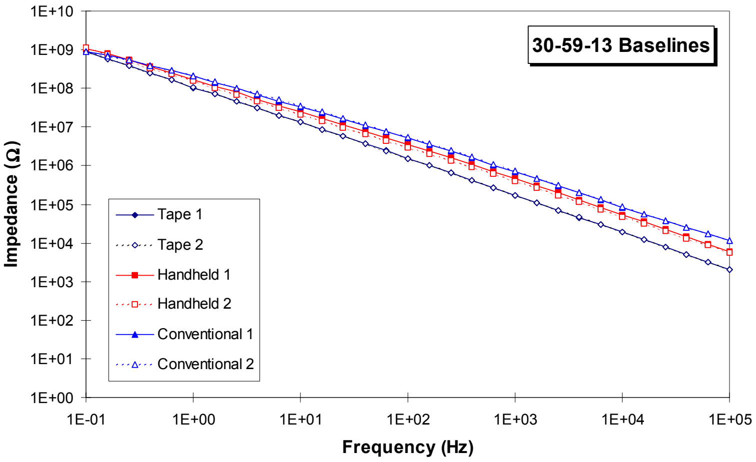

Figure 8. Impedance spectra of the waterborne CARC before accelerated testing using the tape electrodes, the handheld sensor, and conventional three-electrode EIS. Duplicate measurements are shown.

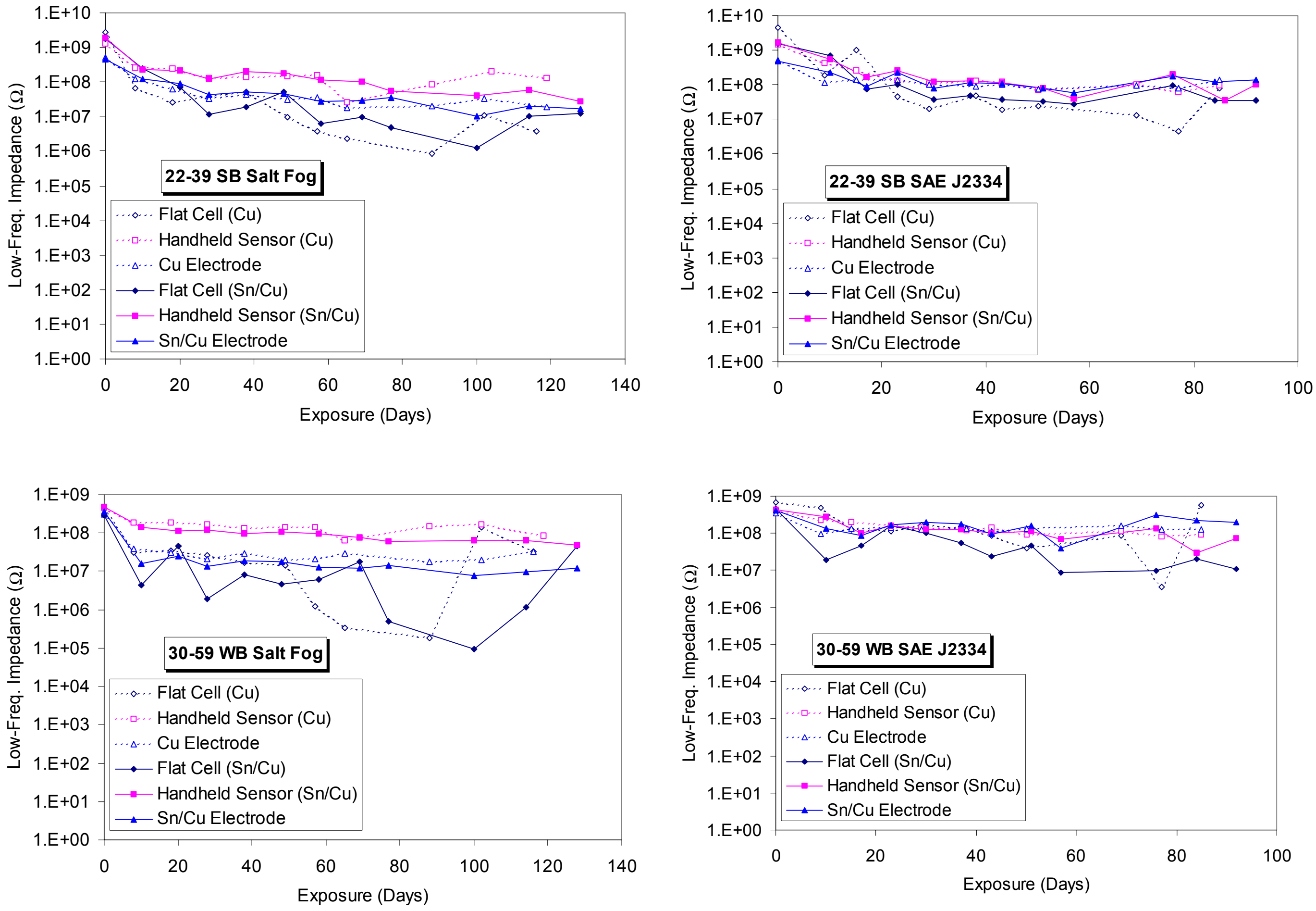

Figure 9. Low-frequency impedance for the solventborne (SB) and waterborne (WB) CARC coatings in salt fog and SAE J2334 testing. Measurements were taken using the three different methods. Different sets of panels are indicated by the solid and dashed/open lines/symbols. The measurements are the average of panels with painted and bare electrodes. The notation of (Cu) or (Sn/Cu) with the Flat Cell and Handheld Sensor data indicates on which panel the measurements were taken; the tape electrodes were not used with the Flat Cell or Handheld Sensor measurements.

to the others indicate that the tape is not only monitoring the protected coating below the electrode, but is monitoring the coating in the surrounding vicinity that is unprotected. Both tape electrodes give equivalent results.

Covering the tape electrodes with CARC does not affect the EIS measurements based on the data to date (Figure 10). However, the coating does protect the electrodes from corroding in the test environments and would provide protection from gravel impact and other mechanical damage. It would also provide camouflage and protection against chemical agents. Therefore coating or painting the electrodes is recommended.

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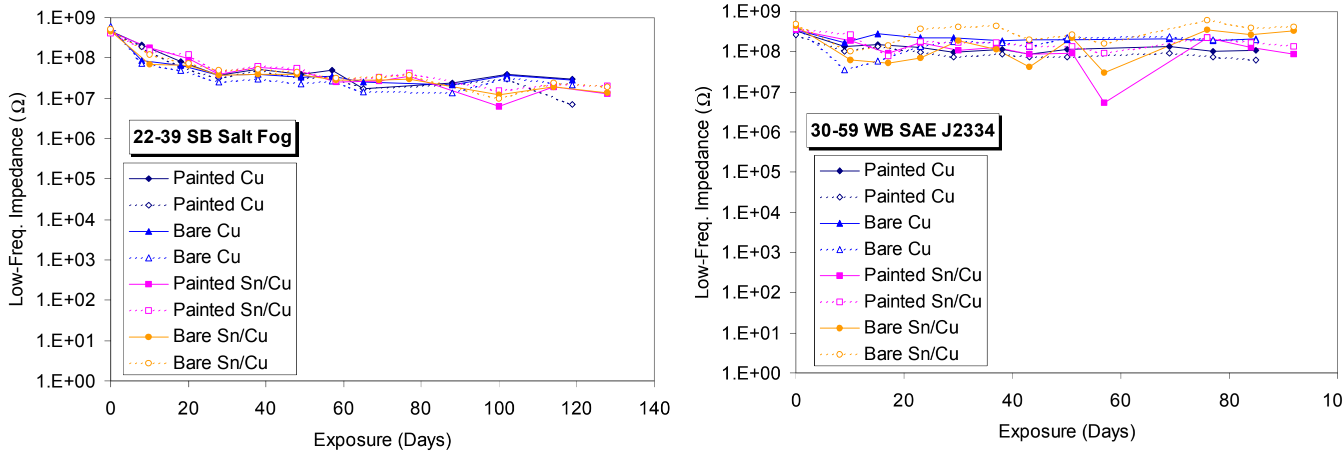

Figure 10. Low-frequency impedance measurements obtained using painted and bare Cu and Sn/Cu tape electrodes. Measurements from duplicate panels are shown.

REFERENCES

[1] General Accounting Office (GAO) "Defense Management: Opportunities to Reduce Corrosion Costs and Increase Readiness," Report 03-753, July 2003.

[2] Gerhardus H. Koch, Michiel P.H. Brongers, Neil G. Thompson, Y. Paul Virmani, Joe H. Payer, "Corrosion Costs and Preventive Strategies in the United States," Report by CC Technologies Laboratories, Inc. to Federal Highway Administration (FHWA), Office of Infrastructure Research and Development, Report FHWA-RD-01-156, September 2001.

[3] M.A. Montjar, *Proc. 2003 Tri-Services Conference on Corrosion* (Las Vegas, NV, 2003).

[4] I.C. Handsy, J. Argento and J. Theis, *Proc. 5th Inter. Aircraft Corrosion Workshop* (Solomons, MD 2002).

[5] Audit Report on "High Mobility Multipurpose Wheeled Vehicle" Office of the Inspector General, DoD, 1993.

[6] I.C. Handsy, *Proc. 5th Inter. Aircraft Corrosion Workshop* (Solomons, MD 2002).

[7] General Accounting Office (GAO) "Report on Army Medium Trucks Information on Delivery Delays and Corrosion Problems," GAO/NSIAD – 99/2/6, (January 1999).

[8] The Bob Stump National Defense Authorization Act of 2002 states "The Secretary of Defense shall develop and implement a long- term strategy to reduce corrosion and the effects of corrosion on military equipment."

[9] G.D. Davis and C.M. Dacres, U.S. Patent 5,859,537, (January 12, 1999). G.D. Davis and C.M. Dacres, U.S. Patent 6,054,038, (April 25, 2000). G.D. Davis and C.M. Dacres, U.S. Patent 6,313,646, (November 6, 2001). G.D. Davis, C.M. Dacres, and L.A. Krebs, U.S. Patent 6,328,878, (December 11, 2001).

[10] F. Mansfeld, *Corrosion* **37**, 301 (1981).

[11] M. Kendig, F. Mansfeld, and S. Tsai, *Corros. Sci.* **23**, 317 (1983).

[12] M. Kendig and J. Scully, "Basic Aspects of the Application of Electrochemical Impedance for the Life Prediction of Organic Coatings on Metals," *Corrosion/89* Paper No. 89032, (Houston, TX: NACE, 1989).

[13] J.R. Scully, *J. Electrochem. Soc.* **136**, 979 (1989).

[14] W.S. Tait, *J. Coat. Technol.* **61**, 57 (1989).

[15] J.N. Murray and H.P. Hack, "Long-Term Testing of Epoxy-Coated Steel in ASTM Seawater Using Electrochemical Impedance Spectrocopy," *Corrosion/90* Paper No. 90140, (Houston, TX: NACE, 1990).

[16] J.A. Grandle and S.R. Taylor, *Corrosion* **50**, 792 (1994).

[17] J.N. Murray, *Prog. Org. Coat.* **31**, 375 (1997).

[18] G.D. Davis, C.M. Dacres, and L.A. Krebs, *Materials Performance* **39**(2), 46 (2000).

[19] G.D. Davis, C.M. Dacres, and L.A. Krebs, "EIS-Based *In-Situ* Sensor for the Early Detection of Coating Degradation and Substrate Corrosion," *Corrosion/2000,* Paper No. 00275 (Houston, TX: NACE, 2000).

[20] L.A. Krebs, G.D. Davis, and C.M. Dacres, "Monitoring Moisture Intrusion and Coating Degradation in the Field," Corrosion/2001, Paper 01430 (Houston, TX: NACE, 2001).

[21] G.D. Davis, L.A. Krebs, and C.M. Dacres, *J. Coatings Technol.* **74**(935), 69 (December 2002).

[22] G.D. Davis, T.G. Vargo, A.W. Dalgleish, and D. Deason, *Mater. Performance* ***43****(8), 32 (2004)*.