Performance Evaluation of CPCs Using Corrosion Sensors – Laboratory and Field Studies

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<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
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Outline

- Introduction
- Laboratory Evaluations
- Field Evaluations
- Summary
Condition Based Maintenance

- **Goal:** reduce inspection cost, while maximizing safety and readiness – optimize maintenance intervals

- **Uses** real-time data to prioritize and optimize maintenance resources

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**Diagram:**
- **Asset/fleet SENSOR**
- **Real-time data**
- **Models**
- **Automated Reasoning**

**Maintenance Task**
Motes Based Technology

- Based on miniature computer platform (motes) containing TinyOS2 operating system.

- Advantages:
  - localized control at each sensor
  - external triggers can be used to activate sensors (e.g., environmental change, signal from other motes or from control hub)
  - on-board data storage
  - on-board communications
  - motes network can optimize data transmission, i.e., allows intelligent distributed sensor network
  - automated data acquisition
**Data Transmission**

- Autonomous sensors – data collection at programmed intervals
- Data routed to base station through reader network
- Base station connected to web portal through data network
Coating Degradation Sensor (CDS)

- Based on EIS
- Changes in impedance magnitude and phase angle values correlate with coating degradation
- Measurement at single frequency
- Rapid data acquisition and analysis
CDS Operation Principle

- Coating degradation is indicated by a drop in impedance values (magnitude and phase angle)

Laboratory Tests

- Performed in Accelerated Exposure Testing (AET) chamber for 31 days
- Temperature: 30 °C
- Relative Humidity: 6 hrs @ 50 % and 6 hrs @ 90 %
- Salt spray: 15 sec every other day
- Salt solution composition: 0.9 wt% NaCl + 0.1 wt% CaCl₂ + 0.25 wt% NaHCO₃
Electrochemical Impedance Tests

- Full impedance spectra measured at days 0, 3, 10, 17, 24 and 31
- Frequency range: $0.05 - 10^5$ Hz
- AC amplitude: 20 mV and 200 mV
- DC bias: 0 mV
- Impedance Magnitude and Phase Angle were determined at 227, 363, 580 and 926 Hz
Results – “The Good”

- Images of corroded samples on Days 0, 3, 10, 17, 24, and 31.
- Graphs showing exposure time, impedance magnitude, phase angle, and corroded surface area.
- Data points for different frequencies (926 Hz, 580 Hz, 363 Hz, 227 Hz, wet and dry).

February 4, 2009
Army Corrosion Summit, 2009
Clearwater Beach, FL
Results – “The Bad”
Results – “The Ugly”

Day 0  Day 3  Day 10
Day 17  Day 24  Day 31

926 Hz, dry
580 Hz, dry
363 Hz, dry
227 Hz, dry
926 Hz, wet
580 Hz, wet
363 Hz, wet
227 Hz, wet
% area corroded

Exposure Time (Days)
0 10 20 30

Corroded Surface Area (%)

Phase Angle (°)

Impedance Magnitude (Ohm)
# Results - Summary

<table>
<thead>
<tr>
<th>CPC</th>
<th>Threshold % area corroded</th>
<th>Recovery during wet part of cycle</th>
<th>Recovery during dry part of cycle</th>
<th>First visual sign of corrosion</th>
<th>Sensor signal indicating corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPC A</td>
<td>60 %</td>
<td>No</td>
<td>Yes</td>
<td>3 days</td>
<td>~18 days</td>
</tr>
<tr>
<td>CPC B</td>
<td>5 %</td>
<td>No</td>
<td>No</td>
<td>17 days</td>
<td>17 days</td>
</tr>
<tr>
<td>CPC C</td>
<td>&gt; 2 %</td>
<td>No</td>
<td>Yes</td>
<td>31 days</td>
<td>31+ days</td>
</tr>
<tr>
<td>CPC D</td>
<td>20 %</td>
<td>Some</td>
<td>Yes</td>
<td>3 days</td>
<td>&lt; 14 days</td>
</tr>
<tr>
<td>CPC E</td>
<td>40 %</td>
<td>Some</td>
<td>Yes</td>
<td>3 days</td>
<td>17 days</td>
</tr>
<tr>
<td>CPC F</td>
<td>20 %</td>
<td>Some</td>
<td>Yes</td>
<td>10 days</td>
<td>17 days</td>
</tr>
<tr>
<td>CPC G – 2 pins</td>
<td>20 %</td>
<td>No</td>
<td>Yes</td>
<td>10 days</td>
<td>&lt; 14 days</td>
</tr>
<tr>
<td>CPC G – 4 pins</td>
<td>20 %</td>
<td>No</td>
<td>No</td>
<td>2 days</td>
<td>5 days</td>
</tr>
</tbody>
</table>
Ranking of CPCs – Visual and Impedance

- **Visual:**
  
  CPC A < CPC D < CPC E < CPC F < CPC B < CPC C

- **Impedance (sensor output):**
  
  CPC E
  CPC D < CPC F < CPC A < CPC C
  CPC B

Formation of rust layer that is impermeable to moisture??

Depth of corrosion damage is also important!
Occluded Sites

Treatment with CPC prior to exposure

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Field Studies

- Sensors exposed to coastal environment at Daytona Beach, FL for 149 days.
- Sensor package acquired and wirelessly transmitted relative humidity, temperature and impedance data to a web portal.
- EIS parameters:
  - Frequency: 1000 Hz
  - AC amplitude: 200 mV
  - Measurement interval: once every hour
Results – The “Bad”

- Initial drop in impedance is due to water uptake.
- Coating failure: drop of impedance below $10^7 \, \Omega$.
- Recovery: during low RH periods, sensor surface dries out.
- Phase angle changes follow impedance magnitude trends.
Sensor Output, RH: 80-100 %

- Most significant changes.
- Water condensation + salt deposits – high conductivity medium for corrosion.
Results – “The Good”

- Initial drop in impedance is due to water uptake.
- No corrosion is observed on treated top surface.
- No significant drop of impedance below threshold.
- No change of phase angle.
Sensor Output, RH: 80-100 %

- No drop below impedance threshold for up to 110 days.
- No change in phase angle.
- This CPC provides excellent corrosion protection even under high humidity conditions.
Cumulative Damage Analysis

\[ \text{Cumulative Damage} = \int_{0}^{t} 10^7 - \text{Impedance Magnitude} \quad \text{if } I < 10^7 \Omega \quad dt \]
Cumulative Damage Analysis

Exposure time (days)
Cumulative damage (Ohm*hr)

Results - Summary

Ranking based on cumulative damage:

CPC D < CPC F < CPC B < CPC C < CPC E

Ranking based on visual observations:

CPC D = CPC B < CPC F < CPC C < CPC E
Performance Ranking of CPCs: Cyclic lab test vs. Daytona Beach field test

\[ y = 1.5 \cdot x - 0.5 \]

\[ R^2 = 0.90 \]
Occluded Sites

Exposure Time (days)
Cumulative Damage (Ohm*hr)

#1130, no CPC
#1131, no CPC
#1105, CPC
Web Portal

[Image of a web portal interface with sensor nodes and data points on a map]
Web Portal

Sensor Locations

Sensor ID and data links
Summary

- It was determined that impedance based coating degradation sensors can be successfully used to detect coating failure and assess the performance of CPCs in coastal environments.

- Laboratory tests showed that the changes associated with coating failure are more pronounced at lower measurement frequencies.

- The sensitivity of the sensor was found to be dependent on the performance of the CPC; better sensitivity was found in case of better performing CPCs.

- The changes in impedance parameters measured during the wet part of the exposure cycle were found to correlate well with visual observations of surface corrosion. In some cases, recovery of the impedance values during the dry part of the cycle was observed.
Summary

- No significant improvement in sensitivity was found when the number of sensor wires embedded in the surface was increased from two to four.
- Field testing of sensor packages at Daytona Beach, FL indicated that it is feasible to collect and wirelessly transmit temperature, relative humidity and impedance data using mote based sensor technology.
- A data analysis method was developed to assess the performance of CPCs based on sensor output.
- The order of performance of different CPCs determined from sensor output in the field and laboratory was found to be in agreement.
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