Review and Assessment of Techniques for Monitoring Environmental Conditions and Stress Corrosion Cracking of Spent Fuel Storage Canisters

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Outline

- Background

- Objectives of the investigation

- Monitoring techniques
  - Temperature
  - Humidity
  - Chloride concentration
  - Stress corrosion cracking

- Summary
Dry Cask Storage Systems (DCSS)

- Most DCSSs are canister based, spent fuel is placed in a welded austenitic stainless steel canister stored inside a concrete vault or overpack
- Airborne chemical species could deposit on the canisters through cooling vents

Schematics of vertical and horizontal canister-based systems
Possibly Monitoring Stress Corrosion Cracking of DCSS

- When exposed to certain brines, austenitic stainless steel has exhibited susceptibility to stress corrosion cracking (SCC), which could compromise the integrity of the canister.
- NRC identified SCC as one of the three top priority degradation mechanisms that need to be addressed.
- Little knowledge of current conditions of deployed canisters.
- Limited inspections and monitoring to date.
- Canisters are not easily inspected because of confined spaces and high radiation fields.
- Functional monitoring of DCSS was identified as one of the top priority, crosscutting issues.
Objectives of the Investigation

- Review and assess the current state of technology for directly monitoring important environmental conditions affecting SCC, as well as crack initiation and propagation.

- Support the development of technical bases for evaluating monitoring technologies which may be proposed by the industry.

Diagram:
- SCC
- Material
- Environment
  - Temperature
  - Humidity
  - Chloride
- Stress
Potentially Suitable Temperature Monitoring Techniques

- Thermocouples
- Resistance temperature detectors
- Radiation thermometers
- Ultrasonic temperature measurement
- Fiber optic temperature sensors
- Silicon temperature sensors
- Thermistors
- Johnson noise thermometers

Reviewed in the paper
## Temperature Monitoring Techniques: Maturity, Measurement Range, Strengths, and Weaknesses

<table>
<thead>
<tr>
<th>Features</th>
<th>Thermocouples</th>
<th>Resistance temperature detectors</th>
<th>Ultrasonic Measurement</th>
<th>Fiber Optic Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maturity</strong></td>
<td>Field deployed for nuclear</td>
<td>Field deployed for nuclear</td>
<td>Field deployed for nuclear</td>
<td>Field deployed for non-nuclear</td>
</tr>
<tr>
<td><strong>Temperature measurement range</strong></td>
<td>Up to 1,700 °C [3092 °F]*</td>
<td>0 to 482 °C [32 to 900 °F]</td>
<td>Up to melting point of the material under test</td>
<td>Several thousand Celsius degrees*</td>
</tr>
<tr>
<td><strong>Strengths</strong></td>
<td>Mature technique, small size, high tolerance to temperature and radiation, long lifetime</td>
<td>Mature technique, high-temperature tolerance</td>
<td>Mature technique, high tolerance to temperature</td>
<td></td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>Good thermal bonds are essential for surface temperature measurements</td>
<td>Low radiation tolerance</td>
<td>Potential fiber darkening and embrittlement</td>
<td></td>
</tr>
</tbody>
</table>

*Varies depending on the type*
Potentially Suitable Humidity Monitoring Techniques

- Capacitance-based humidity sensors
- Chilled-mirror-based humidity sensors
- Electrical-resistance-based humidity sensors
- Leakage-based monitoring

Capacitance-based humidity probe and meter

Measurement Principle of a Chilled-Mirror-Based Humidity Sensor

- LED light source
- Photodetector
- Chilled mirror
- Thermoelectric cooler
# Humidity Monitoring Techniques:
Maturity, Strengths, and Weaknesses

<table>
<thead>
<tr>
<th>Features</th>
<th>Capacitance-Based</th>
<th>Chilled-Mirror Based</th>
<th>Electrical-Resistance Based</th>
<th>Leakage Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ceramic</td>
<td>Polymeric</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Maturity</strong></td>
<td>Commercially available</td>
<td>Commercially available</td>
<td>Commercially available</td>
<td>Field deployed for nuclear</td>
</tr>
<tr>
<td><strong>Strengths</strong></td>
<td>Small size</td>
<td>Small size, wide temperature range, high precision, no hysteresis effects</td>
<td>High accuracy, expandable temperature range, long life, no hysteresis effects</td>
<td>Small size of sensing lines, multi-location monitoring, deployed for nuclear</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>May require frequent calibration, low precision, exhibits hysteresis effects</td>
<td>Low radiation resistance, frequent calibration due to radiation environment</td>
<td>Large size, requires large power, potential periodic cleaning of chilled mirror</td>
<td>Need for sizable monitoring station through which the sensing lines are routed</td>
</tr>
</tbody>
</table>
Potentially Suitable Chloride Concentration Monitoring Techniques

- One-time conductivity-based measurement devices
- Optical: Long-period grating
- Optical: Fluorescence
- Electrical: High electron mobility transistor
- Optical: Absorption spectroscopy

Schematics of Disposable Salt Strip of Conductivity-Based SaltSmart™ Meter

Long-Period, Grating-Based Optical Sensor

Reviewed in the paper
## Chloride Concentration Monitoring Techniques: Maturity, Strengths, and Weaknesses

<table>
<thead>
<tr>
<th>Features</th>
<th>Conductivity-Based SaltSmart™ Meter</th>
<th>Long-Period Grating-Based Optical Sensor</th>
<th>Fluorescence-Based Optical Sensor</th>
<th>High Electron Mobility Transistor-Based Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maturity</strong></td>
<td>Field deployed, limited use in nuclear</td>
<td>Tested in laboratory</td>
<td>Tested in laboratory</td>
<td>Tested in laboratory</td>
</tr>
<tr>
<td><strong>Strengths</strong></td>
<td>Fast and automated method, no sealing to the substrate necessary allowing testing of curved or irregular surfaces</td>
<td>Simple fabrication; easy interrogation using fiber optics; potential for onsite, real-time, and remote sensing</td>
<td>Easy interrogation using fiber optics; potential for onsite, real-time, and remote sensing</td>
<td>Small sample volume; potential for onsite, real-time, and remote sensing</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>One-time use. The highest working temperature is only 50 °C. Measures concentration determined from the conductivity of all dissolved species</td>
<td>Sensitive response to temperature changes; unknown thermal and radiation stability; possible interference by other ions and signal attenuation with increased fiber length</td>
<td>Other halide ions and oxygen may interfere; thermal and radiation stability is unknown</td>
<td>Temperature could affect measurement; thermal and radiation stability is unknown; possible signal attenuation with increased electrical cable length</td>
</tr>
</tbody>
</table>
Intentionally did not focus on non-destructive examination (NDE) technologies used for SCC detection such as ultrasonic, non-linear elastic wave spectroscopy, acoustic emission, guided wave, and eddy current.

Non-NDE technologies identified:

- Fiber optic sensors—Measure the elongation or contraction of the fiber when it is bonded to a structure.
- Crack growth sensor—Self-contained mechanical test system designed to measure crack length.
- Crack propagation sensor—Gauge designed to measure the progress (length) of a crack and its rate of growth in a metal specimen.
Potentially Suitable Stress Corrosion Cracking Sensors

Fiber optic sensors typically used for field applications

Load frame and stress corrosion cracking sensor assembly

Crack propagation sensor
<table>
<thead>
<tr>
<th>Features</th>
<th>Fiber Optic Sensors</th>
<th>Crack Growth Sensor</th>
<th>Crack Propagation Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maturity</strong></td>
<td>Field deployment started in 1980s</td>
<td>Field deployment started in 2009</td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Strengths</strong></td>
<td>Electromagnetic immunity, small size, high-temperature tolerance, corrosion resistance, large area monitoring with single sensor, light weight, long record of field testing</td>
<td>Highly sensitive, sensor does not need bonding to canister</td>
<td>Simple to implement, wide operational temperature, sensor does not need bonding to canister, small size</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>Gamma radiation interference, sensor deployment may be problematic, temperature calibration required</td>
<td>Large size, surrogate sensor (does not measure cracking of actual component), temperature compensation required, local cracking monitoring, limited field testing</td>
<td>Modest crack propagation resolution, unknown field testing, local cracking monitoring</td>
</tr>
</tbody>
</table>
Summary

Techniques to monitor temperature, humidity, chloride, and cracks were evaluated in terms of data collection mode, space requirements, power requirements, sensitivity, longevity, replacement difficulty, monitoring area, amount of data per measurement, maturity, temperature tolerance, radiation tolerance, strengths, and weaknesses.

Adaptation of existing technologies may be possible for temperature, humidity, and crack propagation monitoring. Much more advancement appears to be necessary for chloride monitoring.

To be used in DCSS, all methods would require testing and validation to assure that the sensors would not compromise DCSS functions.

Information may be used to support NRC assessments of possible industry evaluations on functional monitoring of DCSS.
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