LWRS Cable Aging and Cable NDE

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DOE-NE Materials Crosscut Coordination Meeting
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Cable Research Collaboration

**LWRS**
- Keith Leonard (ORNL)
- Thomas Rosseel (ORNL)

**Cable Aging**
- Robert Duckworth (ORNL)

**Cable NDE**
- S.W. (Bill) Glass (PNNL)
- Pradeep Ramuhalli (PNNL)

**Goal:** maximize impact

**Non-LWRS**
- Andrew Mantey (EPRI)
- Sheila Ray (NRC)
- Darrell Murdock (NRC)
- Robert Bernstein (SNL)
- Stephanie Watson (NIST)
- Nicola Bowler (ISU) (NEUP)
- Gary Harmon (AMS Corp)
Nuclear Power Plants (NPPs)

- U.S. NPPs contain *thousands of miles* of electrical cable in hundreds of types and sizes.
- Ramifications of *cable failure* can be significant, especially for cables connecting to: off-site power, emergency service water and emergency diesel generators.

*www.nrc.gov*
Cables in Nuclear Power Plants

Application
• Instrument & Control (81%)
• Power cables (14%)
• Communication (5%)

Design voltage
• Low (≤2kV), Med, High (>46kV)

Construction
• Cables - Conductor, Insulation, Jacket
• Terminations
• Splices

Single Conductor

Multi Conductor

*SAND 96-0344
Polymer Cable Materials

Insulation
XLPE - Cross-linked polyethylene
EPR - Ethylene-propylene (diene) rubber
SiR - Silicone rubber

Jacketing
Hypalon® - Chlorosulfonated polyethylene (CSPE)
Neoprene - Polychloroprene (CR)
CPE - Chlorinated Polyethylene Elastomer
Vinyl - Poly(vinyl chloride) (PVC)

Cables in US Plants\(^1\)
36% of cables are XLPE
36% of cables are EPR
5% of cables are SiR

Cables in Containment\(^2\)
90% of units have XLPE
70% of units have EPR
30% of units have SiR

\(^1\)NUREG/CR-7153, Vol.5 2013
\(^2\)EPRI TR-103841, Rev.1 1994
Polymer Degradation (Aging)

Environmental Stress
- Gamma Radiation
- Heat
- Light
- Moisture
- Vibration

Chemical Changes
- Chain scission
- Cross-linking
- Loss of plasticizer
- Loss of anti-oxidant

Material Changes
- Mechanical (i.e. brittleness)
- Electrical (i.e. resistance)
- Physical (i.e. density)
Cable Aging/NDE Task Activities Map to MAaD Targets

**Activities**

**Cable Aging**
- Aging Methods
- Materials Characterization
- Degradation Pathways
- Models of Aging (Accelerated vs. Long Term)
- Cable Rejuvenation

**Cable NDE**
- Key Indicators
- Current Methods
- New Methods
- Predictive Models

**LWRS Targets for Materials Aging and Degradation**
- Measurements of degradation
- Mechanisms of degradation
- Modeling and simulation
- Monitoring
- Mitigation strategies
Cable Degradation Knowledge Gaps:

- Diffusion limited oxidation (DLO)
  - How to improve correlation between field and accelerated aging?
- Inverse temperature effects (ITE)
  - What dose/temp. combinations avoid ITE in accelerated aging?
- Thermal/radiation exposure
  - At what dose does thermal damage dominate radiation damage?
- Synergistic effects
  - What is the effect of rad/heat exposure sequence on aging?
- Acceptance criteria for characterization techniques
  - What should measured values be for acceptable qualified condition?

*NUREG/CR-7153, Vol.5 2013*
EMDA Cable PIRT Analysis provides insights for prioritized needs

- Up to 35°C, 0 dose rate
- Up to 35-50°C, up to 0.01 Gy/h (1 rad/h)
- Up to 45-55°C, 0.01-0.1 Gy/h (1-10 rad/h)
- Up to 45-55°C, 0.1-1 Gy/h (10-100 rad/h)
- Up to 60-90°C, 0 dose rate


PIRT = Phenomena Identification and Ranking Technique

PNNL-SA-112992
Gamma Exposure Capabilities

PNNL

High Exposure Facility (HEF)
- Temperature control through mechanical convection ovens
- Dose rates up to 1000Gy/h

ORNL

High Flux Isotope Reactor (HFIR) Spent Fuel Gamma Irradiation Facility (GIF)
- Dose rates from 10Gy/h to 100kGy/h

Co-60 Irradiator
- Uniform dose rate of 140 Gy/h
Polymer Aging Characterization and Testing Laboratory at PNNL

Aging

• Advanced protocol ovens with temperature logging
• Dedicated dynamic mechanical analyzer (DMA) for in-situ aging

Test and Characterization

• Test stand with contact extensometer
• Modulated differential scanning calorimeter (M-DSC)
• Digital microscope
• Photographic documentation booth
Inhomogeneous Aging Study
Understanding of Mechanisms

- Diffusion Limited Oxidation
- Nucleation of Degradation
- Effect of Sample Geometry
Microstructure Analysis
Imaging and Quantifying Degradation

- Defect mapping
  - X-ray microtomography
- Chemical mapping
  - TOF-SIMS/XPS
  - X-ray diffraction
  - FTIR/Raman
- Mechanical mapping
  - Nanoindenter

*NUREG/CR-7153, Vol. 5*
Non-Destructive Evaluation (NDE) of Cable Remaining Useful Life

- Coordination Aging and NDE
- Sensitivity analysis of key indicators
- Correlation of destructive and non-destructive data
- Assessment of NDE methods
Nuclear Power Plant Cable Aging Management Strategy

• **Evaluate for susceptibility** – focus on rooms/areas with highest temp and highest radiation. Also give special attention to most safety critical components. Select samples for test.

• **Visual walk-down** looking for visible indications on jackets.

• **FDR, Tan-Delta and other bulk tests** looking for worst case areas of degradation on sample of cables.

• **Local specific NDE** (indenter, capacitance, UT, ...) at local area identified with bulk tests.

• **Repair/replace** where indicated. Consider also replacement in similar environments even if no degradation is observed.
## Condition-Monitoring Techniques for Electric Cables Used in NPPs

*(NRC Reg Guide 1.218)*

<table>
<thead>
<tr>
<th>Test</th>
<th>Applicability</th>
<th>Ends</th>
<th>Damage</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC High Pot/ Step Voltage</td>
<td>Cable – 2/C</td>
<td>Both</td>
<td>Maybe</td>
<td>Not trendable</td>
</tr>
<tr>
<td>Very Low Freq. Tan-Delta</td>
<td>Cable – 2/C</td>
<td>Both</td>
<td>Yes</td>
<td>Not trendable</td>
</tr>
<tr>
<td>Visual / Illum. Borescope</td>
<td>Visible exterior</td>
<td>No</td>
<td>No</td>
<td>Not quantitative</td>
</tr>
<tr>
<td>Indenter</td>
<td>Local Jacket</td>
<td>No</td>
<td>No</td>
<td>Trendable</td>
</tr>
<tr>
<td>Dielectric Loss Dissipation</td>
<td>Cable – 2/C</td>
<td>Yes</td>
<td>No</td>
<td>Not for long/large cable</td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>Cable – 2/C</td>
<td>Both</td>
<td>No</td>
<td>Not trendable/uncertain</td>
</tr>
<tr>
<td>Partial Discharge</td>
<td>Cable – 2/C</td>
<td>Both</td>
<td>Yes</td>
<td>Locates weak point</td>
</tr>
<tr>
<td>Time Domain Reflectometry</td>
<td>Cable – 2/C</td>
<td>Both</td>
<td>No</td>
<td>Limited val for insul.</td>
</tr>
<tr>
<td>Frequency Domain Reflectometry</td>
<td>Cable – 2/C</td>
<td>Maybe</td>
<td>No</td>
<td>Can ID local flaws</td>
</tr>
<tr>
<td>IR Thermography</td>
<td>Under load</td>
<td>No</td>
<td>No</td>
<td>Weak signal for insul.</td>
</tr>
</tbody>
</table>
Cable Health Evaluation

- Destructive test vs. Nondestructive
- Full length cable vs. locally accessible point
- In-situ vs ex-situ (in place or sample to lab)
- Disconnected vs connected/energized
- Shielded vs non-shielded
- Multi vs single conductor
Cable NDE and Condition Monitoring

**Scope:**

- **Identify key indicators of aging**
  - Determine measurements capable of “early warning” of condition degradation
  - Correlate aging with macroscopic material properties

- **Advance state-of-the-art and develop new/transformational NDE methods**
  - Enable in-situ cable condition measurements
  - Demonstrate on laboratory-aged and fielded cables

- **Develop models for predicting condition-based remaining life**
  - Enable condition-based qualification methodology
  - Use cable condition index data, condition-based aging models
Local Spot Measurements

- Indenter
- Capacitance
- Acoustic
- Dielectric Constant
Full Cable Measurements

- Frequency Domain Reflectometry
- Dissipation Factor (tan $\delta$)
- High Pot
- Partial Discharge
Cable NDE and Condition Monitoring

Objectives:

Develop/Demonstrate NDE techniques that provide sensitive, in-situ assessment of cable performance with the ability to:

- Reduce uncertainty in safety margins
- Enable informed replacement planning
- Provide confidence in continued use
Cable Program Summary

Cable Stressors

Chemical Changes

Changes in Properties

Changes in Performance over Time

Aging and Degradation

Chemical changes in polymer

Rejuvenation

Mechanical, physical, and electrical property changes in polymer

Physical Properties

Electrical Properties

Mechanical Properties

NDE Technologies

Remaining Useful Life Prediction

GAPS

Detailed Understanding

Effective Treatments

Key indicators of cable aging

Transformational NDE

Methods for Life Prediction

*LWRS NDE R&D Roadmap PNNL-21731 2012
Questions?

Light Water Reactor Sustainability

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