Evaluation of Phenomena Observed During Accelerated Aging of Cable Insulations

Presented by:
Trevor Toll

Presented at:
Polymers in Nuclear Applications 2021

December 1st, 2021
Why Are We Concerned with Aging of Polymeric Materials?

- Current fleet of reactors is aging
- Plant life extensions
- Critical plant assets including structures, systems, and components are susceptible to age-related degradation
- Focus of our work has predominantly on cable insulation polymers

IAEA PRIS database – November 2021

442 Operating Reactors World-Wide
How Can Cable Aging Be Addressed?

Implementation of cable condition assessment and monitoring tools

**Electrical Tests**
- Time Domain Reflectometry (TDR)
- Frequency Domain Reflectometry (FDR)
- Insulation Resistance (IR)
- Impedance (L,C,R)
- Reverse Time Domain Reflectometry (RTDR)
- Dynamic Time Domain Reflectometry (DTDR)
- DC Resistance
- Voltage Waveform
- Tan Delta
- Withstand
- Partial Discharge

**Mechanical, Thermal, and Chemical Tests**
- Elongation at Break (EAB)
- Indenter Modulus (IM)
- Oxidation Induction Time (OIT)
- Oxidation Induction Temperature (OITP)
- Thermogravimetric Analysis (TGA)
- Density
- Mass Spectroscopy
- Fourier Transform Infrared Spectroscopy (FTIR)
- Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM/EDS)
- Visual inspections and optical microscopy
Cable Condition Assessment and Monitoring Tools Developed Through Accelerated Aging

Through accelerated aging changes that occur in polymer properties due to material degradation can be assessed much faster than natural aging.
Challenges with Polymer Accelerated Aging

- There can be substantial differences in the aging of polymers under natural and accelerated conditions:
  - Material Chemistry
  - Aging characteristics and processes
  - Polymer properties

Examples of accelerated aging phenomena that affect polymer degradation process:

Inverse Temperature Effects
Sequential vs. Simultaneous Aging Effects
Activation Energy Variations with temperature/time
Copper Catalytic Effect
Diffusion Limited Oxidation
### Conducting accelerated aging of cables and insulation polymers to support CM test development.

- **Thermal:** 110°C, 120°C, 130°C, and 135°C (high temperature materials at 190°C)
- **Sequential radiation then thermal:** 30 Mrads lifetime gamma (25 krad/hour), thermal at 120°C (165°C for SR), and 150 Mrads post accident gamma (600 krad/hour; 90 Mrads for SR)
- **Materials:** XLPE, XLPO, EPR, EPDM, CSPE, CPE, PVC, SR, ETFE, PEEK, and Polyimides

<table>
<thead>
<tr>
<th>Sample Type 1</th>
<th>Sample Type 2</th>
<th>Sample Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Sample Type 1" /></td>
<td><img src="image2.png" alt="Sample Type 2" /></td>
<td><img src="image3.png" alt="Sample Type 3" /></td>
</tr>
</tbody>
</table>
Testing Performed to Characterize and Quantify the Effects of Aging Phenomena

- Analyzing insulation polymer degradation using thermal analysis and cross-sectional depth profiling
  - Optical microscopy
  - FTIR Carbonyl Index
  - SEM/EDS analysis

\[
\text{Carbonyl Index} = \frac{\text{Peak Area}_{C=O}}{\text{Peak Area}_{C-H}}
\]
Diffusion Limited Oxidation/Inhomogeneous Oxidation Effects Observed in Polymers

XLPE Sample Type 1 – 3,000 Hours 120°C

XLPE Sample Type 2 – 2,000 Hours 120°C
Diffusion Limited Oxidation/Inhomogeneous Oxidation Effects Observed in Polymers (Cont.)

CSPE/EPR Sample Type 1 – 1,065 Hours 120°C

Oxygen Profile

Carbonyl Index – CSPE

Carbonyl Index – EPR
Copper Catalytic Effect Process

\[ \text{ROOH} + 
\text{Mn}^+ \rightarrow \text{RO}^\cdot + \text{M}(\text{n+1}) + \text{OH}^- \quad (1) \]

\[ \text{ROOH} + \text{M}(\text{n+1}) + \rightarrow \text{ROO}^\cdot + \text{Mn}^+ + \text{H}^+ \quad (2) \]

\[ 2\text{ROOH} \rightarrow \text{RO}^\cdot + \text{ROO}^\cdot + \text{H}_2\text{O} \quad (3) \]

**Copper Profile**

**Discoloration at Insulation Surfaces**

XLPO Sample Types 1 and 2 – 3,000 Hours 130°C

XLPE Sample Type 2 – 2,000 Hours 120°C
Inverse Temperature Effects Observed in Polymers

Polymer Chains

Polymer Chain Scission
Causes substantial decrease in polymer mechanical properties

Gamma irradiation at room temperature

Annealing after gamma radiation exposure

Polymer Chain Crosslinking
Results in substantial recovery of polymer mechanical properties

Graph showing DSC mW vs. Temp Cel for Baseline and 30 Mrad Post Annealing.
Effects on Polymer Properties

- Expected Type 2 to decrease at slower rate due to inhomogeneous aging (DLO). This was not the case.
- Data effected by surface conditions (specifically interior surface degradation).
- Copper catalytic effects between insulation and conductor.
• Results show opposite trend of EAB (Type 1 decreases faster than Type 2).
• Data less impacted by interior surface aging (i.e., copper catalytic effects).
• DLO effects are apparent.
- Difference in end-of-life prediction (Type 1/2 vs Type 3).
- Conservative insulation end-of-life (50% EAB) is reached between 4,000 and 5,000 Hours.
- Differences due to aging phenomena that must be understood and accounted for in the analysis.
How Can Materials Exhibiting Different Aging Effects Be Compared?

- Comparing samples with different levels of inhomogeneous oxidation/DLO could be done using superposition principles.

<table>
<thead>
<tr>
<th>Sample Type 1 Time Shift Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable 1 (EPR)</td>
</tr>
<tr>
<td>Cable 2 (EPR)</td>
</tr>
<tr>
<td>Cable 3 (EPR)</td>
</tr>
<tr>
<td>Cable 4 (EPR)</td>
</tr>
<tr>
<td>Cable 5 (XLPE)</td>
</tr>
<tr>
<td>Cable 6 (XLPO)</td>
</tr>
<tr>
<td>Cable 7 (XLPO)</td>
</tr>
</tbody>
</table>
How Can Materials Exhibiting Different Aging Effects Be Compared? (cont.)

- Ongoing research using sequential radiation followed by thermal accelerated aging and LOCA testing will be used to understand the implications of different aging phenomena on material performance.
Summary of Findings

- Each insulation sample type and material exhibited some type of accelerated aging phenomena under our aging conditions.

- Degradation characteristics varied with:
  - Sample configuration
  - Cable construction
  - Polymer formulation

- Material properties and CM tests exhibited different responses.

- Methods for understanding and accounting for the impact of accelerated aging phenomena on the polymer aging process are being explored.

These effects must be addressed when performing accelerated aging.
Questions