INNOVATING NUCLEAR TECHNOLOGY

Evaluation of Phenomena Observed During Accelerated Aging of Cable Insulations

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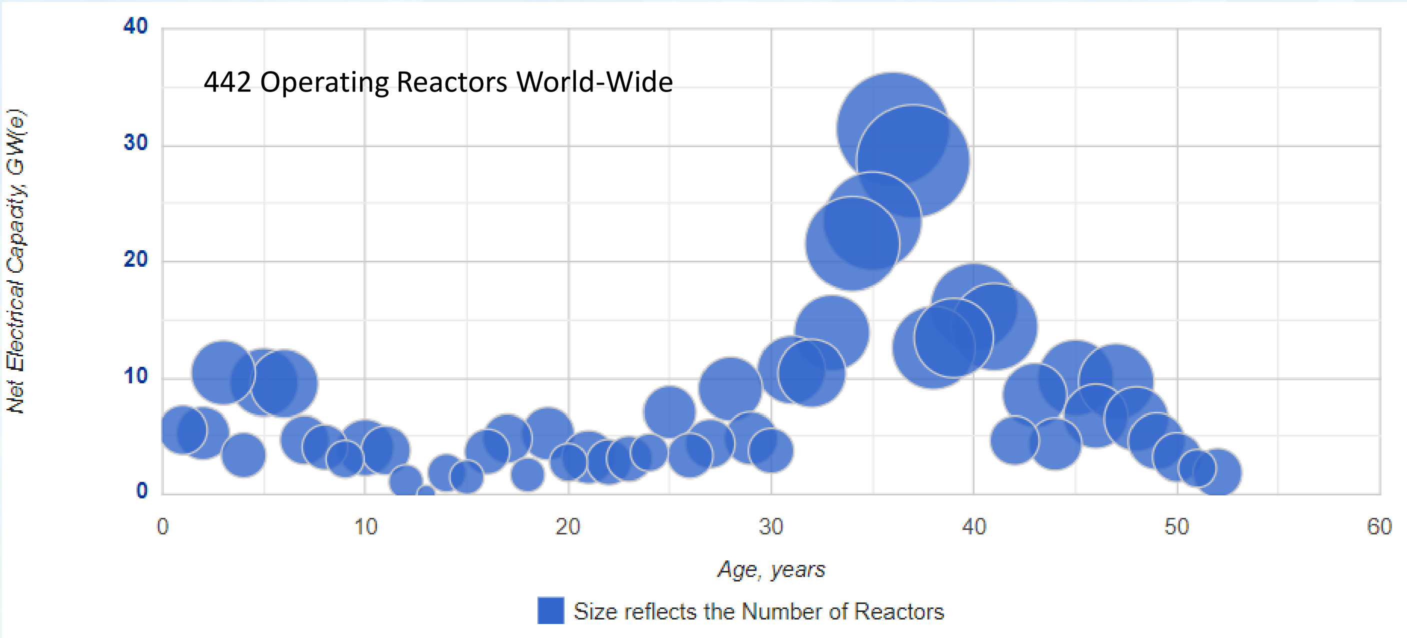
Why Are We Concerned with Aging of Polymeric Materials?



IAEA PRIS database – November 2021

- **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**

How Can Cable Aging Be Addressed?

Implementation of cable condition assessment and monitoring tools

Electrical Tests

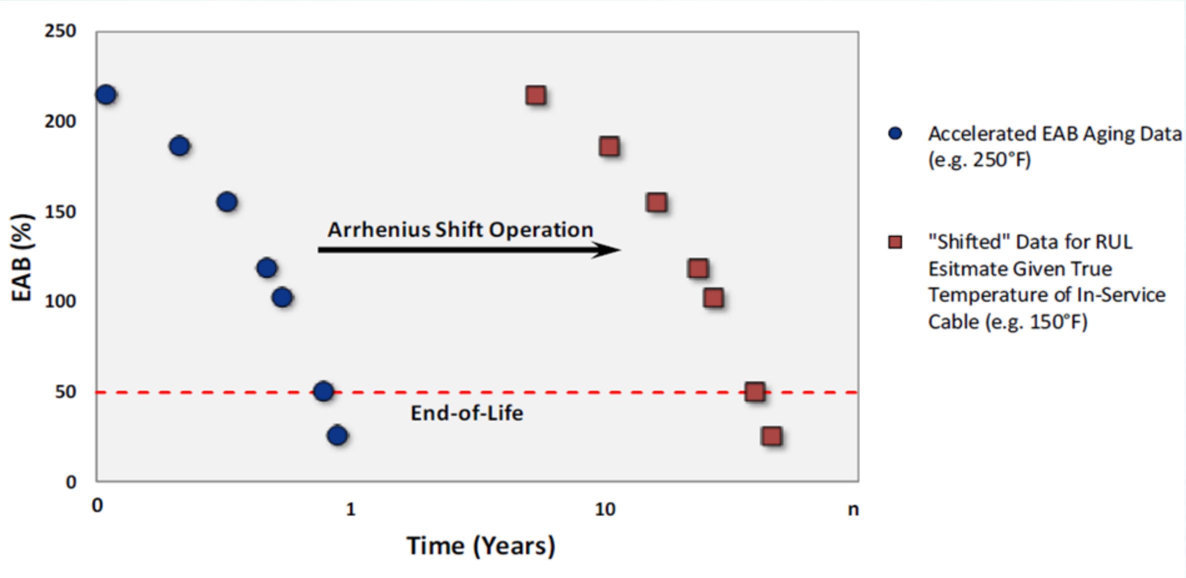
- Time Domain Reflectometry (TDR)
- Frequency Domain Reflectometry (FDR)
- Insulation Resistance (IR)
- Impedance (L,C,R)
- Reverse Time Domain Reflectometry (RTDR)
- Dynamic Time Domain Reflectometry (DTDR)
- DC Resistance
- Voltage Waveform
- Tan Delta
- Withstand
- Partial Discharge

Mechanical Electrical Thermal Chemical

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

These Effects Must Be Understood and Accounted for During Accelerated Aging

- **Conducting accelerated aging of cables and insulation polymers to support CM test development.**
  - Thermal: 110^{o}C, 120^{o}C, 130^{o}C, and 135^{o}C (high temperature materials at 190^{o}C)
  - Sequential radiation then thermal: 30 Mrads lifetime gamma (25 krad/hour), thermal at 120^{o}C (165 ^{o}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

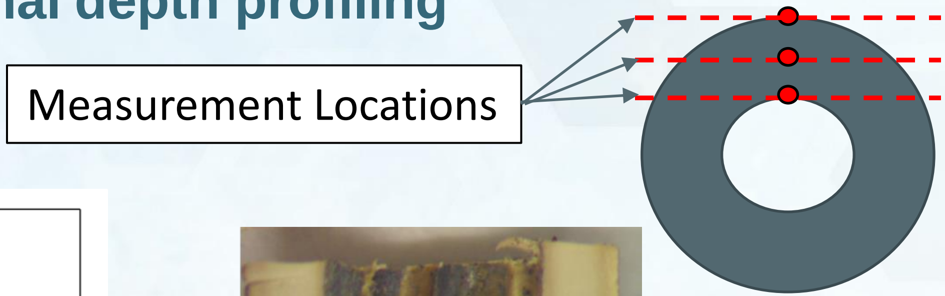
Sample Type 1

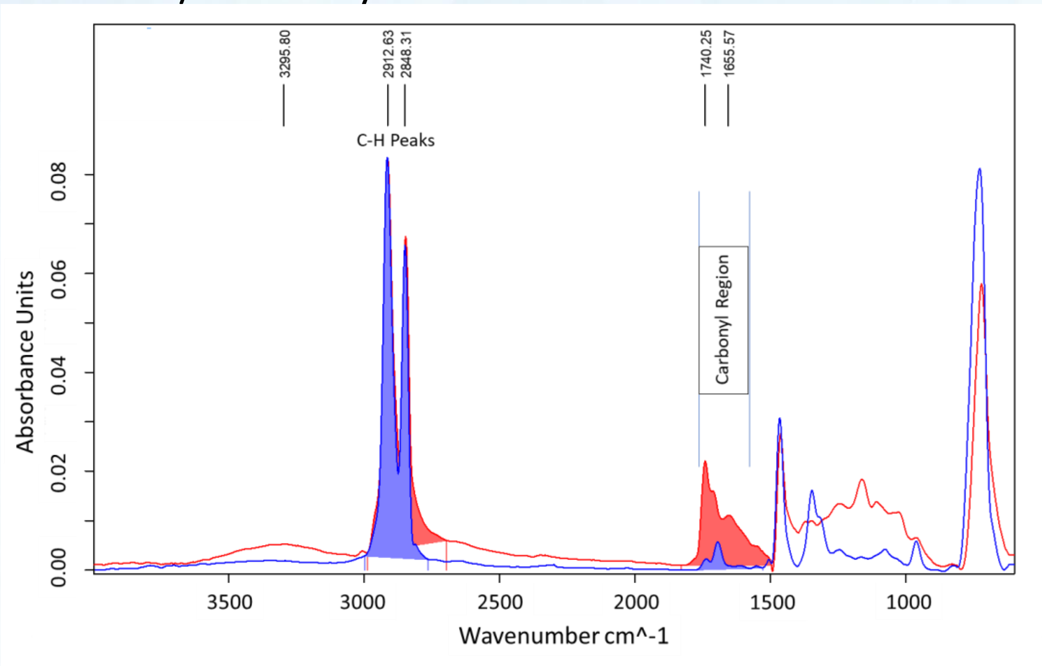
Sample Type 2

Sample Type 3

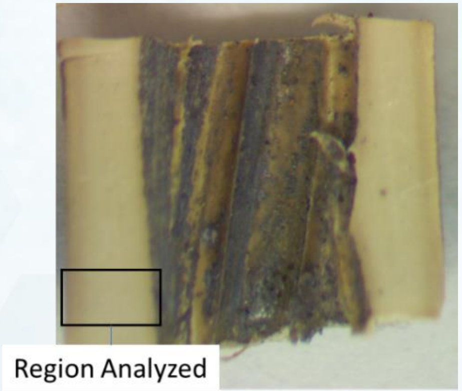
Testing Performed to Characterize and Quantify the Effects of Aging Phenomena

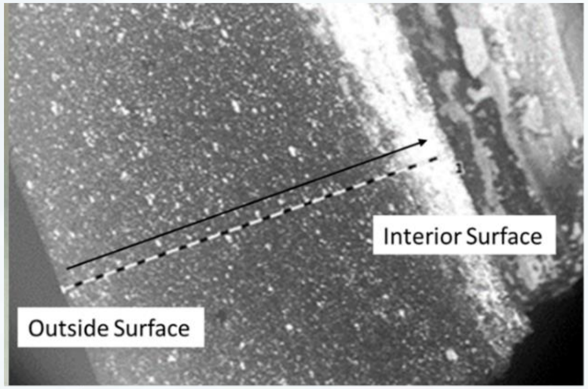
- **Analyzing insulation polymer degradation using thermal analysis and cross-sectional depth profiling**
  - Optical microscopy
  - FTIR Carbonyl Index
  - SEM/EDS analysis



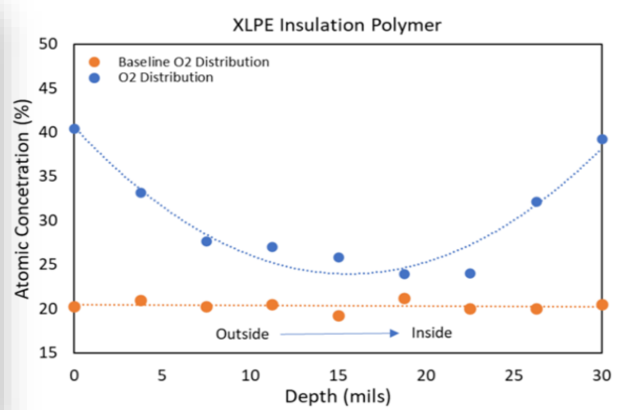


$$Carbonyl\ Index = \frac{Peak\ Area_{C=O}}{Peak\ Area_{C-H}}$$

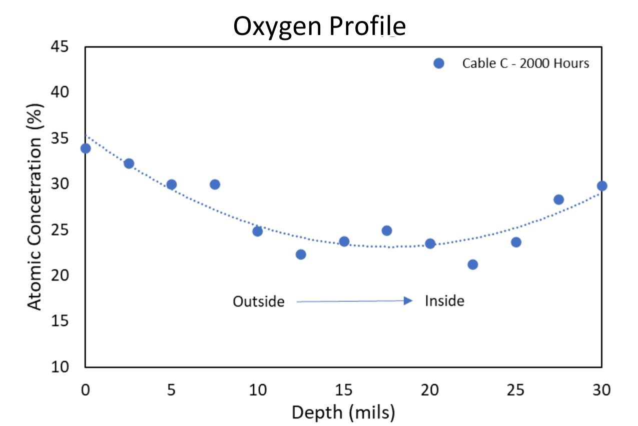




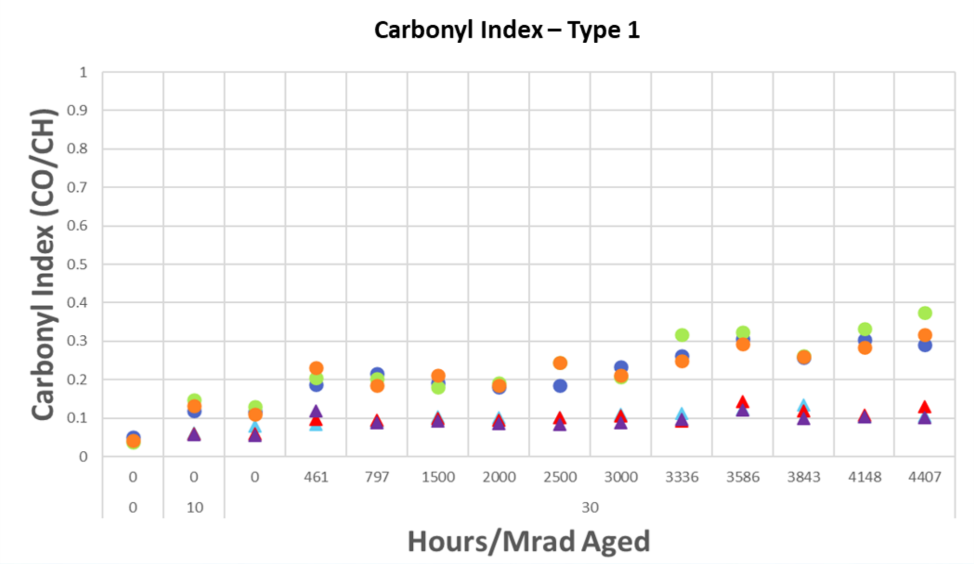
Diffusion Limited Oxidation/Inhomogeneous Oxidation Effects Observed in Polymers



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

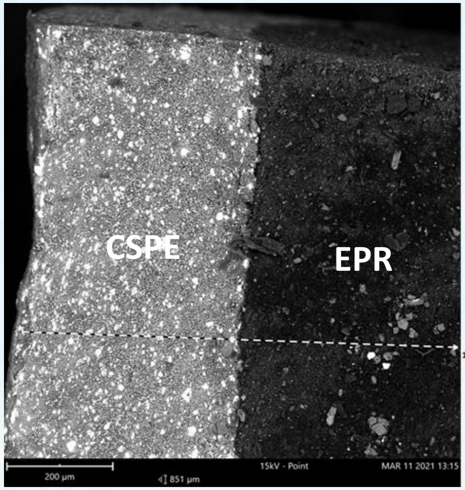


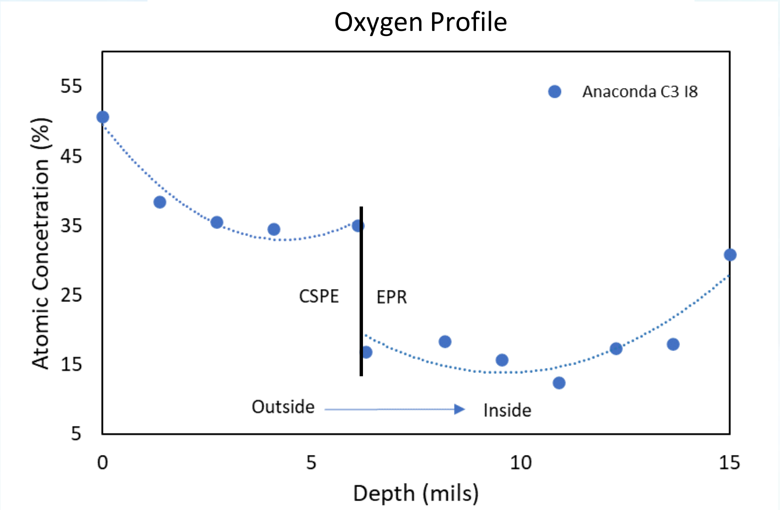
XLPE Sample Type 2 – 2,000 Hours 120°C

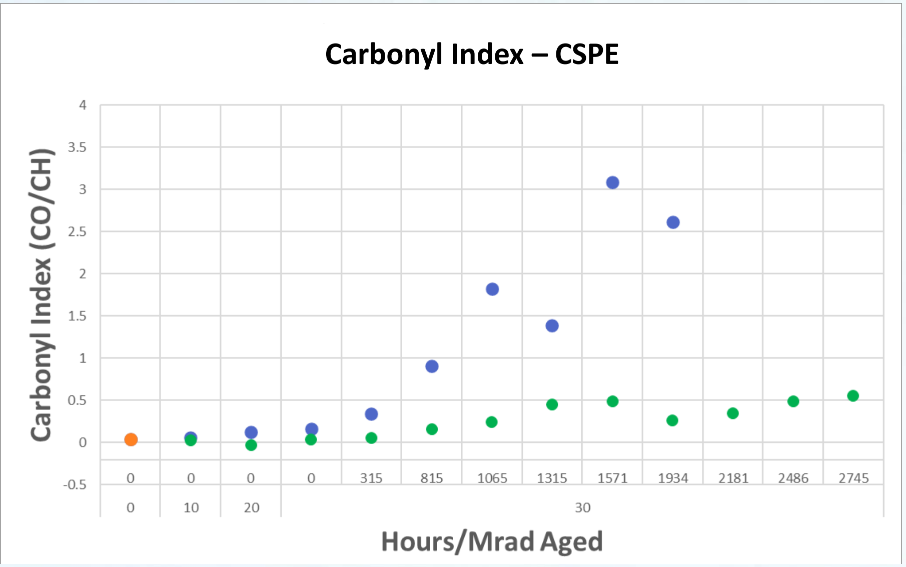


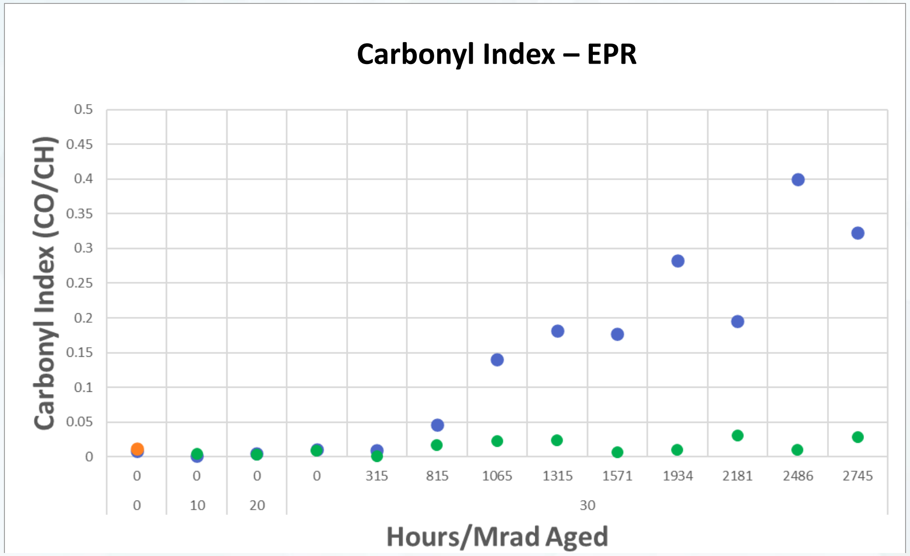
Diffusion Limited Oxidation/Inhomogeneous Oxidation Effects Observed in Polymers (Cont.)

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









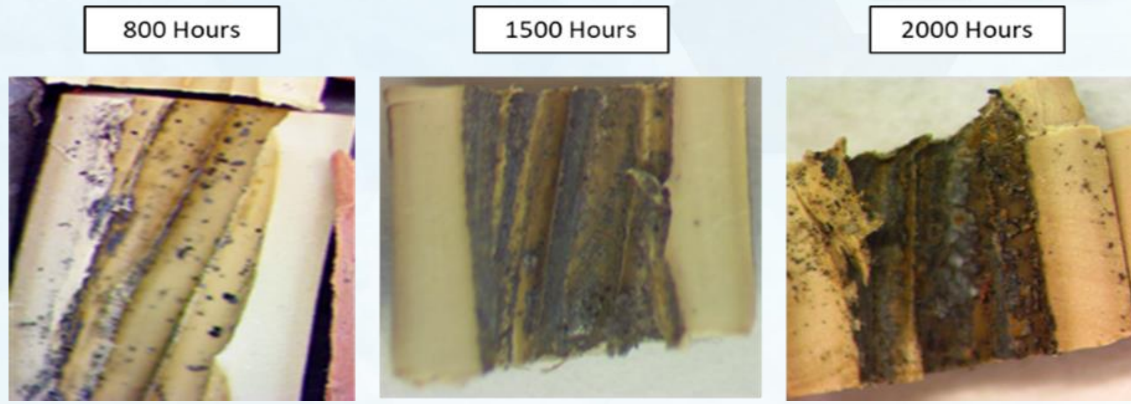
Copper Catalytic Effect Observed in Polymers

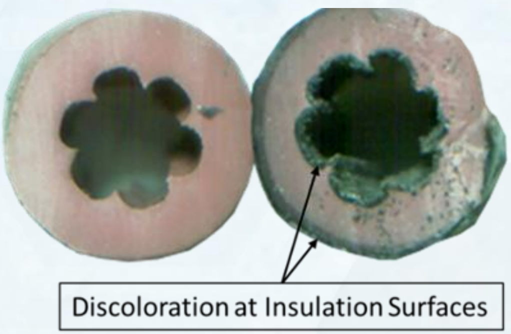
Copper Catalytic Effect Process

$ROOH + M^{n+} \rightarrow RO\bullet + M^{(n+1)+} + OH^-$ (1)

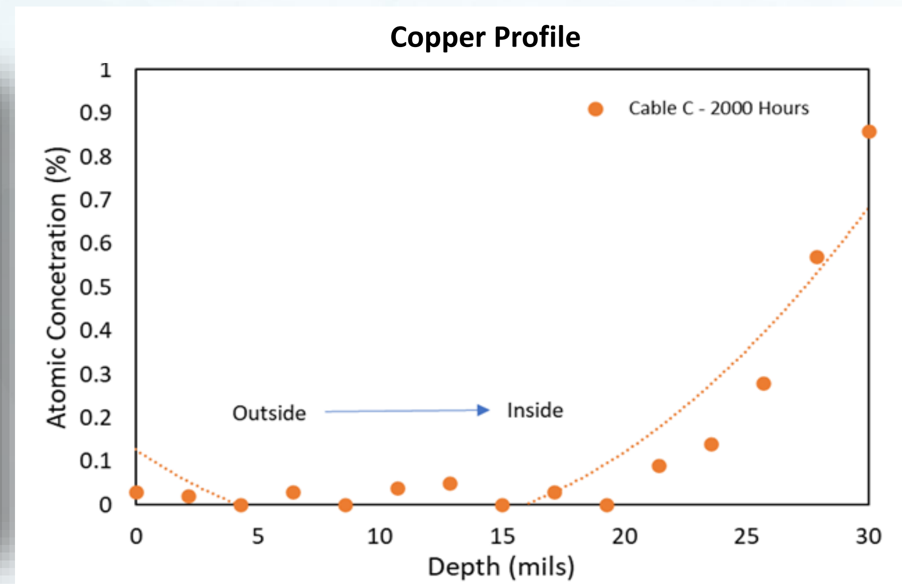
$ROOH + M^{(n+1)+} \rightarrow ROO\bullet + M^{n+} + H^+$ (2)

$2ROOH \rightarrow RO\bullet + ROO\bullet + H_2O$ (3)





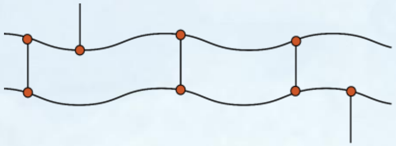
XLPO Sample Types 1 and 2 – 3,000 Hours 130°C



XLPE Sample Type 2 – 2,000 Hours 120°C

Inverse Temperature Effects Observed in Polymers

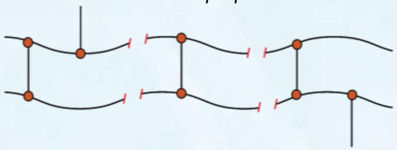
Polymer Chains



Gamma irradiation at room temperature →

Polymer Chain Scission

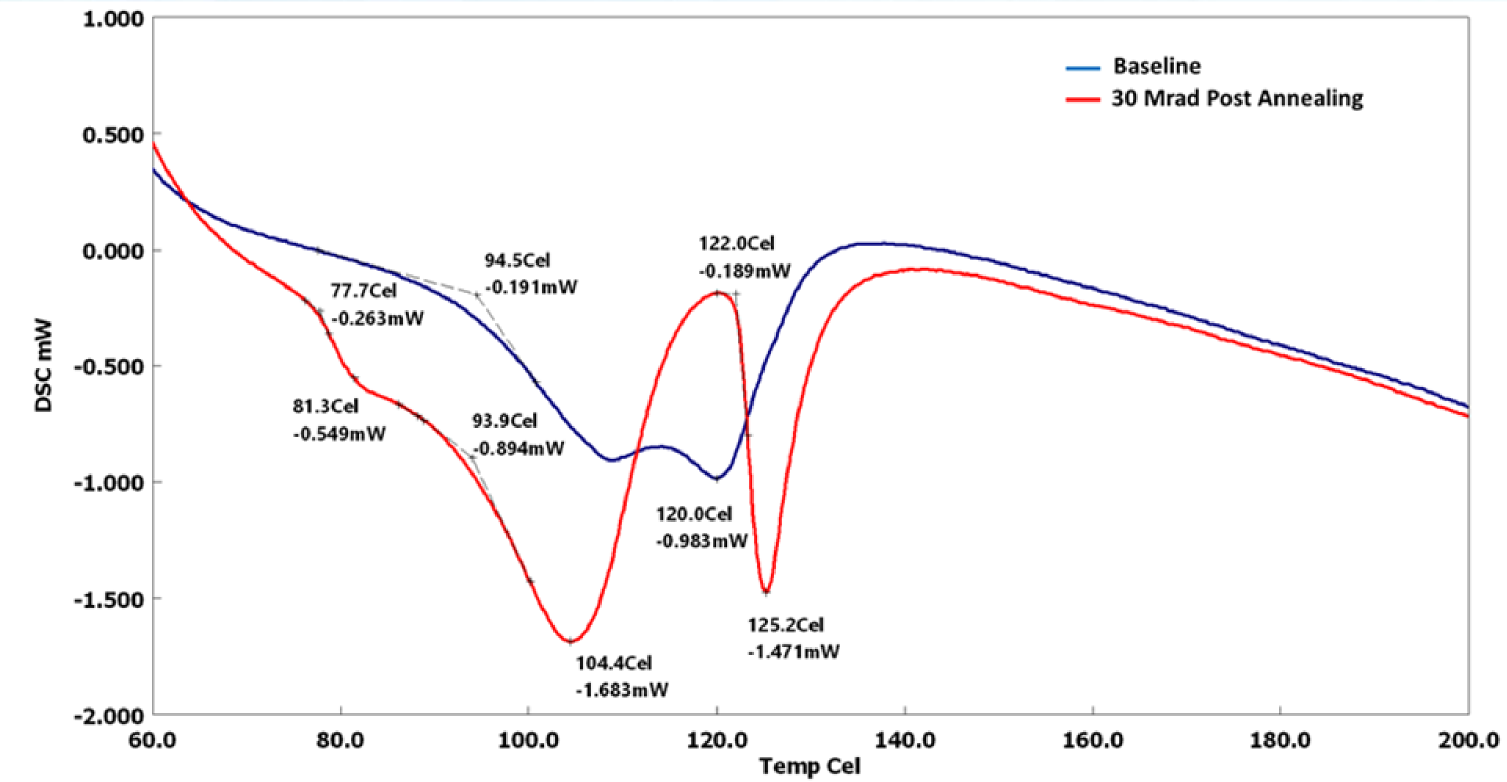
Causes substantial decrease in polymer mechanical properties



Annealing after gamma radiation exposure →

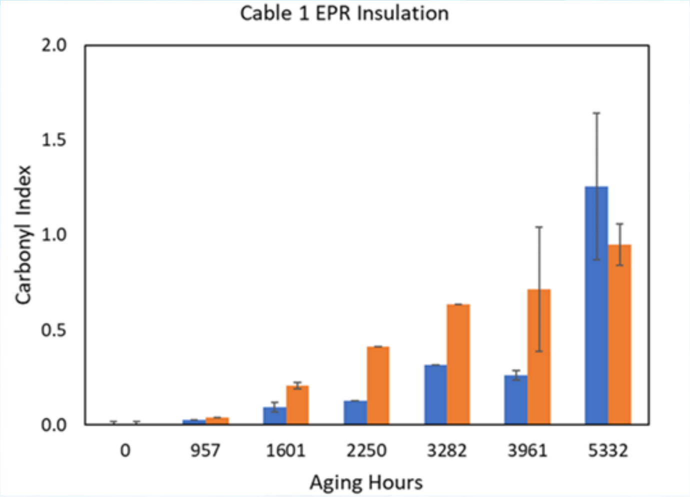
Polymer Chain Crosslinking

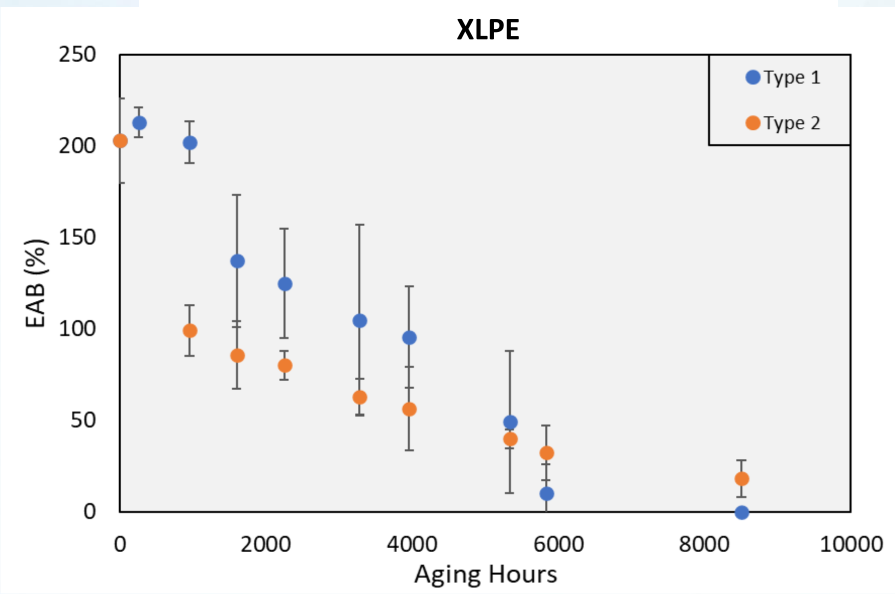
Results in substantial recovery of polymer mechanical properties

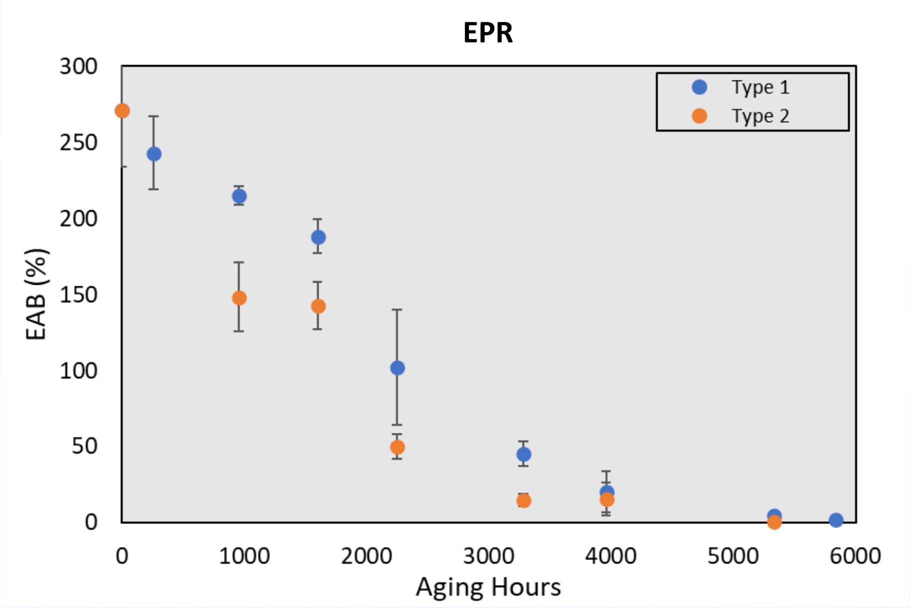


Effects on Polymer Properties

- 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.

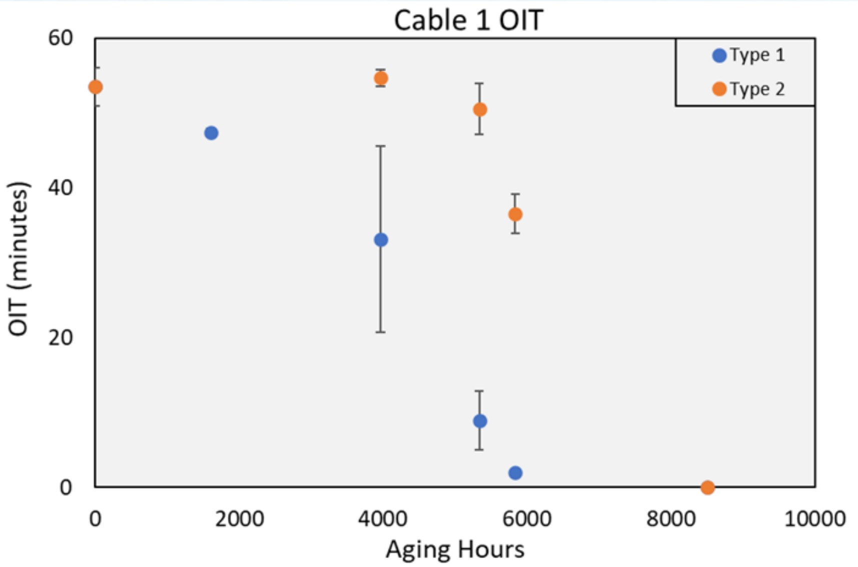


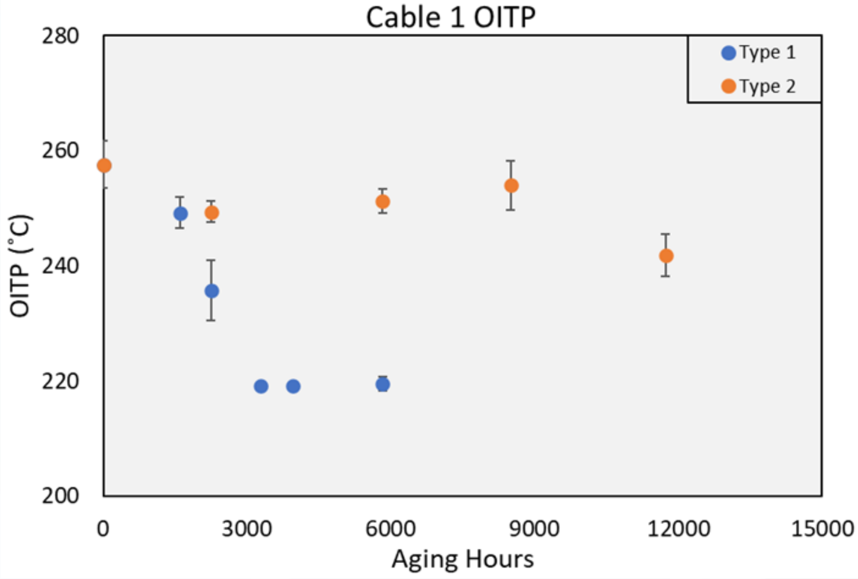




Effects on Polymer Properties (Cont.)

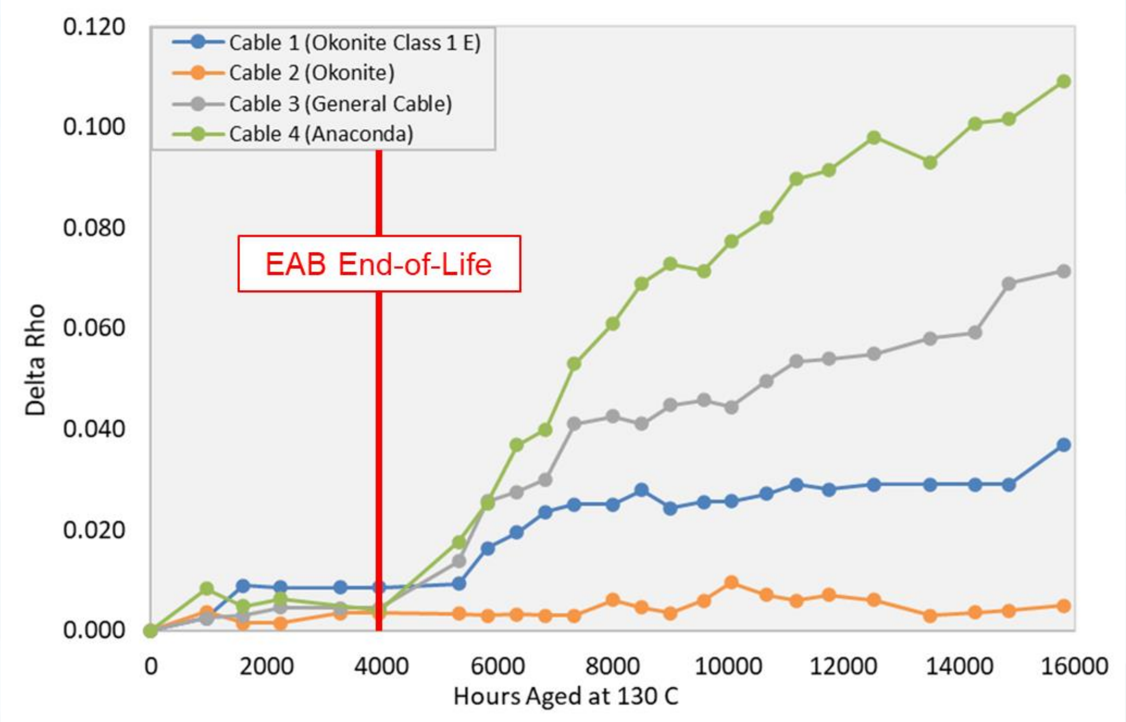
- Results show opposite trend of EAB (Type 1 decreases faster than Type 2).
- Data less impacted by interior surface aging (i.e., copper catalytic effects).
- DLO effects are apparent.



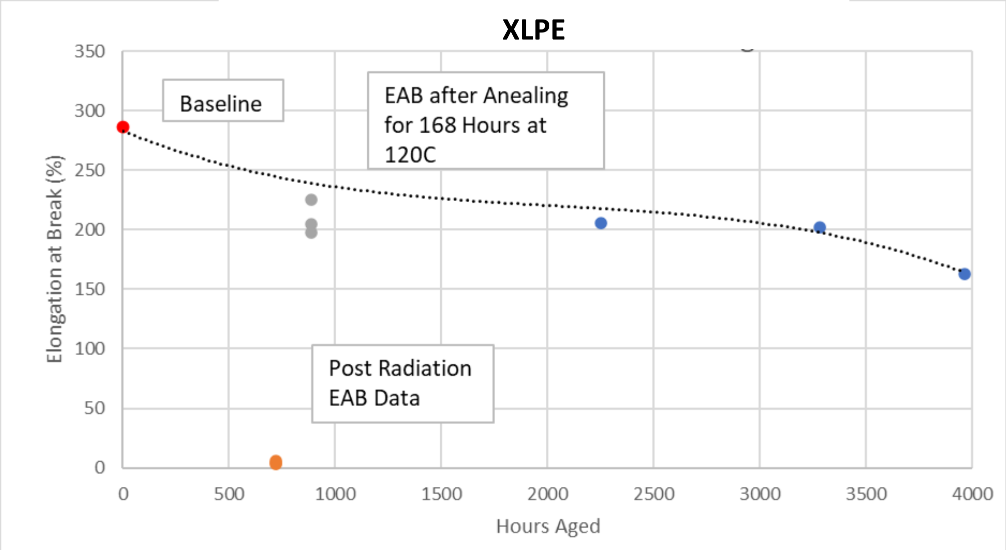


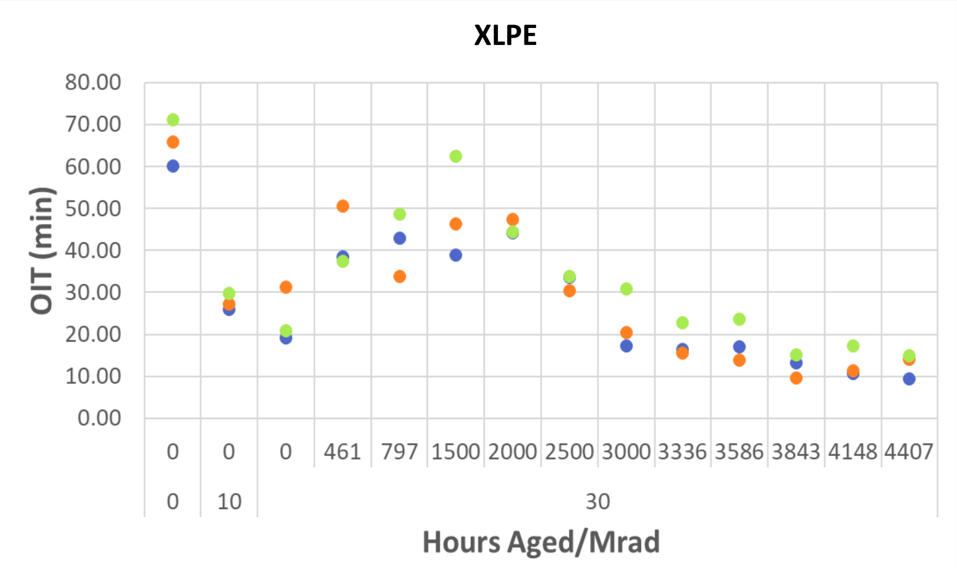
Effects on Polymer Properties (Cont.)

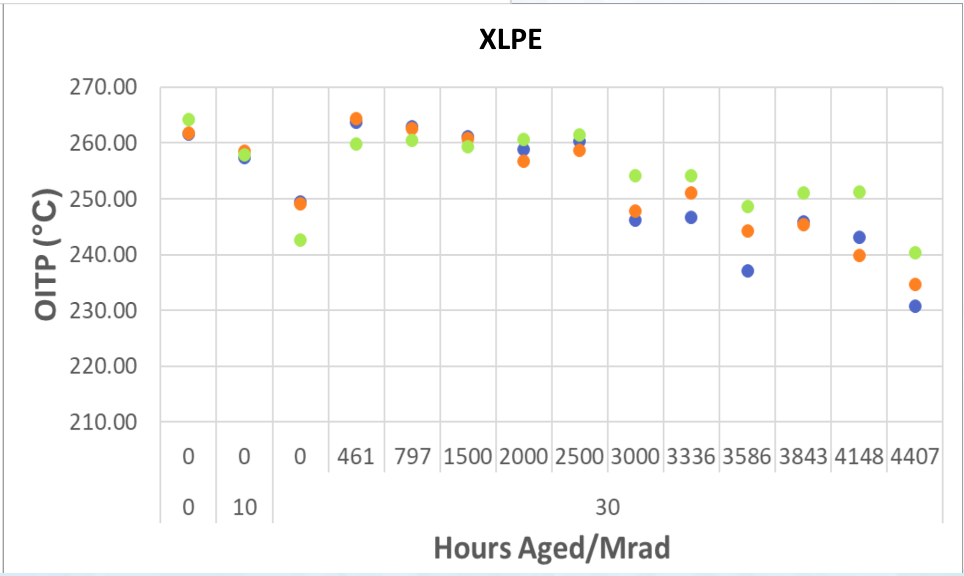
- Difference in end-of-life prediction (Type 1/2 vs Type 3).
- Conservative insulation end-of-life (50% EAB) is reached between 4,000 and 5,000 Hours.
- Differences due to aging phenomena that must be understood and accounted for in the analysis.



Effects on Polymer Properties (Cont.)

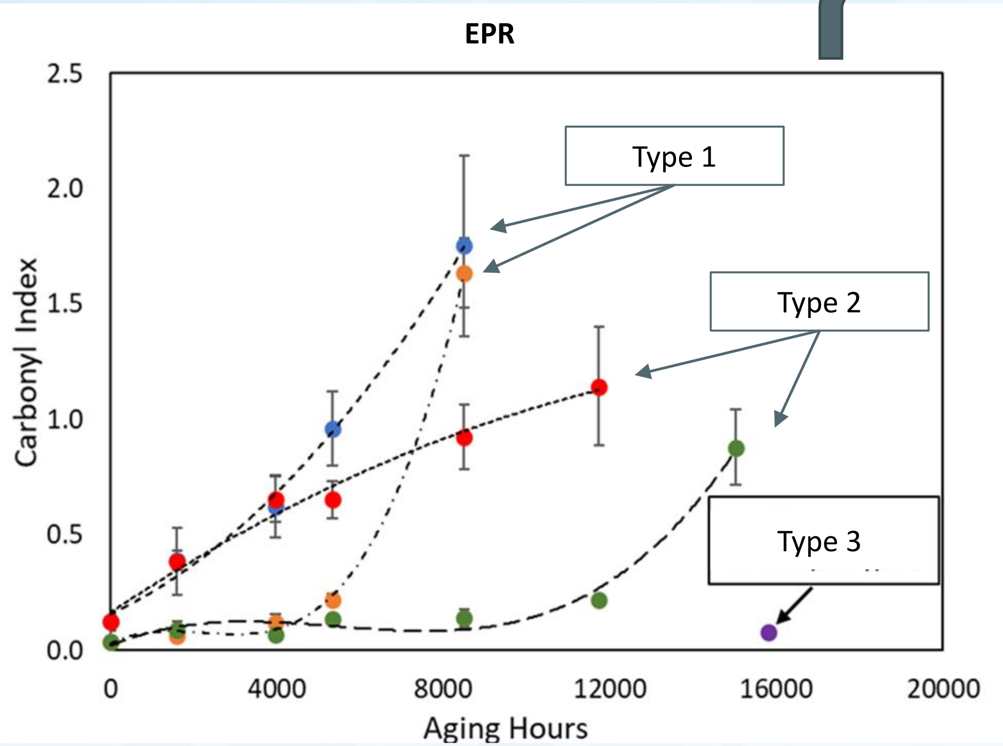


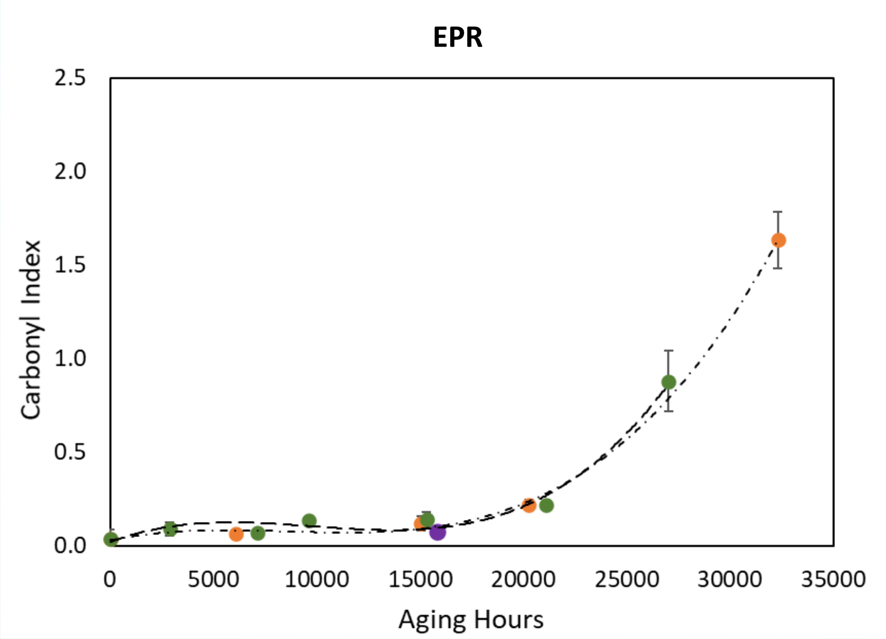




How Can Materials Exhibiting Different Aging Effects Be Compared?

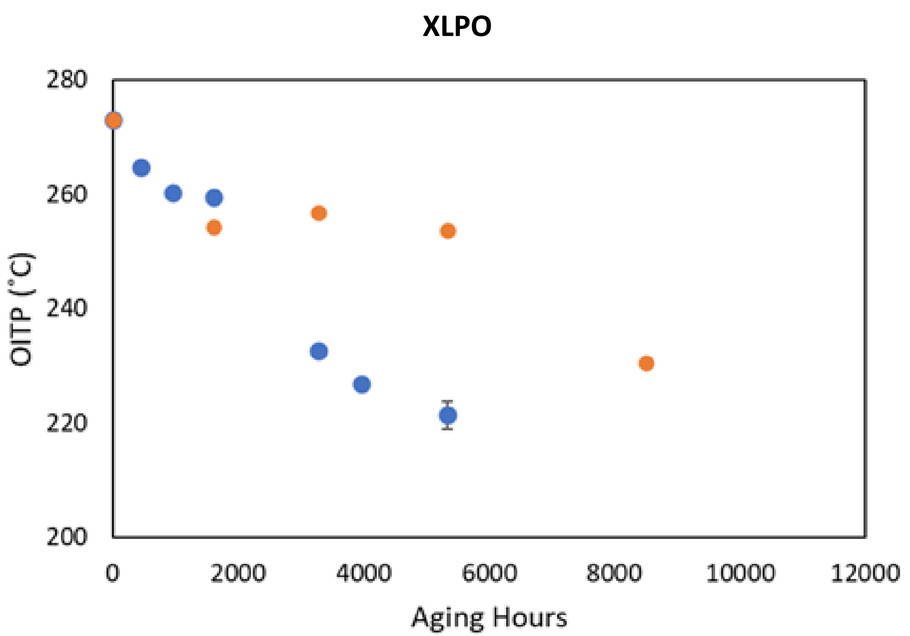
- **Comparing samples with different levels of inhomogeneous oxidation/DLO could be done using superposition principles.**

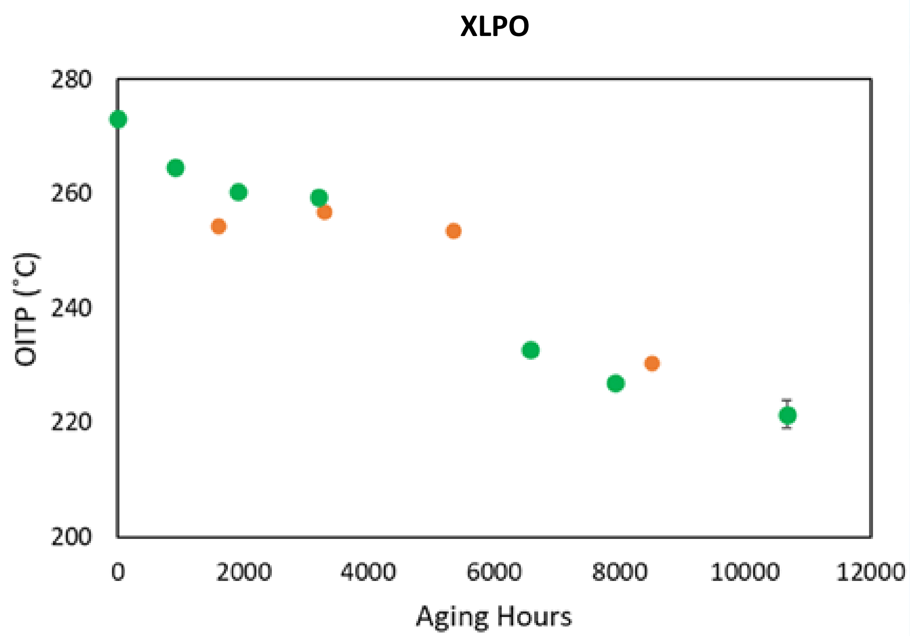




Sample Type 1 Time Shift Factors							
	Cable 1 (EPR)	Cable 2 (EPR)	Cable 3 (EPR)	Cable 4 (EPR)	Cable 5 (XLPE)	Cable 6 (XLPO)	Cable 7 (XLPO)
Time Shift Factors	3.8	5.0	2.2	5.0	1.5	2.9	2.2

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 accleerated aging phenomena on the polymer aging process are being explored**

<u>These effects must be addressed when performing accelerated aging</u>

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Questions