DOE Research on Cable Aging

Pacific Northwest NATIONAL LABORATORY

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Leo Fifield, PNNL

International Workshop on Age-Related Degradation of Cables

NRC Headquarters, One White Flint North, Washington, D.C.

23 January 2020

PNNL-SA-151249

Light Water Reactor Sustainability Program

The LWRS Program conducts research to develop technologies and other solutions to improve the economics and reliability, sustain the safety, and extend the operation of our nation's fleet of nuclear power plants.

An LWRS objective with respect to long-term operations is to manage the aging of [**cables and related systems**] so nuclear power plants can continue to operate safely and cost effectively.

The Light Water Reactor Sustainability (LWRS) Program is focused on the following three goals:

1. *Develop the fundamental scientific basis to understand, predict, and measure changes in [**cable materials and systems**] as they age in environments associated with continued long-term operations of existing nuclear power plants*
2. *Apply this fundamental knowledge to develop and demonstrate methods and technologies that support the safe and economical long-term operation of existing nuclear power plants*
3. *Research new technologies to address enhanced nuclear power plant performance, economics, and safety*

For more information:
Leo Fifield (leo.fifield@pnnl.gov)

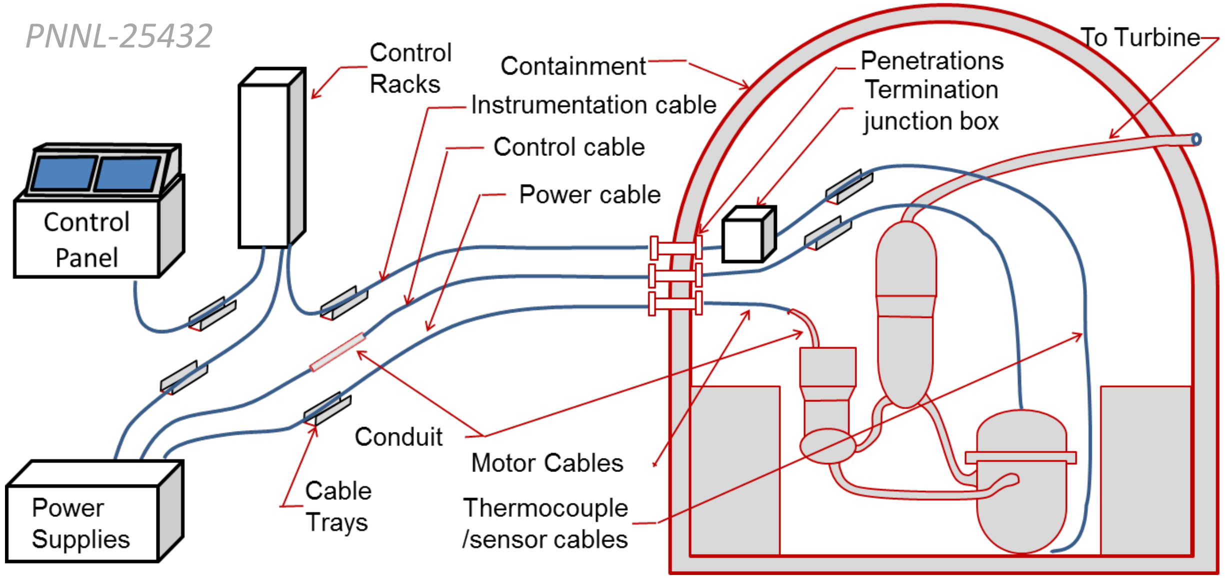
Electrical Cables in U.S. Nuclear Power Plants

Applications
- Instrument and Control (81%)
- Power Cables (15%)
- Communication (5%)

Insulation
- XLPE - cross-linked polyethylene
- EPR - ethylene-propylene rubber
- Silicone Rubber (SiR)

Jacketing
- Hypalon® - Chlorosulfonated PE (CSPE)
- Neoprene - Polychloroprene
- CPE - Chlorinated polyethylene
- PVC - Poly(vinyl chloride)

PNNL-25432



Medium voltage power cable

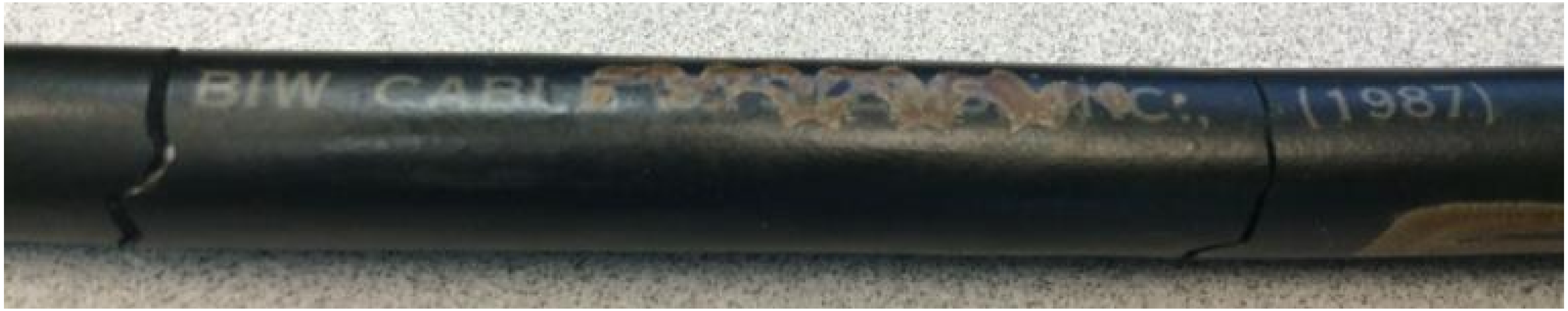
Low voltage Instrument & Control cable

Polymers Degrade Over Time

Environment
- Heat
- Radiation
- Moisture

Chemical Changes
- Bond breaking/forming
- Loss of additives
- Defect initiation

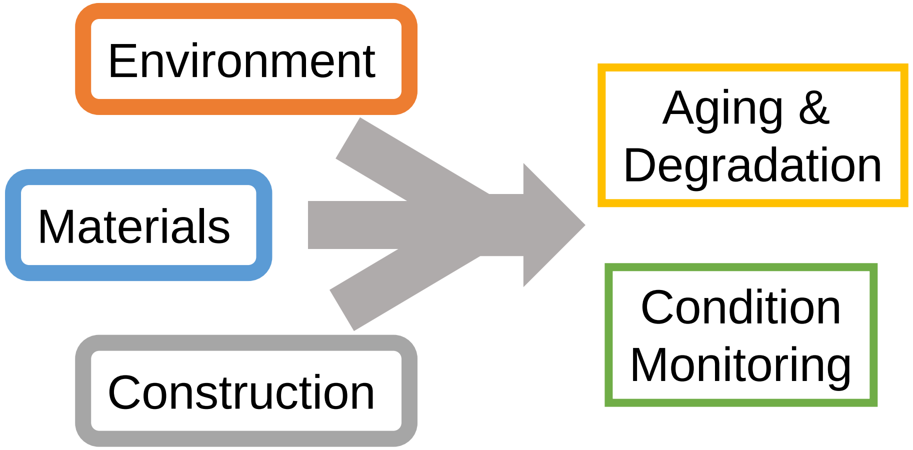
Material Changes
- Embrittlement
- Dimensional change
- Dielectric behavior changes



Cable Aging Management

Cable aging behavior & tools needed to assess condition are determined by cable:

- Component materials
- Construction and
- Operating environment



For example:

- Low voltage BIW cable, circa 1987, EPR insulation & CSPE jacket
- Unshielded, multi-conductor control rod cable
- Installed for 30 years with exposure to 50°C and 0.1Gy/h

What is its expected remaining useful life?

Which NDE techniques can quantify its condition?

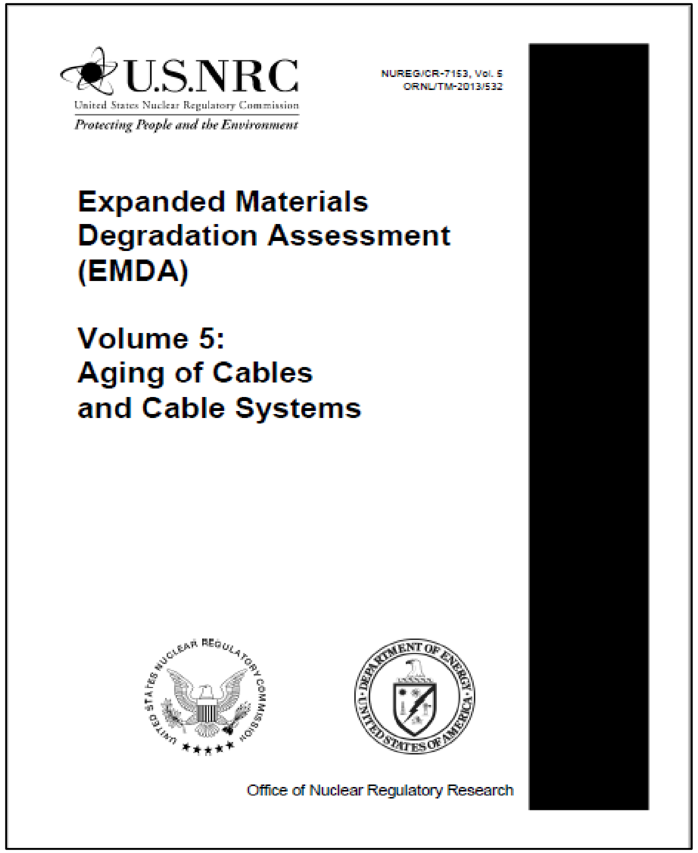
** EPR = ethylene-propylene rubber*
CSPE = chlorosulfonated polyethylene
NDE = non-destructive evaluation

Identified Knowledge Gaps

Cable Aging and Degradation

NUREG/CR-7153 (2014)

- Activation Energies
- Diffusion Limited Oxidation
- Dose Rate Effects
- Inverse Temperature Effects
- Moisture Effects



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7153, Vol. 5
ORNL/TM-2013/532

Expanded Materials Degradation Assessment (EMDA)

Volume 5: Aging of Cables and Cable Systems

Office of Nuclear Regulatory Research

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Insulation Materials

Anaconda Flame-Guard FR-EP EPR

Kerite HTK

Rockbestos XLPE

Brand-Rex XLPE

Samuel Moore Dekoron® EPDM

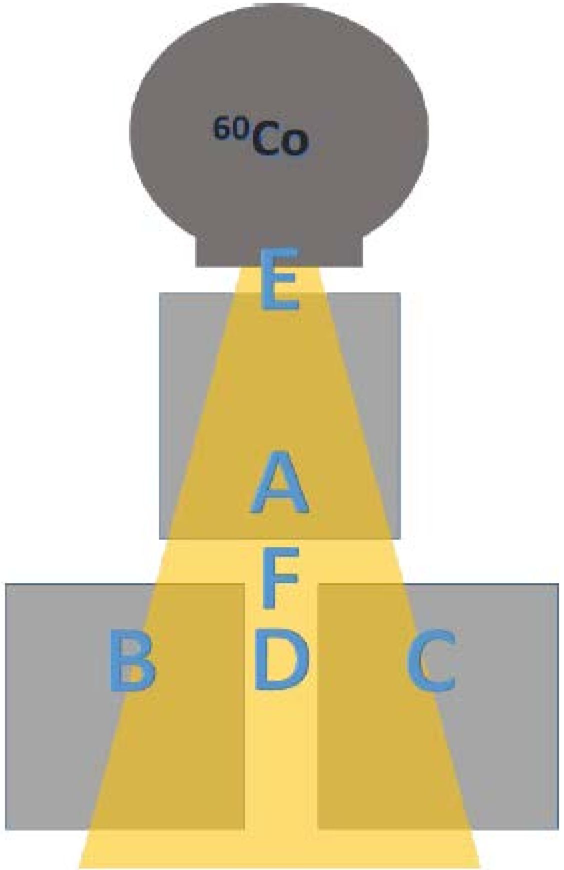
BIW Bostrad 7E EPR-CSPE

Okonite FMR EPR

RSCC Firewall® III XLPE

Brand-Rex Ultrol FR XLPE

Thermal/Radiation Aging at PNNL - High Exposure Facility 2018-2019 Simultaneous Thermal/Gamma Aging Campaign



Activation Energies (E_a)

Issue: Activation energies may be temperature dependent, complicating lifetime prediction using accelerated aging and Arrhenius analysis

Challenges/questions:
- Lower temperature aging takes long times
- Does E_a change with aging? (harvested cable vs new old stock)
- Effective E_a for material combinations (e.g. bonded individual jacket)

Strategy:
- Age & characterize cable materials at series of temperatures
- Confirm correlation of sensitive measures of aging (SMA) with lifetime curves
- Apply SMA to cables aged at lower temperatures

Materials:
- CR3: BE, AE, OE, KH, RX, XX
- NOS: XX, OE, KH, BE, RX

Sensitive measure of aging (SMA) candidates:
- Oxygen consumption (oxygen depletion from aging environment): GC-MS
- Oxidation (oxygen addition to material): TOF-SIMS, XPS, FTIR
- Mass change
- Dielectric constant

Experiment:
- Aging temperatures: 165°C, 150°C, 136°C, 121°C, …
- Characterization:
  - EAB, IM, mass change, FTIR
  - Density, OIT, swell/gel
  - Dielectric constant

Activation Energies (E_a)

Conditions
- Thermal-only
- 165, 150, 136, 121°C

Test Plan
- EAB, IM, d, mΔ
- FTIR (CI)

Limitations
- High temperatures
- Materials used: CR3
- Sensitivity of characterization
- # of samples per condition

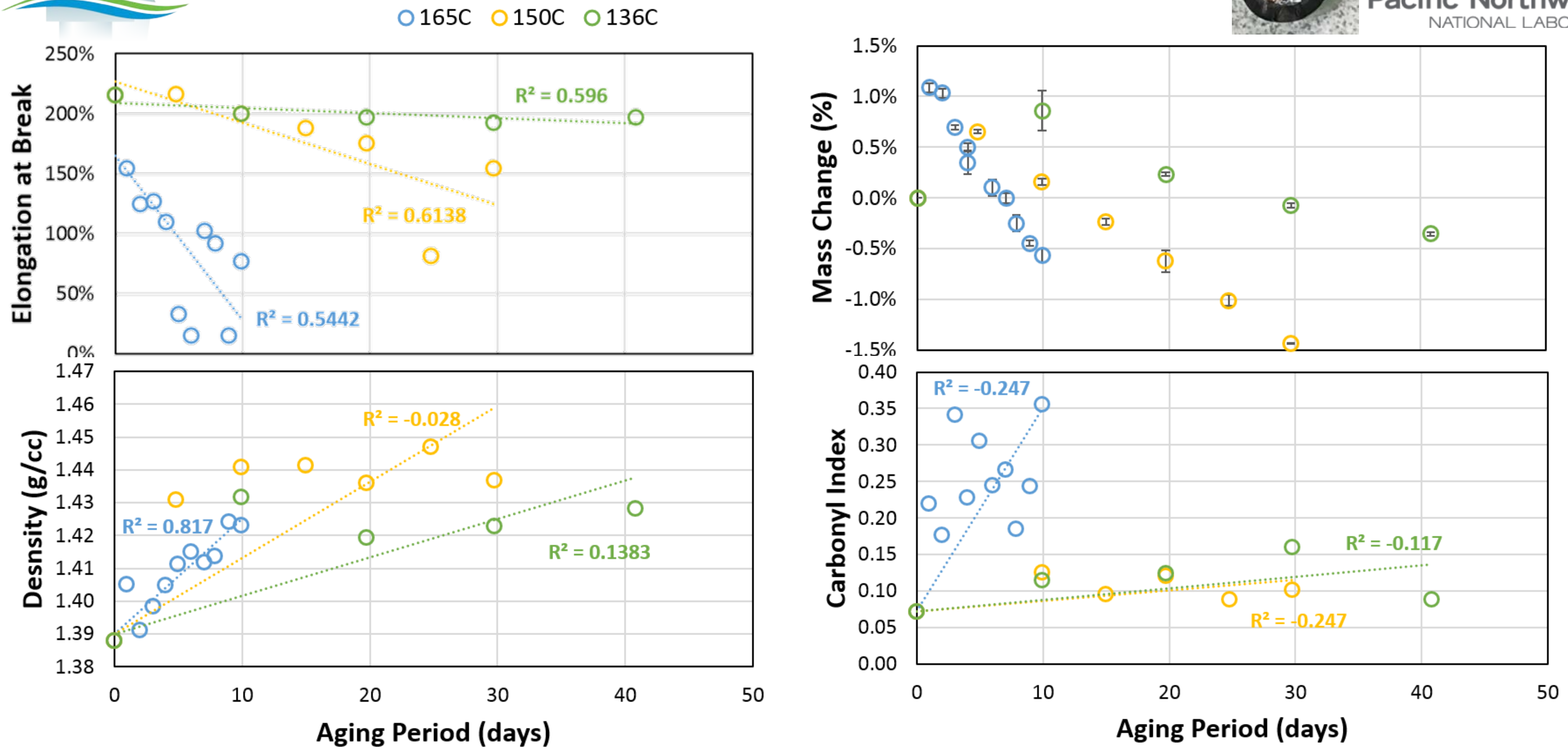
Materials
- Anaconda
- BIW
- Okonite
- BrandRex
- Rockbestos

Results to date
- High Scatter
- mΔ and IM tracked most closely with aging

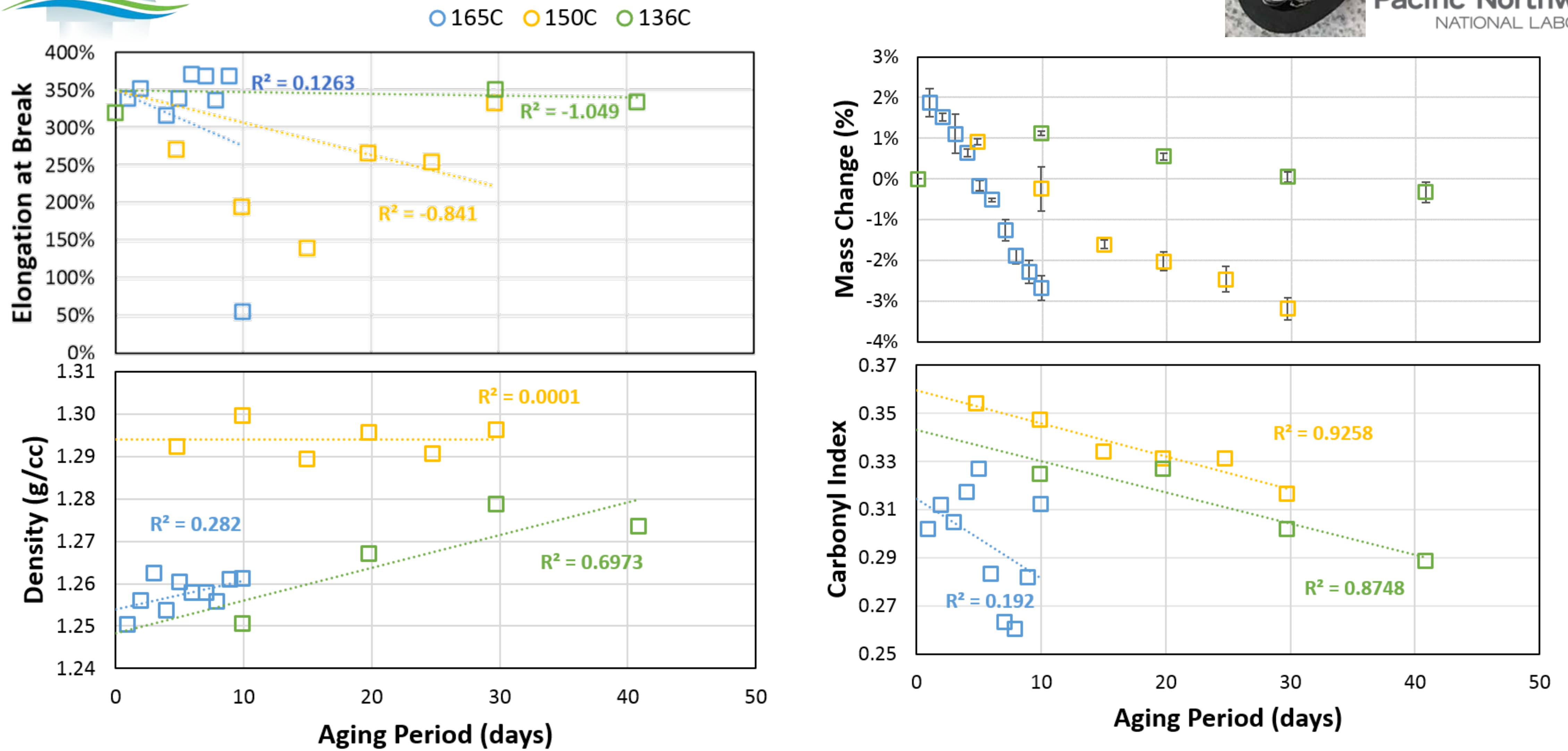
Potential Future Work
- Characterization
  - OIT, OITP
- Lower temps – 109, 99, …
- Sensitive Measures of Aging
  - O_2 Consumption
  - XPS, ToF-SIMS
  - Dielectric constant?

For more information:
Leo Fifield (leo.fifield@pnnl.gov)

AE21 Anaconda EPR white



XX28 BrandRex XLPE white



Diffusion Limited Oxidation (DLO)

Issue: Extreme accelerated aging conditions lead to rapid aging of sample surfaces resulting in diffusion limited oxidation of sample interior and underestimation of thermo-oxidative degradation in Arrhenius-type analysis, especially using EAB

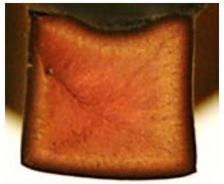
Challenges/questions:
- DLO is material and geometry dependent
- Aging that avoids DLO may take too long
- Which characterization techniques are sensitive to DLO?
- Can DLO simply be avoided through use of very thin samples?
- At which temps/dose rates is DLO important (for each material)?

Strategy:
- Age materials & cable segments at series of temps/dose rates
- Cross-section samples (pot & polish?) to prepare surface
- Investigate cross-sections to find evidence/extent of DLO
- Characterize to determine sensitivity of signal to DLO
  - Surface sensitive & bulk sample techniques
- Look for DLO as a function of sample thickness

Materials:
- CR3: BE, AE, OE, KH, RX, XX
- NOS: XX, OE, KH, BE, RX, SE—cable segments & samples

Experiments:
- Aging temperatures: 165°C, 150°C, 136°C, 121°C, …
- RT gamma dose rates: 1000Gy/h, 500Gy/h, 200Gy/h, 100Gy/h,…
- Slice or cryo-snap to expose cross-sectional surface (pot&polish?)
- Characterize cross-sections to find inhomogeneous aging
  - μFTIR, n/μhardness, TOF-SIMS, XPS
  - μRaman, XRD
- Characterize to determine sensitivity of signal to DLO
  - Average over sample: EAB, mass change, density, swell/gel, OIT
  - Surface sensitive: IM, FTIR
- Effect of sample thickness from insulation straw
  - Cut tube discs in various thickness, Age, Identify signs of DLO

Diffusion Limited Oxidation



Conditions
- Thermal-only
  - 165, 150, 136, 121°C
- Radiation-only
  - 1000, 300, 200, 100 Gy/h

Test Plan
- Cross-sections
  - µFTIR
  - ToF-SIMS
  - Nano Indentation
- Effect on macro signals (EAB)

Limitations
- Model of DLO (ala SNL)
- Materials used
- Conditions explored
- Number of samples per condition tested

Materials
- Thermal
  - Anaconda
  - BIW
  - Okonite
  - BrandRex
  - Rockbestos
- Radiation

Results to date
- Need data
  - Samples need to be prepared for analysis
  - Nanoindenter has just come online

Potential Future Work
- Characterization
  - SEM-EDS, d (thickness location)
  - µRaman
- Additional materials
- Additional temps
- Sample thickness
- Model
- Measure permittivity?

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DLO Mapping

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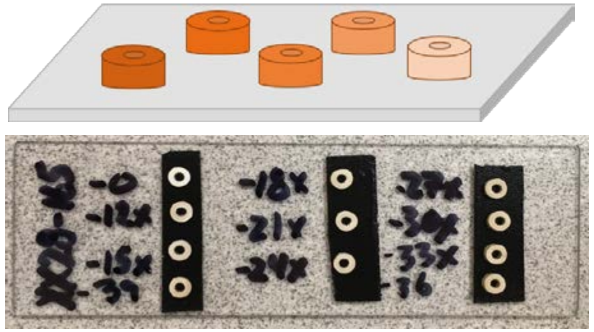
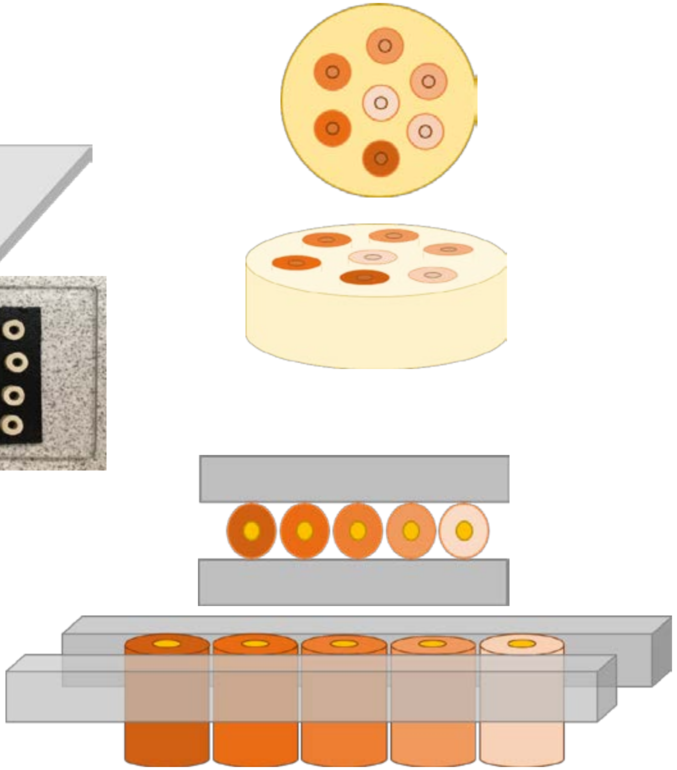
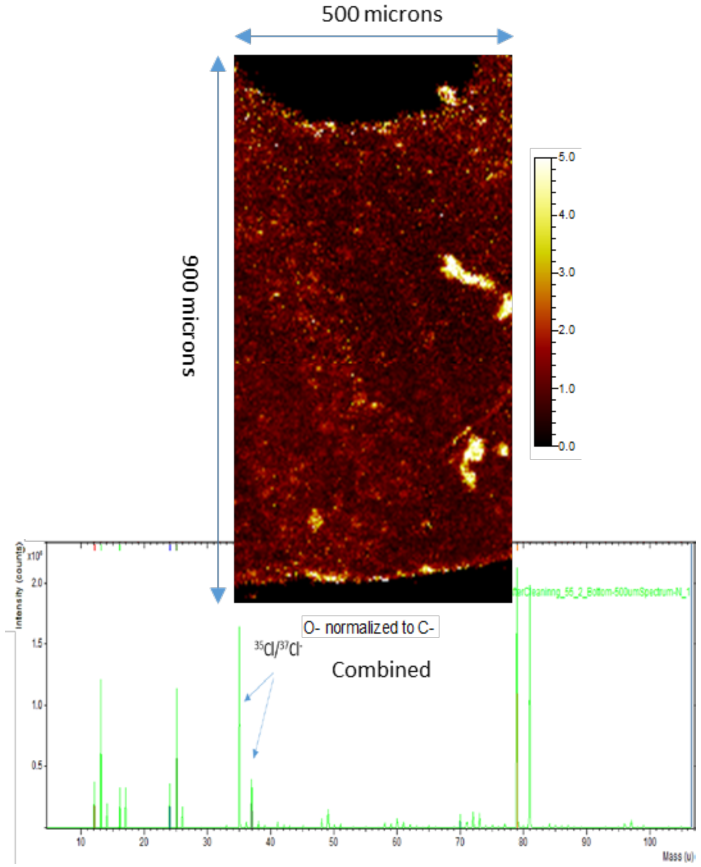
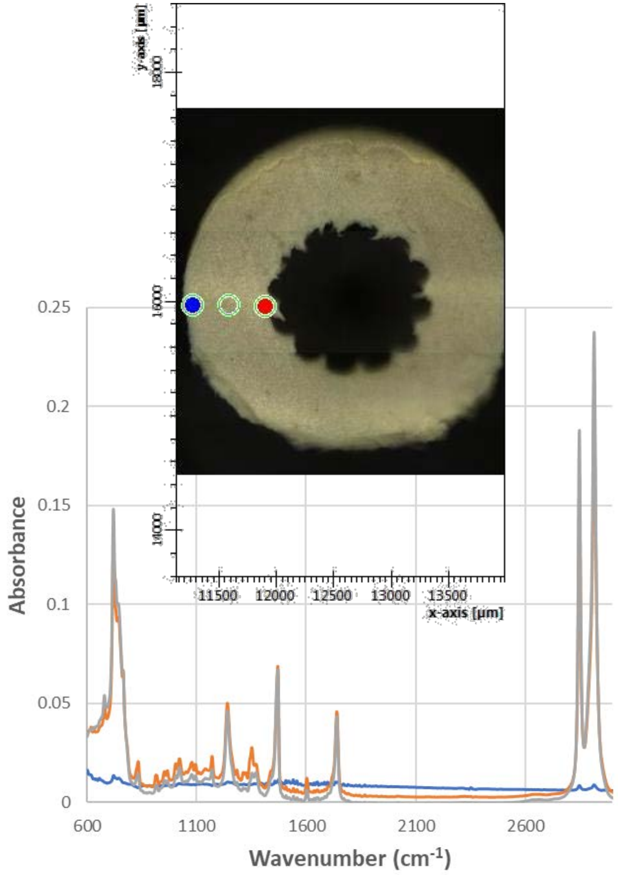


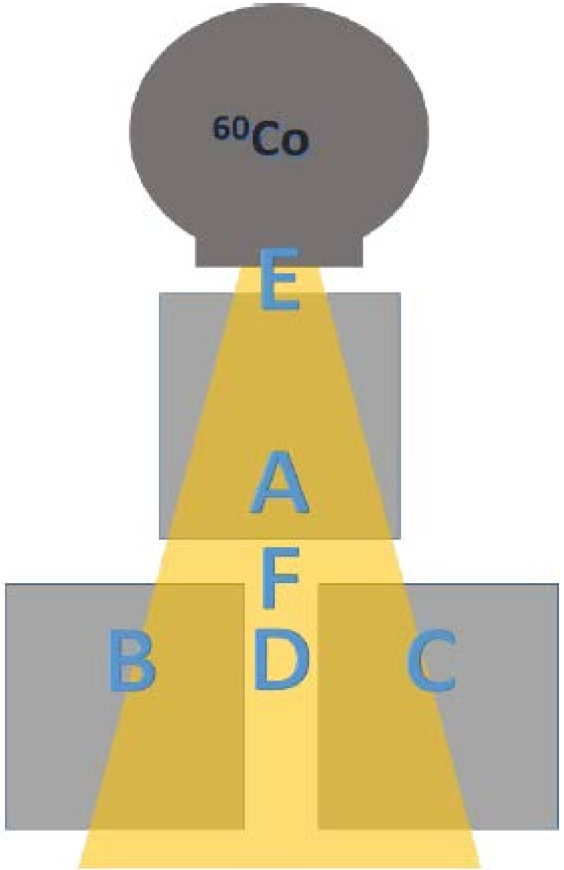






- Nano-Indenter
- Time-of-flight Secondary Ion Mass Spectrometry
- Microscope Fourier Transform Infrared Spectroscopy

PNNL High Exposure Facility 2018-2019 Simultaneous Thermal/Gamma Aging Campaign



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For more information:
Leo Fifield (leo.fifield@pnnl.gov)

PNNL-SA-151249

Dose Rate Effects (DRE)

Issue: Damage due to gamma irradiation may be dose rate dependent, complicating analysis based on total dose equals total damage.

Challenges/questions:

- Very low dose rate exposure takes impractically long to reach high total dose
- Samples spend longer at temperature to get to the same total dose at lower dose rates than at higher dose rates, complicating understanding of degradation factors
- For which rates are DRE important?
- Are DRE material-dependent?

Strategy:

- Start with exposure at RT to remove complication of time at temperature
- Look at degradation vs. dose rate vs. total dose vs. temperature and deconvolute

Materials:

- CR3: BE, AE, OE, KH, RX, XX
- NOS: XX, OE, KH, BE, RX

Experiments:

- RT gamma to common total dose: 30Mrad (300kGy)
  - Range of dose rates: 1800Gy/h, 300Gy/h, 190Gy/h, 100Gy/h,…
- Characterization:
  - EAB, IM, mass change, FTIR
  - Density, OIT, swell/gel
  - Dielectric constant

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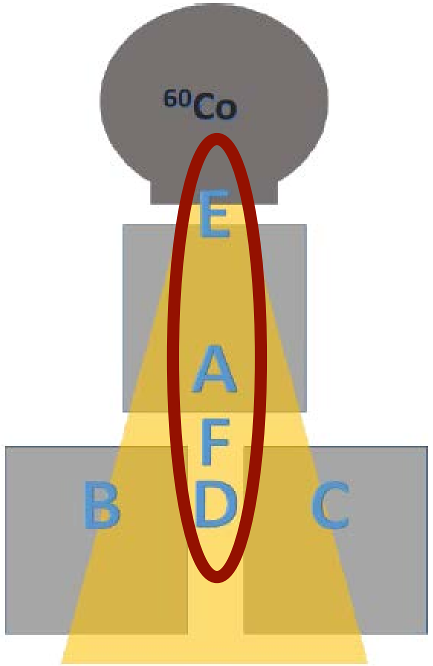
CKG3: DRE

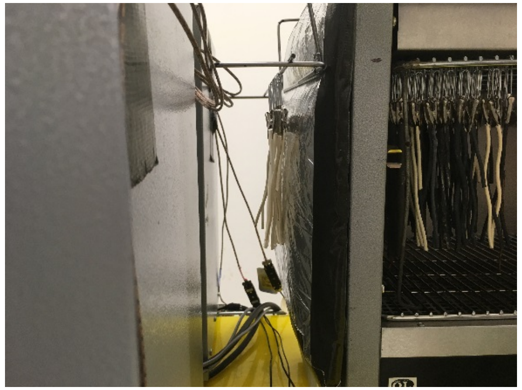


Position D

- 91 cm from C0-60 source
- 26°C
- 100 Gy/h

Position F

- 68.5 cm from Co-60 source
- 28°C
- 190 Gy/h



Position A

- 56 cm from Co-60 source
- 26°C
- 300 Gy/h

Position E

- 24 cm from Co-60 source
- 28°C
- 1890 Gy/h

Inverse Temperature Effects (ITE)

Issue: Polymer material damage from gamma irradiation may actually be greater at lower temperatures than it is at higher temperatures, complicating application of accelerated aging to service condition expectations.

Challenges/questions:

- ITE is material dependent
- Which temps cause ITE in which materials?
- Is ITE dose rate or total dose dependent?

Strategy:

- Age range of materials at identical dose rates/total dose, but at contrasting temperatures--below and above crystalline phase transitions

Materials:

- CR3: BE, AE, OE, KH, RX, XX -- sample sets

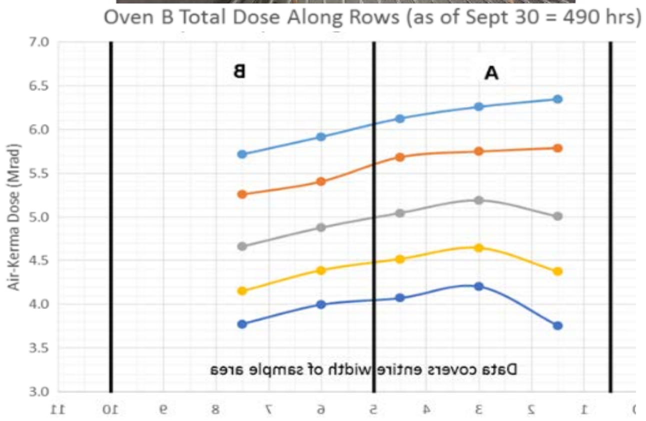
Experiments:

- Age samples in adjacent ovens at common distance from Co-60 source
  - Oven B at 50°C, Oven C at 90°C, D at 26°C Age at ~100Gy/h to 30Mrad (300kGy), with 16 intermediate time points (~140days)
- Move closer to source to keep dose rate constant
- Characterize to determine effect of total dose and contrasting temperature
  - EAB, IM, mass change, FTIR
  - Density, OIT, swell/gel
  - Dielectric constant

ITE

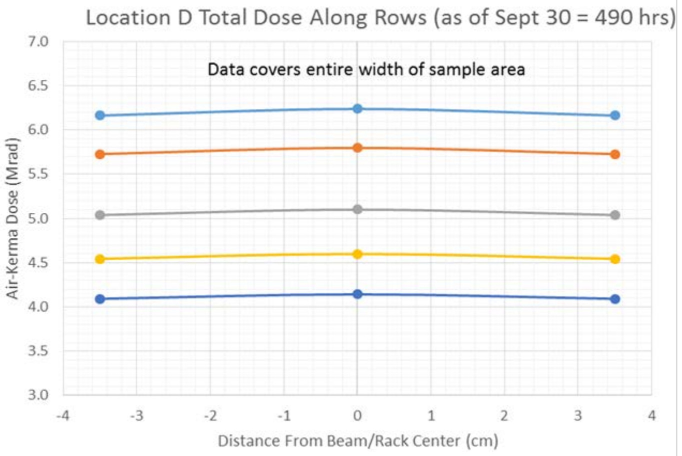
Position B

- 88 cm from Co-60 source
- 50°C
- 100 Gy/h



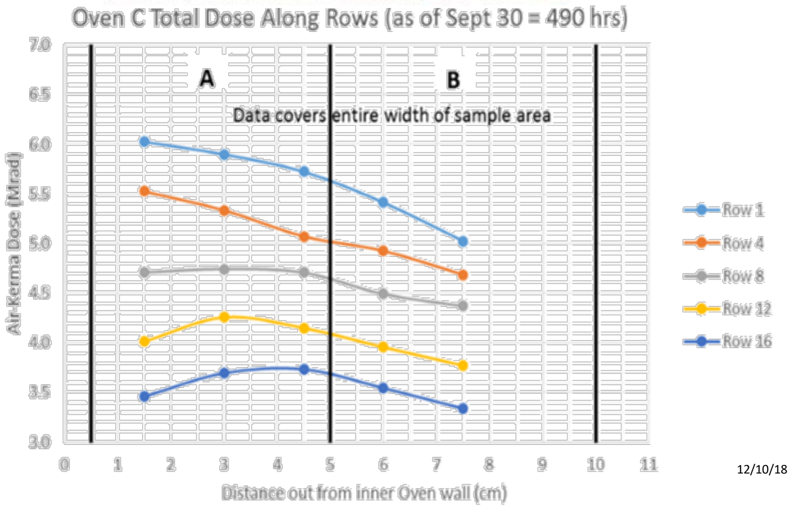
Position D

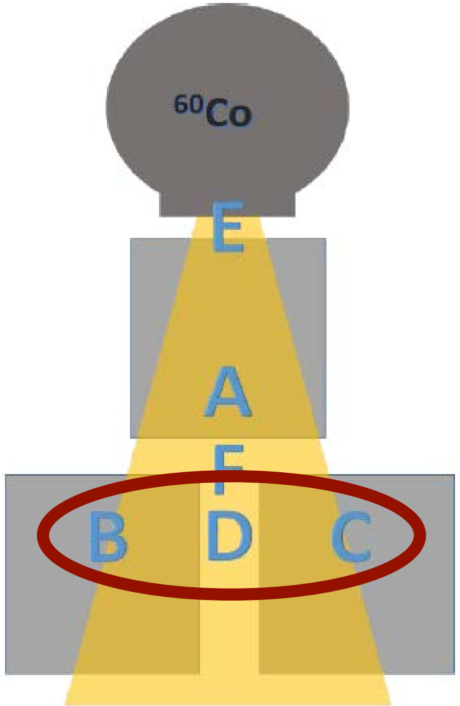
- 91 cm from C0-60 source
- 26°C
- 100 Gy/h



Position C

- 88 cm from Co-60 source
- 90°C
- 100 Gy/h





Synergistic Effects (S/E)

Issue: Cable aging due to gamma dose and temperature may depend on order of exposure: temp + rad, rad + temp & rad/temp may not produce the same degradation results.

Challenges/questions:

- At what conditions does order of exposure matter?
- Does order of exposure matter for all materials?
- What is order of exposure order of severity?

  T/R > R+T > T+R?
- How long do gamma-induction radicals last?

Strategy:

- Keep dose rate, total dose, and temperature constant while varying order of exposure
- Consider variety materials under similar conditions
- Characterize to determine differences in effects
- Measure radical content vs time since exposure

Materials:

- CR3: BE, AE, OE, KH, RX, XX
- NOS: XX, OE, KH, BE, RX

Experiments:

- Age in Oven A at 300Gy/h to 32Mrad (300kGy)
  - At 150°C
  - RT before same time at 150°C
  - RT after same time at 150°C

- Characterize aging
  - EAB, IM, mass change, FTIR
  - Density, OIT, swell/gel

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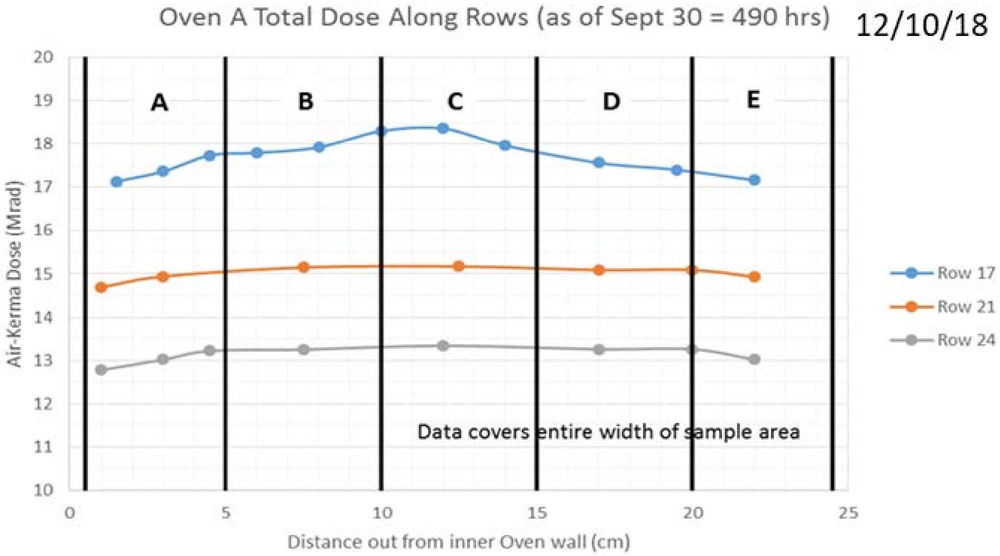
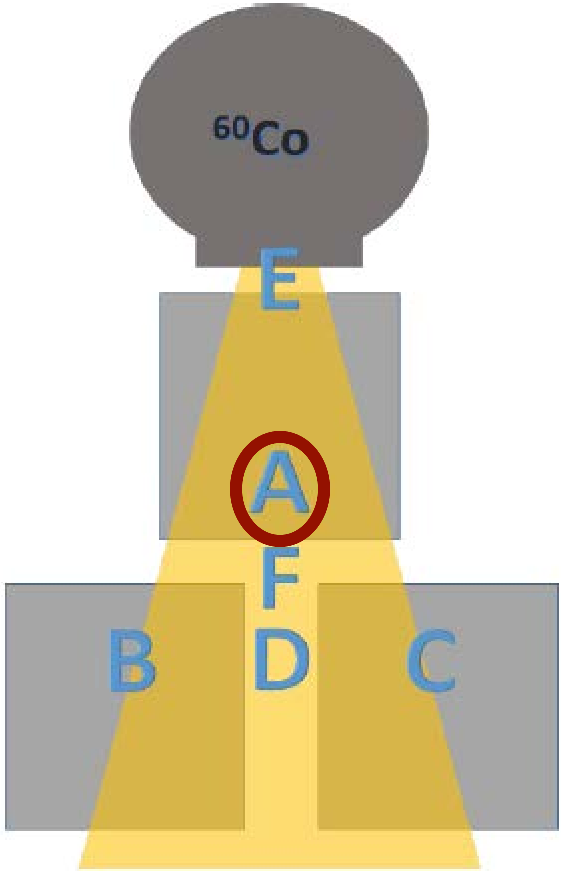
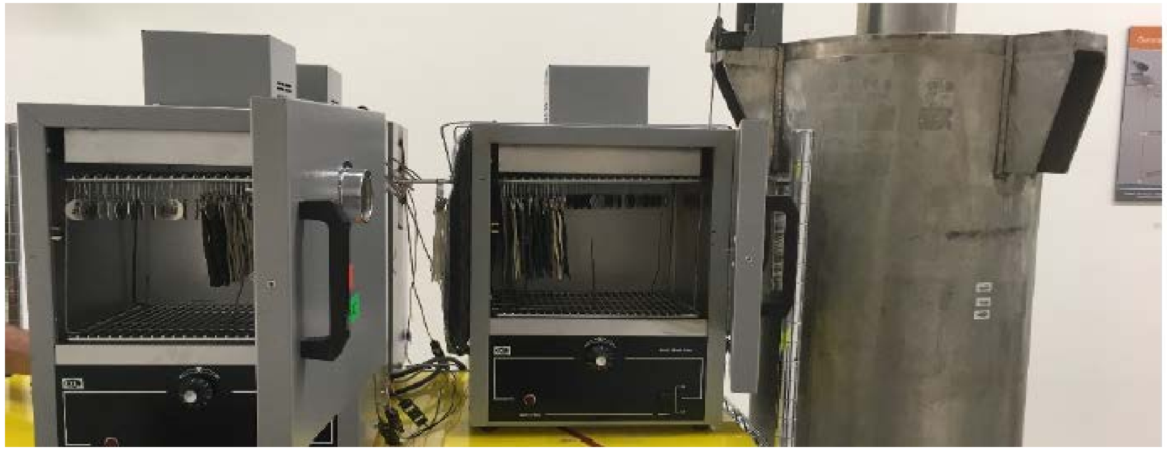
Synergistic Effects (S/E)







Summary: DRE, ITE, S/E

Irradiations concluding in FY19. Analysis begun in FY20

DRE	1800Gy/h, 300Gy/h, 190Gy/h, 100Gy/h	26°C	30 Mrad

ITE	50°C,	100 Gy/h	5, 9, 13, 17, 21, 25, 30 Mrad
	90°C,	100 Gy/h	5, 9, 13, 17, 21, 25, 30 Mrad
	26°C	100 Gy/h	5, 9, 13, 17, 21, 25, 30 Mrad

S/E	T/R	150°C @ 300Gy/h		2, 4, 6, 15, 17, 26, 28, 30, 32 Mrad	
	R+T	300Gy/h, 2, 4, 6, 15, 17, 26, 28, 30, 32 Mrad		+	150°C
	T+R	150°C	+	300Gy/h, 2, 4, 6, 15, 17, 26, 28, 30, 32 Mrad	

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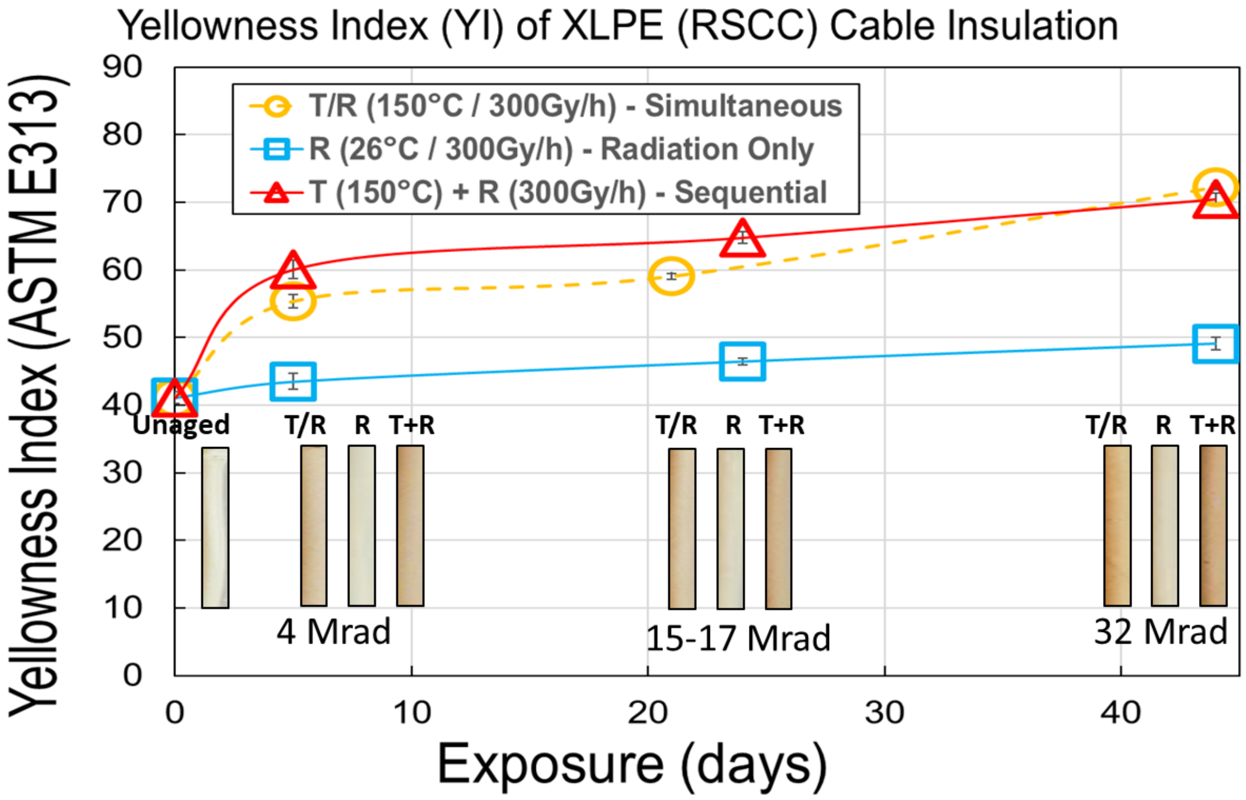
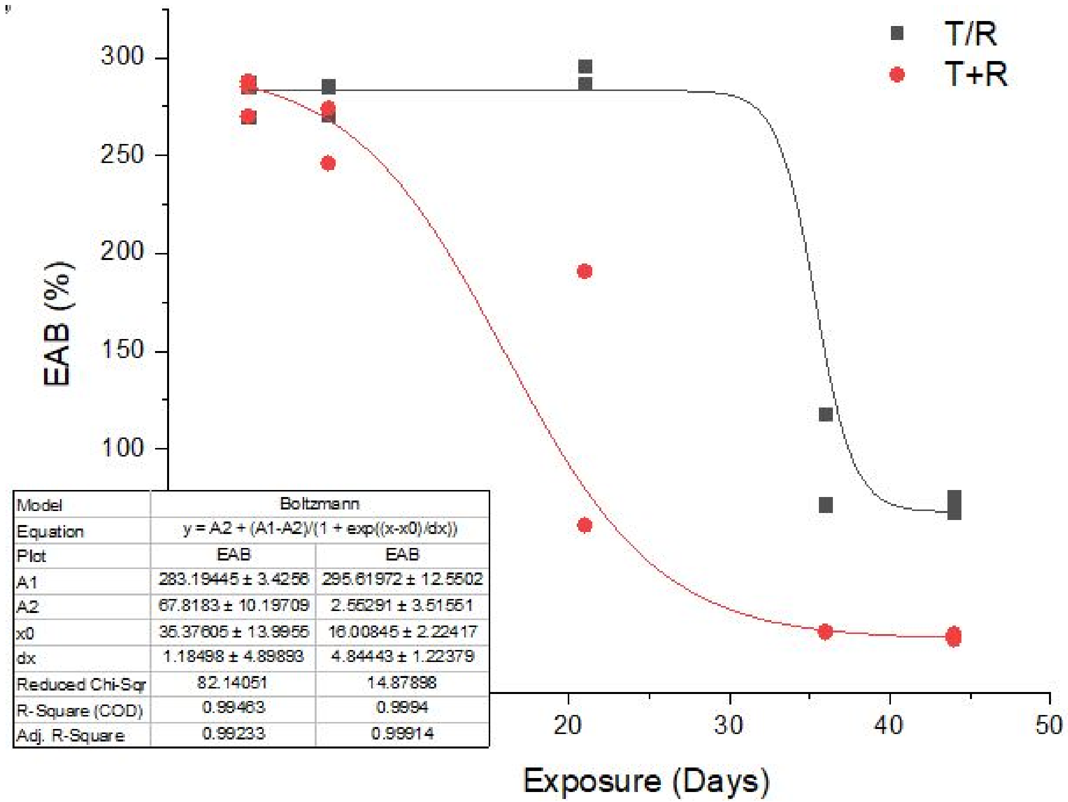
Sequential vs. Simultaneous Aging RSCC XLPE, 150°C 300Gy/h





Model	Boltzmann	
Equation	y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))	
Plot	EAB	EAB
A1	283.19445 ± 3.4256	295.61972 ± 12.5502
A2	67.8183 ± 10.19709	2.55291 ± 3.51551
x0	35.37605 ± 13.9955	16.00845 ± 2.22417
dx	1.18498 ± 4.89893	4.84443 ± 1.22379
Reduced Chi-Sqr	82.14051	14.87898
R-Square (COD)	0.99463	0.9994
Adj. R-Square	0.99233	0.99914

Summary

- PNNL and ORNL are pursuing predictive understanding of nuclear cable aging using extensive suite of aging, testing and characterization capabilities with support from the LWRS Materials Research Pathway

- Collaboration is key
  - EPRI, NRC, National Labs
  - Industry
  - Universities

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