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SNL Updates on Cable Aging Work

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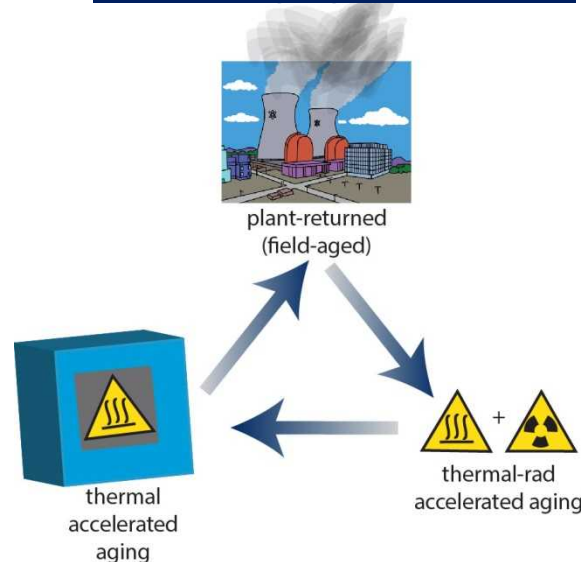# SNL Cable Aging Project Overview

▪ Industry need for requalification of plants to 60+ years

▪ LWRS Project goals: understand current cable insulation material state and expected performance sufficiently well to enable joint decisions with EPRI and NRC for cable requalification or replacement recommendations

Material Aging Correlations

plant-returned
(field-aged)

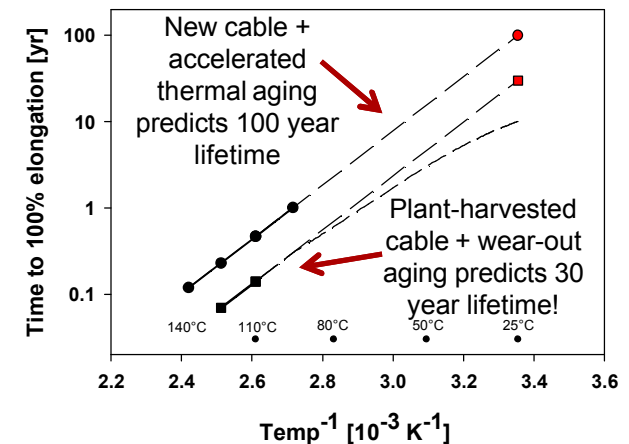thermal
accelerated
aging

thermal-rad
accelerated aging

▪ Address data gaps resulting insufficient technical understanding for long-term, low-temperature (i.e. field-aging conditions) behavior

SNL Cable Aging Project Overview

Research supporting development of guidance for aged material state, remaining life and expected performance including:

- Low T, long-term thermal-rad data for:
  - Accelerated aging of materials
  - Aging of field-returned materials

- Generation of enhanced predictive models

- Validation of predictive models using
field-returned materials

Lifetime Predictions

New cable + accelerated thermal aging predicts 100 year lifetime

Plant-harvested cable + wear-out aging predicts 30 year lifetime!

Time to 100% elongation [yr]

100 · 10 · 1 · 0.1

140°C   110°C   80°C   50°C   25°C

2.2   2.4   2.6   2.8   3.0   3.2   3.4   3.6

Temp^{-1} $[10^{-3} \, \text{K}^{-1}]$

Loss in tensile properties is used as a failure criterion

SNL Quarterly Highlights

- Community interactions

- Historical analysis

- PNNL aging

- Irradiation facility updates

- Request for field-returned materials

- SNL path forward

Building Consensus in predictive cable aging & Industry/Regulatory Interactions

- Participated in EPRI Cable User Group Meeting in Phoenix (Jan 20 – 24, 2014).
  - A consensus of the meeting attendees was reached between EPRI/NRC/PNNL/SNL on the goals of R&D cable aging activities covering predictive models, wear-out aging (field-returned specimens), and CM strategies.
  - SNL to host the next group meeting July 9-10, 2014

- Assisted in EPRI roadmap development

- SNL facilitated community teleconference, "Joint LWRS-EPRI LTO Cable R&D Meeting Reconnect" on December 13, 2013

Consolidate and evaluate previous work for trends and future property cross-correlations
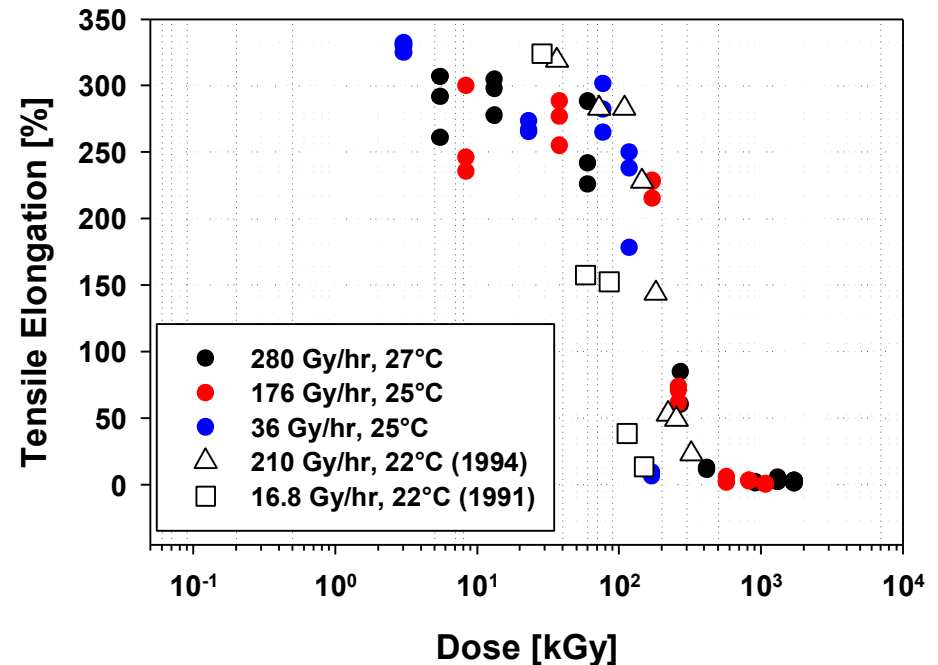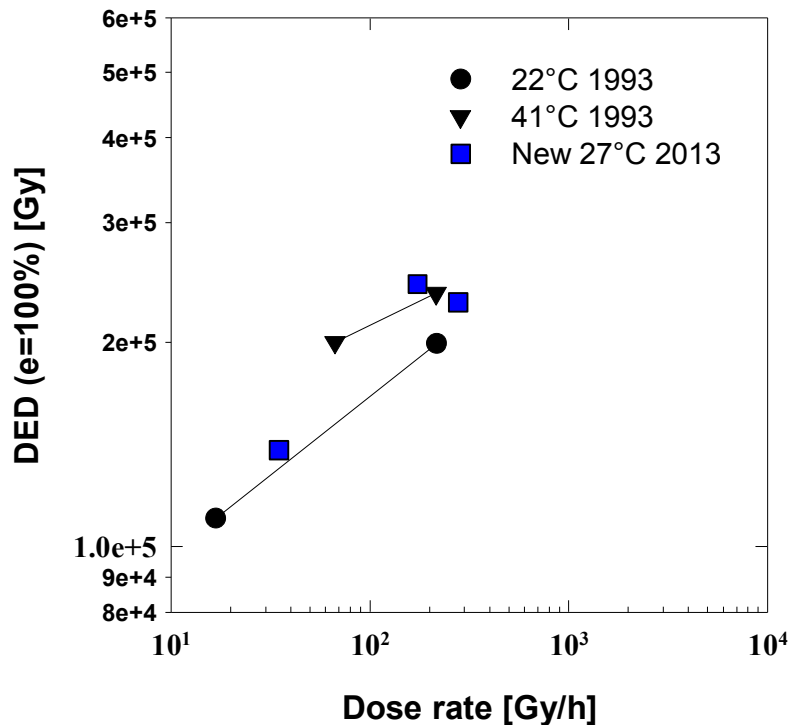

Continue to focus on one or two XLPO, plus perhaps one EPR material as before and supplement with oxidation rates

Historical Analysis

Temp (°C)	Brandrex XLPO	Rockbestos XLPO, black, green and red	Anaconda Durasheeth EPR
50	O	O	O
64		O	
65	O		O
80	O	O	O
95	O		O
99	E		E
100	O	O	E, TS, D, M, O
109	E, O	E, TS, O	E, O
110			E, TS, D, M, S, G
124	O	E, O, NMR$_{green}$, TS	E, O
125	E		E, TS, D, M, S, G, O
138	O	E, O, D, S$_{green}$, G$_{green}$	
140			E, TS, D, M
150	O	E, TS, O	O
151		E, D, S, G (all green)	
160		E	

SNL continues to examine historical data in their effort to finalize thermal-oxidative aging work

**Spatially-Resolved Degradation Models**
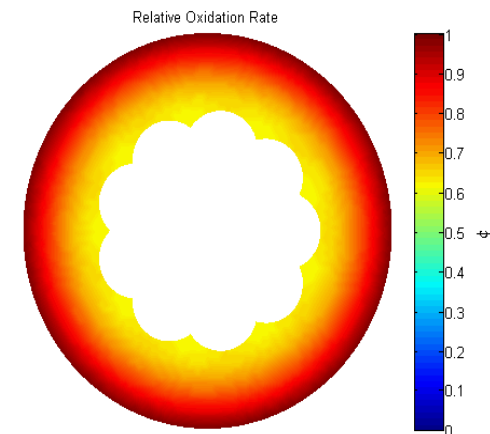
E = elongation
O = Oxidation Rates (estimated
P = Oxygen Permeation Rates
D = density
S = solvent uptake
NMR = T$_2$ NMR relation
G = % Gel
M = modulus, indenter
TS = tensile strength

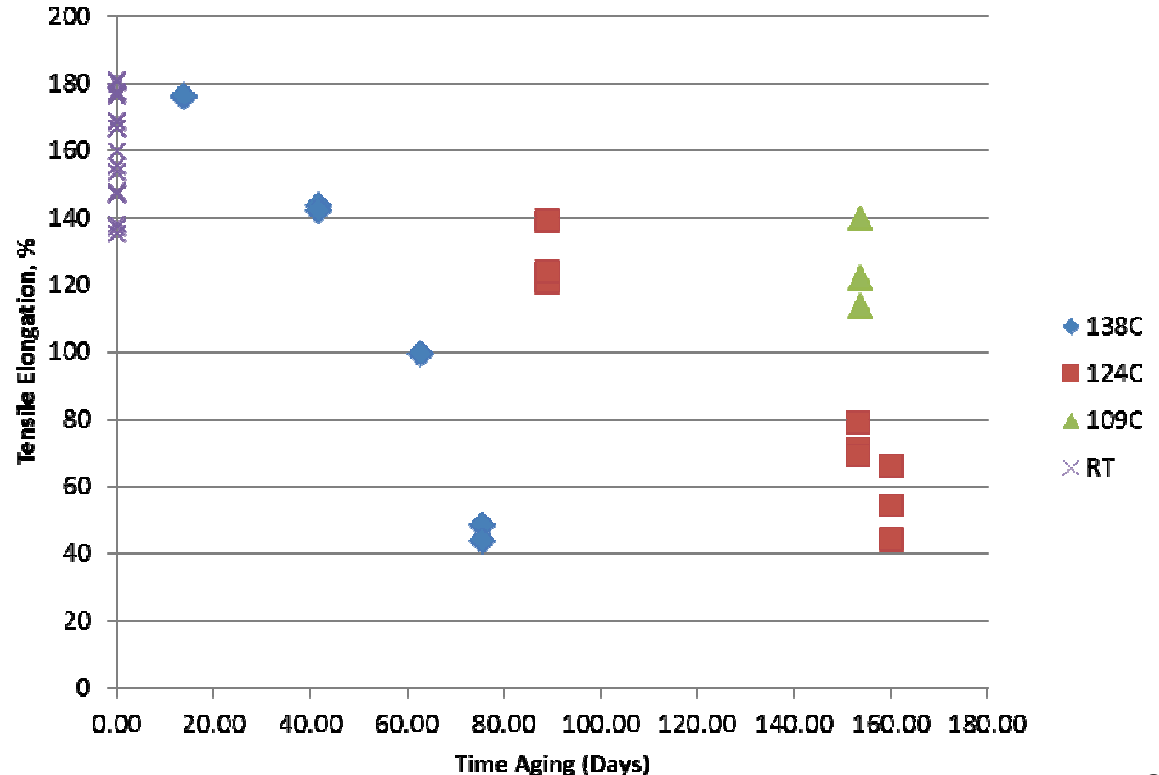Relative Oxidation Rate

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Collaboration with PNNL

- Generated aged samples to assist PNNL with rejuvenation efforts
  - Aged samples (~4 data sets) to be shipped in the next two months to PNNL
  - Effort is ongoing → lower temperature samples aging in progress

**PNNL-aged sample**

DLO evident

Virgin (left) vs. Aged (right)

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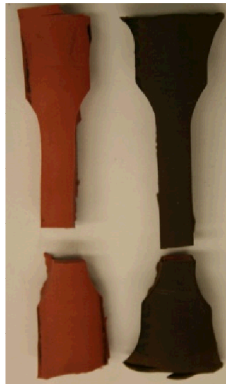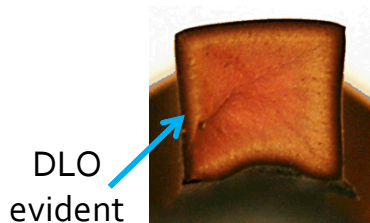
Gamma Irradiation Facility Updates

- Upgrade facility to conduct thermal-radiation experiments - provides unique critical ability to simultaneously expose materials to thermal and irradiation environments

  - Included updated electronics for irradiation experiments to enhance safety

  - Experiments will be more representative of field-aged conditions, resulting in improved models for predictive aging

- Estimated completion: Spring 2014

RAD
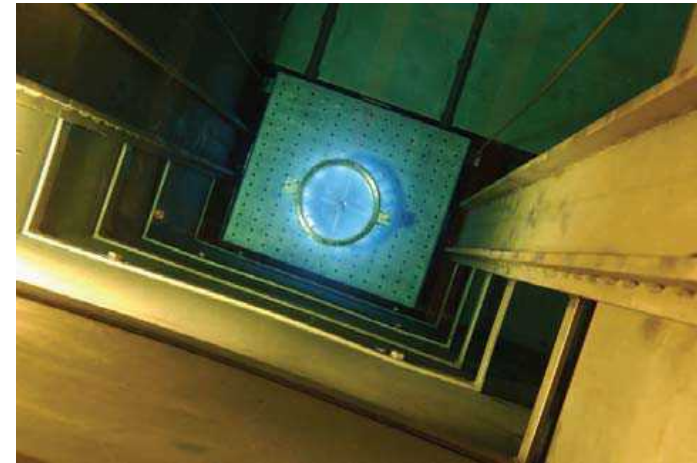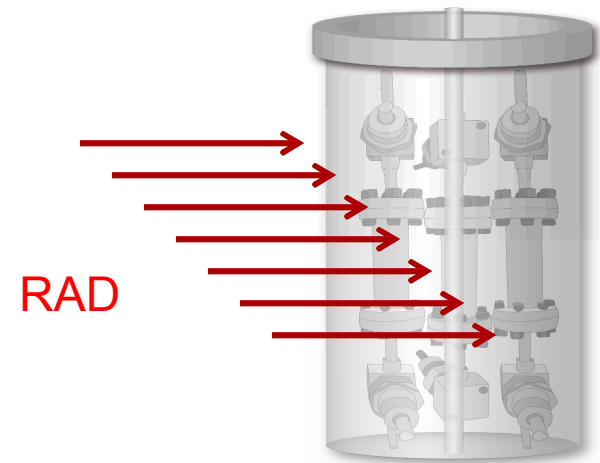
SNL FY14 Summary Status

- Extensive effort by SNL (with community input: EPRI, NRC, PNNL) to support cable requalification
  - Understand current cable insulation material state and expected performance sufficiently well to enable joint decisions with EPRI and NRC for cable requalification or replacement recommendations
- On-going Effort for Acquisition of Field Returned Samples
  - Preference is:
    - Brandrex XLPO with Hypalon Jacket
    - Anaconda Durasheeth EPR, it may likely also have a Hypalon jacket
- HIFIR Incident Cable Samples Analysis Report
  - Experiments completed. Documentation of studies underway from evaluation of HIFIR field return samples
- Argentinian Silicon Cable Radiation Aging Evaluation Report
  - Experiments completed. Collaboration with CNEA completed. Drafting final report
- LICA Experimental Apparatus Radiation Exposure - Location Memo
  - Memo discussing irradiation method and concerns, close to completion

Enhanced Level of Detail

- The following slides provide an enhanced level of detail to cover the work scope of SNL.
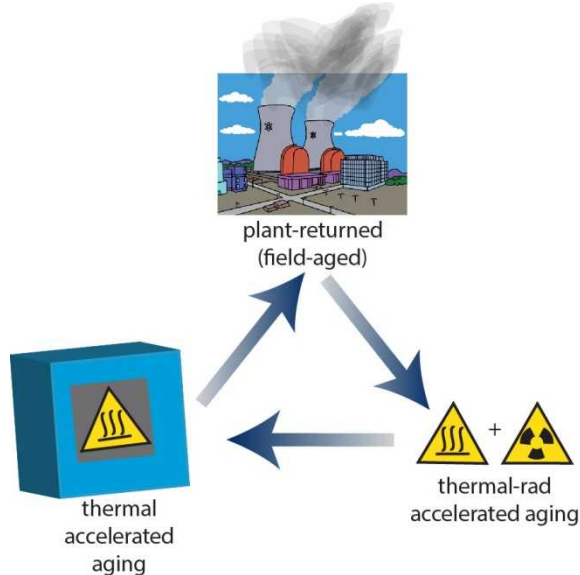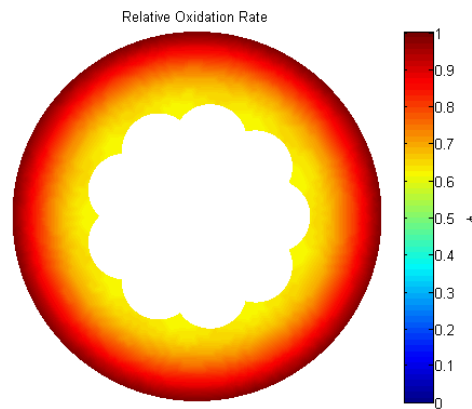
Sandia Vision
Supporting LWRS Requalification Efforts

- **<u>The ultimate goal</u>**:
  - Understand current cable insulation material state and expected performance sufficiently well to enable joint decisions with EPRI and NRC for cable requalification or replacement recommendations
- Deliver science-based engineering solutions
- Provide best guidance for aged material state, remaining life and expected performance
- Combine generic engineering tests with best practices from polymer degradation science
- Develop improved lifetime predictions models which incorporate known material behaviors

Material Aging Correlations

plant-returned (field-aged)

thermal accelerated aging

thermal-rad + accelerated aging

Spatially-Resolved Degradation Models

Relative Oxidation Rate

Surface vs bulk degradation

Lifetime Predictions

New cable + accelerated thermal aging predicts 100 year lifetime

Plant-harvested cable + wear-out aging predicts 30 year lifetime!

Time to 100% elongation [yr]

140°C   110°C   80°C   50°C   25°C

Temp^{-1} [10^{-3} K^{-1}]

Loss in tensile properties is used as a failure criterion

12
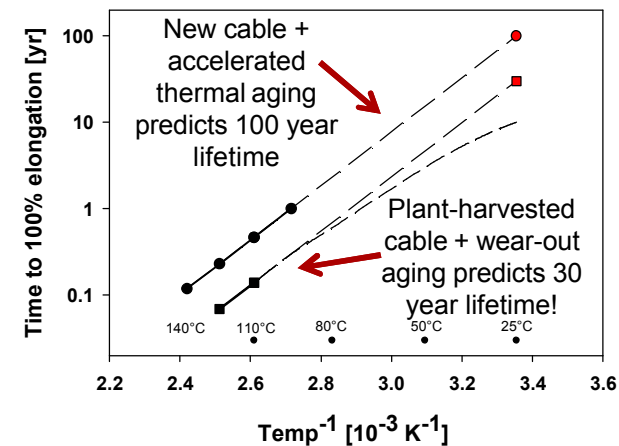
Key Strategies

- Conduct Wear-Out aging studies on field returned cable specimens
  - Assess current aging state where possible
- Develop better predictive aging models which include long term low dose rate low temperature aging phenomena
- Enhance feedback from engineering tests by critically examining data and through application of polymer aging science
- Reduce uncertainties in lifetime predictions by understanding unusual and complex material behavior, deconvolute data where possible
- Incorporate specific cable material behavior as an integral part of lifetime prediction
- Couple experimental strategies with suitable aging and predictive models
- Develop aging models for multi conductor cable assemblies (insulation plus jacket)

- Note: The SNL material science and testing efforts may need to be adjusted based on exptl. feedback and observed material behavior. Tasks may have evolving emphasis as this project progresses subject to expert SNL opinions. This R&D effort will be conducted within published DOE guidelines for research integrity and a sound science and technology base to help guide the nation's critical public policy decisions.

SNL Support to Requalification Efforts

- **Thermal aging only (FY14-15)**
  - Review of existing data and lifetime predictions FY14
  - Conduct exptl. gap-filling work FY15
  - Improved prediction by understanding aging parameters and using feedback from wear-out aging of field returned samples FY15
  - Provide guidance for cable assemblies using spatial degradation models FY15
  - Final report with recommendations for projected lifetimes and constraints FY15

- **Thermal-rad aging of EPR and non-inverse T effect materials (FY15-17)**
  - Review of existing data (dose, temperature) and lifetime predictions FY14
    - Verification checks for E_a, dose rate effects, etc. FY14-15
  - Complete existing (gap-filling) and new high dose rate data FY15
  - Obtain low dose rate data and develop predictive models using feedback from rad-thermal degradation behavior of field returned specimens FY16
  - Final report with recommendations for projected lifetimes and constraints FY17

- **Thermal-rad aging of XLPO and some EPR inverse T effect materials (FY15-18)**
  Note: This group represents the most complex situation!
  - Review of existing data and basic lifetime projections (dose rate, dose, temperature effects) FY15
    - Verification checks for E_a, dose rate effects, etc. FY15-16
  - Complete existing and new high dose rate data FY16
  - Obtain low dose rate data and develop suitable models using feedback from rad-thermal of field returned specimens FY17
  - Final report with recommendations for projected lifetimes and constraints FY18

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SNL Support to Requalification Efforts

- **Thermal aging only (FY14-15)**
  - SNL will consolidate existing thermal aging data and extent with gap filling data sets where possible
  - These aging behaviors are to be compared with wear-out behavior (field returned samples)
  - RISK: If field returned specimens are not available, projections cannot be verified
  - IMPACT: Final report with best estimates for projected residual lifetimes and uncertainties FY15

- **Thermal-rad aging of EPR and non-inverse T effect materials (FY15-16)**
  - SNL will review existing data (dose, temperature) for predicted lifetimes
  - These aging behaviors are to be compared with wear-out behavior (field returned samples)
  - RISK: Field returned specimens are needed to validate predictive models
  - IMPACT : Final report with best estimates for projected lifetimes and uncertainties FY17

- **Thermal-rad aging of XLPO and some EPR inverse T effect materials (FY15-18)**
  Note: This group represents the most complex aging situation!
  - SNL will review existing data and extent with new accelerated aging experiments
  - These aging behaviors are to be compared with wear-out behavior (field returned samples)
  - RISK: Field returned specimens are needed to validate predictive models
  - IMPACT : Final report with best estimates for projected lifetimes and uncertainties FY18

SNL aging experiments, predictive models and correlations with field returned cable materials will enable best residual lifetime projections and consensus decisions (NRC/EPRI) about requalification

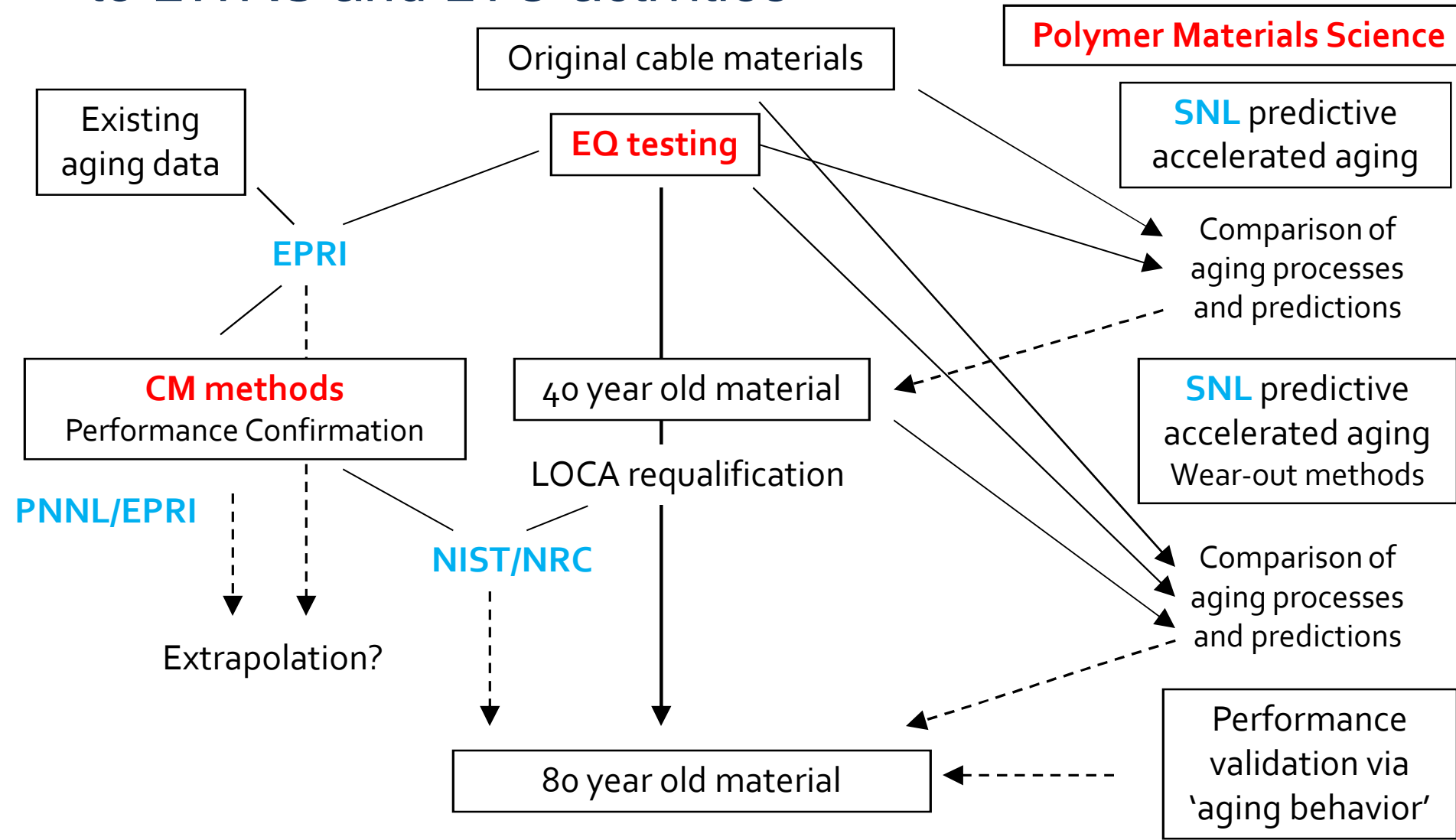# Field returned cable specimens

- **Critically important!**
  - The need for field returned specimens of all three groups with known environmental conditions and exposure history

- **Cable preferences:**
  - Returned cables should address thermal and rad-thermal conditions
  - Materials should display regular and inverse T behavior (some EPR, XLPO)
  - Exposure history should be known as best as possible (T, dose rate, dose)
  - Thermal could be any temperature but higher temperatures are better
  - Rad-thermal should involve high doses at 20-50°C
  - Initial studies should focus on one XLPO and EPR for thermal, thermal-rad
  - We suggest initially Brandrex XLPO and Anaconda Durasheeth EPR

SNL Engagements with Cable Aging Community

- **FY14:** SNL report for HFIR and CNEA, aged samples for PNNL CM methods

  (Note: these are not full requalification studies, but single point data suggesting some life)
- **FY14-15:** Work with EPRI and Oakridge in acquiring some field aged cables
- **FY14-FY18:** Assist EPRI with material science understanding of cable failures
- **FY14-FY18:** Provide the LWRS effort with a material science based framework to deliver engineering solutions for cable aging and requalification
- **FY15:** Provide guidance to NRC on expected correlations of NRC/NIST accelerated cable aging for LOCA requalification with plant conditions
- **FY15:** Assist EPRI with interpretation of SCRAPS data, identification of knowledge gaps
- **FY16:** Assist EPRI and PNNL with CM data interpretation
- **FY17:** Provide best estimation of aging states for NRC/NIST LOCA cables

SNL – Materials Aging Science contributions to LWRS and LTO activities

Polymer Materials Science

Original cable materials

Existing aging data

EQ testing

SNL predictive accelerated aging

EPRI

Comparison of aging processes and predictions

CM methods
Performance Confirmation

40 year old material

SNL predictive accelerated aging
Wear-out methods

PNNL/EPRI

LOCA requalification

NIST/NRC

Comparison of aging processes and predictions

Extrapolation?

80 year old material

Performance validation via 'aging behavior'

SNL offers a critical perspective of materials aging behavior to support CM and EQ
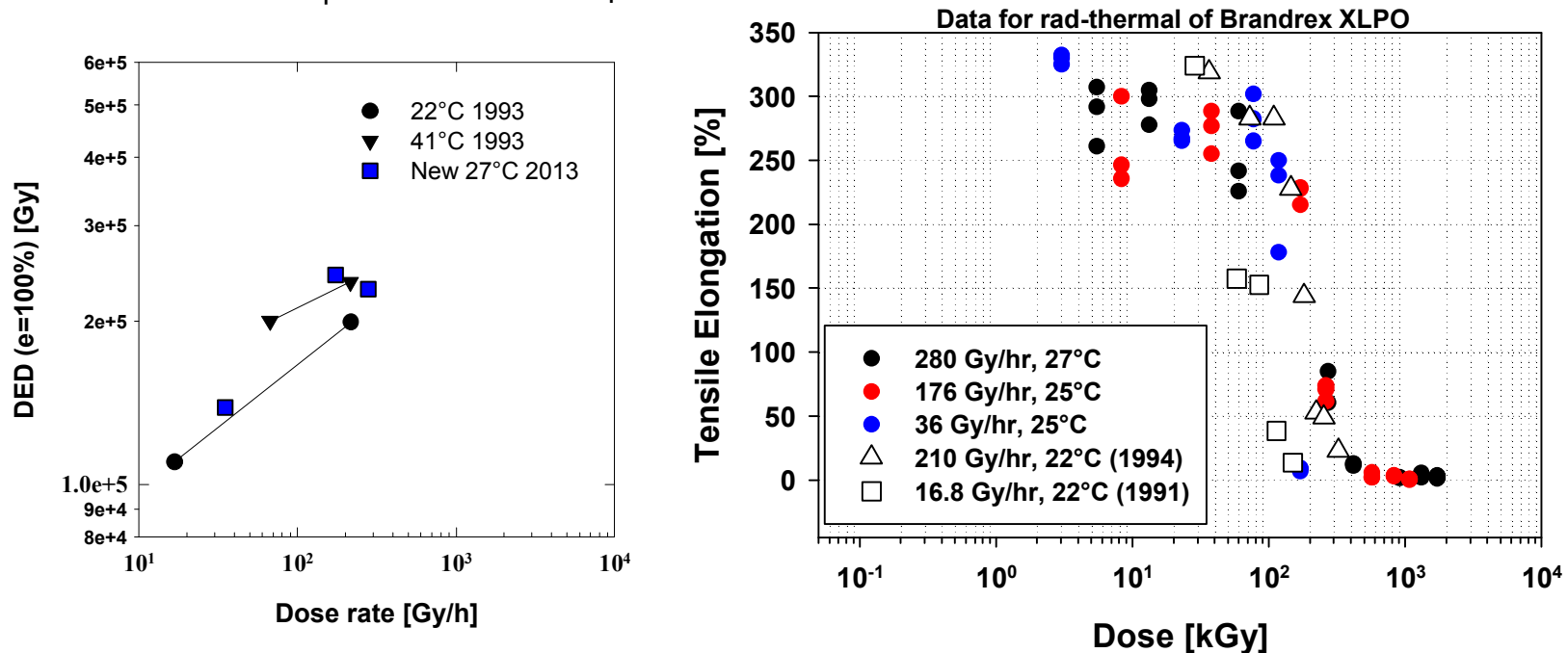
SNL Tasks for FY14

1. Liaise with other parties (EPRI/NIST/PNNL/NRC) and push for a consensus on what is needed in predictive cable aging work
   - EPRI need: Support with identification of gaps in SCRAPS database. A better understanding of inverse temperature and CM-relevant material behavior
   - Sandia contribution: Details were discussed at Phoenix meetings and consensus was reached between attendees (EPRI/NRC/PNNL/SNL)
   - Next face-to-face meeting will be at Sandia in July

2. Reestablish LICA operation so that thermal-rad experiments can be conducted. Commence extensive low dose rate aging experiments with oxidation rate measurements at two temperatures (perhaps 27/40 and 80°C) to cover IT anomaly.
   - Operational LICA is necessary to conduct thermal/rad experiments
   - Data collected from thermal-rad experiments will be used in predictive aging models which will provide guidance for cable lifetimes and subsequent lifetime extension efforts
   - Focus on oxidation rate measurements to develop extrapolations in dose rate models
   - Timeline: Begin experiments by end of March 2014 and continue throughout FY14 and beyond

New LICA Heater Set-Up

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SNL Tasks for FY14

3. Rad-thermal: Consolidate and evaluate previous work for trends and future property cross-correlations. Continue to focus on one or two XLPO, plus perhaps one EPR material as before and supplement with oxidation rates. Consider other materials if EPRI/NIST/NRC have different priorities.

   - Constraints with cans and size of LICA limit the amount of materials we can investigate at once.
   - Oxidation rate measurements compete with tensile and wear out experiments. XLPO and EPR are common insulation materials with XLPO and some EPR materials exhibiting IT behavior
   - Thorough characterization of the materials, including testing for known potential anomalies
   - Timeline: present to end FY14

Data for rad-thermal of Brandrex XLPO

SNL Tasks for FY14

4. Acquire field aged specimens for condition monitoring work and wear-out testing.
   - Wear-out aging studies will be used to predict remaining lifetime in field-aged cables. Thermal only experiments will be conducted first to address thermal degradation behavior for residual lifetimes.
     - Request was given for specific field-aged materials, although we will take anything.
   - In conjunction with accelerated aging studies (#2) this will provide a higher level of confidence on lifetime predictions for license renewal.
   - Timeline: Acquire specimens as soon as possible to be complemented throughout this project

5. Complete radiation location memo, HFIR report, and Argentinian report
   - Will be completed in FY14
   - Reports will formally document work done

6. Review previous literature data for thermal and thermal-rad conditions Complement thermal aging with ox-rate data (where needed) which will help in the preparation of a future document on thermal aging predictions
   - Thermal only to be completed by the end of FY14 to establish where gaps exist
   - Thermal-rad is ongoing, with an emphasis on multiple materials with different behavior
   - Final thermal aging summary to be completed by the end of FY15-16

SNL Tasks for FY14

7. Assist PNNL in their rejuvenation program
   - SNL will provide assistance to the rejuvenation program via sample preparation as well as technical discussion on methods
   - PNNL samples subjected to accelerated aging and will be sent to PNNL for rejuvenation studies
     - 5 aging exposures completed thus far with 9 samples at each condition (3 for SNL, 6 for PNNL)
     - SNL is trying to quantify DLO in these samples, because it could affect PNNL CM data interpretation

PNNL-aged sample

DLO evident
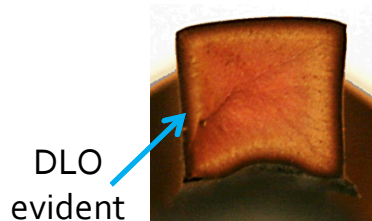
Virgin (left) vs. Aged (right)
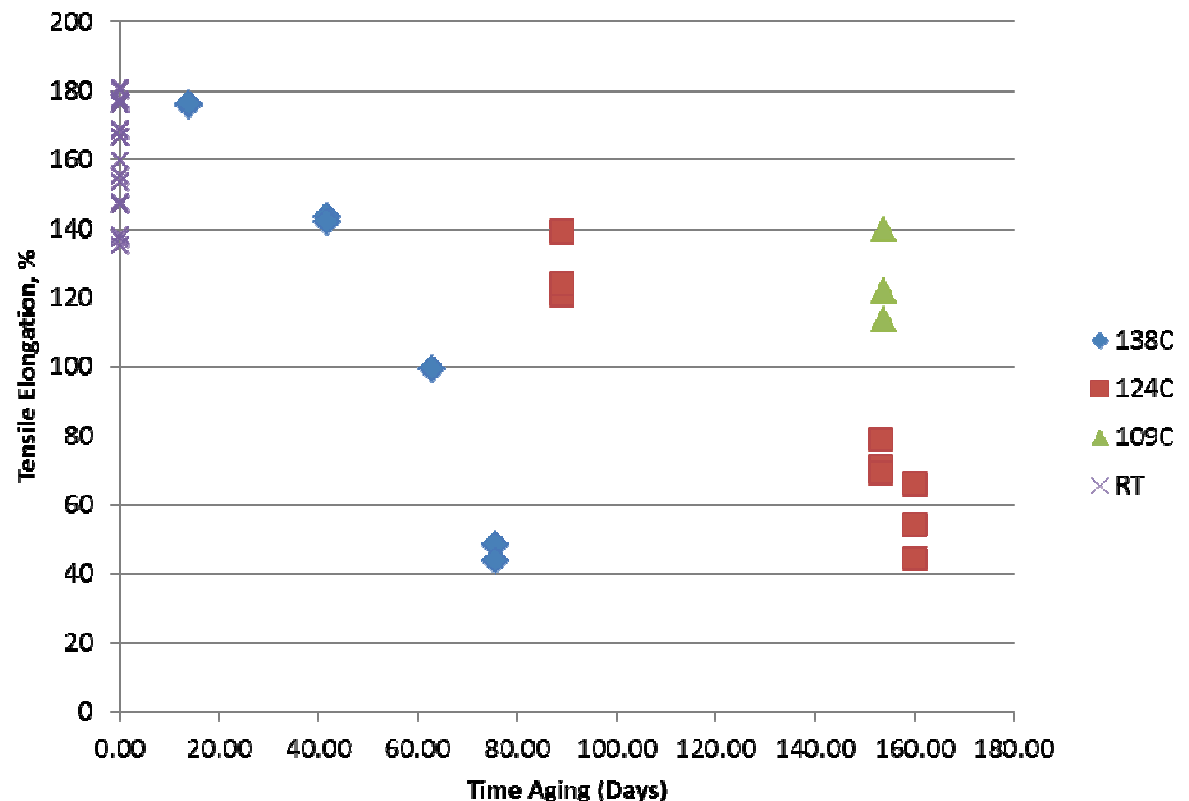
Wear Out Aging

- **Goal: Establish remaining life by determining the fractional aging state**

- Wear out aging should have predictive value which is obtained by trend analysis in multiple data sets

- If single point aging is conducted it should be coupled with guidance from existing aging data or a clear understanding of material behavior

Schematic of wear-out aging under thermal conditions
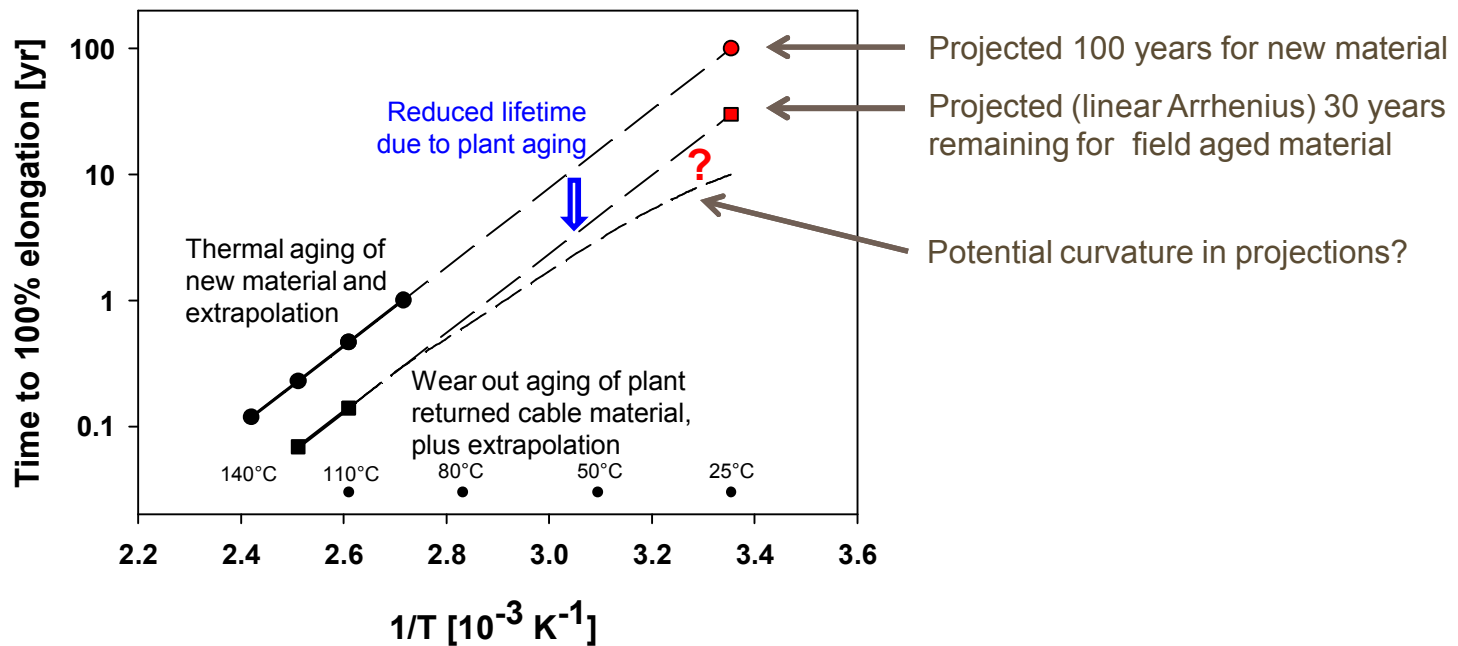
*Wear out aging requires material behavior and reference data, and assumes similar E_a

Original EQ vs. Plant Aging

Goal: Develop a model capability to predict localization of oxidative damage in a cable assembly. This requires individual oxidation rates and O_2 permeation

- Cable degradation behavior depends on local rates which can differ between surface and bulk depending on aging conditions
- DLO is the phenomenon which introduces variations in behavior
- It can happen under thermal and rad-thermal conditions
- This also affects measurements of ox-rates and CM approaches
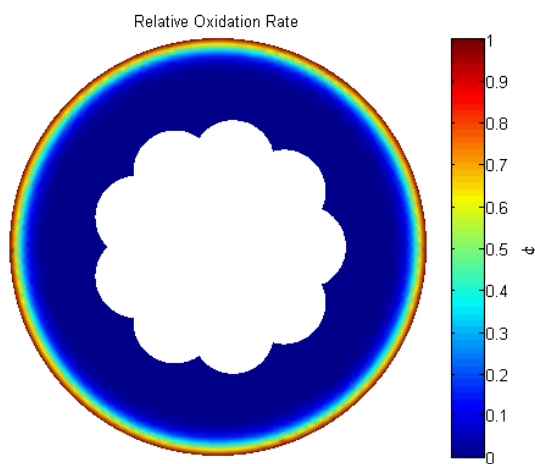
Surface oxidative degradation is likely under EQ testing IEEE323-1974
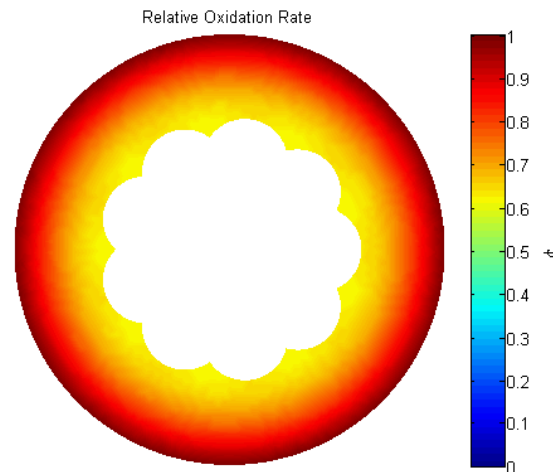
Accelerated rad-thermal conditions, which can apply to NIST/NRC LOCA requalification
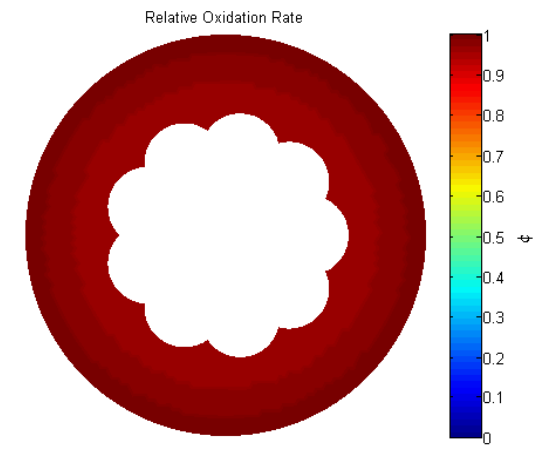
Homogeneous aging expected under plant conditions

Uncertainties due to Inverse T Effects in Rad-Thermal Aging

Goal: Better understanding of aging phenomena and development of lifetime prediction models for cable materials with inverse temperature phenomena
- Inverse T phenomena prevent traditional Arrhenius extrapolations
- This has also implications for the assessment of field-returned samples
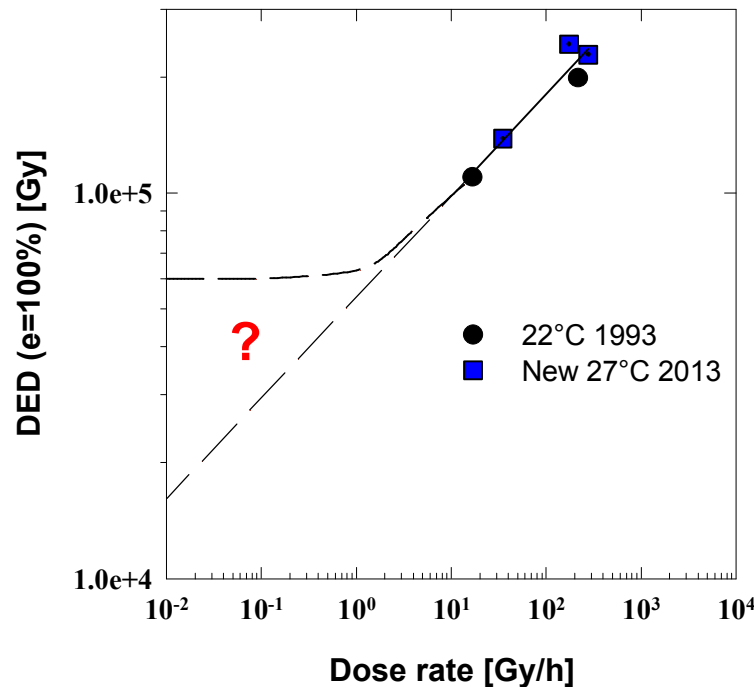

Data for rad-thermal of Brandrex XLPO
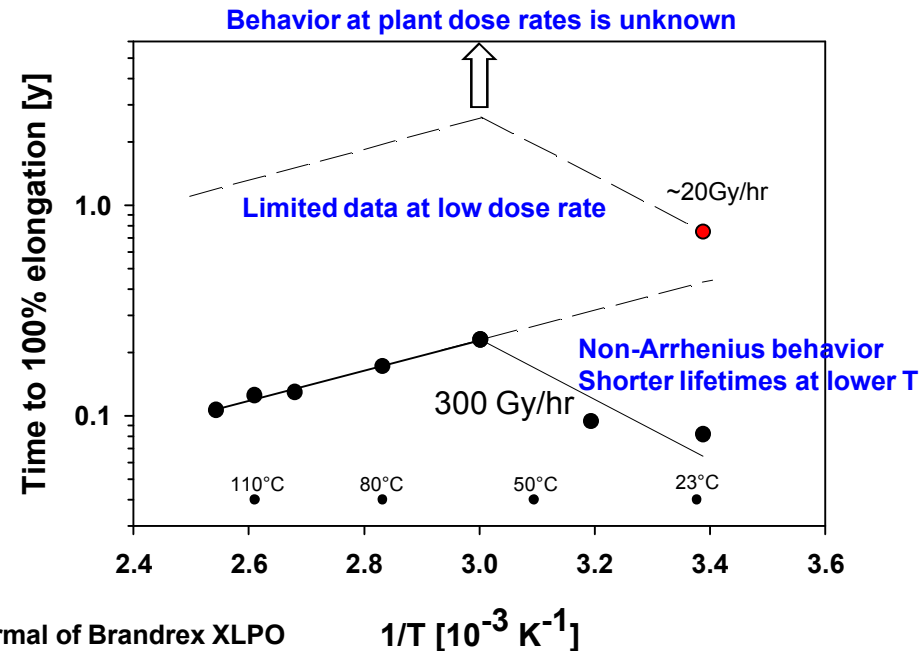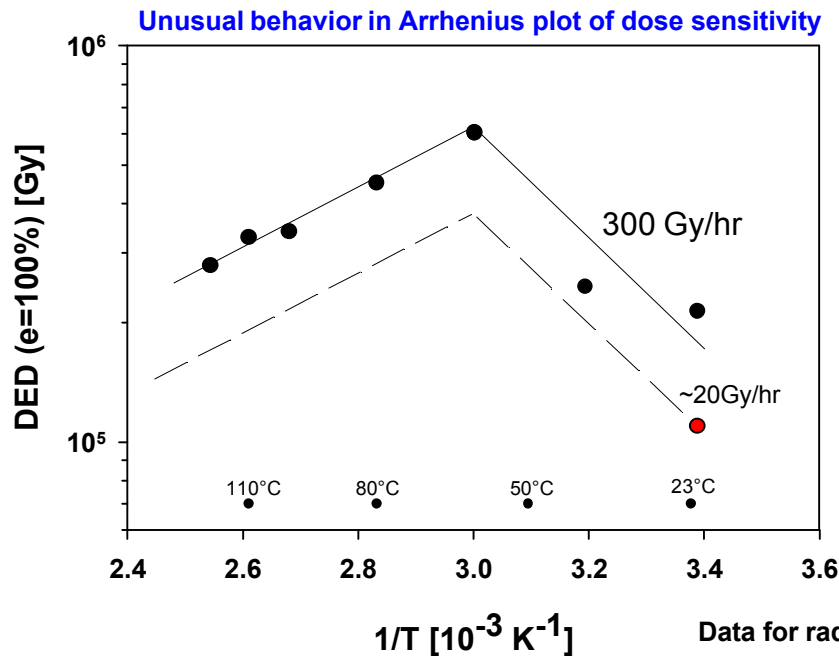
Risk: margins for inverse T behavior under plant conditions are not known because material behavior under low dose rate conditions have not been studied sufficiently!

Uncertainties due to unknown aging behavior at low dose rate conditions

Goal: Conduct oxidation rate measurements as guidance for aging behavior at low dose rate conditions. Data for aging rates at low dose rates do not exist.

- Predictive models depend on clarification of low dose rate trends, i.e. curved versus linear extrapolations
- Field-aged specimens would help validate predictions if similar rates are maintained

Data for rad-thermal of Brandrex XLPO

- **New SNL data from 2012/13 corroborate existing data sets (1993)**

- **At lower dose rates lower dose to equivalent damage are observed**

- **This is due to a balance between radiation and thermally driven degradation**

- **Exact transitions to thermal only behavior are unknown**

- **Extrapolations require some justification for better aging models**