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Sandia National Laboratories

SNL Updates on Cable Aging Work

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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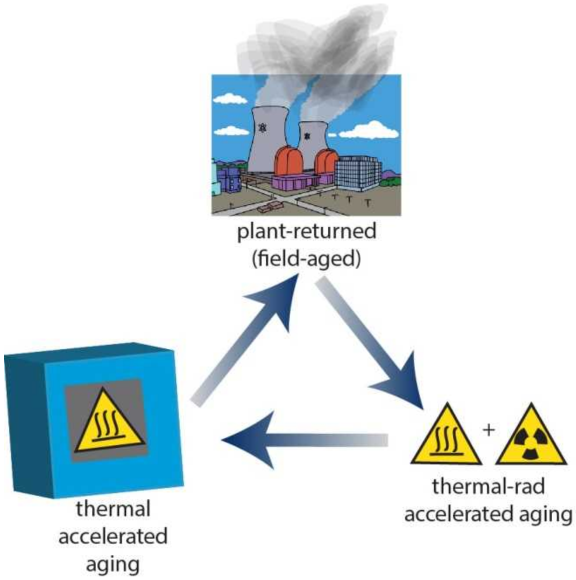
SNL Cable Aging Project Overview

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

Material Aging Correlations

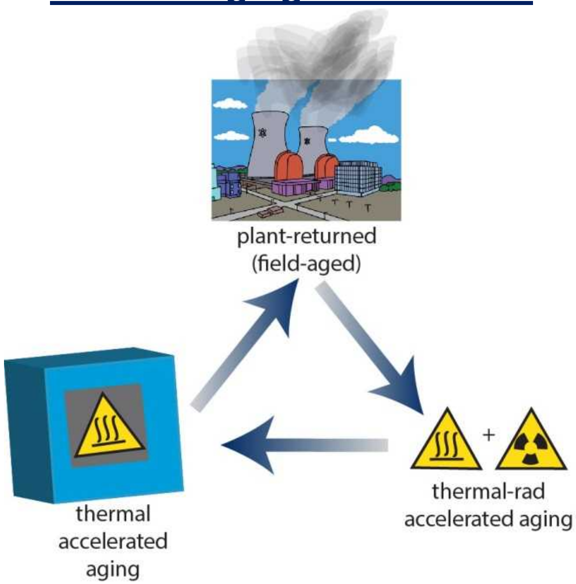


Sandia Vision Supporting LWRS Requalification Efforts

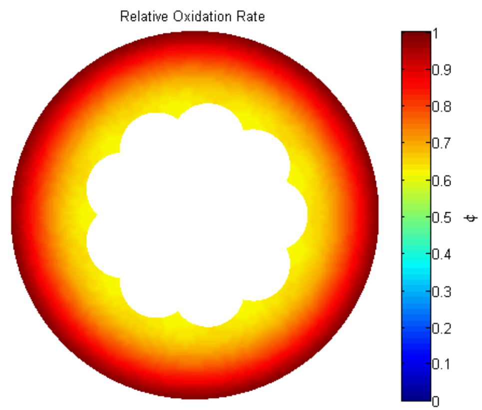
Sandia National Laboratories

- 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

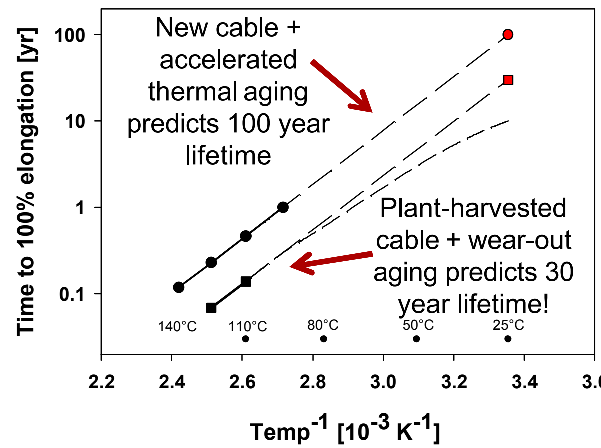


Spatially-Resolved Degradation Models



Surface vs bulk degradation

Lifetime Predictions



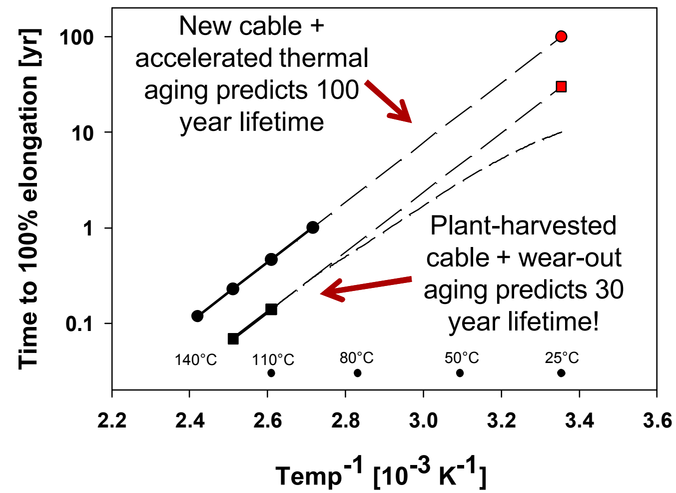
Loss in tensile properties is used as a failure criterion

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
- Development of enhanced predictive models
- Validation of predictive models using field-returned materials

Lifetime Predictions



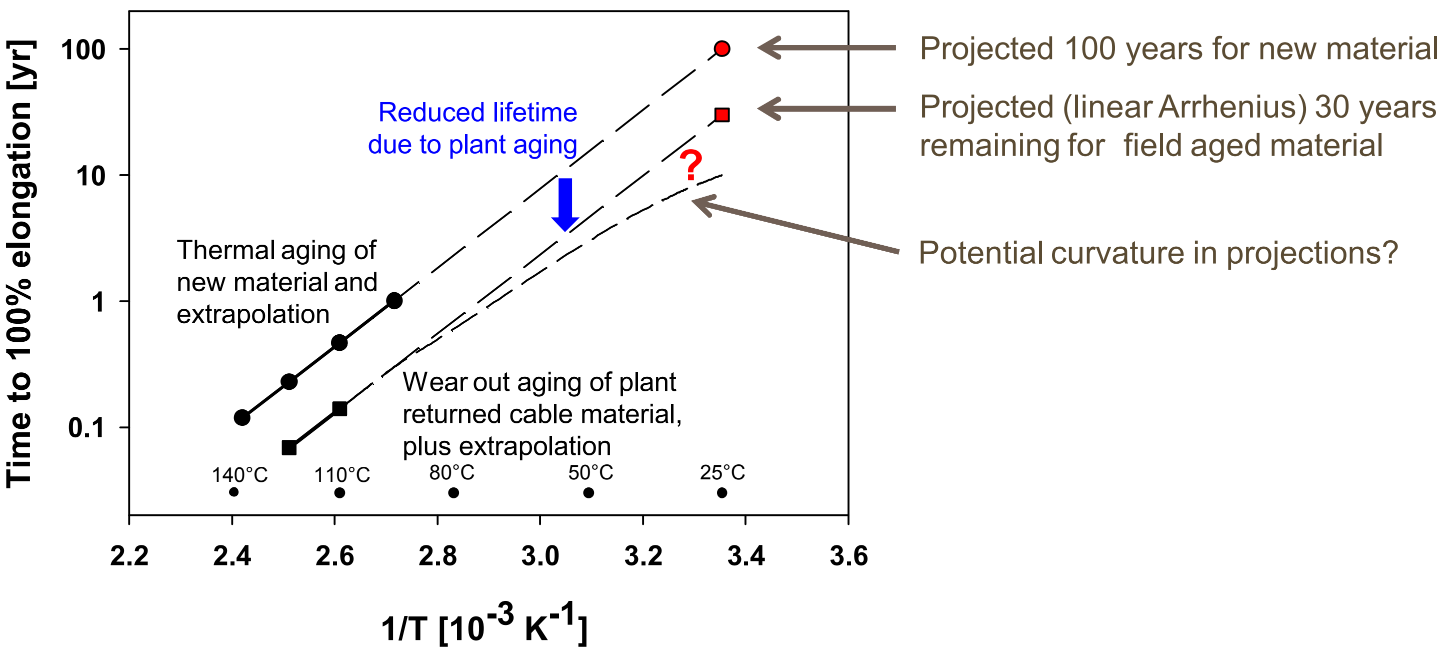
Loss in tensile properties is used as a failure criterion

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 wear out aging is limited to only one aging set, 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**

Field Returned Cable Specimens

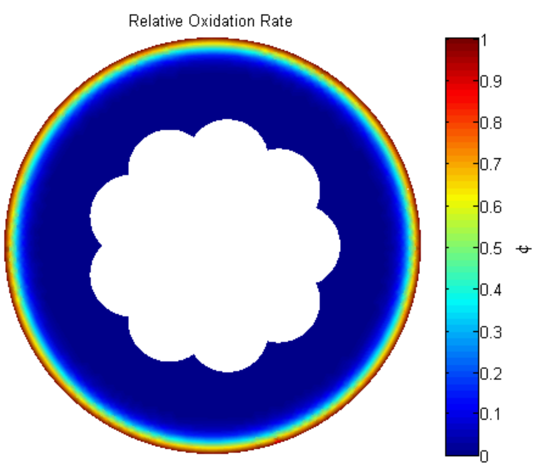
- Critically important!
  - The need for field returned specimens of all three groups with known environmental conditions and exposure history

- 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

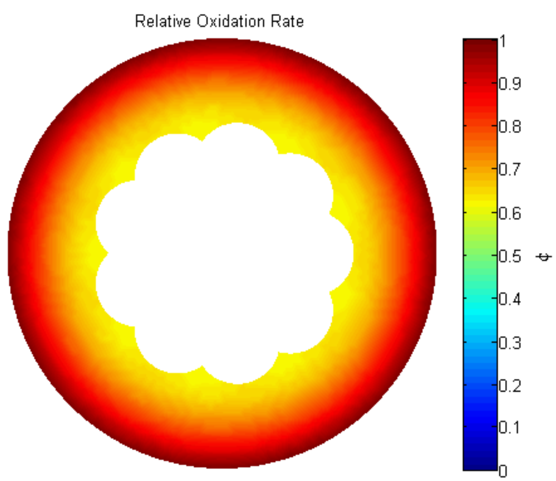
Original EQ vs. Plant Aging

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

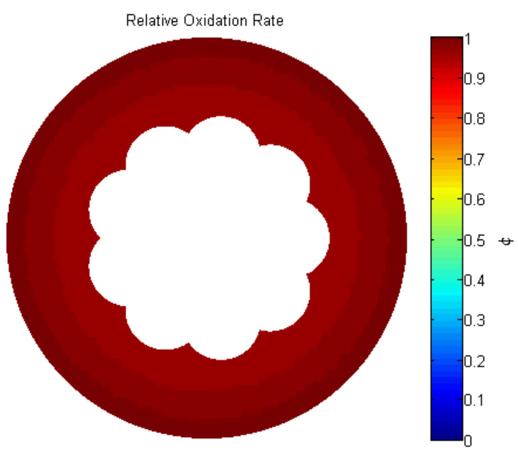
- Cable degradation behavior depends on local rates which can differ between surface and bulk depending on aging conditions
- DLO is the phenomenon which introduces variations in behavior
- It can happen under thermal and rad-thermal conditions
- This also affects measurements of ox-rates and condition monitoring approaches



Surface oxidative degradation is likely under EQ testing IEEE323-1974



Accelerated rad-thermal conditions, which can apply to NIST/NRC LOCA requalification

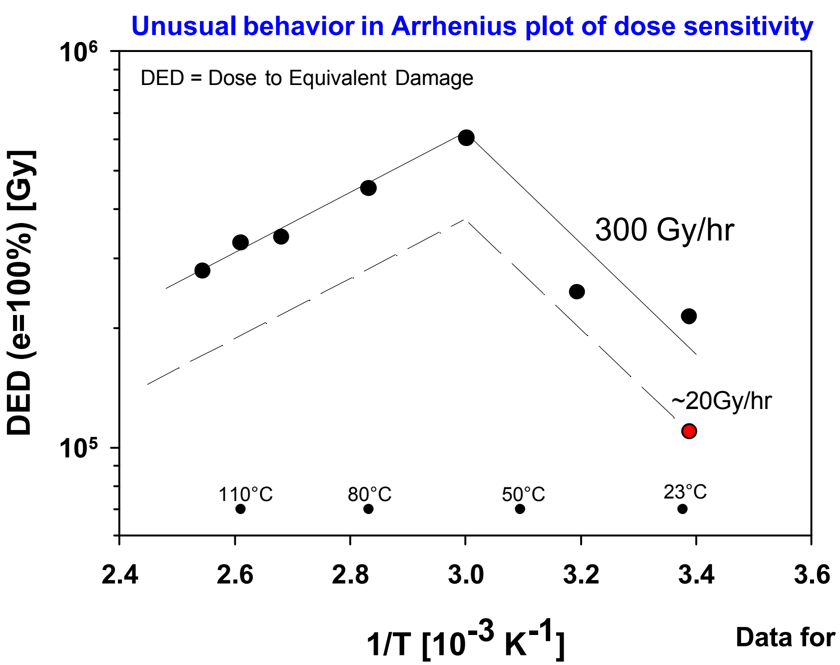


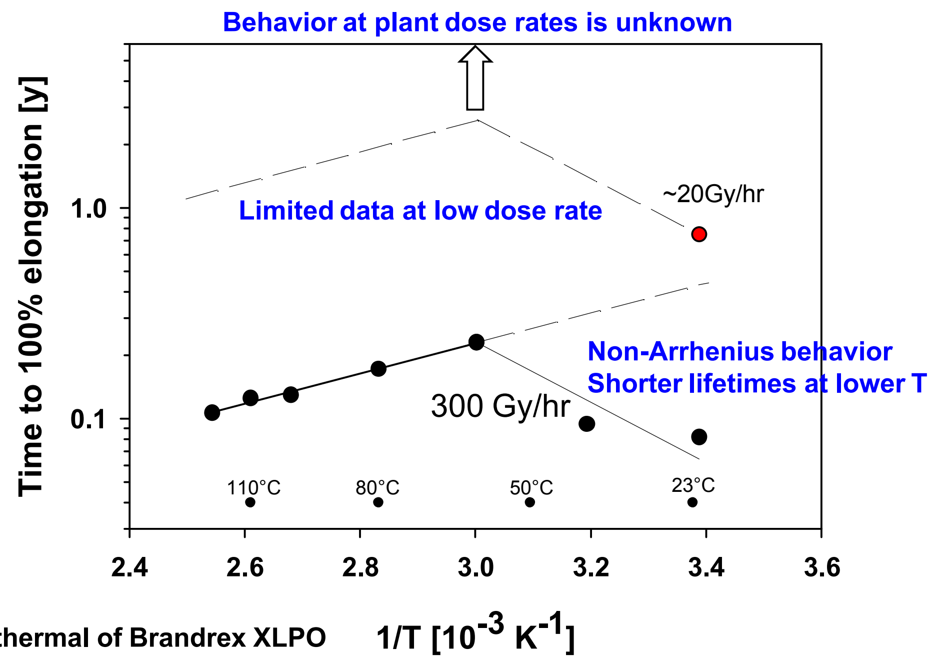
Homogeneous aging expected under plant conditions

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





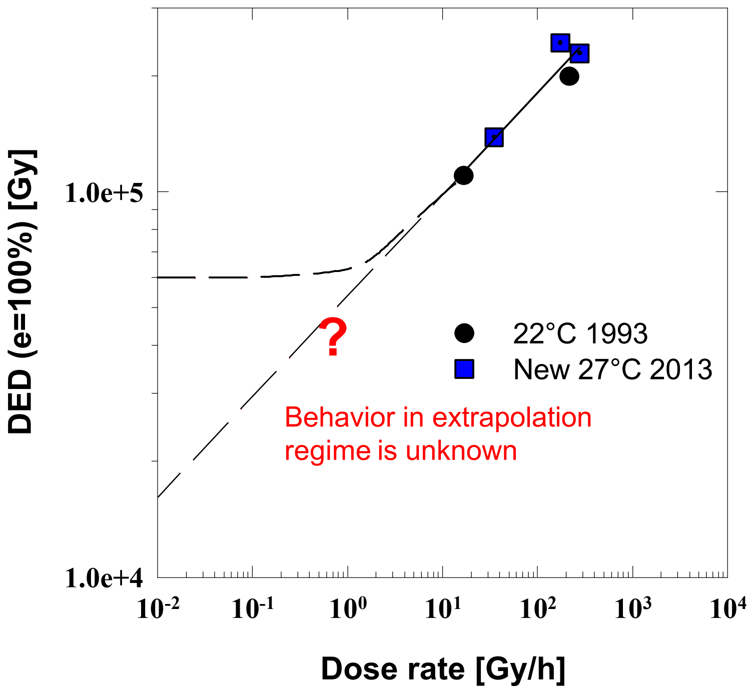
Data for rad-thermal of Brandrex XLPO

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)**
- **Lower dose rates are consistent with lower dose to equivalent damage (DED)**
- **This is due to a balance between radiation and thermally driven degradation**
- **Exact transitions to thermal only behavior are unknown**
- **Extrapolations require some justification using better aging models**

Justification

- The above testing (wear out aging, DLO, etc.) will help us to create better predictive models, which require an understanding of fundamental material behavior and aging mechanisms.

SNL Support for 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 EPR inverse T effect materials (FY15-18)**

  Note: This group represents the <u>most complex aging</u> 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

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 Tasks for FY14

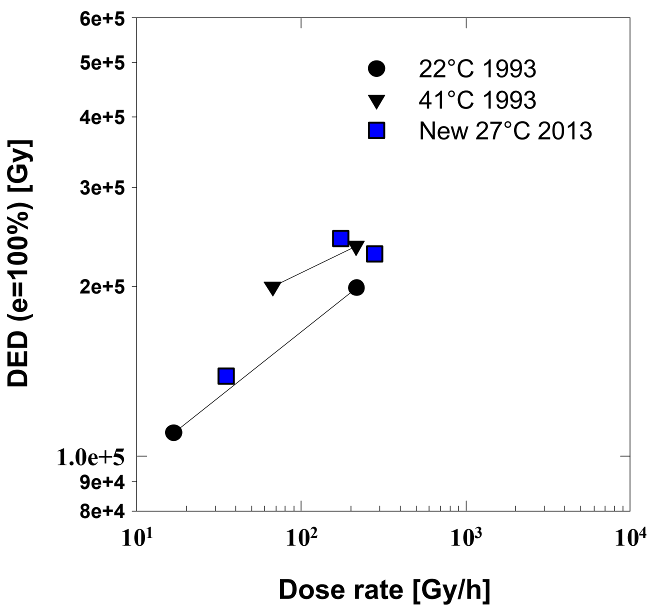
1. **Liaise with other parties (EPRI/NIST/PNNL/NRC) and push for a consensus on what is needed in predictive cable aging work**
   - EPRI need: Support with identification of gaps in SCRAPS database. A better understanding of inverse temperature and CM-relevant material behavior
   - Sandia contribution: 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

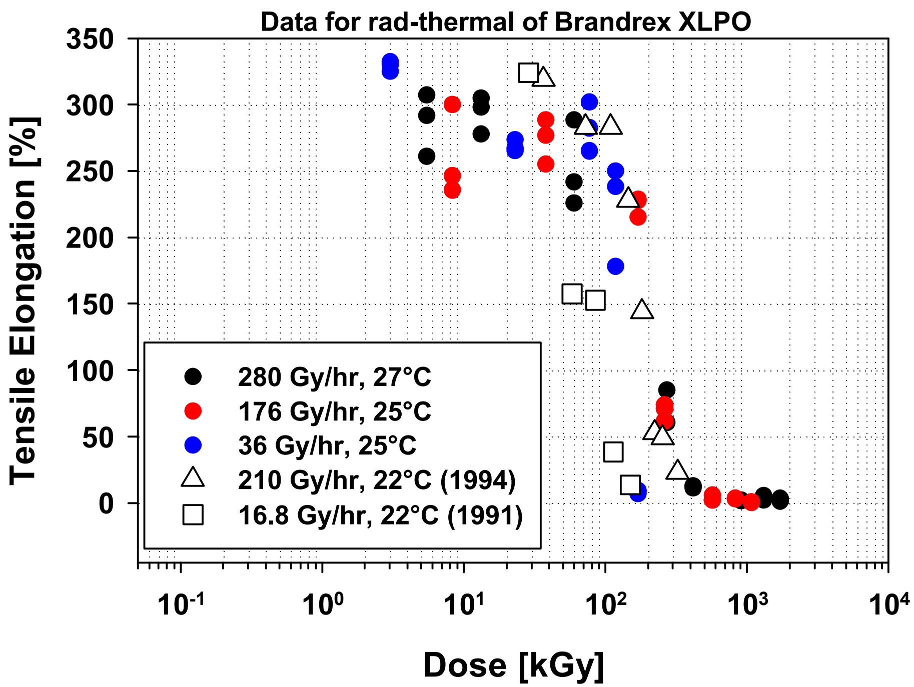
2. **Reestablish LICA operation so that thermal-rad experiments can be conducted. Commence extensive low dose rate aging experiments with oxidation rate measurements at two temperatures to cover IT anomaly**
   - Operational LICA is necessary to conduct thermal/rad experiments
   - Data collected from 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

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





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 Schedules, Milestones & Deliverables

Operations Activities (OA) Annual Work Plan	
Key Milestone/Deliverable	**Delivery Date**
Monthly Updates	Ongoing through FY14
Monthly Teleconferences	Ongoing through FY14
Deliver Aged Samples to PNNL	Ongoing through FY14
Acquisition of Field Returned Samples: Deliver table listing field aged samples desired, by cable type and environmental history	March 10, 2014
Power Point Presentation on SNL LWRS cable aging program for DOE NE Quarterly Program Review.	March 19, 2014
Support ORNL presentation to NRC on cable aging research to support life extension	April 10, 2014
LICA Experimental Apparatus Radiation Exposure Location Memo	May 10, 2014
LICA Operational	April 30, 2014
Initiate rad-thermal experiments in LICA	April 30, 2014
Joint LWRS-EPRI LTO Cable R&D Meeting hosted by SNL	July 9-10, 2014
Assist in preliminary analysis of degradation modes	August 31, 2014
Deliverables in MPO 4000128678, 01/14/2014	
Report detailing integration plan for joint cable research with EPRI and other stakeholders	April 11, 2014
HFIR Cable Samples Evaluation Report	July 16, 2014
Argentinian Silicon Cable Radiation Aging Evaluation Report	September 17, 2014
Year-End Summary Report	September 30, 2014

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

SNL Quarterly Highlights

- SNL schedules, milestones & deliverables
- Community interactions
- Historical analysis
- PNNL aging
- Irradiation facility updates
- Request for field-returned materials
- SNL path forward

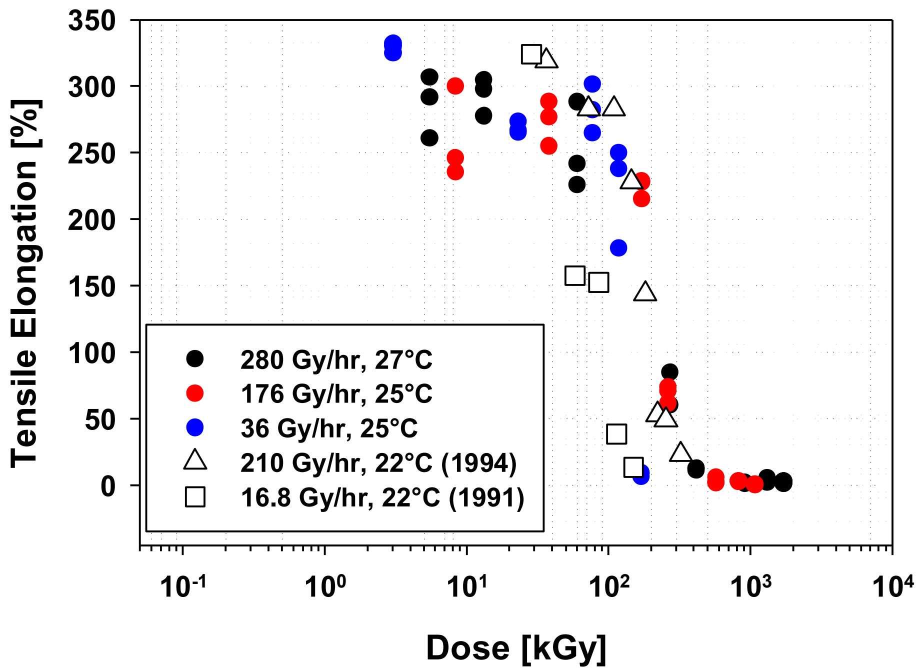
Building Consensus in predictive cable aging & Industry/Regulatory Interactions

- 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

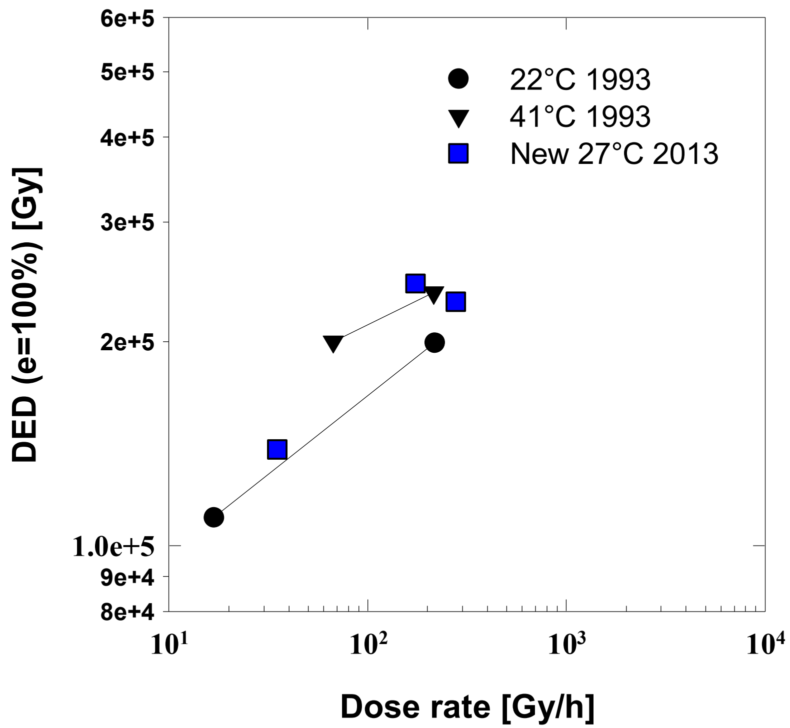
Brandrex XLPO LICA exposure

- **Consolidate and evaluate previous work for trends and future property cross-correlations**
  - Continue to focus on one XLPO and one EPR material, as before, where these tensile data must be correlated with oxidation rates for extrapolative purposes.
  - Data from 2012-2013 are in agreement with observed aging behavior from the 1990's.

Rad-thermal data for Brandrex XLPO

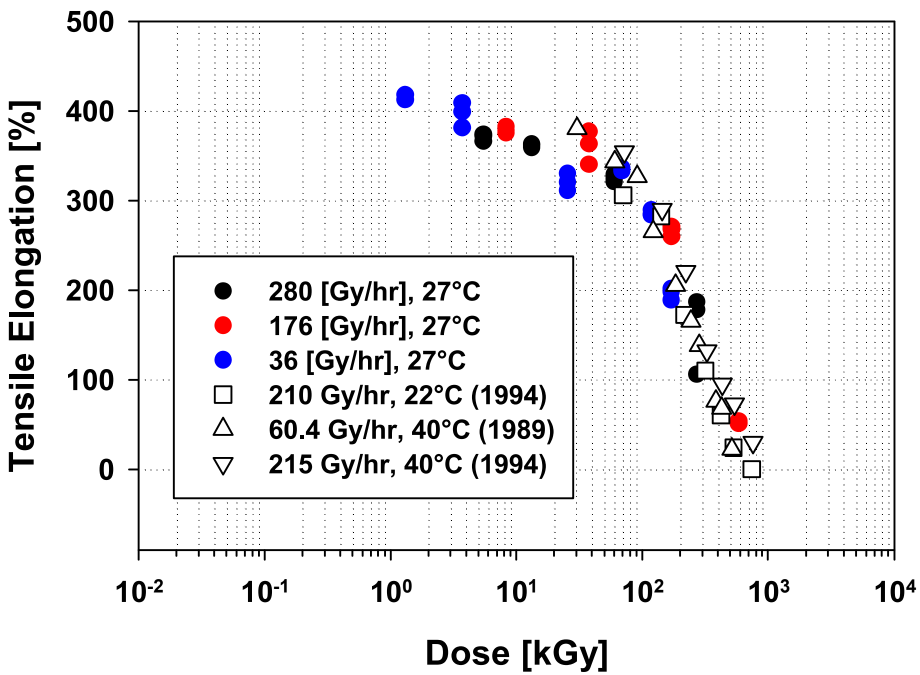


Corresponding failure doses for Brandrex XLPO



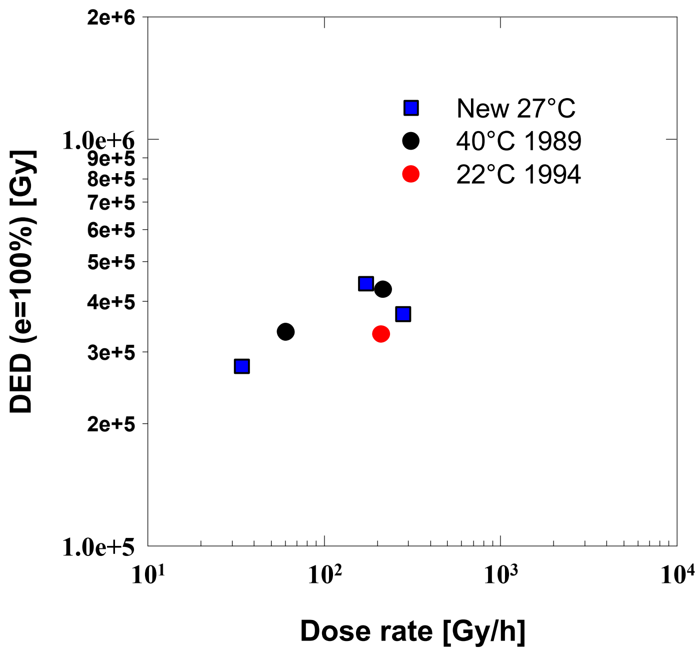
Eaton Dekoron EPR LICA exposure

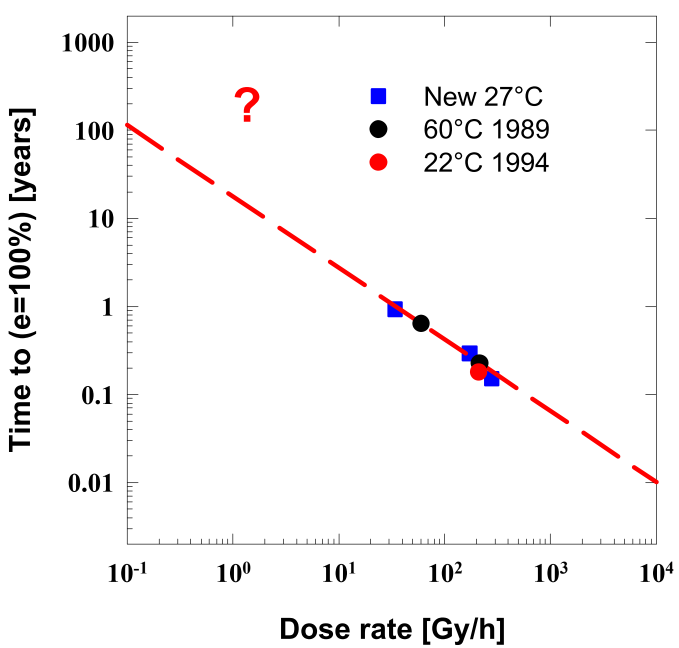
- **Comparison of rad degradation at low T, 1990s work and 2012-13**
  - As part of LWRS program Dekoron EPR tensile specimens were exposed at different dose rates
  - Lowest dose rate at 11 Gy/h has not yet yielded any loss in elongation
  - New 2013 data are in agreement with existing data sets from 1989 - 1994
  - The challenge of how to extrapolate to lower dose rate conditions remains



Eaton Dekoron EPR LICA exposure

- **Comparison of rad degradation at low T, 1990s work and 2013**
  - New 2013 data are in agreement with existing data sets
  - The challenge of how to extrapolate to low dose rate conditions remains
  - Significant extrapolations, is a linear approach realistic?
  - Both data sets have the same value for existing knowledge and identical challenges for future work
  - These data are only an overview and have not been T-dose rate superposed
  - Inverse temperature behavior is apparent in DED plot





Historical Analysis

- SNL continues to examine historical data in their effort to finalize thermal-oxidative aging work.
- Create a compilation of all available material characterization and aging data to identify gaps.
  - Fill gaps in known aging behavior
  - Use data for improved predictive models.

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	

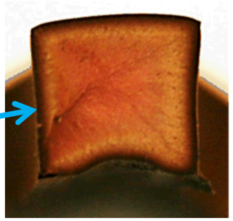
E= elongation
O = Oxidation Rates (estimated)
P = Oxygen Permeation Rates
D = density
S = solvent uptake
NMR = T_2 NMR relation
G = % Gel
M = modulus, indenter
TS = tensile strength

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 → aging of lower temperature samples is in progress

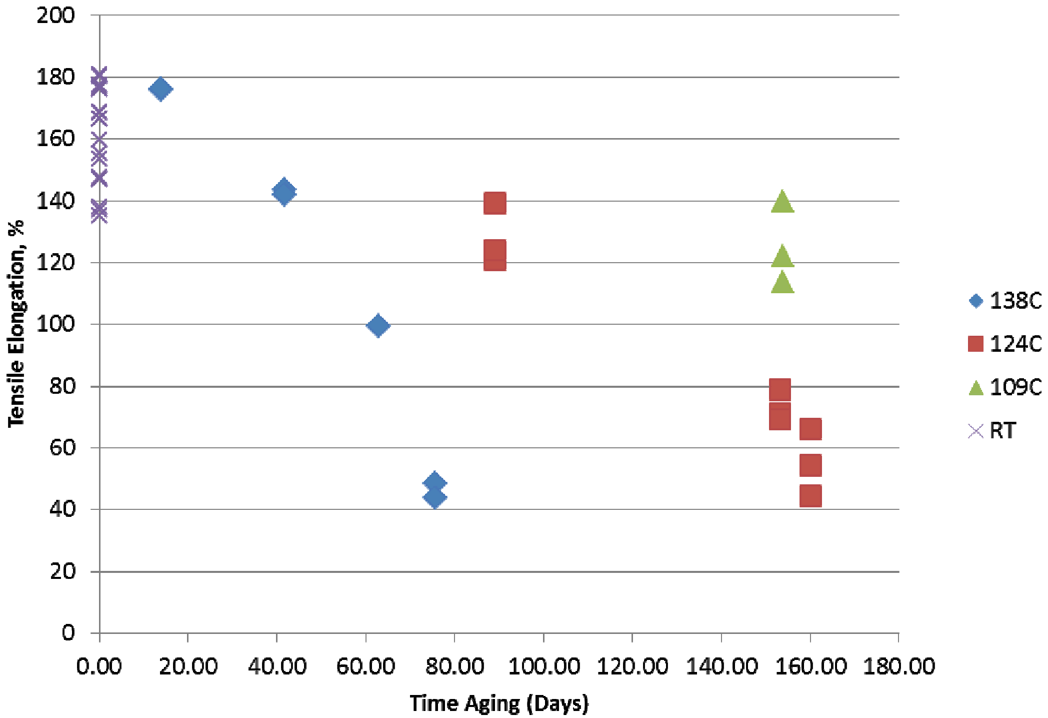
PNNL-aged EPR sample

DLO is evident, dominant surface oxidation



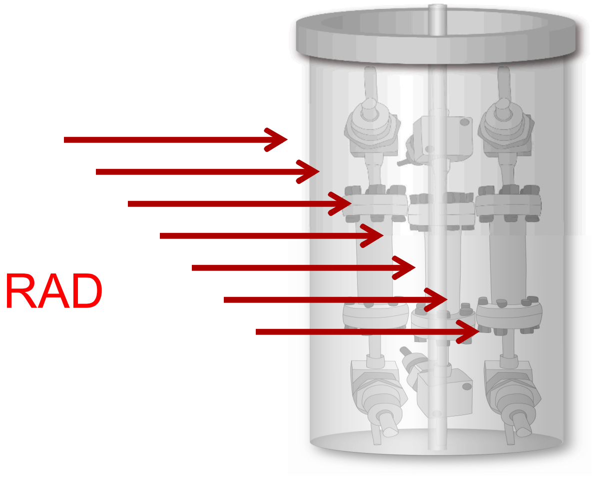
Virgin (left) vs. Aged (right)

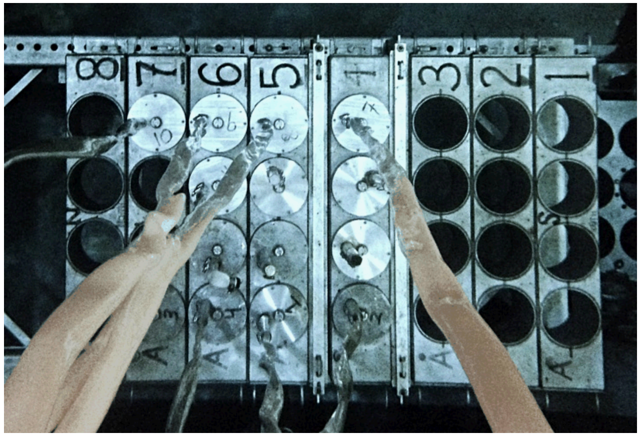
Rapid Thermal Aging of a Thick EPR Insulation



Gamma Irradiation Facility Updates

- Upgrade facility to conduct thermal-radiation experiments →provides unique, critical ability to simultaneously expose materials to thermal and irradiation environments
  - Updated electronics for irradiation experiments to enhance safety
  - Repaired aging cans
  - Experiments will be more representative of field-aged conditions, resulting in improved models for predictive aging
- Estimated completion: Spring 2014





Additional Slides

Key Strategies

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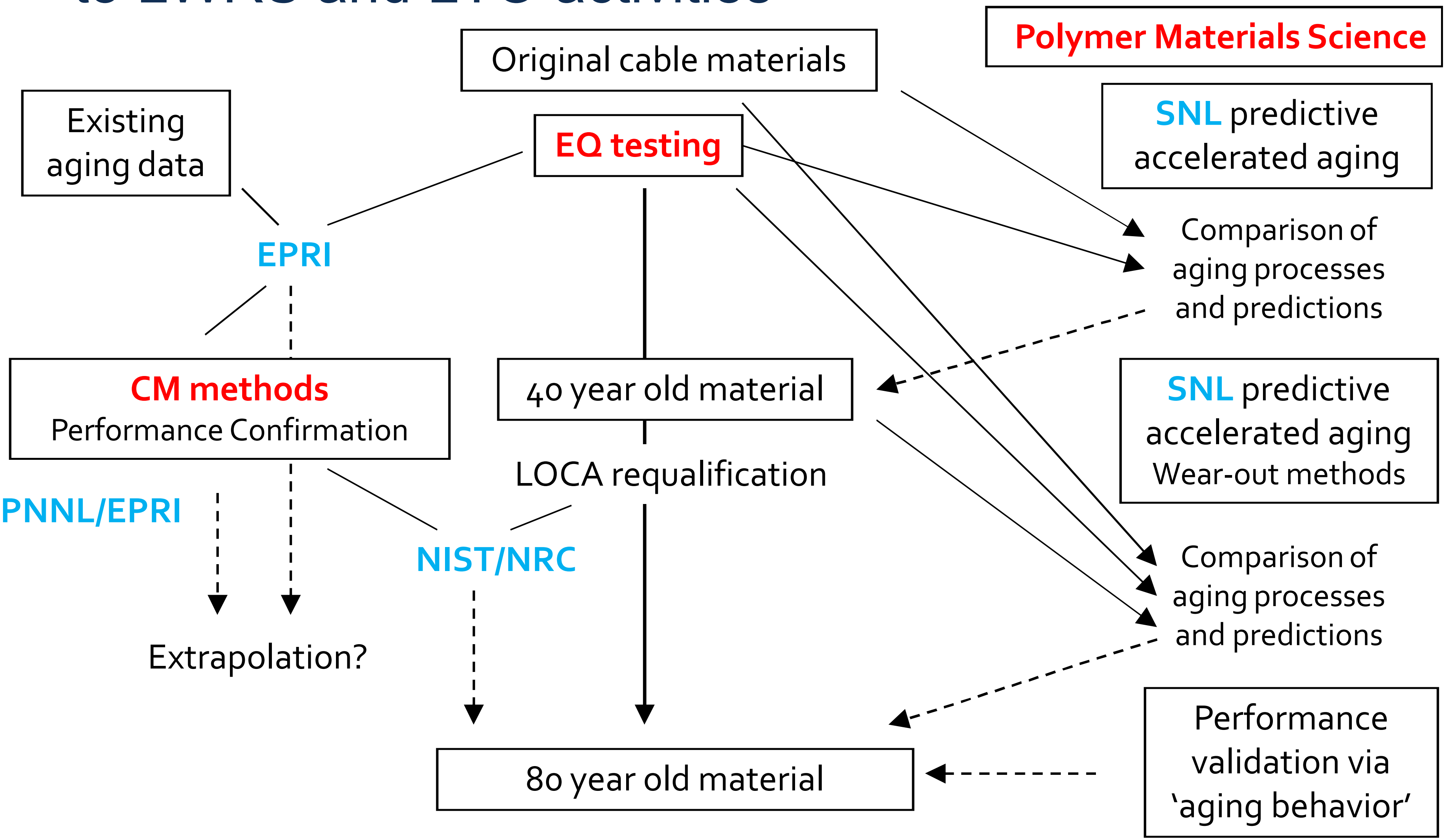
- Conduct Wear-Out aging studies on field returned cable specimens
  - Assess current aging state where possible
- Develop better predictive aging models which include long term low dose rate low temperature aging phenomena
- Enhance feedback from engineering tests by critically examining data and through 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 – Materials Aging Science contributions to LWRS and LTO activities



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