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Summary Report of Cable Aging and Performance Data for Fiscal Year 2014

Predictive Aging Research Supporting Nuclear Power Plant Relicensing Decisions under the DOE/NE LWRS Program

Milestone: M2LW-14OR0404013

Celina, M., Redline, E., Bernstein, R., Giron, N., Quintana, A., and White II, G.V.

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Abstract

As part of the Light Water Reactor Sustainability Program, science-based engineering approaches were employed to address cable degradation behavior under a range of exposure environments. Experiments were conducted with the goal to provide best guidance for aged material states, remaining life and expected performance under specific conditions for a range of cable materials. Generic engineering tests, which focus on rapid accelerated aging and tensile elongation, were combined with complementary methods from polymer degradation science. Sandia's approach, building on previous years' efforts, enabled the generation of some of the necessary data supporting the development of improved lifetime predictions models, which incorporate known material behaviors and feedback from field-returned 'aged' cable materials. Oxidation rate measurements have provided access to material behavior under low dose rate thermal conditions, where slow degradation is not apparent in mechanical property changes. Such data have shown aging kinetics consistent with established radiation-thermal degradation models.

ACKNOWLEDGEMENTS

We gratefully acknowledge ongoing technical support at the LICA facility and extensive sample handling provided by Maryla Wasiolek and Don Hanson. Sam Durbin and Patrick Mattie are recognized for valuable guidance throughout the year and assistance in the preparation of the final report. Doug Brunson is appreciated for sample analysis, compilation and plotting of experimental data.

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1 INTRODUCTION

As outlined in Work Package LW-14OR040401 (Rev. 1), the fiscal year 2014 (FY14) Light Water Reactor Sustainability (LWRS) cable aging and degradation work scope focused on completing research to identify and understand the degradation modes of cable insulation under varying environmental conditions. This is an essential step to predicting the performance of cable insulation under extended service conditions. Such data are clearly critical to develop and deliver a predictive model for cable insulation degradation. Both refined aging data and predictive models will enable more focused inspections, material replacements, and better-informed regulations. The development of in-situ mitigation strategies coupled with ongoing condition monitoring activities may also allow for an alternative to cable replacement and would be of high value to the industry by avoiding costly replacements.

Sandia National Laboratories (SNL) has been involved with nuclear power plant cable aging research needs since ~1977. The earliest work, covering the period from 1977 through 1986, was sponsored by the U. S. Nuclear Regulatory Commission (NRC). As a continuation, the Department of Energy (DOE) sponsored additional work in the late 80's and mid 90's. Over this period, SNL aged more than 15 different insulation and jacket materials typically used as nuclear power plant safety cables. The materials were oven-aged at multiple temperatures for various times and also radiation-aged under many combined dose-rate/temperature conditions. These extensive studies also included moderate aging conditions with exposures of up to 5 years. For virtually every aged sample, tensile elongation measurements were made. In addition, for selected samples, other property measurements, such as modulus profiling, density changes and gel content, were conducted. Over the years, most of the aged samples were retained at SNL. This unique asset, which we refer to as SCRAPS (Sandia's Cable Repository for Aged Polymer Samples), allowed us to much more efficiently address the cable aging objectives of the Nuclear Energy Plant Optimization (NEPO) program. Data from the current and past research has also been accumulated and placed in the Cable Polymer Aging Database (CPAD) in a separate NEPO Task. The CPAD database is available from the Electric Power Research Institute (EPRI).

SNL leads the research activities on quantifying and setting boundaries for cable performance in environments with elevated temperatures and humidity. Current efforts focus on cable systems expected to be the most susceptible to long-term aging under radiation-thermal conditions, for example, cross linked polyolefin (XLPO) and ethylene-propylene-rubber (EPR), which are both materials where complex aging phenomena have been previously observed.

The FY14 tasks support the continuation of long term, low dose rate aging studies for some key insulation materials. In addition, identifying the critical needs and areas of concern are a priority for nuclear power plants in terms of low voltage cables and designing the next set of experiments. Despite decades of research and numerous investigations which have included low voltage cable aging, more effort is required to address the shortcomings of existing studies. To enhance the fundamental understanding of nuclear power plant low voltage cable aging, we worked to acquire field aged materials in order to validate our current lifetime prediction models and obtain a better quantification of existing aging states. Due to difficulties accessing field-aged materials with known histories, complementary methods focusing on sensitive oxidation rate measurements were pursued.

The overall research and development (R&D) cable aging efforts at SNL are focused on a number of important research goals. These goals have been identified as part of ongoing discussions between SNL and the cable aging community, including EPRI, the National Institute of Standards and Technology (NIST), the NRC, and Pacific Northwest National Laboratory (PNNL). The research conducted at SNL represents a significant contribution to the coordinated research efforts agreed upon by the Oak Ridge National Laboratory (ORNL) DOE funding agency and EPRI [1,2].

1.1 Development of Improved Predictive Aging Models for Cable Materials

SNL is engaged in the development of a better understanding of cable material degradation processes. A major focus is on the characterization of material behavior during accelerated aging and qualification testing, and to use such aging trends for model-based performance predictions in nuclear power plant environmental conditions. Such models will also form the basis for wear-out aging studies, which aim to assess aging state and remaining margin for field returned cable specimens. Better predictive models require a number of input parameters ranging from quantification of primary oxidation chemistry and spatial distribution of degradation to the reasons for overall mechanical property changes and the kinetics thereof. The SNL approach involves combining existing aging data with additional experiments which will offer a more comprehensive framework for the underlying nature of material degradation processes. Commencing radiation-thermal exposure with oxidation rate measurements was one direction pursued to acquire thus far non-existent complementary data in FY14. Similarly, obtaining oxidation rates for a pre-aged material were a goal as they support wear-out aging approaches, as well as the quantification of oxygen permeability with temperature for a cable material as input for spatial degradation models.

1.1.1 Gap-Filling for Thermal Aging and Characterization of Radiation-Thermal Aging Behavior

As part of these activities existing aging data were reviewed. Substantial accelerated thermal aging data exist for nearly all important insulation types where tensile elongation changes were monitored in the time frame of weeks to a few years as part of earlier accelerated aging studies. However, only limited data are available which probe low temperature oxidation sensitivities or quantify oxygen diffusion phenomena. This means that current performance extrapolations are not as refined as they could be. Further, the exact differences in material aging behavior between qualification testing, accelerated laboratory aging, and environmental plant aging are not known. Tensile data offer useful trends, but timeframes are generally limited. To overcome such limitations, knowledge of oxygen transfer behavior into materials coupled with the intrinsic oxidation rates is one strategy for a better understanding of aging processes under varying environmental conditions. Oxidation rates can probe aging behavior at low temperatures or low dose rate conditions and offer aging relevant information, where tensile elongation changes are not accessible due to time constraints. This report combines our perspective of gap-filling needs with ongoing experimental work.

1.1.2 Assist Cable Aging Community and Achieve Consensus for Research and Development Activities

A better coordination of R&D efforts and community interaction is needed to facilitate information exchange and enable the development of overarching research directions. SNL contributed to multiple meetings as documented in this report and offered technical opinions/guidance for work being conducted at NIST/NRC and EPRI. As part of these meetings the need for field retrieved materials with known environmental conditions to be used for wear-out aging and aging state assessments was also conveyed to the community on multiple occasions and mutually agreed upon as a priority focus.

1.2 Summary Report Format

This report meets the requirements for DOE/NE LWRS Program Milestone: M2LW-14OR040401. It includes an FY14 year-end summary of the SNL activities on predictive aging research supporting nuclear power plant relicensing decisions. Specifically, the report is a summary of FY14 activities including new experimental data investigating the radiation effects at low dose-rates and plant relevant temperatures for EPR, silicon rubber, and XLPO representative materials, work towards understanding relevant nuclear power plant cable conditions, development of predictive aging models, support for PNNL rejuvenation experiments, collaboration with the domestic and international cable aging programs, and associated deliverables.

Section 2 is a summary of SNL research activities in FY14 supporting the LWRS cable aging program. It includes an assessment of cable aging performance data and implications for new data not documented in existing deliverables. Section 3 contains a summary of the FY14 deliverables. Appendix A includes a timeline and outline of all the FY14 SNL research activities and deliverables.

The Appendices include the key programmatic documents, deliverables, and milestones generated in FY14.

2 LWRS CABLE AGING PROGRAM IN FY14

2.1 Review of Existing Thermal Only Aging Data

Much work has been invested over the last 30 years in our understanding of cable aging phenomena. Extensive experiments were conducted for thermal aging and aging behavior under combined radiation-thermal environments. SNL data and material aging trends, as well as the interpretation for predictive aging models were summarized in three major reports [3-5]. Since accelerated aging studies are often limited to a maximum of a few years when relying on changes in tensile elongation as an aging indicator, SNL has explored the use of oxidation rates as a method to probe otherwise inaccessible lower aging stress environments [6-9], which more closely resemble real plant conditions.

As part of the coordinated cable aging research activities conducted by EPRI, NRC and DOE, there has also been an emphasis on the identification of gap–filling needs in areas where insufficient data may exist. There is a consensus that while high temperature thermal only aging data are available for many materials, performance predictions often depend on the underlying challenges associated with extrapolations.

2.1.1 Accomplishments in FY14

- Reviewed the thermal only aging data for the most important cable types based on previous SNL work in this area.

- Concluded that sufficient high temperature data exist which provide guidance for high temperature activation energy and relative performance differences above 100°C. Very few materials have been studied at lower temperatures. Aging was conducted down to 80°C only for less stable materials, such as a neoprene jacket.

- Conducted a re-evaluation of available thermal aging tensile data for ten materials for time-temperature superposition shift factors and time to 100% tensile elongation to enable plotting of data.

- Generated overview plots of high temperature relative performance for 10 important cable materials chosen as representative examples, i.e. covering XLPO, EPR, Hypalon®, CPE and Neoprene (see Figure 1 and Figure 2).

- This overview (Figure 1) demonstrates that all projections using linear Arrhenius extrapolations (for example shown in Figure 3) suggest sufficient longevity, on the order of above 100 years at 60°C under thermal conditions for most materials, excluding a neoprene jacket material type.

- Reviewed available O_2 permeation data and concluded that little is known about the underlying permeability for these materials. This represents a major knowledge gap.

- Reviewed existing limited oxidation rate data, which were taken at lower temperatures to provide guidance for activation energies. Limited data are available for four materials, which was done as exploratory screening work in previous studies (Figure 2).

- Lack of oxidation rate data besides for those four materials represents a knowledge gap. Due to the extended aging times required for changes in tensile elongation to be observable at temperatures below 100°C, such data are one feasible avenue to better understand low temperature material behavior. Better predictive models will require such measurements, unless sufficient confidence in expected performance could be established from existing aging data (a consensus in the cable aging community would be required, which would eliminate this issue), or through suitable feedback from field returned samples, which could provide trends in wear out aging behavior and relative performance decrease over previous plant use.

- Based on all thermal aging work conducted at SNL, Arrhenius curvature with changing E_a (activation energy) as a function of temperature cannot be predicted, but has to be experimentally determined [8-10]. Limited guidance is available for thermal aging of four cable insulation materials from oxidation rates. For XLPO insulation materials low temperature oxidation rate measurements (Figure 2) can be compared with traditional accelerated aging studies at higher temperatures (generally above 100ºC, see Figure 1). These existing data suggest a drop in E_a (when comparing high temperature tensile data with lower temperature oxidation rates) from ~ 100 to 70 kJ/mol for Brandrex, and ~ 130 to 100 kJ/mol for Rockbestos, respectively. For an Anaconda EPR material there is some evidence for a drop in E_a from approximately 130 to 100 kJ/mol. A Rockbestos Neoprene cable jacket material showed a decrease in E_a from about 95 to 80 kJ/mol.

- In summary, comprehensive accelerated thermal aging data exist mostly in the range of 160 to 100°C. Oxidation rates are available for four materials, all suggesting Arrhenius curvature towards lower temperatures. The major gap-filling needs exist in the acquisition of more oxidation rate data at lower temperatures, oxygen permeability for essentially all materials, and feedback from field returned cables for the identification of partial aging state and validation of existing extrapolation assumptions.

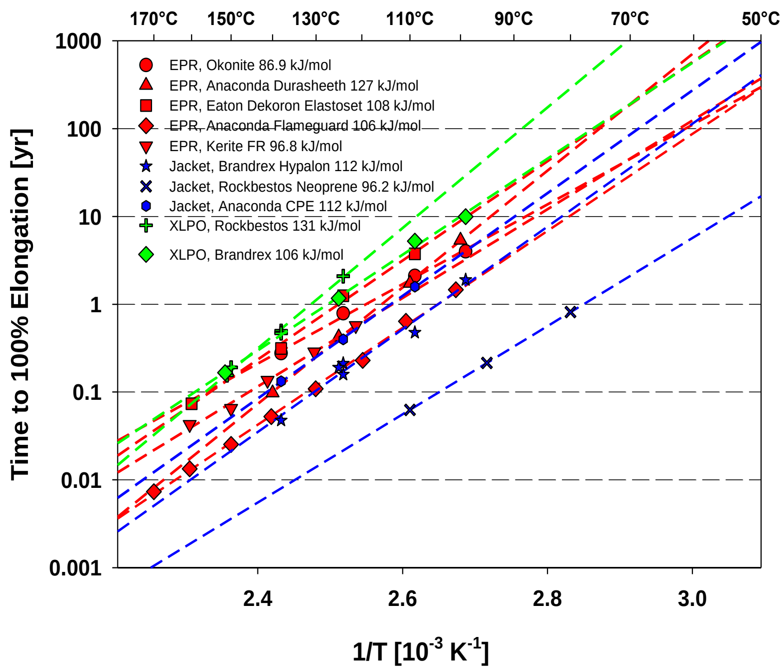

Figure 1 **Comparison of thermal aging behavior shown as time to 100% elongation from previous accelerated aging studies. Linear extrapolations may suggest adequate performance towards the 60-50°C regime for most materials, yet these linear Arrhenius assumptions have not been validated. In general, XLPO appears to age better than EPR, and both better than chlorinated materials, with neoprene clearly being a poorly performing material relative to the other polymers studied. These data were compiled from existing SNL SCRAPS sources.**

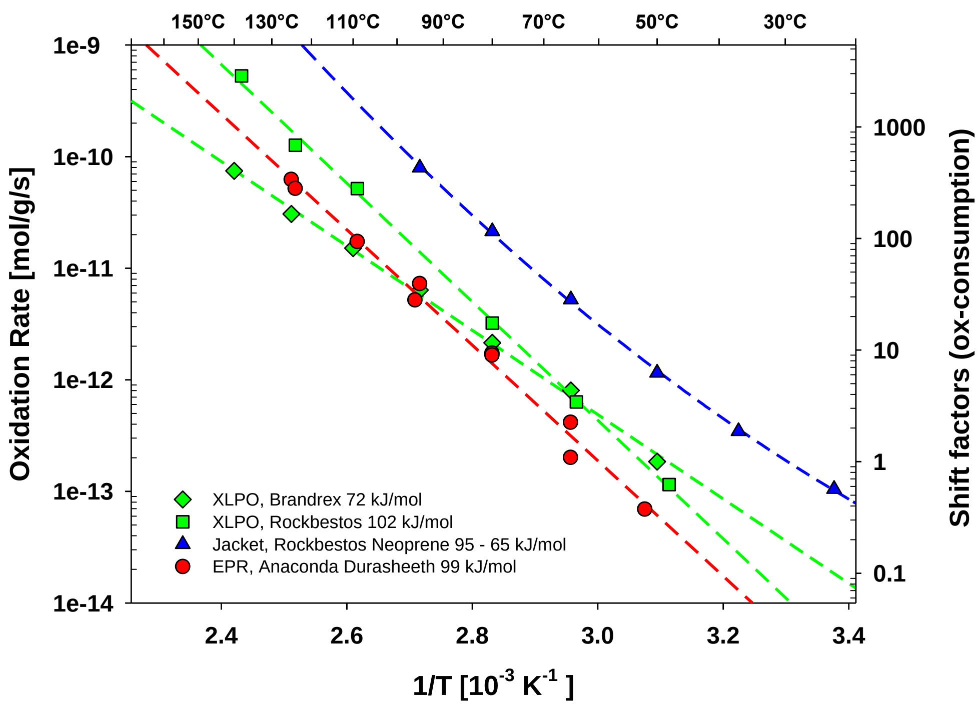

Figure 2 **Summary of previously measured oxidation rate data for four materials. These data were compiled from data published in [3] and previously unreported SNL studies.**

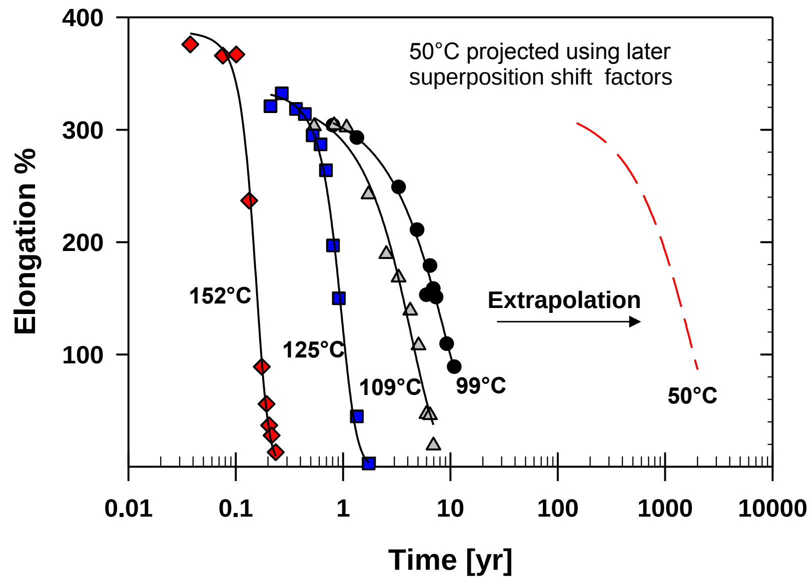

Figure 3 Example of available aging trends from SCRAPS, here shown for the decay in tensile elongation for Brandrex XLPO. High temperature shift factors from tensile elongation provide some guidance for expected low temperature behavior shown for 50°C (predicted with 106 kJ/mol). This is an area where oxidation rate measurements as additional gap filling work could provide more confidence.

2.2 Gap Filling Study – Example of Oxidation Rates for Thermal Aging of Dekoron XLPO

Dekoron XLPO was investigated for radiation aging at room temperature (nominal pool temperature of 28°C) at the Low Intensity Cobalt Array (LICA) facility through FY12-13. These aging trends are discussed later in this report. Besides these existing data for radiation thermal exposure, the aging behavior of this material is not particularly well understood.

2.2.1 Accomplishments in FY14

- Limited thermal oxidation rates (Figure 4) between 125 and 80°C were determined as a gap filling measure. Prepared samples and measured oxidation rates to determine an oxidative activation energy.

- Experiments could only be conducted for a limited time frame due to a limit in the total number of available ampoules, which had to be used in parallel for the evolving LICA exposures starting in May 2014.

- In total, 16 individual exposure and oxidation rate analyses were conducted for this study in FY14 yielding data for oxidation behavior as shown in Figure 4.

- This analysis shows that oxidation rates can quickly provide an overview for oxidative aging sensitivity of a material and the underlying temperature dependence of thermo-oxidative degradation (here an E_a of 90 kJ/mol).

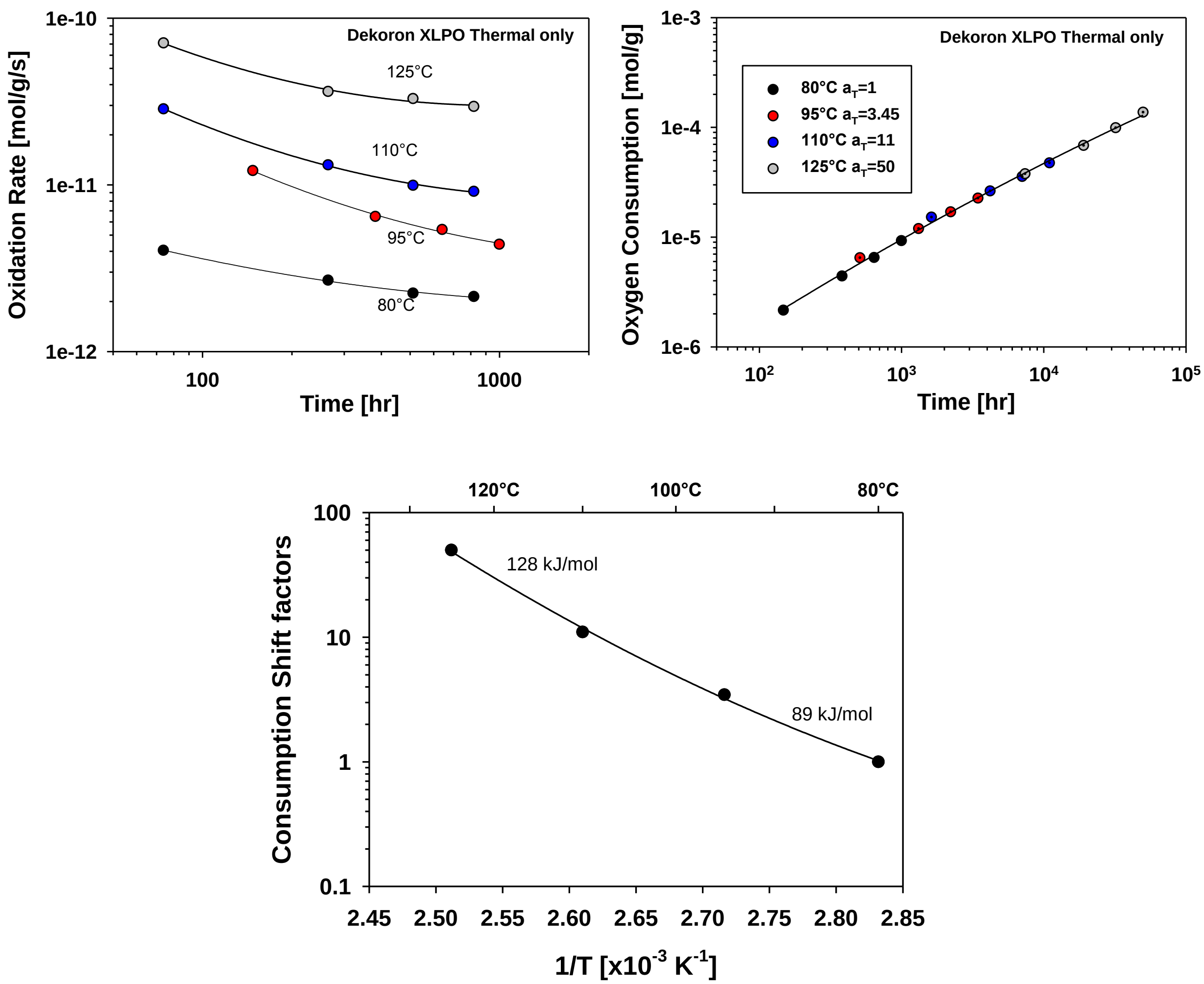

Figure 4 **Oxidation rates acquired in FY14 for a Dekoron XLPO material (top, left, shifted data plot in top, right) showing an activation energy of ~ 90 kJ/mol between 125 and 80ºC (bottom, center). Oxidation rates can provide guidance for lower temperature degradation behavior, for which tensile data are not accessible due to exposure time constraints.**

2.3 Continuity in Thermal Aging Process – Oxidation Rates for Partially Aged Materials

Of interest for aging predictions is whether materials demonstrate a reasonably linear and consistent aging behavior. Strong induction behavior where little changes occur followed by rapid degradative changes with quick material failures are particularly difficult to predict. In comparison, when an ongoing aging reaction occurs and the corresponding rate can be measured, time dependent predictions can be made more easily. Another aspect is related to the rating of 'wear-out aging' or the quantification of relative performance decrease in a field returned material. When linear aging behavior (as integrated damage accumulation) at a constant rate represents the underlying material degradation process, partial aging assessments are much more feasible and a field returned material can be fractionally rated for remaining performance margins.

2.3.1 Accomplishments in FY14

- As a gap-filling proof of principle method development, we used oxidation rate measurements to assess the continuity of aging kinetics for a previously aged Brandrex material under thermal only conditions.

- Limited specimens of Brandrex insulation thermally aged at 109°C were available from legacy sample storage at SNL and used for this study. Samples had been aged for extended time, namely for ~ 2.5, 5, and 7 years at 109°C. The material was brittle after 7 years exposure with ~ 20 % residual tensile elongation.

- These samples were used to prepare a set of oxidation rate samples for analysis at 50, 80 and 110°C. The focus was to evaluate what influence the relative pre-aging state (oxidative damage) may have on the magnitude of ongoing oxidation rates.

- In total, 30 individual exposures and oxidation rate analyses were conducted for this study. The single point data for the unaged material (see Figure 5) were available from existing studies.

- We conclude that the aging behavior proceeds with a reasonably constant rate behavior.

- There are indications for a subtle increase in relative rate towards the later stages of material degradation (see Figure 5, right), but this is in no way of a magnitude which would prevent partial aging assessments.

- Overall, these experiments demonstrate that for this material fractional aging states should be quantifiable based on linear aging behavior in simple 'wear out' aging studies. This would be applicable to accelerated aging of field returned specimens and a 'remaining margin rating' of residual performance in tensile elongation or similar properties.

    - For example, if accelerated thermal aging of a 40 year old field returned material were to yield a relative remaining lifetime (brittle behavior) of 3.5 years at 110°C, one could confidently argue for an expected lifetime on the order of 80 years when assuming a linear additive aging process.

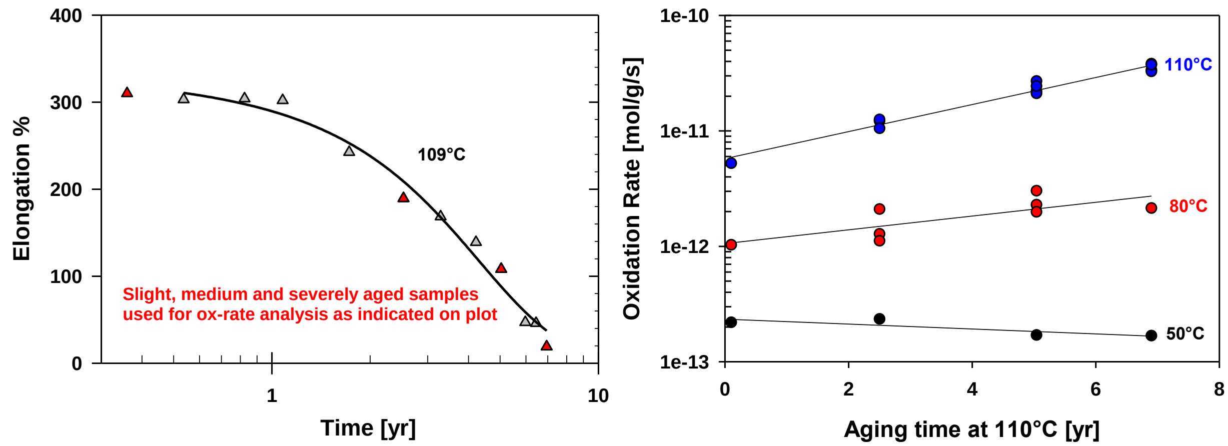

Figure 5 (Left) Elongation versus time plot for slight, medium and severely aged samples used for the oxidation rate analysis plot on right. (Right) Oxidation rates applied as a method to probe linearity of the thermal aging process for pre-aged Brandrex XLPO insulation. The degradation proceeds reasonably steady with time, i.e. aging state itself does not have a major feedback effect on momentary aging rate.

2.4 Oxygen Permeability

It is firmly established that cable/jacket degradation progresses via oxidation of the material either under thermal or radiation-thermal conditions. Oxidation is the leading degradation pathway, which results in long-term deterioration of these materials. The lack of knowledge of O_2 permeation represents a gap-filling need. Improved knowledge of O_2 diffusion through cable insulation and jacket materials is necessary for a number of reasons:

- There are significant differences in the aging processes of these materials between qualification testing, accelerated aging experiments in the laboratory and long-term aging phenomena. This leads into the issue of whether diffusion limited oxidation (DLO) conditions apply or whether cables age homogeneously. Lack of data in this area has prevented remaining operational margins from being established.

- Diffusion and permeability of O_2 for a given material as a function of temperature is required in order to rate specific accelerated aging conditions and provide guidance to the community on whether DLO interferes and what the prevailing degradation mechanism (i.e. oxidative or non-oxidative conditions) under any aging conditions may be. Planned NIST/NRC experiments should benefit from an assessment of DLO conditions in comparison with qualification testing.

- A spatially resolved degradation model can only be utilized if suitable input parameters exist.

- As mentioned in the SNL 'remaining cable performance margin assessment' report (SAND 2013-2388) [5], verified O_2 permeability data sets for many materials do not exist. There are only estimations for a few XLPO materials with unknown behavior above 50°C.

2.4.1 Accomplishments in FY14

- Developed an experimental approach and prototype fixture to measure O_2 diffusion through a cable insulation specimen.

- Conducted 32 individual measurements to quantify flux behavior with different partial pressures and temperatures for a Brandrex cable insulation material; these experiments were carried out to demonstrate a proof of principle experimental approach and feasibility of acquiring such data.

- Applied a Fickian-based diffusion model to a cylindrical geometry to extract permeability from equilibrium flux measurements. This required a detailed understanding of the mathematics of diffusion processes relevant to this geometry and how to determine the underlying material permeability.

- Succeeded - for the first time - to measure permeability between room temperature and 140°C for a XLPO cable insulation material (as summarized in Figure 6) for all partial pressures examined.

- Permeability has been made available as a critical input parameter into a spatially resolved first generation degradation model.

- Based on the material behavior observed during these permeation flux measurements, which showed no dependence on partial pressure (see Figure 6), we also conclude that the single-sided oxygen exposed Brandrex insulation is not subject to DLO conditions under thermal only oxidative degradation conditions at temperatures up to 140°C. Open insulation specimens with two-sided oxygen access during traditional accelerated thermal aging will be equally unaffected by DLO.

- Note: There appear to be slightly different formulation types of Brandrex XLPO low voltage control cables insulation. For instance, SNL noticed some variations in oxidation rates and thermal aging behavior in studies 20 years ago. The most recent cable spool, apparently purchased by SNL in the early 1990's, is labeled Brand-Rex XLP/CU power and control cable 3/C #12 600V Sun Res XHHW Type TC(UL). This material was used for the permeability characterization. It is possible that an earlier version of the same cable type may have slightly higher permeability and be less sensitive to DLO degradation behavior under specific irradiation conditions.

- Permeability is an important material property that when coupled with oxidation rates enables modeling the spatial distribution of oxidation. Figure 7 shows a demonstration of spatially dependent oxidation rates for a Brandrex XLPO cable assembly. Such models require oxidation rates and permeability input for insulation and jacket material. They yield the spatial distribution of oxygen concentration in a cable assembly, as well as localized oxidation rate (shown in Figure 7), where, for example, most of the oxidation occurs in the jacket materials and also with a gradient from the outer to the inner sections of insulation.

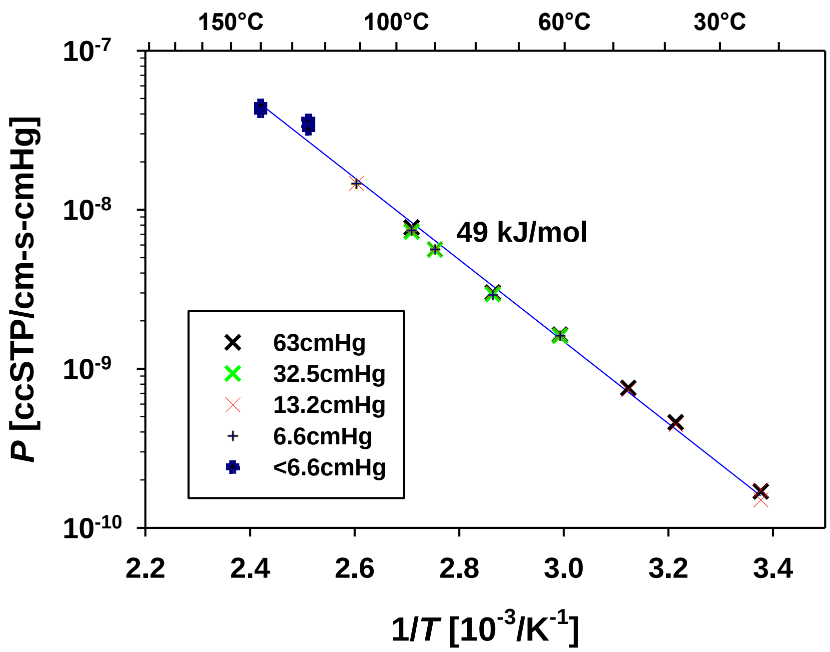

Figure 6 **Oxygen permeability for Brandrex XLPO determined for multiple partial pressures with temperature. The purpose of collecting this data is to understand what, if any, influence DLO may have on aging data as a function of temperature. Permeability was calculated for circular geometry applicable to this insulation. SNL is not aware of such data being available in the past.**

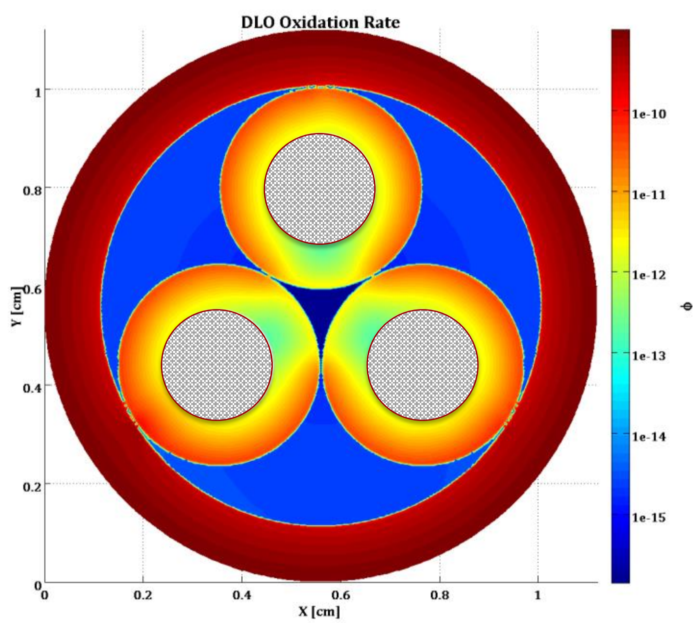

Figure 7 **Demonstration of spatially dependent oxidation rates for a Brandrex XLPO cable assembly. Such models are feasible as long as oxidation rates and permeability are known for insulation and jacket materials. Oxygen permeability is a critical input parameter for complex 2D FEM codes.**

2.5 Evaluation of Tensile Degradation Data from LICA Irradiation Study of FY12-13

As part of previous FY 12-13 activities, three materials were irradiated in LICA at room temperature (pool temperature usually ~ 28°C) at four dose rates ranging from ~ 12 to 280 Gy/h; the materials investigated were Brandrex XLPO, Dekoron XLPO and Dekoron EPR. Degradation was monitored with the decrease in tensile elongation (elongation at break, EAB), with the aging trends conveyed to the LWRS MAaD Pathway lead program on multiple occasions. No comparisons with existing SNL data from the 90's aging studies for these materials were provided in the past.

2.5.1 Accomplishments in FY14

- Acquired and compiled all recent aging data (SNL FY12-13 effort) for these materials and checked aging exposure for times and applicable dose rates for each sample. Determined cumulative doses accommodating the decline in dose rate due to ^{60}Co decay for each sample analysis.

- Retrieved existing SNL aging data, which were conducted in late 1980's to early 1990's, at similar dose rates. Existing aging data for the Dekoron XLPO were only available at 60°C. Newly obtained data at room temperature (RT) represent an addition to the knowledge base.

- Prepared superposition plots (Figure 8 through Figure 10) of all available aging data for three materials at RT conditions.

- Prepared summary DED plots (Figure 8 through Figure 10 on right side) showing dose rate dependent aging levels for the Brandrex XLPO and Dekoron EPR materials, and a dose rate independent behavior for the Dekoron XLPO material. The nature of the dose rate effect means that as the dose rate is lowered, lower doses are required to result in similar aging levels, i.e. remaining tensile elongation. Understanding such dose rate effect is important for predictive purposes.

- The uncertainty in tensile elongation measurements is 0.01, or 1%. See Appendix D for details.

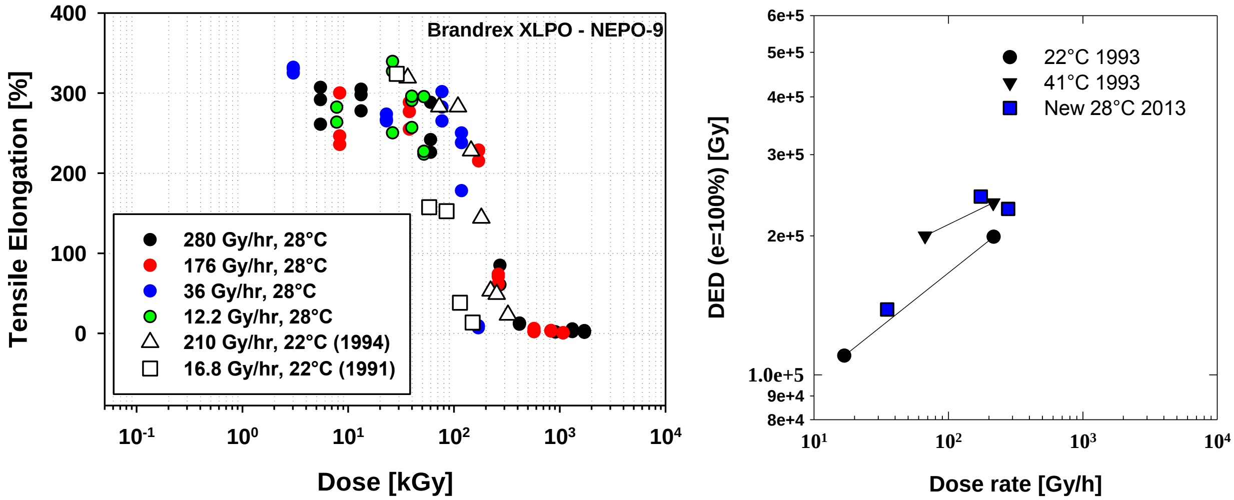

Figure 8 Summary of radiation aging data at RT (left) and DED analysis (right) for Brandrex XLPO. Recent aging data are consistent with previously observed aging behavior.

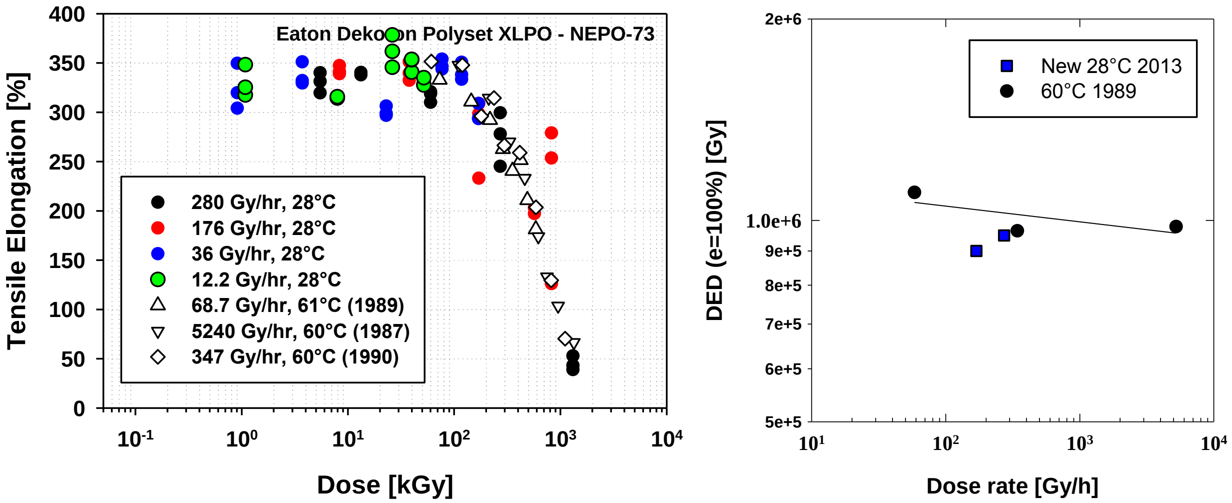

Figure 9 Summary of radiation aging data at RT (left) and DED analysis (right) for Dekoron XLPO. Recent aging data are consistent with previously observed aging behavior. Data for 68.7 Gy/h (1989) were extrapolated to 100% tensile elongation.

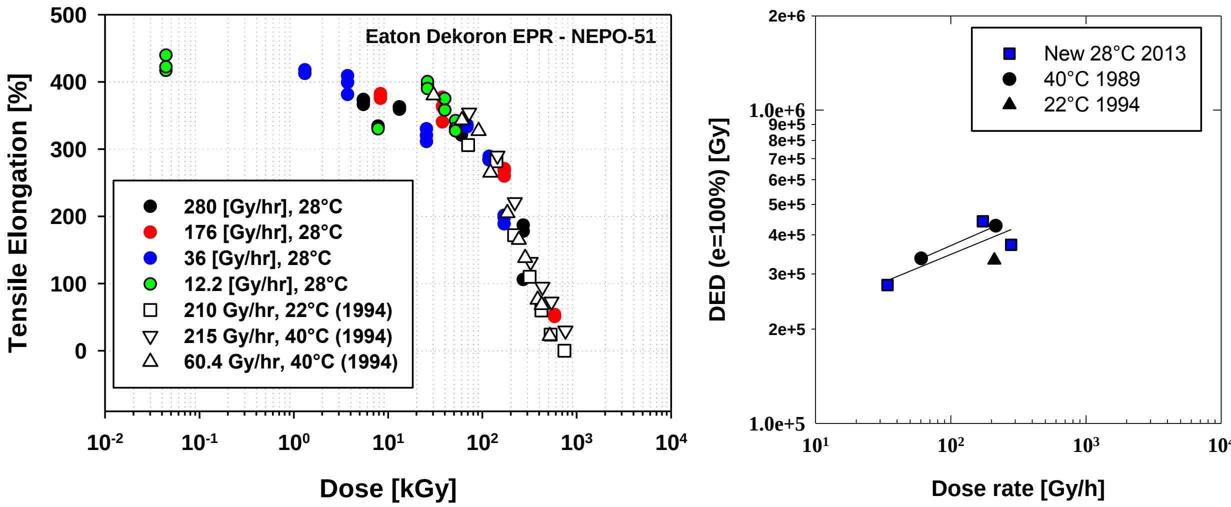

Figure 10 Summary of radiation aging data at RT and DED analysis for Dekoron EPR. Recent aging data are consistent with previously observed aging behavior. Data for 36 Gy/h were extrapolated to 100% tensile elongation.

2.6 Repair and Qualification of LICA Controller System for Radiation-Thermal Exposure

At the beginning of FY14 LICA was not operational and all thermal exposure experiments had stopped. An uncontrolled thermal runaway had occurred and it was found that there were neither over-temp protections nor electrical circuit breakers in place. The existing system was unsafe and unpredictable from both an Environmental Safety & Health and SNL safety requirement perspective. Therefore, the system was redesigned and rebuilt from the ground up. The required upgrade work was supported by additional internal SNL funding.

2.6.1 Accomplishments in FY14

- Redesigned LICA control system with dual temperature controllers. A dominant over-temp controller acts as an independent safety switch. Two thermocouple read-outs provide confidence in actual temperature conditions. Temperature is logged on a data acquisition system. Figure 11 shows a photograph of the new controller system.

- Electrical ground fault circuit interrupters, triggering at 50 mA earth leakage current, were incorporated on each control circuit. Circuits were checked with applied resistor bleed.

- Exposure cans that had leaked were repair-welded in the machine shop.

- Remaining cans were wired and all PVC connection tubing was checked.

- Kapton® insulated heater wires, which had ground fault issues due to scratches were repaired.

- Control system and exposure can wire connections went through a comprehensive ‘engineered safety’ review. The control system for operation of eight thermal cans was approved by ESH by the end of April 2014.

- After final dosimetry and start-up tuning, the system was operational by the end of May 2014.

Figure 11 New controller system that was designed and built in FY14. It allows for independent control of eight heated LICA exposure cans.

2.7 Dosimetry for LICA Radiation-Thermal Exposure System

Dose rates for the far field locations at the beginning of FY14 were unknown. Previous exposures had been limited to four positions (rows 4 through 7), and there were inconsistencies between previously measured and historical dose rates. The effect of height limits and related gradients in the exposure field was undocumented.

2.7.1 Accomplishments in FY14

- Evaluated historical dose rates with projections to April 2014 and compared with dose rates previously measured in FY12-13. Established the best applicable dose rate conditions.

- Conducted an extensive experimental dosimetry series to establish exact legacy conditions as to allow for best dose rate data to be applied to experiments in FY12-13.

- Engaged with LICA facility to add three new exposure rows into the exposure field. This enabled access to rows 9 through 11, which offer low dose rate conditions.

- Engaged with LICA personnel and placed extra ^{60}Co pencils to maximize near field dose rates. An additional activity of ~65 % (835 Ci) was added and pencils slightly repositioned to maintain best field symmetry, raising the row 4 dose rate from ~180 Gy/h to 380 Gy/h in May of 2014.

- Succeeded in the deployment of an 8 x 2 array (16 total) of operational exposure cans, with half at RT and half heated.

- Conducted dosimetry to establish dose rate field properties from row 4 through 11.

- Conducted dosimetry to document height dependence on local can dose rates for cans 4 and 5, since it could affect oxidation rate ampoules or tensile specimens.

- April – May 2014: Assessment of legacy LICA layout using five separate experiments, totaling 49 TLDs sets (four per position). Multiple dosimetry measurements were conducted because of a lack of consistent replication of the results reported by SNL in 2012. It was established that there is significant variability in the dose rate in near field positions depending on the height at which dosimeters are placed. Once dosimetry was conducted at the same height as was done in 2012, similar decay-corrected dose rates were obtained.

- June 2014: New pencil assembly assessment with 2 experiments, totaling 44 TLD sets. Blocking and heating cans were swapped in each experiment to quantify the shielding effect of the central brass can component. TLDs were placed at two different heights in can positions 4 through 6.

- In FY14 a total of 93 individual dosimetry experiments (four TLDs per location) were conducted and an operational exposure facility with well-characterized dose rates and thermal control of eight cans was made available. This was a major goal for the LWRS program and SNL now offers access to dose rates from 380 to 0.5 Gy/h available for tensile specimens and ox-rate ampoules (the available dose rates and positions are summarized in Figure 12).

- In terms of accelerated aging conditions this dose rate range offers access to a large variation in exposure acceleration factors with nearly three orders of magnitude between the lowest and highest dose rate. For example, at a dose rate of 0.5 Gy/h, a nominal dose of 10 or 20 Mrad is accumulated in ~ 23 or 46 years, respectively. At 380 Gy/h such exposure levels would be reached in only 11 or 22 days, respectively. The lowest dose rate is within range of conditions that could be encountered during plant aging situations, where plant conditions have been characterized as 0.6 Gy/h (60 rad/h), for a total integrated dose (TID) of 0.2-0.4 MGy (20-40 Mrad) over 40 years. In other words, a failure dose of 20 Mrad deposited over 80 years will require 0.285 Gy/h.

- At high dose rates in proximity to the ^{60}Co source the absorbed energy in polymers is generally less (~0.85 times) than in CaF_2 used for dosimetry and can be quantified using the mass energy absorption coefficient for CaF_2 and the polymers of interest. This factor has been used in the past for exposure doses in accelerated aging studies of polymers and cable materials at SNL. The ratio of absorbed dose between CaF_2 and polymers (based on relative mass energy absorption coefficient) depends on the relative energy of the gamma photon. Since the radiation field farthest away from the source involves significantly lower photon-energies, we expect the absorbed energy correlation factor (ratio of relative mass energy absorption coefficient) to be location specific. Since funding and time was limited this FY, it was not possible to develop suitable models which accommodate energy attenuation, back-scattering and the general photon-energy composition as a function of location to derive the location specific energy absorbance for hydro-carbon based polymers, in comparison with primary CaF_2 dosimetry. This aspect of location specific absorbed dose for polymers for the current LICA geometries and sample distance from source ought to be part of any future refined dosimetry. With this in mind, any dosimetry and radiation exposure experiments which include dose rate and cumulative doses in this study were interpreted based on primary CaF_2 equivalent exposure dose.

- Note: The ambient pool temperature throughout the year is regarded as an average of approximately 28ºC, but 31ºC in the hottest July/August timeframe has been measured because the building is not particularly well air-conditioned.

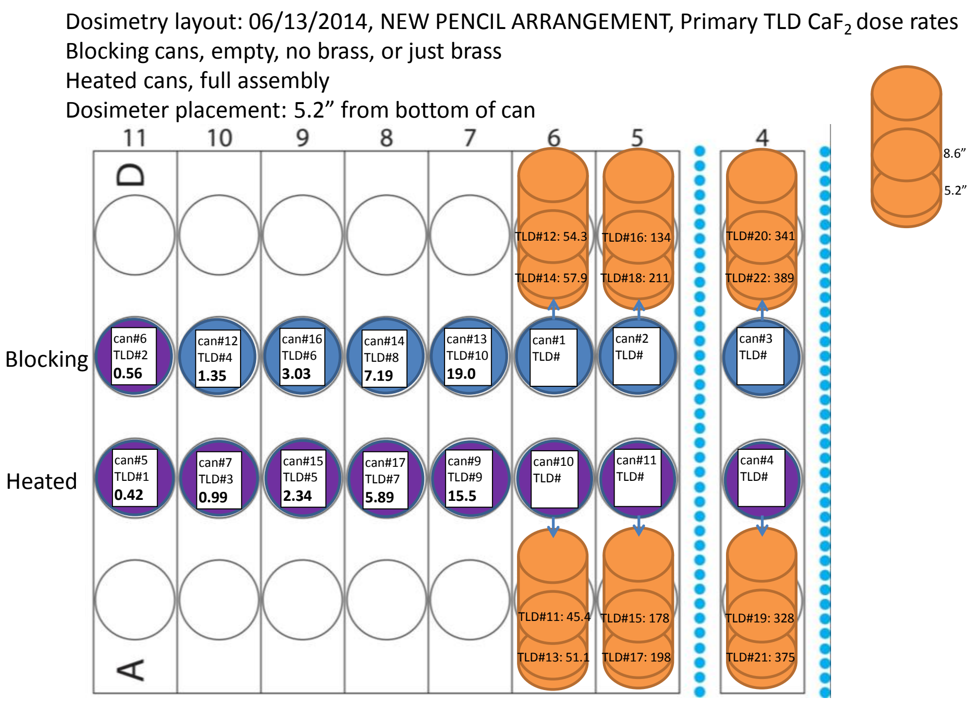

Figure 12 Schematic of the newly available dose rate and exposure locations at LICA. These went into operation with a new temperature control system (over-temp and ground fault protection approved by extensive ESH reviews) in May 2014.

2.8 Oxidation Rates under Radiation-Thermal Conditions

Traditional aging studies with loss in tensile elongation as an aging indicator are normally limited to a maximum of three to five year time frame. For most cable or jacket materials of interest to the LWRS program such aging studies were conducted under thermal and to a lesser degree under radiation-thermal conditions with varying dose rates as part of the SNL efforts in the 1980's and early 90s. The key challenge with lifetime prediction and any assessment of remaining margin is that long-term predictions have to be made from a limited data set under accelerated aging conditions. SNL research has shown for many other polymeric materials that degradation sensitivities and Arrhenius behavior can be supplemented by oxidation rate measurements [6,7,9], which probe material degradation sensitivity at partial aging states and not when complete material damage may have occurred, as is often the case with a significant loss in tensile elongation. This is even more important when induction time behavior prevents any visible property changes during extended moderate aging conditions, hence when aging data offer little predictive value. Oxidation rates serve the purpose of understanding material behavior as a driving force for degradation kinetics and offer additional predictive value when other property changes are not apparent.

There have been a few oxidation rate screening studies under radiation-thermal conditions at higher dose rates, but no systematic studies have been conducted in the past. For radiation-thermal conditions, comprehensive oxidation rate data also offer an opportunity to probe the nature of a combined theoretical radiation-thermal aging model. Oxidation rates allow for the separation of thermal and radiation driven degradation processes and enable predictions by extracting activation energies from experiments conducted at different temperatures. As part of the FY14 LWRS effort we introduced and initiated the collection of such data.

2.8.1 Accomplishments in FY14

- We used the newly operational LICA facility as discussed above.

- We conducted a calibration sequence and multiple instrument checks, as a quality measure for measuring correct rates with the Oxzilla system. We also replaced the detector fuel cell as part of maintenance for instrumental stability.

- Screening studies were conducted in December and January at four dose rates for three materials (Brandrex XLPO, Dekoron EPR and Dekoron XLPO) to acquire basic oxidation rates. This was necessary for two reasons: namely, to check if DLO would complicate data acquisition at the higher dose rates and also to acquire guiding rates, which would then allow us to determine appropriate sample weights and exposure timing for a large sample series. Brandrex XLPO showed an average rate of ~ 1.2e-9 mols/Gy/g, Dekoron EPR of ~ 7e-10 mols/Gy/g, and Dekoron XLPO of 6.3e-9 mols/Gy/g. DLO effects (i.e. declining rate at higher dose rates) appeared to contribute for the most recently acquired Brandrex material (~ 1 mm insulation wall thickness, cable spool from early 1990's), but conclusive quantification was not possible due to lack of sufficient data.

- These screening studies involved a total of 50 independent Oxzilla sample measurements. Each sample required individual ampoule assembly, leak testing, back-filling, LICA exposure and retrieval, followed by oxygen deficit analysis with signal acquisition, integration and compilation into a data summary file. Total handling time for a single data point is approximately one hour.

- After LICA was approved by ESH and dose rates were established by the end of May, systematic radiation-thermal exposures for Brandrex XLPO (old late 80's material) and Dekoron EPR at RT (ambient pool temperature of 28°C) and at 60°C using the heated cans were commenced.

- These studies required cycling a total of 32 samples (two materials with eight dose rate positions at RT and 60°C). Repetitive measurements were taken to provide the data which are shown in the summary plots (see Figure 13 and Figure 14). The first 60°C series was lost, as the row 5 can flooded and triggered a temperature controller shut-down event. The GFCI's for the power outlets around the LICA pool could not handle loads greater than 2 A and therefore power had to be provided from an outlet farther away.

- In August 2014, after acquisition of initial RT and 40°C data these experiments were expanded to include an 80°C series for Brandrex XLPO and Dekoron EPR for the full dose rate range.

- These experiments for two materials, three temperatures and eight dose rates, involved the analysis of 226 samples. Within the time constraints of this fiscal year additional aging temperatures could not be investigated.

- For the first time such data are experimentally accessible and demonstrate the temperature effect at low dose rates as predicted by theoretical aging-models, plus a beginning dose rate effect for EPR at the higher dose rates (i.e. an upward trend in ox-rate with dose rate). DLO behavior for Brandrex at the highest dose rates is close to developing as predicted from aging models (see next section), but did not yet interfere with these measurements. This was experimentally cross-checked by a comparison of uncut insulation specimens (atmospheric oxygen access from both sides) with finely chopped pieces less subject to DLO conditions. The two material shapes did not reveal distinctly different oxidation rates. Under DLO conditions the uncut sample should have shown noticeably lower oxidation rates. For the data plots shown below a best line fit through the data includes both the uncut and cut sample specimens.

- Systematic studies like these allow for the refinement of aging models and systematic material comparisons. Future work should use such data sets to deconvolute the thermal and radiation processes based on individual activation energy and parallel thermal and radiation driven oxidative degradation chemistry. Additional data at 100 and 120°C will be highly beneficial.

- DLO interference for the Dekoron EPR is less of a concern as it has somewhat higher permeability, lower oxidation rates and is thinner than the Brandrex XLPO material.

- Most importantly for the LWRS program research goal of better understanding aging phenomena at low temperature, low dose rate conditions as a basis for cable requalification [5], unusually high oxidation rates at lower dose rates were not observed (see Figure 13 and Figure 14). These initial experiments document that for RT conditions the temperature driven contribution to the degradation process is relatively small and that the oxidation rates per Gy are reasonably independent of dose rate. Only a subtle increase in ox-rate per Gy with lower dose rates is observed. This means that a first generation of predictive cable aging models could accommodate the dominant radiation sensitivity with total failure dose as the basis for lifetime extrapolations. The oxidation rates can provide the relevant boundary conditions when coupled with DED data from existing tensile elongation studies, where the latter of course are limited to higher dose rate conditions, generally above 10 Gy/h.

- It is also important to recognize that at the higher dose rates oxidation rates do not change much with accumulated dose, i.e. when sequential exposure doses increase substantially and represent significant aging of the material. This means that the material behaves rather steadily with time and dose accumulation. This is consistent with the observations for reasonably steady thermal only ox-rate data with increasing aging state discussed earlier.

- The maximum 95% uncertainty associated with thermal-only (mol/g/s) and radiation-thermal (mol/g/Gy) oxidation rate measurements conducted over short experimental exposure times are 2.1E-14 mol/g/s and 2.0E-10 mol/g/Gy, respectively. See Appendix D for details.

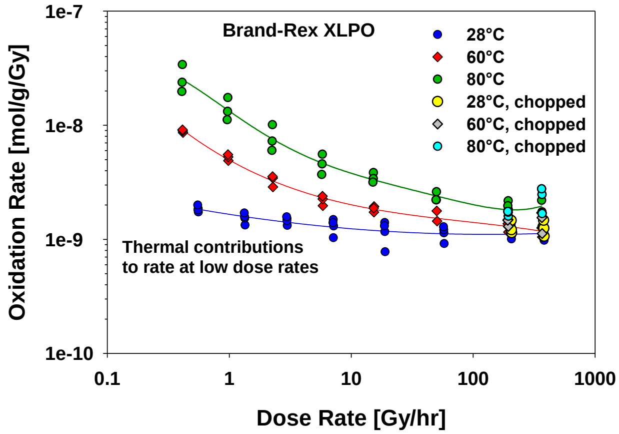

Figure 13 **Radiation-thermal aging characterization with oxidation rates for Brandrex XLPO (left) and Dekoron EPR (right). The expected thermal influence on relative rates are visible at the lower dose rates, as is a subtle dose rate effect for the EPR material at higher dose rates. Besides this additional dose rate effect these trends are consistent with theoretical predictions for combined rad-thermal degradation. Such data offer deconvolution opportunities for thermal and radiation processes and could establish the underlying activation energies.**

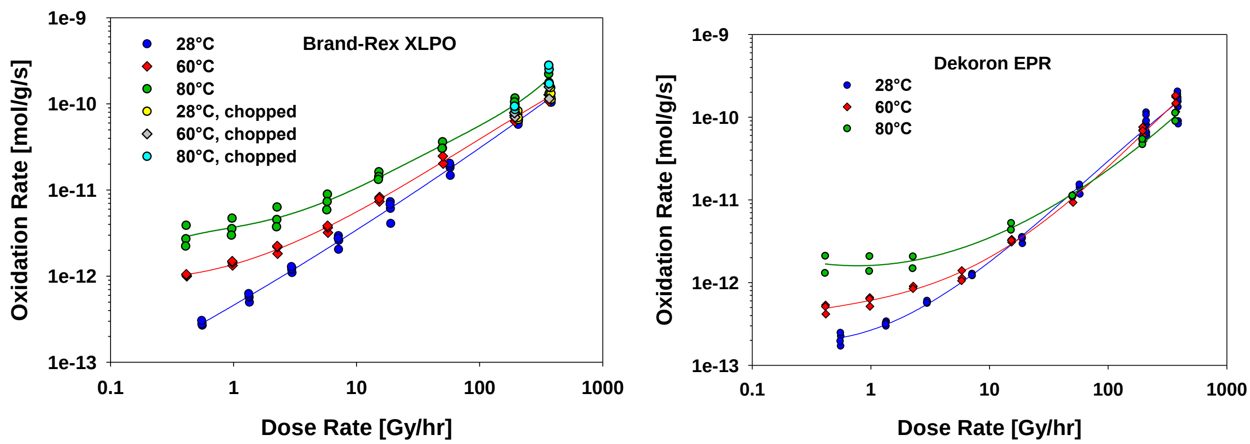

Figure 14 **The corresponding oxidation rates in mols/g/s for radiation-thermal degradation of Brandrex XLPO (left) and Dekoron EPR (right). At dose rates above 100 Gy/h these ox-rates are on the order of 1e-10 mols/g/s, which is a level where DLO effects may be potentially present based on the measured permeability for this material. Samples for the two highest dose rates were therefore analyzed as finely chopped and uncut specimens.**

- An initial screening study, which was started in August at the end of FY activities, was conducted for the two jacket materials over the full dose rate range available at RT. The Brandrex and Dekoron cables both use Hypalon® (chlorosulfonated polyethylene) as the jacket material. The Brandrex Hypalon® has a thickness of ~1.6 mm and the Dekoron EPR a thickness of ~1.5 mm. Model predictions for these materials suggest that DLO should interfere at the highest dose rate of 380 Gy/h at RT for uncut specimens with atmospheric O_2 access from both sides. This applies for an anticipated oxidation rate of ~5e-10 mols/g/s and is apparent in the plots below. In this case, permeation would need to be greater than ~5e-9 ccSTP/cm-s/cmHg to eliminate DLO, which would be higher than expected for Hypalon® at RT. At the next lower dose rate (205 Gy/h) the oxidation measurement could still be affected by DLO. This would happen if, for an oxidation rate of ~1e-10 mols/g/s, the permeability is lower than ~1e-9 ccSTP/cm-s/cmHg. Unfortunately, the exact permeability data for these materials are not known.

- The jacket material evaluation study had to be limited to single data points due to time constraints at the end of this fiscal year. In total 16 samples were prepared and analyzed. The oxidation rate data are shown in Figure 15.

- From a material aging perspective, it is intriguing that the four materials investigated (Brandrex XLPO, Dekoron EPR, and the two Hypalon® jacket materials) show very similar oxidation rates of ~ 1e-9 mols/g/Gy at RT, mostly independent of dose rate. This likely demonstrates an underlying behavior of hydro-carbon based polymers under irradiation conditions, with radiation dominated H-abstraction and free radical chemistry involving oxidation purely initiated on a per absorbed dose basis. Thermal initiation of degradation chemistry at RT is expected to be low and material differences are not significant, unless dose rate effects contribute at very high dose rates. Of course, with increasing temperature, when parallel processes will become more important, material differences should then be more noticeable. In fact, this is apparent when comparing the Brandrex XLPO and Dekoron EPR for all three temperatures investigated. An increase in temperature is more important for the XLPO and the EPR shows a subtle dose rate effect.

- From these measurements it is concluded that a cable assembly, i.e. a three conductor core Brandrex cable for example, will be severely diffusion limited at the highest dose rate when O_2 is only available from one side, i.e. the surface of the jacket material. The transition from jacket to XLPO material can be modeled in its simplest form as a 1D two material condition. Assuming a permeability of 1e-9 ccSTP/cm-s/cmHg (i.e. a value on the order of what the rate-measurement data suggest, see discussion above) would imply DLO through the jacket material to prevent homogeneous oxidative degradation of the XLPO all the way down to 18 Gy/h (see Figure 16). This analysis is consistent with the fact that for two sided O_2 access at RT and 380 Gy/h the Brandrex XLPO is just at the point of being DLO affected, and the Hypalon® jacket material clearly is subject to DLO, as the oxidation rate measurements showed. Below is an example of such simulations for a specific jacket permeability at RT. Once actual permeability is available for cable jackets more refined predictions for cable assemblies could be provided. This situation of transitions between heterogeneous (DLO controlled) and homogeneous degradation with dose rates has been discussed as the reason for fundamental differences in the aging mechanism between ambient aging and qualification testing and represents an important aspect in accelerated aging studies of cable assemblies [3].

- Note: The exposure dose rates documented in this study are based on primary CaF_2 dosimetry and have not been corrected for LICA location and material specific energy absorption coefficient ratios to accommodate differences in the absorbed energy for CaF_2 and the polymers.

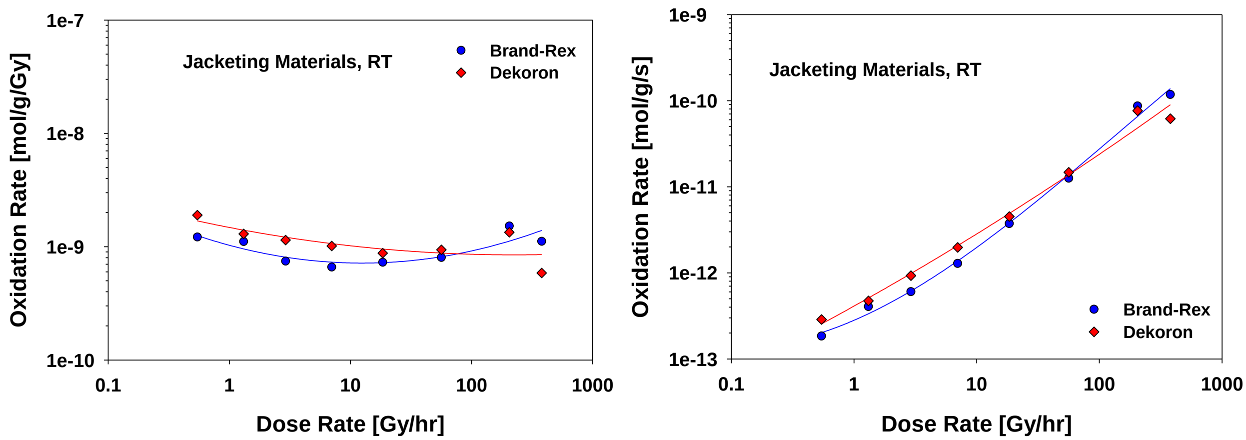

Figure 15 Radiation-thermal aging characterization with oxidation rates for Brandrex and Dekoron Hypalon cable jackets (left) and the corresponding oxidation rates in mols/g/s (right).

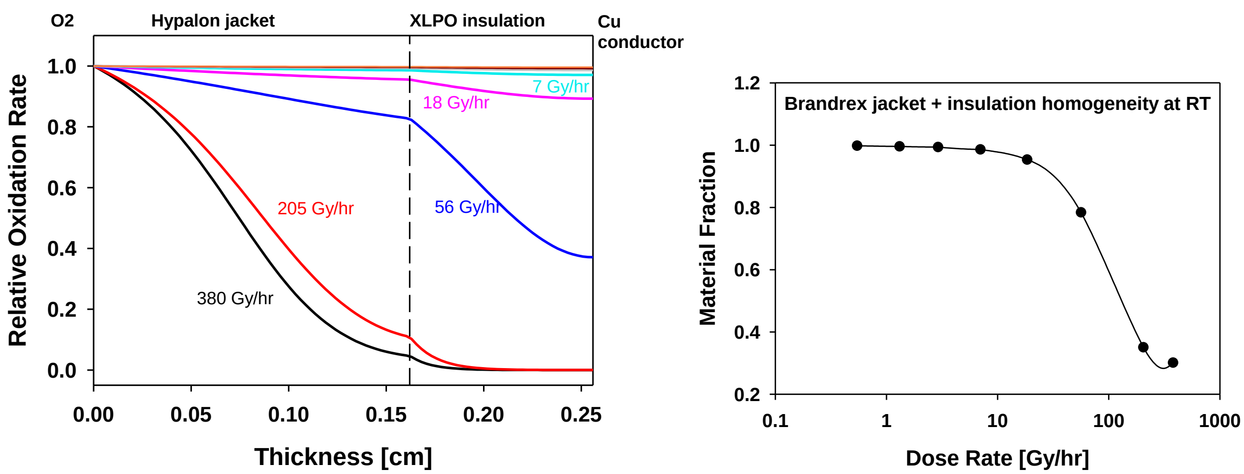

Figure 16 Demonstration of a simple spatial oxidation model for expected conditions in a Brandrex cable assembly under irradiation at RT (left) and the overall material fraction experiencing oxidative degradation (right). This 1D two material model uses the ox-rates determined in this study and a best estimation for jacket permeability. In this case the jacket, due to its intrinsic high oxidation rate, will act as an O_2 access barrier at the higher dose rates. The degradation will become homogenous at lower dose rates (here 7 Gy/h) with the XLPO insulation then experiencing significant oxidative damage. This situation has been discussed as the reason for fundamental differences in the aging mechanism between ambient aging and qualification testing and represents an important aspect in accelerated aging studies of cable assemblies [5].

2.9 Considerations for Diffusion Limited Oxidation Behavior for Radiation-Thermal Accelerated Degradation of Brandrex XLPO

There were some concerns that the LICA Brandrex XLPO material may show DLO complications at the higher dose rates. Such behavior complicates the determination of the material oxidation rates on a per weight basis for uncut specimens due to thickness limitations. As mentioned before, initial oxidation rate screening experiments showed the material being at the boundary of DLO degradation profile formation. Unfortunately, there appear to be slightly different formulation types of Brandrex XLPO available. Permeability was determined for insulation taken from a different cable spool than for oxidation rates, due to insufficient material availability for all LICA samples that were necessary. It is possible that an earlier version of the same cable type (the material for which the oxidation rate with dose rate series was measured) may have slightly higher permeability and be less sensitive to DLO degradation behavior under specific irradiation conditions.

2.9.1 Accomplishments in FY14

- Acquired O_2 permeability data for Brandrex XLPO as a proof of principle analysis.

- Conducted repetitive ox-rate measurements under LICA radiation-thermal conditions at the two highest dose rates for uncut and cut specimens, i.e. where DLO could interfere and prevent simple rate measurements. This is important since rates are expressed on a per weight basis and if not all of the material oxidizes equally, then an arbitrarily lower average oxidation is measured. Hence for proper ox-rate determination DLO conditions must be understood and eliminated if possible. If in doubt, two samples need to be compared with different thickness and checked for similar rates. Another way of crosschecking the analysis situation is by evaluating the DLO situation with simple model projections.

- A circular geometry DLO model was applied and DLO profiles were predicted for known combinations of permeability and oxidation rates (see Figure 17 through Figure 19).

- These models predict that at the highest dose rate of 380 Gy/h, the oxidation rates are sufficiently high that DLO could introduce complication into the analysis.

- Since permeability has a relative high activation energy of 49 kJ/mol, oxidation rates would have to increase with a higher E_a than this value to result in more pronounced DLO as the temperature is raised.

- The data obtained at the three temperatures offer an intriguing perspective, namely that the radiation dominated degradation process is not particularly sensitive to temperature. While the oxidation rates increase somewhat as the temperature is raised towards 80°C, this increase is insufficient to compensate for the concurrently increasing permeability and the net effect is a small reduction in overall DLO sensitivity.

- Having measured the oxidation rates at these conditions it was also possible to model predicted profiles with varying permeability. This is important should a slightly different Brandrex XLPO with similar ox-rates show a reduced permeability. This may in fact have been the situation in the initial screening studies where DLO was more of a concern.

- It was possible to project boundary oxidation rate conditions for all temperatures to distinguish between homogeneous (non-DLO) and heterogeneous (DLO) accelerated aging conditions for the material where permeability has been determined. These projections were conducted for both single sided and two-sided oxygen contact and are summarized in Figure 20.

- For example, for DLO behavior to develop at 140°C, the effective oxidation rates would have to be driven above 1e-8 mols/g/s for two-sided and 3e-9 mols/g/s for single sided conditions by the combined radiation-thermal process. It is currently unknown how this combined process develops at higher temperatures for effective oxidation rates.

- Similarly, the transition to DLO effects with increasing dose rates for single-sided and double-sided air exposure can be projected and this was accomplished for the three temperatures where rate data are available. Again, consistent with the discussion above the DLO contribution decreases slightly with increasing temperature.

- These experiments offer a fundamental perspective and resolution of combined radiation-thermal degradation. It is possible that the radiation dominated process may in fact show a non-linear Arrhenius behavior, e.g. with relatively low E_a at lower temperatures and a higher E_a at higher temperatures. If so, then DLO will become more important as the temperature increases at high dose rates, which is important for rapid accelerated aging exposures and, of course, qualification testing environments.

- It is important to also recognize that qualification testing involves cable assemblies and that the barrier effect, which is introduced by the jacket material, contributes two-fold, namely with loss of O_2 due to reaction and as an additional diffusion obstruction. Severe DLO conditions are projected for cable assemblies under high temperature high dose rate conditions with oxidation limited to the insulation surface and oxygen mostly consumed in the jacket material.

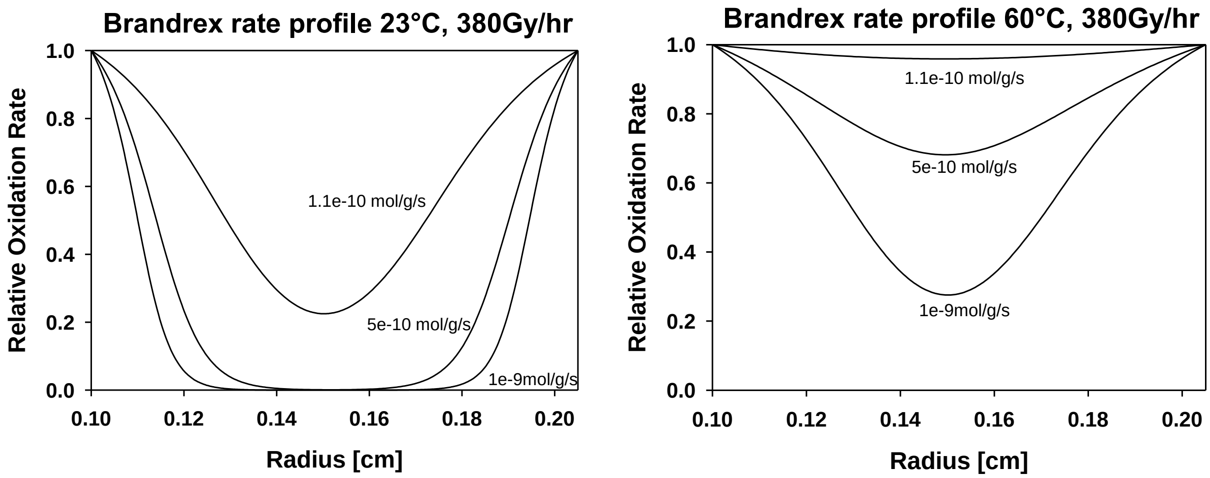

Figure 17 **Predicted degradation profiles for Brandrex XLPO cable insulation in LICA accelerated aging experiments at 23°C (left) and 60°C (right) with varying oxidation rates. In this case the conductor core is removed and both surfaces have access to oxygen in air. Because O_2 permeability is available (1.6e-10 ccSTP/cm-s-cmHg at 23 °C and 1.6e-9 ccSTP/cm-s/cmHg at 60°C) profiles can be modeled as a function of oxidation rate. These plots show that DLO effects (spatially dependent oxidation) are expected if the effective oxidation rates introduced mostly by the radiation initiated degradation process (380 Gy/h) are greater than ~ 1e-10 mol/g/s at 23 and 60°C.**

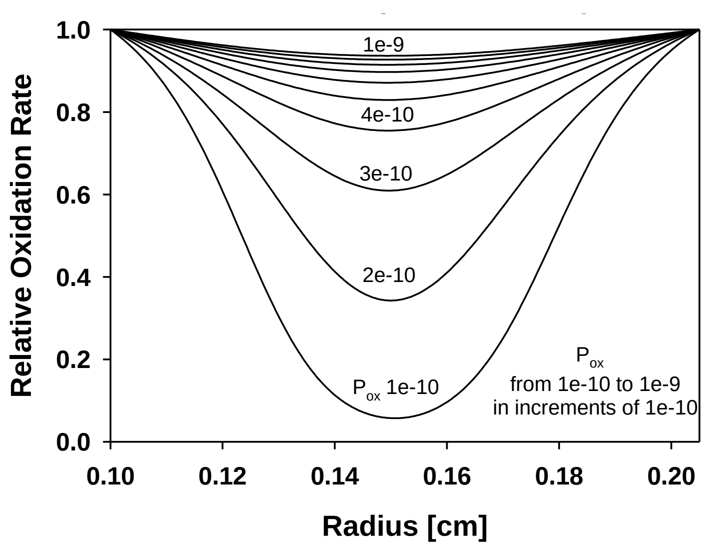

Figure 18 **Predicted degradation profiles for Brandrex XLPO cable insulation in LICA accelerated aging with varying permeability for 380 Gy/h and 60°C. In this case the conductor core is removed and both surfaces have access to oxygen in air. At these conditions an oxidation rate of 1.1e-10 mols/g/s was measured. An experimentally determined permeability of 1.6e-9 ccSTP/cm-s/cmHg at 60°C is at the margin of DLO profile development (here 90% homogeneity is predicted for 1.4 e-9 ccSTP/cm-s/cmHg). Slightly lower permeability or higher oxidation rates will result in DLO profiles and affect oxidation rate measurements for original sample geometry under these conditions.**

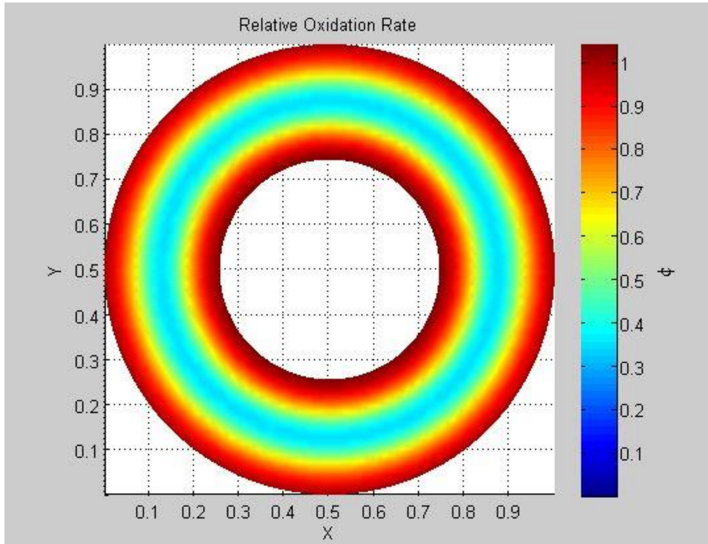

Figure 19 Example of the predicted oxidation heterogeneity (DLO behavior or preferential edge oxidation) during LICA accelerated aging exposure at 380 Gy/h and RT for a Brandrex XLPO. This is for air access at both sides with 13.2 cmHg O_2 partial pressure in ABQ, a wall thickness of ~ 1.9 mm, an oxidation rate of 1.1 e-10 mols/g/s, O_2 permeability 1.6e-10 ccSTP/cm-s-cmHg and beta of 5). We believe that the Brandrex XLPO type studied this year may have less DLO because of slightly higher permeability.

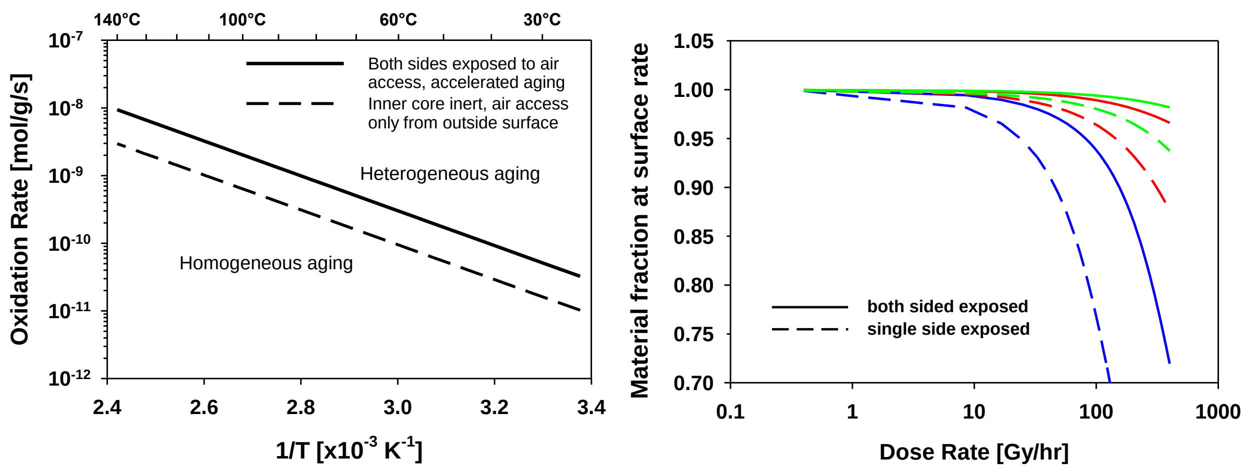

Figure 20 (Left) Predicted transitions between homogeneous (90% material fraction profile) and heterogeneous aging for Brandrex XLPO cable insulation as a function of overall oxidation rates should they result from thermal or combined radiation-thermal aging conditions. (Right) Transition to DLO effects with increasing dose rates for single sided and double-sided air exposure at three temperatures. Interestingly, the DLO level decreases slightly with increasing temperature. This is due to the relatively high activation energy for permeability (49 kJ/mol) and the fact that oxidation rates are not driven significantly higher with temperature (at least at these three temperatures) at high dose rate conditions.

2.10 Cable Aging Integration, Collaboration and Technical Support Activities during FY14

Within this DOE sponsored activity, SNL continued to provide expertise in polymer degradation and lifetime predictions as a science-based framework for the purpose of understanding the current condition of cable materials and residual performance projections in nuclear power plant environments. The ultimate goal is to assess and quantify current cable material state and expected performance sufficiently well to enable joint decisions with EPRI and NRC for cable material requalification or replacement recommendations. The work this FY included interpretation and advice on data and experimental methods, providing key input and guidance to both regulators and industry stakeholders. These included the NRC, DOE, EPRI, NIST, PNNL, ORNL, and other domestic and international stakeholders. Given the diversity of cable materials, environments, and histories across the U.S. fleet of commercial nuclear power plants, there are many competing needs for research that must be addressed in a timely manner to support relicensing decisions. In order to meet the LWRS programmatic goals and support DOE mission requirements, SNL provides the critical knowledge needed for evaluation of cable aging performance data and implications.

2.10.1 Accomplishments in FY14

Activities this FY included consultation, leadership, and participation in joint LWRS-EPRI Cable LTO integration activities. SNL provided detailed PowerPoint presentations for LWRS program leadership team stakeholder briefings. SNL also provided consultation, leadership and participation on international standards and committees. SNL offered consultation and evaluation of collaborative R&D efforts at PNNL and NIST, as well as international programs at CNEA. Integration included strategic planning, road mapping collaborative R&D efforts, identification of environments and cable types for acquisition for validation studies. Specifically, SNL hosted several joint LWRS-EPRI cable LTO integration meetings and teleconferences, and participated in 4 meetings total in this FY. SNL staff attended two face-to-face meetings at EPRI in Dallas, TX and at the EPRI cable users group meeting in Phoenix, AZ. SNL provided quarterly LWRS technical presentations. SNL helped reach a consensus with the cable aging community on a roadmap and path forward as detailed in a complete report detailing integration plan for joint cable research with EPRI and other stakeholders during the fall months. We prepared PowerPoint presentation with additional detail on cable aging studies supporting lifetime extension for NRC DLR program meeting on April 29th. SNL experts also provided a technical briefing for the LWRS MAaD Pathway lead in at a face-to-face meeting in Oak Ridge, TN. SNL staff attended and presented our work at the IEEE/PES Insulated Conductor Committee (ICC) Meeting in Kansas City in May 2014. Cable Aging Integration, Collaboration and Technical Support Activities during FY14 are outlined specifically in the activity timeline in Appendix A.

2.11 Considerations for Acquisition of Field-Aged Cables

The ultimate goal of all cable aging R&D activities is the confirmation or rejection of a reliable performance state for existing cable systems under extended operating conditions. This is part of the requalification process and feeds into NPP license renewal goals. There can be no doubt that predictive aging models based on accelerated aging data will always have an embedded degree of uncertainty, assumptions and predictive nature. The best avenue to re-qualify materials is a validation of predictive aging models with the state of field returned specimens and a quantification of margins, which have either been used up in their application environment or may remain for future performance. As part of this process field aged cable materials will need to be made available to the research community for current condition and remaining margin assessment studies.

In order to commence such evaluations, Sandia National Laboratories is seeking the following field-returned, low voltage cables acquired from nuclear power plants. Ideally, the cumulative exposure history for temperature and radiation doses should be known and reported as best as possible.

2.11.1 Data Needs for Field-Returned Cable Exposure History

A) Thermal only exposure:
   a. Average temperature
   b. High temperature limits

B) Combined radiation-thermal exposure:
   a. Dose rate
   b. Cumulative dose
   c. Average temperature
   d. Maximum temperature

2.11.2 Exposure Conditions for First Batch of Field-Returned Cables

A) Thermal only exposure:
   a. Preferred would be 40°C - 50°C
   b. If only 30°C or ambient T is available, this will still be useful.

B) Combined radiation-thermal exposure:
   a. Emphasis on maximum radiation exposure dose
   b. Temperature ideally not higher than 50°C
   c. High exposure dose is of most interest

2.11.3 Priority Materials to Enable Overview Perspective

A) XLPO materials:
   a. Brandrex
   b. Rockbestos
   c. Eaton Dekoron Polyset

B) EPR materials:
   a. Anaconda Durasheeth
   b. Okonite
   c. Anaconda Flameguard
   d. Eaton Dekoron Elastoset
   e. Kerite

C) Jacket materials:
   a. Hypalon®
   b. Neoprene
   c. Chlorinated polyethylene

2.12 Summary of LWRS Cable Aging Program in FY14

The SNL R&D efforts for the LWRS cable aging program conducted through FY14 have focused on a number of important areas. Much progress has been achieved and the following was accomplished:

- Identification of existing knowledge gaps with data reviews and community discussions.

- A review of existing data from the historical SNL cable aging database with a comparison of ten cable insulation materials for thermal only aging conditions.

- A review of aging data acquired in FY12-13 for cumulative dose and aging trends of three insulation materials to enable a comparison with existing aging data and DED evaluation. These recently conducted experiments are fully consistent with the previously observed behavior.

- The development of analytical methods for characterization of O_2 permeation in cable insulation materials.

- Implementation of concepts towards visualization of spatially dependent degradation processes in cable assemblies.

- New oxidation rate measurements for thermal only aging of 'aged' insulation as a foundation for wear-out aging approaches of field retrieved materials.

- Thermal controller re-design and implementation for safe operation of LICA sample exposure, systematically reviewed as part of ESH and SNL engineered safety requirements.

- LICA improvements which now enable access to an operational radiation-thermal exposure facility with dose rates in eight positions between 0.5 and 380 Gy/h.

- Collection of new oxidation rate data of two insulation materials across the full available dose rate range. Limited data as guidance for the jacket material were also obtained. With an international perspective this is first ever known data set of this type. Such data offer opportunities for deconvoluting thermal and radiation driven processes in future work.

- A systematic evaluation of DLO behavior under high dose rate conditions for the Brandrex material to validate the determined oxidation rates.

This broad based cable material characterization approach offers a foundation for an improved and fundamental understanding of aging processes and behavior under laboratory accelerated aging, qualification testing or field aging conditions. This is necessary to ultimately provide confident and scientifically founded data for the quantification of aging states of field returned materials and an assessment of remaining operational margins for requalification and license renewal for nuclear power plants.

Additionally, much support was provided to the cable aging community (EPRI, NIST, NRC, PNNL) in multiple meetings and R&D update discussions throughout the year as documented in a separate section of this report (see Appendix). A consensus was reached for the need to better understand aging processes as a requirement for improved predictive aging models. This is the topic where SNL is the leader in this community with extensive and documented expertise in polymer degradation and characterization of cable material aging phenomena.

The continuation of this work will focus on combining laboratory accelerated aging and predictive models with the feedback from field retuned materials when subjected to wear-out aging exposure. The challenges with quantifying extended cable lifetimes under a range of conditions also originates from the large number of individual cable/jacket materials and manufactures, with, unfortunately, often variable behavior under accelerated aging conditions. We believe that similar data sets and approaches as demonstrated this fiscal year will enable systematic comparisons of cable materials. This will offer an opportunity to group better and weaker performing materials for requalification purposes. On this note, it is possible that the most appropriate cable requalification approach will ultimately embrace a combination of predictive aging models, behavior of field returned materials and ongoing condition monitoring activities. For the latter to succeed, a systematic understanding of aging phenomena and correlations between aging state and condition monitoring parameters are required. This SNL work also provides the foundation for the selection of the most relevant and justifiable cable condition indicators.

3 SUMMARY OF OTHER FY14 DELIVERABLES

3.1 Integration Plan

This report summarizes the efforts for development of coordinated research activities between SNL and EPRI with regard to cable insulation aging programs. The memo report serves to fulfill the milestone from the statement of work (Memorandum Purchase Order 400128678): *Complete report detailing integration plan for joint cable research with EPRI and other stakeholders during the fall months; due 04/11/14.* See Appendix E for the full report.

3.2 PNNL Aged Samples Report

Ethylene propylene rubber (EPR) samples (15 kV Okoguard® aerial jumper cable) were obtained from Pacific Northwest National Laboratory (PNNL) and exposed to accelerated isothermal aging at Sandia National Laboratories. The purpose of this work was to generate a set of samples for rejuvenation work at PNNL. Each set of samples were exposed to different aging conditions (time and temperature) to ensure a widespread range of mechanical properties. Tensile tests were conducted throughout the aging process to observe the degradation of the material. To help elucidate aging behavior, the samples were placed in ovens ranging in temperature from 40°C to 138°C. A subset of these samples were analyzed and shipped to PNNL in June of 2014. See Appendix F for the full PNNL Aged Samples report.

3.3 Location Memo Report

The purpose of this study was to assess local radiation dose rate gradients within aging cans at the Low Intensity Cobalt Array (LICA) facility at Sandia National Laboratories. As radiation studies are an integral part of SNL's support of DOE's Light Water Reactor Sustainability (LWRS) program, it is important to understand whether or not the radiation dose rate gradients could affect aging data, and, if so, to what degree. Therefore, a series of dosimetry experiments were conducted to measure dose rates at different locations within the aging cans.

We concluded that while dose rate scatter throughout the can will exist, an approach of attempting to quantify and deconvolute such scatter with tensile elongation studies is not attractive. The quantification of local dose rate variations is very challenging (if not impossible) using these techniques if the material degradation behavior is not clearly understood. A much better approach to establish the nature of dose rate dependent degradation behavior for cable materials would be systematic experiments conducted over a large dose rate regime by using multiple aging cans in near and far field positions. See Appendix G for the full Location Memo report.

3.4 High Flux Isotope Reactor Report

The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL, located in Oak Ridge, TN, USA) is a neutron flux based research facility that is used by more than 500 researchers annually across a wide breadth of scientific areas. After a cable related incident at the facility, questions were raised with regard to the condition and aging/degradation of a certain cable insulation type. While these cables were not qualified to be nuclear power cables, they were similar enough that given the tools, techniques, and expertise developed for nuclear power plant cable insulation studies, SNL was asked to examine samples from HFIR. The goal of the study was to assist the HFIR facility understand the current status and provide first order predictions for the aging and degradation of their cable insulation. Sandia National Laboratories was provided ~16 m of various colored low voltage (one conductor, 1.3 mm wall thickness insulation, 900 Type THW 600 V) Anaconda Densheath (EPR) cables that were estimated to be ~45 years in age. The cables were removed from the High Flux Isotope Reactor at Oak Ridge National Laboratory (HFIR at ORNL) during an outage with the intention to assess how the cables aged with time.

The accelerated aging data for the 45-year field returned Anaconda Densheath EPR obtained from the High Flux Isotope Reactor at Oak Ridge National Laboratory has confirmed the suggested long lifetimes predicted from previous studies on Anaconda Durasheath EPR. The data sets, while not implying a complete aging study, confirm that adequate mechanical performance (i.e. >50%-100% elongation at break) remains for HFIR cable insulations and that there is likely on the order of decades of remaining life. Given that the question of remaining lifetime has been reasonably addressed, no further studies on this material are recommended. See Appendix H for the full HFIR report.

3.5 Comisión Nacional de Energía Atómica Report

A silicone (SiR) cable, which was stored in benign conditions for ~30 years, was obtained from Comisión Nacional de Energía Atómica (CNEA) in Argentina with the approval of NA-SA (Nucleoelectrica Argentina Sociedad Anonima) in collaboration with the US-Argentine Binational Energy Working Group (BEWG). Physical property testing was performed on the as-received cable. This cable was artificially aged to assess behavior with additional analysis. SNL observed appreciable tensile elongation values for all cable insulations received, indicative of good mechanical performance. Of particular note, the work presented provides correlations between measured tensile elongation and other physical properties that may be potentially leveraged as a form of condition monitoring (CM) for actual service cables. This work is an initial study that should be complimented with location-mapping of environmental conditions of Argentinean plant conditions (dose and temperature) as well as retrieval, analysis, and comparison with in-service cables. See Appendix I for the full CNEA report.

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APPENDIX A: SNL LWRS FY14 ACTIVITY TIMELINE

FY14 Funding

Date	Description	Amount
10/01/14	FY13 Carryover	~$80K
01/24/14	MPO 4000128678	$150K
05/09/14	MPO 4000128678– MOD1	$150K
07/17/14	MPO 4000128678– MOD2	$125K
	Total FY14 Funding	$425K (~$500K)

FY14 Deliverables and Research Activities

10/03/2013 – 10/04/2013 – Joint LWRS-EPRI LTO Meeting #1. Face-to-face meeting between between SNL, ORNL, PNNL, NRC, EPRI, and NIST in Dallas, TX.

11/08/2013 – Teleconference between J. McElhanon/ LWRS MAaD Pathway Lead to discuss program, new staff support, and Pathway Lead request for Sandia-LWRS 1, 3, and 5-year vision for program.

11/19/2013 – M. Celina & E. Redline join project.

11/19/2013 – Began discussions with LICA facility staff regarding upcoming radiation and radiation-thermal experimental plans.

11/21/2013 – Delivered FY2014 Q1 highlight slides to LWRS MAaD Pathway Lead.

11/26/2013 – Established number of cans available for LICA tests.

12/04/2013 – November highlights sent to LWRS MAaD Pathway Lead.

12/11/2013 – Teleconference between SNL/ORNL: "FY14 LWRS Cable Aging Program Strategy and Roadmapping". This meeting was held to solidify programmatic objectives for FY14 and discuss program road mapping for FY15 and beyond. Established funding level at $450K for FY14.

12/12/2013 – Began preliminary oxidation rate screening experiments at room temperature at LICA facility covering multiple dose rates. Three materials were investigated: Brandrex XLPO, Dekoron EPR, Dekoron XLPO.

12/13/2013 – Joint LWRS-EPRI LTO Meeting #2. Teleconference between SNL, ORNL, PNNL, NRC, EPRI, and NIST. "Joint LWRS-EPRI LTO Cable R&D Meeting Reconnect". The purpose of the meeting was to continue the discussion and discussion and progress we made at the meeting at EPRI in Dallas, TX on Oct. 3-4.

12/18/14 – Submitted updated slides outlining SNL FY14 work plan and milestones to LWRS MAaD Pathway lead.

01/08/2014 – Began collecting second experimental set of oxidation rate screening data at room temperature at LICA facility covering multiple dose rates. Three materials were investigated: Brandrex XLPO, Dekoron EPR, Dekoron XLPO.

01/08/2014 - December highlights sent to LWRS MAaD Pathway Lead.

01/08/2014 – SNL team institutes weekly LWRS team internal collaboration meetings. Team meets every Monday morning to discuss project and status on activities.

01/20-2014 – 01/24/2014 – Joint LWRS-EPRI LTO Meeting #3. Attended EPRI Cable User group meeting in Pheonix, AZ. Reached a consensus with the cable aging community on a roadmap and path forward.

01/30/2014 - Sandia receives $150K of FY14 LWRS funding from ORNL.

01/31/2014 – Began collecting third experimental set of oxidation rate screening data at room temperature at LICA facility covering multiple dose rates. Three materials were investigated: Brandrex XLPO, Dekoron EPR, Dekoron XLPO.

02/07/2014 - Began collecting fourth experimental set of oxidation rate screening data at room temperature at LICA facility covering multiple dose rates. Three materials were investigated: Brandrex XLPO, Dekoron EPR, Dekoron XLPO.

02/10/2014 – January highlights sent to LWRS MAaD Pathway Lead.

02/13/2014 – Began DLO experimental investigations at LICA on Brandrex XLPO, Dekoron EPR, and Dekoron XLPO.

02/13/2014 – Slide deck sent to LWRS MAaD Pathway Lead after his request for SNL slides which documented discussions about suggested community R&D directions we had during the face-to-face meeting in Phoenix in January 2014.

02/18/2014 – Completed temperature controller rack electrical safety Environmental Safety & Health review of the completely redesigned and rebuilt temperature controller system for LICA.

02/21/2014 – Second round of DLO experiments at LICA.

03/04/2014 – Teleconference with LWRS MAaD Pathway Lead, J. Aubert, J. McElhanon to discuss interpretation of Sandia data.

03/07/2014 – Set up temperature controller rack at LICA. Checked all cans to see how many were available for heating. Also noted which cans leaked.

03/17/2014 – SNL Monthly Status Report submitted to LWRS MAaD Pathway Lead. Including financial data and updated spend plan forecasting.

03/17/2014 – SNL emailed target acquisition list of field return cable types and updated draft of EPRI roadmap for cable aging to LWRS MAaD Pathway Lead.

03/18/2014 – Conducted LICA Facility walk-through and engineered safety readiness review.

03/19/2014 - Emailed technical PowerPoint presentation for the March 26 LWRS quarterly review to LWRS MAaD Pathway Lead.

03/21/2014 – Continued temperature controller rack set up at LICA.

03/24/2014 - Created additional slides for the March 26 LWRS quarterly review for the LWRS MAaD Pathway Lead and emailed that revision on this date.

03/28/2014 – LICA heating can set-up. All repairs were made to the cans at this point.

04/04/2014 – Dosimetry performed at LICA in columns B & C, rows 4 – 11.

04/04/2014 – SNL Monthly Status Report submitted to LWRS MAaD Pathway Lead. Including financial data and updated spend plan forecasting..

04/07/2014 –SNL LWRS project work plan submitted to LWRS MAaD Pathway Lead for formal concurrence.

04/08/2014 – Completed the LWRS milestone from the statement of work (Memorandum Purchase Order 400128678): Complete report detailing integration plan for joint cable research with EPRI and other stakeholders during the fall months.

04/10/2014 - Prepared PowerPoint presentation with additional detail on cable aging studies supporting lifetime extension for NRC DLR program meeting on April 29th. Updated slides after Face-to-Face discussion held on April 17 at ORNL. Assisted ORNL with clarification of slide content.

04/14/2014 – Dosimetry performed at LICA in columns A, B, C, D, rows 4 and 5 to investigate symmetry of field.

04/17/2014 – ORNL/SNL face-to-face meeting in Oak Ride, TN, to discuss program and LWRS objectives

04/21/2014 – SNL provided final slides to LWRS MAaD Pathway Lead for the for NRC DLR briefing on 5/6/14.

04/22/2014 – Dosimetry performed at LICA. This was a re-run of the same set-up used when dosimetry was performed on 02/15/2012 to compare current dose rates with the expected dose rates based on the 2012 data.

04/29/2014 – Dosimetry performed at LICA. This was a repeat of 04/22/2014 because we had a discrepancy between the predicted values from 2012 to the actual values obtained from the 04/22 test.

05/02/2014 – April highlights sent to LWRS MAaD Pathway Lead.

05/04/2014 to 05/07/2014– SNL attendance of IEEE/PES Insulated Conductor Committee (ICC) Meeting in Kansas City.

05/05/2014 – Dosimetry performed at LICA with height investigation in row 4.

05/06/2014 – Participated in the “Post NRC Division of License Renewal Meeting Update Call”.

05/06/2014 – SNL receives additional $150K FY14 LWRS funding

05/07/2014 – SNL Monthly Status Report submitted to LWRS MAaD Pathway Lead. Including financial data and updated spend plan forecasting.

05/19/2014 – Pencils added to LICA array to increase field.

06/04/2014 – Dosimetry of columns B &C, rows 4 – 11 to determine dose rates with new array at LICA.

06/06/2014 – Aged samples shipped to PNNL.

06/09/2014 – Deliverable: Memo for SNL-aged samples sent to PNNL.

06/09/2014 – May highlights sent to LWRS MAaD Pathway Lead.

06/10/2014 – SNL Monthly Status Report submitted to LWRS MAaD Pathway Lead. Including financial data and updated spend plan forecasting.

06/13/2014 – Conducted a repeat dosimetry measurement of 06/04/2014.

06/16/2014 – Deliverable: Radiation location memo review and approval completed and emailed to LWRS MAaD Pathway Lead.

06/16/ 2014 – Began acquiring thermal aging data for previously aged specimens. These experiments probed wear-out material behavior and continuity of oxidation rates with increased aging state at three different temperatures: 50, 80 and 110°C.

06/19/2014 – Began radiation and radiation-thermal experiments at LICA on Brandrex XLPO (16 samples of this material in total – 8 rad and 8 radiation-thermal) and Dekoron EPR (16 samples of this material in total – 8 rad and 8 radiation-thermal) at room temperature and at 60°C.

07/08/2014 – June highlights sent to LWRS MAaD Pathway Lead.

07/09/2014 – 07/10/2014 – SNL hosts Joint LWRS-EPRI LTO Cable R&D Meeting #4. Participants from EPRI, PNNL, ORNL, SNL, NRC, and NIST were present either in person or via telephone. Each participating organization was asked to present on their recent research progress and future plans. The roadmap was also discussed and users came to a consensus on path forward.

07/10/2014 – SNL Monthly Status Report submitted to LWRS MAaD Pathway Lead. Including financial data and updated spend plan forecasting.

07/14/2014 – 07/15/2014 – Presentations and meeting minutes emailed to joint LWRS-EPRI LTO Cable R&D Meeting #4 participants and LWRS MAaD Pathway Lead.

07/14/2014 – SNL receives final $125K of FY14 LWRS funding.

07/14/2014 - Completed the LWRS milestone from the statement of work (Memorandum Purchase Order 400128678): A final report on the work performed on the HIFR cables.

07/25/2014 – Teleconference with LWRS TIO and LWRS MAad Pathway Lead to discuss LWRS QA requirements.

August – September 2014 – Continued thermal only, radiation, and radiation-thermal aging experiments on Brandrex XLPO and Dekoron EPR. Radiation-thermal experiments were conducted at 60 and 80°C.

08/07/2014 – SNL Monthly Status Report submitted to LWRS MAaD Pathway Lead. Including financial data and updated spend plan forecasting.

08/08/2014 – SNL submitted completed LWRS QA Interface Document to LWRS MAaD Pathway Lead and LWRS TIO.

08/11/2014 - Emailed technical PowerPoint presentation for the LWRS quarterly review to LWRS MAaD Pathway Lead.

08/20/2014 – SNL submitted completed Error Propagation Analysis Document to LWRS MAaD Pathway Lead.

09/17/2014 – Completed the LWRS milestone from the statement of work (Memorandum Purchase Order 400128678): A final report on the silicone cable insulation (CNEA collaboration).

09/17/2014 – FY2014 year-end report completed. Fulfills DOE/NE LWRS Program Milestone Report: M2LW-14OR0404013.

APPENDIX B: SNL LWRS WORK PLAN

Sandia National Laboratories

MPO 4000128678
IEW Project 177265
LWRS Cable Aging Project

Fiscal Year 2014 to 2018 Work Plan

April 2014 Update

United States Department of Energy
Sandia Site Office

National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

ACRONYMS

CM	Condition Monitoring
DLO	Diffusion Limited Oxidation
DOE	Department of Energy
E_a	Activation Energy
EPR	Ethylene Propylene Rubber
EPRI	Electrical Power Research Institute
EQ	Equipment Qualification
FY	Fiscal Year
FYWP	Fiscal Year Work Plan
LICA	Low Intensity Cobalt Array
LTO	Long Term Objective(s)
LWRS	Light Water Reactor Sustainability
MAaD	Materials Aging and Degradation
MPO	Memorandum Purchase Order
NDE	Non-Destructive Evaluation
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
P	Permeability
PNNL	Pacific Northwest National Laboratories
R&D	Research & Development
SCRAPS	Sandia Cable Repository for Aged Polymer Samples
SNL	Sandia National Laboratories
SOW	Scope of Work
SSC	Structures, Systems And Components
T	Temperature
XLPO	Crosslinked Polyolefin

1 PROJECT MANAGEMENT INFORMATION

Project Baseline Summary (PBS) and Title	MPO 4000128678 IEW 177265 *SNL LWRS Cable Aging Project*
Performing Contractor:	Sandia National Laboratories Program Director: Peter Davies, Org. 06200 Program Department Manager: Patrick Mattie, 06233 Activity Department Managers: James McElhanon, 01835 James Aubert, 01819 Principle Investigators / Subject Matter Experts: Robert Bernstein, Mat Celina, Erica Redline
Work Breakdown Numbers/Titles	Level 1: 01: Robert Bernstein R&D 02: Mat Celina R&D 03: Erica Redline R&D
LWRS Materials Aging and Degradation Project Lead	Jeremy Busby, Oak Ridge National Laboratory
LWRS Technical Integration Office, Director	Kathryn A. Mccarthy, Idaho National Laboratory
LWRS Program Director	Richard A. Reister, U.S. DOE, Office of Nuclear Energy

1.1 LWRS Materials Aging and Degradation Project

Components serving in a nuclear reactor plant must withstand a very harsh environment including extended time at temperature, neutron irradiation, stress, and/or corrosive media. The many modes of degradation are complex and vary depending on location and material. However, understanding and managing materials degradation is key for the continued safe and reliable operation of nuclear power plants.

Extending reactor service to beyond 60 years will increase the demands on materials and components. Therefore, an early evaluation of the possible effects of extended lifetime is critical. The recent NUREG/CR-6923 gives a detailed assessment of many of the key issues in today's reactor fleet and provides a starting point for evaluating those degradation forms particularly important for consideration in extended lifetimes. While life beyond 60 will add additional time and irradiation, the primary impact will be increased susceptibility (although new mechanisms are possible).

The Materials Aging and Degradation (MAaD) pathway within the LWRS program is charged with R&D to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear reactors. The work will provide data and methods to assess performance of structures, systems and components (SSCs) essential to safe and sustained reactor operations. The R&D products will be used by utilities, industry groups and regulators to affirm and define operational and regulatory requirements and limits for materials in reactor SSCs subject to long-term operation conditions, providing key input to both regulators and industry.

The objectives motivation and organization of the MAaD pathway within the Light Water Reactor Sustainability Program is documented in ORNL/LTR-2012/327, Revision 0, *Light Water Reactor Sustainability Program, Materials Aging and Degradation Technical Program Plan*. The plan provides detail on the individual research tasks within the MAaD, describes the outcomes and deliverables of the MAaD, and lists the requirements for performing this research.

2 CABLE AGING PROJECT DESCRIPTION

2.1 Statement of Need

The motivation for R&D in this area comes from the need to address the aging management of in-containment cables at nuclear reactors. With nearly 1000 km of power, control, instrumentation and other cables typically found in a nuclear reactor facility, it would be a significant undertaking to inspect all of the cables. Degradation of the cable jacket, electrical insulation, and other cable components are key issues for assessing the ability of the currently installed cables to operate safely and reliably for another 20 to 40 years beyond the initial operating life. Currently, little or no data exist on long-term cable performance in nuclear power plants. In order to ensure reliable operation of sensors, controls, and monitoring systems, cable lifetimes and degradation must be understood. Cable insulation may undergo several forms of degradation due to extended exposure to a service environment that may include submersion in water, high humidity, elevated temperature, mechanical stress, and/or exposure to irradiation. Failure of cable insulation can lead to shorts and disconnects in important low and medium voltage cabling and signal cables.

This particular project will focus on thermal and radiation-thermaliation oxidative degradation for lifetime predictions of low voltage cable insulation and jacket materials using laboratory testing, improved predictive models, and in-service components for evaluation. This program excludes medium voltage and wet or submerged environmental conditions at this time.

This Fiscal Year 2014 to FY2018 Work Plan (FYWP) documents cable aging support to the Light Water Reactor Sustainability (LWRS) program. Within this DOE sponsored activity Sandia National Laboratories (SNL) will offer expertise in polymer degradation and lifetime prediction as a science based framework for the purpose of understanding current condition of cable materials and residual performance projections in nuclear power plant environments. The ultimate goal is to assess and quantify current cable material state and expected performance sufficiently well to enable joint decisions with EPRI and NRC for cable material requalification or replacement recommendations. Consistent with DOE mandated policies on scientific integrity, SNL will provide R&D services, which aim for high scientific and technical quality, objectivity, and can be supported through independent peer review. A sound science and technology base will help guide and inform the nation's critical public policy decisions and advance the energy security of the U.S.

The R&D outcome of this study will be used by utilities, industry groups and regulators to affirm and define operational and regulatory requirements and limits for materials subject to long-term operation conditions, providing key input to both regulators and industry. Given the diversity of cable materials, environments, and histories across the U.S. fleet of commercial nuclear power plants, there are many competing needs for research that must be addressed in a timely manner to support relicensing decisions. In order to meet the LWRS programmatic goals and support DOE mission requirements, research tasks within must meet at least one of the following key criteria:

- Degradation modes, which are already occurring and will grow more severe during extended lifetimes.
- Degradation modes with little or no mechanistic understanding and in need of long-term research.
- Degradation modes, which may be problematic for extended lifetimes with little/no supporting data.
- Degradation modes where work can follow-on or complement other national or international efforts.
- Areas where technical progress can be made in the near term.
- Identifying, formulating, and prioritizing all of these competing needs has been done in a collaborative manner with industrial and regulatory partners.

As stated in the relevant technical overview research plans for LWRS activities, such as ORNL/LTR-2012/327, Revision 0 and INL/EXT-12-24562, the focus of research directions and goals are repeatedly emphasized as:

- Development of the scientific basis for understanding and predicting long-term environmental degradation behavior of materials.
- Assessment of accelerated testing techniques, high quality data and mechanistic understanding delivered via reports and technical papers.
- Development of the fundamental scientific basis to understand, predict and measure changes in materials and systems, structures and components as they age, as well as identification of areas of concern and details of failure mechanisms.

Additionally, two primary activities for cable aging research in LWRS are listed below from *Light Water Reactor Sustainability Program, Materials Aging and Degradation Technical Program Plan* ORNL/LTR-2012/327, Revision 0, along with key outcomes for each task.

- Mechanisms of cable degradation: provides understanding of role of material type (i.e., EPR, XLPO, etc.), history, and environment on cable insulation degradation; understanding of accelerated testing limitations, support to partners in modeling activities, surveillance, and testing criteria.
- Techniques for NDE of cables: provides new technologies to monitor material and component performance.

In line with this intended focus, SNL science based experimental work and material testing efforts will focus on a mechanistic understanding of cable material aging behavior. This will examine the correlation of condition monitoring methods with prevailing aging phenomena, and the development of suitable predictive aging models, all targeted to enable justifications for cable requalification decisions. The SNL material science and testing efforts may need to be adjusted based on evolving experimental feedback and the complexity of observed material behavior. Sub-tasks may have changing emphasis as this project progresses and will be adjusted subject to the relevant assessments and opinions of SNL experts in coordination with program managers.

As part of this project and individual tasks the SNL team will deliver science-based engineering solutions addressing cable degradation mechanisms and provide best guidance for aged material states, remaining life and expected performance. As part of the execution of this project generic engineering tests will be combined with best practices from polymer degradation science to develop improved lifetime predictions models which incorporate known material behaviors and feedback from field returned 'aged' cable materials.

Research on the mechanisms of cable degradation should provide: an understanding of the role of material type, history, and the environment on cable insulation degradation, an understanding of accelerated testing limitations, and support to partners with modeling activities, surveillance, and testing criteria. This project will provide experimental characterization of key forms of cable and cable insulation in a cooperative effort with NRC and EPRI. Tests will include evaluations of cable integrity following exposure to elevated temperature, humidity, and/or ionizing irradiation. These experimental data will be used to evaluate mechanisms of cable aging and determine the validity or limitations of accelerated aging protocols. The experimental data and mechanistic studies can be used to help identify key operational variables related to cable aging, optimize inspection and maintenance schedules to the most susceptible materials/locations, and, in the long-range, design more tolerant materials.

The LWRS MAaD Pathway description of the Mechanisms of Cable Degradation activity is listed below from the *Light Water Reactor Sustainability Program, Materials Aging and Degradation Technical Program Plan* ORNL/LTR-2012/327, Revision 0, FY14 project milestones specifically addressed by the tasks documented in Section 3.0 of this work plan are in bold:

Product: Assessment of accelerated testing techniques, high quality data and mechanistic understanding delivered via reports and technical papers, support for model and performance predictions.

Lead Organization: Sandia National Laboratories.

Current Partners: For coordinated research activities SNL will partner with EPRI (technical input), NRC/NIST (technical input, complementary research scope) and PNNL (exchange of information and samples for PNNL aging mitigation strategies).

Recently Completed SNL Research Activities
The following describes recently accomplished SNL research output relevant to cable aging and performance predictions.

- NEPO report SAND2005-7331 "Nuclear Energy Plant Optimization (NEPO) Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials"
- Completed report detailing highest priority needs and concerns for future testing of cable insulation, SAND 2010-7266 "Review of Nuclear Power Plant Safety Cable Aging Studies with Recommendations for Improved Approaches and for Future Work"
- Published document on assessment of remaining margins for existing nuclear power plant cables, SAND2013-2388 "Nuclear Power Plant Cable Materials: Review of Qualification and Currently Available Aging Data for Margin Assessments in Cable Performance"
- Initiate testing on key degradation issues for cabling and cable insulation, *November, 2010*
- Initiate evaluation of possible mitigation techniques for cable insulation degradation, *March 2011*

Project Milestones/Deliverables:

- Provide data and testing progress for cable insulation aging and degradation, *on annual basis*
- **Assist in key analysis of key degradation modes of cable insulation, August 2014**
- **Initiate predictive modeling capability for cable degradation, November 2014**
- Complete assessment of cable mitigation strategies, September 2015
- Begin benchmarking of cable degradation model, March 2016
- Deliver predictive model for cable degradation, August 2017
- Future milestones and specific tasks will be based on the results of the previous year's testing, as well as ongoing, industry-led research.

Value of Key Milestones to Stakeholders: Research to identify and understand the degradation modes of cable insulation (2014) is an essential step to predicting the performance of cable insulation under extended service conditions. This data is clearly critical to develop and deliver a predictive model for cable insulation degradation (2017). Both will enable more focused inspections, material replacements, and more informed regulations. The development of in-situ mitigation strategies (2015) may also allow for an alternative to cable replacement and would be of high value to industry by avoiding costly replacements.

This plan documents project targets from FY14 to FY18.

2.2 Future Work Objectives

The following Sandia National Laboratories (SNL) key strategies are the underlying theme used in generating the work scope of this program:

1. Conduct Wear-Out aging studies on field returned cable specimens.
    - Assess current aging state where possible

2. Develop better predictive aging models which include long term low dose rate low temperature aging phenomena.

3. Enhance feedback from engineering tests by critically examining data and application of polymer aging science.

4. Reduce uncertainties in lifetime predictions by understanding unusual and complex material behavior and deconvoluting data where possible.

5. Incorporate specific cable material behavior as an integral part of lifetime prediction.

6. Couple experimental strategies with suitable aging and predictive models.

7. Develop aging models for multi conductor cable assemblies (insulation plus jacket).

The following is SNL's multi-year vision for cable aging work in support of LWRS and plant relicensing:

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

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

3. **Thermal-rad aging of XLPO and some EPR inverse T effect materials**
    Note: This group represents the most complex situation

- Review of existing data and basic lifetime projections (dose rate, dose, temperature effects)
- Verification checks for E_a, dose rate effects, etc.
- Compare existing and new high dose rate data
- Obtain low dose rate data and develop suitable models using feedback from rad-thermal of field returned specimens
- Final report with recommendations for projected lifetimes and constraints

Overall SNL contributions to LWRS and LTO R&D activities:

- **Goal:**
  - Develop a science based predictive aging and materials characterization effort to critically examine and support condition monitoring and EQ based lifetime extrapolation and re-qualification approaches

- **Justification:**
  - There is evidence for mechanistic variations in the aging behavior of cable insulation materials, which adds complexity and is not easily understood and extrapolated with EQ testing and CM methods
  - CM methods may provide momentary performance confirmation, but are limited in predictive value
  - Material aging behavior varies and may be different for 40-60 year old cables

- **Challenges:**
  - There is a significant amount of work due to the number and variations in insulation and jacket materials, new methods and models needing to be developed, and limits in exposure facility, time and funding constraints (more work than current funding allows)

3 WORK TO BE PERFORMED AND EXPECTED RESULTS

The following is a list of Sandia National Laboratories' (SNL) proposed FY14 tasks with individual milestones necessary to achieve the program goals discussed in Section 2. The FY14 tasks listed in this section include the tasks and deliverables listed in MPO#4000128678 dated 01/14/2014 (Attachment A) as well as additional tasks not yet funded.

3.1 FY14 Tasks and Beyond

3.1.1 Deliverables from SOW for FY14

Staff from ORNL, HFIR, will provide samples of cable that was removed in January 2012 from HFIRs MH3/HX Cell conduits for examination, inspection and testing. The cable is being provided solely to expand the basis of knowledge that currently exists in the nuclear industry regarding cable. EPRI/Sandia personnel are not being asked to postulate any potential accident scenarios that could be associated with the cable. Prior to publication or release to the public of any results findings or conclusions from examinations, inspection, or testing EPRI/Sandia personnel will provide HFIR staff copies of said information and the opportunity to review said information to ensure the completeness and accuracy of the information supporting the results, findings, or conclusions.

Sandia Laboratory must provide all resources necessary to accomplish the tasks and deliverables described in this statement of work (SOW). The deliverables as called out in Memorandum Purchase Order 400128678 is as follows:

1) Complete report detailing integration plan for joint cable research with EPRI and other stakeholders during the fall months; due 04/11/14
2) A final report on the work performed on the HFIR cables; due July 16th 2014 (per our agreement with ORNL this must be reviewed by them before it goes truly public).
3) A final report on the silicone cable insulation (CNEA collaboration); due Sept 17th 2014.

3.2 Proposed Activities for the Remainder of FY14 and Beyond

Subject to the availability of additional FY14 funding and beyond, SNL proposes to engage in the following activities which will accommodate the direction and milestones documented in the *Light Water Reactor Sustainability Program; Materials Aging and Degradation Technical Program Plan*[1]:

1. Acquire relevant plant cable insulation for additional testing
2. Complete key analysis of key degradation modes of cable insulation
3. Initiate predictive modeling capability for cable degradation
4. Complete assessment of cable mitigation strategies
5. Begin benchmarking of cable degradation model
6. Deliver predictive model for cable degradation
7. Future milestones and specific tasks will be based on the results of the previous years testing, as well as ongoing, industry-led research

SNL recognizes the above LWRS program goals and the subsequent sections address SNL research contributions toward completing these activities.

1. Acquire relevant plant cable insulation for additional testing

   While in existing LWRS documentation this milestone has been described as completed, SNL recognizes this task as an ongoing activity, where field retuned cable materials must be continuously acquired through collaboration between SNL, EPRI (plant operators), and ORNL. Any inability to acquire field returned cable materials represents a risk factor to the successful completion of this task.
2. Complete key analysis of key degradation modes of cable insulation

The SNL key contribution to this milestone is an expansion of thermal and thermal-radiation degradation of cable materials and acquisition of relevant data.

3. Initiate predictive modeling capability for cable degradation
   This is recognized as an important component of the SNL-LWRS program and the additional proposed FY14 work contains aspects that feed into this milestone. SNL also recognizes that this is a long-term ongoing activity.

4. Complete assessment of cable mitigation strategies
   SNL is supporting PNNL rejuvenation studies via accelerated aging of PNNL materials. This milestone requires further clarification with PNNL and ORNL regarding milestone goal, materials selection and evaluation of this potential technology.

5. Begin benchmarking of cable degradation model
   SNL has and will continue to engage in collection of relevant aging parameters, mechanistic description, and refinement of existing models. SNL's goal is to develop models that will allow a correlation between laboratory aged materials and the aging state of field retuned cable materials. It is important to recognize that a single model may not be feasible due to significant variation in material behaviors due to established complications from DLO, inverse temperature effects and non-Arrhenius behavior. Because of this, this milestone is a long term goal requiring a sound technical basis.

6. Deliver predictive model for cable degradation
   Existing predictive cable degradation models have continuously improved over time. An enhanced understanding of the complexity has introduced additional uncertainty in the models, therefore this requires a comprehensive approach which must incorporate an improved scientific basis for polymer degradation phenomena.

7. Future milestones and specific tasks will be based on the results of the previous years testing, as well as ongoing, industry-led research
   SNL will support this milestone based on additional communication between ORNL, EPRI, NRC, and NIST, as new tasks will be collectively identified.

Recognizing the programmatic scope of the LWRS effort and in additional communication with ORNL and EPRI, SNL proposes the following more focused and specific research activities subject to additional funding (new MPO) for FY14 and beyond. For all of these tasks beginning in FY14, progress will be documented in monthly and annual reports.

3.2.1 Liaise with other parties (EPRI/NIST/PNNL/NRC) and push for a consensus on what is needed in predictive cable aging work

This subtask is related to LWRS activities:

1. Acquire relevant plant cable insulation for additional testing
2. Complete key analysis of key degradation modes of cable insulation
3. Initiate predictive modeling capability for cable degradation
6. Deliver predictive model for cable degradation
7. Future milestones and specific tasks will be based on the results of the previous years testing, as well as ongoing, industry-led research

Sandia will assist EPRI with identification of gaps in the SCRAPS database and communicate with EPRI in User Group meetings or teleconferences as needed. Two cable user group teleconferences are to be scheduled by EPRI in FY14. The next face-to-face cable user group meeting will be at Sandia, July 9-10, 2014. EPRI and ORNL will assist SNL with acquisition of field aged cables. SNL will discuss with EPRI the scope and content of predictive models as part of the joint roadmap development.

As part of this activity SNL will also provide documentation for HFIR and CNEA cable studies, and aged samples to PNNL. Where SNL has relevant expertise we will discuss the aging behavior of cable materials with EPRI, Oakridge, NIST-NRC and PNNL to identify and fill gaps in the mechanistic understanding of degradation processes and to acquire suitable field returned specimens. SNL will also assist EPRI with a material science understanding of cable failures and interpretation of SCRAPS data via identification of knowledge gaps. SNL will provide the LWRS effort with a materials science based framework to deliver engineering solutions for cable aging and requalification, assist EPRI and PNNL with CM data interpretation, and provide best estimation of aging states for NRC/NIST LOCA cable and guidance to NRC/NIST for correlation of accelerated cable aging for LOCA requalification with plant conditions. These are ongoing activities and SNL will participate in meetings and communications as technical needs and additional follow-up work tasks develop. Activities commenced in October 2013 and will continue.

3.2.2 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.

This subtask is related to LWRS milestones:

2. Complete key analysis of key degradation modes of cable insulation
3. Initiate predictive modeling capability for cable degradation
5. Begin benchmarking of cable degradation model
6. Deliver predictive model for cable degradation
7. Future milestones and specific tasks will be based on the results of the previous years testing, as well as ongoing, industry-led research

The LICA facility is an integral part of accomplishing the LWRS milestones. The LICA facility requires substantial engineered safety modifications such that the capability is safe by design, as well as expansion of exposure capabilities. The LICA facility is necessary to conduct thermal/rad experiments to derive input data for predictive aging models which will provide guidance for cable lifetimes and subsequent lifetime extension efforts. SNL will conduct oxidation rate measurements to develop extrapolations with dose rate models; thermal/rad experiments are expected to begin by end of April 2014 and continue throughout FY14 and beyond.

3.2.3 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.

This subtask is related to LWRS milestones:

1. Acquire relevant plant cable insulation for additional testing
2. Complete key analysis of key degradation modes of cable insulation
3. Initiate predictive modeling capability for cable degradation
5. Begin benchmarking of cable degradation model
6. Deliver predictive model for cable degradation

SNL proposes to focus initially on a representative XLPO and EPR material with the goal of correlating field returned materials with accelerated laboratory aging behavior. This will be conducted by implementing a large range of dose rates in LICA, and via oxidation rate measurements for better predictive aging models. This will be complimented with tensile and wear out experiments if LICA exposure locations are available. XLPO and EPR are common insulation materials with XLPO and some EPR materials exhibiting inverse temperature behavior. SNL and EPRI will coordinate the acquisition of suitable materials. This will begin in FY14 and will continue through F18. Progress will be documented in monthly and annual reports.

3.2.4 Acquire field-aged specimens for condition monitoring work and wear-out testing.

This subtask is related to LWRS milestones:

1. Acquire relevant plant cable insulation for additional testing
2. Complete key analysis of key degradation modes of cable insulation
3. Initiate predictive modeling capability for cable degradation
5. Begin benchmarking of cable degradation model
6. Deliver predictive model for cable degradation

Field returned materials are a key requirement for the success of the LWRS program. They will be used to verify and validate predictive aging models and will deliver guidance for requalification and license renewal decisions. In particular, wear-out aging studies will be used to quantify remaining performance (‘lifetimes’) of field-aged cables. Thermal only experiments will be conducted first to address thermal degradation behavior. This will begin in FY14 and will continue through F18, but requires assistance from EPRI and ORNL. Progress will be documented in monthly and annual reports.

3.2.5 Complete radiation location memo

This subtask is related to LWRS milestones:

2. Complete key analysis of key degradation modes of cable insulation
6. Deliver predictive model for cable degradation

This work is conducted to understand the variation in dose rate dependent aging data gathered from the LICA experimental facility. This Radiation Location Memo will be completed by May 10, 2014.

3.2.6 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

This subtask is related to LWRS milestones:

2. Complete key analysis of key degradation modes of cable insulation
3. Initiate predictive modeling capability for cable degradation
5. Begin benchmarking of cable degradation model
6. Deliver predictive model for cable degradation

This work is necessary to establish solid reference database to validate and verify a predictive aging model. SNL hopes to improve predictions by understanding the complexity of aging parameters and using feedback from wear-out aging of field returned samples. Aside from documenting progress in annual reports, and conversations, a final document will be prepared in FY18 to provide guidance for requalification and license renewal decisions. Note that this should be possible for some materials, but perhaps not all cables based on experimental feedback, and SME opinions. For FY14 the existing thermal cable aging data will be reviewed to establish gaps. For the following years, similar work will be conducted for the thermal-rad condition. This will begin in FY14.

3.2.7 Assist PNNL in their rejuvenation program

This subtask is related to LWRS milestones:

4. Complete assessment of cable mitigation strategies

SNL will provide assistance to the rejuvenation program via sample preparation as well as technical discussion of characterization methods. PNNL samples subjected to accelerated aging at SNL will be sent to PNNL for testing and rejuvenation studies. A first shipment will occur by May FY14, with additional shipments of aged samples as the aging dictates.

3.2.8 LWRS materials aging & degradation program support & integration

This subtask is related to LWRS milestones:

1. Acquire relevant plant cable insulation for additional testing
2. Complete key analysis of key degradation modes of cable insulation
4. Complete assessment of cable mitigation strategies
6. Deliver predictive model for cable degradation
7. Future milestones and specific tasks will be based on the results of the previous year's testing, as well as ongoing, industry-led research

This subtask describes a commitment by SNL to foster a productive and collaborative relationship with Jeremy Busby, LWRS Pathway Lead, and other relevant parties.

- Complete work plan outlining project objectives with milestones and schedules defined. March 31, 2014
- SNL will prepare technical slides for ORNL as needed, such as March and April updates.
- Monthly reporting using new template. Commenced March 2014.
- SNL will support bi-annual project review meetings in person with Jeremy Busby, LWRS Pathway Lead. Commence April 2014.
- SNL will conduct monthly teleconferences with Jeremy Busby, LWRS Pathway Lead.
- SNL will support similar coordinated research activities with NRC-NIST and PNNL via meetings, teleconferences, and email communication as needed.

3.3 Science-Based, Long-term R&D Objectives

The strategic goals of the LWRS MAaD pathway are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess performance of SSCs essential to safe and sustained nuclear power plant operations. This information must be provided in a timely manner in order to support licensing decisions within the next 5-7 years. Near-term research is focused primarily on providing mechanistic understanding, predictive capabilities, and high-quality data. Longer-term research will focus on alternative technologies to overcome or mitigate degradation.

LWRS MAaD pathway goals from 2018-2023 include longer-term R&D that is expected to deliver key results in the 5-10 year program window. Highlights will include delivery and deployment of NDE sensors, predictive modeling tools, and mitigations strategies.

SNL longer term goals supporting the development of predictive modeling tools include development of material science framework will focus on the following necessary research areas to develop a better understanding of material behavior:

- **Ability to quantify Diffusion Limited Oxidation (DLO)**
  - DLO affects all accelerated aging. What does this mean for existing data sets, Equipment Qualification (EQ), current aging studies and condition monitoring?

    - Measure oxidation rates and permeability (P), with temperature (T), to develop quantitative models and set framework for material properties
    - DLO needs to be quantified. This requires suitable models to predict oxidation profiles as a function of dose rate, temperature, material type and geometry
    - Need to measure ox-rate and permeation for multiple materials for range of temperature, degradation state and dose rates
    - Need to develop methods to determine permeation for insulation specimens (experimental permeation for cylinders and indirect approaches via dose rate variation)
    - Develop quantitative models which will enable a better characterization of integrated oxidative states under varying degradative conditions

- **Probe accelerated aging towards low dose rates, low doses and T**
    - Develop rad thermal predictive models, guidance for extrapolations
    - Can ox-rate help with predictions? How does inverse-T contribute?
    - Conduct extensive aging studies towards low T low dose rates
    - Examine material behavior for inverse T, dose rate dependencies and other mechanistic variations (critical oxidation levels)
    - Develop better understanding of material behavior to quantify when radiation exposure becomes less important
    - Examine if there is a commonality in failure oxidation levels which could be used for extrapolative models
    - Establish how oxidation rates could be used for predictive purposes

- **Condition monitoring affected by DLO and inverse T**
    - Provide advice on DLO and aging state for other projects if requested
    - Inverse T effect and DLO need to be understood as they feed into field-aged samples and CM approaches
    - Quantify heterogeneity aspects for highly accelerated radiation aging via DLO
    - Guidance needs to be provided on mechanistically driven differences in material states as they could affect CM methods
    - Establish the differences between 'polymer material' and electrically based CM
    - Document complications for CM approaches when aging is affected by inverse T and when accelerated aging versus plant conditions suggest homogeneous vs. heterogeneous aging behavior applies

- **Wear out aging**
    - Probe fractional aging behavior, show example for condition monitoring plus follow up aging, fast-slow and slow-fast, explore test options and material behavior. Can dose rate dependencies be identified, explore gel-swell as indicator
    - Understand the aging behavior in comparison with field returned materials
    - Explore the application of 'wear out aging' to laboratory and field specimens
    - Probe fractional aging behavior, examine fast-slow and slow-fast cumulative aging behavior, explore test options and material behavior, can dose rate dependencies be identified in this manner?
    - Explore suitability of gel-swell or other methods as indicators

    - Need to identify at least one suitable diagnostic tool
    - DLO, inverse T and dose rate condition need to be carefully considered
    - Proof of principle study for XLPO (Brandrex) and EPR
    - **Key goal: Couple basic condition monitoring with cumulative aging approaches**

- **Thermal only aging**
    - Consolidate data, add oxidation rates where needed and generate best Arrhenius plots and likely extrapolations, add DLO quantification
    - Compile and examine existing data, add quantification of DLO which requires oxygen permeability, oxidation rate and cylindrical models
    - Support existing aging kinetics with oxidation rates for validation and extrapolative purposes
    - Generate best Arrhenius plots and likely extrapolations for intrinsic thermal behavior, note: this does not include combined thermal-humid environments
    - Define failure states and couple with shift factors for lifetime prediction purposes
    - Compile data into report with guidance for individual materials
    - Comment on aging of single insulation versus cable assemblies

3.4 Key Planning Assumptions

This section summarizes the major assumptions embedded within the proposed work scope tasks for this FY and beyond. Key planning assumptions are:

3.4.1 Acquisition of field aged samples

We will ask the project partners for field-aged materials as soon as possible to begin wear-out aging work. Retrieved cables will be studied for current aging state and remaining life extrapolations. Data will be correlated with previous aging data and knowledge of material behavior to improve aging models and predictions. Obtaining field aged cables is an integral aspect of this project.

3.4.2 Development of suitable predictive models

Any lifetime extrapolation of polymeric materials relies on assumptions and best guesses for specific aging parameters and an understanding of individual material behavior. There is no guarantee that sufficient information can be obtained in all cases for multiple materials under various exposure conditions to result in justifiable, scientifically defensible, confident or most plausible residual lifetime extrapolations. There is an intrinsic uncertainty associated with extrapolations as well as quantification of residual performance margins. This project aims to narrow uncertainty via an improved understanding of material behavior and confirmation of previous material performance via field returned specimens.

3.4.3 *Ability to clearly define aging behavior*

While generic engineering tests may provide some guidance for lifetime projections of specific cable materials under wear out conditions, it is, however, known that for many materials and exposure conditions the aging behavior is rather complex. This means that project success depends on a much better understanding of aging phenomena under low dose rate and combined environmental conditions within a detailed material science framework. Success depends to a large degree on understanding aging mechanistic variations and specific material behavior, as well as oxygen diffusion phenomena, DLO, oxidation rate behavior and correlations between degradation chemistry and physical property changes for different materials under various exposure conditions. Unless such aspects are sufficiently addressed this project will have significant constraints and embedded uncertainty.

3.5 FY14 Budgeted Cost Baseline Profile

3.5.1 *Total Annual Cost Profile*

FY13 carryover: $80,634
Proposed FY14 BA: $450,000
Total Budget for FY14: $530,634

3.5.2 *Time-Phased Budgeted Cost*

(Dollars in Thousands)														FY14
														Totals
		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	
FY 13 Carry Over	Actual	19.8	15.5	22.0	24.2	-.9	--	--	--	--	--	--	--	80.6
	Planned	19.8	15.5	22.0	24.2	-.9	--	--	--	--	--	--	--	80.6
FY14	Actual	0.0	0.0	0.0	5.9	40.7	62.5	--	--	--	--	--	--	109.1
	Planned	0.0	0.0	0.0	5.9	40.7	62.5	54.5	68.2	54.5	54.5	68.2	41	450.0

3.5.3 *Budgeted Cost Assumptions*

Proposed FY14 total budget of $530.6K (Originally $450K – Based on discussion between Busby/Bernstein 12/2013, increased to $530K due to additional tasking and labor for March – April 2014).

FY13 carry-over funding (October 2013 - Jan 30, 2014): $80K (Spent to on–board Redline, Celina, support LICA, cable user group meetings, etc.)

Received $150K under MPO 4000128678 on 1/31/2014

Line item expenditures/estimated costs for FY14:

- ORNL Trip 4/16-4/17- $10K
- HFIR Report - $30K
- Argentinian Report - $30K
- Location Memo - $ 2K
- LICA Readiness - $50K

- Year End Report - $10K
- Task 3.2.8 - $20K

Sub Total: $152K

FY14 Proposed Technical Work is estimated at a level of effort of $378K supporting the technical tasks and experiments described in Section 3.2.

Further granularity regarding the proposed spending supporting FY14 tasks will be provided during the SNL cable aging program review meeting at ORNL on April 17, 2014.

3.6 FY14 Schedules, Milestones and Deliverables

Operations Activities (OA) Annual Work Plan		
Key Milestone/Deliverable	**Delivery Date**	**Driver**
Monthly Updates	Ongoing through FY14	LWRS reporting requirement
Monthly Teleconferences	Ongoing through FY14	SNL/ORNL communication plan
Deliver Aged Samples to PNNL	Ongoing through FY14	3.2.7 Assist PNNL in their rejuvenation plan subtask
Acquisition of Field Returned Samples: Deliver table listing field aged samples desired, by cable type and environmental history	March 10, 2014	3.2.4 Acquire field-aged specimens for condition monitoring work and wear-out testing subtask
Power Point Presentation on SNL LWRS cable aging program for DOE NE Quarterly Program Review.	March 19, 2014	3.2.8 LWRS material aging & degradation program support & integration subtask
Support ORNL presentation to NRC on cable aging research to support life extension	April 10, 2014	3.2.8 LWRS material aging & degradation program support & integration subtask
LICA Experimental Apparatus Radiation Exposure Location Memo	May 10, 2014	3.2.5 Complete radiation location memo subtask
LICA Operational	April 30, 2014	Necessary to have LICA operational for rad-thermal experiments to begin.
Initiate rad-thermal experiments in LICA	April 30, 2014	Data will form the basis for improved predictive models
Joint LWRS-EPRI LTO Cable R&D Meeting hosted by SNL	July 9-10, 2014	Community engagement and consensus building
Assist in preliminary analysis of degradation modes	August 31, 2014	LWRS focus – needs further clarification from Jeremy Busby, Pathway Lead
1.1.1.1 Deliverables in MPO 4000128678, 01/14/2014		
Report detailing integration plan for joint cable research with EPRI and other stakeholders	April 11, 2014	Milestone 1, MPO 4000128678
HFIR Cable Samples Evaluation Report	July 16, 2014	Milestone 2, MPO 4000128678

Argentinian Silicon Cable Radiation Aging Evaluation Report	September 17, 2014	Milestone 3, MPO 4000128678
Year-End Summary Report	September 30, 2014	LWRS reporting requirement

4 COMMUNICATIONS

4.1 Monthly Reporting

The project will provide a monthly summary and status report documenting the incremental progress towards completion of each of the tasks conducted within each reporting period. The monthly report will list a summary of the technical progress for each of the FY tasks, any anticipated or encountered problem areas, plans or the next month, status of key milestones listed in Section 4 of this work plan, products and monthly financial status.

4.2 Bi-annual program review meetings

Sandia will coordinate with the LWRS Materials Aging and Degradation Project Lead to participate in semi-annual face-to-face project review meetings. Based on the current schedule of activities one will be scheduled in April 2014 and the second October 2014 or as close to those time periods as possible. It is preferable to have one meeting at SNL and one meeting at ORNL. Sandia will report on the activities and tasks listed within this work plan.

4.3 Monthly Teleconferencing Between SNL & ORNL

Sandia will engage in monthly teleconferencing updates with ORNL subject to availability of both parties.

4.4 Other

Correspondence with LWRS Materials Aging and Degradation Project Lead, or other LWRS program leadership as needed over the duration of the project work scope. Email communications, teleconferences and attendance at program and or industry collaborative workshops.

5 PROJECT RISK IDENTIFICATION

5.1 Risk Register Data

1. Competing DOE priorities could require personnel time and thus their removal from the program, permanently or temporarily.
2. Discontinuity of funding.

3. The inability to acquire well-characterized field aged returned cable materials represents a risk factor to the successful completion of this task.
4. Facility issues or unexpected non-availability of LICA. Limitations in LICA can capacity, such that complimentary tensile wear out experiments cannot be conducted in parallel with oxidation rate experiments for predictive models.
5. Limits in conducting some specific science based research activities which SNL subject matter experts deem necessary to meet the objectives of LWRS. Differing opinions between SNL and other partners may exist regarding the value, goals and outcomes of some scientific based research sub-tasks as they evolve.

5.2 Risk Mitigation Actions

1. Addressing any unexpected personnel changes, three staff members are currently listed as principle investigators and part of the SNL-LWRS team. It is unlikely that all three would separate from the program in FY14 (temporarily or permanently).
2. Program manager will be made aware of any funding concerns. Staff is prepared to mitigate long term constraints to insufficient funding by notifying program manager.
3. The unavailability of field-aged materials is a significant risk to this program. A mitigation strategy involves studies on "new" cables, which will be used to create better performance prediction models while waiting for field returned cables.
4. In terms of LICA availability, previous thermal excursions in irradiation facility resulted in SNL providing internal funding to repair and replace materials. Further issues are not expected but unforeseen events are a possibility. Additional aging cans to increase capacity will require additional funding sources.
5. In terms of research conduct SNL will exercise best judgment and offer relevant expertise in polymer material degradation science and engineering. SNL offers suitably qualified subject matter experts with substantial experience in polymer material aging phenomena. This expertise will be made available with integrity and any interpretation of research data will be conducted in an open, honest and unbiased manner which could withstand a critical peer-review process by other qualified subject matter experts.

6 KEY PERSONNEL

6.1 Technical direction

Contract Manager, Jeremy Busby, who can be reached at:

Jeremy T. Busby
Phone: (865) 241-4622
Email: (busbyjt@ornl.gov)

Technical direction includes interpreting specifications, providing needed details, and suggesting possible lines of inquiry. Technical direction must not constitute new work or affect overall project cost or period of performance, without a modification to this work plan. Technical direction must be confirmed in writing to the DOE laboratory.

6.2 Sandia Principle Investigators / Subject Matter Experts

Erica Redline
Erica Redline is a Senior Member of the Technical Staff in the Organic Materials department at Sandia National Laboratories in Albuquerque, NM. Erica's primary research interests involve polymers, polymer composites, and failure/degradation mechanisms and structure property relationships in polymeric materials. She received a B.S. from the Pennsylvania State University with a concentration in polymer science and a Ph.D. from the University of Minnesota focusing on toughening thermoset polymers. Erica spent two years working in the Polymer Engineering group at E. I. DuPont de Nemours & Co. in Wilmington, DE where she was responsible for the design and scale-up of manufacturing processes for new polymer products and foodstuffs. In that role, Erica used in situ monitoring of extrusion processes to improve product consistency of a reactive polymer blend. She also assisted in creating an alternative, lower-cost way to process food additives using traditional polymer processing equipment. Additionally, Erica served as DuPont's technical lead for an outside contracting job where her team identified different packaging materials and their processing/application methods to reduce the customer's product losses. Erica came to Sandia in October of 2013 to begin investigating polymer aging and degradation. She is currently studying elastomer performance in high temperature, high pressure environments as well as degradation pathways of polymeric materials in thermal and thermal-radiation environments. Erica is an active member in several professional and technical groups including: Society of Plastics Engineers, Society of Women Engineers, American Chemical Society, and the Energy Rubber Group. Phone: (505) 845-9161 Email: emredli@sandia.gov

Mat Celina
Mathew Celina is a Principle Member of the Technical Staff in the Materials Characterization and Performance department at Sandia National Laboratories in Albuquerque, NM. He is an internationally recognized researcher and subject matter expert with R&D interests in polymer materials science and chemistry related to the performance assessment, optimization, qualification, characterization, degradation and lifetime prediction of polymeric materials. He has experience as an academic lecturer at a technical university, held positions in small and large industry, has acted as an independent expert witness and has provided consultancy support for numerous projects related to polymer materials performance. He obtained a chemical engineering degree with emphasis on polymer materials, plus an M.S. and Ph.D. degree in physical polymer chemistry with a focus on polymer degradation concepts. He has lived and worked in three countries (USA, Australia, Germany) with extended stays in the UK and France. He routinely reviews research papers for multiple peer-reviewed journals and acted as the US editor of the journal 'Polymer Degradation and Stability' from 2006-11. He is a key member of the global polymer degradation academic community and engages in the organization of conferences. Other highlights are: Invited associate professor (3 month sabbatical) at ENSAM in Paris/France in 2006 and invited visiting professor for 2014. Organizer of symposium #113 'Polymer Performance and Degradation' at the 2005 Int. Pacifichem conference. Organizer of the ACS symposium 'Polymer Degradation, Optimization and Performance' at the 2007 ACS

National Spring meeting. Invited key note address and organizer at the 2009 PPC11 Ultimate Stability of Nano-structured Polymers and Composites symposium. Editor of the ACS symposium series book #978 Polymer Durability and Radiation Effects. Editor of the ACS symposium series book #1004 Polymer Degradation and Performance. Organizer for symposium #64 ‘Polymer Materials Performance, Degradation and Optimization’ at the 2010 Int. Pacifichem conference. Invited key note address for the 2010 Modification Degradation and Stabilization of Polymers Conference. Invited plenary lecture and committee member for 2012 MODEST conference in Prague "Polymer Oxidation and its Impact on Materials Performance and Lifetime Prediction". Organizer of the upcoming ACS fall 2014 POLY symposium ‘Polymer Degradation, Performance and Ultimate Stability’ and a session at the 2015 Pacifichem. He has been a member of an international scientific committee reviewing materials aging R&D as part of a IRSN managed 10 yearly re-qualification and safety review of all operational French nuclear power plants, and more recently provided an assessment of the scientific framework for cable material performance margins for the US nuclear regulatory commission. He is familiar with radiation effects on polymers, space degradation and dose rate anomalies, degradative property correlations and the challenges with Arrhenius behavior for lifetime prediction and extended qualification needs. In summary: Broad science and engineering based knowledge in polymer materials science and chemistry, materials performance and optimization strategies. Intellectual leader of many past research programs, as evidenced by key contributions, many well-referenced first authorship papers, and past SNL performance reviews.
Phone: (505) 845-3551 E-mail: mccelin@sandia.gov

Robert Bernstein

Robert Bernstein is a Principle Member of the Technical Staff in the Organic Materials department at Sandia National Laboratories in Albuquerque, NM. Throughout his career he has tried to maintain a broad science based background. He earned a bachelor’s degree in Chemistry and a bachelor’s degree in Biology, along with a minor in Spanish from University California, Irvine. He then obtained a Ph.D. in Chemistry from University of California, Los Angeles (UCLA). In the group of Prof. Christopher Foote his research area was physical organic photochemistry with emphasis on singlet oxygen studies. Subsequently, he performed post-doctoral work at UCLA in another group focusing on polymer studies involving the induction of chirality to polyaniline. In 2000 he began work at Sandia National Laboratories in the Organic Materials Department in the area of polymer aging and degradation. He continues to age and degrade along with the various organic materials of concern for customers both internal and external to Sandia. A few examples of the types of programs he has worked on; nuclear power plant wire insulation, various o-ring materials, aircraft wire insulation, missile defense materials, conducting polymers, capacitor materials, nuclear weapon materials, and general organic polymer studies on materials of interest to both the Department of Defense/Department of Energy community as well as commercial companies. His work has included organic material problem solving, compatibility concerns, material aging issues such as predictions of physical property changes as a function of time, and even detailed mechanistic understanding of the chemistry of degradation. He is always looking for new programs that will utilize his problem solving skills, hopefully ones that will move him into areas he has not previously explored. Phone: (505) 284-3690 E-mail: rbernst@sandia.gov

7 REFERENCES

(1) Busby, J. T. "Light Water Reactor Sustainability
Program; Materials Aging and Degradation Technical Program Plan," Fuel Cycle and Isotopes Division, Oak Ridge National Laboratory for U.S. Department of Energy, Office of Nuclear Energy, 2012.

(2) Memorandum Purchase Order 4000128678, 01/14/2014, UT-Battelle, LLC to Vendor Number 900040-Sandia Corporation – Sandia National Laboratories.

(3) *DOE-NE Light Water Reactor Sustainability Program and EPRI Long-Term Operations Program – Joint Research and Development Plan*, Revision 2, April 2013. INL/EXT-12-24562.

A. MEMORANDUM PURCHASE ORDER 4000128678

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY

UT-Battelle, LLC
Acting under contract DE-AC05-00OR22725
With the U.S. Department of Energy
Internet: http://www.ornl.gov/adm/contracts/index.shtml

Page 1 of 4

MEMORANDUM PURCHASE ORDER

Vendor Address

Vendor Number: 900040
SANDIA CORPORATION
SANDIA NATIONAL LABORATORIES
P.O. Box 5800
ALBUQUERQUE NM 87185-0100

Ship To:

Attn: 4000128678
UT Battelle, LLC for the Dept. of Energy
c/o Oak Ridge National Laboratory
1 Bethel Valley Road, Bldg 7001
Oak Ridge TN 37830

Submit Invoices To:

UT-Battelle, LLC - Accounts Payable
Email pdf file to ornlap@ornl.gov or
Fax to 865-241-1080

Agreement Form

Purchase Order:	**4000128678**
Purchase Order Date:	01/24/2014
Payment Terms:	Net 30 Days - No discount
Buyer:	ICP/Susan Horne
Phone:	865-241-2873
Fax:	865-241-1034
Email Address:	HORNESS@ORNL.GOV
Performance Period Begin:	01/24/2014
Performance Period End:	09/30/2014

(X) Please sign and return one copy as acceptance of this purchase order. (*Checked if applicable*)	**UT-Battelle, LLC (Company) agrees to award this Purchase Order to the vendor named above. The rights and obligations of the parties to this Purchase Order are subject to and governed by this document and any documents attached or incorporated by reference.**
Signature / Date: Tonya Vigil 1-27-14	**Signature / Date:** Susan Horne — Digitally signed by Susan Horne DN: cn=Susan Horne, o=Contracts Division, ou, email=horness@ornl.gov, c=US Date: 2014.01.24 15:10:57 -05'00'
Name / Title: Sonya Vigil SNL WFO Office	**Name / Title:** Susan Horne / Subcontract Administrator

Supplies or Services and Prices
Furnish the following in accordance with the terms of the purchase order.
Show purchase order number on all packages, B/L, and, if required, invoices.

Item	Material/Description	Quantity	UM	Deliver By	Unit Price	Extended Price
1	Complete report detailing integration	1.00	JOB	09/30/2014	$ 150,000.00	$ 150,000.00
					Total Value Excluding Tax	$ 150,000.00

MEMORANDUM PURCHASE ORDER
4000128678

Specifications/Statement of Work

STATEMENT OF WORK
01/10/2014

Staff from Oak Ridge National Laboratory's (ORNL) High Flux Isotope Reactor (HFIR) will provide samples of cable that was removed in January 2012 from HFIR's MH3/HX Cell conduits for examination, inspection, and testing. The cable is being provided solely to expand the basis of knowledge that currently exists in the nuclear industry regarding cable. EPRI/Sandia personnel are not being asked to postulate any potential accident scenarios that could be associated with the cable. Prior to publication or release to the public of any results, findings, or conclusions from examinations, inspection, or testing, EPRI/Sandia personnel will provide HFIR staff copies of said information and the opportunity to review said information to ensure the completeness and accuracy of the information supporting the results, findings, or conclusions.

Deliverables:

(1) Complete report detailing integration plan for joint cable research with EPRI and other stakeholders during the fall months; due 4/11/14.
(2) A final report on the work performed on the HFIR cables; due July 16th (per our agreement with ORNL this must be reviewed by them before it goes truly public).
(3) A final report on the silicone cable insulation (CNEA collaboration); due Sept 17th.

Payment Information

MPO - Accounting Method

(a) This order is a Memorandum Purchase Order (MPO) issued for services to be performed or supplies to be furnished which are required in connection with Company work for DOE. Accounting for the cost of the services or supplies shall be in accordance with the DOE Accounting Handbook. Invoices must be submitted in accordance with the MPO line items. Total amount of order should not be exceeded without prior written approval of the Company.

General Provisions

NOTE: Standard government forms (SF) mentioned herein are available at http://www.gsa.gov/forms. Other forms, clauses, articles, and documents are available at our web site, http://www.ornl.gov/adm/contracts/documents.shtml.

Any Representations and Certifications submitted by the Seller that resulted in this document are incorporated by reference.

All articles and documents incorporated by reference, including those made a part of General Provisions, apply as if they were set forth in their entirety.

Tasks to be performed under the terms and conditions of DOE Contract DE-AC004-94AL85000.

Special Provisions

NOTE: Standard government forms (SF) mentioned herein are available at http://www.gsa.gov/forms. Other forms, clauses, articles, and documents are available at our web site, http://www.ornl.gov/adm/contracts/documents.shtml.

All articles and documents incorporated by reference, including those made a part of Special Provisions, apply as if they were set forth in their entirety.

Technical Direction

The clause, Technical Direction (Jan 2006), is incorporated by reference and amended as follows: "Performance under this subcontract is subject to the technical direction of the Company's Technical Project Officer (TPO):"

TPO Name: Jeremy T. Busby
TPO Telephone: 865-241-4622
TPO Email Address: busbyjt@ornl.gov

Key Personnel

(a) The following personnel are considered to be essential to the work being performed hereunder:

Robert Bernstein, Project Lead

(b) The Seller must notify the Company before diverting any listed person(s) to another program, providing justification (including proposed substitutions) in sufficient detail to permit evaluation of the impact on the program. No diversion shall be made without the consent of the Company; provided, that the Company may ratify a diversion in writing and the ratification shall constitute consent. The list of key personnel may be revised by mutual agreement during the period of this subcontract.

Worker Safety & Health Program

This is not a subcontract as defined by DOE Acquisition Guide Subchapter 70.10 (Mar 2003). Work performed at the Oak Ridge National Laboratory (ORNL) shall be in accordance with UT-Battelle's Worker Safety and Health Program (WSHP) and work control documents.

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY

UT-Battelle, LLC
Acting under contract DE-AC05-00OR22725
With the U.S. Department of Energy
Internet: http://www.ornl.gov/adm/contracts/index.shtml

MEMORANDUM PURCHASE ORDER
4000128678

Electronic Funds Transfer(EFT)

Electronic Funds Transfer (EFT) expedites payments to subcontractors and is our preferred method of payment. A remittance notification (email or fax) is automatically generated to you at the time of payment. To sign up for EFT, revise your banking information, or contact us to verify your current payment information, visit http://www.ornl.gov/adm/contracts/eft.shtml.

Vendor Account Status System(VASS)

For detailed payment information or inquiries concerning invoices and payments, visit the UT-Battelle, LLC Accounts Payable Vendor Account Status System(VASS) at http://www.ornl.gov/adm/ap/ or telephone (865)241-4151.

DO NOT INCLUDE SALES OR USE TAXES

See Blanket Certificate of Resale at http://www.ornl.gov/adm/contracts/documents.shtml.

Sandia National Laboratories

Operated for the U.S. Department of Energy by
Sandia Corporation
Albuquerque, New Mexico 87185-1386

Inter-Entity Work Order Number: 4000128678 **Amendment No.** 0
Period End Date: 9/30/2014

No action will be taken until the MPO/Cash Order is signed and accepted by both the requesting and performing contractors and if necessary, approved by the Sandia Site Office-Contract Officer for work > 1 Million dollars.

This is to confirm that work performed under this order will be performed in accordance with the terms and conditions of the contract between Sandia Corporation and the NNSA (DE-AC04-94AL85000), as implemented by its internal corporate policy requirements.

Terms and conditions of Contract DE-AC04-94AL85000 and its implementing policies will prevail.

Note: If no Period of Performance end date has been indicated on the work order, an end date of 9/30/2014 will be used. If you do not agree with this date, please provide the correct date and fax to (505) 844-6918.

WFO Partnership Business Office
Donna Kao
MS-1389 (10509)
505-284-2974

Email: REIMBFND@SANDIA.GOV

Exceptional Service in the National Interest

APPENDIX C: QUALITY ASSURANCE PLAN

Sandia National Laboratories

LWRS Cable Aging Project

Quality Assurance Interface Document

August 2014

United States Department of Energy
Sandia Site Office

National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

ACRONYMS

CGPA	Corporate Governance Policy Area
CPS	Corporate Policy System
ILMS	Integrated Laboratory Management System
LWRS	Light Water Reactor Sustainability
MAaD	Material Aging and Degradation
MPO	Memorandum purchase order
NNSA	National Nuclear Security Administration
P-D-C-A	Plan-Do-Check-Act
QA	Quality Assurance
QAP	Quality Assurance Program
QAPD	Quality Assurance Program Description
R&D	Research and Development
SNL	Sandia National Laboratories
SSC	Structures, systems and components

-PURPOSE

This Quality Assurance Program (QAP) Interface Document describes the application of and interfaces with the Sandia National Laboratories (SNL) QAP for Light Water Reactor Sustainability (LWRS) Program activities (including implementing procedures) and identifies authorized deviations and clarifications. The scope of this document includes the organizational structure, functional responsibilities, levels of authority, interfaces and controls for managing, performing, and assessing the functions related to the LWRS program activities performed at SNL.

The LWRS Program QAP Description (QAPD) addresses each of the criteria in 10 CFR 830.122, "Quality Assurance Criteria," DOE Order 414.1, "Quality Assurance," and the requirements from ASME NQA-1-2008, and NQA-1a-2009 Addenda, "Quality Assurance Requirements for Nuclear Facility Applications."

The LWRS Program QAPD is applicable to all LWRS Program activities and participants and is implemented using a *graded approach*, where the requirements specified are tailored to a level commensurate with the needs for each type of work scope being performed. Participants are not required to have in-place or establish an NQA-1 fully compliant program in order to meet the requirements of the LWRS Program QAPD. A crosswalk is used to demonstrate compliance to the applicable requirements for the work scope being accomplished at SNL for the LWRS Program.

SNL has a required National Nuclear Security Administration (NNSa)-approved QA Program that complies with the requirements of 10 CFR 830, Subpart A, "Quality Assurance Requirements," as applicable, and DOE Order 414.1.

SNL's corporate QAP is the overall set of expectations established to assign responsibilities and authorities, define workflow policies and requirements, and provide for the performance and assessment of work. The QAP is implemented through the SNL Corporate Policy System (CPS) and Integrated Laboratory Management System (ILMS). The QAP was developed through establishment of a quality framework defined by Corporate Procedure CG100.5.6, Achieve Quality and Mission Success, and implemented using a distributed approach across SNL. CG100.5.6 establishes corporate expectations, authorities, and accountabilities for use of Plan-Do-Check-Act (P-D-C-A) quality principles and defect prevention methodologies to improve mission and service performance while simultaneously fulfilling contractual obligations embedded in the criteria of DOE O 414.1D, Quality Assurance. Corporate process CG100.6, Assure Performance Process, establishes SNL expectations, authorities, and accountabilities for action to assess, monitor, and improve SNL's management processes and operations.

The purpose of the SNL QAPD, Rev. 4.0, SNL-QAPD-2014-05-30, Effective Date: 2014-05-30, is the QAP document required by DOE O 414.1D and 10 CFR 830, Subpart A, Quality Assurance Requirements. The QAPD describes how SNL meets the requirements of DOE O 414.1D and 10 CFR 830, Subpart A. The Sandia Corporate Governance Policy Area (CGPA) is responsible for the maintenance of the Sandia QAP. Detailed discussions of the distributed approach, requirements flow down, implementation, approach for achieving quality products and services, and requirements flow down and implementation are found in the SNL QAPD. SNL's electronic file and records management systems, including ILMS, CPS, and CGPA, support QAP implementation, assessment, maintenance, and improvement. Descriptions of these systems are also are found in the SNL QAPD.

-PROJECT MANAGEMENT INFORMATION

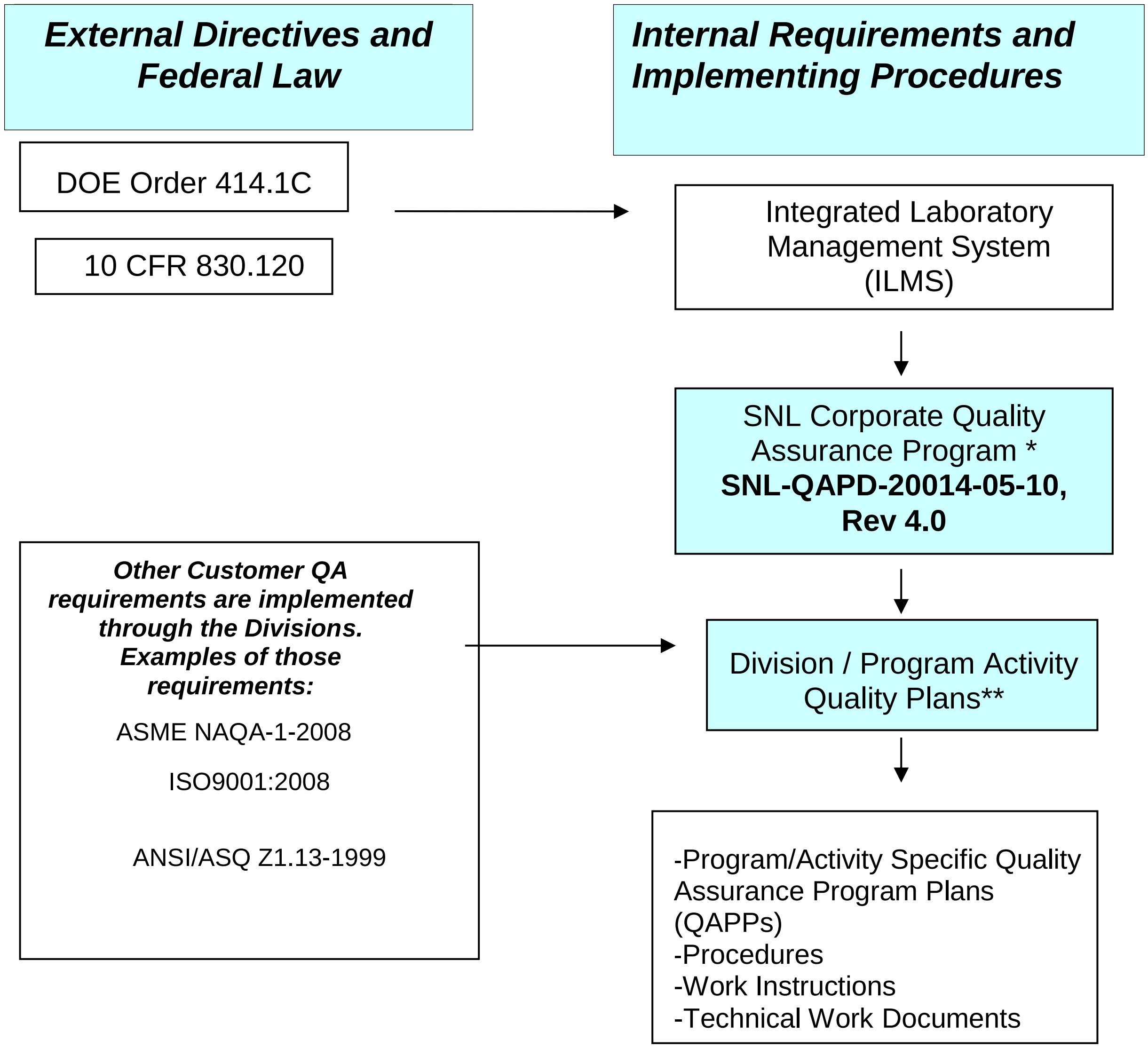
Project Baseline Summary (PBS) and Title	MPO 4000128678 IEW 177265 *SNL LWRS Cable Aging Project*
Performing Contractor: Sandia National Laboratories	Program Director: Peter Davies, Org. 06200 Program Senior Manager: Susan Pickering, 06230 Program Department Manager: Patrick Mattie, 06233 Activity Department Senior Managers: Mark Smith, 01830 Fredrick D. Wall, 01819 Activity Department Managers: James McElhanon, 01835 James Aubert, 01819 Principle Investigators / Subject Matter Experts: Robert Bernstein, 01835 Mat Celina, 01819 Erica Redline, 01835 Activity Department QA Point of Contact: Dorean Chaleunphonh, 10618
LWRS Materials Aging and Degradation Pathway Lead	Jeremy Busby, Oak Ridge National Laboratory
LWRS Technical Integration Office, Director	Kathryn A. Mccarthy, Idaho National Laboratory
LWRS Program Director	Richard A. Reister, U.S. DOE, Office of Nuclear Energy

- QA Program Interface Document Scope and Applicability

The Materials Aging and Degradation (MAaD) pathway within the LWRS program is charged with research and development (R&D) to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear reactors. The work will provide data and methods to assess performance of structures, systems and components (SSCs) essential to safe and sustained reactor operations.

Section 3.0 is an LWRS activity crosswalk (Table 1) that identifies the requirements relationship between the criteria from Sandia's DOE/NNSA-approved QAP and DOE Order 414.1 to NQA-1-2008 and NQA-1a-2009 Addenda.

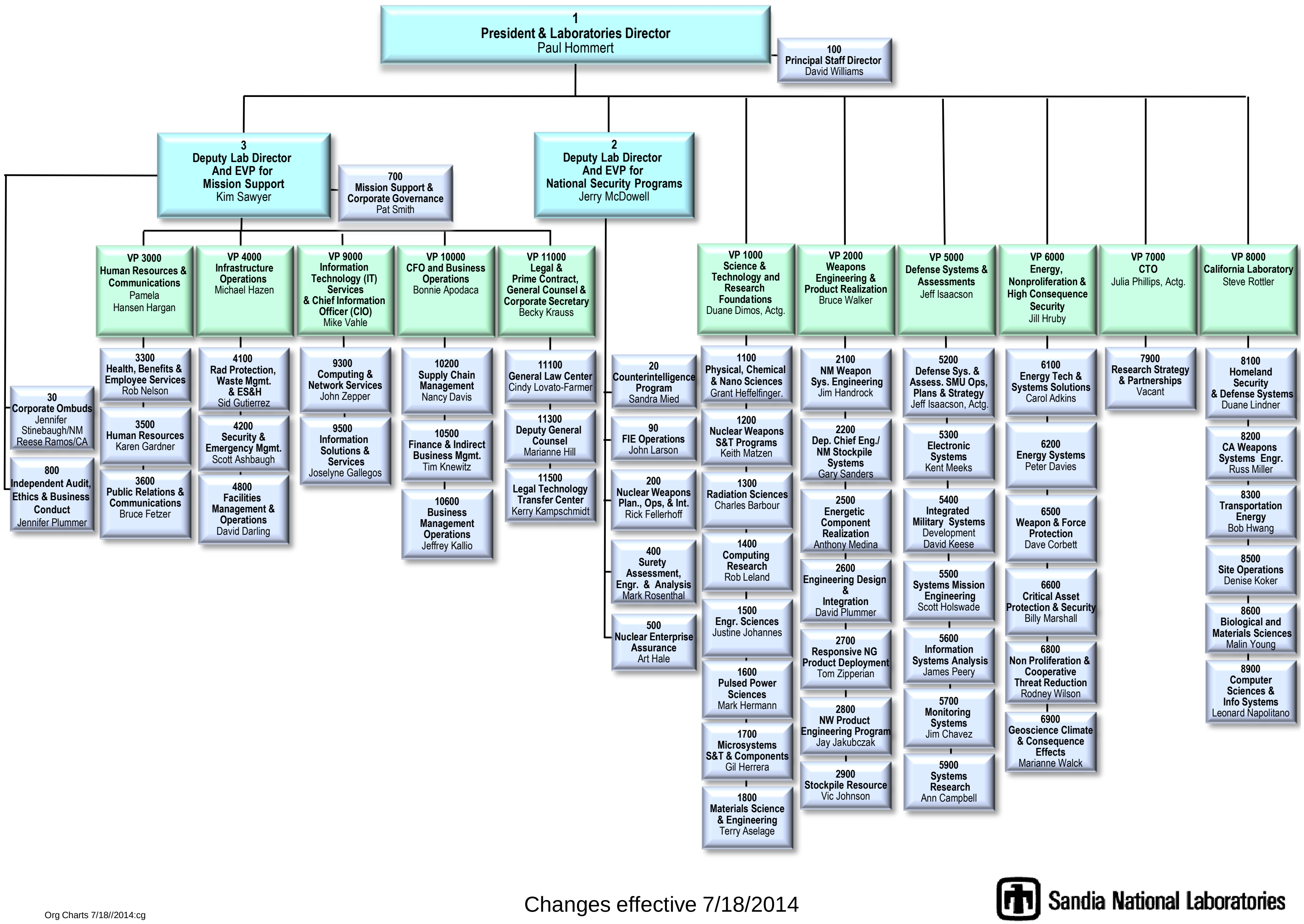
The crosswalk identifies the quality program controls that are used at Sandia and apply to LWRS R&D program activities when quality requirements are imposed. These practices ensure implementation of the applicable QA requirements selected for work packages, subcontracts and memorandum purchase orders (MPO). These practices provide repeatability, traceability and validity of the data or end product. This version of the crosswalk defines activities within the LWRS Program life-cycle phase that are defined as basic research, applied research and development work – Not Intended for Nuclear Regulatory Commission (NRC) Licensing. These research data will be used to provide understanding of research subjects and guide development and to validate research results and provide design input for NRC licensing. This document is applicable to personnel involved in LWRS activities at SNL. Personnel performing work at Sandia are required to comply with the requirements defined in this document.



* Approved by DOE/NNSA Sandia Site Office

Figure 1 - SNL Quality Assurance Program Document Hierarchy

Figure 2 – Sandia Organizational Structure



-DEMONSTRATING COMPLIANCE WITH LWRS PROGRAM QA (TABLE 1)

Sandia QAPD, Rev. 4.0, SNL-QAPD-2014-05-30, Effective Date: 2014-05-30			LWRS Program	Center 1800
DOE Order 414.1D Element	Corporate Policy & Procedures		NQA-1 Part IV, Subpart 4.2	Comments/Substantiation/Criteria/Evidence
	Corporate	Entity		
Criterion 1 - **Management Program -** (a) Establish an organizational structure, functional responsibilities, levels of authority, and interfaces for those managing, performing, and assessing work. (b) Establish management processes, including planning, scheduling, and providing resources for work.	CG100.5, CG100.8.2, ESH100.1.GP.2, ESH100.1.GP.3, ESH100.1.WPC.1	Work Planning and Control Criteria for Safe Design of Operations	601 NQA-1, Requirement 1: Organization	• For research activities, Center 1800 follows: ○ Sandia's Engineered Safety for Plan and Control Work, ○ Sandia's Integrated Laboratory Management System (ILMS), ○ Draft SNL LWRS Program Plan- April 2014 Update, LWRS Project Plan (as documented in ORNL/LTR-2012/327 Revision 0, Light Water Reactor Sustainability Program, Materials Aging and Degradation Technical Program Plan), ○ LWRS Pathway Lead, and the ○ LWRS Cable Aging Project, Quality Assurance Interface Document – Sections 1 and 2
Criterion 2 –Management Personnel Training & Qualifications – (a) Train and qualify personnel to be capable of performing assigned work. (b) Provide continuing training to personnel to maintain job proficiency.	HR100.1 -.3 ESH100.2.GEN.2 ISS100.5.7		609 NQA-1, Requirement 7: Control of Processes	• Personnel are trained on processes, equipment, and procedures to ensure work is being conducted properly. Training compliance is tracked in TEDS/HR Queries. ○ Worker qualification and certification is part of WP&C ○ Staff Aug personnel receive a brief overview of safety plan • PIs and SMEs have the knowledge and skills necessary to perform tasks that meet acceptance and performance criteria (PhDs in Chemistry or related fields). Data can be found in HR Queries.
Criterion 3 **Management** **Quality Improvement -** (a) Establish and implement processes to detect and prevent quality problems. (b) Identify, control, and correct items, services, and processes that do not meet established requirements. (c) Identify the causes of problems, and include prevention of recurrence as a part of corrective action planning. (d) Review item characteristics, process implementation, and other quality-related information to identify items, services, and processes needing improvement.	CG100.5, CG100.5.5, SCM100.3.13, ESH100.4, ISS100.3.1, ESH100.1.GP.3, ESH100.1.WPC.1	Defect Prevention Strategy Research Quality Document	602 NQA-1, Requirement 2: Quality Assurance and 608 NQA-1, Requirement 8: Identification and Control of Items	• Center 1800 uses AIS to track assessments and corrective actions. ○ Center uses self-assessments to detect and prevent problems. Assessments completed are driven by individual managers: ▪ Ad hoc (as needed) ▪ Specific to customer quality requirements ○ Center 1800 performs analysis (root cause, extent of condition reviews) as part of its corrective action planning. ○ Center 1800 performs management review meetings to review, identify, and discuss issues and define improvement activities. • Work processes and supporting documentation are defined and work and operating procedures are developed and implemented with respect to Center 1800's WP&C process. WCAs are stored and maintained in Center 1800's SharePoint repository. • Laboratory notebook or hard drive storage of data of data is a QA record. Documents and records are controlled in accordance with corporate documented procedure / process. • Technical peer review process is used and integrated within the work process (e.g., electronic R&A system) as well as through annual reports and project milestones.
Criterion 4 – Management Documents and Records – (a) Prepare, review, approve, issue, use, and revise documents to prescribe processes, specify	IM100.2, ESH100.1.2.GEN.3, HR100.2.15,		606 NQA-1, Requirement 6: Document Control and 617 NQA-1,	• Center 1800 uses corporate procedures and electronic file systems for review and approval, document control, and records. Internal SharePoint sites have been created as local document control for specific work, such as ES&H/WP&C. ○ Laboratory notebook or hard drive storage of data of data is a QA record. Documents and records are

Sandia QAPD, Rev. 4.0, SNL-QAPD-2014-05-30, Effective Date: 2014-05-30			LWRS Program	Center 1800
DOE Order 414.1D Element	Corporate Policy & Procedures		NQA-1 Part IV, Subpart 4.2	Comments/Substantiation/Criteria/Evidence
	Corporate	Entity		
requirements, or establish design. (b) Specify, prepare, review, approve, and maintain records.	ESH100.1.GP.3		Requirement 17: Quality Assurance Records	controlled in accordance with corporate documented procedure / process. • Work processes and supporting documentation are defined and work and operating procedures are developed and implemented with respect to Center 1800's WP&C process. WCAs are stored and maintained in Center 1800's SharePoint repository.

Criterion 5- Performance Work Process –
(a) Perform work consistent with technical standards, administrative controls, and hazard controls adopted to meet regulatory or contract requirements using approved instructions, procedures, etc.
(b) Identify and control items to ensure their proper use.
(c) Maintain items to prevent their damage, loss, or deterioration.
(d) Calibrate and maintain equipment used for process monitoring or data collection.
	CG100.5, CG100.8.2 , CG100.8.1, IM100.3.5, ESH100.2, ESH100.3, SCM100.3, CG100.5.5 CG100.8.1	Planning and Control Criteria for Safe Design of Operations	605 NQA-1, Requirement 5: Instructions, Procedures, and Drawings, 612 NQA-1, Requirement 12: Control of Measuring and Test Equipment, 613 NQA-1, Requirement 13: Handling, Storage, and Shipping	• Center 1800 has an internal WP&C process to identify and control hazards. AIS is used to identify and control risks.
				• Center 1800 follows corporate processes to identify and control property and chemical inventories.
				• Center 1800 uses corporate process to maintain items to prevent their damage, loss, or deterioration.
				  ○ Center 1800 has been proactive in disposing legacy chemicals.
				  ○ Proactive in evaluating and understanding current state of equipment
				• Local procedures are maintained for ES&H and WP&C activities and are held in a local SharePoint site.
				• Local processes to calibrate and maintain equipment. Documented in laboratory notebooks or local SharePoint site. Sandia serves as the primary Standards Laboratory (PSL) for the entire DOE/NNSA standards and calibration system. All standards used for calibration by the Measurement Standards Laboratory (MSL) at Sandia, are calibrated to PSL primary reference standards that are directly traceable to the National Institute of Standards and Technology or to basic physical phenomena. As part of its calibration services, the MSL maintains a recall system and a listing of each calibrated item, the calibration interval, item identification number, and other pertinent data. Information about measurement and test equipment (M&TE) used to obtain data or calibrate another instrument or system is entered into the MSL recall system. The MSL initiates recall on a cycle determined by instrument stability and use.
				• CG100.8.1 *Perform Work*, SNL requires the calibration of M&TE used in activities that will affect the quality of products or services delivered by Sandia

Criterion 6 – Performance Design –
(a) Design items and processes using sound engineering/scientific principles and appropriate standards.
(b) Incorporate applicable requirements and design bases in design work and design changes.
(c) Identify and control design interfaces.
(d) Verify/validate the adequacy of design products using individuals or groups other than those who performed the work.
(e) Verify/validate work before approval and implementation of the design
	CG100.5, CG100.8.1,	Planning and Control Criteria for Safe Design of Operations	603 NQA-1, Requirement 3: Design Control and 615 NQA-1 Requirement 15: Control of Nonconforming Items	• Local procedures are maintained for ES&H and WP&C activities and are held in a local SharePoint site.
				• As defined in Center 1800's WCA for Thermal Radiation Degradation, research activities are approved and documented.
				  ○ Calculations and analyses are fully checked by a qualified individual other than the originator and are signed and dated as checked. Results and methods used for calculations and analysis are documented.
				  ○ The documentation of nonconforming items is identified and controlled as defined by the researcher. Corrective actions are specified and approved for nonconforming items and are documented in AIS.
				• Nonconformances are subject to the requirements of CG100.5.5, *Control Item, Service, and Process Nonconformances* and are documented by the specific organizations according to their procedures, which include proper segregation and reportability information.

Criterion 7 – Performance	CG100.5, SCM100.3		604 NQA-1, Requirement 4:	• Procured items and services are controlled to ensure conformance with specified requirements. Controls provide for the following as appropriate: source evaluation and selection, evaluation of the objective evidence

Sandia QAPD, Rev. 4.0, SNL-QAPD-2014-05-30, Effective Date: 2014-05-30			LWRS Program	Center 1800
DOE Order 414.1D Element	Corporate Policy & Procedures		NQA-1 Part IV, Subpart 4.2	Comments/Substantiation/Criteria/Evidence
	Corporate	Entity		
Procurement – (a) Procure items and services that meet established requirements and perform as specified. (b) Evaluate and select prospective suppliers on the basis of specified criteria. (c) Establish and implement processes to ensure that approved suppliers continue to provide acceptable items and services.			Procurement Document Control and 607 NQA-1, Requirement 7: Control of Purchased Materials, Items, and Services	of quality furnished by the supplier, and examination of items or services upon delivery or completion for conformance to procurement specifications. • Center 1800 procures items using the appropriate corporate SCM channels (JIT, PR, etc.). • Center 1800 works with SCM to evaluate and select prospective suppliers on the basis of specified criteria. • Center 1800 follows corporate procedure to ensure that approved suppliers continue to provide acceptable items and services. ○ Center 1800 has a contractor safety process (job brief)

Criterion 8 –
Performance
Inspection and Acceptance Testing –
(a) Inspect and test specified items, services, and processes using established acceptance and performance criteria.
(b) Calibrate and maintain equipment used for inspections and tests.
	CG100.5, CG100.8.1		610 NQA-1, Requirement 10: Inspection, 611 NQA-1, Requirement 11: Test Control, 612 NQA-1, Requirement 12: Control of Measuring and Test Equipment, and 614 NQA-1, Requirement 14: Inspection, Test, and Operating Status	• Center 1800 follows corporate procedures to inspect and test items, services, and processes.
				  • Center 1800 uses local processes to calibrate and maintain equipment. Test methods are documented in laboratory notebooks, peer reviewed reports, journal articles, and LWRS milestones.
				  •

Criterion 9 –
Assessment Management Assessments –
Ensure that managers assess their management processes and identify and correct problems that hinder the organization from achieving its objectives
	CG100.5, CG100.6.3, ESH100.4.FI.1, CG100.6.6 , ESH100.4.FI.3, CG100.6.9		616 NQA-1, Requirement 16: Corrective Action	• Management assessments and inspections are held at least biannually and are planned, scheduled, and performed. The results of these activities are documented in AIS. Follow-up actions are taken to verify implementation and effectiveness of corrective action.
				• Center 1800 uses AIS to track assessments and corrective actions.
				  ○ Center uses self-assessments to detect and prevent problems. Assessments completed are driven by individual managers:
				    ▪ Ad hoc (as needed)
				    ▪ Specific to customer quality requirements
				  ○ Center 1800 performs analysis (root cause, extent of condition reviews) as part of its corrective action planning.
				• Center 1800 performs management review meetings to review, identify, and discuss issues and define improvement activities

Criterion10 –
Assessment Independent Assessments –
(a) Plan and conduct independent assessments to measure item and service quality and the adequacy of work performance and to promote improvement.
	CG100.5, CG100.6.7, CG100.6.3, CG100.6.9, CG100.6.6, ESH100.4.FI.3		618 NQA-1, Requirement 18: Audits	• Independent assessments are planned, scheduled and performed as necessary. Assessments are documented in AIS or local SharePoint site.
				  ○ Center 1800 managers are encouraged to plan assessments to focus on performance of work with significant consideration given to performing activities in a safe and compliant manner while achieving the goals of the organization.
				  ○ Center 1800 ensures that independent assessments are completed by technically qualified and

Sandia QAPD, Rev. 4.0, SNL-QAPD-2014-05-30, Effective Date: 2014-05-30			LWRS Program	Center 1800
DOE Order 414.1D Element	Corporate Policy & Procedures		NQA-1 Part IV, Subpart 4.2	Comments/Substantiation/Criteria/Evidence
	Corporate	Entity		
(b) Establish sufficient authority and freedom from line management for independent assessment teams. (c) Ensure that persons conducting independent assessments are technically qualified and knowledgeable in the areas to be assessed.				knowledgeable personnel who are not responsible for supervising or performing the work under review. ▪ Materials Science External Review Board (independent environmental scan) ▪ NW – through the RPP cycle when new materials are being supported by NW ▪ Externally – staff are peer reviewed – fellowships, scientific publications, etc.
Attachment 3 – **Suspect/** **Counterfeit Items Prevention –** How is oversight conducted, MOW training, inspection process, control, disposition, reporting requirements, trend analysis	CG100.5.5, SCM100.3.13, ESH100.4.RPT.3, CG100.6.9, CG100.6.6		N/A	Follow the Sandia Suspect/Counterfeit (S/CI) Program, which provides an effective, well integrated process intended to prevent the introduction of S/CI through Sandia's supply chain. (SCM100.3.13)
Attachment 4 **Safety Software Quality Assurance For Nuclear Facilities** - Requirements, configuration management, verification and validation, inventory, grading levels	IM100.3.5		N/A	Software systems also require verification to ensure functional requirements are met. The researcher shall ensure the systems and subsystems are operating properly. Center 1800 follows Sandia corporate procedure.

ACRONYMS:	
AIS – Assurance Information System*	R&A – Review and Approval
ES&H – Environmental Safety & Health	SCM – Supply Chain Management
JIT – Just in Time	WCA – Work Control Authorization
PR – Purchase Request	WP&C – Work Planning & Controls

*The Assurance Information System (AIS) tool provides organizations with a management review application that documents identified risks, the mitigation activities to manage that risk, schedule and track control activities such as assessment, and track corrective actions when mitigation activities are found to be ineffective or not performing as required.

-REFERENCES

10 CFR 830, Subpart A, Quality Assurance Requirements, *Code of Federal Regulations*, Office of the Federal Register.

ASME NQA-1-2000, *Quality Assurance Requirements for Nuclear Facility Applications.*

ASME NQA-1-2008, NQA-1a-2009, Subpart 2.14, *Quality Assurance Requirements for Commercial Grade Items and Services.*

ASME NQA-1-2008, 1a-2009, Part IV, Subpart 4.2, *Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.*

ASME NQA-1-2008, Part III, Subpart 3.3, Appendix 3.1, *Guidance on Qualification of Existing Data.*

DOE Order 414.1D, *Quality Assurance.*

SNL-QAPD-2014-05-30, Rev 4.0, Sandia's Quality Assurance Program Description, Effective Date: 2014-05-30.

PLN-4360, Revision 0, Quality Assurance Program Plan for Light Water Reactor Sustainability Program, Effective Date: 02/05/2013.

INL/MIS-10-19844, Revision 1, Light Water Reactor Sustainability Program Quality Assurance Program Description Document, April 2012.

APPENDIX D: ERROR PROPAGATION ANALYSIS

The error and uncertainty inherent to an experimental result are critical to the accurate interpretation of the data. Therefore, the maximum uncertainties in the experimental measurements are estimated in this section. Results of this analysis are given, followed by a general description of the method used and a brief explanation of the source of each reported measurement uncertainty.

The overall standard uncertainty of an indirect measurement *y*, dependent on *N* indirect measurements x_i, is defined in Equation G.1. The standard uncertainty associated with an indirect measurement is analogous to the standard deviation of a statistical population.

$$u^2 = \sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i} u_i \right)^2 \qquad \text{G.1}$$

Here, *u* is used to define the standard uncertainty of a measurement.

The expanded uncertainty *U* is reported in this appendix and defines the bounds that include 95% of the possible data. The expanded uncertainty is usually defined as some multiple of the standard uncertainty. For purposes of this report, all uncertainty measurements are assumed to behave according to a normal distribution. Therefore, Equation G.2 shows the definition of the expanded uncertainty as used in the following sections for a 95% confidence interval, where the factor of 1.96 has been rounded to a value of 2.

$$U = 2 \cdot u \qquad \text{G.2}$$

G.1 Elongation at Break

The elongation at break (EAB) is measured according to Equation G.3.

$$\text{EAB} = \frac{\text{E}}{\text{E}_\text{o}} \qquad \text{G.3}$$

The expanded uncertainty in the EAB is 0.01, or 1.0% of the measurement, as shown in Table G.1.

Table G.1 Uncertainty in elongation at break.

Measurement, x_i	Units	Value	Expanded uncertainty, U_i	Influence coefficient ($U_i \cdot [(\partial \text{EAB}/\partial x_i)/\text{EAB}]$)	Contribution
E	mm	64.0	0.1	0.0016	0.02
E_o	mm	50.0	0.5	0.0100	0.98
EAB	--	1.28	0.01	0.0101	1.00

G.2 Thermal Only Oxidation Rate

The oxidation rate for thermal-only tests is measured according to Equation G.4, where *m* is the mass of the sample and *t* is the time the sample is aged.

$$\text{Oxidation Rate} = \frac{O_2 \text{ Consumption}}{m \cdot t} \qquad \text{G.4}$$

The maximum expanded uncertainty in the oxidation rate is 2.1E-14, or 8.3% of the measurement, as shown in Table G.2. Typically, experiments are conducted for longer times than shown in Table G.2, which serves to increase the O_2 consumption and can lower the uncertainty by as much as an order of magnitude.

Table G.2 Uncertainty in thermal-only oxidation rate.

Measurement, x_i	Units	Value	Expanded uncertainty, U_i	Influence coefficient ($U_i \cdot [(\partial\text{Ox Rate}/\partial x_i)/\text{Ox Rate}]$)	Contribution
O_2 consumption	mol	5.4E-07	4.5E-08	0.0833	1.000
m	g	0.50	1.0E-05	0.0000	0.000
t	s	4320000	900	0.0002	0.000
Oxidation Rate	mol/g/s	2.48E-13	2.1E-14	0.0833	1.000

G.2 Rad-Thermal Oxidation Rate

The oxidation rate for thermal-only tests is measured according to Equation G.5, where again *m* is the mass of the sample and *t* is the time the sample is aged.

$$\text{Oxidation Rate} = \frac{O_2 \text{ Consumption}}{m \cdot t \cdot \text{Dose Rate}} \qquad \text{G.5}$$

The maximum expanded uncertainty in the oxidation rate is 2.0E-10, or 10% of the measurement, as shown in Table G.3. This uncertainty is quoted for a sample aged for a relatively short period and exposed to the lowest dose rate. This uncertainty scales inversely with the dose rate. Therefore, the uncertainties for the same sample exposed at dose rates of 1 and 5 Gy/h are 4.2 and 1%, respectively.

Table G.3 Uncertainty in rad-thermal oxidation rate.

Measurement, x_i	Units	Value	Expanded uncertainty, U_i	Influence coefficient ($U_i \cdot [(\partial\text{Ox Rate}/\partial x_i)/\text{Ox Rate}]$)	Contribution
O_2 consumption	mol	7.1E-07	4.5E-08	0.0625	0.356
m	g	5.00	1.0E-05	0.0000	0.000
t	s	540000	900	0.0017	0.000
Dose rate	Gy/h	0.500	0.042	0.0840	0.644
Oxidation Rate	mol/g/Gy	1.9E-09	2.0E-10	0.1047	1.000

G.3 Sources for Uncertainty

The sources of uncertainty for the measured quantities described in the previous sections are briefly described in Table G.4, Table G.5, and Table G.6 for EAB, thermal-only oxidation rate, and rad-thermal oxidation rate, respectively.

Table G.4 Sources of uncertainty in the measurement of EAB.

Measurement, x_i	Units	Value	Expanded uncertainty, U_i	Uncertainty Source
E	mm	64.0	0.1	Digital display (Resolution limit)
E_o	mm	50.0	0.5	Scale resolution (Resolution limit)

Table G.5 Sources of uncertainty in the measurement of thermal-only oxidation rate.

Measurement, x_i	Units	Value	Expanded uncertainty, U_i	Uncertainty Source
O_2 consumption	mol	5.4E-07	4.5E-08	Detection limit (Observed measurements and in situ calibrations)
m	g	0.5	1.00E-05	Scale resolution (Resolution limit)
t	s	4320000	900	15 minutes (Observed heat up/cool down times)

Table G.6 Sources of uncertainty in the measurement of rad-thermal oxidation rate.

Measurement, x_i	Units	Value	Expanded uncertainty, U_i	Uncertainty Source
O_2 consumption	mol	7.1E-07	4.5E-08	Detection limit (Observed measurements and in situ calibrations)
m	g	5	1.00E-05	Scale resolution (Resolution limit)
t	s	540000	900	15 minutes (Observed heat up/cool down times)
Dose rate	Gy/h	0.500	0.042	1.96*Std. Dev. (Observed TLD measurements)

APPENDIX E: INTEGRATION PLAN

Operated for the U.S. Department of Energy by

Sandia Corporation

date: *April 08, 2014*

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subject: *Integration plan for joint cable research with EPRI*

The purpose of this memo is to summarize the efforts for development of coordinated research activities between SNL and EPRI with regard to cable insulation aging programs. This memo serves to fulfill the milestone from the statement of work (Memorandum Purchase Order 400128678): *Complete report detailing integration plan for joint cable research with EPRI and other stakeholders during the fall months; due 04/11/14.*

1) Attendance at EPRI Winter Cable User Group Meeting

The SNL team participated in a January 2014 EPRI sponsored planning meeting in Phoenix which was a two day meeting specifically focused on integration of the stakeholders goals. SNL presented a single PowerPoint slide to stimulate technical discussions (See original document for Appendix A). A consensus of the meeting attendees was reached between EPRI/NRC/PNNL/SNL on the objectives of R&D cable aging activities covering predictive models, wear-out aging (field-returned specimens), and condition monitoring strategies. All of these activities were seen by this group as supporting the requalification efforts and incorporated into the EPRI LTO roadmap (See original document for Appendix B). Part of the SNL team also attended the Cable Users Group meeting that immediately followed the planning session. This was done to provide the SNL team further insight into plant operators' concerns and issues. SNL received encouraging feedback from EPRI (See original document for Appendix C).

2) EPRI Roadmap

SNL, along with NRC and PNNL, assisted EPRI in their formulation of a LTO cable aging roadmap. SNL attended and provided input both at the Joint LWRS-EPRI LTO Cable R&D

meeting, in Dallas October 2013 as well as the EPRI meeting in Phoenix in January 2014. In addition the roadmap was discussed at the SNL-lead teleconference in December 2013 between EPRI, NRC, NIST, ORNL, and PNNL. E-mail exchanges on the topic were also done. The current version (03/2014) of the EPRI roadmap is attached (See original document for Appendix B). SNL contributions for the LTO are defined as:

- SNL Phase I literature review
- DOE/SNL research on diffusion limited oxidation (DLO), synergistic effects and inverse temperature (IT) effects on cable
- Assessment of condition monitoring effectiveness for DLO & IT
- DLO quantification methodology development
- Predictive aging model (dose & temperature)→extended condition
- Conceptual wear out aging methodology
- Lifetime prediction model (thermal only)

3) SNL Path Forward

a) SNL participated in a teleconference with ORNL in December 2013. The topic of discussion was the path forward for SNL cable work. PowerPoint slides were provided as a framework for the discussion. The PowerPoint slides which were presented are attached (See original document for Appendix D).

b) A set of PowerPoint slides created after the Phoenix meeting was sent out to ORNL on 02/13/14; the slides detail the SNL proposed strategies to address existing knowledge gaps. The presentation includes strong commonalities between SNL and EPRI along with input from PNNL and NRC (See original document for Appendix E). They could form the basis for follow up conversations with the stakeholders during the upcoming July meeting.

c) SNL is hosting the next Joint LWRS-EPRI LTO Cable R&D meeting in July 2014. EPRI will coordinate the next two teleconferences supporting this effort.

Based on these teleconferences, meetings, and documents, the SNL team is confident that the milestone of a joint working plan (SNL integration plan with EPRI) is accomplished, has reasonable pathways, and is beneficial to the community. It should be noted, that as with any research plan, iteration and refinement are important tools; there is the distinct possibility that results and resources could alter the suggested path forward subject to ongoing engagement with the stakeholders. The SNL team expects that these changes will be clearly communicated through regular meetings and conversations with all the stakeholders.

Acknowledgement

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

APPENDIX F: PNNL AGED SAMPLES MEMO

Operated for the U.S. Department of Energy by
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To: Kevin Simmons

From: Guillermo A. Mata (1835), Amy R. Garner (1835), Mat Celina (1819), Erica Redline (1835), James McElhanon (1835), and Robert Bernstein (1835)

Subject: EPR Aging Study

Date: June 4, 2014

1. Introduction

Ethylene propylene rubber (EPR) samples (see Figure 1) were obtained from Pacific Northwest National Laboratory (PNNL) to be exposed to accelerated isothermal aging at Sandia National Laboratories (SNL). The purpose of this work is to generate a set of samples for rejuvenation work at PNNL. Each set of samples were exposed to different aging conditions (time and temperature) to ensure a widespread range of mechanical properties. Tensile tests were conducted throughout the aging process to observe the degradation of the material. One of the concerns in accelerated aging is diffusion-limited oxidation (DLO) which causes nonhomogeneous aging within the sample and tends to be more pronounced at higher temperatures. To address this problem, a wide spectrum of aging temperatures were employed – some for quick generation of samples (higher temperature, high DLO probability), and some for more long term (lower temperature, low DLO probability). Modulus profiling is one tool that can be used to understand the extent of DLO (if any) in these samples; this analysis can be included as part of the future work plan.

Figure 1: Labeled samples for PNNL

2. Experimental

2.1 Materials

Materials were obtained from Kevin Simmons at PNNL. The material is 15 kV Okoguard® aerial jumper cable EPR insulation. To help elucidate aging behavior, the samples were placed in ovens ranging in temperature from 40 °C to 138 °C. As shown in Figure 2, samples were provided as 7.5 cm long dog-bone shaped specimens to enable tensile testing.

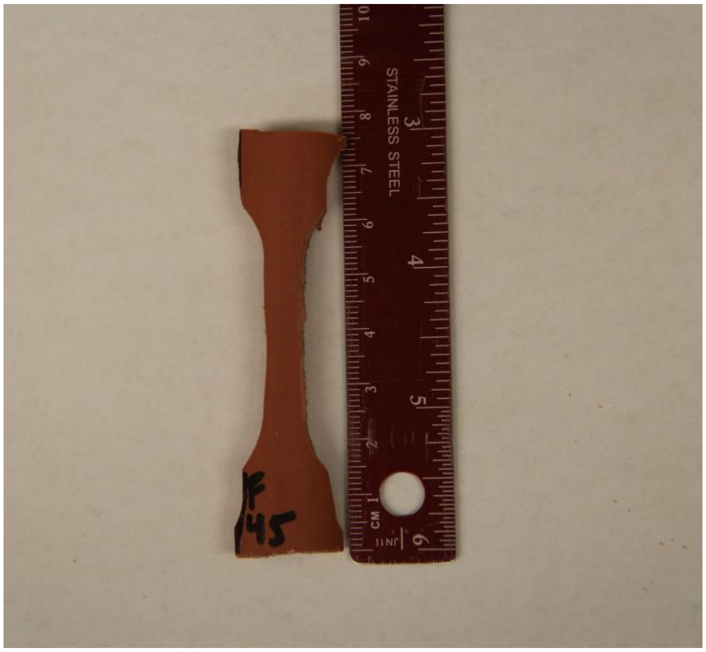

Figure 2: Virgin EPR specimen

2.2 Tensile Testing

Samples were tested on an Instron 5564 series equipped with pneumatic grips and extensometer clips that enabled direct ultimate tensile elongation values to be obtained. The initial jaw separation and strain rate were 4.0 cm and 12.7 cm/min, respectively.

2.3 Elongation Baseline Targets

Due to discrepancies found between PNNL and SNL regarding tensile elongation values, baseline targets were developed to efficiently compare work. Tensile elongation is the value elongation percentage obtained at maximum force. It is postulated that the large difference could be due to the absence of a strain gauge. E/E_0 is another target that expresses the tensile elongation as a ratio between virgin material and aged material. Table 1 contains the initial baseline targets.

Table 1: Baseline Elongation Targets

PNNL Original Target	Sandia Target EAB[a]	E/E_0
367%	156%	100%
200%	85%	54%
150%	65%	42%
100%	40%	26%
50%	Not Required	Not Required

[a] PNNL original target values were developed prior to aging in order to help establish a baseline. The Sandia Target EAB was then developed to help effectively compare the SNL and PNNL tensile elongation values. E/E_0 is a ratio with E representing the tensile elongation of the aged material and E_0 representing the tensile elongation of virgin material. This value is utilized to help compare the PNNL and SNL targets.

Table 2 contains information regarding the initial number of samples placed in each oven and the current number of samples remaining. The initial number of samples placed at each temperature was obtained from known (experimentally determined) characteristics of polymer aging.

Table 2: Number of Samples Aging

Sample Temp. (ºC)	Initial No. Samples	No. Samples Currently Aging
23	45	31
40	36	36
64	36	36
80	36	36
109	45	27
124	45	0
138	10	0

3. Results

3.1 Virgin EPR

Figure 3 shows tensile elongation of virgin EPR. The mechanical properties measured for virgin EPR were 164% (average tensile elongation) ± 17% (standard deviation) for tensile elongation, 9.5 ± 0.6 MPa for tensile strength, and a maximum force prior to breaking of 90 ± 7 lbs. Tensile strength was calculated by dividing the maximum force by the cross-sectional area. The cross-sectional area (average value of 0.42 ± 0.029 cm^2) was determined by measuring the depth and the width in the middle of each specimen.

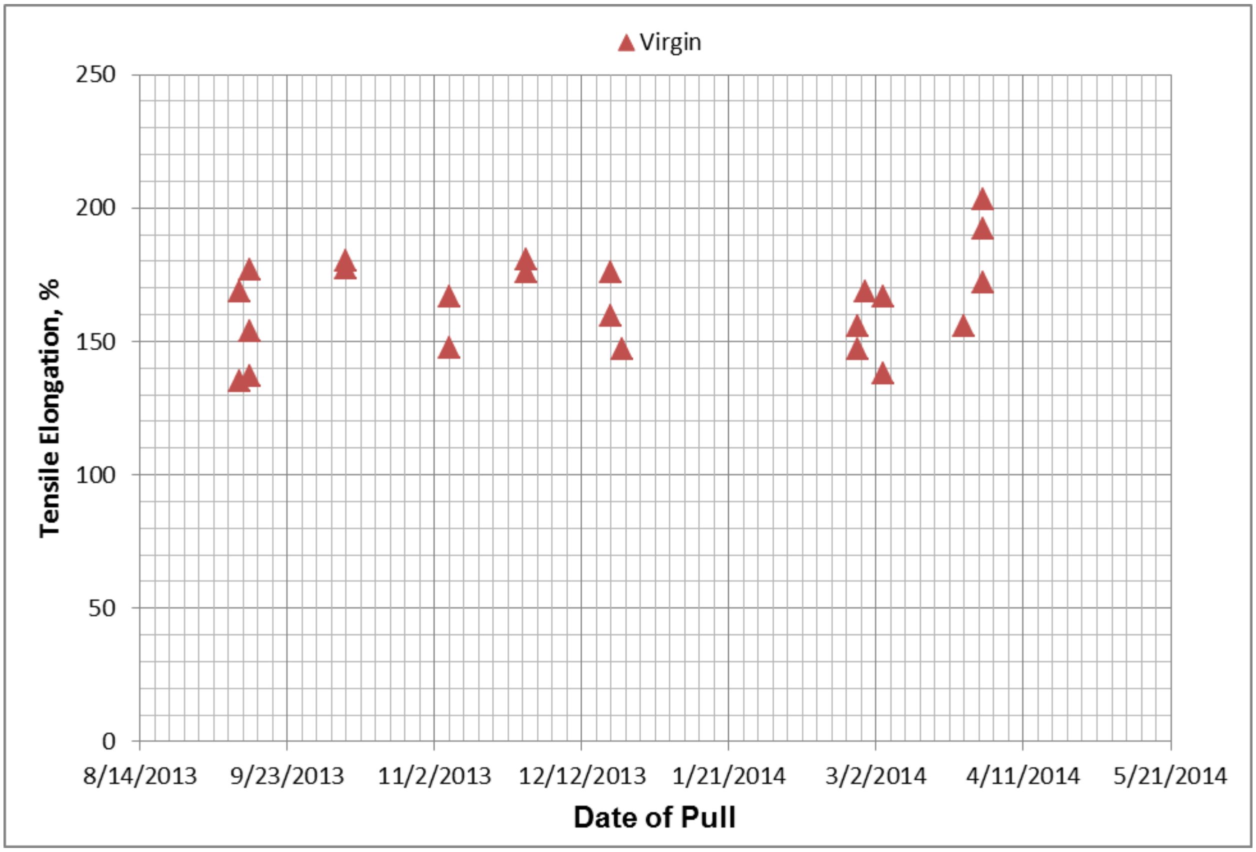

Figure 3: Control Samples

3.2 EPR aged at 138 °C

Aging began on September 25th, 2013 on ten EPR samples. As seen in Figure 4, samples aged at 138 °C degraded over a period of ~80 days. The remaining three samples were not tested after the ~80 days because they were too brittle and would not provide useful results. These results enabled a baseline model to be developed to give a more definitive aging scheme for samples aged at lower temperatures. Lower temperature samples age at a slower rate than higher temperature samples. Using past experience in combination with a simple Arrhenius model to approximate rate drops for time spans at elevated temperatures, an aging scheme was developed.

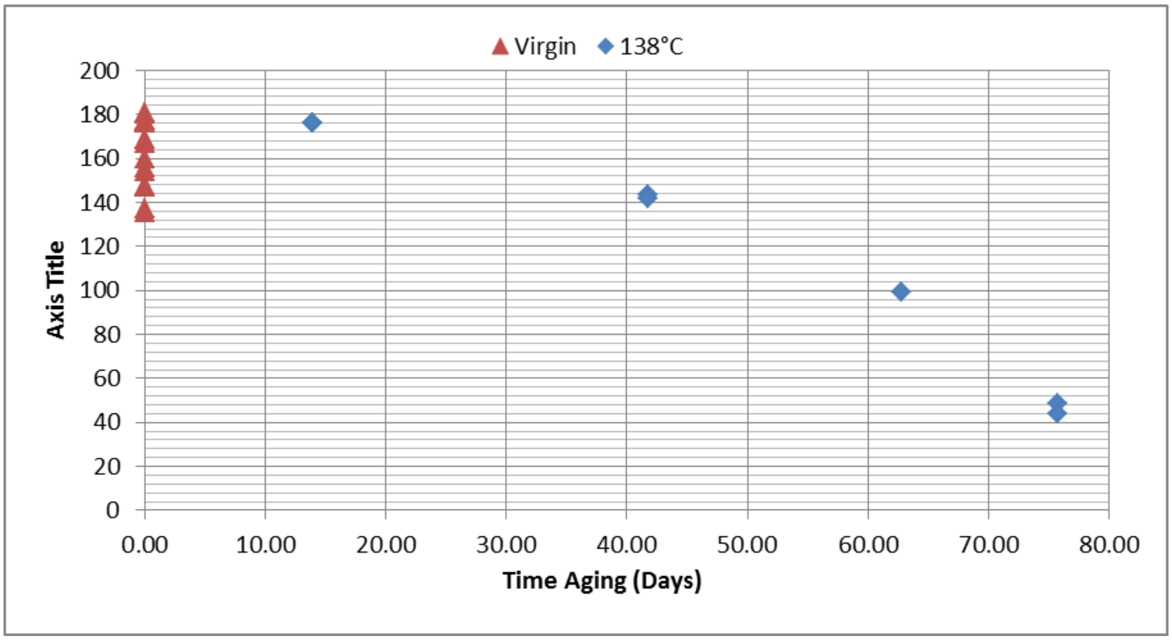

Figure 4: Tensile elongation vs. aging time at 138 °C for EPR rubber

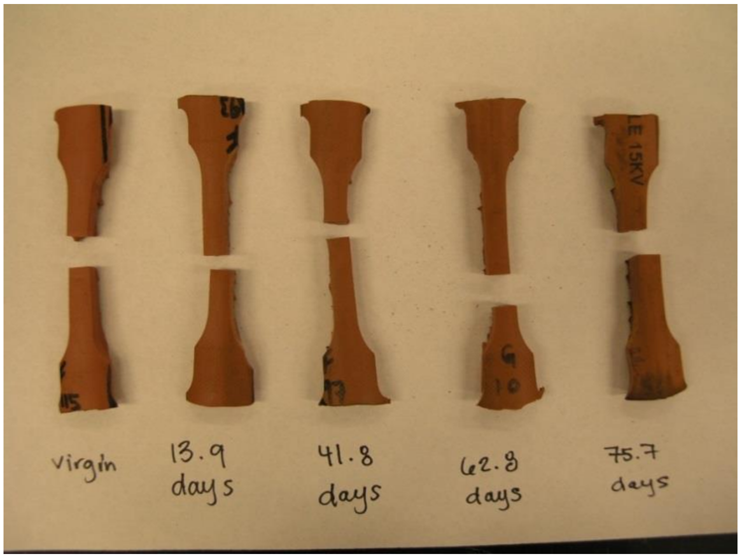

Figure 5: Aged 138 °C samples

3.3 EPR aged at 124 °C

Forty-five samples were initially placed in a 124 °C oven. Samples were monitored and a pulling scheme was developed based on data from 138 °C specimens. Figure 6 contains data for samples aged at 124 °C. There is a significant loss in tensile elongation over a period of 170 days. **Table 3** contains a summary of the data.

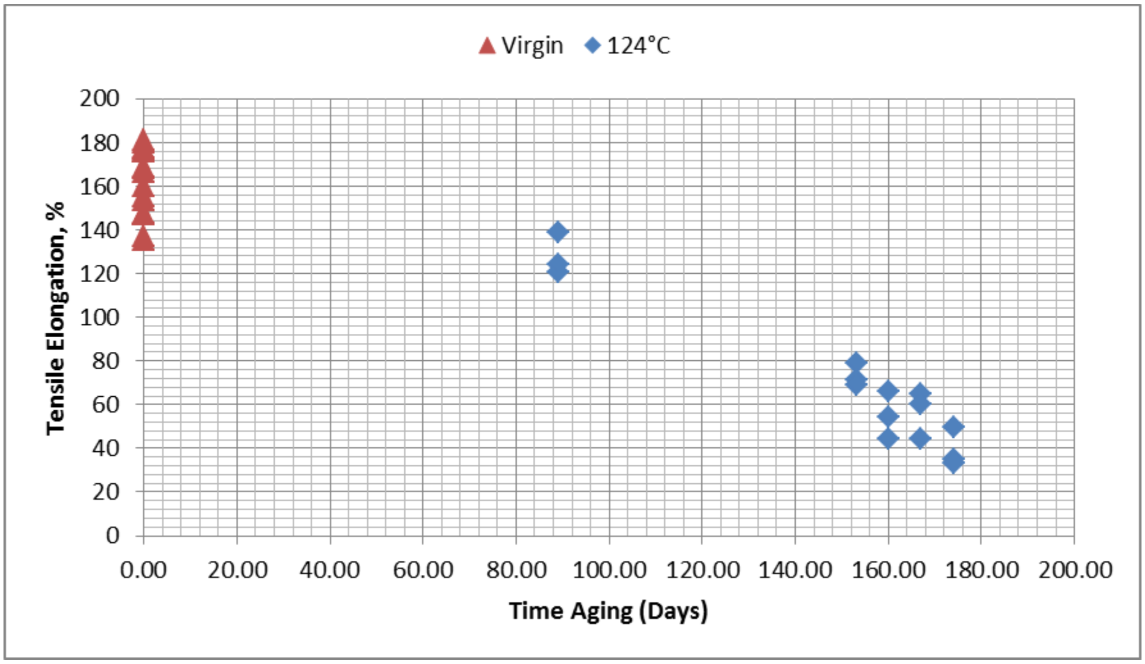

Figure 6: Tensile elongation vs. aging time at 124 °C for EPR rubber

Table 3: 124 °C Data

Time Aging (Days)	Tensile Elongation (%)	E/E_0
89	128	80
153	73	45
160	55	34
167	56	35
174	39	24

3.4 EPR aged at 109 °C

Figure 7 contains data for samples aged at 109 °C. Tensile elongation decreases slightly after a period of ~150 days. The samples will continue to be monitored closely as they age.

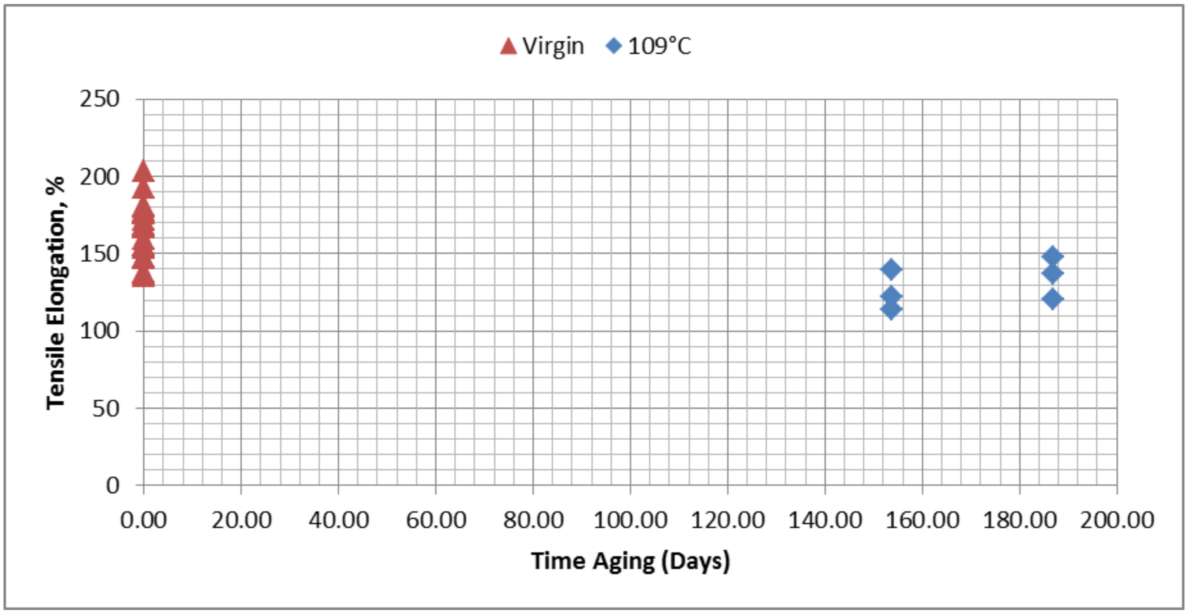

Figure 7: Tensile Elongation 109 °C

Table 4: 109 °C Data

Time Aging (Days)	Tensile Elongation	E/E0
154	125	78
187	135	84

Future work

A set of samples will be removed from the 109 °C and 80 °C ovens during summer 2014. This will provide data to further develop accelerated aging curves and verify that the samples are aging as expected. DLO should be less of a concern at these temperatures. However, DLO cannot be verified without any data such as Modulus Profiling or visual confirmation. Future work could involve Modulus Profiling of the samples.

Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SAND2014-4328 P

APPENDIX G: LOCATION MEMO REPORT

Sandia National Laboratories

Operated for the U.S. Department of Energy by
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Albuquerque, New Mexico 87185-1411

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Subject: *Radiation Location Memo*

Influence of Local Dose Rate Effects on Cable Radiation Aging Studies

1. Introduction:

The purpose of this study was to assess local radiation dose rate gradients within aging cans at the Low Intensity Cobalt Array (LICA) facility at Sandia National Laboratories. As radiation studies are an integral part of SNL's support of DOE's Light Water Reactor Sustainability (LWRS) program, [1,2] it is important to understand whether or not the radiation dose rate gradients could affect aging data, and, if so, to what degree. Therefore, a series of dosimetry experiments were conducted to measure dose rates at different locations within the aging cans. Additionally, a crosslinked polyolefin (XLPO) was aged at the known dose rate locations and the elongation at break and gel content were measured; these properties are commonly used to investigate polymer aging and were chosen to help understand how local dose rate variance may be observed in these types of analyses.

2. Experimental:

2. 1 Materials

The cable material chosen was labeled as: *Brand Rex XLP/CU Power and Control Cable 3/C #12 600V SUN RES XHHW Type TC (UL).* Only the black XLPO insulation was examined in these studies.

2.2. Dosimetry & Aging Study

A significant effort was employed to maintain consistent location and configuration of the samples and dosimeters during aging experiments to minimize any potential dose rate variance effects due to placement. Samples/dosimeters were first aligned within a basket which was separated into positions using a coarse wire mesh (Figure 3). Then, the basket was aligned with the aging can by arranging the basket into the aging can's internal canister with two screws located on the back of the canister (Figure 4). Cans were then lined up within LICA such that the "umbilical cord" was always facing away from the source pencils located in front of and behind row 4 (Figure 5). The umbilical cord enables constant air flow to the aging specimens while they are being irradiated and can be used as an external reference point because it is welded in place on the can. This methodology ensured that the aging canisters were always placed in the same orientation, relative to the ^{60}Co sources, each time specimens were removed during the multi-month experiment. Finally, XLPO specimens were radiation-aged in position A5 (Figure 6) in the LICA facility. Can locations in row 5 are known to have the strongest dose rate gradient due to the single side proximity to the source pencils.

Calcium fluoride thermoluminescent dosimeters (TLDs) were used to measure dose rate. A 0.84 correction factor was used to amend for the absorption at high photon energies (i.e. close to the source). One set of dosimetry experiments was conducted in the spatial (x-y) plane with TLDs at the bottom of the basket in positions A, C, X, Y, and Z (Figure 3). A second set of dosimetry experiments were run in positions A4 and D4 to look at potential dose rate variance along the height (z direction) of the can. Figure 7 shows a schematic illustration of the experimental configuration for the height-dependence test, along with the actual dosimeter heights in both positions investigated. Note that "heated" cans are those containing the inner brass canister (with or without heating band) while blocking cans normally do not contain the inner brass and heating mantle. Figure 8 displays a side view of the aging can, inner brass canister with heating band, and basket containing samples along with their relative height positions that can be inferred from the ruler and markings on the can.

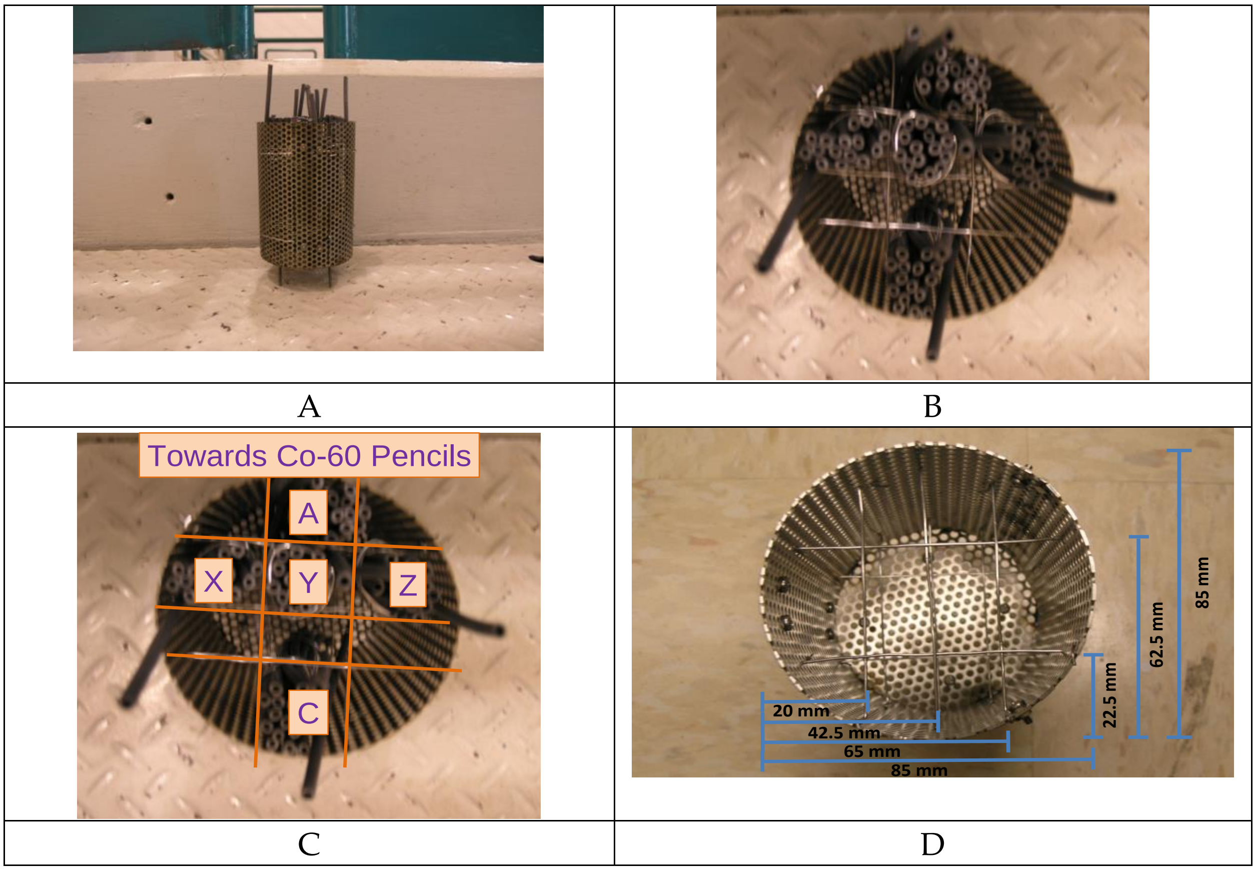

Figure 3. Images demonstrating (A) side view (B) top-down view of basket containing the XLPO samples, (C) the location-naming scheme used in this study and (D) typical dimensions of the sample basket.

Figure 4. Image showing alignment of internal sample canister within aging can.

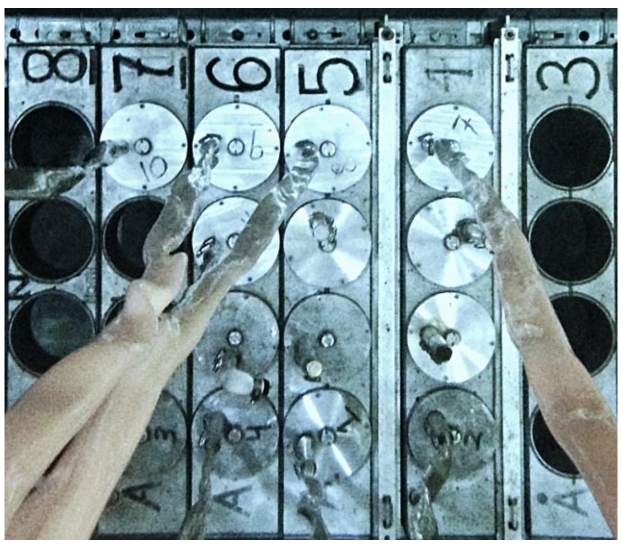

Figure 5. Top-down view of aging cans in the LICA showing can alignment with "umbilical cords" facing away from the sources. Sources are located on either side of Row 4.

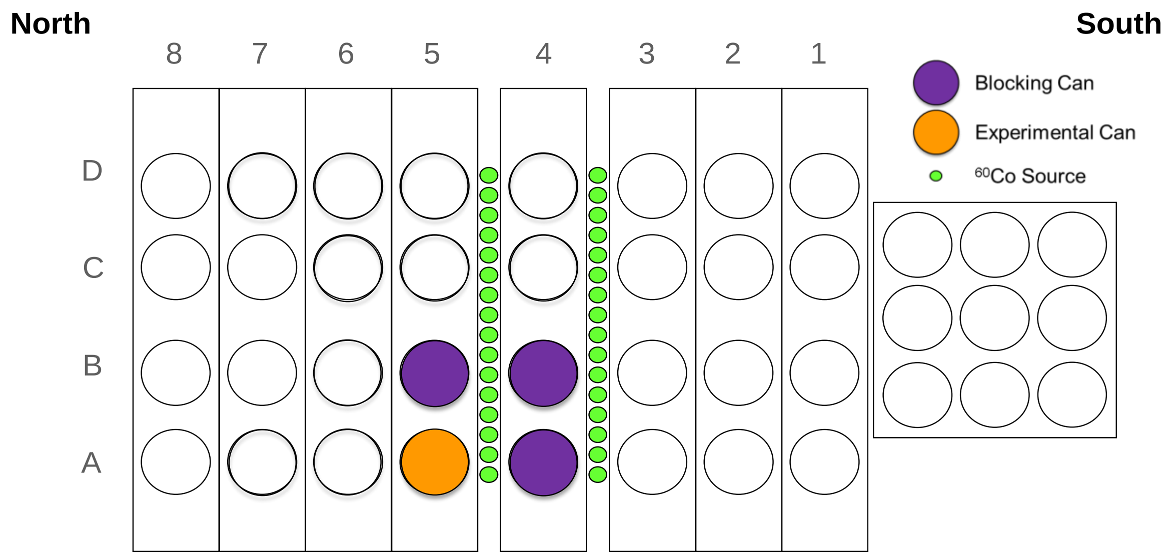

Figure 6. Schematic illustration of LICA facility and placement of experimental can for the spatial (x-y) position study.

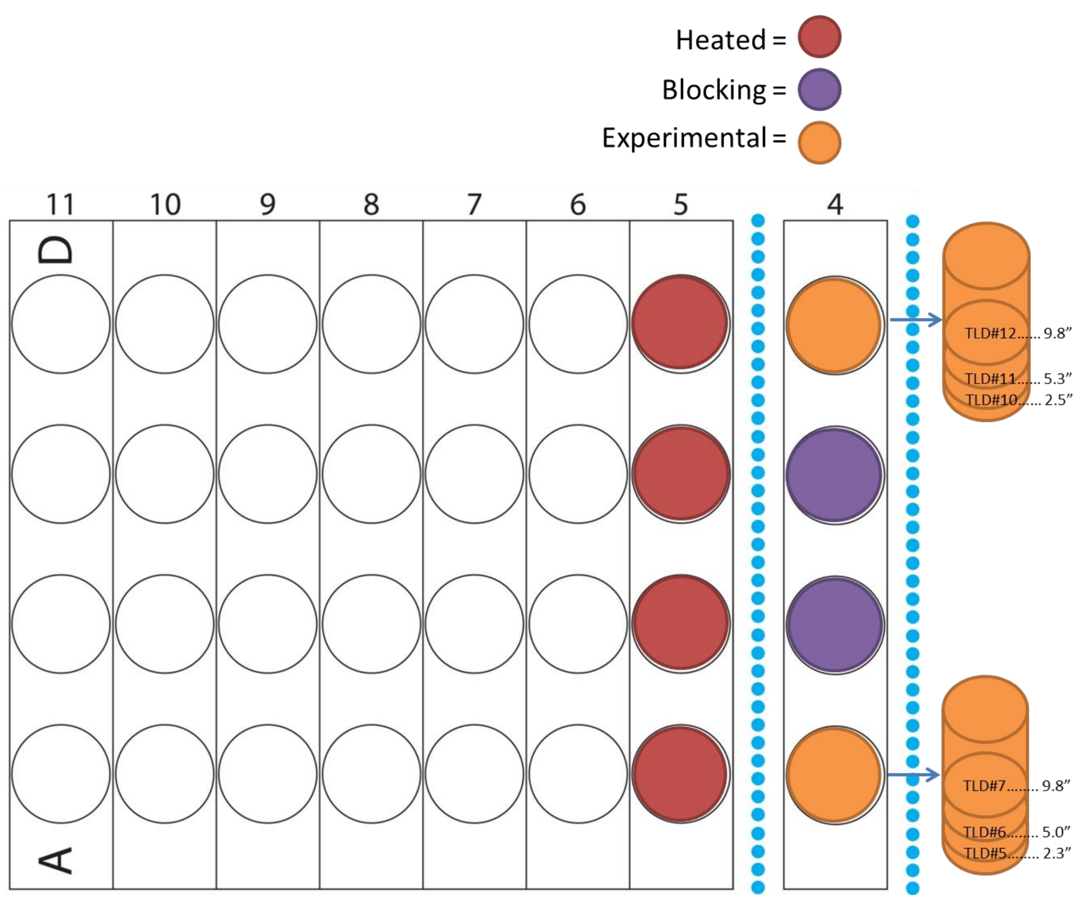

Figure 7. A schematic illustration of the can layout in the LICA facility for dosimetry experiments based on sample height.

2.3 Tensile Testing

All cable specimens were carefully stripped from their metal conductor prior to aging. All laboratory irradiated specimens were aged as cylinders and were measured to be ~11 - 15 cm in length. Some specimens were purposely cut to be longer in length (~15.2 cm); these longer cable insulation specimens were leveraged in gel-content analysis experiments in which the sample extended above the height of the sample basket. Control and exposed samples were measured on an Instron 5564 series equipped with pneumatic grips and extensometer clips that enabled direct ultimate tensile elongation values to be obtained. The initial jaw separation and strain rate were 6.35 cm and 12.7 cm/min, respectively. To account for material variation, data were acquired in triplicate for most time intervals; control specimens (no radiation aging) were tensile tested in conjunction with aged specimens to confirm no variation occurred during the study.

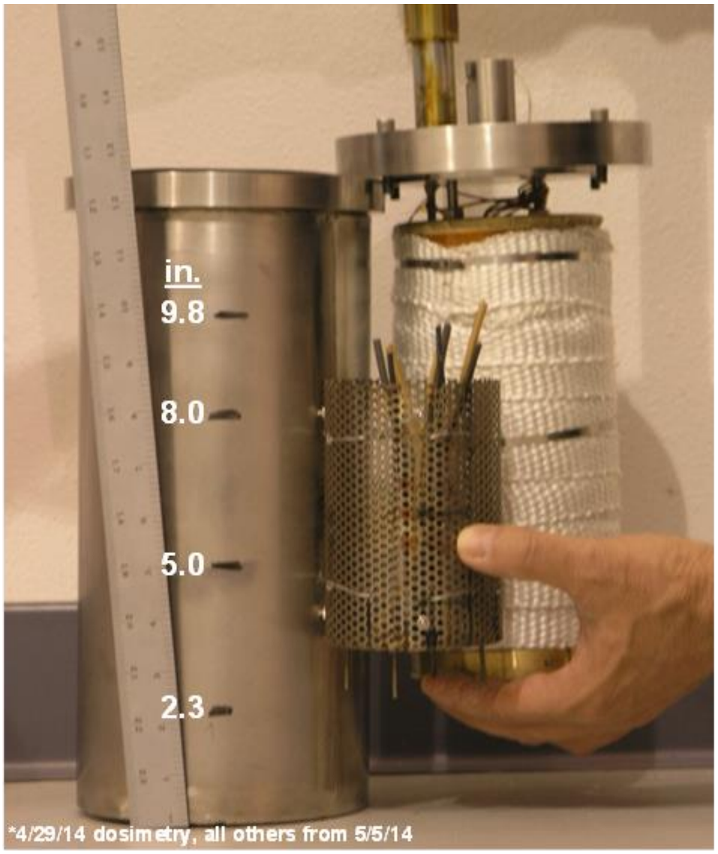

Figure 8. Side view of aging can, inner canister, and basket with samples showing height position of each. Height is marked in inches on the side of the aging can.

2.4 Gel Content Analysis

Cable specimens from the control and exposed material were solvent extracted for eight hours using xylenes (boiling point of 136 – 140°C) under refluxing conditions to determine gel content. Approximately 10 – 20 mg of the cable insulation specimens were placed directly into the solvent prior to heating. A condenser was used to ensure reflux conditions and minimize solvent loss. The soluble component of cable insulation dissolved out of the sample into the hot solvent. When the process was complete, the flasks were allowed to cool very briefly. Then, a Buchner funnel and filter were placed atop a large Erlenmeyer flask or conical flask and the hot solvent poured into the funnel so the remaining cable insulation specimen could be isolated on the filter paper. The process was done in this manner so the sample mass could be measured while in a swelled state and before large solvent loss. After weighing, cable insulation samples were dried in a fume hood. The samples were then transferred into aluminum pans and placed in a heated (80 °C) vacuum oven for overnight drying and the removal of trace solvents. A final weight was obtained of the dried sample to determine mass loss for gel content analysis.

3. Results

3.1 Dose Rates

Spatial dose rate information at the bottom of the can in position A5 are presented in Table as both dose rate and as a percentage of the maximum dose rate measured. These values indicate that the largest variance in dose rate was observed to be from the front (Position A, closest to source) to the back of the can (Position C, farthest from source), where approximately a 35% difference was noted. Contrarily, from side-to-side, about an 8% maximum dose rate difference was determined, which is consistent with the usual scatter in dose rates collected by CaF_2 dosimetry.

Table 1. PE corrected dose rate and dose rate percentage of max as a function of x-y position within an aging can in LICA position A5.

Spatial Position in Can	PE Corrected Dose Rate (Gy/hr)	Dose Rate (% of max)
A (front)	177	100
C (back)	114	65
X (left)	142	80
Y (middle)	155	88
Z (right)	156	88

Dose rate as a function of height within the aging can is presented in Table 2 for positions A4 and D4 in LICA. Note that these values were measured approximately one year after the x-y spatial dosimetry and were taken from Row 4 rather than Row 5. From these data an approximately 26% drop in dose rate was determined from the bottom of the can to the top. If one assumes a similar height-dependence on dose rate in position A5, a comparison of the most diverging positions (i.e. front-to-back and top-to-bottom) could see as much as a 60% difference in dose rate.

Table 2. PE corrected dose rate and dose rate percentage of max as a function of height in LICA positions A4 and D4.

	A4 Position in LICA[i]		D4 Position in LICA[i]	
Height in Can (in.)	PE Corrected Dose Rate (Gy/hr)	Dose Rate (% of max)	PE Corrected Dose Rate (Gy/hr)	Dose Rate (% of max)
2.5	177	97	173	95
5	183	100	182	100
9.8	136	74	135	74

[i.] **Note: Rates are taken one year later than spatial dose rates and are therefore about 12% weaker.**

3.2 Tensile Testing

Tensile elongation at break (EAB) measurements were performed on control (virgin) cable insulation specimens each day that data was collected for aged cable specimens and measured to be ~300 ± 40%; this data can be found in Figure 9. EAB as a function of exposure time for the position in the front (A) and back (C) of the can is plotted in Figure 10 and shows the trends for the most significant local dose rate variations, but also with any dose rate effects remaining unresolved. A statistical analysis of EAB versus exposure time including the 95% confidence intervals is plotted in Figure 11 and shows that the data sets for positions A and C are identical. Data for positions X, Y, and Z, for which dose rate variance is much lower, can be found separately in Figure 12.

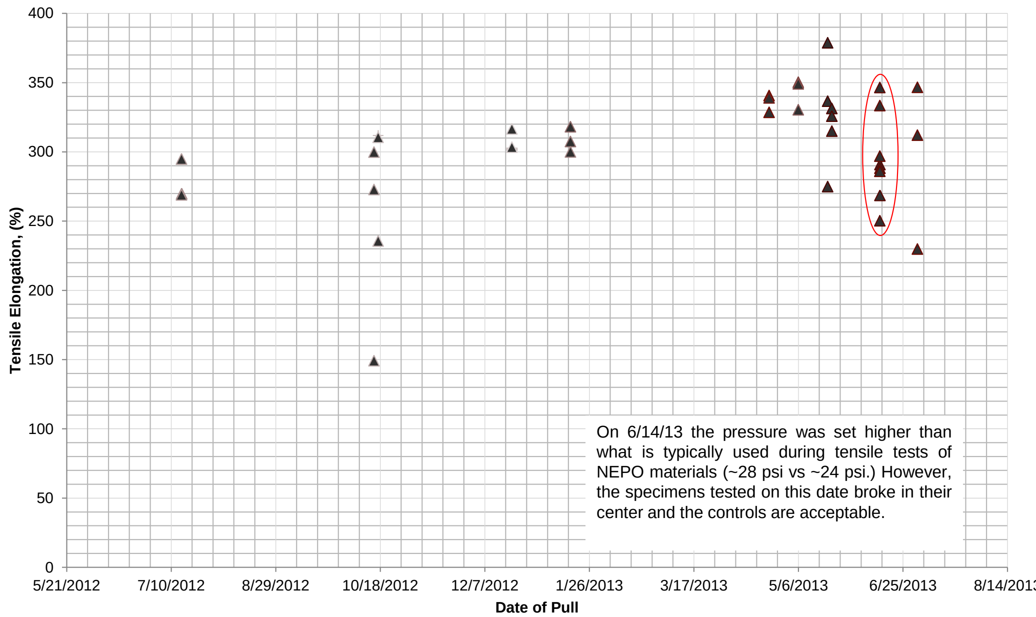

Figure 9. Tensile elongation at break for control samples plotted versus the day the samples were tested.

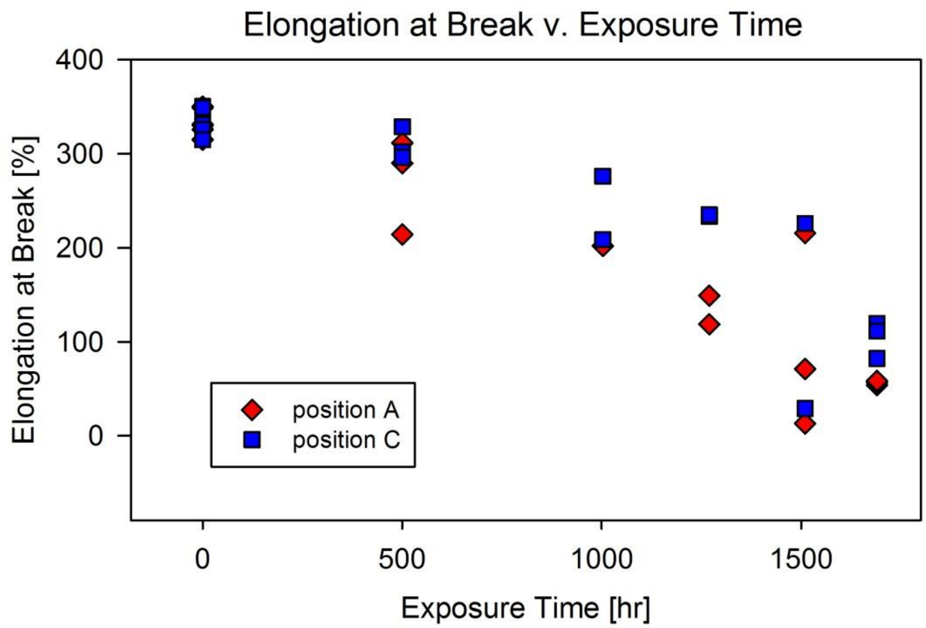

Figure 10. Tensile elongation at break as a function of exposure time at the front (A-177 Gy/h) and back (C-114 Gy/h) positions in the aging can. The can was placed in LICA location A5.

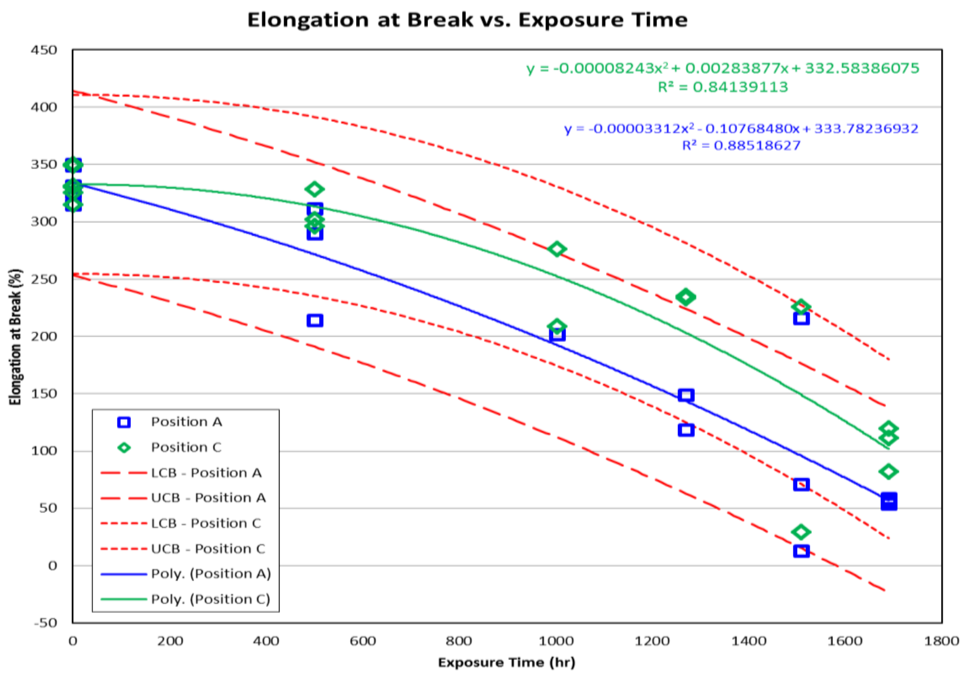

Figure 11. Tensile elongation at break as a function of exposure time at the front (A-177 Gy/h, open blue squares) and back (C-114 Gy/h, open green diamonds) positions in the aging can with statistical analysis. The solid lines show a least squares, second order polynomial fit for position A (blue) and C (green) data. Also plotted are the 95% confidence intervals for position A (red dashed lines) and position C (red dotted lines).

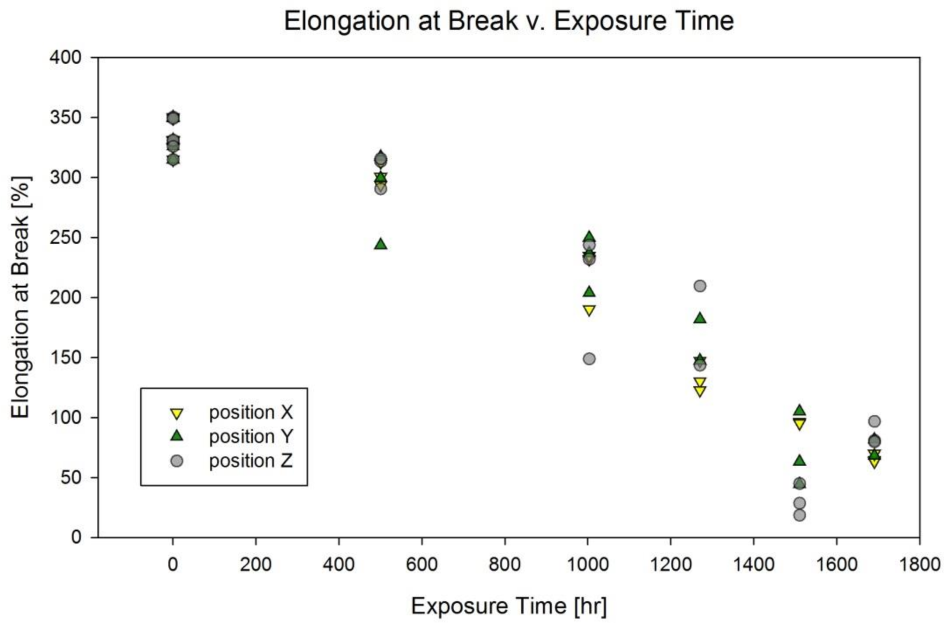

Figure 12. Tensile elongation at break as a function of exposure time at the left (X-142 Gy/h), middle (Y-155 Gy/h), and right (Z-156 Gy/h) positions in the aging can. The can was placed in LICA location A5.

Figure 13 presents the EAB data as a function of actual cumulative dose when taking into account the local dose rate differences of 177 (position A) versus 114 Gy/hr (position C). As expected based on previous work (see References 3-5), the tensile EAB decreased with increasing radiation exposure, with the lower dose rate decreasing more rapidly than the higher rate after about 175 kGy. Statistically, the EAB data for positions A and C are identical using a 95% confidence level. However, as shown in the plot of EAB versus spatially resolved dose accumulation including the 95% confidence intervals (Figure 14), the two data sets are beginning to diverge as the total dose increases, though the experiment would need to be carried out to higher doses to fully elucidate this trend.

EAB versus dose for positions X (142 Gy/h), Y (155 Gy/h), and Z (156 Gy/h) are plotted separately in **Error! Reference source not found.** for clarity. A plot of EAB versus exposure time and EAB versus dose for all positions tested (A,C, X, Y, Z) can be found in the Appendix Figures A-1 and A-2, respectively.

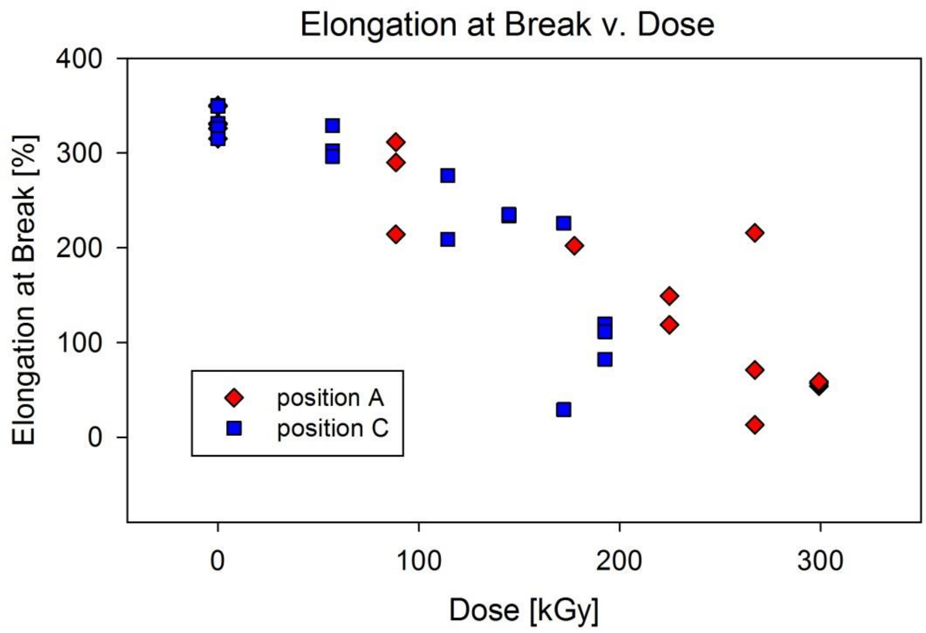

Figure 13. Tensile elongation at break as a function of dose at the front (A-177 Gy/h) and back (C-114 Gy/h) positions in the aging can. The can was placed in LICA location A5.

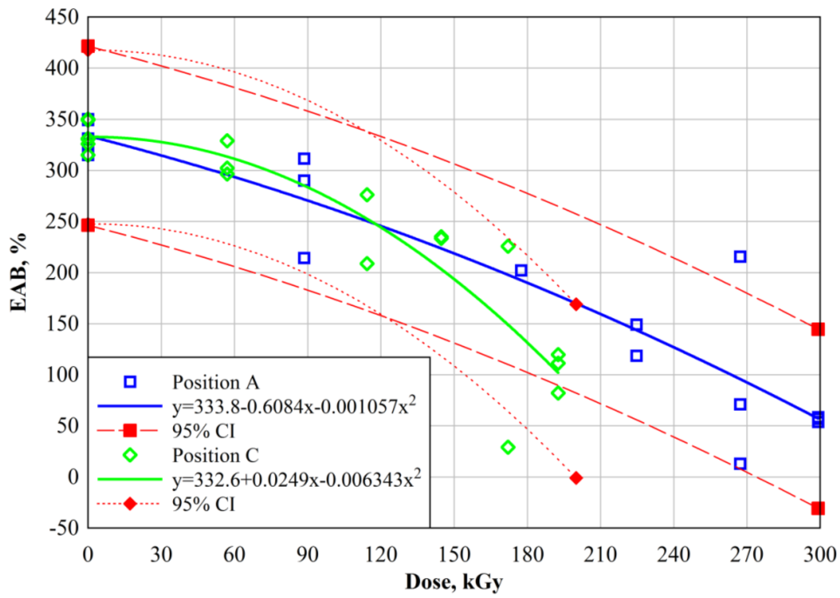

Figure 14. Tensile elongation at break as a function of dose at the front (A-177 Gy/h, open blue squares) and back (C-114 Gy/h, open green diamonds) positions in the aging can with statistical analysis. The solid lines show a least squares, second order polynomial fit for position A (blue) and C (green) data. Also plotted are the 95% confidence intervals for position A (filled, red squares and dashed line) and position C (filled, red diamonds and dotted line).

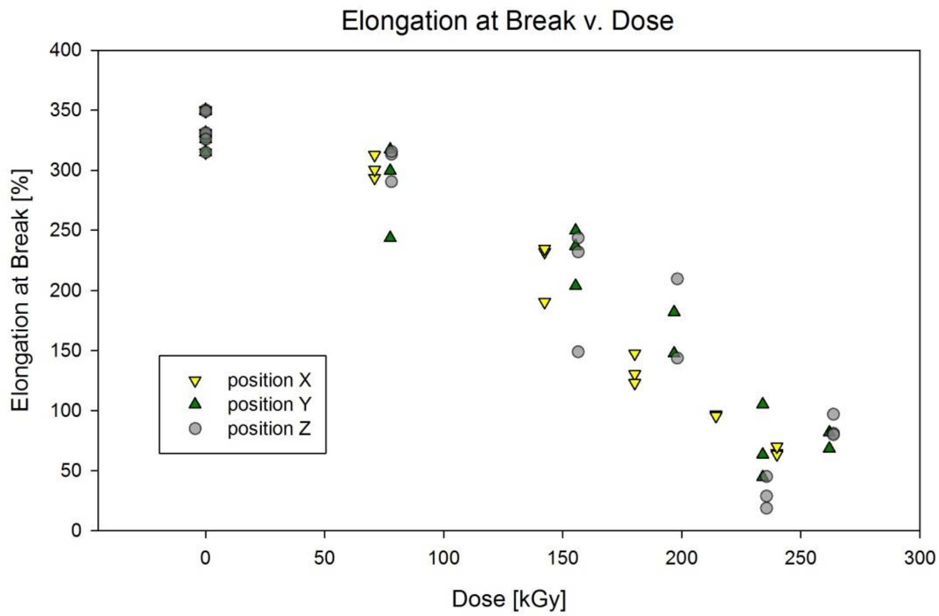

Figure 15. Tensile elongation at break as a function of dose at the left (X-142 Gy/h), middle (Y-155 Gy/h), and right (Z-156 Gy/h) positions in the aging can. The can was placed in LICA location A5.

Since the specimen is presumed to fail at the weakest point (i.e. where the largest dose was accumulated), it is not anticipated that the height dependent exposure variation in the can will necessarily be a complicating factor for this test. Nevertheless, certain prudence in sample positioning must be undertaken to minimize unknown behavior associated with dose rate variance at this position as other tests may be more sensitive.

The purpose of all LICA exposure studies is to establish material degradation behavior (failure doses) as a function of dose rate. It is, however, also clear that due to scatter in any aging data sets, two experiments with similar dose rates (here limited to local can variance) are insufficient to establish the exact magnitude of any underlying dose rate effects. For such studies multiple dose rate experiments, ideally over a large dose rate range, will need to be conducted to minimize intrinsic scatter and obtain a justifiable quantification of the material dose rate behavior.

3.3 Gel Content Analysis

Albeit an excellent metric for identifying variation in material/mechanical performance, tensile testing inherently has a relatively large experimental error. Gel content analysis provides researchers an alternate physical property to monitor aging state; the caveat is that gel content analysis requires correlations or calibrations with mechanical performance. On its own, gel content data are often of little value.

Gel/swelling studies were effectively performed for samples in two different axes. The first is based on the same methodology as for tensile EAB, i.e. defined by distance from the pencils from the front to the back of basket and from side to side. These details were the crux of the EAB experiments because the cable insulation specimens needed to be of significant length; however, for gel content analysis experiments, the perpendicular axis (defined as the top to bottom of cans) could also be explored. Samples were taken from four different locations: above the basket top, top of basket, middle of basket, and bottom of basket (Figure 16). Since dose rate was only known for the top and bottom of the basket (Figure 16, green and red, respectively), only data from those heights were included in the subsequent plots. Gel content for those two heights in the front (A) and back (C) positions of the basket are presented in Figure 17 as a function of exposure time and in Figure 18 as a function of total dose. Unaged (virgin) samples were also analyzed and found to have a gel content of 58.5 ± 0.3%.

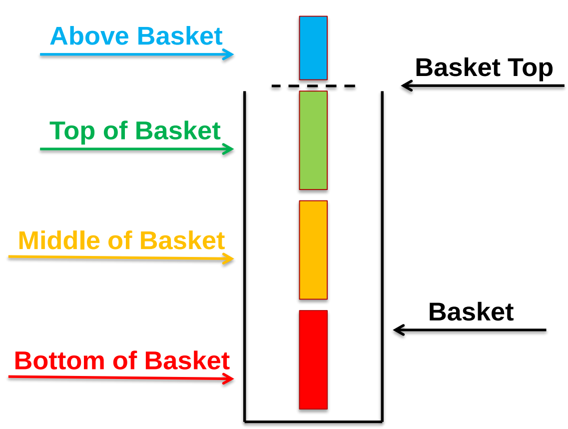

Figure 16. Schematic illustration of height sampling locations for gel content experiments.

It appears that there is no significant difference in the gel content for samples obtained in the vertical direction when accounting for experimental scatter. From the front to the back of the basket there could be a slight difference (on the order of one or two percent), however, we must also note that this material is not particularly sensitive to gel content measurements and that another material may show more pronounced divergence as a function of local dose rates within the exposure can. As part of inverse temperature studies it was shown that the Brandrex and other XLPO materials are relatively insensitive to gel content changes when irradiated at room temperature (see References 3—5). Therefore, one must recognize that additional experimental scatter can be introduced into the material exposure response unless samples are placed as carefully as possible and with spatial dose rate variations understood for sample placement in the horizontal and vertical planes for Rows 4 and 5 at the LICA facility.

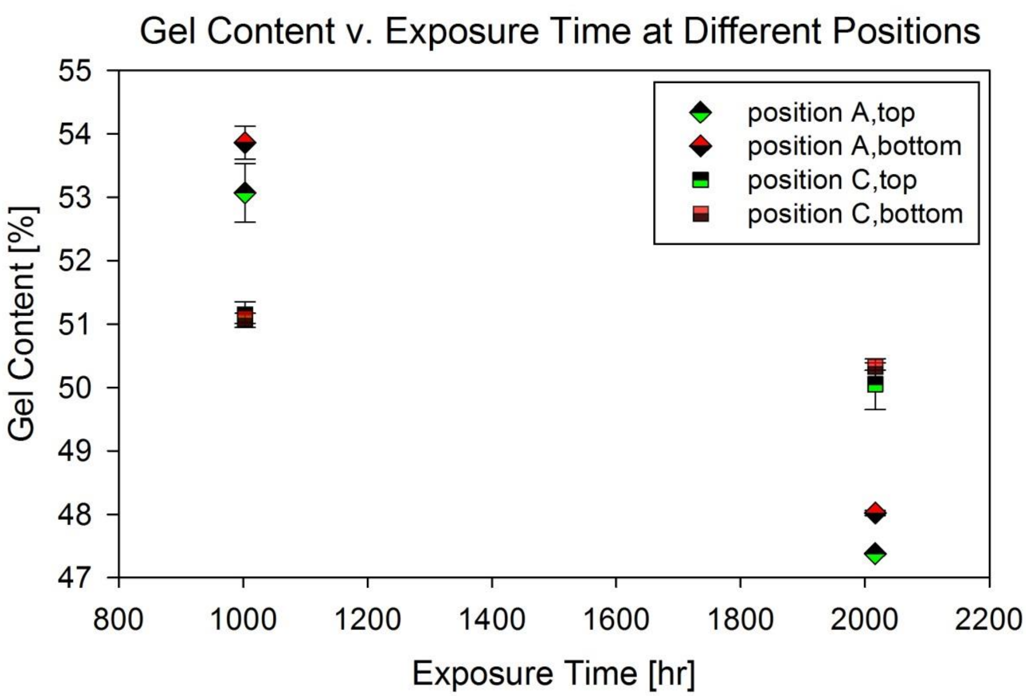

Figure 17. Gel content as a function of exposure time. Position A is at the front of the can closest to the pencils and position C is at the back farthest from the pencils. Figure 16 shows where the "top" and "bottom" of the samples were located. Data is plotted as the average of two samples with error bars representing the spread of the data.

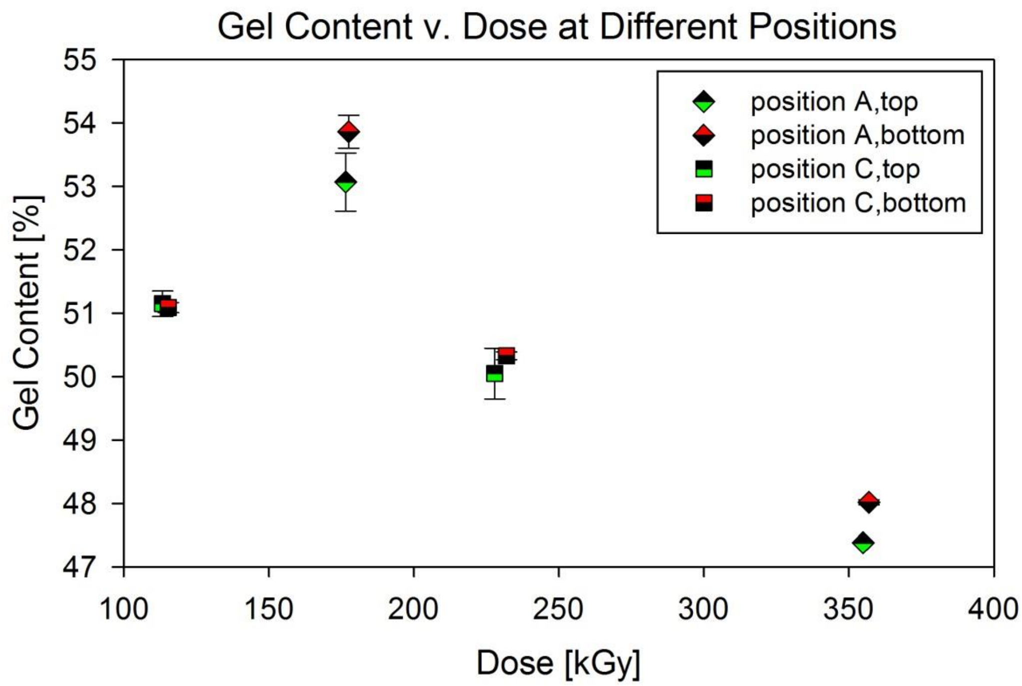

Figure 18. Gel content as a function of dose. Position A is at the front of the can closest to the pencils and position C is at the back farthest from the pencils. Figure 16 shows where the "top" and "bottom" of the samples were located. Data is plotted as the average of two samples with error bars representing the spread of the data.

4. Conclusions

The aim of this study was to evaluate local radiation dose rate gradients within aging cans at the LICA facility. We conclude that while dose rate scatter throughout the can will exist, an approach of attempting to quantify and deconvolute such scatter with tensile elongation studies is not attractive. The quantification of local dose rate variations is very challenging (if not impossible) using these techniques if the material degradation behavior is not clearly understood. Materials may have different dose rate dependencies and degradative differences due to spatially variable dose rates which may or may not exist and be visible. In essence, using EAB as a relative dosimetry indicator is not advisable, nor should it be used in place of primary CaF_2 dosimetry. (One key reason that CaF_2 is used as a dosimeter is its insensitivity to dose rates variations.) If the material of interest happens to have a dose rate dependent degradation behavior, then such behavior will superpose on any local and perhaps unknown dose rates within the can. It is possible that the sum of these two effects could completely cancel out and only random scatter in primary data (whether elongation at break or any other aging indicator) may appear if neither the relevant dose rates nor material dose rate behavior are considered when the data set is examined.

In the current study, the tensile degradation behavior was measured in an experiment where known dose rate variance is present in the aging can. Interestingly, the resulting data set in terms of tensile degradation versus nominal (average) deposited dose or exposure time showed only a minor deviation in position-dependent trends. It could, therefore, be argued that the data appears mostly as intrinsic scatter with no useful information on spatial dose rate sensitivity or that the material may just have a large variance in overall degradation behavior. This of course could happen, but a similar data set could also evolve if a dose rate effect compensates for spatial dose rate variations. In fact, the current Brandrex XLPO material has been examined over a large dose rate regime at room temperature in the past and it is well established that it shows a dose rate dependent behavior (See References 3 – 5). For the current data set, it means that a higher failure dose is required at higher dose rates and a lower failure dose at lower dose rates. This leads to an intriguing analysis and recognition, namely: if the material shows no dose rate effect then an elongation versus average dose or time plot should show local dose rate variations and the primary degradation trends would diverge. However, if a dose rate effect applies, then this evolving divergence in trends is partially compensated for and the data set may not drift apart and could even coalesce to an apparent single scatter distribution. Despite the data scatter issues, the more important question is whether the non-apparent deviation would be due to scatter or material behavior, and that decision cannot be made with this data set. The arguments here imply that unless dose rate effects and local rates are independently analyzed and understood, any average data set has no meaningful information for dose rate influence, no matter what type of scatter may or may not exist.

In conclusion:

- Local dose rate variations within the LICA exposure cans exist, with row 5 having the largest variation. (Row 5 is in proximity to the location of single sided ^{60}Co pencils.)
- The magnitude of dose rate variance in row 5 can be on the order of 35% lower in the position furthest away from the source from the front to the back of the can.
- ^{60}Co decay should be accounted for in all experiments.

- For the larger variations as documented here, for example, positions A and C (177 and 114 Gy/h, respectively) diverging trends are expected to be noticed when tensile data are plotted versus cumulative dose calculated based on prior spatial dosimetry. However, further testing would need to be conducted to validate the trend.
- For row 5, best practices should be applied whenever possible to a) be cognizant of spatial dose rate variations up to 35%, b) place material in center position, and c) if not possible to at least incorporate best estimates for actual dose rates for any material retrieval and following data calculations.
- Primary CaF_2 dosimetry should be used for visualizing or quantifying spatial dose rate variance in cans. It is intrinsically risky to use direct material responses (e.g. tensile elongation for cable insulation) in place of CaF_2 dosimetry as primary trends are convoluted if materials display significant dose rate effects and such behavior is not taken into account.
- It is possible that for some materials where no dose rate effect applies, primary data could show statistically significant divergence in aging trends as a function of small position variations.
- A much better approach to establish the nature of dose rate dependent degradation behavior for cable materials would be systematic experiments conducted over a large dose rate regime by using multiple aging cans in near and far field positions.

5. Acknowledgements

The authors thank Ken Gillen for suggesting the study of the radiation location effects at the LICA facility. We would also like to thank the following SNL team members for their experimental contributions to this work: John Schroeder, Amy Garner, Derek J. Wichhart, and Samuel Durbin.

6. References

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(5) Gillen, K. T.; Clough, R. L. "Predictive Aging Results in Radiation Environments," *Radiation Physics and Chemistry*, **41**, (1993) 803-815.

7. Appendix

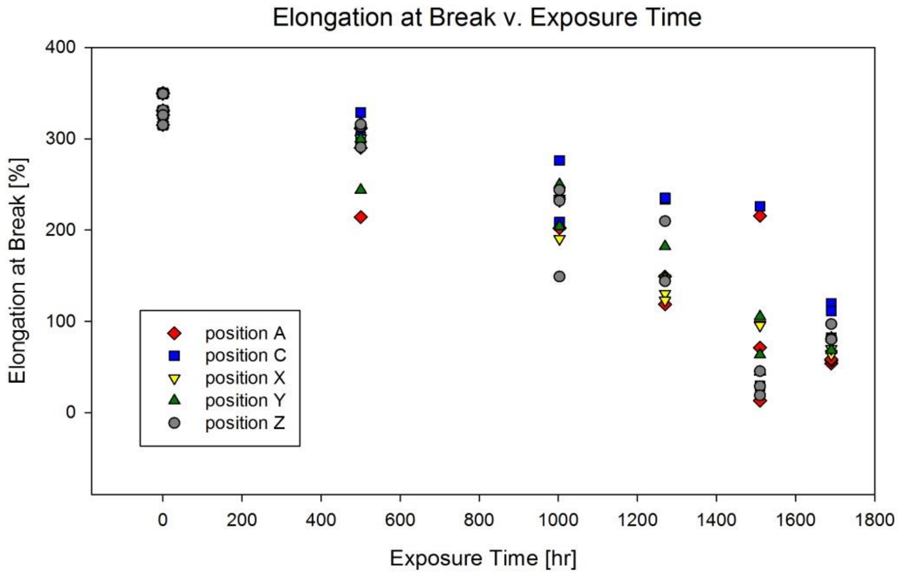

Figure A-1. Tensile elongation at break as a function of exposure time at the front (A-177 Gy/h), back (C-114 Gy/h), left (X-142 Gy/h), middle (Y-155 Gy/h), and right (Z-156 Gy/h) positions in the aging can. The can was placed in LICA locations A5.

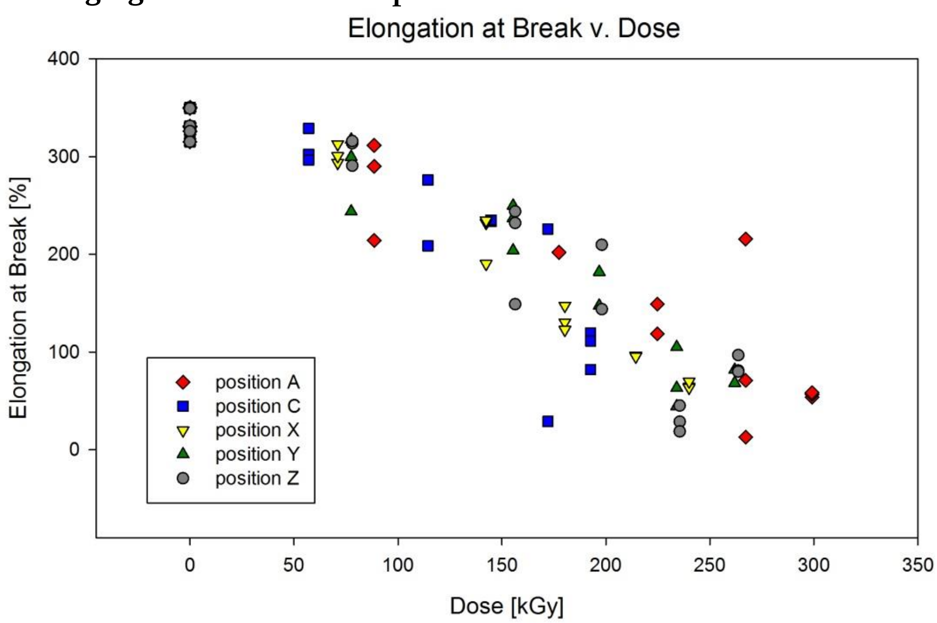

Figure A-2. Tensile elongation at break as a function of exposure time at the front (A-177 Gy/h), back (C-114 Gy/h), left (X-142 Gy/h), middle (Y-155 Gy/h), and right (Z-156 Gy/h) positions in the aging can. The can was placed in LICA locations A5.

APPENDIX H: HFIR REPORT

Aging Assessment of an Oak Ridge National Laboratory High Flux Isotope Reactor (HFIR) Service Cable

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1. Introduction

Nuclear energy is one industry where aging of safety-related materials and components is of great concern. Many U.S. nuclear power plants are approaching, or have already exceeded, 40 years of age. Analysis comparing the cost of new plant construction versus long-term operation under extended plant licensing through 60 years strongly favors the latter option. To ensure the safe, reliable, and cost-effective long-term operation of nuclear power plants, many systems, structures, and components must be evaluated. Furthermore, as new analytical techniques and testing approaches are developed, it is imperative that we also validate, and if necessary, improve upon the previously employed Institute of Electrical and Electronic Engineers (IEEE) qualification standards originally written in 1974 [1]. Fortunately, this daunting task has global support, particularly in light of the new social and political climate surrounding nuclear energy in a post-Fukushima era.

Today, the U.S. has several nuclear power plants operating on extended licenses. Recent polling data obtained from the utilities indicate that the key concerns are cables and piping [2,3]. As such, SNL is collaborating with colleagues in other Department of Energy and Department of Commerce laboratories, U.S. Nuclear Regulatory Commission, industry, and partners abroad as part of a collaborative approach to clearly identify 1) what work has been done in the past to investigate cable degradation, 2) what are the relevant cable aging conditions (temperature, humidity, dose/dose rates), 3) what experiments are of highest priority that are required to model and therefore estimate the remaining lifetimes of existing cables, and 4) potential sources to retrieve service cables of interest to the nuclear power industry.

The High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL, located in Oak Ridge, TN, USA) is a neutron flux based research facility that is used by more than 500 researchers annually across a wide breadth of scientific areas [4]. After a cable related incident at the facility, questions were raised with regard to the condition and aging/degradation of a certain cable insulation type. While these cables were not qualified to be nuclear power cables, they were similar enough that given the tools, techniques, and expertise developed for nuclear power plant cable insulation studies, SNL was asked to examine samples from HFIR. The goal of the study was to assist the HFIR facility understand the current status and provide first order predictions for the aging and degradation of their cable insulation.

2. Experimental

2.1 Materials

Sandia National Laboratories, Albuquerque, New Mexico was provided ~16 m of various colored low voltage (one conductor, 1.3 mm wall thickness insulation, 900 Type THW 600 V) Anaconda Densheath (EPR) cables that were estimated to be ~45 years in age. The cables were removed from the High Flux Isotope Reactor at Oak Ridge National Laboratory (HFIR at ORNL) during an outage with the intention to assess how the cables aged with time. Conversations with HFIR personnel indicated that the approximate service conditions were ~27°C with ~70% RH; none of the cables provided were exposed to radiation.

Xylenes (Electronics Use Grade, 99+%, Acros) and isopropanol (HPC grade, 99.9%, Fisher) were used as received.

2.2 Accelerated Aging

All HFIR cable insulations were subjected to thermal-oxidative aging environments in air circulating ovens at temperatures ranging between 40 $\pm$ 2°C and 138 $\pm$ 2°C for up to ~536 days (~1.5 years). Specimens were removed from the aging ovens at various points in time for thermal and mechanical analysis.

2.3 Tensile Testing

Cable insulation specimens for tensile testing were carefully stripped from their metal conductor prior to aging. All insulation specimens were aged as tubes that were measured to be ~150 mm in length. Tensile testing (5.1 cm initial jaw separation, 12.7 cm/min strain rate) was performed on an Instron 5564 series equipped with pneumatic grips and extensometer clips that enabled ultimate tensile elongation values to be obtained. Tensile measurements were performed in triplicate for samples aged at each time period; control specimens were periodically tested to determine any variation in tensile elongation that may have occurred with room temperature aging during the study (see Figure).

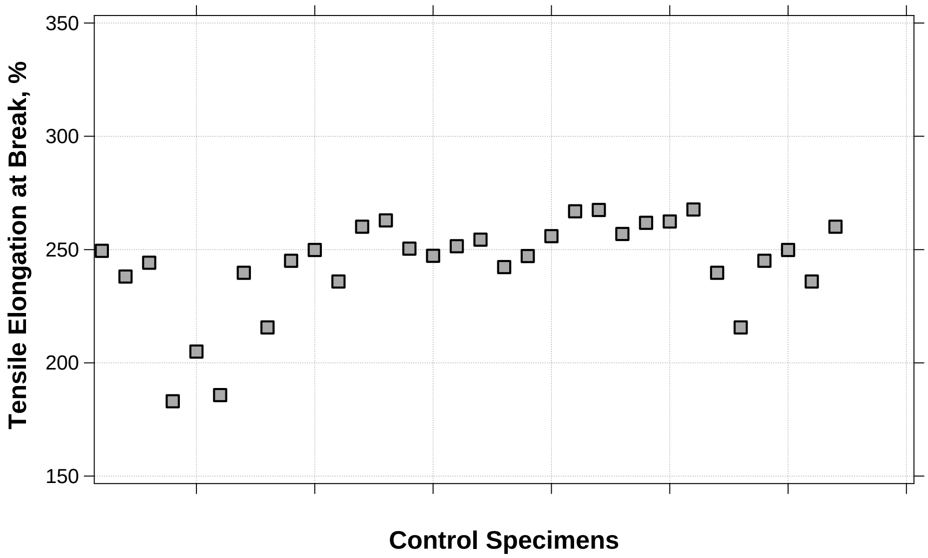

Figure 1: Ultimate tensile elongation data for as-received Anaconda Densheath EPR cables returned from HFIR at ORNL (~45 yrs of age, T_{avg} ~27°C, RH ~70%) measured periodically over the duration of the laboratory accelerated aging study (~1.5 yrs). Since the data were not recorded by date taken, the abscissa reflects the individual control samples.

2.4 Gel Content and Solvent Factor Uptake Analysis

Solvent factor uptake measurements were performed by refluxing a known weight (w_o) of cable insulation in xylenes between 6 and 8 hrs. The swollen specimens recovered from the solvent (w_s) were weighed to determine the mass of the absorbed solvent. Subsequently, the wet specimens were dried in a vacuum oven held at 80°C for at least 4 hrs. The final weight (w_f) of the insulation was then recorded. The recorded solvent uptake factor is equal to the ratio of w_s to w_f. Comparatively, the gel content is equal to the ratio of w_f to w_o.

$$Solvent\ Uptake\ Factor = {}^{w_s}/_{w_f}$$

$$Gel\ Content = {}^{w_f}/_{w_0}$$

w_s= swollen weight

w_f= final weight; dried via vacuum

w_0= initial weight

2.5 Density

The Archimedes principle was employed to measure the macroscopic densities of as received and laboratory aged cable insulations [5-7]. In short, specimens of approximately 50 to 200 mg were weighed both in air and then in isopropanol on a microbalance. Density calibrations were performed using glass calibration balls of accepted density.

3. Results and Discussion

3.1 Tensile Elongation

The as-received tensile elongation at break (EAB) for cable insulations returned from HFIR was measured to be approximately 250 ± 21%. An accepted point of reference for significant materials degradation of nuclear power plant cable insulations is 50% ultimate tensile elongation [5], but 100% remaining tensile has also been used to rate performance and is used in this report for some conservative projections. Clearly, the EAB for the HFIR cable insulations were measured to be greater than this threshold.

Figure 2 shows the primary tensile elongation data measured for Anaconda Densheath cable insulations as a function of various laboratory aging times and temperatures. The measured tensile EAB for cable insulations aged at 109°C and above were reduced to less than 50% EAB in ~4000 hrs or less, depending on the aging temperature. Comparatively, no significant reduction in EAB was observed after more than 10,000 hrs (>1.3 years) of aging at 80°C and below. It should be noted that according to cursory thermal studies using differential scanning calorimetry there is a thermal transition at approximately 80°C for the virgin material. Partial melting transitions have been identified in other materials with the potential to complicate the aging behavior and are often associated with Arrhenius curvature [5,8,9].

The acquired aging data provide the following guidance: For the upper temperature range between 138 and 109°C a meaningful time-temperature data superposition is possible and yields 81 kJ/mol as an activation energy (E_a). The lower temperature data can be shifted in time, but a rigorous shift factor determination cannot be conducted because no real property change has occurred, which would allow the corresponding time factors to be indisputably established. However, the 80°C aging data also show that no decay in EAB occurred up to 10440 hours of exposure. This means that some guidance for the lower temperature material aging behavior can be obtained by comparing the measured 'non-aging' at 80°C with an extrapolation from the 138-109°C regime using the 81 kJ/mol. A shift factor extrapolation with this E_a yields 0.134 for 80°C. As discussed later this relative 80°C performance can also be used to guide extrapolations to lower temperatures.

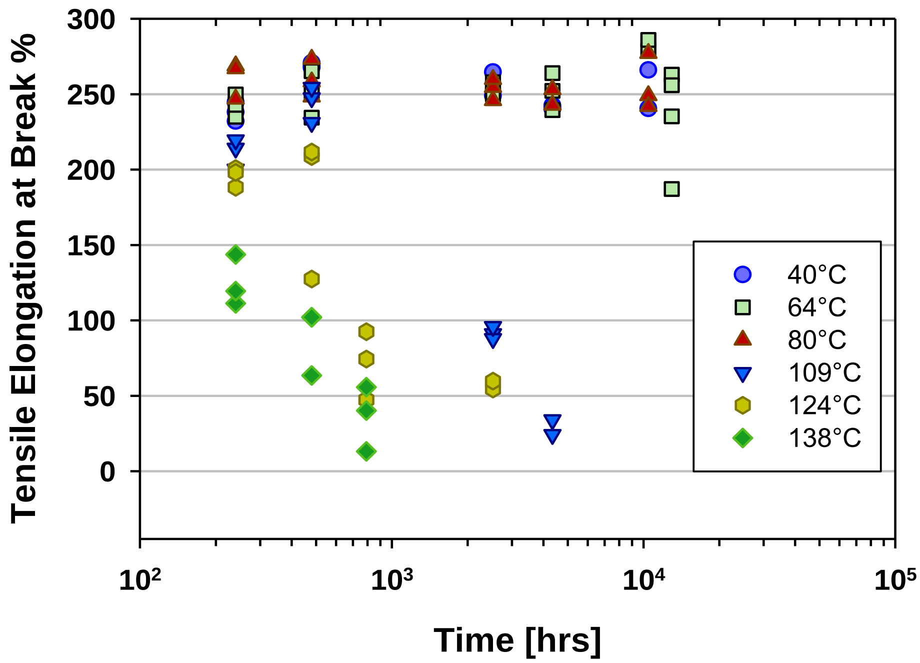

Figure 2: Ultimate tensile elongation data for Anaconda Densheath EPR cables returned from HFIR at ORNL (~45 yrs of age, T_{avg} ~27°C, RH ~70%) as a function of aging time and temperature.

As a first data analysis, Figure 3 shows the superposed 138-109°C tensile data yielding 81 kJ/mol (for a definition and explanation of this methodology, see reference [10]) for the cable insulations returned from HFIR. Albeit, additional long-term data should be collected to enable a better assessment, particularly at the lower temperatures (note that extended aging is normally not part of a screening study), the 138-109°C and the 80°C behavior provide suitable guidance for this material. The authors wish to point out that due to the lack of extended data the lower temperature EAB data (80°C and below) demonstrated no significant curvature in any Arrhenius analysis, but it also renders any superposition of the data highly subjective. The lower temperature data neither prove nor disprove the presence of curvature. Additional data would be needed to validate or refute the suggested shift factors and projections. For illustrative purposes of potential Arrhenius curvature, 30 and 50 kJ/mol are used later for projections, however it should be pointed out that the only scientifically substantiated number is 81 kJ/mol, which is based on the high temperature data. For clarification, the subjective shift factors in this document are in red and the objective ones in black bold.

Figure 3 also shows the corresponding shifted data for 80°C and below when a single E_a of 81 kJ/mol is applied. Furthermore, this plot also contains two dotted average EAB decay curves showing the average behavior for the confirmed and shifted aging at 138-109°C (left curve) and an average curve (right curve) which includes the 80°C and lower temperature data for this shift condition (i.e. single E_a of 81 kJ/mol). We note the following: The 80°C performance appears better than the 81kJ/mol extrapolation would suggest, since the last data point (the original 10440 hours) is now located to the upper right of the combined aging curve. It also suggests that the aging curve is likely a little steeper in its decay for the projected 80°C behavior than observed for the 138-109°C regime. Most importantly, the measured cable insulation 'stability' at 80°C is not worse than the 81 kJ/mol extrapolation would suggest. As a trend the observed aging even appears slower at 80°C than the prediction would imply. However, this would suggest an activation energy somewhat larger than determined for the upper temperature regime (with 81 kJ/mol) to compensate for this trend in a superposition analysis, but changes to a higher E_a with a drop in temperature have not been well documented in the literature, and such a behavior would be quite unusual. Alternatively, a higher E_a may be relevant between 138-80°C with the 80°C behavior providing that guidance, but then the observed aging at 138 and 124°C would be too slow. Therefore, the most likely explanation for the good stability at 80°C is a steeper degradative EAB loss behavior at this temperature.

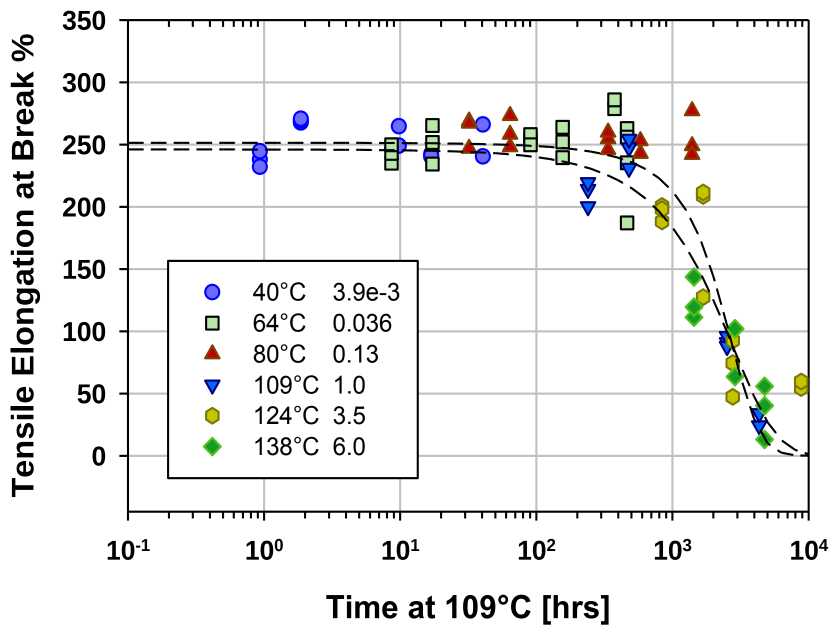

Figure 3: Superposition to 109°C of the 138, 124, 109°C data yielding shift factors and time shift of the lower temperature data (64 and 40°C) based on shift factors resulting from extrapolation with a single E_a of 81 kJ/mol. Note that the 40 and 64°C data are positioned more at earlier times due to relatively low shift factors for these two temperatures.

A second data analysis is shown in Figure 4, which is based on a superposition using 81 kJ/mol to 80°C as before, but instead of continuing with 81 kJ/mol to lower temperatures, shift factors are rather obtained from a projection with 30 kJ/mol to lower temperatures. This is evident by the fact that the 40 and 64°C data are now positioned further to the right consistent with larger relative shift factors given by lower E_a. Again a steeper degradation curve for the degradative EAB loss behavior for combined data set is evident. We also note that the longest 64°C exposure data point (12928 h) is quite close to the 80°C 'stable material' time in this superposition. This suggests that the material likely does not age with an E_a much lower than 30 kJ/mol between 80 and 64°C. A superposition with 30 kJ/mol below 80°C is likely a worst case scenario. Not enough information is available to justify any comment about the 40°C limited exposure measurement.

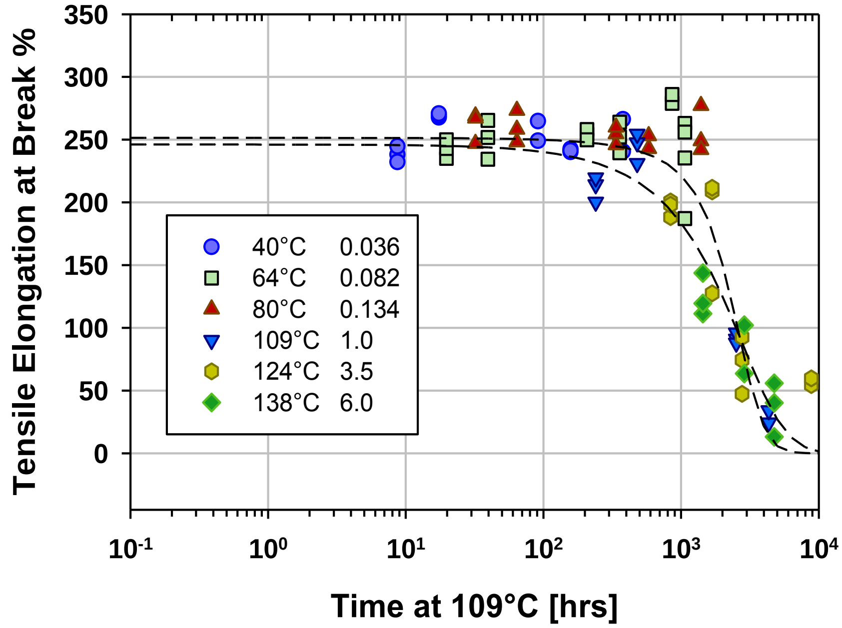

Figure 4: Superposition to 109°C of the 138, 124, 109°C data yielding shift factors and time shift of the lower temperature data based on shift factors resulting from extrapolation with 81 kJ/mol to 80°C and then projected towards lower temperature with 30 kJ/mol. Note that the 40 and 64°C data are positioned further to the right and a steeper degradation curve for the combined data set (138 to 40°C) is implied.

As mentioned before, there is insufficient evidence in the measured data set to suggest curvature in the Arrhenius plot below 80°C and at minimum 80 kJ/mol is given between 138 and 80°C. Projections with a reduced E_a below 80°C are therefore provided to demonstrate conservative aging predictions. Arrhenius curvature does not apply to each material and in general may apply or may not. Based on all thermal aging work conducted at SNL curvature cannot be predicted, but has to be experimentally observed [8-10]. Limited guidance is available for thermal aging of related cable insulation materials. For XLPO insulation materials low temperature oxidation rate measurements suggest a drop in E_a from about 100 to 70 kJ/mol for Brandrex, and about 130 to 100 kJ/mol for Rockbestos, respectively. For an Anaconda EPR material there is some evidence for a drop in E_a from approximately 130 to 100 kJ/mol. A Rockbestos Neoprene cable jacket material showed a decrease in E_a from about 95 to 80 kJ/mol.

Considering such trends it is reasonable to accommodate performance projections for the Anaconda Densheath cable insulations with a drop from 80 to 50 kJ/mol towards RT conditions not as given and experimentally confirmed behavior, but rather as a conservative data analysis. As mentioned above a drop below 30 kJ/mol is unlikely based on the data obtained in this study and 30 kJ/mol is therefore regarded as a worst case scenario. Figure 5 is a plot of the shift factors (Arrhenius [10]) determined from the superposed Anaconda Densheath EPR tensile EAB data. By leveraging only shift factors for data acquired at 109°C and greater, the activation energy (E_a) was calculated to be ~81 kJ/mol. Based on the shape of the tensile data and an E_a of ~81 kJ/mol the remaining service life (50% elongation) would be predicted as ~400 years. Additionally, potential changes in the E_a to, for example 30 or 50 kJ/mol, are incorporated in the Arrhenius plot at the lower temperatures (< 80°C). Assuming an E_a could be estimated to be as low as ~30 kJ/mol would drastically reduce the predicted remaining service lifetime from centuries to decades. This analysis emphasizes the importance of understanding material behavior over a range of temperatures and that care must be taken when using these types of accelerated aging data for predicting remaining lifetimes.

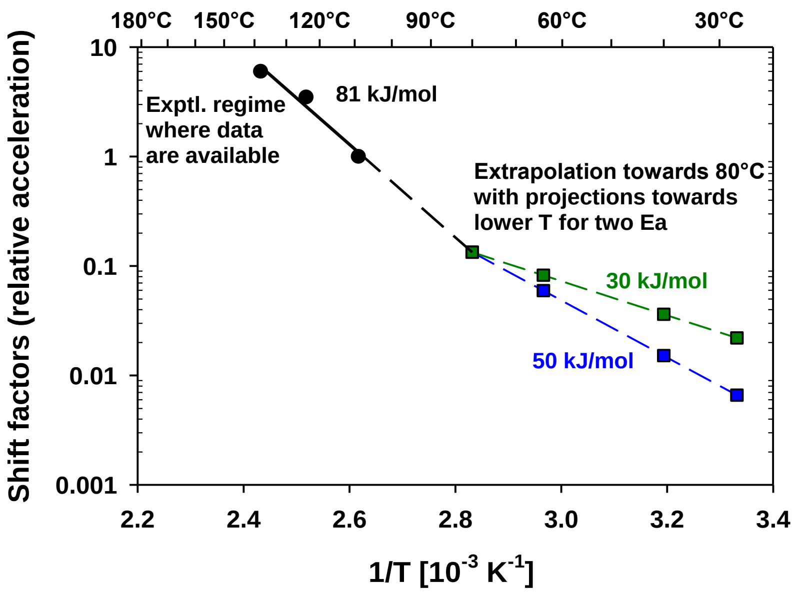

Figure 5: Shift factor plot highlighting experimental and extrapolation regions for two assumed activation energies below 80°C.

A complementary way to represent a shift factor plot and the corresponding predictions is given by plots of estimated time to 100% elongation or projected aging curves (Figure 6 and Figure 7). Figure 6 demonstrates the time to 100% elongation as a function of temperature where data are available and for lower activation energies below 80°C, i.e. 30 or 50 kJ/mol if they should apply. Figure 7 further illustrates the impact of uncertainty in the low temperature E_a, from 80 kJ/mol to 30 kJ/mol, and the resulting effect on remaining cable lifetime. An additional uncertainty is the shape of the decay curve in EAB as a function of temperature. In this projection an identical curve shape is assumed as provided by the high temperature data when superposed with 81 kJ/mol, which may not reflect actual behavior. Both plots show projected lifetimes (100% elongation) for 27°C on the order of a few decades (50 kJ/mol) and ~ 15 years for the worst case scenario of 30 kJ/mol.

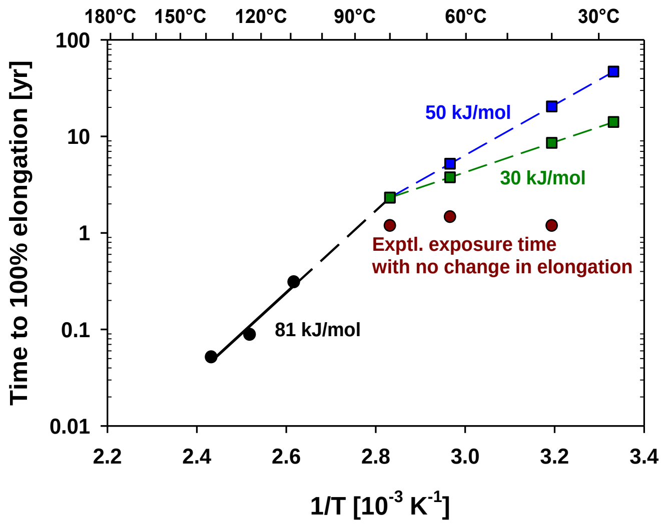

Figure 6: Actual (138 to 109°C data) and projected times to 100% elongation for two assumed activation energies below 80°C.

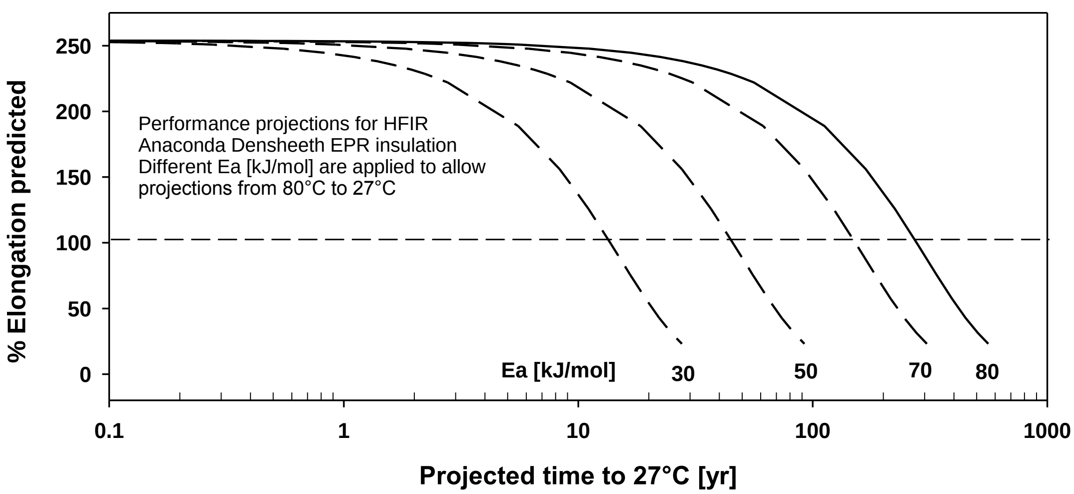

Figure 7: Projected performance at 27°C for different activation energies in the range of ~80 kJ/mol to ~30 kJ/mol. In this case the average aging curve is dominated by the behavior at the higher temperatures (138 to 109°C) where aging data exist. This approach deemphasizes the measured stability at 80°C and its projections.

Given that uncertainty exists in the development of the aging curve (decay of EAB) at lower temperatures, as well as the dominance of the high temperature data in the average aging curve, an important data point exists in the experimentally confirmed cable insulation 'stability' at 80°C, as measured by 10440 hours of exposure with no reduction in EAB. This time implies an absolute minimum performance and can be projected to lower temperatures with any activation energy (see Figure 8). While a continuation below 80°C with 80 kJ/mol would suggest above 100 years of 'no aging' performance, a possibly lower E_a of 50 kJ/mol still projects ~ 30 years for no change, and the worst case scenario of 30 kJ/mol predicts ~ 10 years. There is no evidence that the E_a should drop from 80 to 30 kJ/mol, but a drop from 80 to 50 kJ/mol is a reasonable assumption and is consistent with changes that have been obtained for other materials via oxidation rate measurements. We therefore conclude that the most reasonable projection from the observed 80°C behavior with 50 kJ/mol predicts ~ 30 years with no aging followed likely by a few decades of the transition to reduced EAB and ultimately brittle properties.

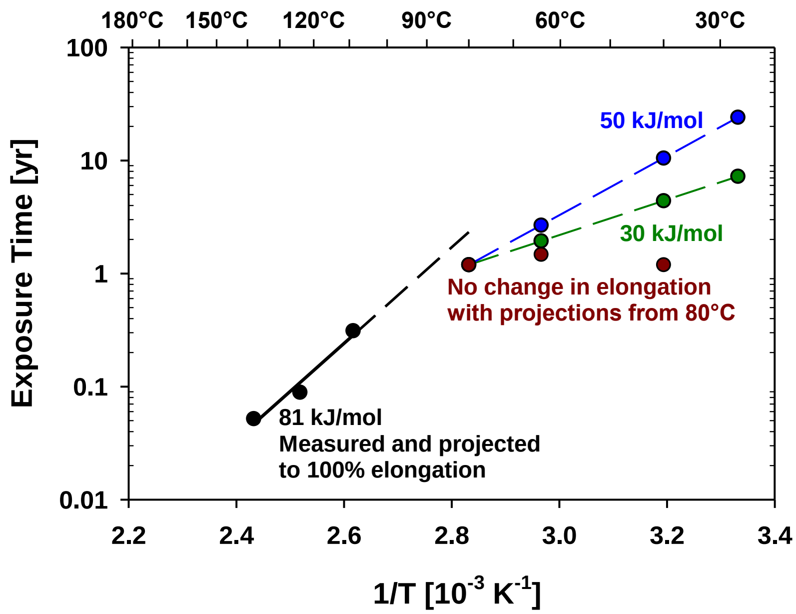

Figure 8: Actual (138 to 109°C data) and projected time to 100% elongation at 80°C in comparison with projections for minimum performance, i.e. no change in EAB, for two assumed activation energies below 80°C.

While to the best of our knowledge this exact material has not been studied previously, the authors may, however, compare these new data to the closest material for which data already exists. For instance, Gillen and Bernstein investigated Anaconda Durasheath EPR cable insulation aging [5] and determined E_a to be ~100-128 kJ/mol which is slightly different than our initial (previously published) prediction of ~103 kJ/mol [11] and the 81 kJ/mol discussed throughout this report, nevertheless suggesting significant lifetimes remaining. Again, this highlights the limits of using only "high" temperature, short time intervals for aging predictions, but does not change the overall conclusions.

The aging behavior of the Anaconda Densheath cable insulation is consistent with the performance of other EPR materials previously presented [5] demonstrating significant predicted service lifetimes. The E_a values support previous work; however, given the shape of the tensile data the most realistic E_a is likely somewhere between 30 and 80 kJ/mol for thermal-oxidative aging conditions. A more precise understanding of the E_a value for this material could be determined using aging data collected over longer periods of time at lower temperatures.

However, the goal of these efforts was to demonstrate whether or not this particular service cable has substantial life remaining, which, even when considering our lowest estimation of (E_a ~30 kJ/mol), still predicts a few decades of remaining service life (Figure 7).

3.2 Density

Material properties such as density are often measured in addition to gel content and solvent uptake factors in aging experiments because these data can provide insight to the underlying degradation mechanism(s) and/or be utilized as a condition monitoring technique.

Figure 9 shows density measurements of laboratory aged Anaconda Densheath EPR insulations returned from HFIR. As with the tensile data, significant changes in the density data are only observed at the higher laboratory aging temperatures wherein density increases with increased aging time.

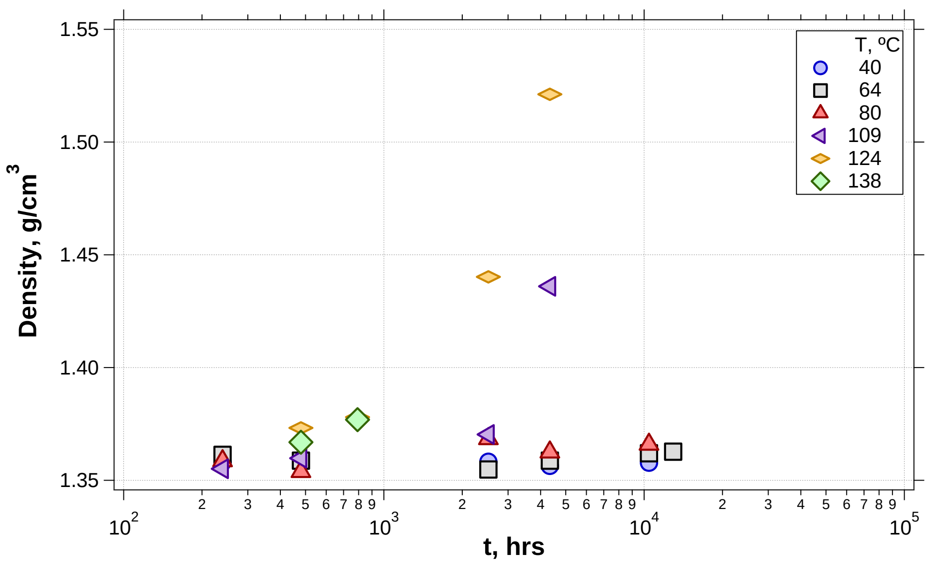

Figure 9: Density plotted as a function of aging time for Anaconda Densheath EPR insulation aged at various temperatures.

Similar to the tensile EAB data, the density data were superposed; Figure 10 shows the resulting curve and relevant shift factors. It is worthwhile to note that the shift factors for density were similar to those determined for tensile EAB. An Arrhenius plot was also made using a worst case E_a estimated to be ~30 kJ/mol for density. Figure 11 shows the predicted density behavior, along with tensile EAB, with an E_a of 30 kJ/mol. In this particular instance, there is a reasonable correlation between tensile EAB and density measurements. Significant changes in density correlate with a substantial reduction in elongation at break (brittle behavior). These correlations suggest that density measurements may be a viable condition monitoring (CM) technique that can be leveraged towards 'health monitoring' of existing service cables; however, further work would be warranted.

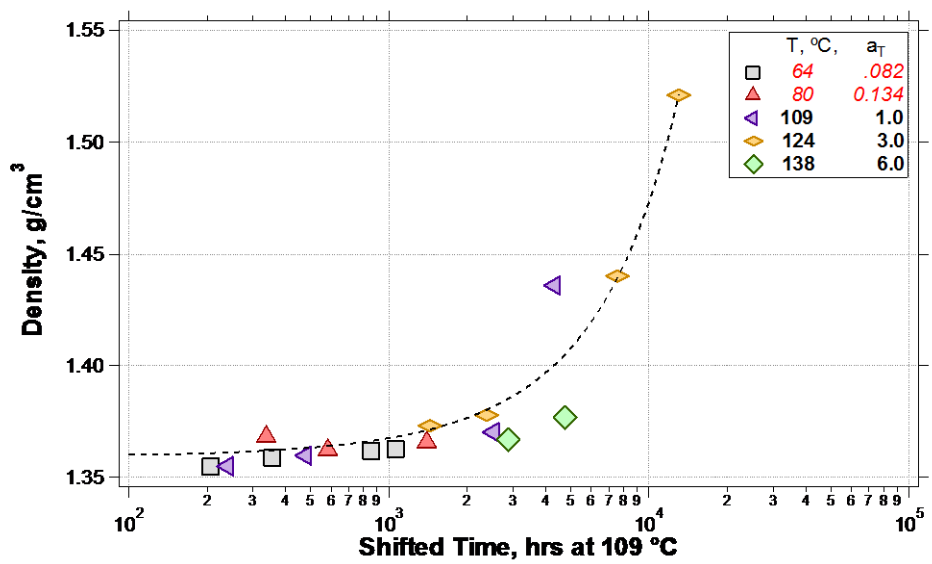

Figure 10: Time-temperature superposition of density data at a reference temperature of 109°C for Anaconda Densheath EPR insulation aged at various temperatures with an assumed E_a of 30 kJ/mol below 80°C. Note: the subjective shift factors in are in red italics and the objective ones in black bold.

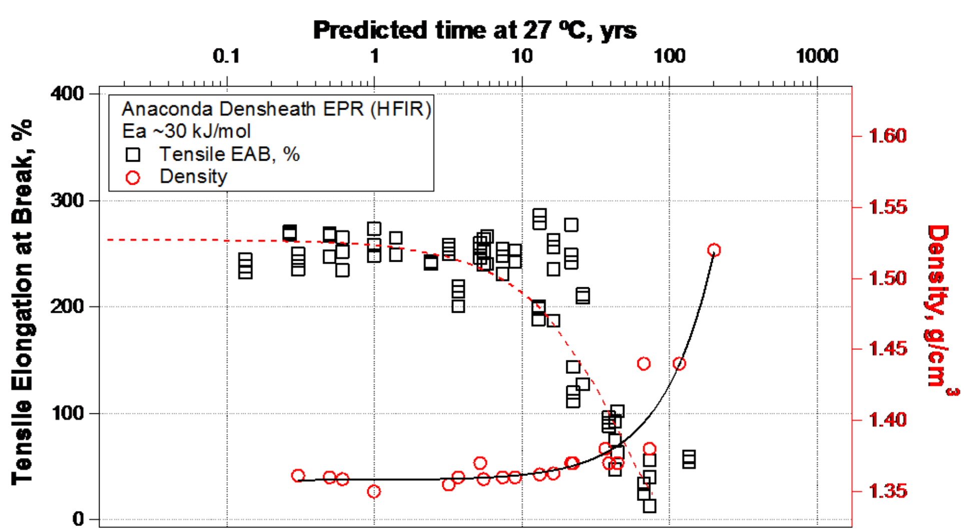

Figure 11: Shifted tensile and density data at a reference temperature of 109°C for Anaconda Densheath EPR with an assumed E_a of 30 kJ/mol below 80°C.

3.3 Gel Content and Solvent Uptake Factor Analysis

Gel content and solvent uptake factors provide insight into the molecular structure of polymers. More explicitly, these data can be used to elucidate crosslink density. Polymers commonly degrade via two thermal-oxidation mechanisms: chain scission or crosslinking. These degradation mechanisms are responsible for variation in both chemical and mechanical properties, which ultimately correlate to performance. An increase in gel content, along with decreased solvent uptake suggests that the crosslink density has increased; crosslinking is the dominant degradation mechanism. The reverse trends are expected if chain scission is the dominant degradation mechanism.

Gel content and solvent uptake factors were measured for the HFIR cables, both as received and laboratory aged. Figure 12 shows tensile elongation data versus percent gel content. As the tensile elongation at break decreases, the gel content increases. These results suggest that crosslinking is the dominant underlying mechanistic pathway during the thermal-oxidative aging process for these cable insulations. At approximately 50% tensile elongation, the gel content was measured to be ~78%, or about a 250% increase in gel content. If the aged cable had a higher gel content, e.g. 90%, this condition monitoring technique would be less effective in correlating chemical properties to mechanical properties [5]. Based on Figure 12, a validated correlation between tensile elongation and gel content useful for condition monitoring is not possible and confirms previous claims [5] for EPR aged under similar conditions. However, the key points of Figure 12 are the trend of gel content with varying tensile elongation, as well as identifying the potential of this technique for condition monitoring of service cables.

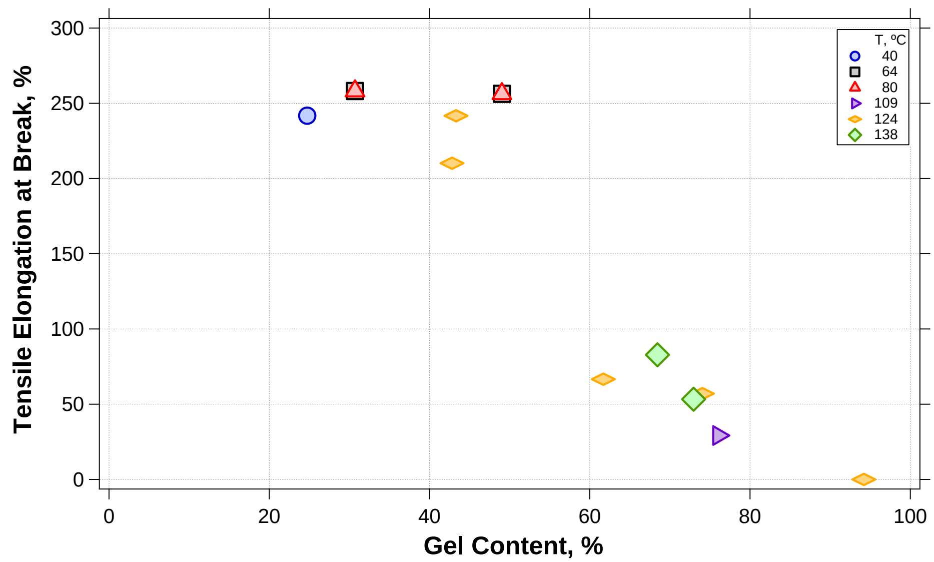

Figure 12: Tensile elongation at break plotted as a function of gel content measured for Anaconda Densheath EPR service cables that were aged at various temperatures.

Comparatively, Figure 13 shows tensile elongation at break plotted with increasing solvent uptake. The data demonstrate that as tensile elongation at break decreases, the solvent uptake factor decreases—another indication that crosslinking is the dominant underlying degradation pathway. Phenomenologically, this makes sense - as the molecular weight of the polymer increases and the crosslinking density increases, the tensile elongation decreases and solvent can less readily diffuse into the matrix. It is important to note that at approximately 50% elongation at break, the solvent uptake factor was determined to be ~1.6 to 1.7 which is about a 60% decrease in solvent uptake from the as received cable insulation.

Previous work by SNL [5] suggested that gel and uptake data measured for EPR cables provides little to no indication that the end of life was approaching due to induction time behavior. Further details can be found in SAND2005-7337 referring to EPR-04, Anaconda Durasheath EPR. The initial gel content measurement for Anaconda Durasheath EPR was determined to be ~81% [5]. Comparatively, the Anaconda Densheath EPR cables received from HFIR was measured to have an initial gel content of ~23%. Clearly, the HFIR service cables (Densheath) have a much lower overall crosslink density than the previously studied cables (Durasheath).

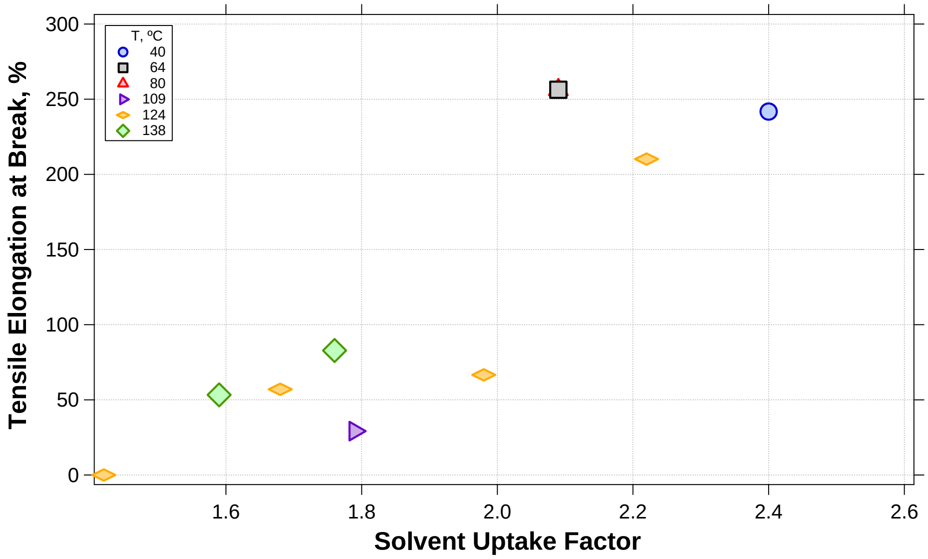

Figure 13: Solvent uptake factor plotted as a function of tensile elongation data measured for Anaconda Densheath EPR cables returned aged at various temperatures.

It should be noted, however, that most of the gel, swelling, and density data taken for reduced elongation conditions (e.g., after substantial degradation) occurs at the higher aging temperatures (between 138°C to 109°C) where the presence of diffusion-limited oxidation (DLO) effects may complicate these correlations. Such effects might be anticipated for this 1.3 mm thick Anaconda Densheath EPR material since important DLO effects were observed for the thinner (1.0 mm thick) Anaconda Durasheath EPR at similar aging temperatures [5]. Since there is a significant continuing interest in developing and using CM techniques to both determine the condition and predict the remaining lifetimes of actual plant aged cables, the importance and implications of DLO effects on the correlations of CM measurements and mechanical properties should always be considered.

4. Conclusions

While a substantial amount of work has been performed to assess the thermal-radiation degradation of EPR cables, additional experimental evidence is still warranted for improved lifetime predictions. The accelerated aging data for the 45-year field returned Anaconda Densheath EPR obtained from the High Flux Isotope Reactor at Oak Ridge National Laboratory has confirmed the suggested long lifetimes predicted from previous studies on Anaconda Durasheath EPR. Differences in formulation between Densheath and Durasheath EPR materials are readily observed in Arrhenius activation energy values and subsequent predicted aging performance. Irrespective of how lower E_a should apply towards lower temperatures (which represents Arrhenius curvature), projections are consistent with many EPR materials, suggesting significant lifetimes. Despite a possible reduction in the activation energy from 80 to 50 kJ/mol below 80°C, projections still suggest a few decades of acceptable performance at 27°C. This study also demonstrates that an extended exposure at a mid-range temperature such as 80°C, where no noticeable aging was observed in more than 10,000 hours, can be of guiding value for lower temperature performance projections. The current data sets, while not implying a complete aging study, confirm that adequate mechanical performance (i.e. >50%-100% elongation at break) remains for HFIR cable insulations and that there is likely on the order of decades of remaining life. Given that the question of remaining lifetime has been reasonably addressed, no further studies on this material are recommended.

Acknowledgement

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APPENDIX I: CNEA REPORT

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Radiation Testing of a Low Voltage Silicone Nuclear Power Plant Cable

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Abstract

This report summarizes the results generated in FY13 for cable insulation in support of the Department of Energy's Light Water Reactor Sustainability (LWRS) Program, in collaboration with the US-Argentine Binational Energy Working Group (BEWG). A silicone (SiR) cable, which was stored in benign conditions for ~30 years, was obtained from Comision Nacional de Energia Atomica (CNEA) in Argentina with the approval of NA-SA (Nucleoelectrica Argentina Sociedad Anonima). Physical property testing was performed on the as-received cable. This cable was artificially aged to assess behavior with additional analysis. SNL observed appreciable tensile elongation values for all cable insulations received, indicative of good mechanical performance. Of particular note, the work presented here provides correlations between measured tensile elongation and other physical properties that may be potentially leveraged as a form of condition monitoring (CM) for actual service cables. It is recognized at this point that the polymer aging community is still lacking the number and types of field returned materials that are desired, but Sandia National Laboratories (SNL)—along with the help of others—is continuing to work towards that goal. This work is an initial study that should be complimented with location-mapping of environmental conditions of Argentinean plant conditions (dose and temperature) as well as retrieval, analysis, and comparison with in-service cables.

ACKNOWLEDGMENTS

Gratitude is expressed to Dr. Jeremy T. Busby (ORNL) and Dr. Thomas M. Rosseel (ORNL) for their instrumental roles in acquiring the cables included in SNL's studies. Special thanks are given to Mark E. Stavig, Donald J. Hanson, and Maryla Wasiolek for their contributions to this work. Additional gratitude is also given to Dr. Mathew Celina for his review and Differential Scanning Calorimetry (DSC) assistance, as well as Dr. Erica Redline for her review of this manuscript.

NOMENCLATURE

BEWG	Binational Energy Working Group
CM	Condition Monitoring
CNEA	Comision Nacional de Energia Atomica
DED	Dose-to-equivalent Damage
DLO	Diffusion Limited Oxidation
DOE	Department of Energy
FY	Fiscal Year
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronic Engineers
LICA	Low Intensity Cobalt Array
LWRS	Light Water Reactor Sustainability
NA-SA	Nucleoelectrica Argentina Sociedad Anonima
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
SiR	Silicone Rubber
SNL	Sandia National Laboratories

1. INTRODUCTION

Nuclear energy is one industry in which the aging of safety-related materials and components is of concern and warrants further research [1], particularly as an increasing number of U.S. nuclear power plants (NPPs) are operating on extended licenses (beyond 40 years of age) [2]. To ensure the safe, reliable, and cost-effective long-term operation of NPPs, many systems, structures, and components should be evaluated through surveillance programs, modeling, predictive aging studies, or a combination of these approaches. Furthermore, as new analytical techniques and testing approaches are developed, it is imperative that we also validate, and if necessary, improve upon the previously employed Institute of Electrical and Electronic Engineers (IEEE) qualification standards originally written in 1974 [3]. Fortunately this challenging task has widespread support.

Today, the U.S. has several nuclear power plants already operating on extended licenses. Recent polling data obtained from the utilities indicate that the key concerns for potential aging phenomena are cables and piping [1,2]. As such, Sandia National Laboratories (SNL) is collaborating with colleagues in other Department of Energy (DOE) and Department of Commerce (DOC) laboratories, the U.S. Nuclear Regulatory Commission (NRC), industry, and partners abroad as part of a collaborative approach to clearly identify: 1) what work has been done in the past to investigate cable degradation, 2) what are the relevant cable aging conditions in plant environments (e.g. temperature, humidity, dose/dose rates), 3) what are the highest priority experiments required to model and therefore estimate the remaining lifetimes of existing cables, and 4) identify potential sources to retrieve service cables which could test current assumptions for aging processes.

The goal of the study was to leverage existing resources (the Low Intensity Cobalt Array (LICA) facility at SNL, Albuquerque, NM, USA) to generate and share mutually beneficial polymer aging data, as agreed upon in the US-Argentine Binational Energy Working Group (BEWG). SNL's contributions reflect only one facet of a broader US-Argentine collaboration, which was facilitated by the DOE, and directed by the U.S. State Department. Because both US (approximately 5% of US NPPs employ low voltage silicon rubber (SiR) cable insulations [4]) and Argentine (Atucha I, a pressurized Heavy Water Reactor located in Buenos Aires Province) NPPs employ low voltage SiR cable insulations, the data in this report complement existing SiR cable insulation data [5,6] and can be collectively used in the development of lifetime predictive models for SiR cable insulations. Note that this investigation was not intended to perform an exhaustive long-term polymer aging study on SiR cable insulations; the aging conditions were mutually negotiated by Comision Nacional de Energia Atomica (CNEA) and SNL staff based on existing data [5,6].

2. EXPERIMENTAL

2.1. Materials

An approximately 1.5 m section of an unused, stored, low voltage SiR cable was received from the CNEA, see Figure 1. The SiR cable (both jacket and low voltage insulations are apparently the same elastomer type with 4.3 mm and 0.6 mm wall thicknesses, respectively) had 34 insulated conductors and was about 30 years old; the cable manufacturer was not readily apparent but is believed to be from the same manufacture as those cables employed in Atucha I. This particular cable was stored at ambient conditions in a warehouse, but discussions with CNEA reveal that analogous service cables are exposed to both gamma radiation and elevated temperatures.

Figure 1 - Silicone rubber cable specimen (scale in centimeters); photo taken from previously published report [6]**.**

2.2. Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) was used to screen for any thermal transitions related to crystallinity. Experiments were performed on a TA Instruments DSC Q200. DSC sample specimens on the order of 10 mg were used. The nitrogen gas flow was maintained at ~20 mL/min. The samples were run at a ramp rate of 10 °C per minute. Temperature and enthalpy were calibrated with the commonly used indium standard.

2.3. Accelerated Aging

Cable specimens from CNEA were aged in a combined radiation-thermal environment between 39 ± 2 Gy/hr and 37 ± 2 Gy/hr, at the beginning and end of the radiation exposure, respectively, at 100 °C. Aging was conducted for a total accumulated dose of about 135 kGy. The dose rate was adjusted from 33 ± 2 Gy/hr [CaF_2] by employing a correction factor of 0.84, which compensates for the absorption at high photon energies [7]. It should be noted that this correction factor is appropriate for hydrocarbon based absorptivity, but for consistency with previous studies at SNL, is used in this study of SiR cable insulations. Any future studies should consider reevaluation of the appropriate correction factor for absorptivity of silicone based materials. To account for the decay rate of ^{60}Co during the 3600 hr experiment, an average dose rate of 38 ± 2Gy/hr was employed for all dose calculations. Specimens were removed from the Low Intensity Cobalt Array facility (LICA, SNL, Albuquerque, NM, USA) at varying points in time for thermal, chemical, and mechanical analysis [8].

2.4. Tensile Testing

Cable insulation specimens for tensile testing were carefully stripped from their metal conductor prior to aging. All insulation specimens were aged as tubes that were measured to be ~150 mm in length. Tensile testing (5.1 cm initial jaw separation, 12.7 cm/min strain rate) was performed on an Instron 5564 series equipped with pneumatic grips and extensometer clips that enabled direct ultimate tensile elongation values to be obtained. Tensile studies were usually performed in triplicate for each time period; control specimens were periodically tested to demonstrate the intrinsic variation in tensile elongation for the unaged material (see Figure 3).

2.5. Gel Content and Solvent Factor Uptake Analysis

Solvent factor uptake measurements were performed by refluxing a known weight (w_o) of cable insulation in xylenes approximately eight hours. The swollen specimens recovered from the solvent (w_s) were weighed to determine the mass of the absorbed solvent. Subsequently, the ‘wet’ specimens were dried in a vacuum oven held at 80°C overnight to achieve a constant final weight. The final weight (w_f) of the insulation was then recorded. The recorded solvent uptake factor is equal to the ratio of w_s to w_f. Comparatively, the gel content is equal to the ratio of w_f to w_o.

$$Solvent\ Factor\ Uptake = {}^{w_s}/_{w_f}$$

$$Gel\ Content = {}^{w_f}/_{w_0}$$

w_s= swollen weight

w_f= final weight; dried via vacuum

w_0= initial weight

2.6. Density

Archimedes’ principle was employed to measure the macroscopic densities of as received and laboratory aged cable insulations [9-11]. In short, specimens of approximately 50 to 200 mg were weighed both in air and then in isopropanol on a microbalance. Density calibrations were performed using glass calibration spheres of accepted density.

3. RESULTS AND DISCUSSION

3.1. Differential Scanning Calorimetry

DSC was performed on the as received SiR cable insulations. As expected for an amorphous polymer, neither the jacket nor the insulation material showed any thermal transitions of relevance to this aging study. This was observed for multiple samples. However, a small thermal transition between 80 and 120°C was noticeable for an individual SiR sample, which after wiping the insulation with an isopropanol moistened tissue was no longer detectable. We believe that isolated insulation specimens may contain small surface contamination, which is barely detectable in a DSC scan. Figure 2 shows the DSC scans for SiR samples in comparison with commonly encountered polyolefin based insulation materials (XLPO, EPR).

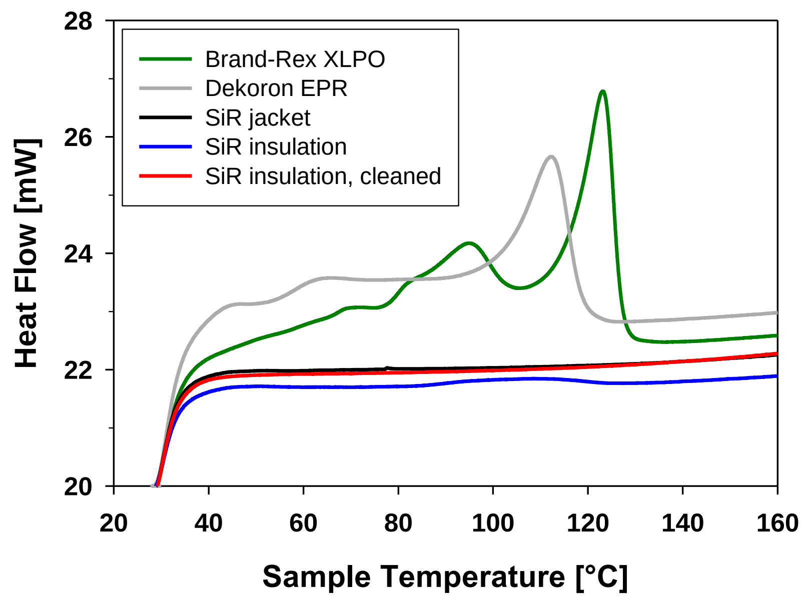

Figure 2 - Differential Scanning Calorimetry (DSC) scan of the as-received SiR cable insulation and comparison with XLPO and EPR.

3.2. Tensile Testing

Tensile elongation at break for the as-received cable insulation was measured to be 114 ± 9% at SNL, which suggests a substantial amount of "life remaining" [3], however the initial specification/qualification demands are unknown. Comparatively, previous measurements of the same SiR cable insulations, performed at CNEA, determined the tensile elongation at break to be ~175%. Varying results could be due to the fact that CNEA does not employ extensometers while measuring tensile properties to quantify true strain.

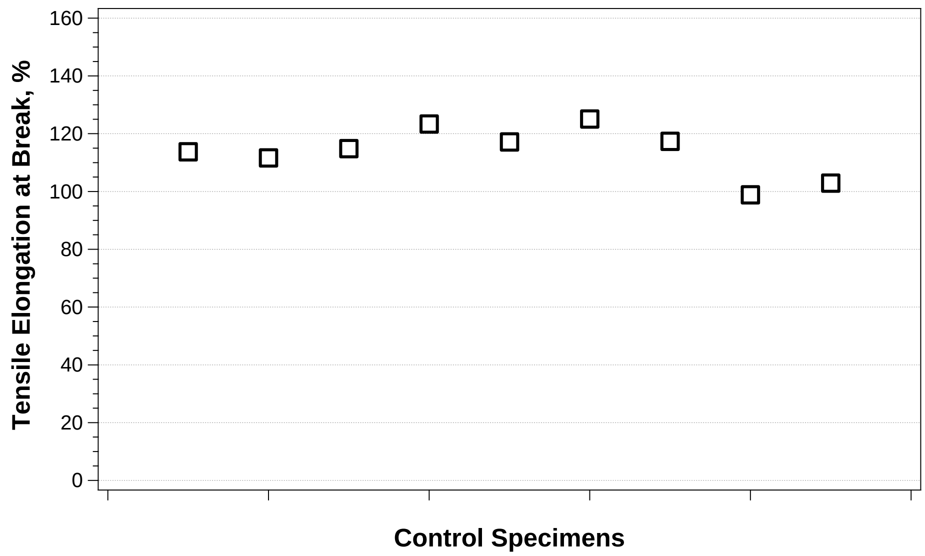

Figure 3 - Ultimate tensile elongation data for as-received SiR cable insulation. The abscissa reflects the individual control samples.

Figure 4 shows the degradation of tensile elongation at break with increasing dose (and time) for the SiR cable insulation. Degradation to ~50% elongation at break (absolute) occurs after exposure to ~110 kGy when maintained at 100 °C. Figure 5 shows the normalized tensile elongation at break decay as a function of dose for SiR cable insulations exposed at both SNL and CNEA (dose rate = 15 kGy/hr, T ~23 °C) [6]; note that the SNL data obtained at the highest total dose consists of three overlapping points. Albeit the decay in tensile elongation at break is similar from 0 Gy to ~20 kGy, the curves arguably diverge and could be attributed to 1) the temperature difference between both experiments and 2) diffusion limited oxidation (DLO) for the cables exposed to a very high dose rate at CNEA (~15 kGy/hr), and 3) dose rate effects that result in degradation mechanism changes. Future assessment of the SiR cable insulations exposed to radiation at CNEA could validate the DLO claim (e.g., to quantify edge effects through modulus profile measurements [9-11]). However, oxygen permeability in silicone is generally high and oxidation rates are rather low, therefore DLO may not be a contributing factor.

Japan Nuclear Energy Safety Organization Safety Standard (JNESS) performed simultaneous thermal-radiation aging experiments on SiR cable insulations from three varying manufacturers [5]. Because each of the SiR cable insulations varied in initial tensile elongation properties (aside from testing methodologies, i.e. extensometer use), one may compare these data by generating a dose-to-equivalent damage (DED) chart. Figure 6 shows simultaneous thermal-radiation aging data for SiR cables aged at 100 °C with varying dose rates, including data from the literature [5]. The CNEA data is omitted from the plot because it was not performed at 100 °C. Future efforts to develop predictive aging models for SiR cable insulations could leverage these data, along with additional experiments, and approximations regarding the environmental conditions service cables are exposed to (e.g., temperature, dose rate, expected service life).

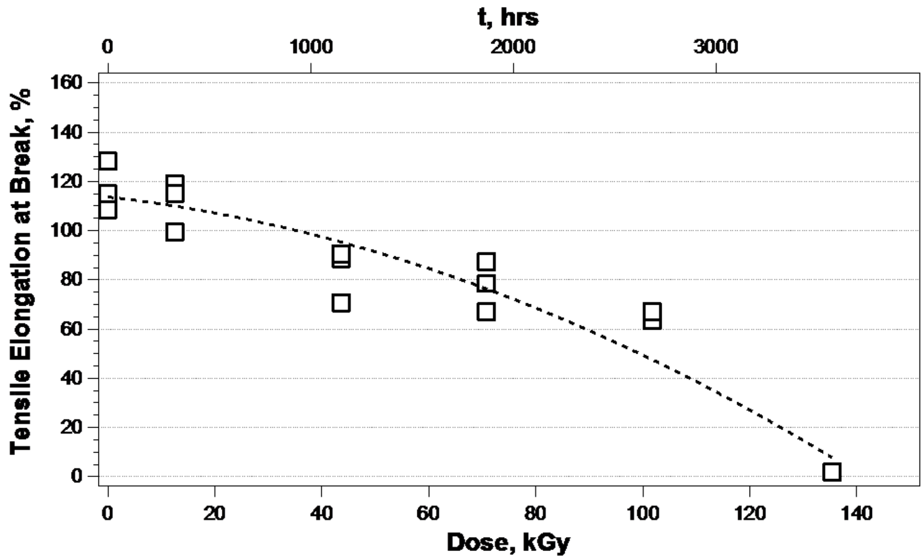

Figure 4 - Ultimate tensile elongation data for SiR cable insulations aged at 100 °C and ~38Gy/hr.

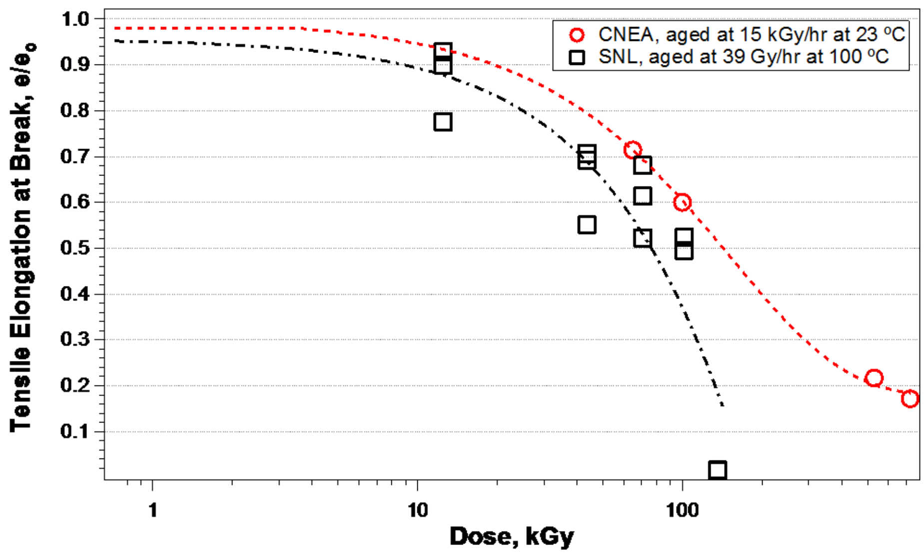

Figure 5 - Ultimate tensile elongation data for SiR cable insulations aged by SNL (100 °C and ~38 Gy/hr) and CNEA (23 °C and ~15 kGy/hr) [6]**.**

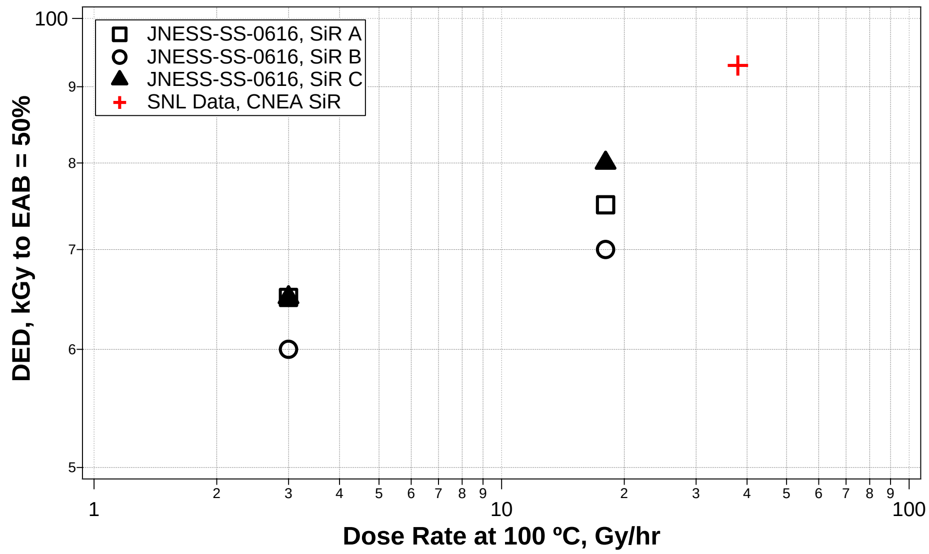

Figure 6 – Dose-to-equivalent damage data (DED = 50%) for previously published data [5] **plotted with SNL data discussed in this report.**

3.3. Gel Content and Solvent Uptake Analysis

To develop a better fundamental understanding of what chemically occurs during simultaneous thermal/radiation aging of the silicone rubber insulations, gel and solvent uptake analysis was performed. Figure 7 shows that the virgin cable has very high initial gel content (~96.5%); nevertheless, as the aging time and dose increase, the gel content also increases in a subtle manner, indicative of additional crosslinking despite an originally heavily crosslinked material. The observed gel content and solvent uptake factor (see Figure 8) behaviors clearly suggest that crosslinking is occurring as a function of aging; however, the change is very small (arguably ~2-3%). A much larger data set would be required to understand the experimental variability and how that relates to the small changes observed.

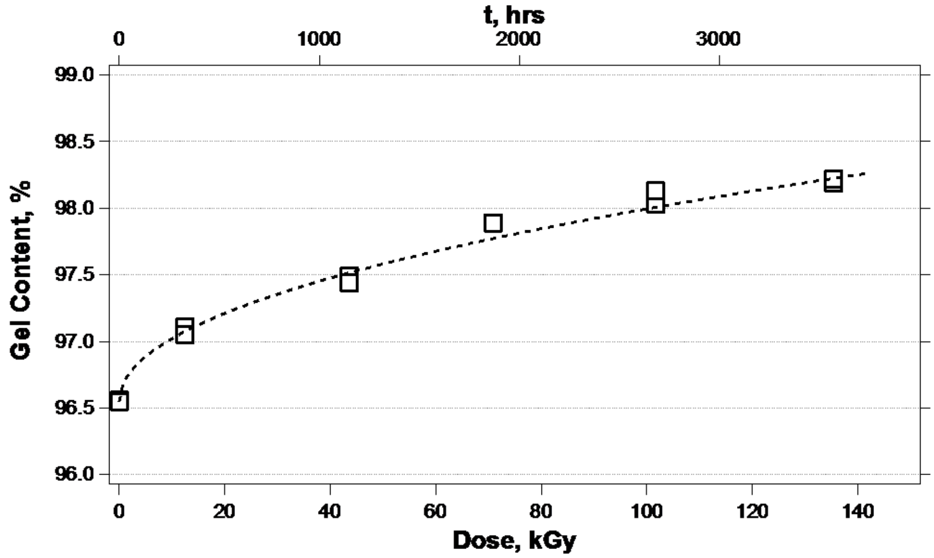

Figure 7 - Gel content data for SiR cable insulations aged at 100 °C and ~38 Gy/hr.

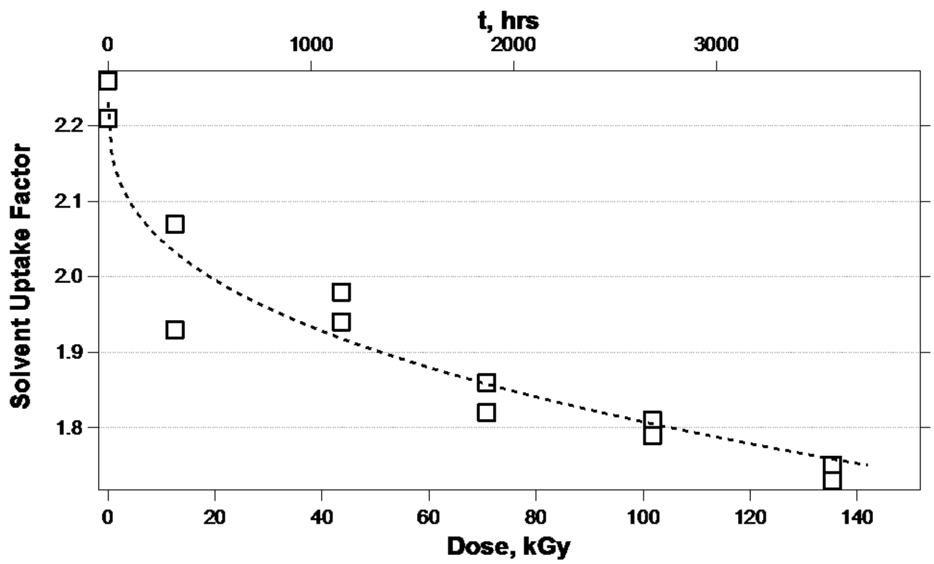

Figure 8 - Solvent uptake factor data for silicone rubber cable insulations aged at 100 °C and ~38 Gy/hr.

3.4. Density

The densities of the virgin and aged SiR cable insulations were also measured. Figure 9 shows the density is constant (within experimental error) for the aging conditions studied out to where the cable is no longer useable (based on reduced tensile elongation). As previously demonstrated, these new data confirm that density is not sensitive enough to be leveraged for CM for this material [9].

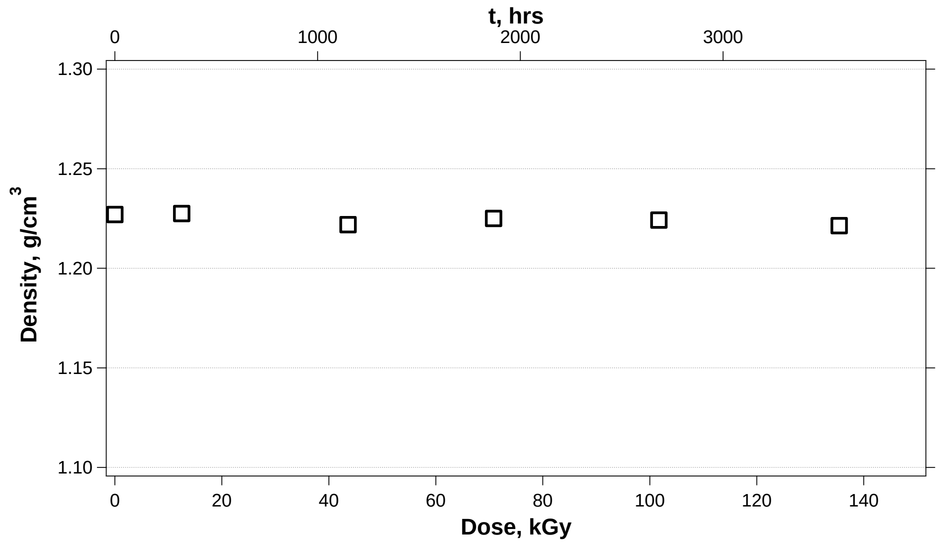

Figure 9 - Density data for silicone rubber cable insulations aged at 100 °C and ~38 Gy/hr.

4. CONCLUSIONS

Preliminary screening studies have been performed to assess virgin SiR cable insulations, analogous to those employed by CNEA in Atucha I. As such, much work is still warranted e.g., location-mapping of environmental conditions of plant conditions (in progress), as well as retrieval, analysis, and comparison with in-service cables (planned for life extension of Atucha I). These would support the goals to develop and validate predictive models of the long-term aging of these cable material types, and develop suitable condition monitoring techniques. Completion of more extensive characterization tasks were outside the scope of this study.

Basic mechanical and chemical aging data measured for the SiR cable insulation offered generic trends to evaluate aging behaviors of key cables analogous to service cables in combined thermal/radiation environments. Future analysis of these data and collaboration through the US-Argentine BEWG may result in further studies and opportunities to perform accelerated aging on actual service cables. Of the CM techniques employed in this study, solvent uptake factor analysis, despite only small changes due to an initial high crosslink state, appeared to be the most promising CM technique in this scoping study. SNL will strive to use these and other CM techniques in polymer aging programs to aid the development of future in-service diagnostic abilities.

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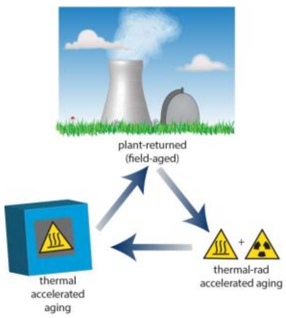
APPENDIX J: SNL HIGHLIGHT SLIDES FROM FY14

Sandia Vision Supporting LWRS Requalification Efforts

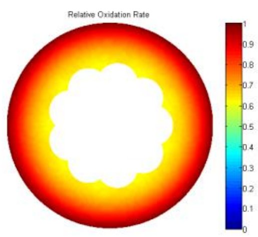
Sandia National Laboratories

- **The ultimate goal**:
  - Understand current cable insulation material state and expected performance under extended service conditions to enable decisions 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

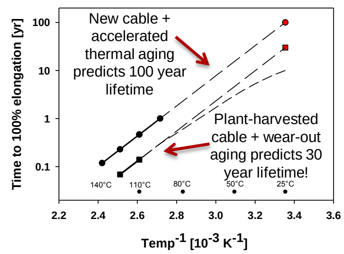


Spatially-Resolved Degradation Models



Surface vs bulk degradation

Lifetime Predictions



Loss in tensile properties is used as a failure criterion

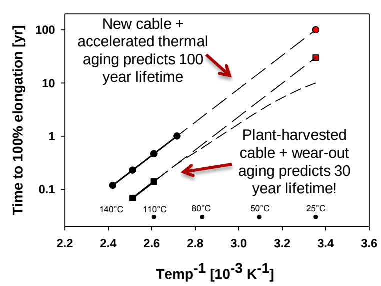
SNL Cable Aging Project Overview

Sandia National Laboratories

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

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)

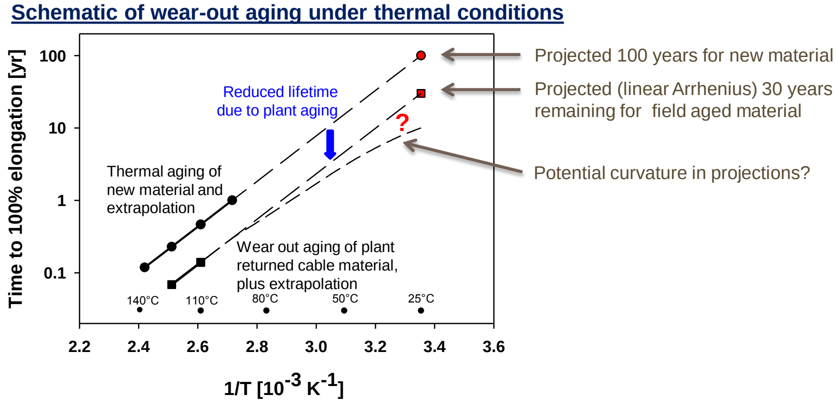
- Note: The SNL material science and testing efforts may need to be adjusted based on exptl. feedback and observed material behavior. Tasks may have evolving emphasis as this project progresses subject to expert SNL opinions. This R&D effort will be conducted within published DOE guidelines for research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

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

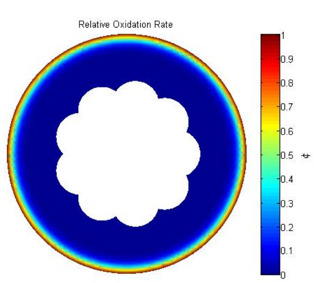
- Critically important!
  - The need for field returned specimens of all three groups with known environmental conditions and exposure history

- 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

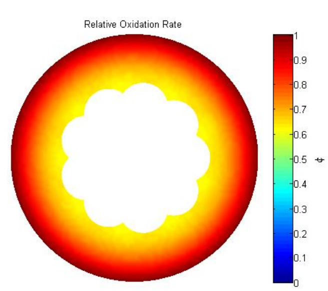
Original EQ vs. Plant Aging

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

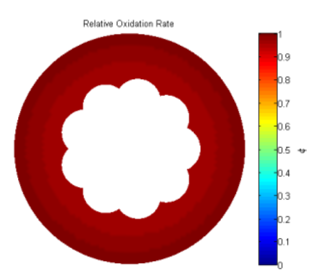
- Cable degradation behavior depends on local rates which can differ between surface and bulk depending on aging conditions
- DLO is the phenomenon which introduces variations in behavior
- It can happen under thermal and rad-thermal conditions
- This also affects measurements of ox-rates and condition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



Surface oxidative degradation is likely under EQ testing IEEE323-1974



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

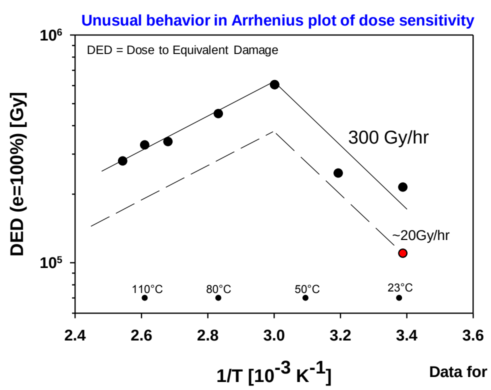


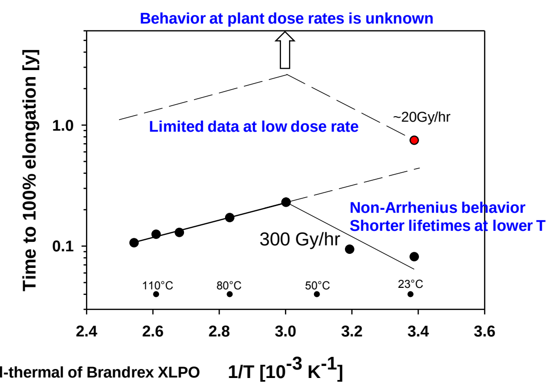
Homogeneous aging expected under plant conditions

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



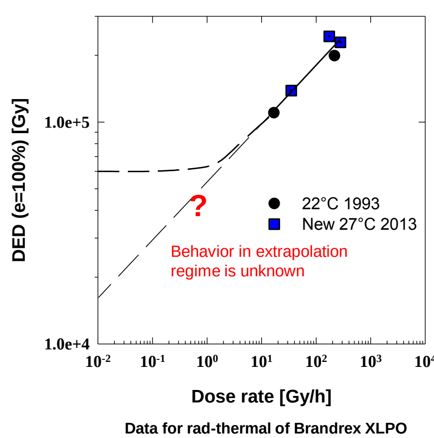


Risk: margins for inverse T behavior under plant conditions are not known because material behavior under low dose rate conditions have not been studied sufficiently!

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



- **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**

SNL Support for Requalification Efforts

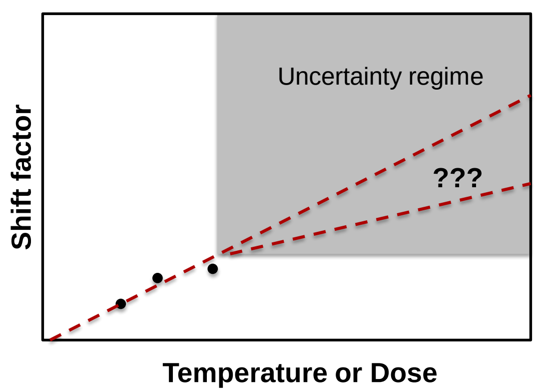
- **Thermal aging only (FY14-15)**
  - SNL will consolidate existing thermal aging data and extent with gap filling data sets where possible
  - These aging behaviors are to be compared with wear-out behavior (field returned samples)
  - RISK: If field returned specimens are not available, projections 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 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

SNL Approach to Requalification Efforts: Maximizing Confidence

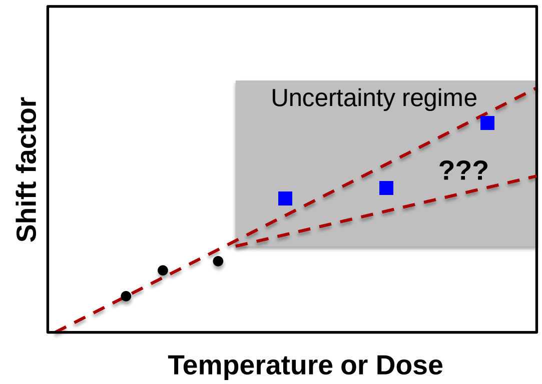
- Using a one-prong approach provides little confidence in predictive capabilities, e.g. limited accelerated aging data at high temperatures with no low temperature guidance



SNL Approach to Requalification Efforts: Maximizing Confidence

Sandia National Laboratories

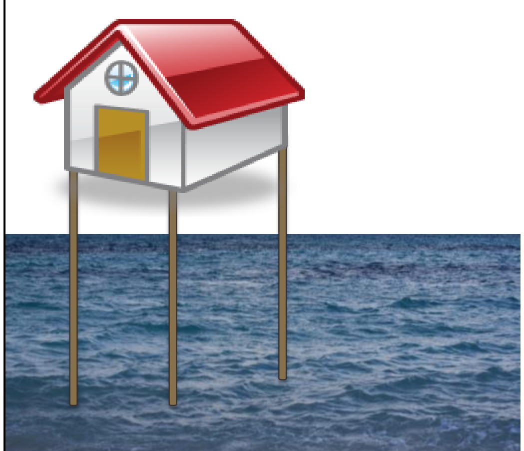
- Low temperature guidance obtained from oxidation rates of the unaged material.
- Oxidation rates provide access to data which oven aging cannot produce within a reasonable timeframe (months vs. multiple years)

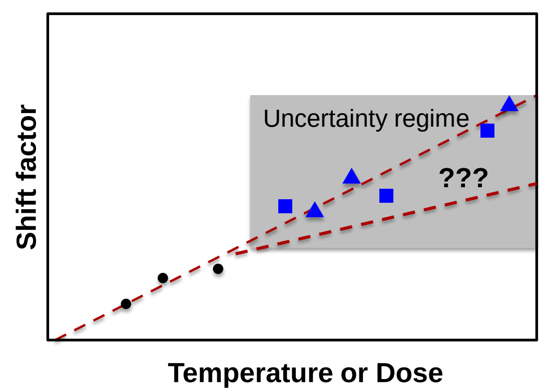


SNL Approach to Requalification Efforts: Maximizing Confidence

Sandia National Laboratories

- Add oxidation rates of field-aged materials

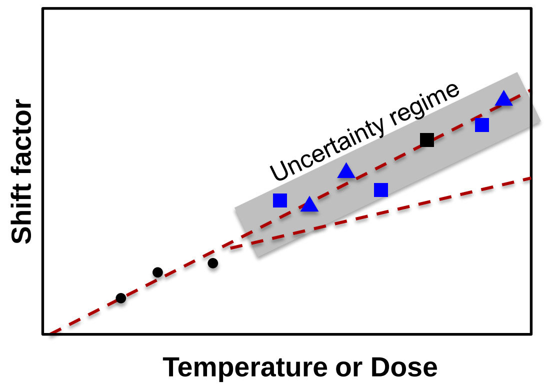




SNL Approach to Requalification Efforts: Maximizing Confidence

Sandia National Laboratories

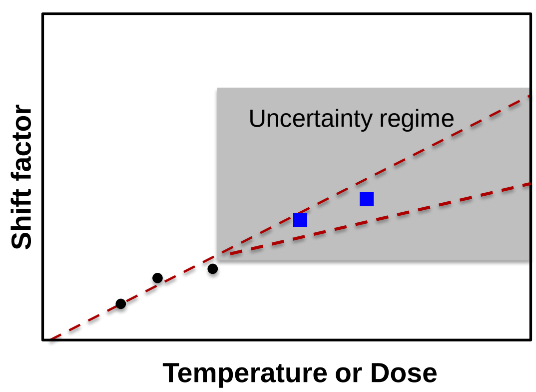
- Specific wear-out aging experiment of field-returned materials under performance limiting conditions



Where are we now?

Sandia National Laboratories

- Have an overview of accelerated aging behavior at high temperatures for many materials
- Have a limited data set of oxidation rates for unaged materials
- Some screening data for oxidation rates under rad-thermal but not sufficient for modeling purposes



Where are we going?

- Expand data set for XLPO and EPR:
  - Rad-thermal aging 300 – 0.2 Gy/hr beginning when dosimetry is finished and a useable field has been established
    - Obtain oxidation rates for the materials
      - Will begin having actual tangible data within three months, but the cumulative experiment takes much longer (e.g. a couple years)
  - Thermal only review and gap filling
    - Review of all previous literature and SCRAPS data for XLPO and EPR
    - Compliment existing data with oxidation rates (aged and/or unaged materials)

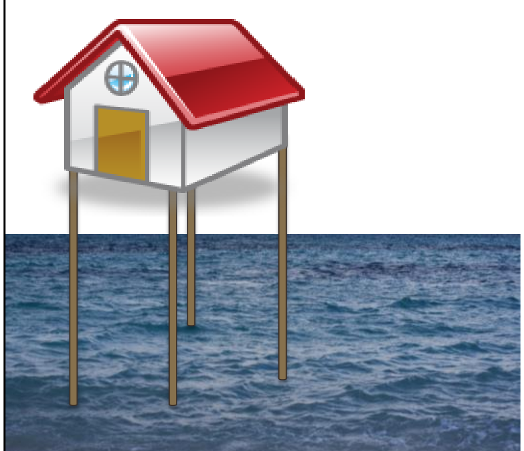
- Wear out aging of field-returned materials*

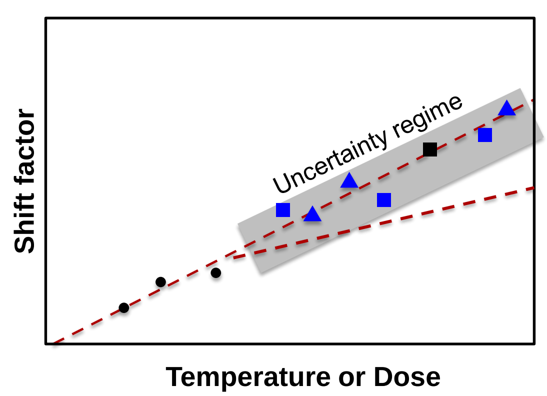
- Improved modeling capabilities

***Have yet to acquire field-returned specimens!**

Where are we going?

- We will ultimately use the data in models to predict aging behavior and accommodate known anomalies to provide best guidance for performance predictions

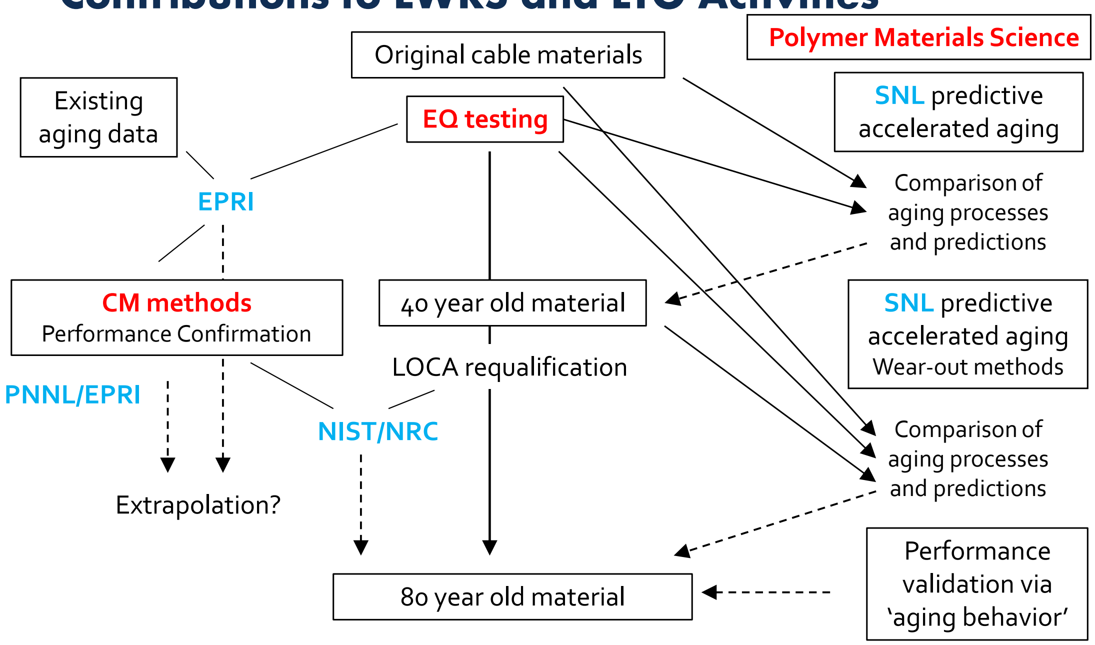




SNL Engagements with Cable Aging Community

- **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

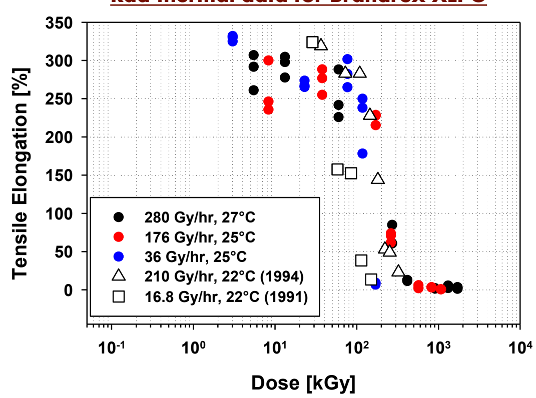


SNL offers a critical perspective of materials aging behavior to support CM and EQ

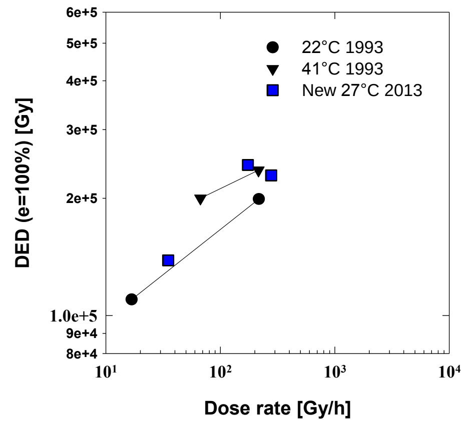
Brandrex XLPO LICA Exposure

- **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

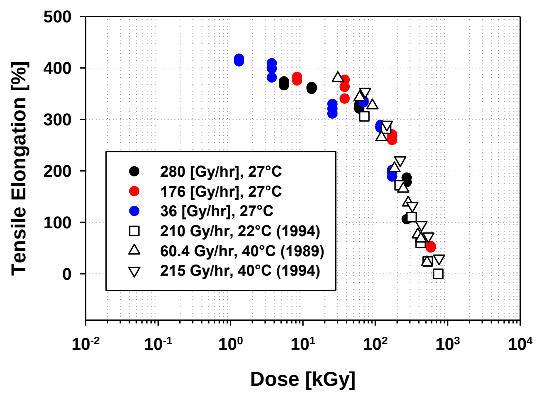


Corresponding failure doses for Brandrex XLPO



Eaton Dekoron EPR LICA Exposure

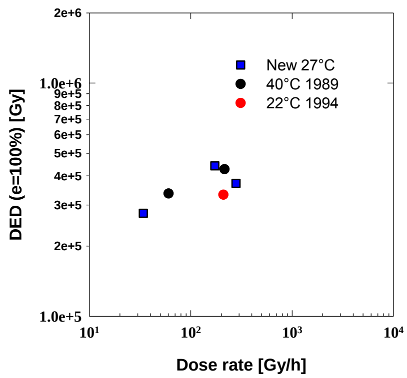
- **Comparison of rad degradation at low T, 1990s work and 2012-13**
  - As part of LWRS program Dekoron EPR tensile specimens were exposed at different dose rates
  - Lowest dose rate at 11 Gy/h has not yet yielded any loss in elongation
  - New 2013 data are in agreement with existing data sets from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

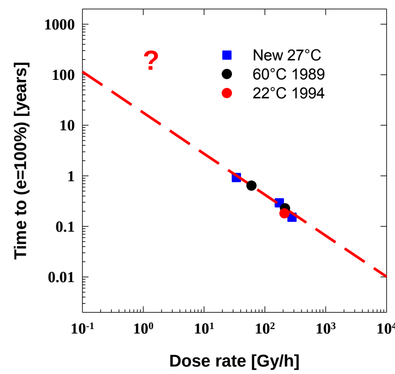


Dekoron® Wire & Cable LLC INDUSTRIAL CABLE SOLUTIONS

Eaton Dekoron EPR LICA Exposure

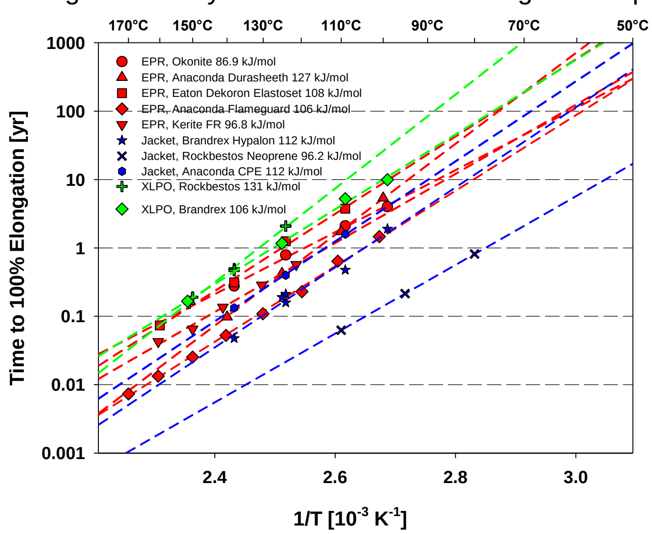
- **Comparison of rad degradation at low T, 1990s work and 2013**
  - New 2013 data are in agreement with existing data sets
  - The challenge of how to extrapolate to low dose rate conditions remains
  - Significant extrapolations, is a linear approach realistic?
  - Both data sets have the same value 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





Overview of thermal aging data

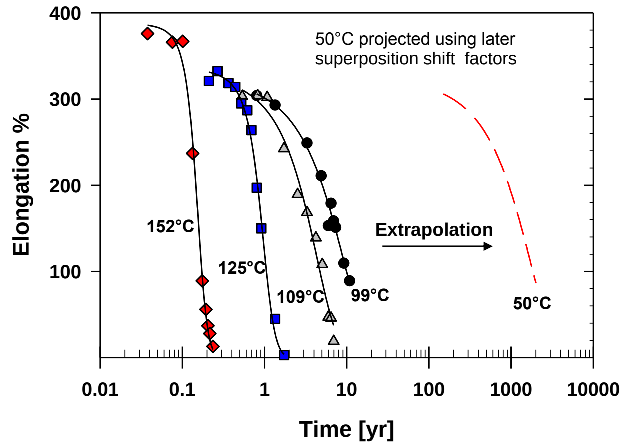
- Thermal aging data are available from SCRAPS aging studies
- Tensile elongation decay was monitored for a range of temperatures



Aging data normally not available below 100°C
Extrapolation uncertainty, linear versus curved Arrhenius behavior

Extrapolation of thermal aging Brandrex

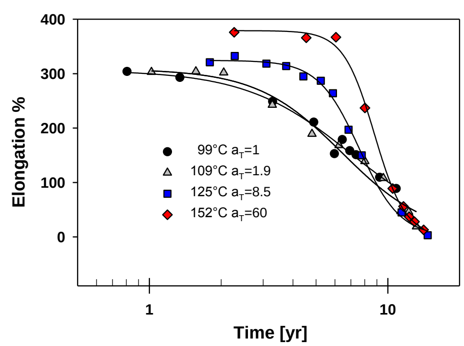
- Thermal aging data for 150°C to 100°C from the 1990's are available
- How should extrapolations be conducted? Is linear Arrhenius realistic?



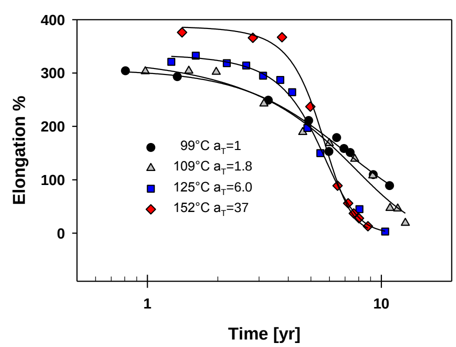
Thermal aging data sets are limited, extrapolations are needed

Extrapolation of thermal aging Brandrex

- Aging characteristic vary, more sudden drop of elongation at high T
- No common aging behavior in decrease of tensile elongation



Time temperature superposition for late data

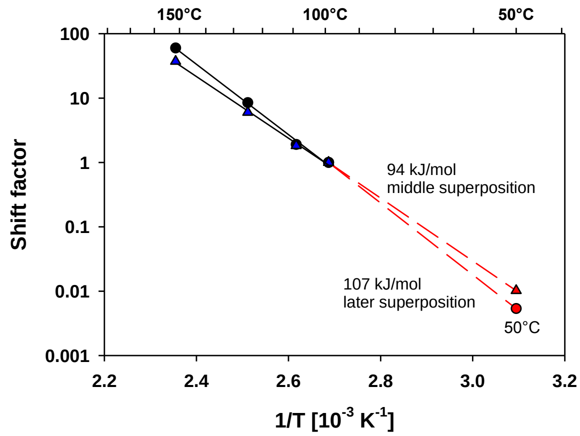


Time temperature superposition for mid-data

Aging curve (loss in elongation) clearly depends on temperature
Data superposition is subjective

Extrapolation of thermal aging Brandrex

- Aging acceleration factors depend on primary data superposition
- This means there is uncertainty from tensile degradation behavior
- Further, any curvature in Arrhenius plot at lower T is unknown



Shift factor projections based on linear Arrhenius suggest 0.005 to 0.01 times slower aging at 50°C than observed at 100°C

E_a below the lowest aging temperature is unknown

Enhance confidence of extrapolations

- **Multiple aspects need to be considered for performance extrapolations:**

PRIMARY DEGRADATION CHEMISTRY → MECHANICAL PROPERTY LOSS

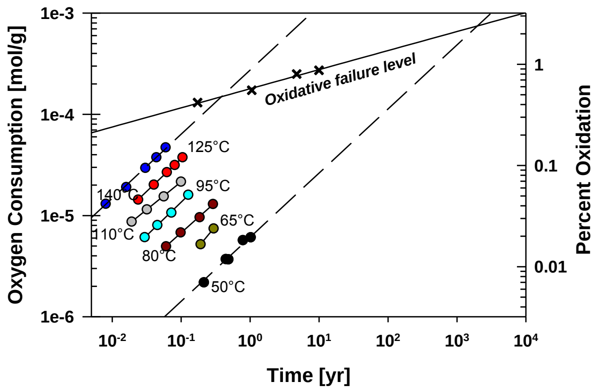
Oxidation rates – Oxidation levels (rate behavior with time) - Tensile behavior

- Time projections in mechanical property changes need to be correlated with cumulative oxidation as the dominant degradation pathway
- Limited high T mechanical data sets CANNOT sufficiently guide Arrhenius behavior and projections towards lower temperatures
- Oxidation rates and their time dependence should be obtained over an extended temperature-time range
- Oxidation state (chemical conversion) needs to be evaluated for correlation with any other failure state (defined end of life criterion)

SNL had repeatedly shown that an understanding of oxidation behavior can improve performance predictions

Oxidation level at failure

- Oxidation is the primary chemical process which results tensile changes
- Aging predictions can be made when rate behavior is known
- Oxidation level at failure can depend on temperature

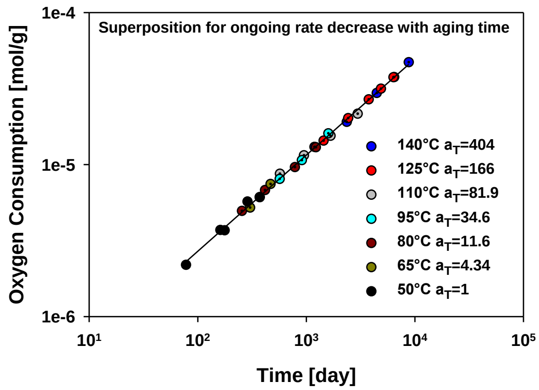


- **Oxidation level at failure is based on known failure times (mechanical data at ~150, 125, 110, 100°C) and extrapolation of oxidation level progression with time (t-T superposition)**
- **Project 2.5% oxidation at 50°C**
- **Project ~ 4% oxidation at RT**

Oxidation levels are estimated for high T aging where 100% tensile elongation was observed and projected towards lower T

Superposition of oxidation rates

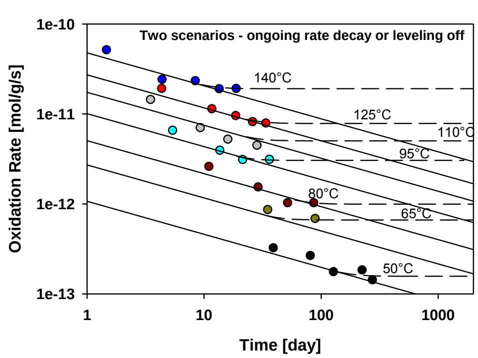
- Rate behavior is an integral part of the degradation process and performance prediction
- Rates are available from early behavior of unaged material
- Integration of rates yields oxidation level
- Superposition yields acceleration factors for cumulative oxidation

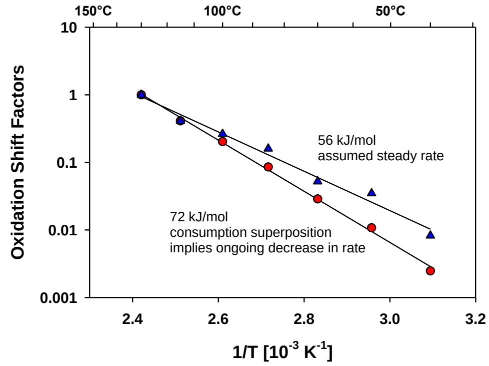


Rate behavior allows prediction of cumulative oxidation

Superposition of oxidation rates

- Oxidation rates are only available for short initial aging time frames
- Here, early rate behavior shows declining rates
- Rates decrease, but a further decrease is not guaranteed
- Rates may also level off

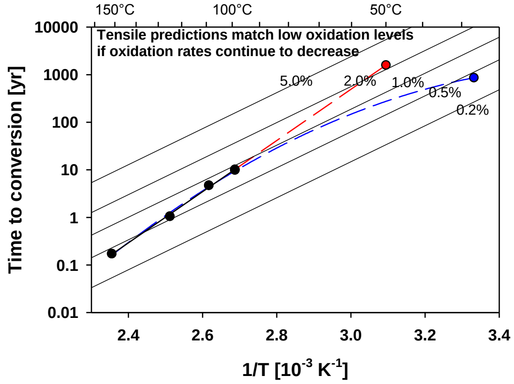


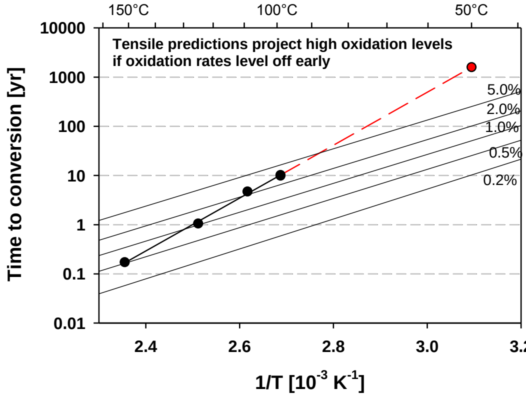


Better predictions require extensive work to probe oxidation rates for aged material

Time predictions for oxidation levels

- Oxidation levels to 100% elong. must be reasonable
- Prediction of time to specific extents of oxidation can be used to examine predictions for tensile behavior
- Correlations can improve performance predictions

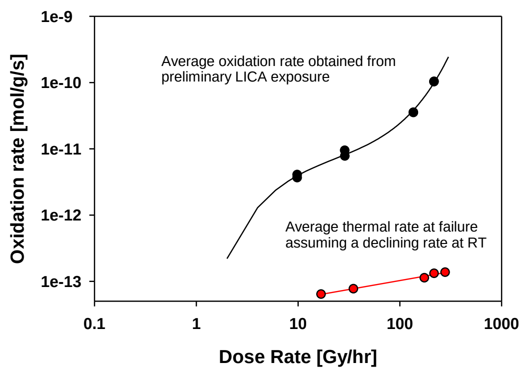


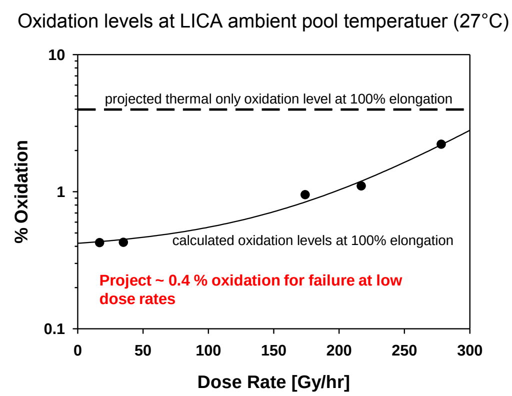


Faster extensive oxidation at low T suggests shorter lifetime

Rate behavior for rad-thermal

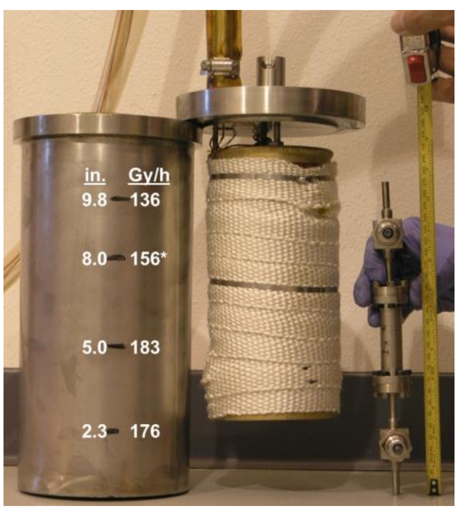
- Similar guidance should be feasible for radiation environments
- Only very limited screening numbers exist
- This project aims to establish the oxidation behavior and rate projections when radiation damage contributes
- Is material behavior coupled or do separate processes drive degradation?





Project low oxidation levels at low dose rate radiation aging
Discrepancy between thermal and radiation projections

Rates and oxidation levels for rad-thermal



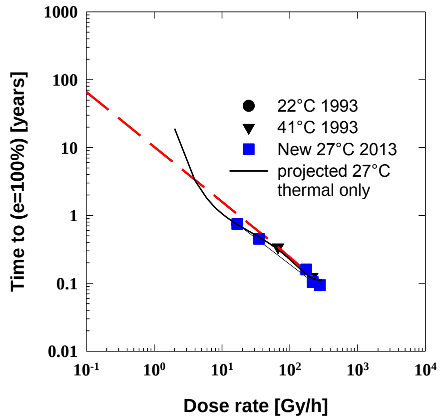
Polymer samples located in ampoule are positioned between 4 to 5" from bottom of can, where dosimetry reflects actual exposure conditions

Acquisition of oxidation rates under varying dose rates

Rates and oxidation levels for rad-thermal

Sandia National Laboratories

- A better understanding of dose rate effects on oxidation behavior in these environments and how cumulative oxidation levels relate to the decrease in tensile elongation will assist us in developing better predictive aging models for low dose rate conditions

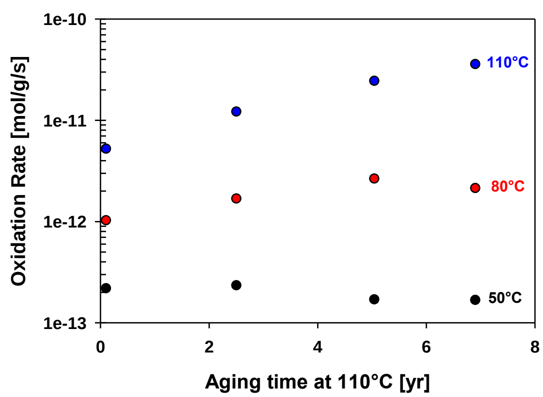


Better low dose rate performance if thermal rate decreases at RT with time

Ox-rates of aged Brandrex XLPO

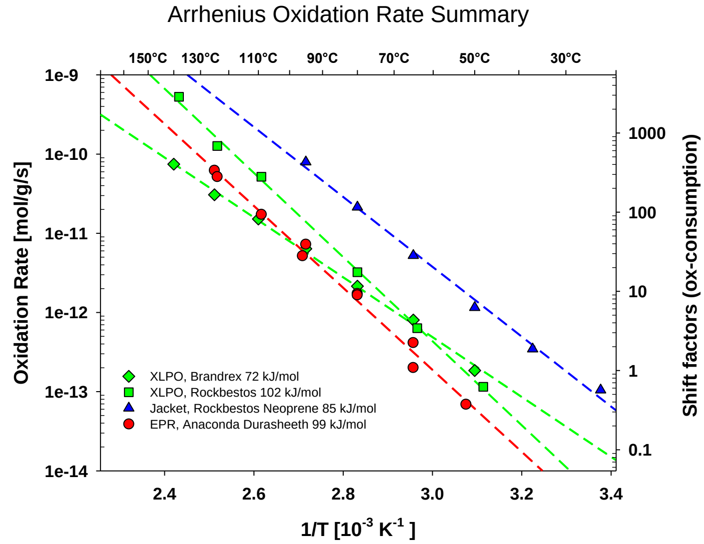
Sandia National Laboratories

- Long term aged Brandrex XLPO is available from SCRAPS aging studies
- At 110°C failure it takes about 10 years to reach 100% elongation
- Aged specimens were used to measure thermal ox-rates



No drop in ox-rates is observed with increasing aging state
If these rates remain steady the material will oxidize faster

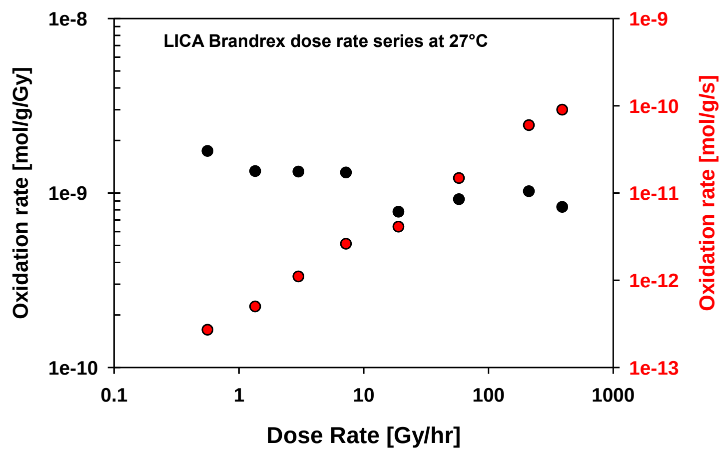
Oxidation rates for thermal degradation



Comparison of four materials where data exist
Ea for ox-rate is lower than for high T tensile decay

Ox-rates with dose rate

- Preliminary guiding study of Brandrex XLPO with LICA exposure
- A range of dose rates from 0.4 to 340 Gy/h is now available in LICA (8 positions)
- New XLPO material was used to assess oxidation
- In theory, a thermal component should increase the rates at low dose rates



Ox-rate per Gy is reasonable steady towards lower dose rates at 28°C

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