



## **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.

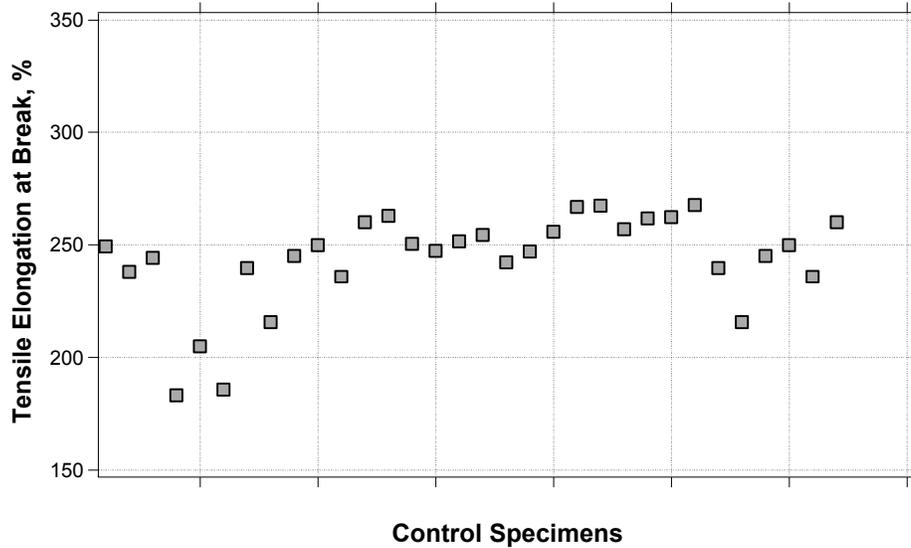
Xylenes (Electronics Use Grade, 99+%, Acros) and isopropanol (HPC grade, 99.9%, Fisher) were used as received.

### *2.2 Accelerated Aging*

All HFIR cable insulations were subjected to thermal-oxidative aging environments in air circulating ovens at temperatures ranging between  $40 \pm 2^\circ\text{C}$  and  $138 \pm 2^\circ\text{C}$  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 1).



**Figure 1:** Ultimate tensile elongation data for as-received Anaconda Densheath EPR cables returned from HFIR at ORNL (~45 yrs of age,  $T_{avg} \sim 27^{\circ}\text{C}$ , 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 ( $w_0$ ) 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  $80^{\circ}\text{C}$  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  $w_0$ .

$$\text{Solvent Uptake Factor} = w_s/w_f$$

$$\text{Gel Content} = w_f/w_0$$

$w_s$ = 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.

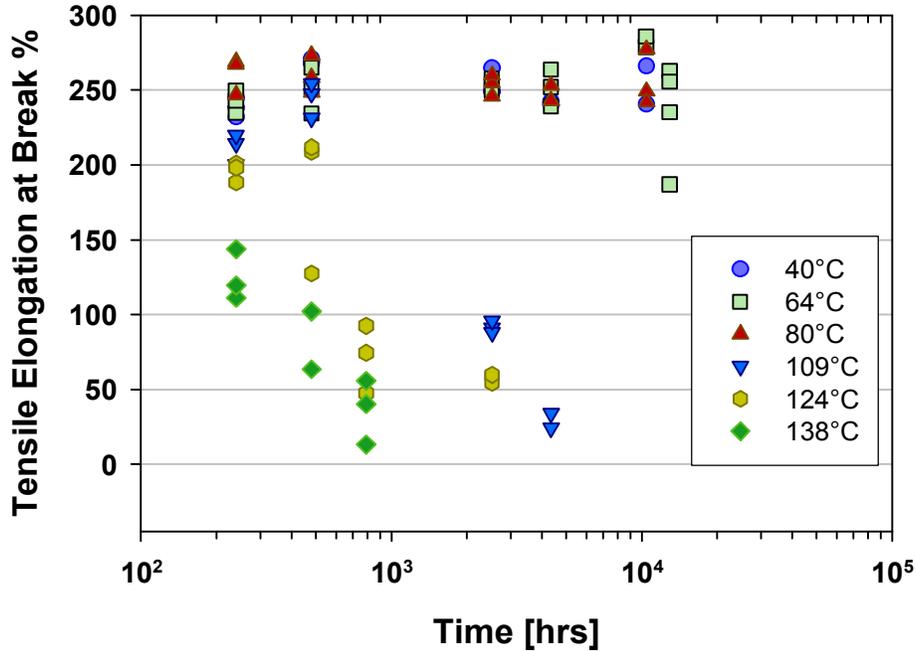
## 3. Results and Discussion

### 3.1 Tensile Elongation

The as-received tensile elongation at break (EAB) for cable insulations returned from HFIR was measured to be approximately  $250 \pm 21\%$ . 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.

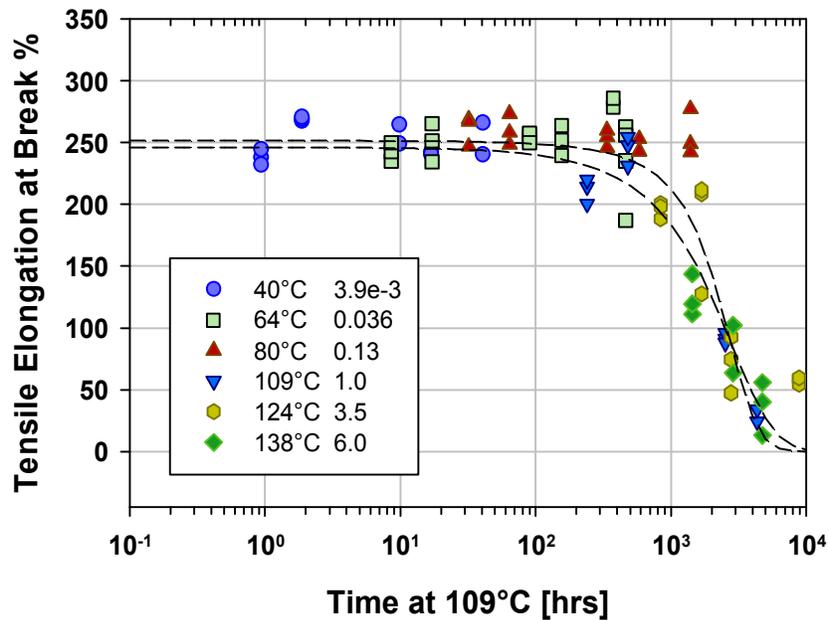


**Figure 2:** Ultimate tensile elongation data for Anaconda Densheath EPR cables returned from HFIR at ORNL (~45 yrs of age,  $T_{avg} \sim 27^\circ\text{C}$ , RH ~70%) as a function of aging time and temperature.

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

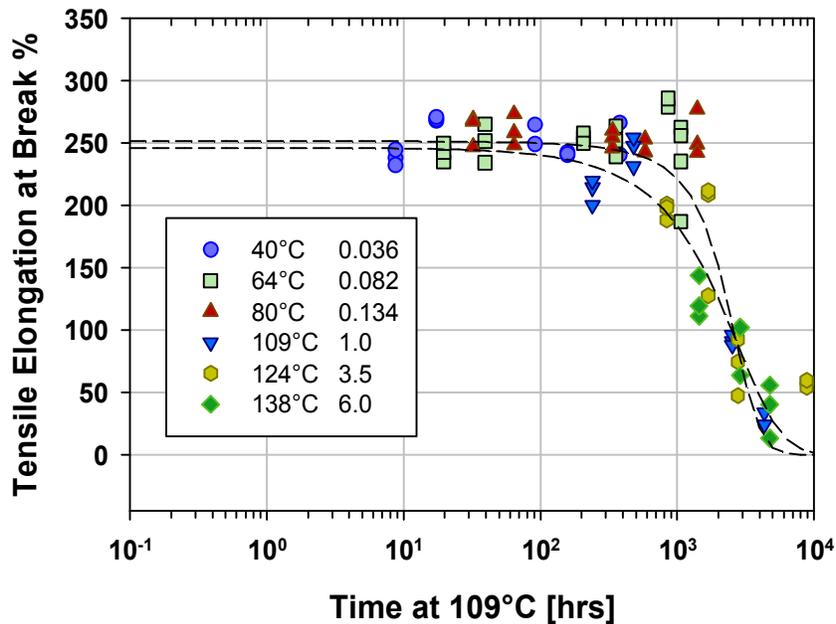
point (the original 10440 hours) is now located to the upper right of the combined aging curve. It also suggests that the aging curve is likely a little steeper in its decay for the projected 80°C behavior than observed for the 138-109°C regime. Most importantly, the measured cable insulation ‘stability’ 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.

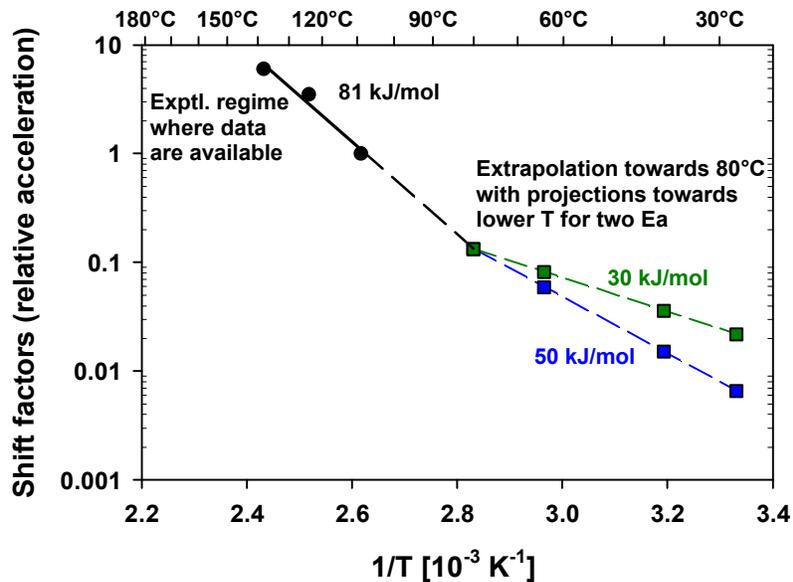


**Figure 4:** Superposition to 109°C of the 138, 124, 109°C data yielding shift factors and time shift of the lower temperature data based on shift factors resulting from extrapolation with 81 kJ/mol to 80°C and then projected towards lower temperature with 30 kJ/mol. Note that the 40 and 64°C data are 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.

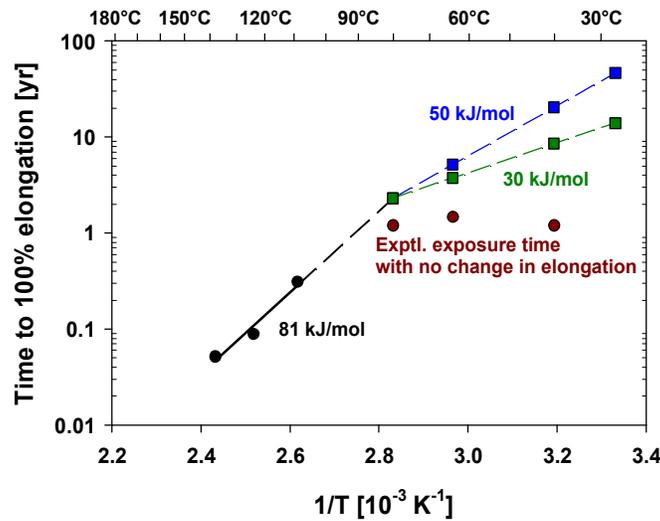
Considering such trends it is reasonable to accommodate performance projections for the Anaconda Densheath cable insulations with a drop from 80 to 50 kJ/mol towards RT conditions not as given and experimentally confirmed behavior, but rather as a conservative data analysis. As mentioned above a drop 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.

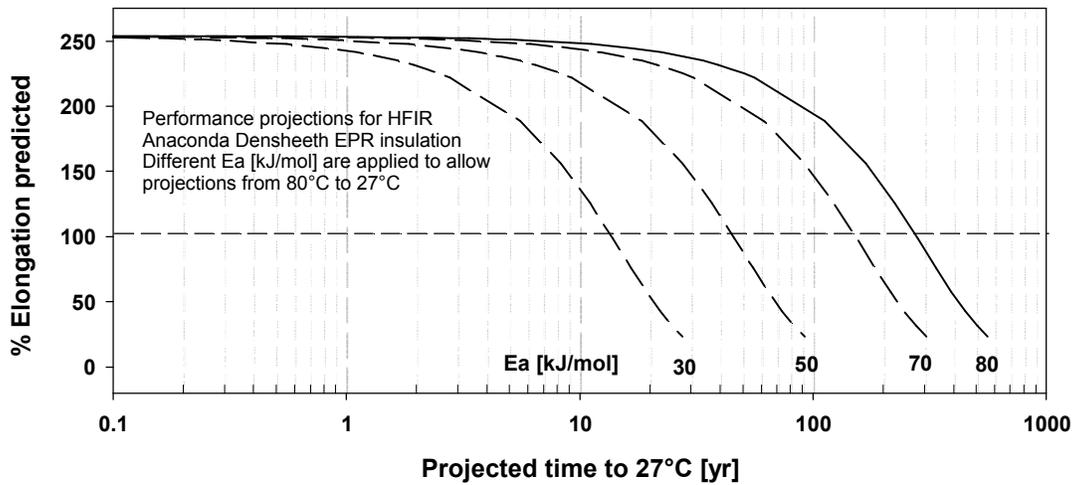


**Figure 5:** Shift factor plot highlighting experimental and extrapolation regions for two assumed activation energies below 80°C.

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.



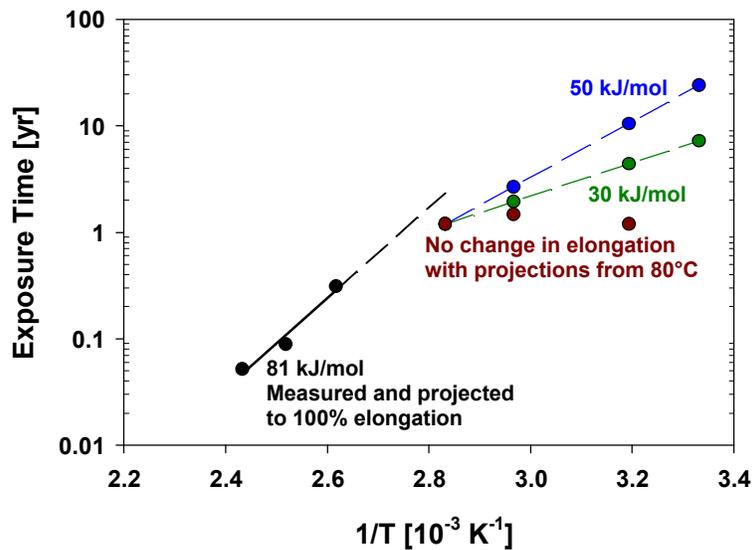
**Figure 6:** Actual (138 to 109°C data) and projected times to 100% elongation for two assumed activation energies below 80°C.



**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.

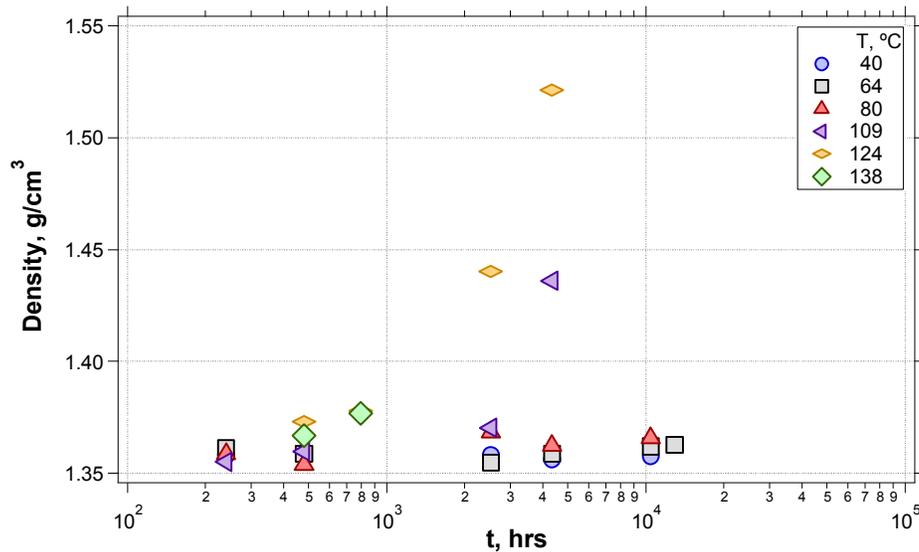
The aging behavior of the Anaconda Densheath cable insulation is consistent with the performance of other EPR materials previously presented [5] demonstrating significant predicted service lifetimes. The  $E_a$  values support previous work; however, given the shape of the tensile data the most realistic  $E_a$  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 ( $E_a \sim 30$  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.

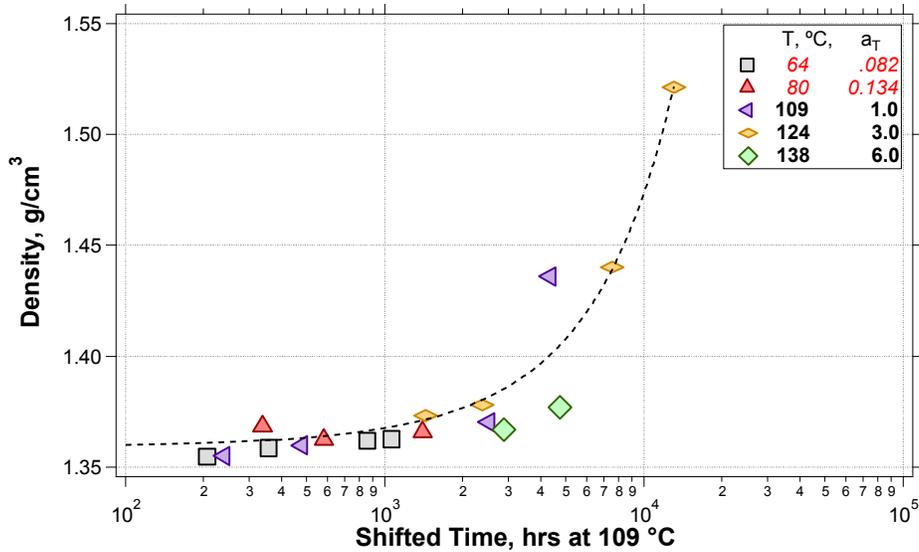
Figure 9 shows density measurements of laboratory aged Anaconda Densheath EPR insulations returned from HFIR. As with the tensile data, significant changes in the density data are only observed at the higher laboratory aging temperatures wherein density increases with increased aging time.



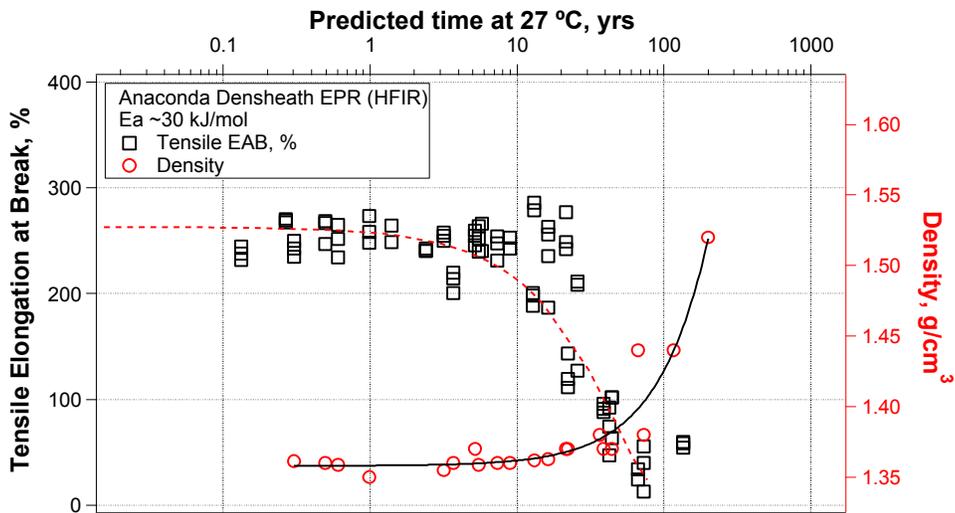
**Figure 9:** Density plotted as a function of aging time for Anaconda Densheath EPR insulation aged at various temperatures.

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  $\sim 30$  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.

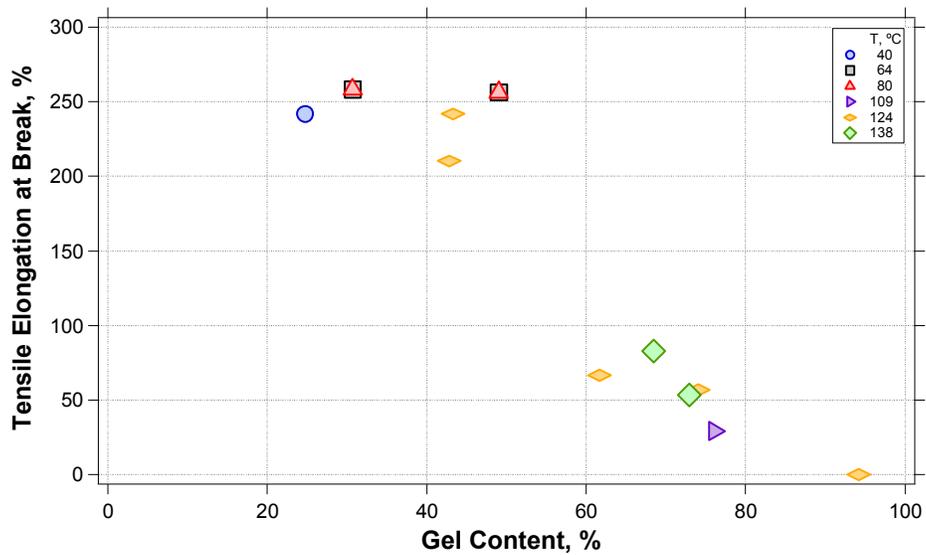


**Figure 11:** Shifted tensile and density data at a reference temperature of 109°C for Anaconda Densheath EPR with an assumed  $E_a$  of 30 kJ/mol below 80°C.

### *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.

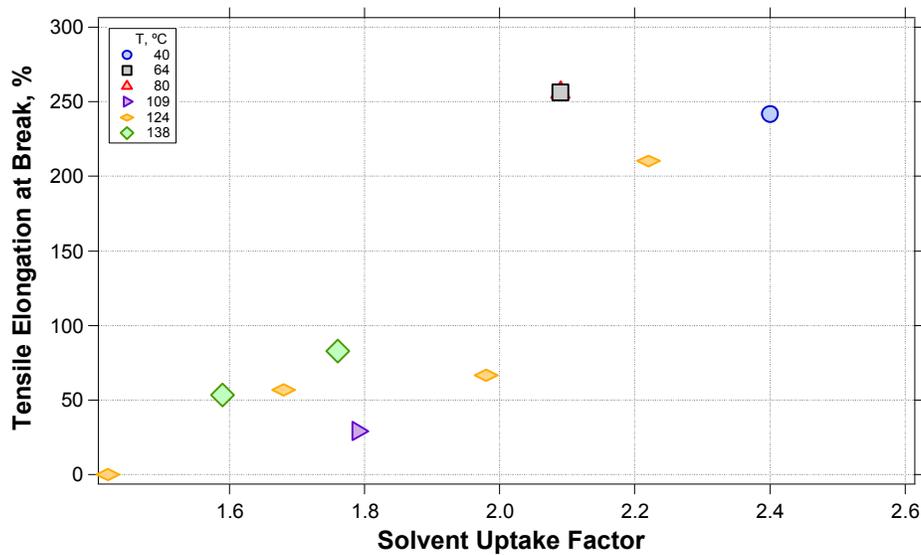
Gel content and solvent uptake factors were measured for the HFIR cables, both as received and laboratory aged. Figure 12 shows tensile elongation data versus percent gel content. As the tensile elongation at break decreases, the gel content increases. These results suggest that crosslinking is the dominant 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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## References

1. IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations. 1974;IEEE Std 323-1974
2. Busby JT. Light Water Reactor Sustainability: Materials Aging and Degradation Pathway Technical Program Plan. ORNL/LTR-2012/327. September 2012
3. Busby JT, Nanstad RK, Stoller RE, Feng Z, Naus DJ. Materials Degradation in Light Water Reactors: Life After 60. ORNL White Paper on Materials for LWRSP.
4. The High Flux Isotope Reactor at Oak Ridge National Laboratory.
5. Gillen KT, Assink RA, Bernstein R. Nuclear Energy Plant Optimization (NEPO) Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials. 2005;SAND2005-7331
6. Gillen KT, Celina M, Clough RL. Density measurements as a condition monitoring approach for following the aging of nuclear power plant cable materials. Radiat Phys Chem. DOI:10.1016/S0969-806X(99)00333-3
7. Gillen KT, Clough RL, Dhooge NJ. Density Profiling of Polymers. Polymer. 1986;27:225
8. Celina M, Gillen KT, Assink RA. Accelerated aging and lifetime prediction: Review of non-Arrhenius behaviour due to two competing processes. Polym Degrad Stab. 2005;90:395-404
9. Celina M, Gillen KT, Wise J, Clough RL. Anomalous aging phenomena in a crosslinked polyolefin cable insulation. Radiat Phys Chem. 1996;48:613-626

10. Gillen KT, Celina M, Clough RL, Wise J. Extrapolation of accelerated aging data-Arrhenius or erroneous? Trends Polym Sci (Cambridge, U K ). 1997;5:250-257
11. White II GV, Schroeder JL, Sawyer PS, Wichhart DJ, Garner A, Mata GA, Gillen KT, Bernstein R. Aging Assessment of Service Cables. ;SAND2013-2448P