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Review of Nuclear Power Plant Safety Cable Aging Studies with Recommendations for Improved Approaches and for Future Work

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Abstract

Many U. S. nuclear power plants are approaching 40 years of age and there is a desire to extend their life for up to 100 total years. Safety-related cables were originally qualified for nuclear power plant applications based on IEEE Standards that were published in 1974. The qualifications involved procedures to simulate 40 years of life under ambient power plant aging conditions followed by simulated loss of coolant accident (LOCA). Over the past 35 years or so, substantial efforts were devoted to determining whether the aging assumptions allowed by the original IEEE Standards could be improved upon. These studies led to better accelerated aging methods so that more confident 40-year lifetime predictions became available.

Since there is now a desire to potentially extend the life of nuclear power plants way beyond the original 40 year life, there is an interest in reviewing and critiquing the current state-of-the-art in simulating cable aging. These are two of the goals of this report where the discussion is concentrated on the progress made over the past 15 years or so and highlights the most thorough and careful published studies. An additional goal of the report is to suggest work that might prove helpful in answering some of the questions and dealing with some of the issues that still remain with respect to simulating the aging and predicting the lifetimes of safety-related cable materials.

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EXECUTIVE SUMMARY

Many U. S. nuclear power plants are approaching 40 years of age and there is a desire to extend their life for up to 100 total years. Safety-related cables were originally qualified for nuclear power plant applications based on IEEE Standards that were published in 1974. The qualifications involved procedures to simulate 40 years of life under ambient power plant aging conditions followed by simulated loss of coolant accident (LOCA). Over the past 35 years or so, substantial efforts were devoted to determining whether the aging assumptions allowed by the original IEEE Standards could be improved upon. These studies led to better accelerated aging methods so that more confident 40-year lifetime predictions became available.

In particular, three of the aging assumptions used were found to be overly simplistic. Thermal aging was typically carried out at a few high temperatures, then they were modeled with an Arrhenius function to derive an Arrhenius activation energy E_a and finally the results were extrapolated to ambient conditions assuming no change in E_a. Recent studies show that E_a often drops at low temperatures, reducing the extrapolated lifetime. For radiation aging, an equal damage, equal dose assumption (e.g., no dose rate effects) was used. Careful studies have now shown that dose rate effects that reduce extrapolated material lifetime are both common and expected and come from several different mechanisms. Finally, for simulating combined radiation plus thermal environments, sequential aging (usually thermal aging followed by room temperature radiation aging) was allowed whereas recent studies show that simultaneous aging is usually much more severe.

Since there is now a desire to potentially extend the life of nuclear power plants way beyond the original 40 year life, there is an interest in reviewing and critiquing the current state-of-the-art in simulating cable aging. These are two of the goals of this report where the discussion is concentrated on the progress made over the past 15 years or so and highlights the most thorough and careful published studies. An additional goal of the report is to suggest work that might prove helpful in answering some of the questions and dealing with some of the issues that still remain with respect to simulating the aging and predicting the lifetimes of safety-related cable materials.

Some of the important conclusions reached in the report and recommendations for future work follow:

1. One important area of research should involve deriving better knowledge of the actual in-containment aging environments seen in operating nuclear plants. Such information would be extremely useful for determining the relative importance of thermal aging versus radiation effects and, therefore, how much research must be devoted to such things as "inverse temperature" effects (faster degradation at a given dose rate as the temperature is reduced).

2. For analyzing thermal aging data, time-temperature superposition (similar shapes for degradation curves at all temperatures when data is plotted versus log of the aging time) should always be used to assure that the underlying chemical degradation is not changing as the temperature changes.

3. In looking for non-Arrhenius behavior for thermal aging data, the greatest confidence in any conclusions comes through the use of "direct" evidence which entails obtaining evidence directly from data on the primary degradation parameter of interest.

4. When "direct" evidence is unavailable, "indirect" evidence should be obtained from a sensitive secondary degradation parameter that 1) can be shown to be intimately related to the primary degradation parameter and 2) can be shown to have the same E_a value at aging temperatures that overlap those of the primary degradation parameter

5. Oxygen consumption results could be helpful for determining whether the E_a values of important materials (neoprene, CSPE, EPR/EPDM, XLPE/XLPO) drop below the regions accessible to elongation measurements in any reasonable timeframe.

6. The dose to equivalent damage (DED) approach is the superior approach for analyzing and extrapolating accelerated combined environment (radiation plus temperature) experiments.

7. For EPR/EPDM and XLPO/XLPE materials aging under combined radiation plus temperature conditions, the possible presence of "inverse temperature" effects (degradation rates are faster as the temperature is reduced for a constant radiation dose rate) must be looked for by carrying out some combined environment simulations at aging temperatures in the 22°C to 50°C range.

8. If inverse temperature effects occur, combined environment experiments versus dose rate at one or two constant temperatures in the range between 22°C and 50°C should be considered as the only viable predictive approach.

9. When "inverse temperature" effects are absent, we outlined what we consider to be the best approach for simulating combined environment aging conditions. This involves the use of the principles underlying the DED approach wherein time-temperature-dose rate shifts are carried out using verified E_a values such that the acceleration of the thermal pathway, the acceleration of the radiation initiation and the time compression factor are the same.

10. The Wear-out approach is highly recommended for estimating remaining lifetimes of materials that are easily accessible in nuclear plants (e.g., at cable terminations). It is extremely advantageous for materials that show "induction-time" behavior (little degradation versus aging time until a very rapid drop-off in properties just before material failure) since many condition monitoring approaches would give little warning of imminent failure for such materials. The use of a Wear-out degradation parameter that is non-destructive and requires small pieces of sample (e.g., density) is clearly advantageous.

11. To apply the Wear-out approach, it would be highly desirable to try and acquire small pieces of cable materials with known aging histories from operating plants.

12. For LOCA simulations, the importance of the oxygen concentration in the atmosphere during the actual LOCA and during the simulation should be considered.

INTRODUCTION

Many U. S. nuclear power plants are approaching 40 years of age and there is a desire to extend their life for up to 100 total years. When first built, safety-related equipment such as the cable materials of interest to the current report, were subjected to qualification testing intended to demonstrate that the equipment would remain functional if a major accident such as a loss-of-coolant accident (LOCA) occurred at any time during the 40-year expected operation of the plant. The qualification entailed two basic parts, accelerated aging of the component to simulate its condition up to 40 years of normal plant environments followed by an accident (LOCA) simulation.

The qualification approach used for cables in U. S. plants was specified in two IEEE documents from 1974[1-2]. For the aging part of the approach, the IEEE documents allowed accelerated thermal aging simulations to be done by taking measurements at a few high temperatures, modeling the results with an Arrhenius function and assuming that the Arrhenius behavior could be extrapolated to the much lower temperatures of relevance to actual power plant conditions. For simulating the aging effects of radiation, an equal damage, equal dose assumption was allowed so that the total dose of interest was typically simulated at an extremely high dose rate, such as 10 kGy/h (1 Mrad/h). Aging simulation was usually done sequentially with the thermal environment preceding the radiation environment.

Over the past 35 years or so, substantial efforts were devoted to determining whether the aging assumptions allowed by the original IEEE Standards could be improved upon. These studies led to better accelerated aging methods so that more confident 40-year lifetime predictions became available. In particular, careful long-term studies indicate that many materials have important non-Arrhenius behavior such that the Arrhenius activation energy (E_a) determined under short-term, high temperature aging conditions drops to a lower value as the temperature is reduced to conditions closer to the ambient plant conditions[3-7]. This drop implies that low temperature predictions made from extrapolating high-temperature E_a values can over-estimate the lifetime of materials at low temperatures. A second shortcoming of the IEEE approach has to do with the equal dose, equal damage assumption for simulating radiation aging effects. This assumption is equivalent to the assumption that dose rate effects (DRE) are absent. Numerous careful studies now show that DRE are extremely common[8-12]. DRE are caused by many different phenomena. First of all, radiation aging is always undertaken at some temperature T and the thermal aging chemical degradation pathways caused by temperature can interact with the radiation-induced chemical degradation pathways to enhance the overall degradation rate. Thus, if the dose rate is changed at a given temperature, the relative ratio of thermally-induced chemistry and radiation-induced chemistry will change, leading to DRE. In other instances, true chemical DRE come

directly from the radiation-induced chemical pathways, as found for PVC and low density polyethylene materials[13]. Finally, DRE often occur due to diffusion-limited oxidation (DLO), a purely physical phenomenon[14-19]. Since DLO effects become much more significant when degradation occurs quickly (e.g., at high dose rates), the high dose rates allowed by the IEEE Standards often guaranteed important DLO effects[20]. Finally, there is substantial evidence that the sequential thermal aging followed by radiation aging allowed in the IEEE Standards usually leads to much lower degradation than a combined $R + T$ accelerated aging environment[21].

The knowledge gained over the past 30 years has led to improved accelerated aging approaches and improved data analyses. For accelerated thermal aging, lower temperature, longer time exposures are often used to reduce the extrapolation distances and ultrasensitive analytical techniques related to the degradation variable of interest are often employed to obtain E_a results at temperatures close to or beyond the extrapolation temperature of interest. Radiation and thermal aging are carried out under simultaneous aging conditions to better simulate the actual plant aging situation. In addition, aging conditions are chosen such that the importance of DLO effects for both thermal and radiation aging are eliminated, minimized or taken into account.

The existence of non-Arrhenius effects, radiation dose-rate effects and synergistic effects would seem to imply that historic aging qualification studies using the IEEE Standards might result in less aging than would actually occur during a typical 40-year lifetime. This is not necessarily the case, however, since unpublished environmental measurements in actual operating plants now indicate that the aging environments for most cables appear to be milder than those assumed in the original qualifications[22]. For instance, a 500 kGy (50 Mrad) aging dose was assumed over the 40-year lifetime in the IEEE Standard, whereas it is now felt that, except for some "hot spots", most cables see a maximum of 100-200 kGy (10-20 Mrad) over 40 years[22]. With respect to "hot spots", aging management practices are being implemented by plant operators where such conditions are found and cables are inspected and tested in those locations. It is clear from this discussion that a first important area of future research should involve deriving better knowledge of the actual in-containment aging environments seen in operating nuclear plants.

A major purpose of this report is to review the recent progress made towards gaining confidence in the ability of accelerated aging methods to reasonably simulate the aging of safety-related cable materials under typical nuclear power plant aging conditions. Over the past 30 years or so, there have been countless studies by numerous workers in many different countries. Many of these reports are from not easily available sources (e.g., Conference proceedings). Others are lacking in important details or were not published in English. With this in mind, we were forced to concentrate this review on the most complete and thorough studies available with a bias towards work done in the past 15 years. A very good review of safety-related cable qualification work done up to the mid-90s was published by M. Subudhi[21]. In this review (Fig. 2.4 and Table 2.1), Subudhi shows that the most popular cable insulation materials in U. S. plants are XLPE/XLPO

and EPR/EPDM whereas the most popular jackets are CSPE (hypalon) and chloroprene (neoprene). Our analyses will therefore focus predominantly on these 4 materials.

A second goal of our report is to suggest work that might prove helpful in answering some of the questions and dealing with some of the issues that still remain with respect to simulating the aging and predicting the lifetimes of safety-related cable materials.

ACCELERATED THERMAL-AGING

Chloroprene (neoprene) cable jacketing materials

As noted earlier, substantial evidence for non-Arrhenius behavior has now been shown for numerous polymeric materials[3,5-7,19,23-29]. The most compelling evidence comes from the monitoring of the same material property over an extended temperature range that is broad enough to confirm the non-Arrhenius character directly. An example comes from studies[5] of an Okonite neoprene cable jacketing material where aging was done at 8 temperatures ranging from 131°C to 24°C (up to 24 years at the lowest temperature). Tensile elongation measurements (the gold standard for following mechanical degradation) were obtained at each aging temperature versus the aging time; the results are shown in Figure 1.
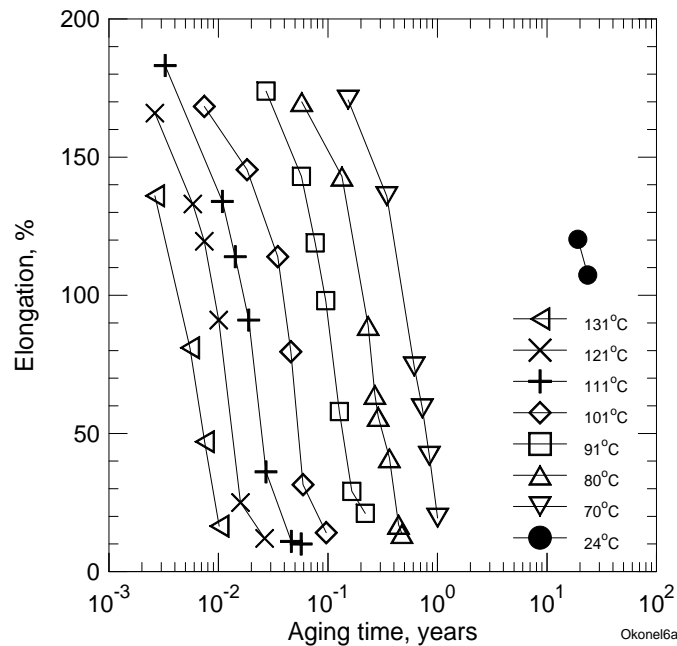

Figure 1.   Elongation versus aging time at the indicated aging temperatures for an Okonite neoprene cable jacket.

Often an Arrhenius analysis of such data would select some level of degradation such as the time to 50% remaining elongation and plot these times on an Arrhenius plot (e.g., log of the time to 50% elongation versus inverse absolute temperature). A superior approach that utilizes all of the data instead of a single processed point derived after smoothing the time-dependent data at each temperature involves the so-called time-temperature superposition (t-T) approach[3-4]. It is based on the assumption underlying accelerated aging that raising the aging temperature raises all of the relevant degradation reactions by a constant amount which implies that the ratio of times to any selected amount of degradation at two temperatures will be related by a constant multiplicative factor. This assumption implies that the shape of the degradation curves at various temperatures will be identical when plotted versus log of the aging times (a constant multiplicative factor represents a constant horizontal shift for a log time plot). The results shown in Figure 1 appear to have similar shapes at the various aging temperatures in accord with the constant acceleration assumption. To apply t-T superposition, we first select a reference temperature T_{ref} typically the lowest experimental temperature (24°C in the present case). We then take the data at the next lowest temperature (70°C) and empirically determine the multiplicative shift factor a_T such that multiplying the times associated with the second temperature by a_T gives the best overlap of these data with those at the reference temperature. We continue to do this procedure by stepping up sequentially in temperature until all of the data are shifted to 24°C. The results of this procedure are shown in Figure 2, which also shows the shift factors a_T used for each temperature (a_T is unity at the reference temperature).
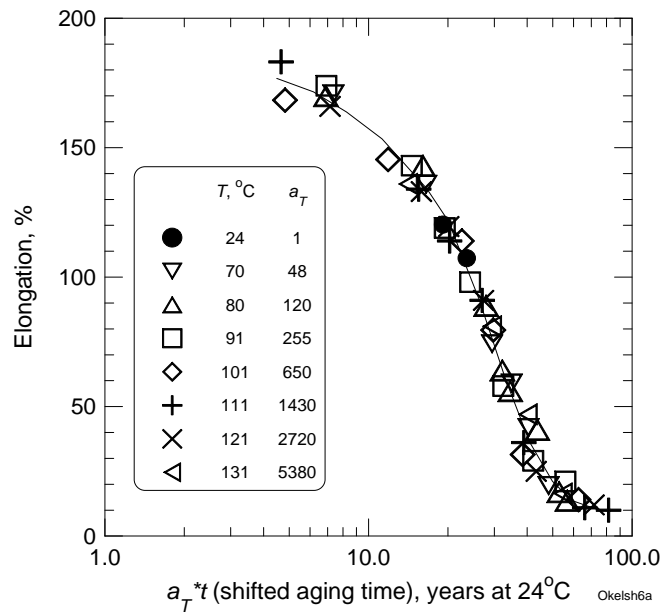

Figure 2. Time-temperature superposition of the data from Figure 1.

It is clear from the results that excellent t-T superposition occurs for this data over a very large temperature range. The results predict that the elongation of this material at an

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aging temperature of 24°C will reach 100% and 50% after approximately 25 years and 38 years, respectively. We next plot the shift factors on an Arrhenius plot, shown in Figure 3. The results show clear non-Arrhenius behavior with the high temperature E_a value of 89 kJ/mol (1 kJ/mol = 0.239 kcal/mol = 0.01036 eV) dropping to ~71 kJ/mol below 70°C. Since only elongation results were utilized to show the non-Arrhenius behavior, this is an example of "direct" evidence of non-Arrhenius behavior.

In cases where the data from the primary degradation variable of interest (e.g., elongation) does not span a large enough temperature range to observe non-Arrhenius behavior, non-Arrhenius behavior is often found by following another secondary degradation variable that 1) is intimately related to the variable of interest and 2) has a sensitivity that allows measurements to be made at temperatures lower than the bottom of the temperature range available from the primary degradation variable. In such instances, we refer to the non-Arrhenius evidence as "indirect". One parameter often found to be intimately connected to the elongation is the oxygen consumption rate, since the presence of oxygen often totally dominates the degradation of polymeric materials when aged in an oven. This can be seen, for instance, in Figure 4 which compares aging of the Okonite neoprene material at 150°C under air versus nitrogen. Clearly the presence of oxygen totally dominates the degradation of this material. For this reason, one might expect the amount of oxygen consumed to be correlated with changes in elongation and this is indeed found to be the case[5].
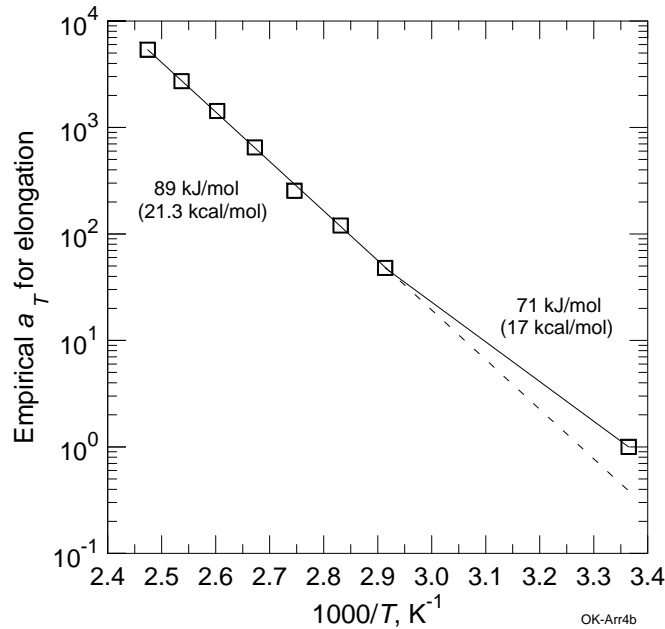
Figure 3. Arrhenius plot of the shift factors shown on Figure 2 for the neoprene cable jacketing material.
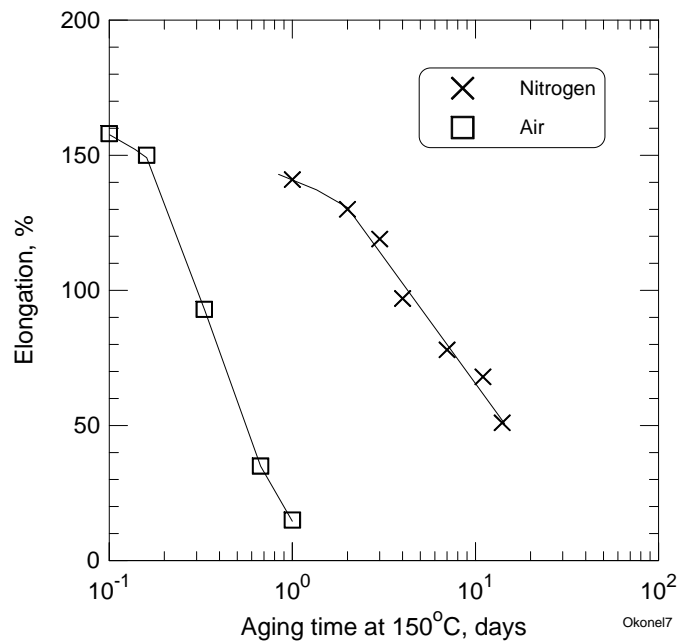
Figure 4. Elongation results of Okonite neoprene versus aging time at 150°C in air versus nitrogen.

On the other hand, attempting to use a degradation parameter that is not closely related to elongation to extend the elongation results to lower temperatures will prove useless. For instance, Figure 5 shows TGA weight loss results under nitrogen and air for this same material at 144.5°C. Little difference is noted in the air versus nitrogen results all the way out to mechanical property "failure" even though it is clear from Figure 4 that oxidation totally dominates the degradation.

Figure 5. Weight loss results for the Okonite neoprene versus aging time at 144.5°C in air versus nitrogen.

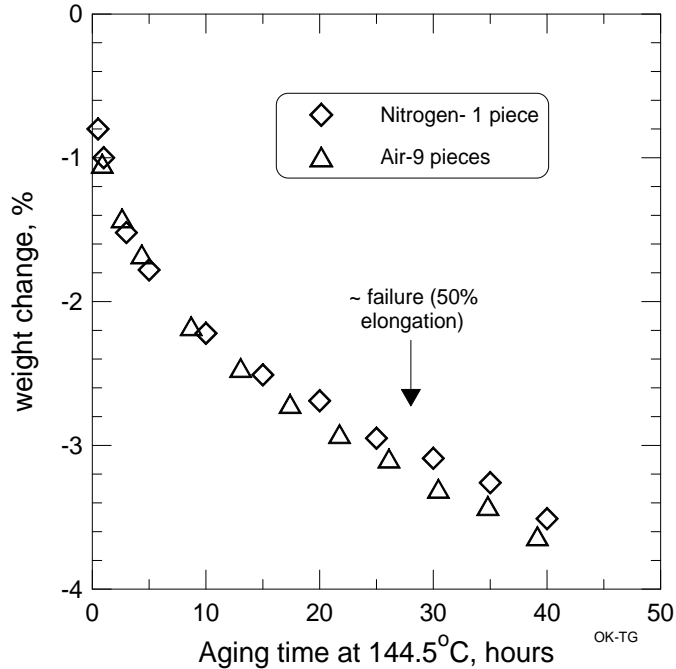The important message from the above discussion is that a sensitive parameter being used to extend the Arrhenius plot of elongation to temperatures lower than the range used for the elongation measurements must be intimately correlated to elongation. The first piece of evidence for such a correlation is chemical evidence such as that shown in Figure 4. An additional critical piece of evidence is to obtain Arrhenius data for the sensitive parameter that overlaps part of the temperature range used for elongation measurements and show that data in this temperature range is consistent with the elongation results in this region.

As an example, we look at results for a Rockbestos Firewall III neoprene cable jacketing material[5]. For this material, elongation results were obtained at three temperatures (80, 95 and 110°C) which were time-temperature superposed at 80°C as shown in Figure 6. Oxygen consumption rate data was obtained from 95°C down to 25°C thereby providing some overlap with the elongation results. After transforming the oxygen consumption rate data to oxygen consumption versus time data, the latter were time-temperature superposed leading to the results shown in Figure 7. Figure 8 shows an Arrhenius plot of the shift values obtained from the elongation results together with the shift factors (normalized to 80°C) obtained from the oxygen consumption results. It is immediately clear that the oxygen consumption results are consistent with the elongation results in the overlap temperature region, compelling evidence that the extrapolation using the oxygen consumption results is valid. In addition the results show a drop in the Arrhenius E_a from ~96 kJ/mol above 80°C to ~76 kJ/mol below that temperature. These results are in

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reasonable agreement with the results for the Okonite neoprene above and below 70°C (89 and 71 kJ/mol).
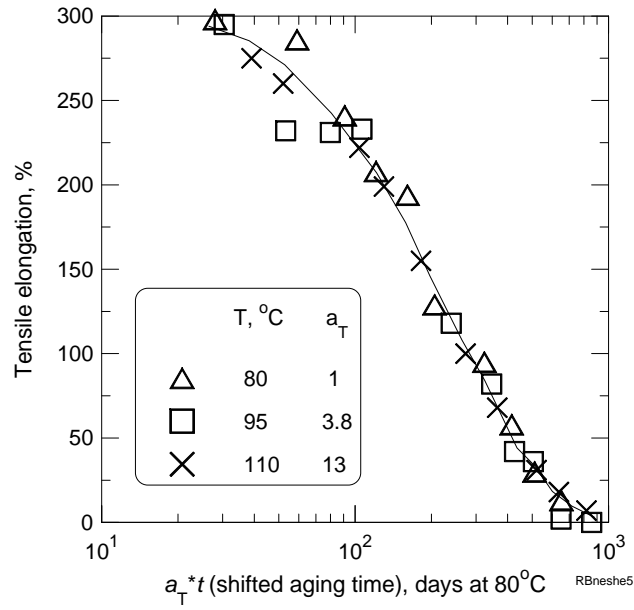

Figure 6.   Time-temperature superposed elongation data for Rockbestos Firewall III neoprene material.
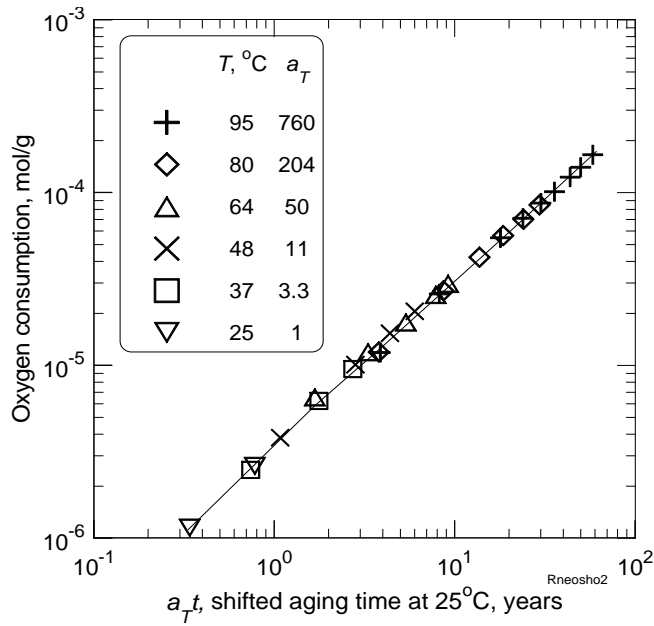
Figure 7. Time-temperature superposition of oxygen consumption results for Rockbestos Firewall III neoprene.
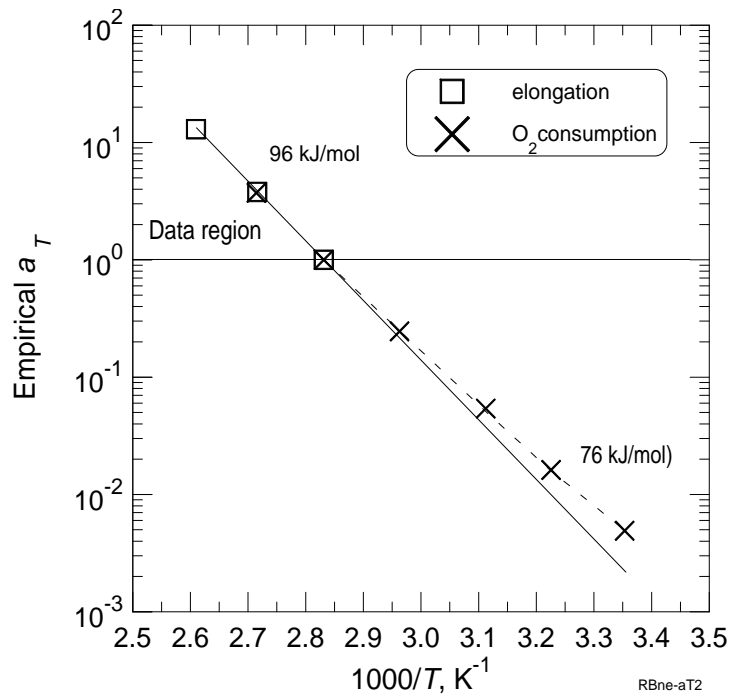

Figure 8. Arrhenius plot of the Rockbestos Firewall III neoprene shift factors from elongation and oxygen consumption results.

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Although the E_a results for these two neoprene cable jacketing materials are similar, it is quickly apparent that the Rockbestos material is superior to the Okonite material. One can see this by noting from Figure 1 that the Okonite material reaches 50% elongation after ~0.32 years (115 days) whereas Figure 6 shows that the Rockbestos material reaches 50% elongation after ~420 days. Actual elongation data exists for a neoprene cable jacketing material that had aged in a nuclear power plant environment for times up to 25 years at 44°C[30]. This data is plotted versus aging time in Figure 9. Also shown on this figure are interpolated results for the Okonite material and extrapolated predictions for the Rockbestos material. The latter are derived by shifting the superposed results at 80°C from Figure 6 to 44°C using the shift factor results from Figure 8. Two things are clear from these results. First of all there are variations to be expected for various neoprene materials in their thermal robustness caused by differences in their formulations. Perhaps more important, however, is the observation that neoprene jackets might be anticipated to perform poorly with respect to long-term thermal exposures under nuclear power plant aging conditions. As we will see later, the addition of radiation can reduce their lifetimes even more. Even so, it should be remembered that jacketing materials are not as critical as insulation materials to the viability of safety-related cables since two of the main purposes of jacketing are to act as an aid when the cable is initially installed in the plant and to protect the insulation materials from such things as nicks during plant operation and maintenance.
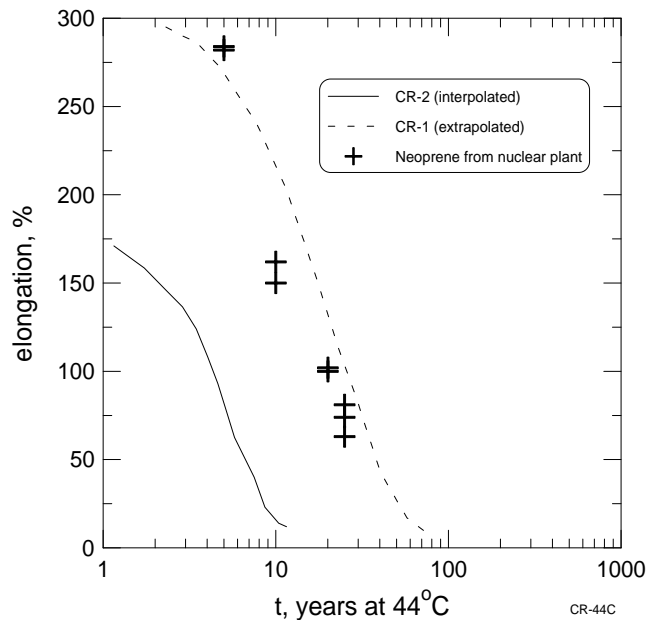

Figure 9. Neoprene jacket elongation results (crosses) from an operating nuclear power plant for times up to 25 years at 44°C together with interpolated results for the Okonite material and extrapolated results for the Rockbestos material at this temperature.

Comments on JNES Report[12]

The above discussion described in detail several important points that have been highlighted numerous times[3-5,7,30-32] and should be addressed when attempting to simulate low temperature thermal aging using accelerated aging techniques. These include

1) the recommendation that time-temperature superposition be used for data analyses so that the constant shape assumption underscoring constant chemistry is confirmed in addition to the fact that all of the data are used in the analyses instead of a single processed data point at each temperature,

2) the use of an ultrasensitive degradation parameter (e.g., oxygen consumption) that is well correlated with the primary degradation parameter (e.g., elongation)

3) confirmation that the E_a value of the ultrasensitive degradation parameter correlates with the E_a value for the primary degradation parameter in temperature regions where the data overlap.

Unfortunately, these recommendations are not always followed. For instance, JNES recently published an extensive report titled The Final Report of The Project of "Assessment of Cable Aging for Nuclear Power Plants"[12]. This report contains a lot of very useful information on both aging and accident simulations as well as information relevant to condition monitoring. With respect to thermal aging, however, the report seems to ignore the above recommendations. Instead of utilizing time-temperature superposition analyses, the report analyzes the thermal aging data using the times required for elongation at each temperature to drop to 100%. This implies that a vast majority of the data is disregarded when the authors attempt to estimate E_a values from Arrhenius plots. In addition, data that varies in shape (e.g., their Figure 2.2-5) as the temperature is changed goes unrecognized. In fact the data from this figure only reaches 100% at one of the three temperatures studied, yet somehow they obtain an Arrhenius plot (their Fig. 2.2-6). More confident Arrhenius plots and Arrhenius E_a values would be available from time-temperature superposition procedures.

Since their thermal aging data for their EPR/EPDM, XLPE/XLPO and PVC materials were taken at 100°C, 110°C and 120°C, they assumed a "provisional" E_a value of 62.8 kJ/mol (15 kcal/mol) for temperatures below 100°C. Their explanation (p. 195 of report) states:

"Also, though it differs from elongation at break, some literature states that around 60 kJ/mol (~15 kcal/mol) can be assumed to be appropriate for the activation energy in a region of uniform oxidation acquired with chemo-luminescence analysis"

The authors referenced the work by Yagi, Morita and Seguchi[33-34]. Unfortunately the chemiluminescence (CL) data in these two referenced papers show that the E_a for the studied EPR materials remain constant at ~60 kJ/mol from room temperature up to 120°C -150°C. Therefore there is no correlation with typical elongation E_a values which are substantially greater in the temperature range above 100°C as noted in the quote from the JNES report given above and will also be shown below in our report. Besides not confirming a relationship between elongation and CL results, another major problem with

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CL data is the fact that it is taken very early in the degradation. For instance, in the paper by Yagi and Seguchi[34], the CL data at each temperature was obtained in the first few minutes of exposure at each temperature. We will see below for an EPR material one of the potential problems associated with the use of data that is obtained in the early stages of degradation. We thus conclude that the 15 kcal/mol used in the JNES report[12] for EPR/EPDM, XLPE/XLPO and PVC materials is totally inappropriate and therefore brings into question many of the calculations and conclusions reached in this report.

CSPE (Hypalon) cable jacketing materials

The thermal oven aging of eight different chlorosulfonated polyethylene (CSPE, or hypalon) jacketing materials used in nuclear power plants was reported in a recent publication[7]. The temperature ranges studied varied from material to material but covered the very large temperature range of 70°C to 150°C and aging times up to 5 years. From a tensile elongation point of view, the variations among the eight materials were relatively small with the times required for the elongation to drop to 50% absolute at 100°C ranging from 210 to 760 days. The shift factors derived from time-temperature superposition of the elongation data were very similar for all eight materials and are shown on an Arrhenius plot in Figure 10. These results show definite evidence for non-Arrhenius behavior below ~100°C. Since these data are all from elongation results, this constitutes another case of "direct" evidence for non-Arrhenius behavior.

These results can be extended to lower temperatures utilizing oxygen consumption results since oxidation chemistry appears to dominate the drop in elongation for CSPE materials[7]. Figure 11 shows the Arrhenius plot for the combined shift factors (elongation and oxygen consumption) for the Samuel Moore Dekoron CSPE jacket, whereas Figure 12 shows a comparable plot for the BIW Bostrad 7E CSPE jacket. These results offer further evidence for a drop in E_a to around 94 kJ/mol below ~100°C.
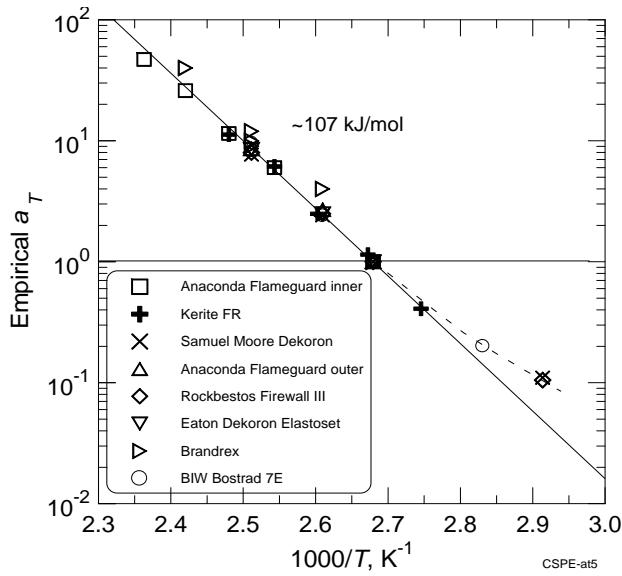
Figure 10. Arrhenius plot of the empirically derived shift factor for eight CSPE cable jacketing materials. All of the results are normalized at 100°C.
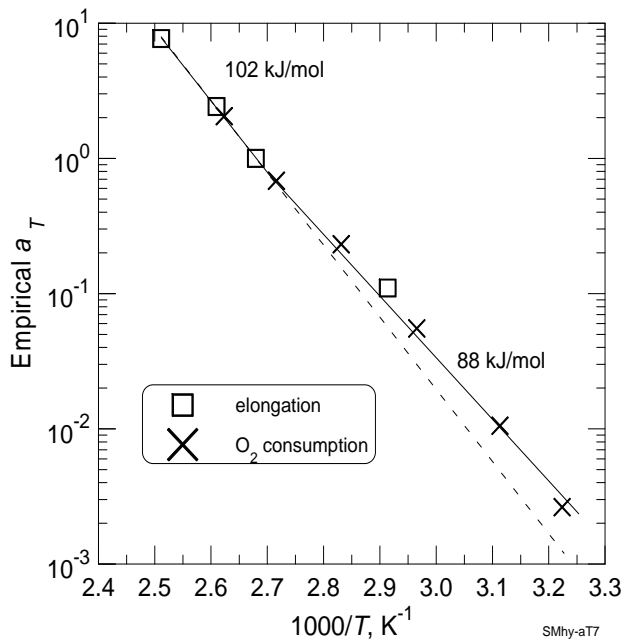

Figure 11. Arrhenius plot of the empirically derived shift factors of elongation and oxygen consumption for a Samuel Moore Dekoron CSPE cable jacketing material. The results are normalized at 100°C.
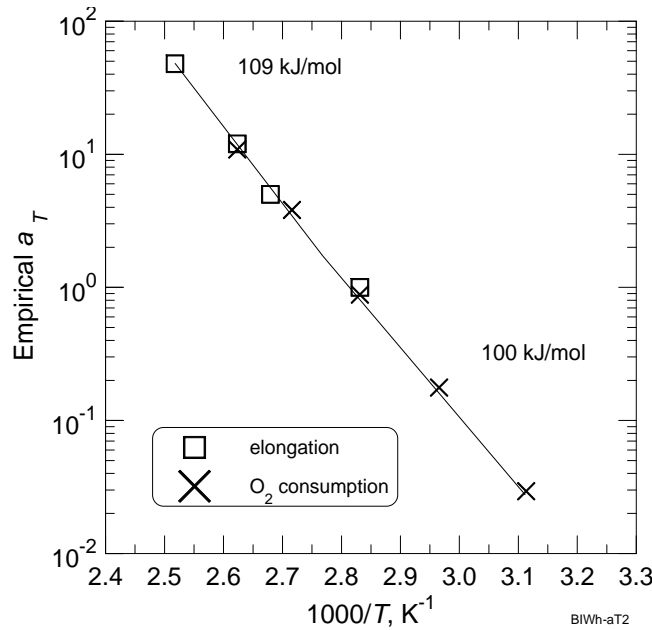
Figure 12. Arrhenius plot of the empirically derived shift factors of elongation and oxygen consumption for a BIW Bostrad 7E CSPE cable jacketing material. The results are normalized at 100°C.

Thermal aging data (from 135°C to 70°C) for another CSPE jacket material was described in a paper by Pinel and Boutard[35]. Their reported 70°C data went out to ~1.25 years but the data actually went out to 5 years[36]. We used the data from their paper plus the longer term 70°C results and analyzed them using time-temperature superposition. The results are shown in Figure 13. Figure 14 shows an Arrhenius plot of these shift value results added to the shift value results for elongation for the other 8 CSPE materials plus the oxygen consumption shift value data. It is clear from this figure that CSPE materials tend to transition from an E_a value of ~107 kJ/mol above ~100°C to an E_a value of ~91 kJ/mol below this temperature. Similar to the situation found for the neoprene materials, the drop in E_a value at low temperatures is fairly moderate.

With the estimated E_a of 91 kJ/mol below 100°C together with the earlier estimate that the elongation of typical CSPE samples reaches 50% absolute in 210 to 760 days, we estimate that the time to 50% elongation at 50°C is ~50 to 200 years. This implies that CSPE jacket materials might experience moderate to severe degradation under typical nuclear power plant thermal aging conditions for extended exposure times (60 to 100 years). Again it should be kept in mind that degradation of cable jacketing materials may not adversely affect the viability of the more important cable insulation materials since the jackets are often present mainly as an installation aid. In cases where bonding occurs between EPR insulation and CSPE individual jackets, the faster aging CSPE can control the aging. If the CSPE ages sufficiently such that it hardens, bending can cause a crack that under certain conditions can penetrate to the conductor. Below ~15% elongation, there is a likelihood of splitting during LOCA[37-39].
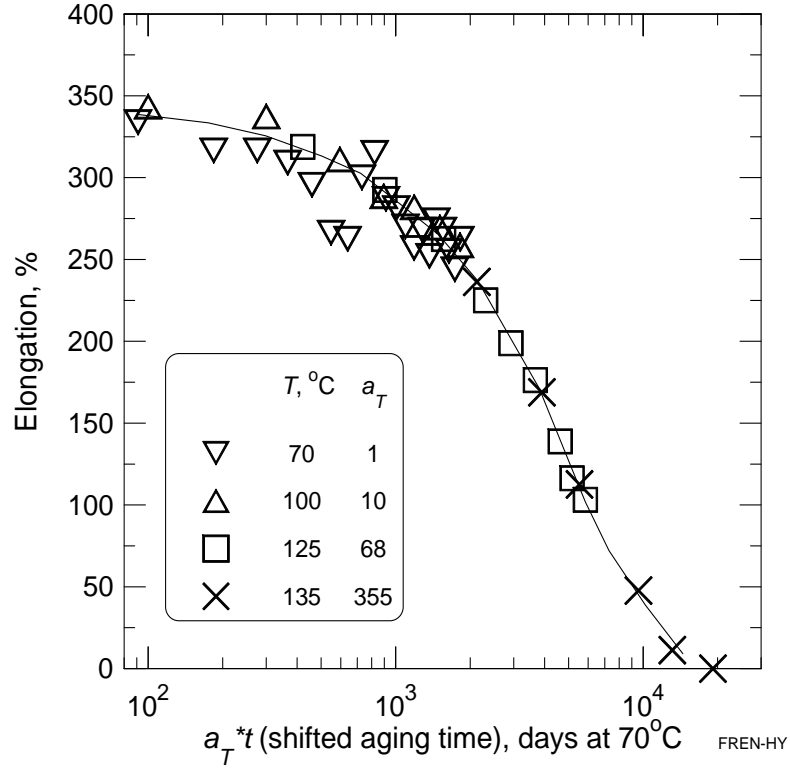
Figure 13. Time-temperature superposition of the data from Pinel and Boutard[35] and the US-French study[36].
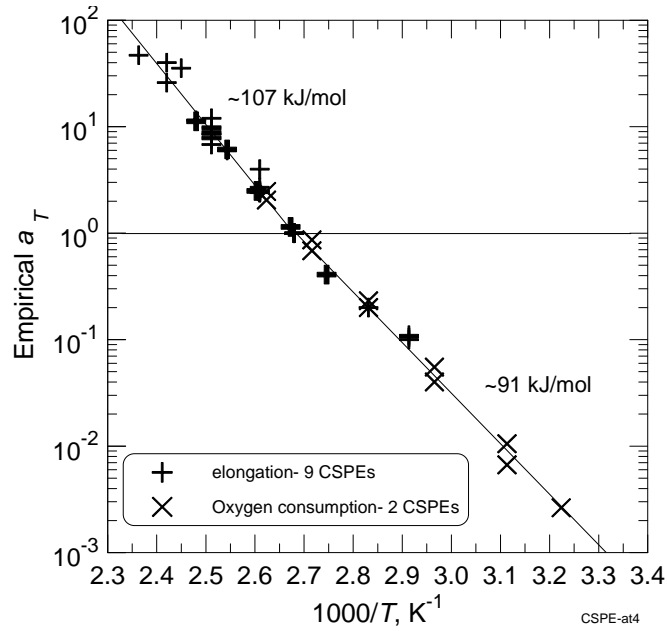

Figure 14. Arrhenius plot of the elongation shift factors for 9 CSPE materials plus oxygen consumption shift factors for two CSPE materials normalized at 100°C

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EPR/EPDM cable insulation materials

There are countless different formulations of ethylene propylene rubber/ethylene propylene diene monomer (EPR/EPDM) materials so differences in properties and aging susceptibility of various cable insulation formulations would be anticipated. We have reported thermal aging results for four such materials that are used as insulation in nuclear power plant safety applications[31]. Based on such things as the ethylene content, these materials vary from rubbery to semi-crystalline as can be seen on Figure 15 that shows DSC scan for the four materials.
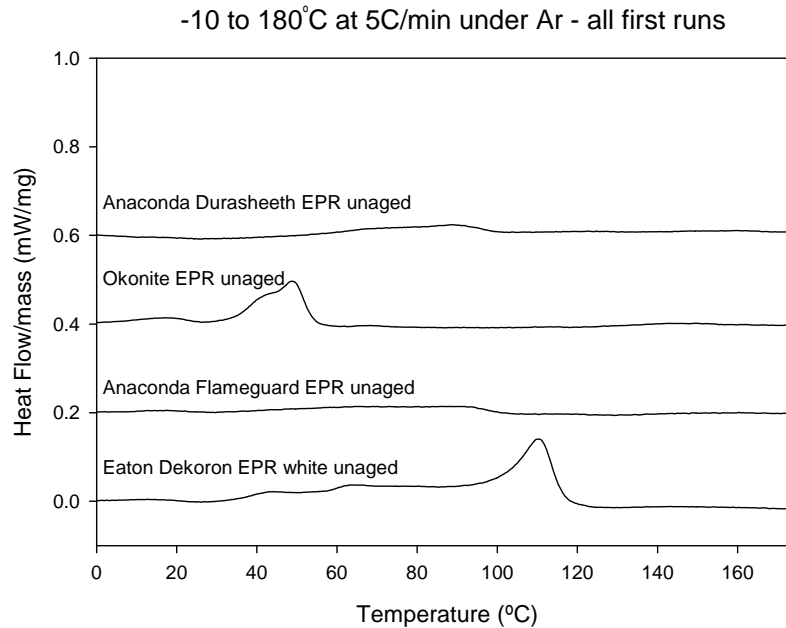
-10 to 180°C at 5C/min under Ar - all first runs

Figure 15. DSC scans for four different EPR/EPDM materials.

It is clear from these results that little crystallinity is evident for the two Anaconda materials whereas crystallinity occurs for the other two EPRs. Even so, the aging response of the two Anaconda materials turns out to be quite different. The Anaconda Flameguard material which is present in many nuclear power plants[21] is reasonably well-behaved as evidenced by its elongation results shown in Figure 16. The fairly rapid drop-off in the elongation from ~150% to 0% is a common characteristic of EPR materials, often referred to as "induction-time behavior". When these data are t-T superposed, they lead to the results shown in Figure 17. Figure 18 shows an Arrhenius plot of the shift factors used in and shown on Figure 17. The data shows excellent Arrhenius behavior from 170°C down to 100°C with an activation energy E_a of 106 kJ/mol. Since the DSC data in Figure 15 shows no noticeable transition point below 100°C, it may be reasonable to extrapolate to lower temperatures using 106 kJ/mol. This would lead to a prediction that reaching 100% elongation at 50°C would take ~270 years. A more confident

extrapolation could be obtained through the generation of oxygen consumption results starting at temperatures above 100°C (to show the correlation with elongation results) and proceeding down to the temperatures of interest to nuclear power plant aging conditions. Even if the E_a value was found to drop to 85 kJ/mol, the time to 100% elongation would be predicted to be ~100 years.
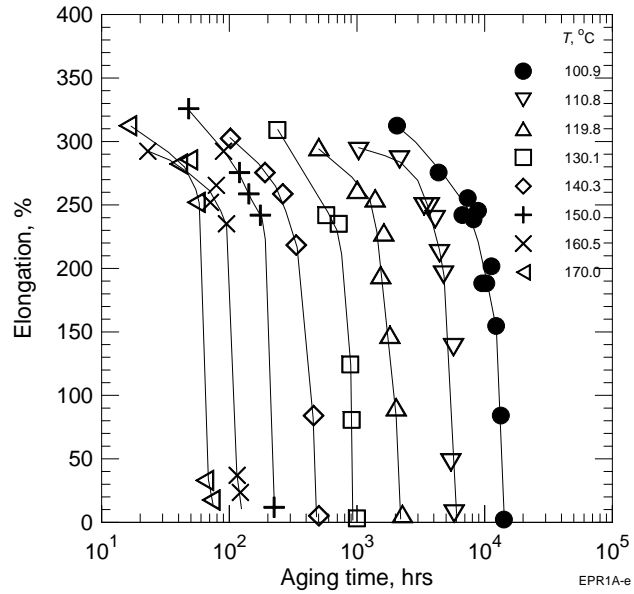
Figure 16. Elongation versus aging time results for the Anaconda Flame-Guard EPR cable insulation at the indicated aging temperatures.
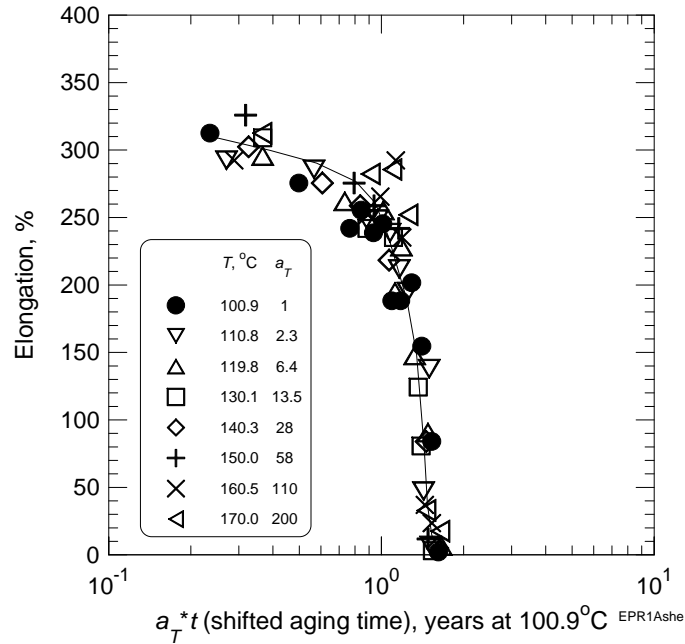
Figure 17. Time-temperature superposition of the elongation data shown in Figure 16.
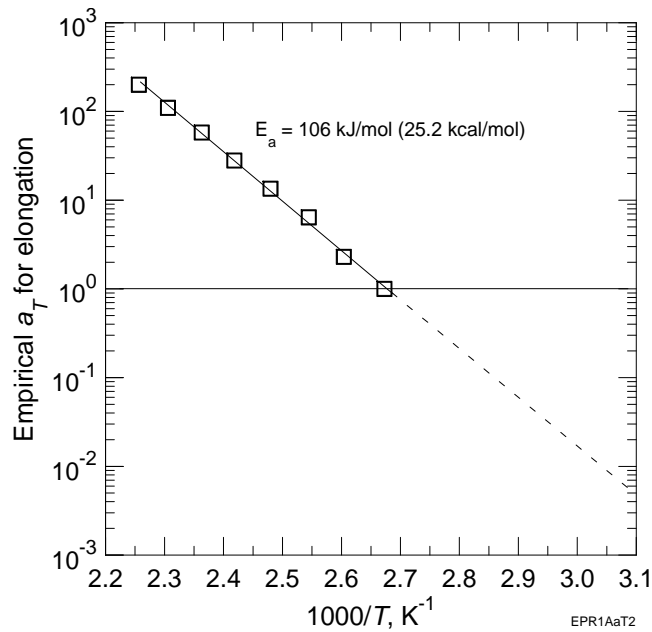
Figure 18. Arrhenius plot using the shift factors from Figure 17.

The situation for the Anaconda Durasheeth EPR material is quite different as evidenced by the elongation results shown in Figure 19 where a change in curve shape is clear as the aging temperature is dropped.
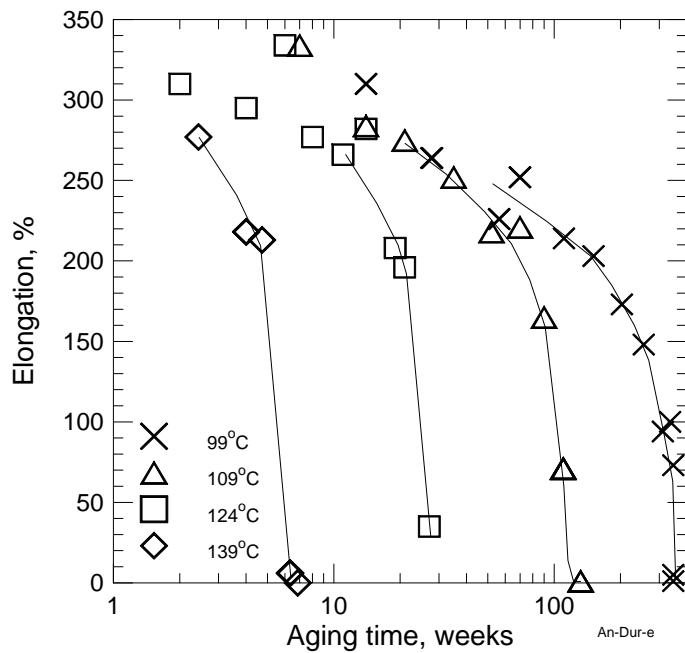
Figure 19. Elongation versus aging time results for the Anaconda Durasheeth EPR cable insulation at the indicated aging temperatures.

This change in shape is clear when we *t-T* superpose these data for best superposition in the severe part of the degradation (100% to 0% elongation) as shown in Figure 20.
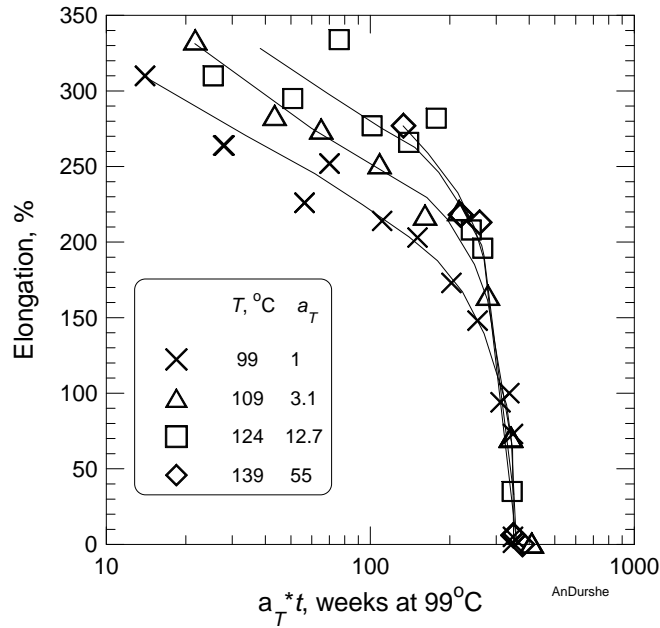
Figure 20. Time-temperature superposition of the elongation data shown in Figure 19 concentrating on the elongation region from ~100% to 0%.

If, on the other hand, we try to achieve the best superposition for the earlier regions of the degradation (~325% to 150% elongation), we obtain quite different values for the shift factors as seen from Figure 21. Arrhenius plots of these two sets of shift factors are shown on Figure 22 where it is clear that the effective E_a values depend strongly on where in the degradation one concentrates the analyses. The lack of superposition implies that the chemistry is changing as one lowers the temperature from 140°C to 100°C which makes it difficult to confidently extrapolate the results to lower temperatures.

Given the ambiguities of the elongation data, it is interesting to examine the information available from oxygen consumption results for this material. The oxygen consumed versus aging time for aging temperatures ranging from 124°C to 52°C is plotted on Figure 23 and the *t-T* superposition of this data is shown in Figure 24. The shift factors derived for this superposition and shown on Figure 24 are plotted on an Arrhenius plot in Figure 25. The E_a derived from this data is ~100 kJ/mol, identical to the E_a value obtained from the early part of the elongation results. This is not surprising once we compare the time scales of the oxygen consumption with those of the elongation results. At the highest temperature used for the consumption experiments (125°C), the consumption data extends out to ~80 days as seen in Figure 23. Comparing this result with the elongation data of Figure 19 shows that 80 days at 125°C corresponds to the earlier part of the elongation degradation curve before the rapid decrease region is reached. Thus the equality of the two 100 kJ/mol E_a values is not surprising.
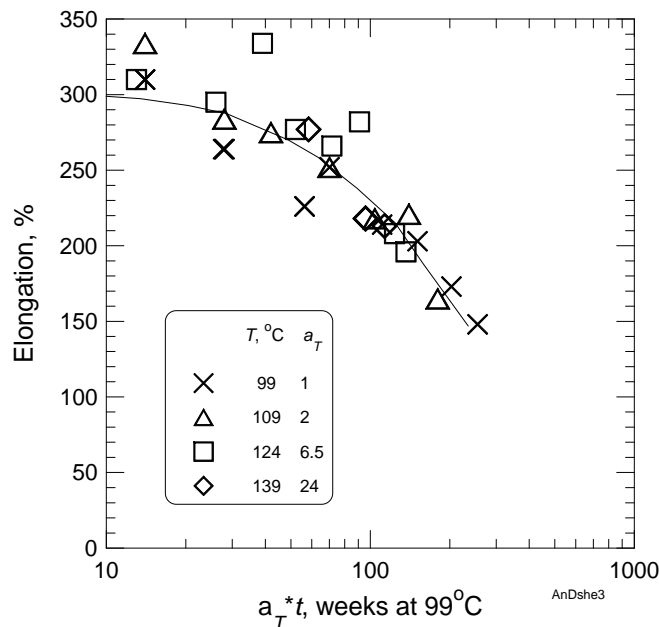
Figure 21. Time-temperature superposition of the elongation data shown in Figure 19 concentrating on the elongation region from ~325% to 150%.
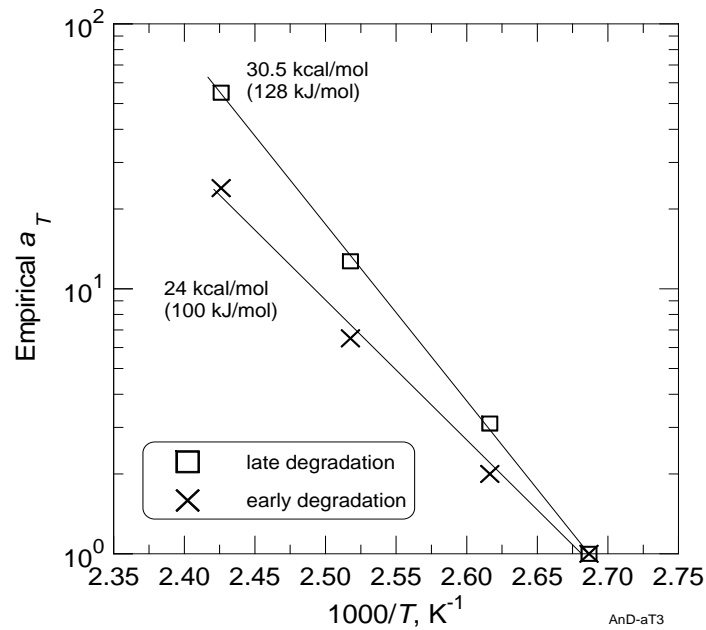
Figure 22. Arrhenius plots of the shift factors used to superpose the early and late parts of the degradation of Anaconda Durasheeth EPR insulation
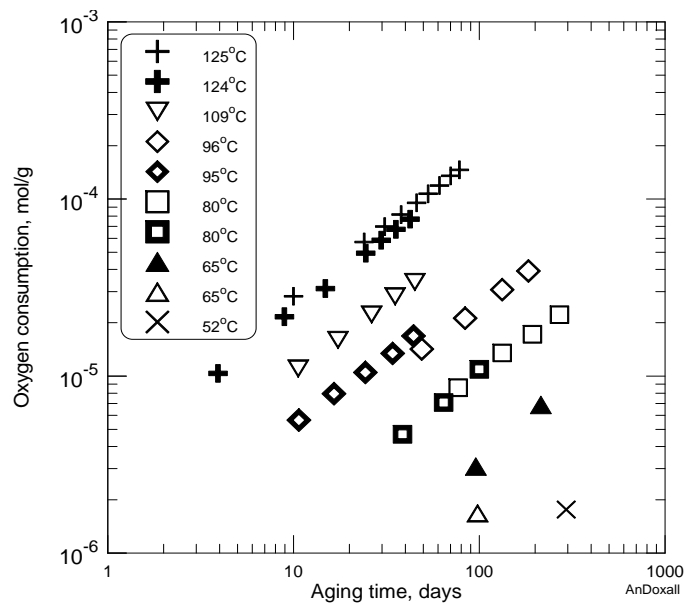

Figure 23. Oxygen consumption versus aging time for Anaconda Durasheeth EPR material at the indicated aging temperatures.
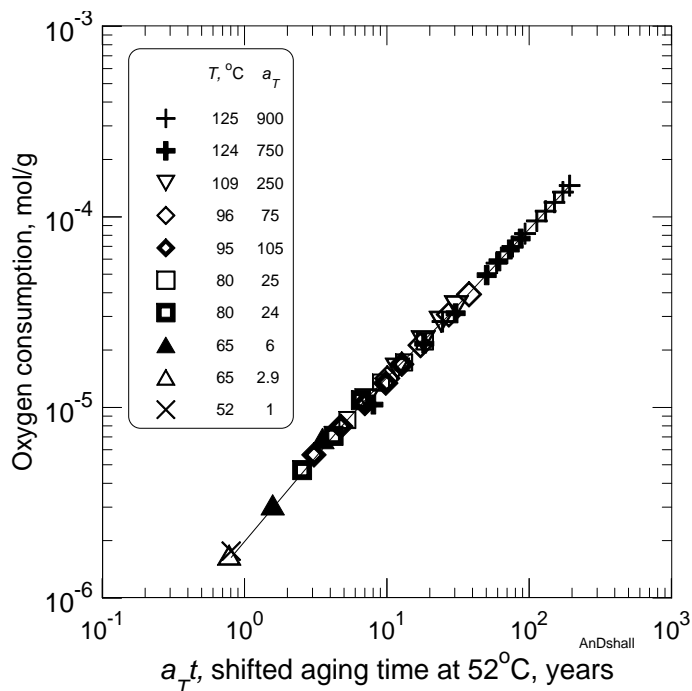
Figure 24. Time-temperature superposition of the consumption results from Figure 23.
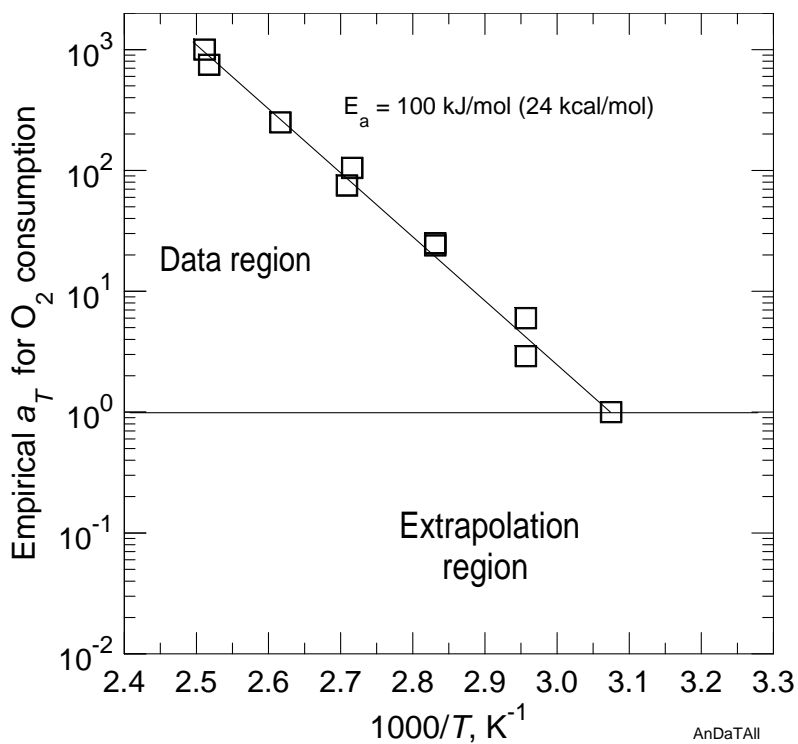
Figure 25. Arrhenius plot of the shift factors derived from the oxygen consumption results for Anaconda Durasheeth EPR.

These results highlight many of the potential pitfalls discussed earlier. If we had chosen to analyze the elongation data at 100% absolute, we might have missed the lack of superposition of the results and would have derived an E_a of ~128 kJ/mol from 140°C down to ~100°C. Since degradation in the early stages of mechanical degradation (elongation) has a much lower value of the activation energy, shorter-term oxygen consumption results or the extremely early times associated with chemi-luminescence measurements would lead to a much lower value of E_a, a value that certainly cannot be trusted for extrapolation to temperatures lower than 100°C.

The elongation results for the Eaton Dekoron Elastoset EPR [31], another material used in nuclear power plants[21], are shown in Figure 26. They follow so-called "induction-time behavior" with a very rapid drop-off in elongation occurring near the mechanical failure of the material. An Arrhenius plot of the shift factors used to superpose these data results in linear (Arrhenius) behavior with an E_a value of 106 kJ/mol. (Figure 27). Since the crystalline melting region for this material is around 110°C (Figure 15) and all of the aging data were obtained at or above this temperature, it is possible that the E_a value might change at lower temperatures. Oxygen consumption measurements would therefore be helpful.

The Arrhenius plot for the shift factors appropriate for the Okonite EPR material are shown in Figure 28 and indicate an E_a equal to 88 kJ/mol[31]. Again oxygen consumption results would be useful to determine whether this value changes at lower temperatures especially since the crystalline melting region is around 45°C (Figure 15).

Figure 26. Elongation versus aging time results for the Eaton Dekoron Elastoset EPR cable insulation at the indicated aging temperatures.

Figure 27. Arrhenius plot of the shift factors derived from the elongation results for Eaton Dekoron Elastoset EPR.
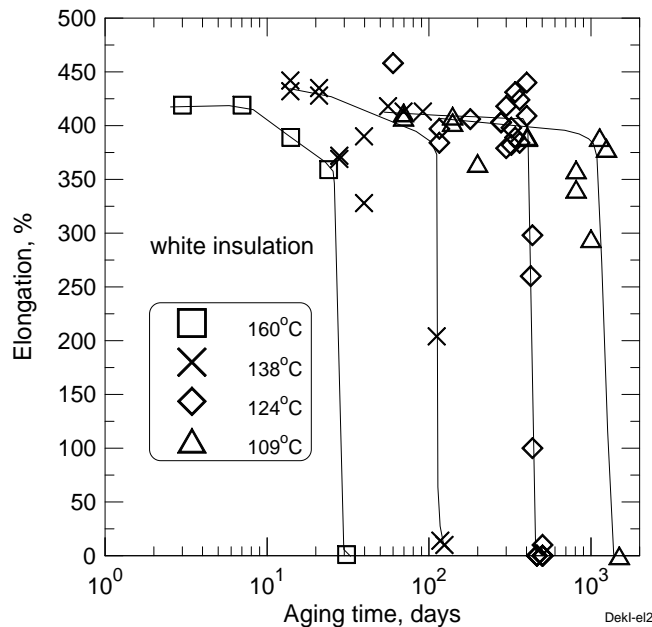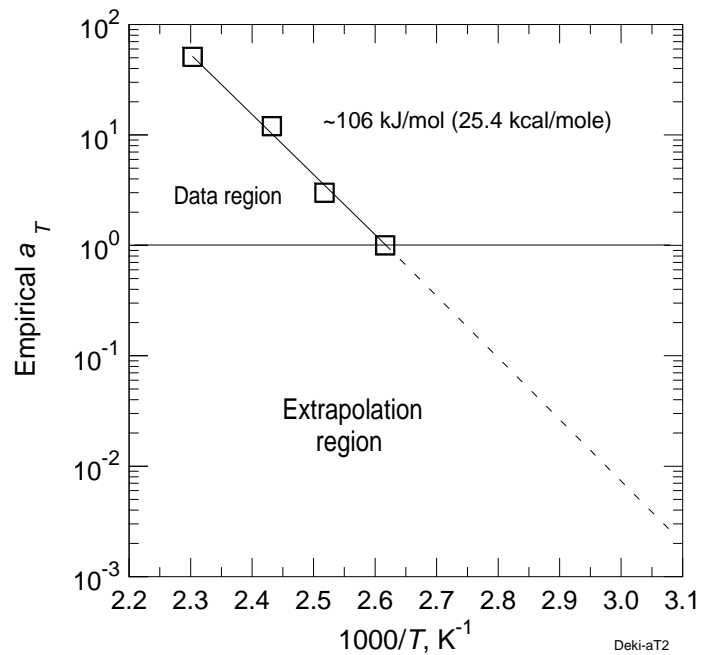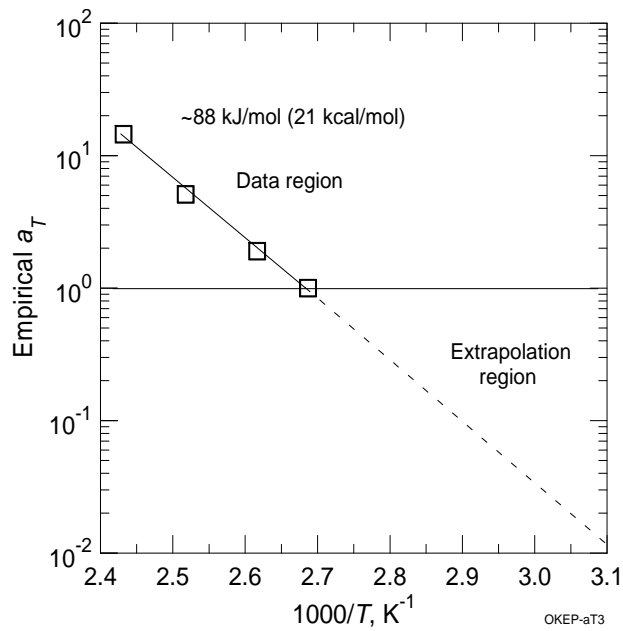

Figure 28. Arrhenius plot of the shift factors derived from the elongation results for Okonite EPR.

With the above results in mind, can we reach any conclusions with respect to typically expected lifetimes of EPR insulation materials when thermal aging dominates during their exposures in nuclear power plant environments? Because of the "induction time behavior" observed for most of these materials where the elongation drops rapidly past from typically 150% to 0%, we can concentrate on this region for analyses. With this in mind, Figure 29 shows an Arrhenius plot of the times required for elongation to drop to 50% absolute versus aging temperature for the four materials discussed above plus data on another EPR cable insulation material from work by Anandakumaran and Stonkus[40]. Although there is some spread in the results, extrapolation of the worst looking material (Anaconda Flameguard) leads to a long estimated lifetime of ~300 years at 50°C. Even though the activation energies for these materials vary from 88 kJ/mol to 128 kJ/mol (dashed line through the Anaconda Durasheeth data), it is clear that quite long lifetimes would be anticipated assuming there is not a drastic change in the activation energies below ~100°C. Careful studies using oxygen consumption techniques would be quite useful in determining whether the E_a values do change in the extrapolation region. For the Anaconda Durasheeth material that showed differing E_a values for the early part of the degradation versus the later part, consumption measurements should be done in the high temperature region out to the "induction-time" fall-off region. In other words, out to ~30 weeks at 124°C and out to ~7 weeks at 139°C. This would allow one to determine whether the oxygen consumption E_a in the later stages of degradation was consistent with the higher E_a found in the later stages of elongation degradation. If so, this would offer some confidence that the 128 kJ/mol E_a might be appropriate for extrapolating this material to lower temperatures, a possibility given the fact that no crystalline melting area exists (Figure 15). Since any attempt to use a sensitive analytical technique in the extrapolation region will by definition be accessing the early part of the degradation, such approaches are of little value for this complex material.

33
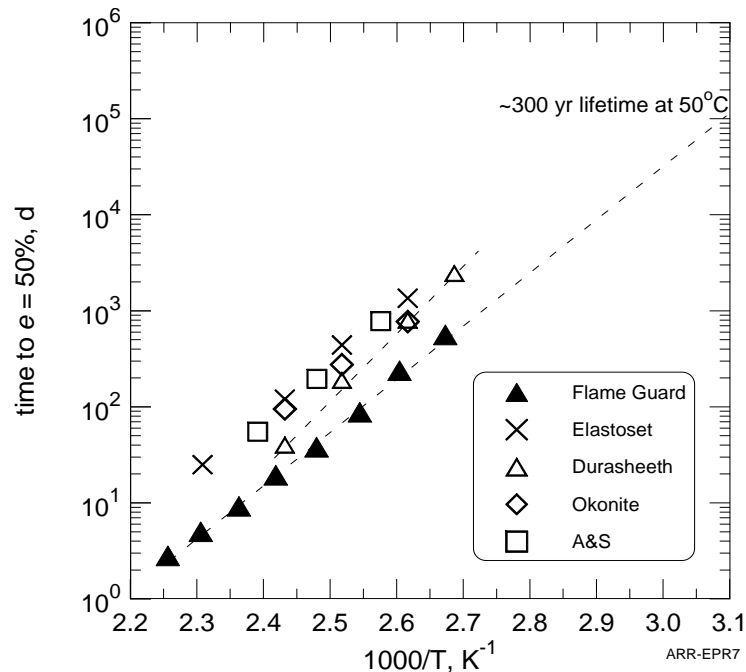
Figure 29. Arrhenius plot of the aging times required for the elongation to reach 50% versus the aging temperature for the four EPRs discussed above plus data from reference[40] denoted by A & S.

It should be noted that the recent JNES Report[12] examined several EPR materials at 100°C, 110°C and 120°C and concluded that their E_a values varied from ~84 to 110 kJ/mol in the same range as the EPR materials discussed above. In addition, their times to 50% elongation at 100°C ranged from ~200 days to 2000 days also reasonably consistent with the results shown in Figure 29. However, as mentioned earlier, they "tentatively" assumed that all of the E_a values dropped to 63 kJ/mol below 100°C.

XLPE/XLPO cable insulation materials

Similar to EPR/EPDM materials, there are countless different formulations of crosslinked polyethylene/crosslinked polyolefin (XLPE/XLPO) materials so differences in properties and aging susceptibility of various cable insulation formulations would be anticipated. We have earlier reported thermal aging results for such materials that are used as insulation in nuclear power plant safety applications[30]. Most of these materials are semi-crystalline as can be seen from the DSC scan of a Brandrex CLPO insulation shown in Figure 30. The major crystalline melting point for this material occurs at ~119°C whereas a smaller peak occurs at ~90°C. Elongation results at four aging temperatures are shown in Figure 31 and include data out to ~11 years at the lowest aging temperature of 99°C. It is clear immediately that the shapes of the curves change versus aging temperature implying a change in the chemical degradation pathway. However, if we look at the two lowest temperature aging curves (109°C and 99°C) obtained below the main melting point of 119°C, they have a similar shape and result in excellent time-temperature superposition (Figure 32).
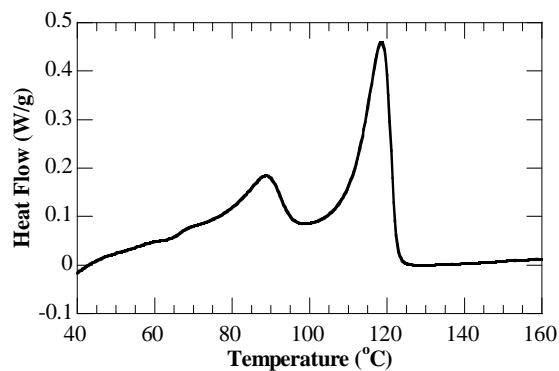
Figure 30. DSC of Brandrex CLPO cable insulation.
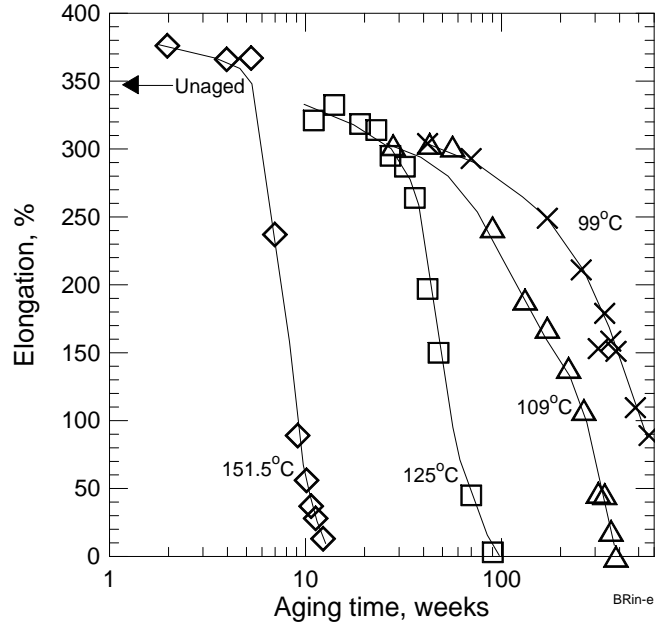
Figure 31. Elongation versus aging time at the four indicated aging temperatures for Brandrex CLPO cable insulation.

Oxygen consumption results were obtained for this material[30] from 48°C to 138°C (thereby overlapping the elongation results). After time-temperature superposing these results, the normalized shift factors obtained for oxygen consumption are plotted on Figure 33 together with the elongation shift factors from Figure 32. Linear behavior exists with an E_a of 72 kJ/mol. Since there is agreement between the two data sets in the overlap region, we feel confident that the superposed elongation data of Figure 32 can be extrapolated to lower temperature conditions. When these data are extrapolated to 50°C, the result is the time scale shown on as the upper x-axis of Figure 32. This predicts that it requires ~420 years at 50°C to reach 50% elongation as indicated by the dashed lines on the figure. Given the relatively low E_a value used for the extrapolation (72 kJ/mol), the long predicted lifetime gives confidence in the robustness of XLPO materials.
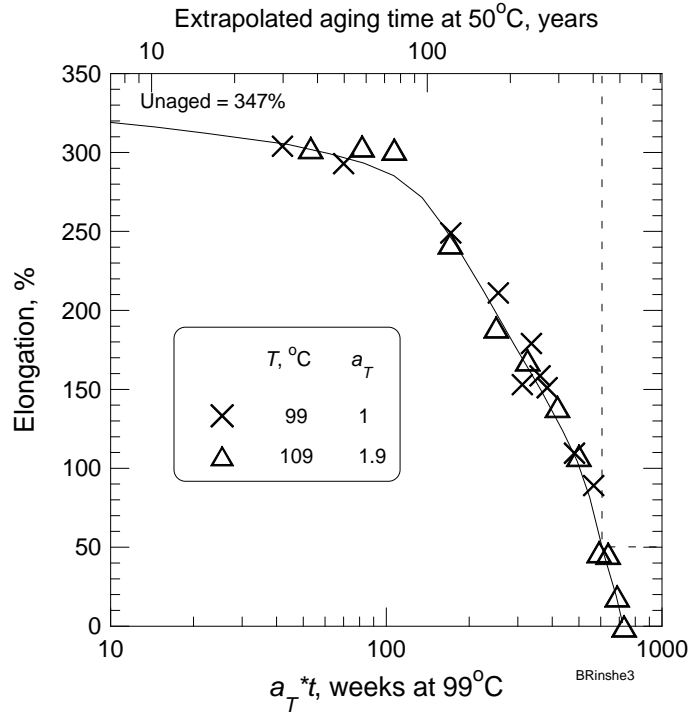
Figure 32. Time-temperature superposition of the 99°C and 109°C elongation results for Brandrex CLPO.
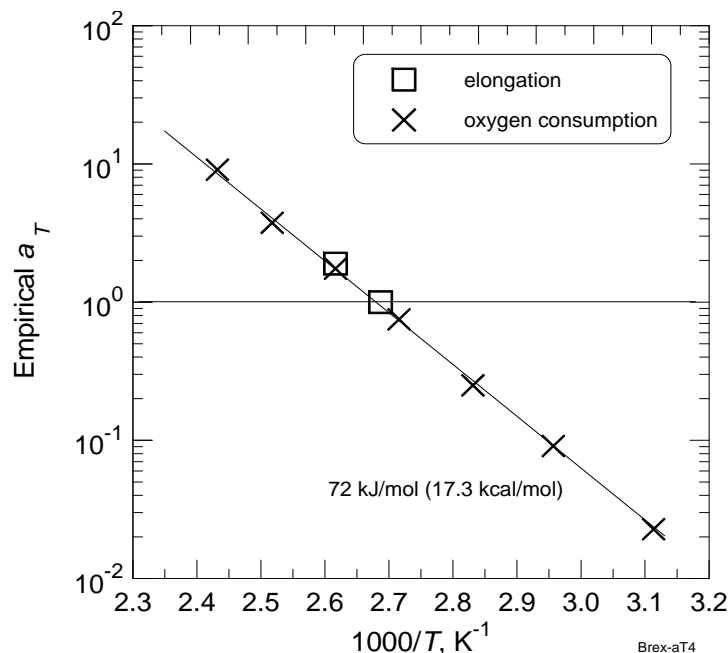
Figure 33. Arrhenius plot of the oxygen consumption shift factors[30] and the elongation shift factors from Figure 32 for the Brandrex CLPO material.

Elongation data for a second XLPO material (ITT Suprenant Exane II) at aging temperatures ranging from 170°C to 91°C is shown in Figure 34. The results have very similar shapes over a very extended temperature range. Since this material has a single crystalline melting region around 124°C, these results imply that the chemistry that controls mechanical degradation (elongation) may be similar above and below the crystalline melting point. When these results are time-temperature superposed, excellent superposition occurs as shown in Figure 35. Figure 36 shows an Arrhenius plot of the shift factors used for the superposition (these are shown on Figure 35). The plot shows extremely linear behavior with an Arrhenius E_a equal to 110 kJ/mol. Given that no evidence of chemistry changes exists (same shape of curves and same E_a values above and below 124°C), extrapolation of these results using 110 kJ/mol seems reasonable. This leads to the 50°C time scale shown as the upper x-axis on Figure 35 where again long-life is predicted. As usual, oxygen consumption experiments would probably be helpful in confirming the extrapolation E_a. It is interesting to note the large difference in the 110 kJ/mol E_a versus the much smaller 72 kJ/mol estimated for the earlier Brandrex CLPO.

The recent JNES Report[12] examined several XLPE materials at 100°C, 110°C and 120°C and concluded that their E_a values varied from ~66 to 110 kJ/mol, a range reasonably consistent with the results for our materials. In addition, their times to 50% elongation at 100°C ranged from ~400 days to ~1200 days compared to ~400 days and 3600 days for our two materials. However, as mentioned earlier, they "tentatively" assumed that all of the E_a values dropped to 63 kJ/mol below 100°C.

Figure 34. Elongation versus aging time at indicated aging temperatures ITT Suprenant Exane II XLPO cable insulation.

Figure 35. Time-temperature superposition of the elongation results from Figure 34.

Figure 36. Arrhenius plot of the shift factors shown on Figure 35.

AGING UNDER COMBINED RADIATION AND TEMPERATURE

Introduction

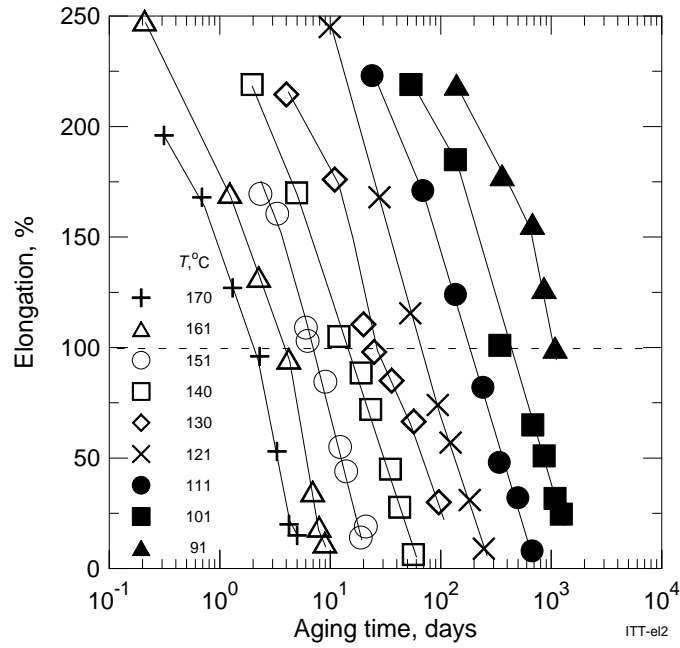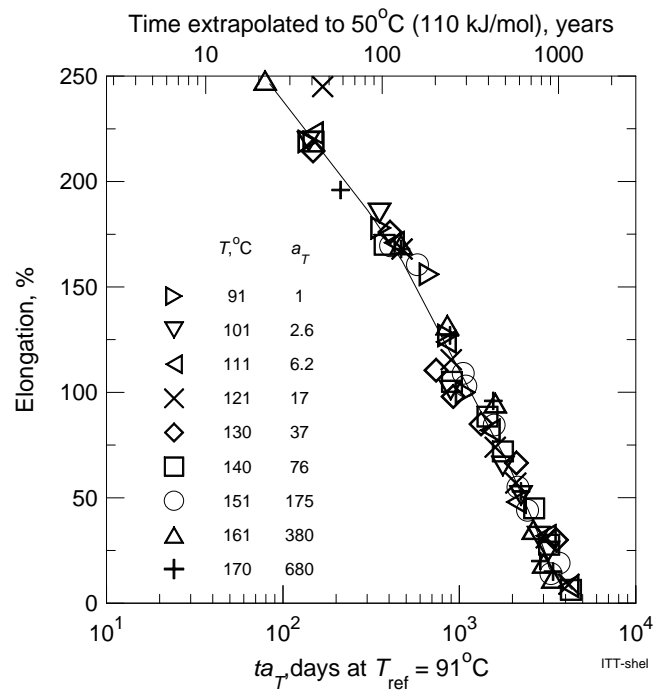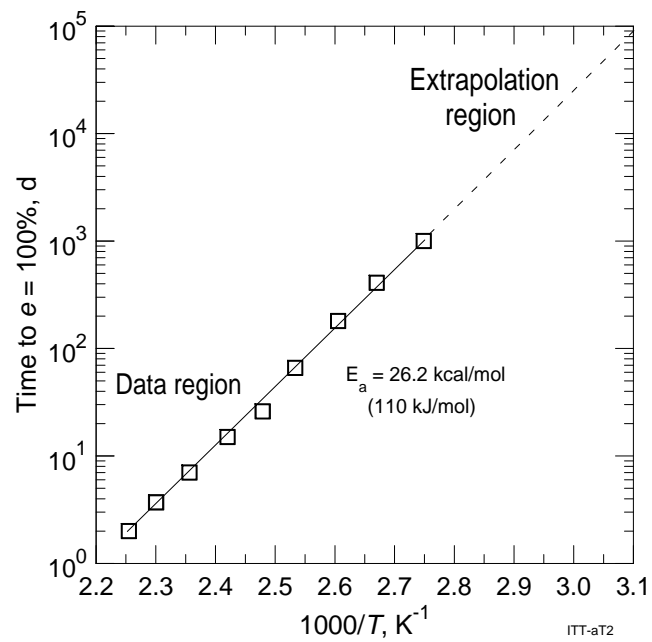During their lifetime, safety-related cables are often subjected to normal aging environments comprising a simultaneous combination of low dose rate radiation plus elevated temperature. The radiation covered in the report is gamma irradiation from Cobalt 60 sources. Based on the requirements used in the original IEEE Standards, most early qualifications simulated such combined environment aging through the use of sequential thermal aging followed by ambient temperature radiation aging[1-2]. As noted above, extremely high dose rates (often around 10 kGy/h) were typically utilized for the radiation exposures under the assumption of equal damage, equal dose. Because of the discovery of both chemical and physical (diffusion-limited oxidation) dose rate effects[8-12,14-17,19], most recent attempts at simulating radiation aging effects have been conducted at much lower dose rates. In addition, substantial evidence now exists that shows that simultaneous simulations of the combined effects of radiation plus elevated temperature is more accurate than sequential exposures and usually leads to more severe degradation[21].

With this conclusion in mind, many studies[12-13,20,30,32,36,41-45] have focused on combined environment simulations at relatively low accelerated temperatures and dose rates. In order to extrapolate such combined environment results to lower dose rates and temperatures, two extrapolation procedures have been developed and highlighted in IAEA[46] and IEC[47] documents. As noted in these documents, both approaches should be cautiously applied when analyzing data influenced by heterogeneous aging effects (e.g., DLO effects). In addition, extreme caution should be used when attempting to extrapolate results through any transition temperature region of a material.

The first approach is referred to as the superposition of time-dependent data (abbreviated from now on as the STD method). This is a totally empirical approach which takes the degradation curves at various combinations of dose rate and temperature and attempts to model the changes of these curves with temperature and dose rate using an empirical equation that has three adjustable parameters, one of which is an activation energy (often chosen to be equal to the thermal-only E_a value). Once these three parameters are determined, the equation is used to extrapolate results to any desired combination of temperature and dose rate. It should be noted, however, that there are important limitations for this empirical approach beyond the two mentioned above. As stated explicitly in both the IAEA[46] and IEC[47] documents,

"This empirical model can only be used for those materials where the shape of the damage parameter versus log (time) curve does not change with temperature and dose rate….. If the curve-shape changes, superposition of data is not possible and the method cannot be used."

Unfortunately this warning is often ignored when the STD method is utilized. For instance, the recent extensive JNES study[12] analyzes all of their combined environment

results using the STD method even though shape changes are obvious for many of their materials. The easiest way to observe these changes is to realize that combined environment data ranges from combined environments that tend to be dominated by thermal effects (highest temperature plus lowest dose rate) to those that tend to be dominated by radiation (lowest temperature plus highest dose rate). In the JNES study of EPR and XLPE cable insulations, combined environment studies were conducted at dose rates of 3 Gy/h, 18 Gy/h and 100 Gy/h in combination with 80°C, 90°C and 100°C aging temperatures. With this in mind, we can compare data reported at 3 Gy/h plus 100°C (the most thermally dominated conditions) with data reported at 100 Gy/h plus 80°C (the most radiation-dominated conditions). Two examples of such comparisons are shown in Figure 37 and Figure 38 for their EPR insulation from Company C and their FR-XLPE insulation from Company B. It is clear for both materials that a large difference in shape occurs for the two opposite regions. In fact, examination of the degradation shapes for all of the remaining combined environment conditions for these two materials shows that the shapes tend to progress towards a more gentle fall-off in properties as the temperature-dominated conditions transition to the radiation-dominated conditions. Another example of inappropriate data analysis using the STD method comes from a second Japanese paper [48]. In this paper, the author's silicone rubber data in their Figure 3.2 shows clear evidence of shape changes yet the authors analyze the data using the STD method (their Fig. 4.2).

Figure 37. The most temperature-dominated and the most radiation-dominated combined environment results for Company C EPR reported in the JNES study[12] .

The second method[13,20,30,32,41-42,46-47,49-51] for analyses of combined environment aging results is referred to as the superposition of DED (dose to equivalent damage) data which we will refer to as the DED method. This approach utilizes concepts similar to time-

temperature superposition with an added dimension (radiation) and led to predictive capabilities for combined radiation-thermal environments through a two-dimensional extrapolation procedure. This procedure is referred to as time-temperature dose-rate superposition (*t-T-DR* superposition), details of which appear in earlier publications [13,20,32]. Instead of the three adjustable empirical constants used by the STD method, the DED approach requires a single parameter, the activation energy E_a. Since this E_a must be equal to the thermal-only E_a in the thermal-dominated region, the E_a derived for thermal-only aging is normally used in the analyses implying that no adjustable parameters are utilized for this approach. In some instances, the DED model can actually be shown to be mechanistically consistent with the underlying degradation chemistry [13]. Because of the simplicity and the non-empirical nature of the DED method, we will use this method for analyses of combined radiation plus temperature results below.

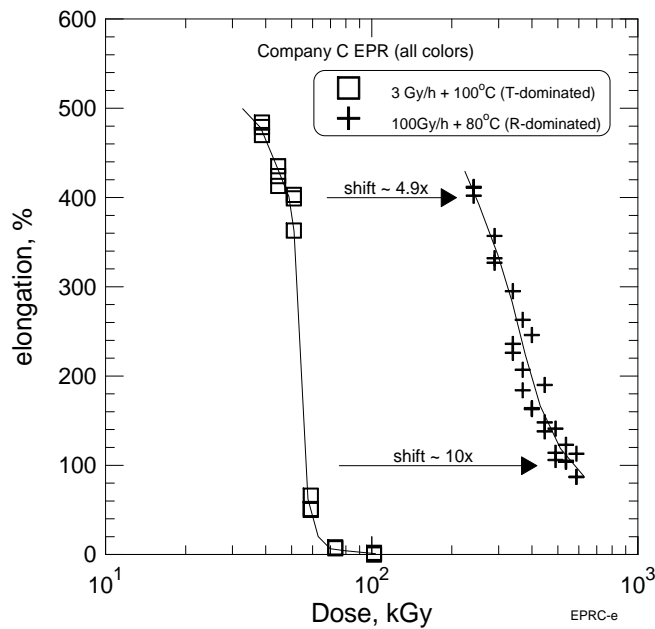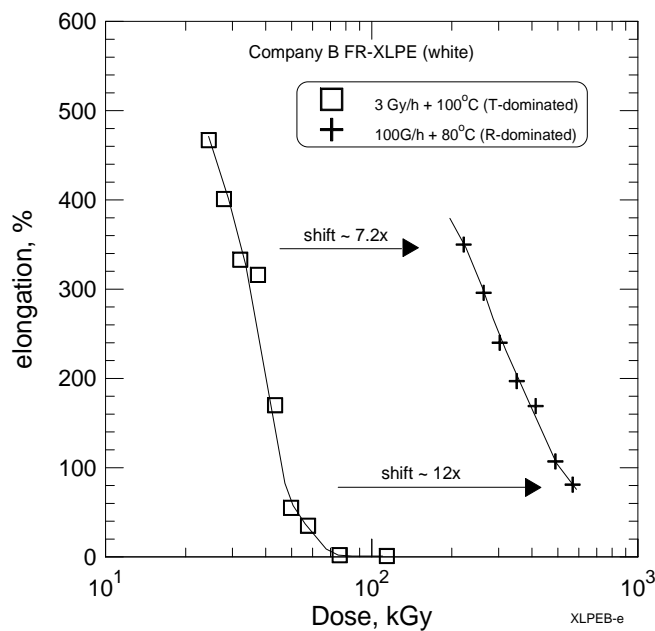
Figure 38. The most temperature-dominated and the most radiation-dominated combined environment results for Company B FR-XLPE (white color) reported in the JNES study[12].

Chloroprene (neoprene) cable jacketing materials

In general, rubbery materials such as chloroprene, CSPE and silicone rubber tend to behave reasonably well in combined radiation plus temperature environments and can be successfully analyzed using the DED approach[20,30,32,50]. Combined environment results for the Okonite neoprene cable jacket material are shown in Figure 39[32]. The data influenced by DLO effects are plotted as triangles whereas the homogeneously aged results are plotted as squares. For this material and for many other materials in oxygen-containing environments, oxidative aging leads to increases in material hardness (modulus). For materials influenced by DLO effects, the air-exposed outside surfaces

will age at the same rate as they would have in the absence of DLO effects (the interior regions will age at a slower rate). Since cracks originating at the air-exposed surfaces often propagate rapidly through the material leading to tensile failure, elongation measurements are often unaffected by DLO effects[3-4,32,52-56] Since this is the case for the Okonite neoprene material, both the homogeneous and the non-homogeneous data are analyzed using the DED method. Since we found above that the E_a values appropriate to this material were 89 kJ/mol above 70°C and 71 kJ/mol below this temperature, these values are used for the *t-T-DR* superposition procedure with the results at a temperature of 50°C shown in Figure 40. Also shown on this figure is the constant time line corresponding to 50°C thermal-only conditions. It is clear that the combined environment data superpose quite nicely and approach the 50°C line as the dose rate is lowered. This curved dashed line through the superposed combined environment data points represents the predicted doses required for the elongation to reach 50% absolute versus the aging dose rate at 50°C. Note that at 50°C, these results imply that thermal-only effects dominate radiation for dose rates below 1 Gy/h implying that thermal environments are usually of more significance for this material.
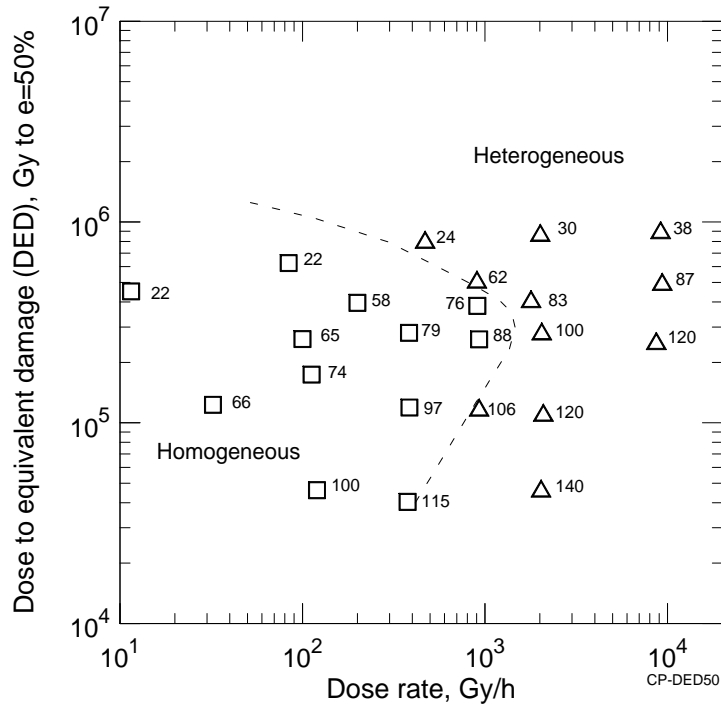
Figure 39. Combined environment results for the Okonite neoprene material where the dose to 50% absolute elongation is plotted versus dose rate and temperature in °C (numbers shown next to symbols). The homogeneously aged results are plotted as squares whereas the non-homogeneous (DLO-affected) are plotted as triangles.

In a similar fashion, the raw data can be analyzed at any other value of the remaining elongation. For instance, when the data is analyzed at 100% absolute elongation and *t-T-*

DR superposed at 50°C, we obtain the results shown in Figure 41. Although temperature aging conditions in safety-related areas of operating nuclear power plants can vary tremendously, most reactors appear to have aging temperatures in the range of 30°C to 60°C[21]. The predicted results shown in Figure 40 and Figure 41 at 50°C can be easily shifted to other temperatures from 30°C to 70°C using the E_a appropriate below 70°C (71 kJ/mol). In addition, such curves can be easily transformed to time to equivalent damage (TED) curves as seen, for example, in Figure 42. Again we see that temperature tends to dominate the degradation of Okonite neoprene.
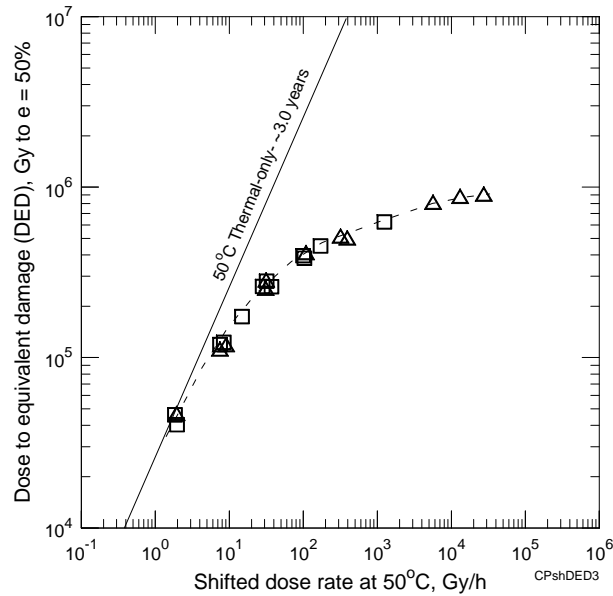
Figure 40. Time-temperature-dose-rate superposition at 50°C for the Okonite neoprene combined environment results from Figure 39.
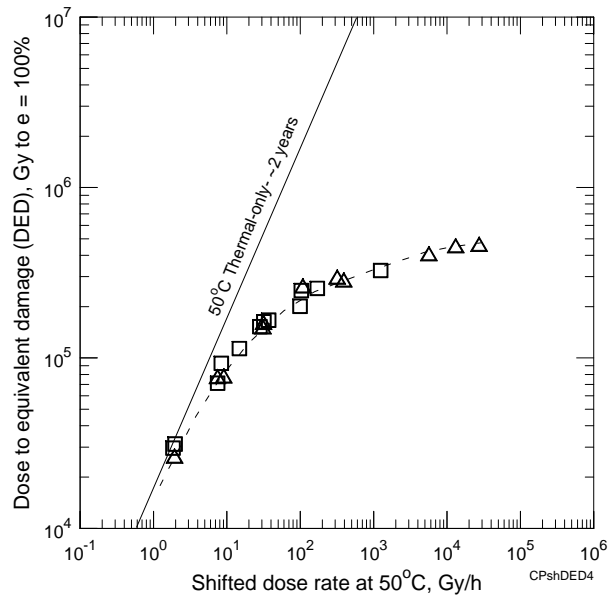
Figure 41. Time-temperature-dose-rate superposition at 50°C for the Okonite neoprene combined environment results for the time required for the elongation to drop to 100% absolute.

Figure 42. Time to equivalent damage (TED) curve that shows predictions of the time required for the elongation of Okonite neoprene to decay to 50% absolute versus aging dose rate and temperature.

As noted in the Introduction to this section of the report, the STD method cannot be applied to materials where the shape of the degradation curves change as the degradation environments change from radiation-dominated to thermal-dominated. No such problem exists for the DED approach because this ap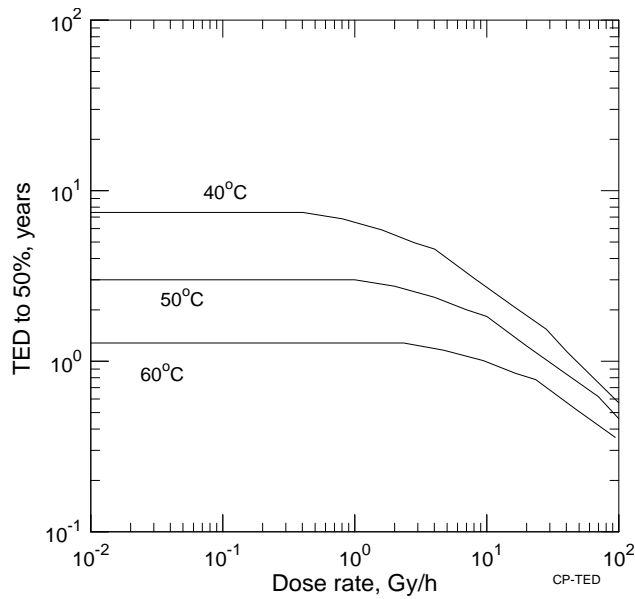proach doesn't care if the shape changes as long as the shape of degradation curves are similar for combined environment aging conditions that represent similar mixes of radiation and temperature. In other words, we would expect similar shapes for all aging conditions in the radiation-dominated region and similar shapes for all aging conditions in the thermal-dominated region even though the shapes in these two regions may be different. A similar conclusion (similar shapes) should hold for mixes between the two limits. These expectations reflect the fact that one might expect the chemistry to change as one progresses from one limit to the other. In fact, for the Okonite neoprene material discussed above, such an effect occurs. By examining Figure 39 and comparing this figure to Figure 40, we note that the three top combined environment conditions (9180 Gy/h + 38°C, 2010 Gy/h +30°C and 470 Gy/h +24°C) are in the most radiation-dominated regime whereas the three bottom combined environment conditions (120 Gy/h +100°C, 377 Gy/h +115°C and 2030 Gy/h +140°C) are in the most thermal-dominated regime. The raw experimental elongation results for these six experiments are plotted in Figure 43 where the difference in shape for the two limiting regions is obvious. Similar to the JNES results shown in Figure 37 and Figure 38, the fall-off in the radiation-dominated region is slower than that in the temperature-dominated region. If the DED approach is attempting to simulate ambient combined environment conditions in the radiation-dominated region, it is utilizing accelerated combined environment experiments focused on the radiation-dominated region so the simulated shape of the degradation curve will reflect the proper region of radiation/temperature space. In fact the observation that reasonable superposition occurs for the *t*-*T*-DR superposed DED plots offers good evidence for the assumptions underlying the DED approach.
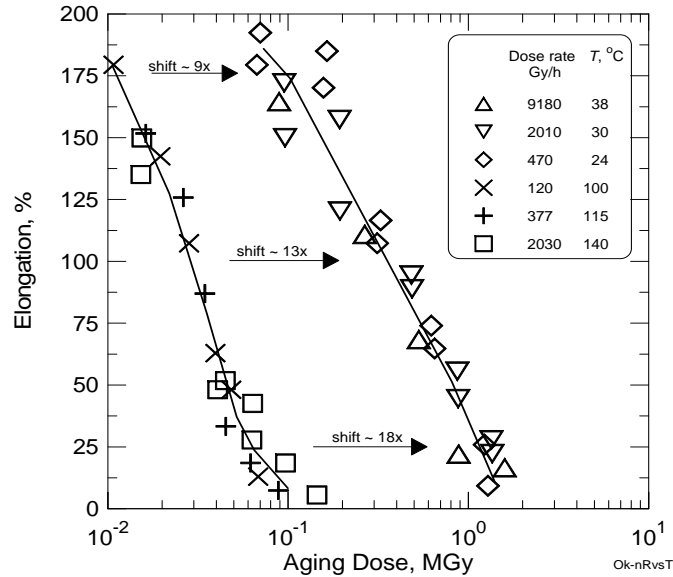
Figure 43. Elongation results for Okonite neoprene cable jacketing material under the six indicated aging conditions. The degradation shape is different for the three which are the most radiation-dominated versus the three which are the most temperature-dominated.

Combined environment data for the Rockbestos neoprene material are much more limited [30] and are shown in Figure 44. Using the 76 kJ/mol E_a value appropriate to heat aging below 80°C, we carry out *t-T-DR* superposition at 50°C with the result shown in Figure 45. Even though the data is quite limited, the fact that the shifted 70°C data point is close to the 50°C data point after shifting indicates that the use of the thermal E_a value looks like a reasonable value to use in the region where radiation effects dominate the degradation (its use in the thermally-dominated region is by definition accurate). Transforming these results to a TED plot leads to Figure 46. From the TED plot we again see for a neoprene jacketing material that thermal aging effects are likely to dominate the degradation of such materials. Comparing the TED results of the Rockbestos material (Figure 46) with those of the Okonite material (Figure 42), we again conclude that, although variations in lifetime can occur for neoprene materials, substantial degradation should be anticipated for most neoprene jackets exposed to typical power plant conditions for extended aging times.
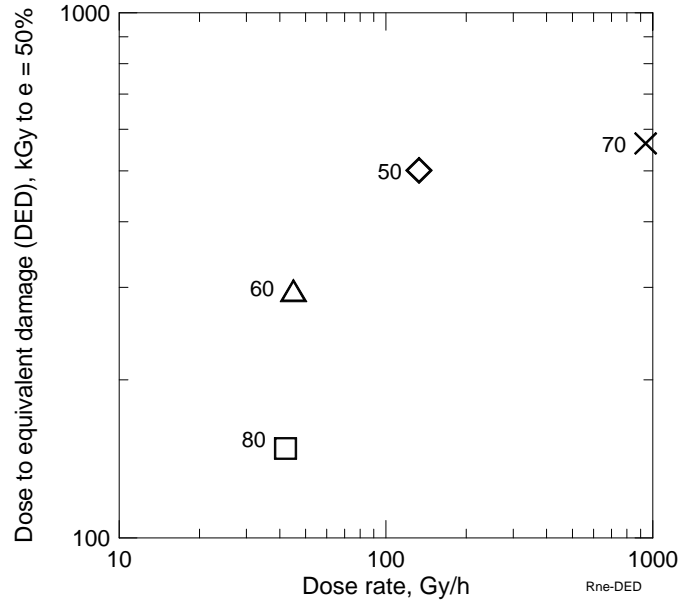
Figure 44. Combined environment results for Rockbestos neoprene where the dose to 50% absolute elongation is plotted versus dose rate and temperature in °C (numbers shown next to symbols).
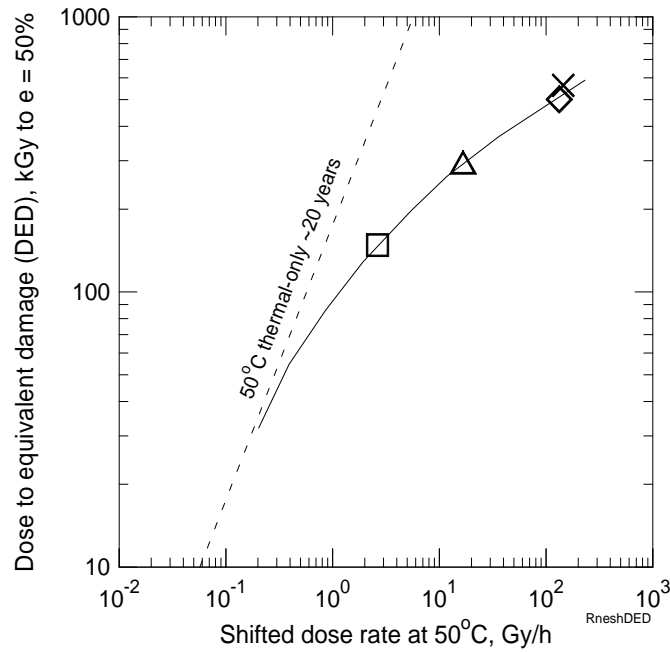
Figure 45. Time-temperature-dose-rate superposition at 50°C for the Rockbestos neoprene combined environment results from Figure 44 together with the 50°C thermal-only limiting dashed line.

Figure 46. Time to equivalent damage (TED) curve that shows predictions of the time required for the elongation of the Rockbestos neoprene to decay to 50% absolute versus aging dose rate and temperature.

CSPE (Hypalon) cable jacketing materials

Extensive combined environment aging data exists for six different CSPE cable jacketing materials[20,30,32]. We reviewed all of these data to obtain the doses required for the elongation to reach 100% and 50%. These data were then time-temperature-dose-rate superposed to 50°C using the thermal E_a values estimated on Figure 14 with the results shown in Figure 47 (dose to 100% elongation) and Figure 48 (dose to 50% elongation). For the six materials under thermal-only aging at 100°C, the times to reach 100% elongation and 50% elongation were ~230±70 days and 325±60 days, respectively. The thermal-only dashed lines at 50°C were obtained from the average values at 100°C transformed using the E_a values estimated on Figure 14. Given the fact that the time-temperature-dose-rate superposition involved results from six different CSPE materials, the observed superposition is remarkable and implies that variations in degradation rates for CSPE materials are relatively small. Since the aging dose rates in nuclear power plants are typically below ~0.3 Gy/h, Figure 47 and Figure 48 predict that radiation effects may lower the expected lifetime of CSPE jackets by up to perhaps a factor of 2 at 50°C. Transforming these two figures to TED plots leads to the results shown in Figure 49 and Figure 50. In general, it appears that CSPE jackets are superior to neoprene jackets under typically expected aging conditions. Even so, these predicted CSPE plots imply that moderate to severe degradation may result for long exposures (60-100 years) to some of the higher level aging environments expected in nuclear power plants.
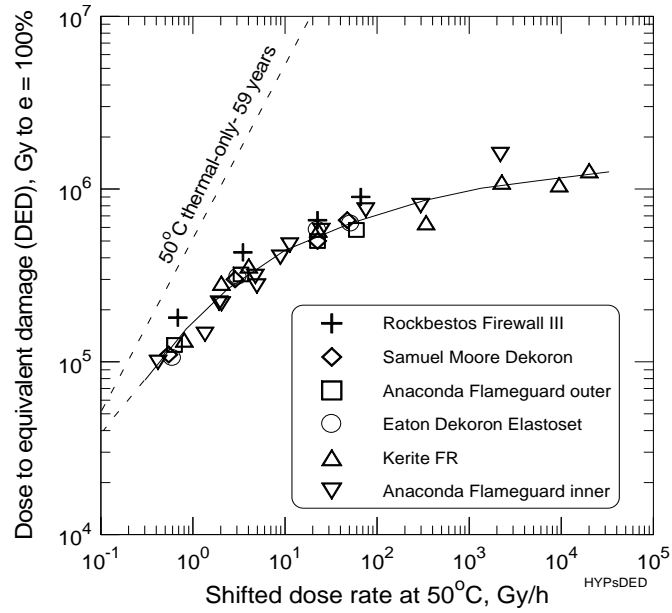
Figure 47.   Time-temperature-dose-rate superposition of the 100% elongation results to 50°C for the six CSPE cable jacketing materials together with the average 50°C thermal-only limiting line (dashed line).
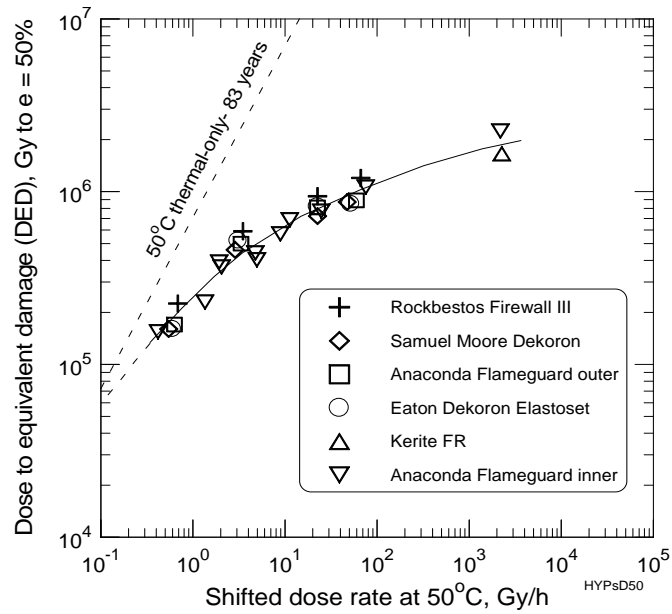
Figure 48.   Time-temperature-dose-rate superposition of the 50% elongation results to 50°C for the six CSPE cable jacketing materials together with the average 50°C thermal-only limiting line (dashed line).
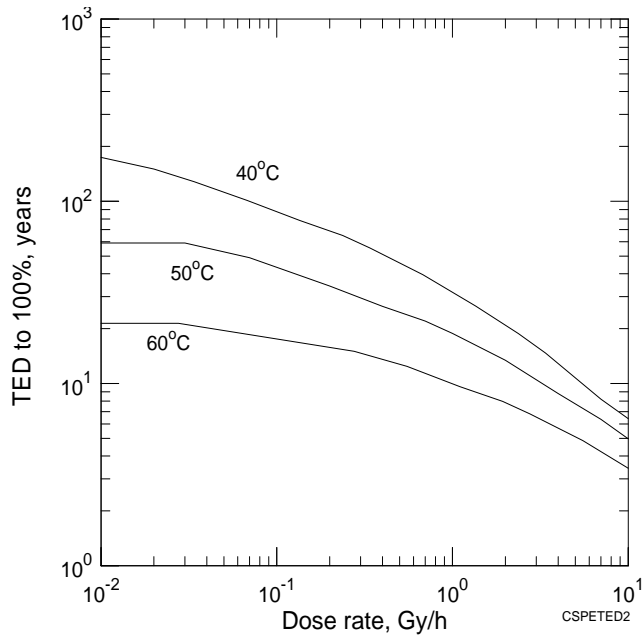
Figure 49. Time to equivalent damage (TED) curve that shows predictions of the time required for the elongation of CSPE materials to decay to 100% absolute versus aging dose rate and temperature.
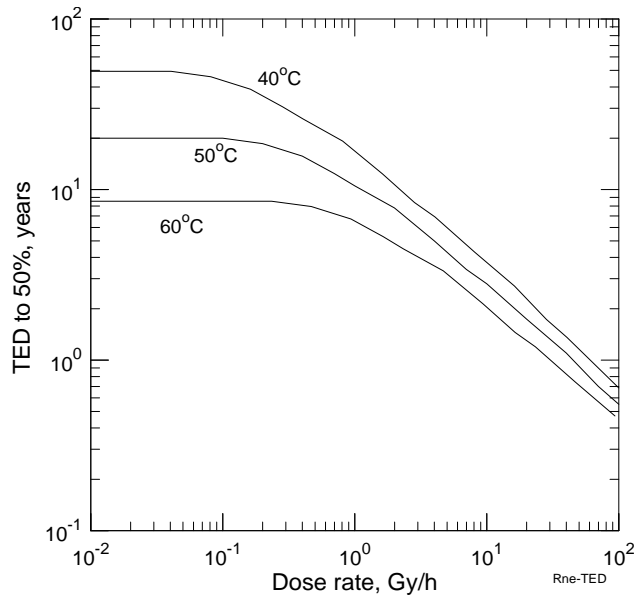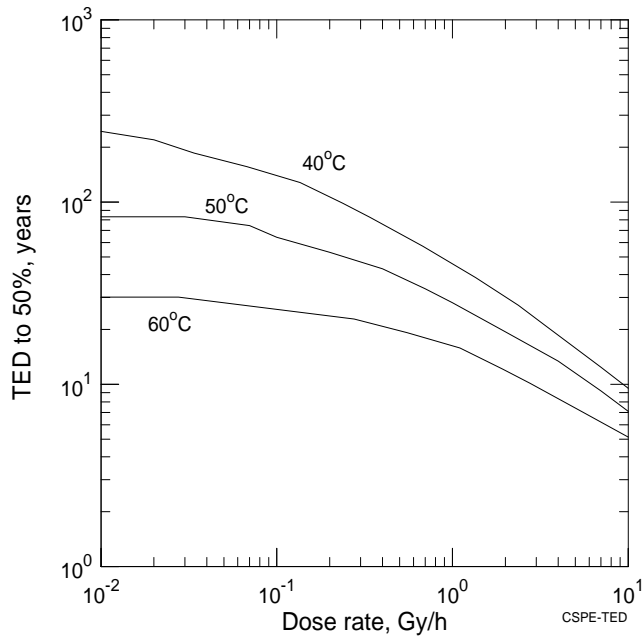

Figure 50. Time to equivalent damage (TED) curve that shows predictions of the time required for the elongation of CSPE materials to decay to 50% absolute versus aging dose rate and temperature.

EPR/EPDM cable insulation materials

In combined radiation plus temperature environments, the situation for EPR/EPDM and XLPE/XLPO materials is more complex than for neoprene and CSPE rubbers. Many EPR/EPDM and XLPE/XLPO materials have so-called "inverse temperature" effects wherein the degradation rate at a constant radiation dose rate is found to be faster at low temperatures (typically at around 60°C or below) than at more elevated aging temperatures[41-42,46,57]. Given that this anomalous behavior occurs in the temperature range that exists for nuclear power plant aging and that such behavior is in contradiction with every aging model (e.g., an increased aging rate corresponds to a decrease in temperature), this phenomenon is quite troubling. Based on our concerns after discovering these effects, we stated that "these counterintuitive effects must be understood before confident lifetime predictions for such materials can be generated"[58].

Since many of these materials have crystallinity, one might suspect that the presence of crystalline melting regions between the low temperatures where such effects enter and the higher temperatures often used in accelerated aging simulations would be a likely reason for such strange behavior. In fact, this is the primary reason that both the IAEA and IEC state that one should not use either the STD method or the DED method to extrapolate through a thermal transition of a polymer[46-47].

The first material that we will examine is the Anaconda Flameguard EPR insulation which shows little evidence of any crystalline melting (Figure 15). Combined environment results showing the dose required to reach 100% absolute elongation versus the combined environment aging conditions are given in Figure 51. Data from Sandia[51] is shown by open squares whereas room temperature (*RT*) data on EPM1 (the same material) from Reynolds[10] is shown by filled squares.
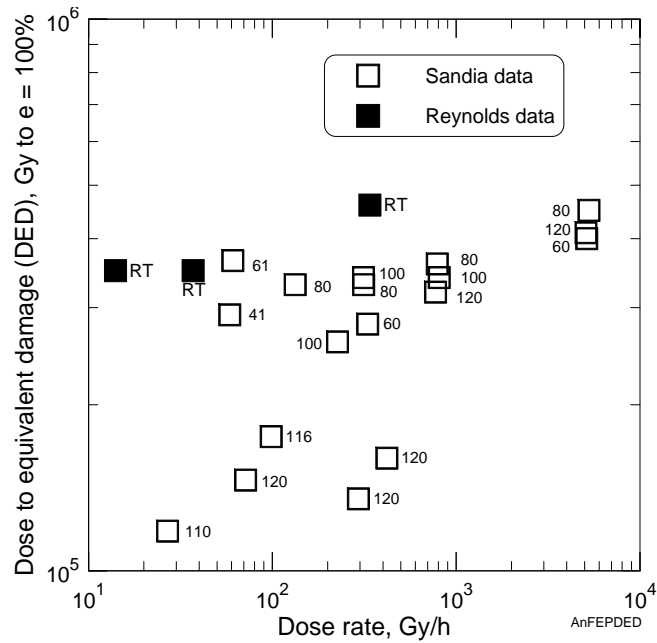
Figure 51. Combined environment results for Anaconda Flamegurd EPR cable insulation where the dose to 100% absolute elongation is plotted versus dose rate and temperature in °C (numbers shown next to symbols). Data from Sandia[51] and Reynolds[10].

Since the thermal E_a value down to 101°C was estimated to be 105 kJ/mol (Figure 27), this value of E_a was used to *t-T-DR* superpose the data from Figure 51 to 50°C. For this superposition, we assumed that *RT* for Reynolds corresponded to 23°C. The results of the superposition are given in Figure 52 and indicate 100% elongation lifetimes of ~295 years at 50°C at very low dose rates, ~140 years at 50°C plus 0.1 Gy/h and ~70 years at 50°C plus 0.3 Gy/h.
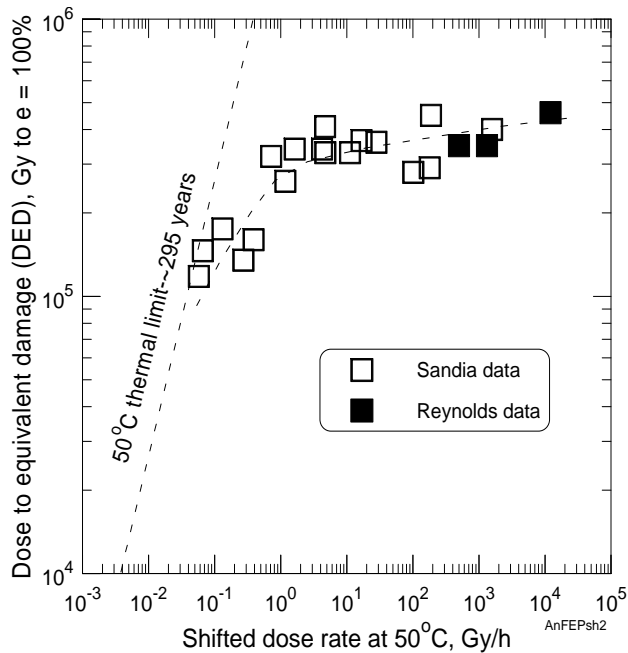
Figure 52. Time-temperature-dose-rate superposition of the 100% elongation results (Figure 51) to 50°C for the Anaconda Flameguard EPR cable insulation using an E_a of 105 kJ/mol. The 50°C thermal-only line is also shown.

As pointed out above, the lowest measured E_a value for EPR materials appears to be around 84 kJ/mol. If we assume without any evidence that the E_a value drops from 105 kJ/mol to 84 kJ/mol below 101°C and use these values to shift the data of Figure 51, the superposed results are given in Figure 53. As might be anticipated, the results of this much more conservative extrapolation results in lower estimated 100% elongation lifetimes of ~95 years at 50°C and very low dose rates, ~74 years at 50°C plus 0.1 Gy/h and ~47 years at 50°C plus 0.3 Gy/h. The assumption of a still smaller low temperature E_a value would lower these projections even further. It is again clear that low temperature oxygen consumption results would be extremely helpful in determining whether any drop in E_a actually occurs.

Figure 53. Time-temperature-dose-rate superposition of the 100% elongation results (Figure 51) to 50°C for the Anaconda Flameguard EPR cable insulation using an E_a of 105 kJ/mol above 101°C and 84 kJ/mol below this temperature. The 50°C thermal-only line is also shown.

Unlike the lack of important evidence for "inverse temperature" effects for the Anaconda Flameguard EPR, the Eaton Dekoron Elastoset EPR has unmistakable "inverse temperature" character. These effects are seen in numerous degradation parameters including elongation, density and gel content as shown (Material C) by Celina and co-workers[41]. Figure 54 shows elongation results (dose to 100%) for this material obtained at Sandia with data at 60°C and above plotted as open squares whereas data at 22°C to 41°C are plotted with filled squares. "Inverse temperature" effects are obvious for the 22°C, 40°C and 41°C data since the results for these three experiments degrade much faster than experiments at similar dose rates but at the higher temperatures of 60°C to 80°C.

DSC scans for the unaged material (Figure 15) indicate a broad melting point region starting at ~40°C with a sharp peak occurring at ~110°C. Since combined environment aging at 80°C enhances the peak from 40°C to 100°C and combined environment aging at 22°C leads to a DSC peak at ~45°C[41], time-temperature-dose-rate extrapolation of the elongation results (Figure 54) to nuclear power plant conditions (e.g., to 50°C) will involve the non-recommended[46-47] extrapolation through the crystalline melting point region. When the data are extrapolated to 50°C using time-temperature-dose-rate superposition with an E_a of 106 kJ/mol (Figure 27), the resulting DED plot (Figure 55) shows the problem that occurs for "inverse temperature" data. If only high temperature (60°C and above) data were obtained, the DED plot would appear to offer a viable

prediction tool under nuclear power plant aging conditions. However, the low temperature results show that such predictions are worthless since power plant aging temperatures are typically below 60°C. Clearly we must focus our attention on the lower temperature region for semi-crystalline materials that show "inverse temperature" behavior.

Figure 54. Combined environment results for Eaton Dekoron Elastoset EPR cable insulation where the dose to 100% absolute elongation is plotted versus dose rate and temperature in °C (numbers shown next to symbols)
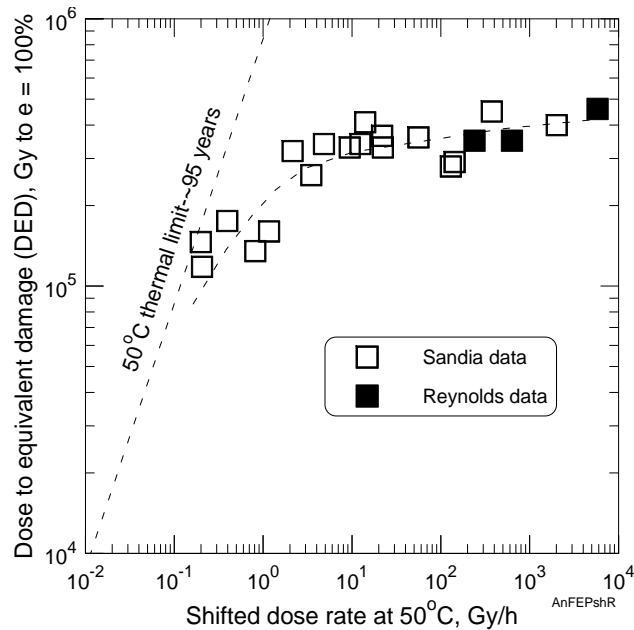
Figure 55. Time-temperature-dose-rate superposition of the 100% elongation results (Figure 54) to 50°C for the Eaton Dekoron Elastoset EPR cable insulation using an E_a of 106 kJ/mol.

XLPE/XLPO cable insulation materials

Virtually every XLPE/XLPO material has a crystalline melting point region. Most have major peaks that range from ~85°C to 130°C with additional melting and broad peaks extending down to 40°C to 50°C as evidenced by typical results for such materials[51]. Thus we might anticipate that many of these materials will exhibit "inverse temperature" effects and that is in fact the case. The first documented instance of "inverse temperature" effects occurred for the Brandrex CLPO material and these effects have been discussed in detail in previous publications[41-42]. Figure 56 shows elongation results (dose to 100%) for this material with data at 60°C and above plotted as open squares whereas data at 22°C to 41°C are plotted with filled squares. "Inverse temperature" effects are obvious for the 22°C and 41°C data since the results for these experiments degrade much faster than experiments at similar dose rates but the higher temperatures of 60°C and higher. DSC scans for the unaged material (Figure 30) indicate a broad peak centered around 90°C and a major peak centered near 120°C. Therefore *t-T-DR* extrapolation of the elongation results (Figure 56) to nuclear power plant conditions (e.g., to 50°C) will involve the non-recommended[46-47] extrapolation through the crystalline melting point region. When the data are extrapolated to 50°C using *t-T-DR* superposition with an E_a of 72 kJ/mol (Figure 33), the resulting DED plot (Figure 57) again shows the problem that occurs for "inverse temperature" data. If only high temperature (60°C and above) data were obtained, the DED plot would appear to offer a viable prediction tool under nuclear power plant aging conditions. However, the low temperature results show that such predictions are worthless since power plant aging temperatures are typically

below 60°C. Again we need to focus our attention on the lower temperature region for semi-crystalline materials that show "inverse temperature" behavior.
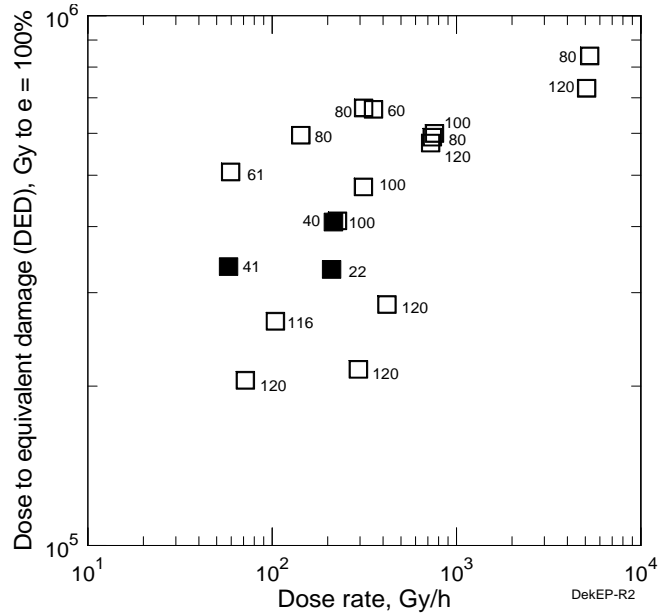

Figure 56. Combined environment results for Brandrex CLPO cable insulation where the dose to 100% absolute elongation is plotted versus dose rate and temperature in °C (numbers shown next to symbols)
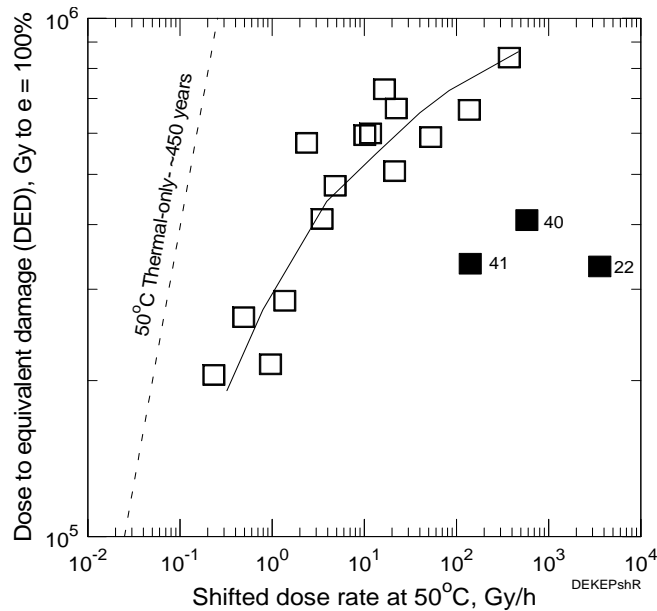

Figure 57. Time-temperature-dose-rate superposition of the 100% elongation results (Figure 56) to 50°C for the Brandrex CLPO cable insulation using an E_a of 72 kJ/mol.

A second example of "inverse temperature" behavior for a CLPO material comes from more limited elongation data for the ITT Suprenant Exane II material described earlier; results showing the dose to 100% elongation versus dose rate and temperature are given in Figure 58[51]. Again it is clear that "inverse temperature" effects are operative at 22°C and 66°C. DSC results for this material show a major melting peak centered around 120°C plus a minor peak at around 50°C[51]. As noted in the thermal aging section above, the changes in elongation with temperature (shapes of curves and the E_a value) were unaffected by passing through the major melting peak at 120°C (thermal aging was done from 91°C up to 170°C). However the results shown in Figure 58 clearly indicate that this is not the case for combined environments at least for temperatures below 70°C. This perhaps suggests that non-Arrhenius thermal aging behavior may enter for temperatures below those probed in the thermal aging experiments. Again this underscores the importance of attempting to obtain oxygen consumption data for this material assuming oxidation dominates the degradation. If we tentatively use the 110 kJ/mol E_a derived from the thermal aging data (Figure 36) to t-T-DR superpose the results from Figure 58 on a DED plot at 50°C, we obtain the results shown in Figure 59. As is clear from the observation that "inverse temperature" effects exist, the DED plot is largely meaningless for temperatures of interest to nuclear power plant aging environments. Again it is important to note that this observation would be absent in the absence of combined environment experiments at low aging temperatures.
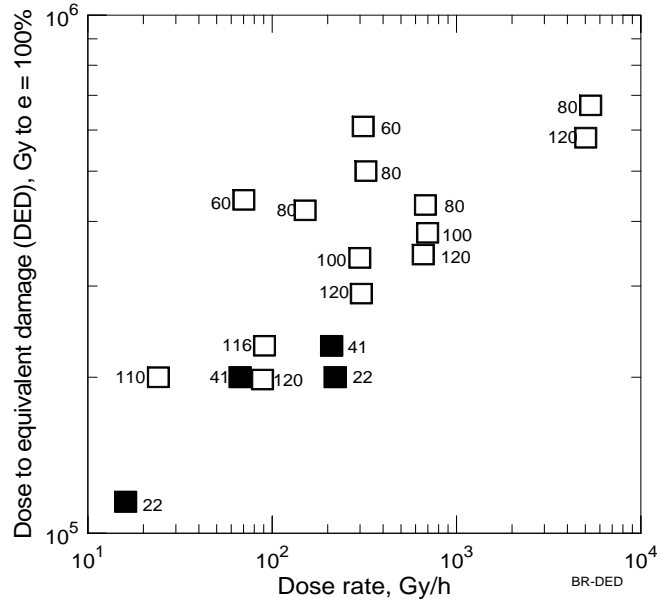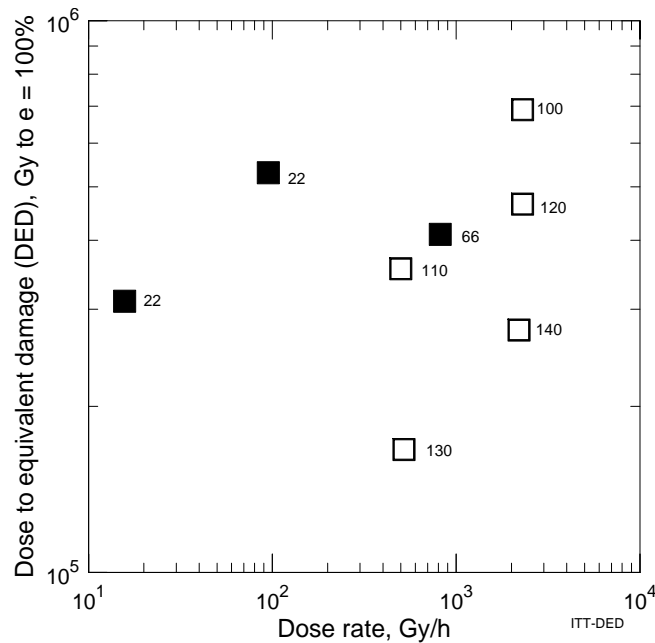

Figure 58. Combined environment results for ITT Suprenant Exane II CLPO cable insulation where the dose to 100% absolute elongation is plotted versus dose rate and temperature in °C.
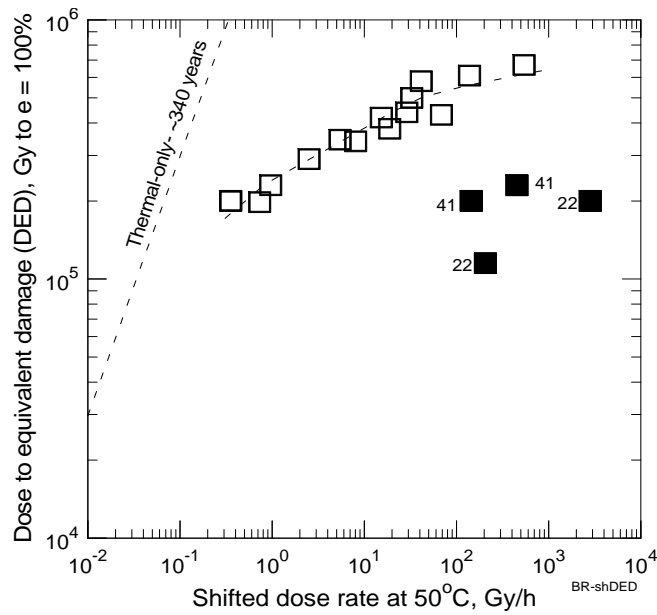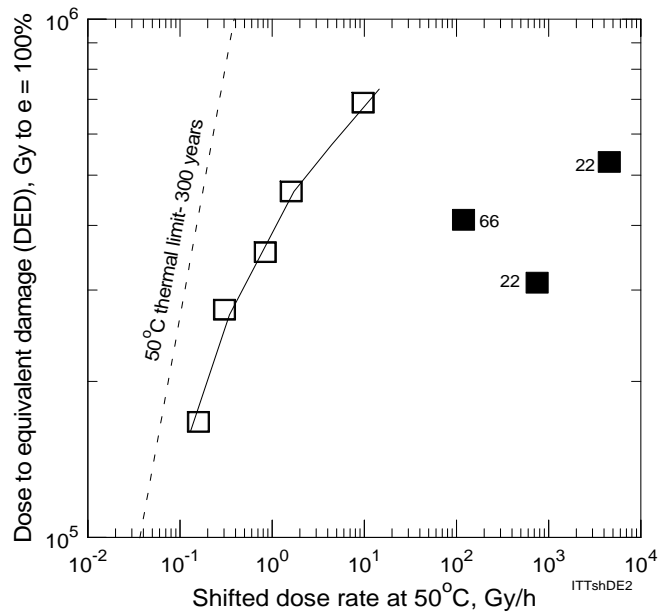
Figure 59. Time-temperature-dose-rate superposition of the 100% elongation results (Figure 58) to 50°C for the ITT Suprenant Exane II CLPO cable insulation using an E_a of 110 kJ/mol.

Comments on "Inverse Temperature" effects

In the previous two sections on EPR/EPDM and XLPO/XLPE materials, we have shown that "inverse temperature" effects apply to many of these materials. Since these effects seem to occur at combined environment temperatures (22°C to ~60°C) that are in the range seen during aging in actual long-term nuclear power plant environments, they need to be addressed and/or understood in order to make lifetime predictions for such materials. In addition, it is clear from the results shown above that combined environment data taken at higher temperatures will not typically offer any evidence that "inverse temperature" effects might exist at lower temperatures. This is an extremely critical observation for studies attempting to model combined environment aging of EPR/EPDM and XLPO/XLPE materials. In other words, one should conduct some combined environment exposures versus dose rate at one or two temperatures between ~22°C to ~60°C in order to determine the possible presence of "inverse temperature" behavior. Unfortunately this is not always done. For instance, in the recently published extensive JNES Report[12], the authors studied five XLPE materials and 4 EPR materials under nine combined environment conditions comprising temperatures of 80°C, 90°C and 100°C in combination with dose rates of 3, 18 and 100 Gy/h. Since no combined environment experiments were conducted at temperatures below 80°C, the results shown above would strongly argue that any "inverse temperature" effects would go undiscovered. Therefore the DED analyses used in the JNES Report to make predictions

and to later choose aging conditions equivalent to specific plant aging scenarios should not be trusted.

Buslik and co-authors recently published a report[50] applying a reliability physics model to the DED approach using Sandia's extensive polymer aging data. For the materials that showed "inverse temperature" behavior they eliminated the anomalous data points from the analyses. Again we would argue that these anomalous data are perhaps the only data of utility when one is confronted with nuclear power plant aging conditions.

So how can we deal with the "inverse temperature" region of most interest to power plant aging conditions. The first thing to notice is, that contrary to expectations, the presence of "inverse temperature" effects implies degradation rates that are much faster than one might expect. For instance, if we were planning aging experiments for the Brandrex CLPO material at a dose rate of 25 Gy/h and we had the results at 110°C shown on Figure 56 (~1 year needed to reach 100% elongation), we would expect lower temperature experiments at 25 Gy/h to take much longer than 1 year to reach 100% so we would never consider an experiment in the low temperature range. Although this assumption would be true for experiments at 90°C and 70°C, when "inverse temperature" effects enter, the times at low temperatures would be reasonable as seen on the figure for the 22°C data point. Therefore, "inverse temperature" effects allow us to access relatively low dose rates at the temperatures where these effects are operative. Thus a viable approach might be obtaining combined environment data at low temperatures (e.g., 22°C to 50°C) versus dose rate. Since these data would be taken at the temperatures of interest to nuclear power plant aging, extrapolations of the temperature would be unnecessary implying that the dose rate data might be able to be directly extrapolated to lower dose rates. This approach can be visualized by plotting the "inverse temperature" results obtained above for the three EPR and XLPO materials; these results are shown on Figure 60. Obtaining results such as these allow extrapolations like those shown by the dashed constant temperature lines, resulting in 100% elongation predictions at lower dose rates. For instance, at 0.1 Gy/h, the extrapolations predict that the times required to reach 100% elongation range from 46 to 114 years. More careful and extensive experiments at low temperatures and dose rates coupled with better knowledge of actual in-plant environmental aging conditions would allow more confident predictions.
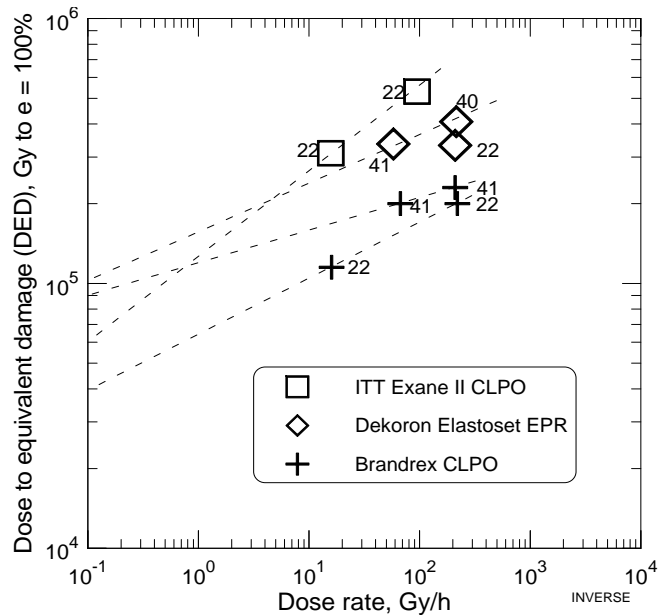
Figure 60. Dose required to reach 100% elongation for the low temperature ("inverse temperature") combined environment experiments of the three indicated materials.

Comments on JNES Procedure for Setting up Accelerated Aging Test Conditions

On page 228f of the JNES Report[12], they outline an approach for setting up accelerated aging test conditions based on the superposition of DED data. We have already detailed two problems we see with this approach especially for EPR/EPDM and XLPO/XLPE materials. The first has to do with their choice of "tentative" 15 kcal/mol values for the thermal E_a below 100°C, a value that is used to *t-T-DR* shift their combined environment results in order to make predictions under aging temperatures and dose rates of relevance to nuclear power plants. The second problem, the likelihood of "inverse temperature" effects for these materials was discussed in great deal in the previous section. The first issue can be corrected by obtaining more reliable estimates of E_a values in the low temperature region. The second issue (possible "inverse temperature" effects) will not enter for materials such as neoprene, hypalon and silicone rubbers and may not be important for some EPR/EPDM and XLPO/XLPE materials. So in principal the JNES approach could be applied in certain instances. Unfortunately, however, there is another potential issue with this approach. The JNES author's approach is to first choose plant aging conditions (e.g., 49°C, 0.1 Gy/h, 60 years in their Fig. 3.3-32) and then use the *t-T-DR* shifting procedure of the DED approach (with E_a chosen to be 15 kcal/mol) to find equivalent aging conditions at 100°C of 21,194 hours at 2.47 Gy/h. According to the logic underlying the DED approach, this would represent a reasonable attempt to accelerate ambient conditions since these accelerated conditions represent an acceleration of 24.7 times in the thermally induced pathway, 24.7 times in the radiation dose-rate

(radiation initiation) and 24.7 times compression in the aging time. However, the JNES procedure then goes through a number of complex iterative steps involving data that must have already been generated at 80, 90 and 100°C in combination with dose rates of 3, 18 and 100 Gy/h to eventually obtain the accelerated aging conditions of 100°C, 100 Gy/h for 2982 hours. This means that the accelerated aging conditions have moved substantially towards a radiation-dominated situation, wherein the accelerated conditions represent an acceleration of 24.7 times in the thermally induced pathway, 1000 times in the radiation dose-rate (radiation initiation) and 176 times compression in the aging time. Such a mix of accelerations certainly leads to less confidence in the simulations. In fact, we saw earlier (Figure 37 and Figure 38) the differences in material response that can occur as one transitions from thermal dominated to radiation dominated chemistry.

Suppose that we use the JNES example used in their Fig. 3.3-32 where plant aging conditions are again 49°C, 0.1 Gy/h, 60 years and assume a more realistic E_a value of 20 kcal/mol. A simple use of the *t-T-DR* shifting procedure of the DED approach leads to the following equivalent conditions at 100°C (7351 hour at 7.15 Gy/h). These conditions represent an acceleration of all three components (thermal, radiation and time) by a factor of 71.5 times. At 110°C, the DED equivalent conditions would be 3635 hour at 14.5 Gy/h, an acceleration of all three components by a factor 145. Note that this simple approach to selecting acceleration conditions does not require the existence of combined radiation plus temperature data and does not require complex iterative calculations.

WEAR-OUT APPROACH

The Wear-out method has been applied to nuclear power plant cable materials[30,59-61] and is based on cumulative damage concepts[62-64]. When applied to thermal aging, it takes materials that have previously aged for a given time under low temperature or ambient aging conditions (T_a) and completes the aging of the material at a higher temperature referred to as the Wear-out temperature (T_w). When the chemistry underlying the degradation is identical at the two temperatures (the overall rate will of course be faster at T_w), a linear relationship is predicted between the time spent at T_a and the time required to reach a certain degree of degradation at T_w. If changes in chemistry occur between the two temperatures, a non-linear relationship will occur. By monitoring the relationship between the times spent at T_a and the time required at T_w to reach a given degradation level (e.g., to a specified "failure" criterion) and extrapolating this relationship to 0 time at T_w, it is often possible to predict the remaining lifetime of the material at T_a.

This approach is ideal for materials that have so-called "induction-time" behavior where the changes in the degradation variable being followed are relatively slow until abrupt changes occur just before failure. Induction-time behavior is commonly observed for EPR materials (e.g., Anaconda Flameguard EPR in Figure 16, Eaton Dekoron Elastoset EPR in Figure 26) as well as some XLPO and PVC materials[12]. If condition monitoring techniques are used to follow field-aged samples versus aging time in the field, anticipating failure for induction-time materials can be difficult since the property being

monitored may not change much until just before failure. Use of the Wear-out approach in such instances can lead to much more confident predictions of remaining life.

It is often noted that for ambient induced degradation in containment, the degradation of the jacket (CSPE or neoprene) is always found to precede that of the EPR/EPDM or XLPE/XLPO insulation. This implies that CM techniques looking at the jacket will give warning when to replace the cable long before degradation of the insulation becomes a concern. However it is likely that all such CSPE field results to date reflect cables exposed to relatively high temperatures coupled with low dose rates (see Figure 50 where 50% elongation requires ~30 years at 60°C plus low dose rates). Our concern is at lower temperatures where potential "inverse temperature" effects could lead to a faster decay for the insulations than for their surrounding CSPE jackets. For instance, at 0.1 Gy/h + 40°C, Figure 49 implies that a CSPE jacket will take ~90 years to reach 100% elongation whereas Figure 60 implies an EPR/EPDM or XLPO/XLPE insulation influenced by "inverse temperature" effects can reach 100% elongation in a similar time period. At 0.6 Gy/h plus 40°C, Figure 49 implies that a CSPE jacket will take ~40 years to reach 100% elongation whereas Figure 60 implies the insulations could reach 100% after around 25-30 years. For dose rates in this same range coupled with temperatures even lower than 40°C, the degradation of the CSPE jacket will be even slower (Figure 49) whereas the degradation rate of the insulation may increase (Figure 60). Thus a CM technique focused solely on the jacket may not always be appropriate. This example again shows the critical importance of determining (1) actual plant environmental aging conditions and (2) the potential importance of "inverse temperature" effects.

As an example of the Wear-out approach, we show in Figure 61 density data versus aging time at 148°C for Eaton Dekoron Elastoset EPR samples that had previously aged at 109°C for times up to ~three years. If we first concentrate on the samples that saw no pre-aging at 109°C (filled circles), we see that following density versus aging time at 148°C leads to very small changes until around 50 days followed by a rapid increase in density. The rapid increase corresponds to "induction-time" behavior where mechanical failure (elongation plummets to zero) quickly occurs. If we simply used density as a condition monitoring approach for aging at 148°C, the results versus aging time would give no warning of failure. If on the other hand, we used the Wear-out approach, the situation becomes much more promising. By taking the pre-aged samples at 109°C and following their density changes at the Wear-out temperature of 148°C, we can select a "failure" criterion based on the place where the density begins to rapidly increase (the dashed line at 1.32 g/cc is chosen in the present case). We then construct a Wear-out plot of the time at 109°C versus the subsequent time at 148°C to reach 1.32 g/cc (Figure 62). The plot is reasonably linear and predicts a 1240 day life at 109°C consistent with the elongation result of Figure 26.

Figure 61. Density results versus aging time at 148°C for white Eaton Dekoron Elastoset EPR samples that were pre-aged at 109°C for the times indicated.

Figure 62. Wear-out plot using data from Figure 61.

This observed linearity allows us to use this fact to make predictions for samples aging at 99°C where elongation failure has not yet occurred. The Wear-out density results are

shown in Figure 63 and the Wear-out plot is shown in Figure 64. Assuming linear behavior for the Wear-out plot, the extrapolated failure prediction at 99°C is ~2570 days.
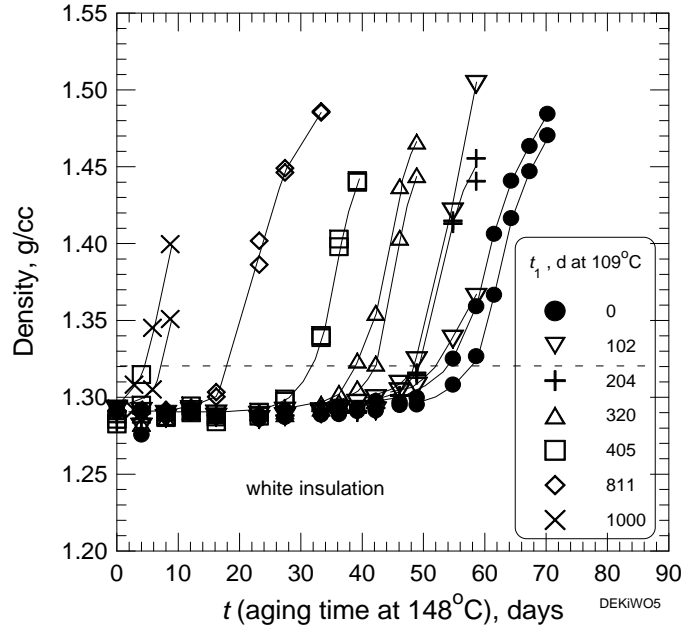

Figure 63. Density results versus aging time at 148°C for white Eaton Dekoron Elastoset EPR samples that were pre-aged at 99°C for the times indicated.
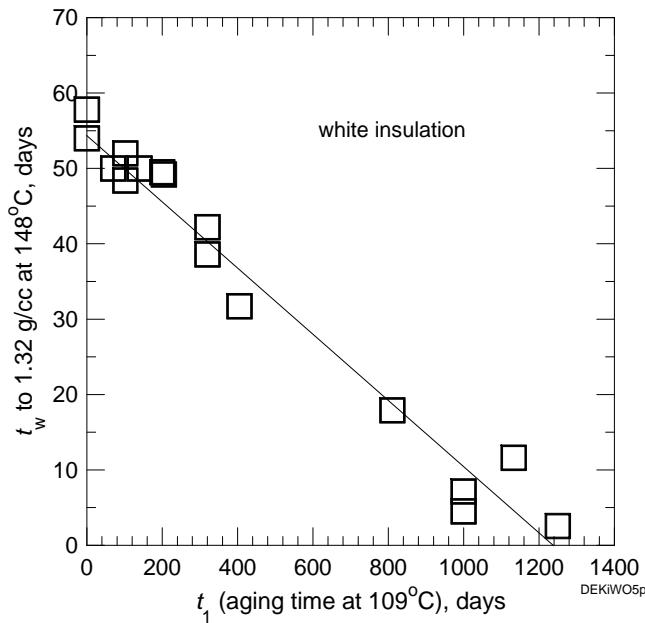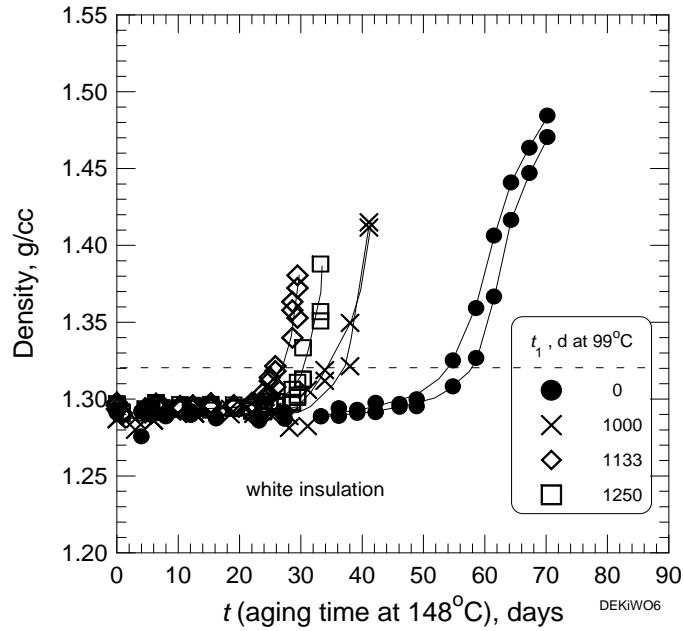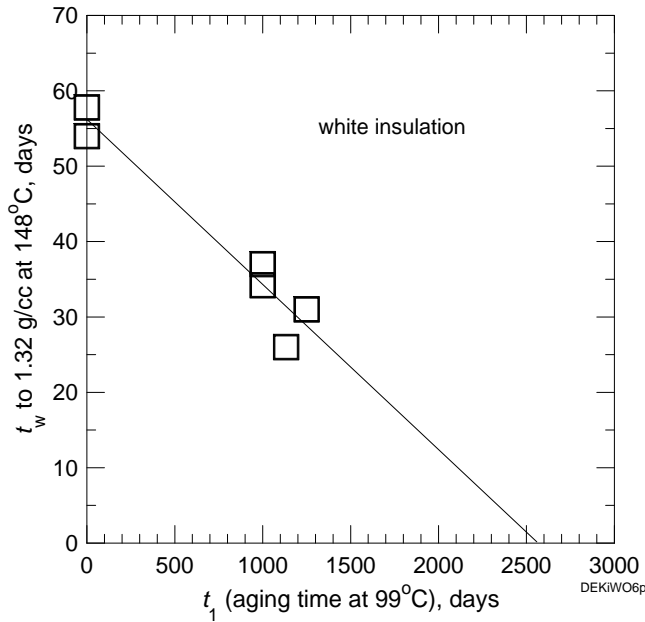

Figure 64. Wear-out plot using data from Figure 63.

The above illustrates the potential utility of the Wear-out approach for predicting the remaining life of materials even in the difficult situation when "induction-time" behavior means that many condition monitoring approaches may fail to anticipate an abrupt failure of the material. Thus a potential recommendation would be that attempts should be made to periodically obtain samples from materials that are aging under nuclear power plant conditions so that these materials can be followed using Wear-out approaches. Insulation samples are most readily available at cable terminations since cable jackets are stripped back at such locations. Oftentimes one might expect some of the worst aging environments at such locations so these regions might be ideal.

However, as seen in Figure 61 and Figure 63, many measurements must be made to obtain a Wear-out plot. Therefore degradation parameters requiring large samples (e.g., elongation) or other destructive techniques could not be accommodated by the relatively small samples that would be typically available at cable terminations. This is where density measurements excel since measurements on very small samples are viable and such measurements can be made non-destructively since the same sample can be aged at T_w, then have its density measured non-destructively, then aged some more, then have its density measured again, etc. Thus only one small sample is required for every aging time at T_a. Finally, as pointed out by Buslik and co-workers[50], Wear-out techniques can also be applied to more complex aging scenarios where the ambient aging scenario incorporates a combination of temperature and radiation. One approach is to match Wear-out combined environment conditions to ambient combined environment conditions using the DED simulation model.

COMMENTS ON LOCA SIMULATIONS

Although the discussion of Loss of Coolant Accident (LOCA) simulations goes beyond the main purpose of this report, a few general comments on important issues are necessary. One important issue concerns the connection between the amount of degradation from aging and the likelihood that that the aged material will survive a LOCA. Over the years, many workers have tentatively concluded that a material with 50% absolute elongation remaining after aging will survive a LOCA simulation[60,65-66] and this observation is noted in the IAEA document[46]. However, recent work from Japan shows that this is not always the case. For instance, one report finds that 50% remaining elongation is sufficient for an ethylene propylene (EP) material and a heat-resistant PVC (HRPVC) material but 60% elongation is needed by a fire retardant EPR (FREPR) material and 150% is required for a silicone rubber material[67]. The recent JNES report[12] shows that many materials with elongation values above 50% after aging fail the subsequent LOCA. Jacobus found, on the other hand, that many materials with 0% elongation after aging passed a subsequent LOCA[43-45]. Such diverse and seemingly contradictory conclusions can be rationalized because of many factors. First of all, there are differences in LOCA procedures used in various countries as noted in Appendix A of a Brookhaven document[68] and these differences as well as differing approaches to aging simulations can have profound effects on the LOCA testing results. In addition, results

can vary dependent on whether the LOCA contains a controlled oxygen overpressure or not. The testing criteria for passage of LOCA also vary among researchers and countries.

Although attempts to correlate the remaining elongation with the viability of a material when exposed to a simulated LOCA should continue, we feel there has not been enough concentration on determining some of the critical parameters needed for a superior LOCA simulation. For example, we believe that one of the most important issues in simulating a LOCA is the amount of oxygen available during the LOCA[69]. Unfortunately only a small percentage of LOCA simulations concern themselves with this issue, a notable exception being work done in France[36]. A recent example of ignoring the possible effects of oxygen during LOCA comes from the 2009 JNES Report[12] where the authors state on p.52

"Since the forced air injection was not considered to agree with the actual conditions in LOCA, it was decided not to use forced air injection."

Although it is true that forced air injection does not occur during a real LOCA, the issue concerns whether oxygen trapped inside containment during a real LOCA has an important effect on the material responses. During a simulated LOCA, the ratio of the air volume to the material volume is undoubtedly much smaller than the ratio operative in a real plant during a LOCA event. Therefore the possibility exists that the oxygen that is trapped during a simulated LOCA will be used up much quicker than the oxygen trapped during a real LOCA, potentially slowing down the degradation rate for the simulated event.

SUGGESTED POSSIBLE RESEARCH AREAS

Based on the current review it is possible to now briefly list some areas of research that would have a significant impact on helping nuclear power plants gain confidence in the viability of their cable materials if plant life is extended beyond 60 years.

The first important area of research involves deriving better knowledge of the actual in-containment aging environments seen in operating nuclear plants. Such information would be extremely useful for determining the relative importance of thermal aging versus radiation effects and, therefore, how much research must be devoted to such things as "inverse temperature" effects.

From a thermal aging point of view, deriving better estimates of E_a values at temperatures below those accessible to elongation measurements need to be derived. Analyses of time dependent results at various temperatures must be done using the *t-T* superposition approach to confirm constancy of the chemical pathways underlying degradation. For materials whose aging conditions can be shown to be dominated by oxidation, oxygen consumption measurements will often allow estimates to be made of E_a at temperatures below those accessible to elongation measurements. However, such measurements (or any other sensitive approach) must be confirmed to be intimately related to the decrease in mechanical properties. In addition, such measurements must be

conducted at several higher temperatures that overlap the temperatures used for the elongation measurements to confirm that their E_a values agree with the elongation E_a values in the overlap region.

Samples of materials from actual nuclear power plants should be periodically obtained and examined using condition monitoring techniques. For materials that show "induction time" behavior (slow changes in degradation parameter until a rapid decrease near the failure point), many condition monitoring approaches may not give any warning of imminent failure. For these and other materials, the Wear-out approach should be applied since it has a better chance of predicting failure. Since only small samples may be available from operating plants, an ideal Wear-out parameter may be the measurement of density. Density measurements require extremely small samples and are non-destructive so the same sample can be used for the repeated density versus Wear-out aging time measurements needed to generate the Wear-out aging data.

For ambient aging situations where both radiation and temperature enter, accelerated combined environment data needs to be generated and analyzed using the DED modeling approach. For materials likely to have "inverse temperature" effects (e.g., EPR/EPDM and XLPO/XLPE), combined environment experiments must be conducted at temperatures in the range of actual interest to nuclear power plant aging conditions (~22°C to 50°C). If these experiments indicate "inverse temperature" effects, dose rate dependency at these temperatures should be carried out so extrapolations to nuclear power plant conditions are possible.

Consideration should be given to examining the possible effects of the oxygen concentration during LOCA simulations. This would involve trying to estimate what sort of oxygen concentrations would be present during an actual LOCA and whether the oxygen concentration during a simulated LOCA does a reasonable job of matching these concentrations.

Another area of concern not reviewed in the current document has to do with the discovery that sections of safety-related cables are often found to be submerged in water for long periods of time[70]. Medium voltage cables in wet environments are known to degrade and eventually fail in various ways including by the development of water trees. For this reason, a recent NRC/DOE Workshop[71] recommends that future research be considered looking into the aging effects of very long-term wetting for both low and medium voltage safety related cables with the goal of developing an accurate aging model.

In addition, there are other possible areas of research that could have a large impact on predictions of cable lifetimes. For instance, we have conducted a very preliminary back-of-the-envelope analysis that led to the surprising conclusion that the aging degradation rate of cable insulations could be $^1/_6$ to ½ the rate predicted from careful accelerated aging simulations. If true, condition monitoring of insulation material removed from operating plants and/or careful accelerated simulations could be used to confirm this conclusion. The analysis suggests the possibility of a simple approach to slowing down

the cable degradation rate plus the likely places where cable degradation might proceed at the quickest rate.

CONCLUSIONS

A summary of some of the important conclusions and recommendations from this report follows:

1. The first important area of research involves deriving better knowledge of the actual in-containment aging environments seen in operating nuclear plants. Such information would be extremely useful for determining the relative importance of thermal aging versus radiation effects and, therefore, how much research must be devoted to such things as "inverse temperature" effects.
2. For analyzing thermal aging data, time-temperature superposition (similar shapes for degradation curves at all temperatures when data is plotted versus log of the aging time) should always be used to assure that the underlying chemical degradation is not changing as the temperature changes.
3. In looking for non-Arrhenius behavior for thermal aging data, the greatest confidence in any conclusions comes through the use of "direct" evidence which entails obtaining evidence directly from data on the primary degradation parameter of interest.
4. When "direct" evidence is unavailable, "indirect" evidence should be obtained from a sensitive secondary degradation parameter that 1) can be shown to be intimately related to the primary degradation parameter and 2) can be shown to have the same E_a value at aging temperatures that overlap those of the primary degradation parameter.
5. Oxygen consumption results could be helpful for determining whether the E_a values of important materials (neoprene, CSPE, EPR/EPDM, XLPE/XLPO) drop below the regions accessible to elongation measurements.
6. The DED approach is the superior approach for analyzing and extrapolating accelerated combined environment (radiation plus temperature) experiments.
7. For EPR/EPDM and XLPO/XLPE materials, the possible presence of inverse temperature effects must be looked for by carrying out some combined environment simulations at aging temperatures in the 22°C to 50°C range.
8. If inverse temperature effects occur, combined environment experiments versus dose rate at one or two constant temperatures in the range between 22°C and 50°C should be considered as the only viable predictive approach.
9. When "inverse temperature" effects are absent, we outlined what we consider to be the best approach for simulating combined environment aging conditions. This involves the use of the principals underlying the DED approach wherein *t-T-DR* shifts are carried out using verified E_a values such that the acceleration of the thermal pathway, the acceleration of the radiation initiation and the time compression factor are the same.
10. The Wear-out approach is highly recommended for estimating remaining lifetimes of materials that are easily accessible in nuclear plants (e.g., at cable

terminations). It is extremely advantageous for materials that show "induction-time" behavior since many condition monitoring approaches would give little warning of imminent failure for such materials.   The use of a Wear-out degradation parameter that is non-destructive and requires small pieces of sample (e.g., density) is clearly advantageous.

11. To apply the Wear-out approach, it would be highly desirable to try and acquire small pieces of cable materials with known aging histories from operating plants.

12. For LOCA simulations, the importance of the oxygen concentration in the atmosphere during the actual LOCA and during the simulation should be considered.

ACKNOWLEDGMENTS

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