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subject: Aging Assessment of Service Cables

1. Introduction

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

Today, the U.S. has several nuclear power plants operating on extended licenses. Recent polling data obtained from the utilities indicate that the key concerns were cables and piping [2,3]. As such, SNL is collaborating with colleagues in other Department of Energy and Department of Commerce laboratories, U.S. Nuclear Regulatory Commission, industry, and partners abroad as part of a multi-prong approach to clearly identify 1) what work has been done in the past to investigate cable degradation, 2) what are the relevant cable aging conditions (temperature, humidity, dose/dose rates), and 3) what experiments are highest on the priority list required to model and therefore estimate the remaining lifetimes of existing cables. As of FY13, the primary focus of SNL's effort has shifted to a more applied approach aimed at improving the accelerated aging predictive models by validating existing models with field returned materials. The timing of such validations depends strongly on when plants are being decommissioned (e.g., Zion Nuclear Power Station) and collaborative efforts and support of the utilities, vendors, research institutions, and the nuclear regulators.

2. Experimental

2.1 Materials

Cables from three different sources were obtained between FY12 and FY13: 1) the High Flux Isotope Reactor at Oak Ridge National Laboratory (HFIR at ORNL), 2) Comision Nacional de Energia Atomica (CNEA in Argentina), and 3) the Zion Nuclear Power Station.

2.1.1 Cables from HFIR at ORNL

SNL received ~50 ft of varying colored low voltage (one conductor, 1.3 mm thick insulation, 900 Type THW 600 V) Anaconda Densheath cables that are ~45 years old. Conversations with HFIR personnel indicated that the approximate environmental conditions which the cables were exposed to were estimated to be ~27 °C with ~70% RH (no gamma irradiation exposure).

2.1.2 Cable from CNEA

SNL received a 1.5 m section of a silicon rubber cable (both jacket and low voltage insulations are the same material type, 4.3 mm and 0.6 mm thick, respectively) which has 34 insulated conductors and is ~30 years old; the cable manufacturer is not readily apparent. This particular cable was stored at ambient conditions; however, these cables are analogous to service cables which are exposed to both gamma radiation and elevated temperatures.

2.1.3 Cable from Zion Nuclear Power Station

We received ~0.4 m of a 480 V black cable (Okonite EPR, bonded jacket insulation—the outer and inner thicknesses were measured to be 1.5 mm and 1.1 mm, respectively) that is ~40 years in age. Unfortunately, we do not know the environmental conditions which the cable was exposed to, other than that it was part of a circuit which resulted in a power failure due to water diffusing through the jacket, i.e. the cable was in a submerged environment.

2.2 Accelerated Aging

All HFIR cable insulations are being subjected to thermal-oxidative aging environments in air circulating ovens at temperatures ranging between 40 ± 2 °C to 138 ± 2 °C; to date, specimens have been aging for up to ~200 days. Specimens are being removed from the aging ovens at varying points in time (from each oven) for thermal, chemical, and mechanical analysis.

Cable specimens from CNEA were aged in a combined simultaneous environment of approximately 39 Gy/hr at 100 °C (total accumulated dose ~140 kGy or 14 Mrad). Specimens were removed from the low intensity cobalt array facility (LICA) at varying points in time for thermal, chemical, and mechanical analysis.

2.3 Tensile Testing

Cable insulation specimens for tensile testing were carefully stripped from their metal conductor prior to aging. All laboratory aged insulation specimens were aged as tubes, and were measured to be ~150 mm in length. The field returned EPR jacketing received from the Zion Nuclear Power station was cut into strips, measured to be ~150 mm long by 6 mm wide by ~2 mm thick. Tensile testing (5.1 cm initial jaw separation, 12.7 cm/min strain rate) was performed on an Instron 5564 series equipped with pneumatic grips and extensometer clips that enabled direct ultimate tensile elongation values to be obtained. All tensile measurements were performed in triplicate for samples aged at each time period, affording statistical analyses; control specimens were periodically tensile tested to confirm no variation occurred during the long-term aging study.

2.4 Gel Content and Solvent Uptake Analysis

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

2.5 Density

Archimedes principle is being employed to make macroscopic density measurements. In short, cable specimens (~50 to 200 mg) are weighed in air and then in isopropanol on a microbalance. Density calibrations are performed using glass calibration balls of known density.

3. Results and Discussion

3.1 Cables from the HFIR, ORNL

As part of our technical goals, SNL has proposed to not only generate new relevant accelerated aging data, but also to validate existing models to enhance the veracity of these predictions and make refinements where appropriate and reasonably possible. As such, SNL has taken on the task (with the help of others supporting the LWRS program) to obtain materials from existing and decommissioning NPPs.

In the FY12, cables were obtained from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL, Oak Ridge, TN). The cables received were exposed to only elevated temperatures (i.e., no radiation). The cables from HFIR are being subjected to further artificial aging in hot dry ovens ranging from 40 °C up to 138 °C; this process is an ongoing effort.

3.1.1 Tensile Elongation

Figure 1 shows tensile elongation data obtained for Anaconda Densheath cables. The as received tensile strength for cables returned from HFIR was measured to be approximately 240% elongation at break. An accepted point of reference for significant materials degradation has been established to be 50% ultimate tensile elongation [1], clearly the HFIR cables are above this threshold.

Comparison of historical models is required to 1) validate (or disprove) existing models and 2) gain a better understanding as to how much life remains for service cables. SNL previously studied Anaconda Durasheath EPR cable insulations [4] and determined activation energy to be 101 kJ/mol by using the Arrhenius equation. The cables returned from HFIR are still being aged, so data cannot be "freely superposed"; however, to make an aging assessment, the previously determined activation energy for Anaconda Durasheath EPR was used to superpose data measured for the Anaconda Densheath EPR cables. Figure 2 shows the superposed tensile data for the cables returned from HFIR. Albeit, more data should be collected for a more valid assessment, particularly at the lower temperatures, the overall shape of the curve does not change with temperature and suggests that the superposition is realistic at this present time. Future data will continue to validate (or disprove) these claims.

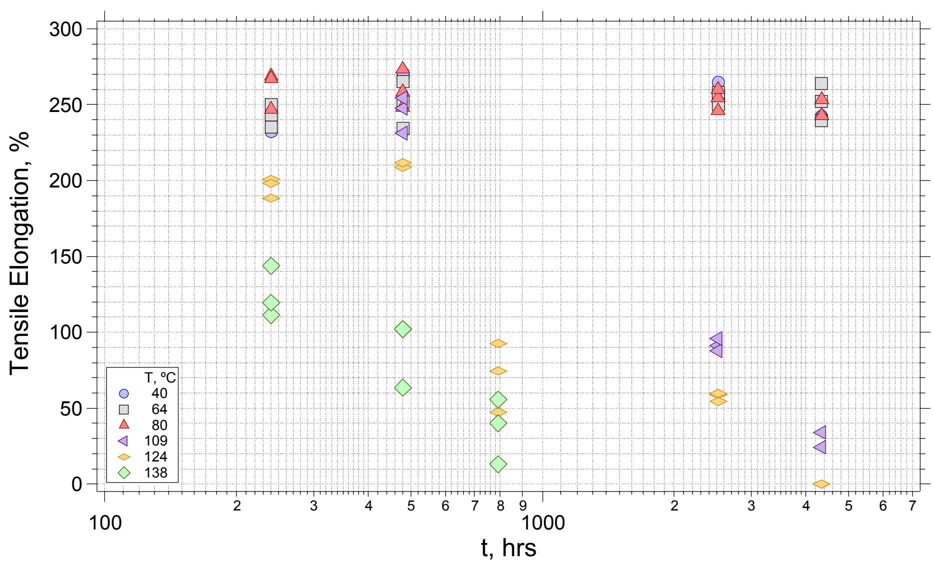

Fig. 1 - Ultimate tensile elongation data for Anaconda *Densheath* EPR cables returned from HFIR at ORNL (~45 yrs of age, T_{avg} ~27 °C, RH ~70%) which were further aged at varying temperatures.

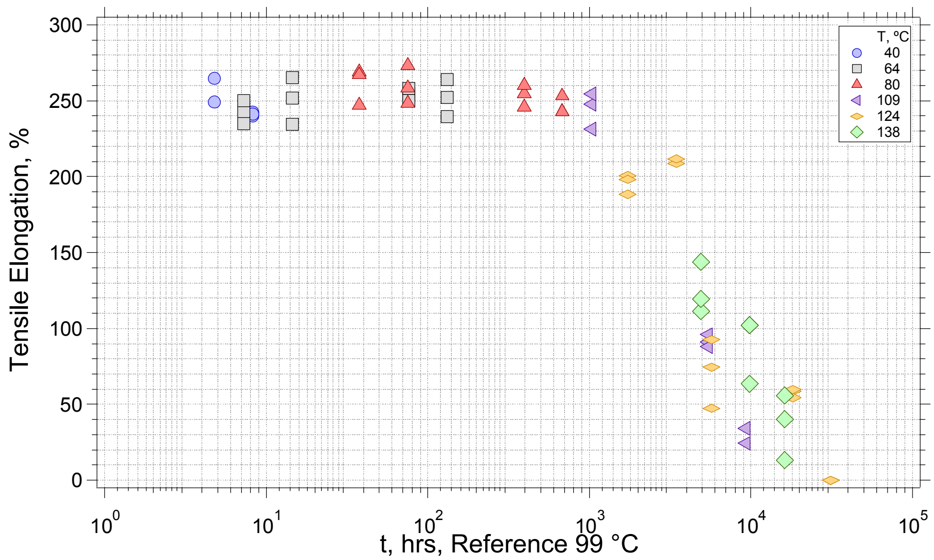

Fig. 2 - Ultimate tensile elongation data for Anaconda *Densheath* EPR cables returned from HFIR at ORNL (~45 yrs of age, T_{avg} ~27 °C, RH ~70%) which were further aged at varying temperatures and superposed by employing an activation energy of 101 kJ/mol as previously determined for Anaconda Densheath EPR [4].

Figure 3 shows the newly obtained wear out results for Anaconda Durasheath and data available for Anaconda Densheath in SCRAPS with a common reference temperature of 99 °C. Based on the SCRAPS accelerated aging data, SNL's prediction curve (shown as the purple dashed line) has a similar shape to the field returned material, particularly as these are not identical cables (i.e., Densheath vs Durasheath EPR) and the laboratory aged cables were under thermal-oxidative conditions (i.e., no humidity). Impressively, the prediction suggests that at these environmental conditions the cable should retain more than 50% tensile elongation for many years to come years at 27 °C and is consistent with data previously presented [4].

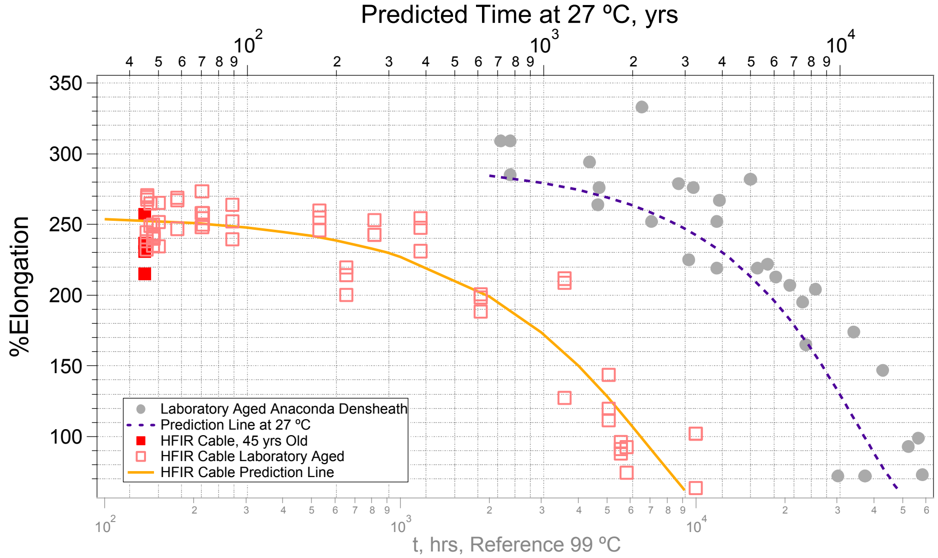

Fig. 3 - Ultimate tensile elongation data for Anaconda *Densheath* EPR cables returned from HFIR at ORNL (~45 yrs of age, T_{avg} ~27 °C, RH ~70%, shown in red) plotted with previously obtained accelerated aging data for Anaconda *Durasheeth* EPR cable data (shown in grey) [4].

3.1.2 Gel Content and Solvent Uptake Analysis

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

Gel content and solvent uptake factors are being measured for the HFIR cables, both as received and further aged through the wear out approach. Figure 4 shows tensile elongation data with varying % gel content measured thus far. As the tensile properties decrease due to thermal-oxidative aging, the gel content increases. These results suggest that crosslinking is the dominant underlying mechanistic pathway. At approximately 50% tensile elongation, the gel content was measured to be ~78% (e.g., ~300% increase in gel content). If the aged cable had a higher gel content, e.g. 90%, this condition monitoring technique would not be as sensitive to correlating chemical properties to mechanical properties [4]. Asserting a concrete correlation between tensile elongation and gel content is not possible at this time, as further testing is warranted. However, the key point of Figure 4 is to note the trend of gel content with varying tensile elongation, as well as identify the potential for employing this type of analytical technique for condition monitoring of service cables.

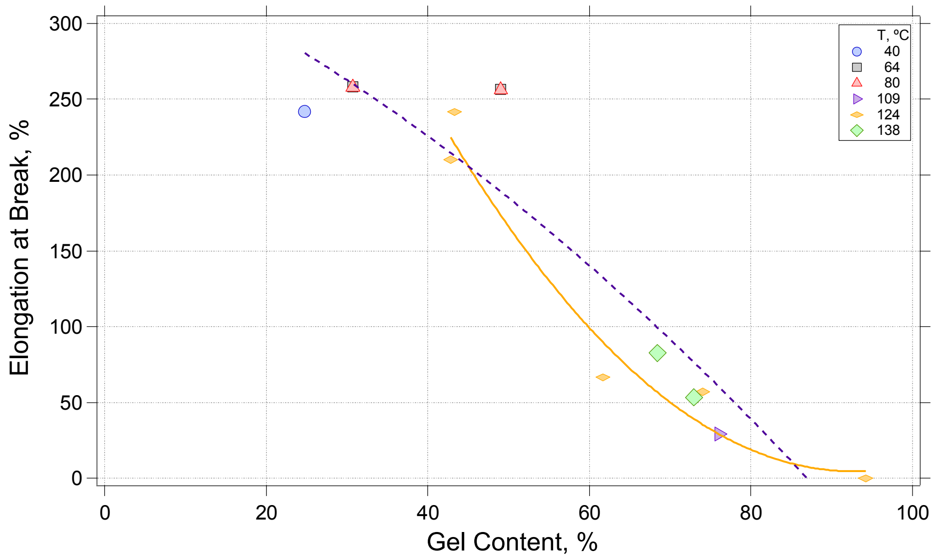

Fig. 4 – Gel content plotted as a function of tensile elongation measured for Anaconda Densheath EPR cables returned aged at varying temperatures. The lines are only meant to guide the reader's eye and do not indicate a mathematical correlation; two different trends are possible from the data.

Comparatively, Figure 5 shows tensile elongation plotted with increasing solvent uptake. The data demonstrates that as the tensile elongation decreases, the solvent uptake factor decreases—another indication that crosslinking is the dominant underlying degradation pathway. Phenomenologically, this makes sense, i.e. as the molecular weight of the polymer increases and becomes brittle, the tensile elongation decreases. It is important to note that at approximately 50% elongation at break, the solvent uptake factor was determined to be ~1.6 to 1.7 (e.g., ~60% decrease in solvent uptake from the as received cable insulation).

Previous work by SNL [4] suggested that gel and uptake data measured for EPR cables provides little to no indication that the end of life was approaching due to induction time. Further detail can be found in SAND2005-7337 referring to EPR-04, Anaconda Durasheath EPR. Albeit this point is valid, SNL's ongoing accelerated aging study of these service cables aims to mitigate these technical concerns. Furthermore, the initial gel content measurements were quite different, e.g., for Anaconda Durasheath EPR the gel content and solvent uptake factor were ~81% and 3.5, respectively. Likewise, the Anaconda Densheath EPR cables received from HFIR were measured to have an initial gel and solvent uptake factors of ~43% and ~2.6, respectively, i.e. the service cables have a much lower overall crosslink density than the previously studied cables.

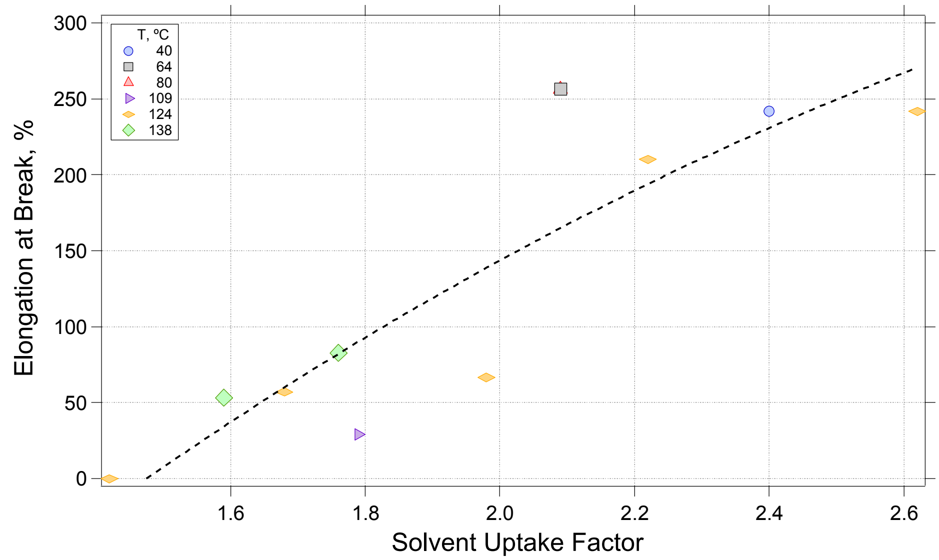

Fig. 5 – Solvent uptake factor plotted as a function of tensile elongation data measured for Anaconda Densheath EPR cables returned aged at varying temperatures. The dashed line is shown only to guide the reader's eye and does not indicate a mathematical correlation.

3.1.3 Density

Material properties like density are often measured, in addition to gel and solvent uptake factors, with aging because it can provide insight to the underlying degradation mechanisms. Figure 6 shows density measurements of Anaconda Densheath EPR insulations returned from HFIR that have been further aged at 124 °C. As the aging time increases, the density increases as well, which correlates to a decreased tensile elongation (see Figure 7). In this particular instance, density variation could be employed as a condition monitoring technique due to its sensitivities to aging time, and ultimately performance.

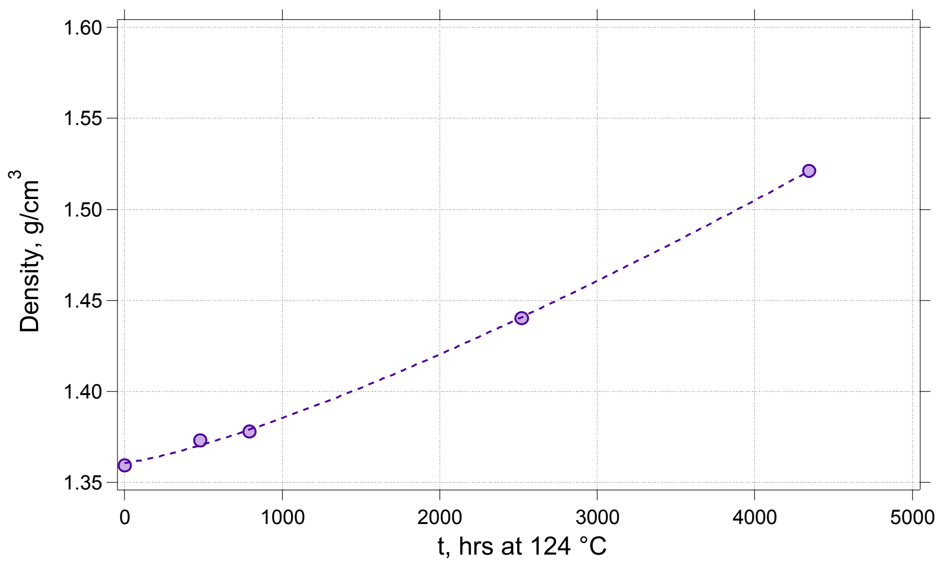

Fig. 6 – Density plotted as a function of aging time for Anaconda Densheath EPR insulation aged at 124 °C. The dashed line is shown only to guide the reader's eye and does not indicate a mathematical correlation.

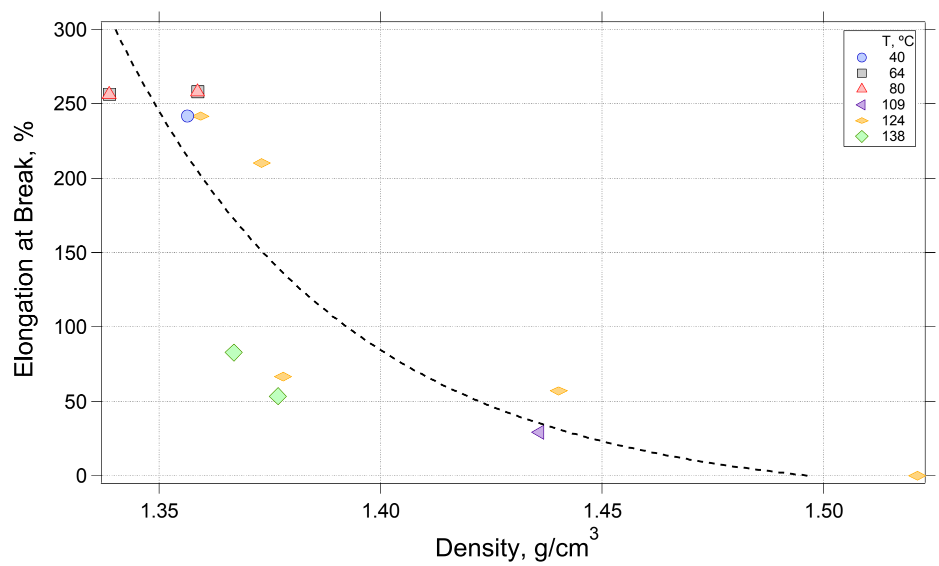

Fig. 7 – Density plotted as a function of tensile elongation for Anaconda Densheath EPR insulation aged at varying temperatures. The dashed line is shown only to guide the reader's eye and does not indicate a mathematical correlation.

3.2 Cable from Comision Nacional de Energia Atomica (CNEA)

As part of SNL's contribution to the United States – Argentine Binational Energy Working Group (BEWG), SNL performed accelerated aging experiments on silicone rubber cables which are analogous to service cables in Argentina. As agreed upon in the BEWG, the cables were aged at approximately 100 °C and 39 Gy/hr in the low intensity cobalt array facility (LICA) at SNL [5].

3.2.1 Tensile Testing

Figures 8 and 9 show the degradation in tensile elongation with increasing dose and time, respectively, for the silicone rubber insulations. The degradation in tensile elongation to ~50% occurs rather quickly (< 3,000 hrs and ~105 kGy) at 100 °C.

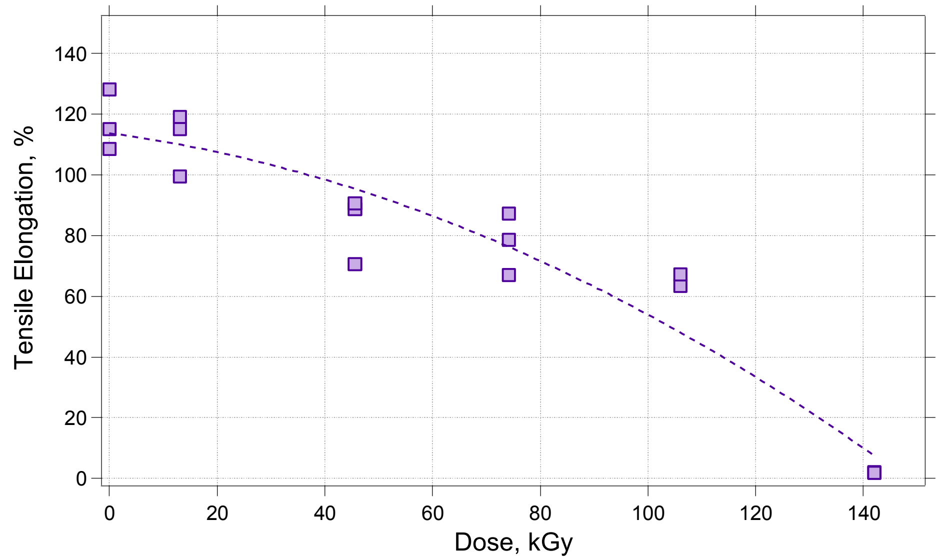

Fig. 8 - Ultimate tensile elongation data for silicone rubber cable insulations aged at 100 °C and ~39 Gy/hr provided by CNEA.

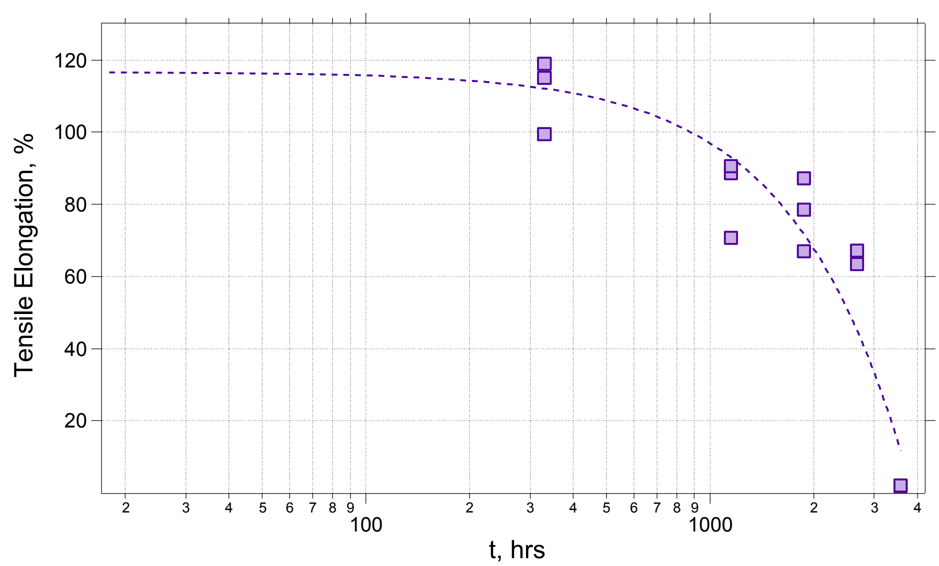

Fig. 9 - Ultimate tensile elongation data for silicone rubber cable insulations aged at 100 °C and ~39 Gy/hr provided by CNEA.

3.2.2 Gel Content and Solvent Uptake Analysis

To develop a better fundamental understanding of what chemically occurs during simultaneous thermal/radiation aging of the silicone rubber insulations, gel and solvent uptake analysis was performed. Figure 10 shows the virgin cable has very high gel content (~96.5%); as the aging time and dose increase so does the gel content. The observed gel content and solvent uptake (see Figure 11) behaviors indicate that crosslinking is the dominant degradation pathway which is responsible for degradation in tensile elongation.

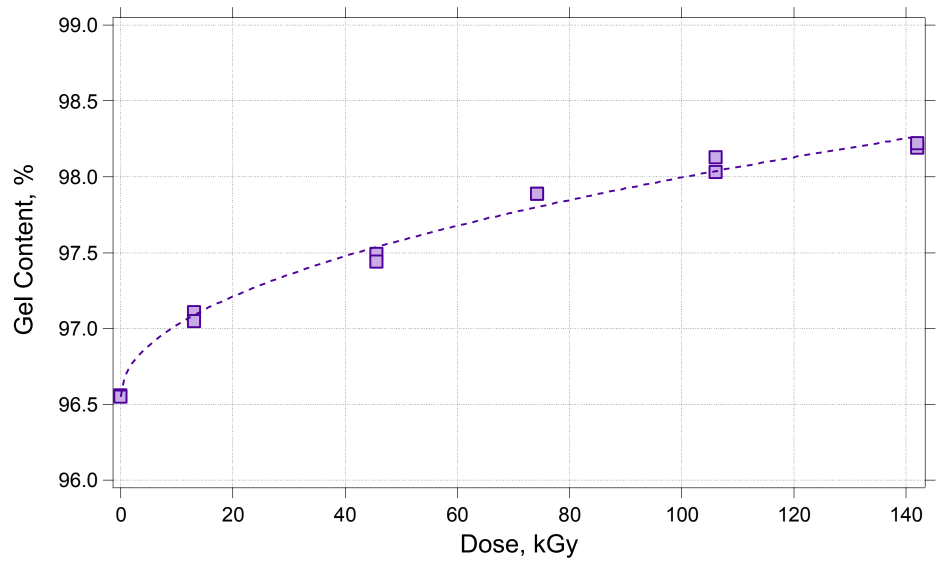

Fig. 10 – Gel content data for silicone rubber cable insulations aged at 100 °C and ~39 Gy/hr provided by CNEA.

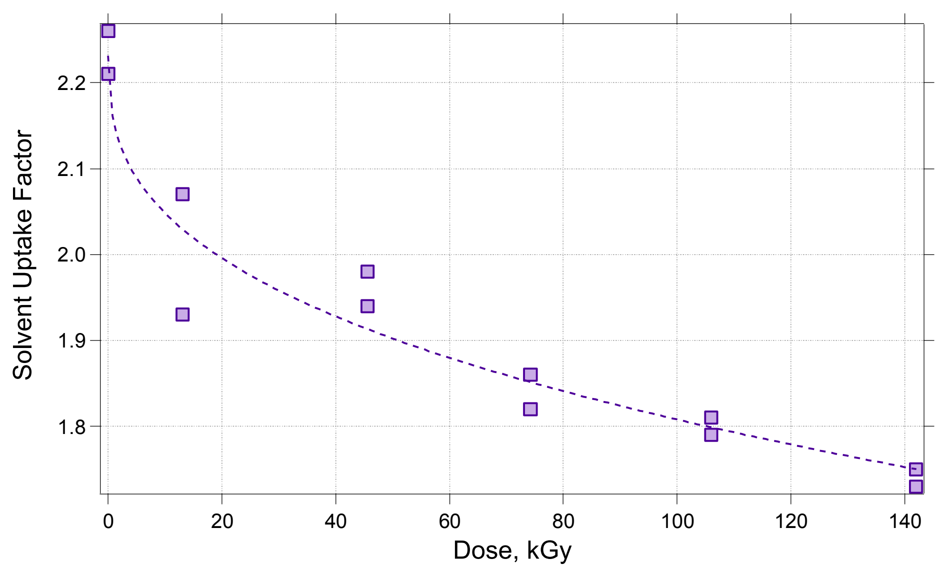

Fig. 11 – Solvent uptake factor data for silicone rubber cable insulations aged at 100 °C and ~39 Gy/hr provided by CNEA.

3.2.3 Density

The densities of the virgin and aged silicone rubber insulations were also measured. Figure 12 shows the density is constant for the aging conditions studied out to where the cable is no longer useable.

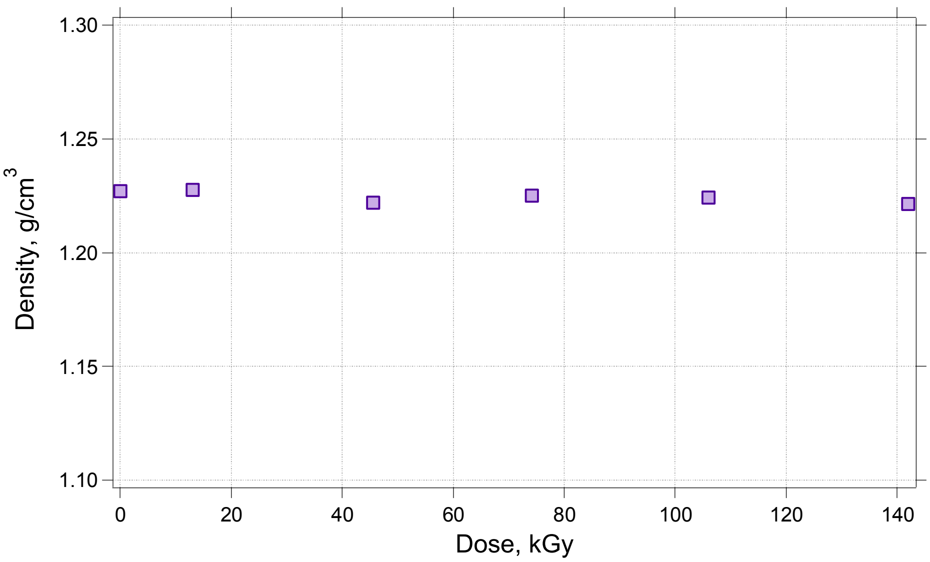

Fig. 12 – Density data for silicone rubber cable insulations aged at 100 °C and ~39 Gy/hr provided by CNEA.

3.3 Cable from Zion Nuclear Power Station

A short length of EPR cable was obtained from the decommissioning Zion Nuclear Power Station. The tensile elongation for the combined jacket/insulation was measured to be approximately 240 %; the density of the cable (both jacket and insulation) was measured to be 1.45 g/cm^3. Not having any environmental history of the cable makes it difficult to perform an aging assessment. Furthermore, knowledge that the cable was in a submerged environment adds an extra layer of complexity to the issue which is outside the work scope of this program.

Albeit inappropriate, Figure 13 shows a comparison of the tensile data measured for the Zion cable to data previously measured for Okonite EPR insulation. To make this comparison, an average thermal environment of 27 °C was assumed. It is quite obvious that no correlation can or should be made in Figure 13 for this service cable. Future SNL effort may involve revisiting this particular cable, but under a revised work scope or alternative funding source.

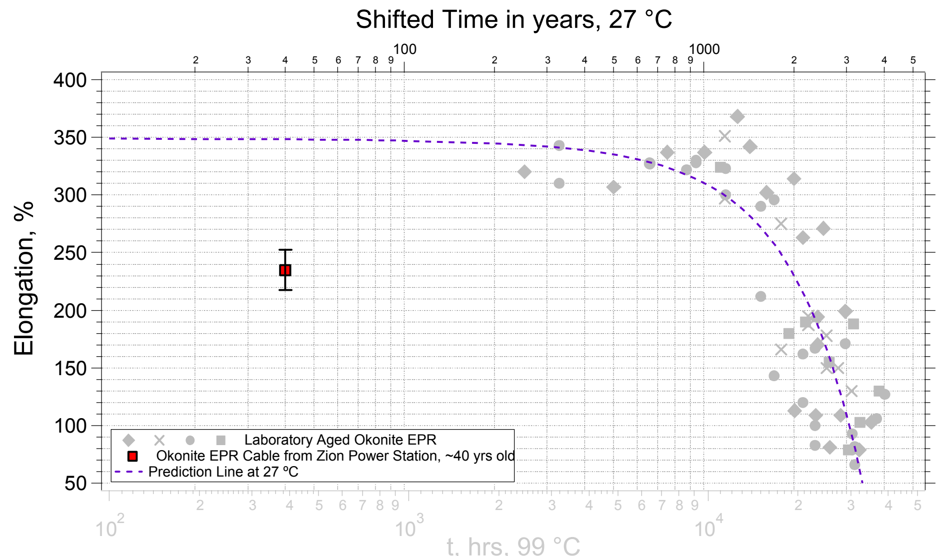

Fig. 13 – Ultimate tensile elongation for as received Okonite EPR cable insulation obtained from the decommissioning Zion Nuclear Power Station, ~40 yrs old. No temperature or humidity data was provided—the cable was noted to have been in a submerged environment as some point in time.

4. Conclusions

A substantial amount of work has been performed to assess EPR and SiR service cables; however, much work is still warranted. To date, the wear out data obtained for the service cables from the high flux isotope reactor at Oak Ridge National Laboratories is proving to be quite useful in aiding the validation of existing Anaconda EPR thermal-oxidative prediction curves. Albeit, divergence from the existing curve is observed with the service cable tensile data, the cable previously studied is a different type of insulation (e.g., Densheath vs Durasheeth). Further accelerated aging will provide critical data that will enhance our understanding of service cable aging.

Mechanical and chemical aging data measured for the SiR cable provided by CNEA enabled a unique opportunity to evaluate aging behaviors of key cables analogous to service cables in combined thermal/radiation environments. Future analysis of this data and collaboration through the US-Argentine BEWG may result in further study or opportunities to perform the wear out technique on actual service cables from the plant.

Lastly, data measured for the service cable obtained from Zion demonstrated that for model validation to be useful, a well-documented service history is required. These results also confirm that cables which have been submerged add an additional layer of complexity to polymer aging and degradation studies. These results and conclusions may one day be leveraged in to additional investigations and future collaborations into submerged cable performance.

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