Impact of CSPE Jackets on Accelerated Aging of Harvested Cable Insulations in Support of Remaining Useful Life Assessments

Sarah Davis
University of Tennessee-Knoxville
Knoxville, TN 37996

Robert C. Duckworth,* Michelle K. Kidder, and Tolga Aytug
Oak Ridge National Laboratory
PO Box 2008, One Bethel Valley Road, Oak Ridge, TN 37831

ABSTRACT

Nuclear power plants (NPPs) are operating beyond their original 40-year operating lifetime, with more than 80% operating on the first license renewal for an extended 20-years. To sustain the effective and cost-effective operation of their electrical cables, understanding cable material performance in current and future environments can lead to effective maintenance strategies and condition monitoring protocols. Addressing the issue of long-term operation and viability, accelerated aging was carried out on chlorosulfonated polyethylene (CSPE) / ethylene propylene rubber (EPR) insulations that were removed from harvested electrical cables. Cables were obtained as part of the Light Water Reactor and Sustainability (LWRS) Zion Harvesting Project in cooperation with Energy Solutions and the U.S. NRC. Zion NPP was in operation for 25 years prior to decommissioning before its 40-year operation license had expired.

For the Boston Insulated Wire (BIW) manufactured EPR insulation with outer CSPE jackets, degradation was observed in mechanical properties with respect to time and temperature was observed. This degradation was impacted by the outer CSPE jacket as the increase in to the time to degradation at the same temperature was observed for EPR insulations with the outer CSPE jacket removed prior to aging. The correlation of IM and density to EAB also suggested that these parameters could also be used effectively in the estimates of activation energy with additional data. Arrhenius analysis on the mechanical degradation as measured by EAB for the two types of BIW EPR insulations with outer CSPE jackets estimated activation energies slightly different (BIW-A without outer CSPE jacket 1.58 eV, BIW-B with outer CSPE jacket 1.10 eV) than the 1.24 eV found in from analysis of EAB data found in Zion NPP BIW insulation documentation. These values were higher than those previously reported of 0.90 eV to 0.96 eV for CSPE and EPR materials in the literature and additional measurements are needed to further validate the increase in activation energy for these harvested materials and possible impact on remaining useful life estimation. Finally, FTIR analysis showed differences in the oxidation as measured by decrease in C-H bonds in EPR insulation and CSPE jackets and increase in C-O bonds in certain cases.

Key words: cable aging, cable insulation, Hypalon, second license renewal

---

* This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy.

1 INTRODUCTION

Assessment of instrument and control (I&C) cable conditions and development of long-term aging models provide needed information for nuclear power plant (NPPs) cable aging management systems [1,2] as NPPs operators look for opportunities to reduce operational and maintenance costs while maintaining a high level of plant reliability. These opportunities take on added importance as utilities in the United States (US) like Dominion Energy, Inc. and Exelon Generation prepare for a second license renewal to operate plants to 80 years [3]. Over several years, coordinated assessments have been carried out by several organization including the US Nuclear Regulatory Commission (NRC), the Electric Power Research Institute and the Department of Energy's (DOE) to identify knowledge gaps [4], active communication and education of key findings with respect to materials and key mechanisms through public forums [5] and technical reports [6-8], and development of online monitoring tools to support these findings [9-11].

While significant technical progress has been made, knowledge gaps remain in insulation and cable jackets with respect to manufacturers and insulations [7, 8] due to their limited availability and absence of manufacturers that are no longer in business. Harvesting of I&C cables during outages in current NPPs for forensic assessment and in decommissioned NPP through collaborative efforts of EPRI, DOE, and the NRC have provided relevant materials. One challenge in the study of harvested materials and its ability to be utilized in cable aging management programs is comparing harvested data to previous work where variations could exist due to different vintages, plant installations, insulation material variations, and unknown plant conditions.

One example of material variations within a single manufacturer can be found with Boston Insulated Wire (BIW), a manufacturer. Figures 1 and 2 show two different cross-sections of harvested BIW I&C cables. The 22 conductors of the multiconductor cable in Fig. 1 were insulated with an inner ethylene propylene rubber (EPR) layer 1.1 mm thick and an outer, colored chlorosulfonated polyethylene (CSPE) jacket 0.4

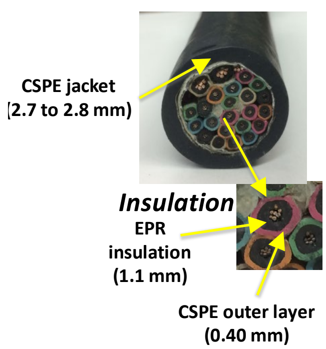


Figure 1. Cross section of BIW auxillary control rod cable that was harvested from current NPP. Results that are related to this cable are referenced as BIW-A in this paper.

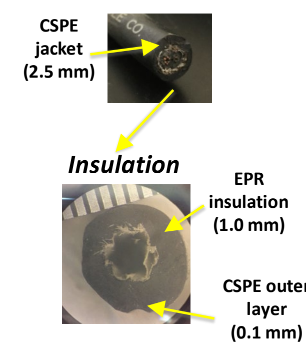


Figure 2. Cross section of BIW power cable that was harvested from Zion NPP. Results that are related to this cable are referenced as BIW-B in this paper.

mm thick, while the two conductors for the cable in Fig. 2 were insulated with a 1.0 mm EPR layer with a 0.1 mm thick CSPE outer jacket. Each cable had a Hypalon™ cable jacket surrounding the insulated conductors with the thickness ranging between 2.5 mm and 2.8 mm. Hypalon™ is a trademarked version of CSPE. Previous work on EPR and CSPE has focused on their performance separately with the EPR analyzed from an insulation standpoint and the CSPE as a cable jacket insulation (EPR) and material properties as separate entities [12-18]. Effort on the EPR insulation and CSPE outer jacket as integrated system has been limited to a handful of studies [19-20].

In order to determine the impact of the CSPE outer jacket thickness on cable aging, accelerated aging experiments with respect to temperature were carried out on harvested BIW I&C outer jacket and insulation. The mechanical and chemical properties of the cable insulations, with the presence and absence of CSPE, were assessed to determine the extent of its performance change after 30 years of operation, analyze the impact of the CSPE covering, and to understand the changes in its chemical structure. When compared to results from previous cable insulation measurements, the dependence of mechanical and chemical properties such as elongation at break (EAB), indenter modulus (IM), fourier transform infrared spectroscopy (FTIR), and density measurements with respect to temperature revealed that degradation occurred earlier than expected when compared to environmental qualification (EQ) data and when the CSPE outer jacket was removed.

2 CABLE AGING AND CHARACTERIZATION

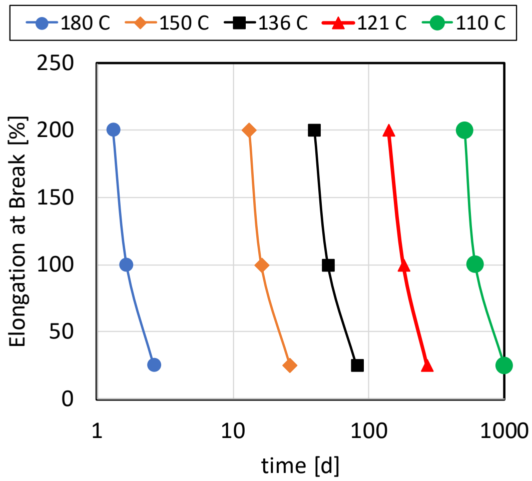
In order to determine the performance of I&C cables, accelerated aging at higher temperatures is employed to extrapolate I&C cable performance. This is done by assuming that the degradation mechanism and the rate of degradation is functionally related to the exposure temperature of the cable. For I&C cables that are qualified for NPPs as well as many other polymers, an Arrhenius analysis is utilized in which the rate of degradation, $\dot{R}$, is expressed as

$$\dot{R} \sim e^{\left[{}^{-E_a}/_{kT}\right]} \tag{1}$$

where E_a is the activation energy, k is the Boltzmann constant 8.617 x 10^{-5} eV/K, and T is the temperature. The rate of degradation is found through the comparison of a measured property, which is often EAB for I&C cables, across different temperatures over time as shown for harvested Zion BIW cable data in Fig. 3. A reference temperature of 110°C is selected and the remaining data is multiplied by a constant, A_T, until it overlaps the reference data. The constant, which is related to the rate of degradation, is plotted as a function of inverse temperature as shown in Fig. 4 and the activation energy of 1.24 eV is obtained from its slope. Utilizing the activation energy and the rate equation above, the remaining useful life for polymers in electrical cables with respect to a time, t_1, for an operational parameter such as 50% elongation at break can be expressed as

$$t_1 = t_2 \, exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \tag{2}$$

where t_2 & T_2, are the time and temperature when the same operational parameter occurs at a higher temperature. It should be strongly emphasized that the operational parameter can vary depending on the specific operational variable used and the assumptions made. For the Zion BIW data shown in Figs. 3 and 4, electrical withstanding testing and not the mechanical properties as a function of the temperature was utilized to estimate the activation energy, 1.141 eV and the 40-year operational life at 90°C. The withstand testing was performed after the cable was exposed to radiation and LOCA exposures consistent with IEEE standards for class IE nuclear grade cables [22, 23]. The differences between activation energies from mechanical and electrical characterizations is worth noting given that data on activation energies is more readily available from mechanical measurements given the amount of cable material is considerably less than electrical methods. While work is currently focused on closing this knowledge gap in a systematic way, EAB will be utilized to calculate the activation energy for the BIW insulations considered in this paper.



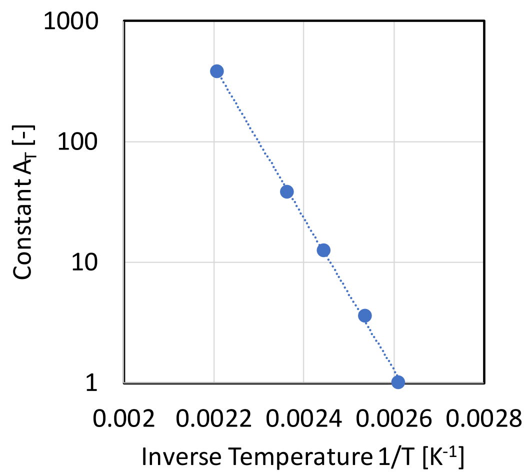


Figure 3. EAB as a function of temperature and time that was taken from EQ documentation for a BIW manufactured cable with EPR/CSPE insulated conductors [21].

Figure 4. Constant, A_T, as a function of inverse temperature for a BIW manufactured cable with EPR/CSPE insulated conductors [21]. Constants found by multiplying time to degradation at a given temperature by the same value until data overlapped reference temperature of 110°C ($A_T = 1$).

Short sections of BIW cable insulations were prepared according to ASTM standard D638-14 [24] and placed into several air convection furnaces (Fig. 5) at temperatures ranging between 130°C to 160°C. Cable specimens were removed periodically over the course of several weeks and the samples were kept at ambient conditions for 24 to 48 hours before commencing the measurements [25]. Mechanical properties of the cable insulations over the duration of the accelerated thermal aging were tracked through EAB and indenter modulus (IM) techniques. Using the guidance from IEC/IEEE 62583-3 [25], cable insulation samples with lengths of 50.8 mm were placed in an Instron 4450 Tensile Tester and the stress

Figure 5. Example of furnace (left) and sample arrangement (right) utilized in accelerated thermal aging of BIW cable insulations.

as a function of strain measured at the rate of 1.27 mm/s until failure occurred. This EAB assessment process was repeated for five samples at each temperature to average out possible material variations. An Indenter Polymer Aging Monitor (IPAM) was used on cable jacket samples prior to EAB measurements to measure the indenter modulus per IEC/IEEE 62582-2 guidelines [26]. The indenter force during the measurements was ramped from 0 to 9 N. The indenter modulus of the cable jacket is calculated from the slope of the change in deformation with respect to the force applied. Specifically, it is the difference in force of 4 N and 1 N (3N) divided by the difference in deformation at 4 N and 1 N.

In addition, chemical analysis of each cable jacket sample was performed utilizing Fourier transform infrared (FTIR) spectroscopy and density measurements to correlate mechanical changes with the changes in the chemical structure of the cable jacket. Given that portable FTIR systems are under consideration for use in cable monitoring programs, the FTIR response could prove viable for a non-destructive evaluation of the jacket. FTIR analysis was carried out with a Digilab FTS 7000 equipped with DTGS detector and a PIKE MIRacle ATR accessory equipped with a diamond crystal. FTIR examines the formation of oxidized species and changes to the chemical bonds through the absorption of infrared energy. More detailed information on FTIR techniques and their use in characterizing polymers can be found in [14,27, 28]. Density measurements were performed with a Mettler Toledo XP205 Delta Range. Density measurements examine the changes in mass of the samples based on the differences in weights in air versus ethanol and have shown strong correlation with elongation at break to track cable condition.

3 RESULTS & ANALYSIS

3.1 Elongation at Break

Figs. 5 & 6 show the differences in EAB for the harvested BIW-A and BIW-B when compared to the EAB BIW cable data from the Zion documentation shown previously in Fig. 3. For both harvested BIW insulations, the difference in EAB with respect to temperature are significantly different with the BIW-A, which was closest to the relative thicknesses of the EPR insulation and CSPE outer jacket. To determine the extent that the CSPE played role in the EAB, the outer CSPE jacket removed from the BIW-A prior to accelerated aging and the EAB compared to the BIW-A data and the Zion documentation (Fig. 7). Unfortunately, the impact of CSPE on BIW-B aging was unable to examined due to the inability to remove the thin CSPE layer without damage to the EPR insulation. When compared to the previous

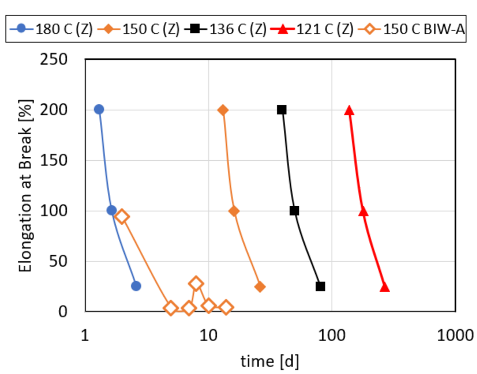


Figure 5. Comparison of EAB for harvested BIW-A to BIW data from Zion documentation [21].

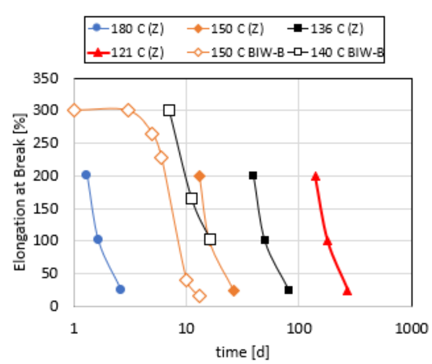


Figure 6. Comparison of EAB for harvested BIW-B to BIW data from Zion documentation [21].

measurements of BIW with the CSPE layer versus without it, the amount of time required to see the drop in EAB at a given temperature is significantly shorter for samples with CSPE. For example, to reach 50% EAB at a temperature of 150°C estimated that it takes ~ 4 days for the harvested BIW cable with CSPE but around 40 days for the same samples without CSPE. While additional systematic EAB data and chemical analysis is needed to confirm the effect of CSPE completely, the change in degradation appears to be impacted by the CSPE thickness

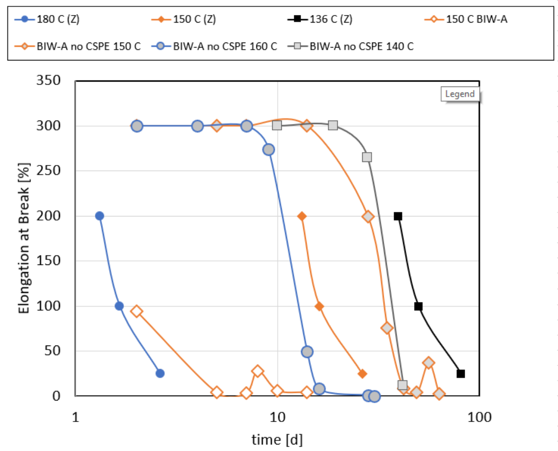


Figure 7. Comparison of EAB as a function of temperature for harvested BIW-A with and without the CSPE outer jacket to EAB BIW data from Zion documentation.

To compare the performance of these two types of cable jackets and estimate the activation energy, Arrhenius constants, A_T, were obtained for harvested cable insulation data from Figs. 6 and 7 when sufficient data assuming a reference temperature where $A_T = 1$ at the lowest measured temperature (Fig. 8). Using (1) and the slope of the exponential curve fit in Fig. 6, the activation energies were estimated to be 1.58 eV for BIW-A without CSPE & 1.10 eV for BIW-B with CSPE. The differences of these activation energys for the the activiation energy for the BIW Zion documenation of 1.24 eV that was calculated from **the EAB data** would indicate the CSPE was not a large factor in rate of degradation utilized in aging estimates. When compared to the activation energy from previous mechanical measurements, the measured activation energies are higher than those for EPR and CSPE that have been reported previously between 0.90 eV to 0.96 eV [8,15,16,18]. The consequence of the higher activiation energy would be that the rate of degradation is not nearly as fast and the remaining useful life could be overestimated. Further mechanical and electrical measurements relative to activation energies should provide some insight on the significance of these observed differences.

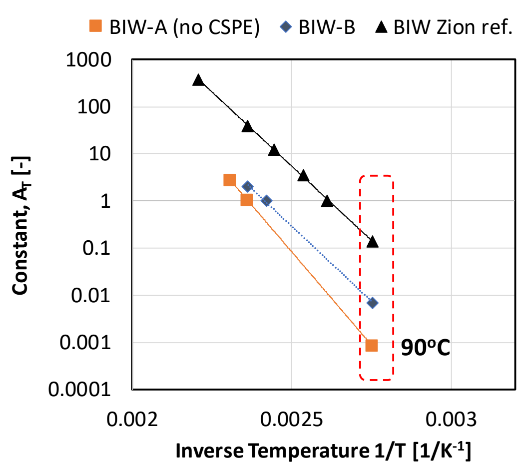


Figure 8. Arrhenius constants as a function of inverse temperature that were found for BIW-A without CSPE and BIW-B. Data from Zion documentation was included for comparison. The lines are the exponential curve fits for each cable insulation and the points for each at 90°C are estimated constants and not actual data.

3.2 Indenter Modulus and Density Measurements

Like the EAB accelerated aging data, degradation of the insulation was measured by indenter modulus and density of the insulation in the harvested BIW cable insulation. For the indenter modulus shown in Figs. 9 & 10 for harvested BIW-A, the increase in IM coincided with respect to time with the drop in EAB even when the outer CSPE jacket was removed from the BIW-A insulated conductor. The temperature dependence of the increase in IM degradation in Fig. 10 is similar to the temperaure dependence degradation of the EAB. The dependence for IM is also observed for BIW-B harvested cable insulations even though the relative increase in IM from 4 N/mm to 11 N/mm is small that was observed

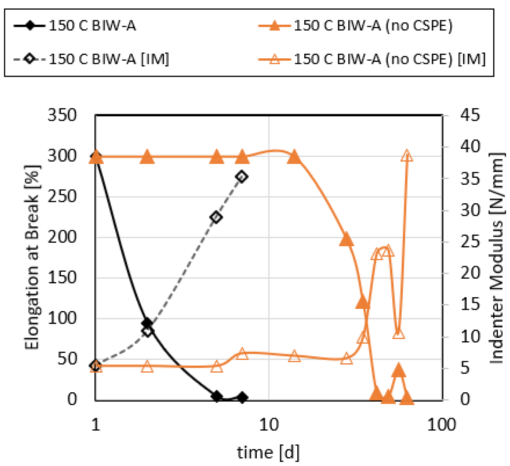


Figure 9. Indenter modulus and EAB as a function of time for accelerated aging at 150°C for BIW-A EPR insulation with and without outer CSPE jacket.

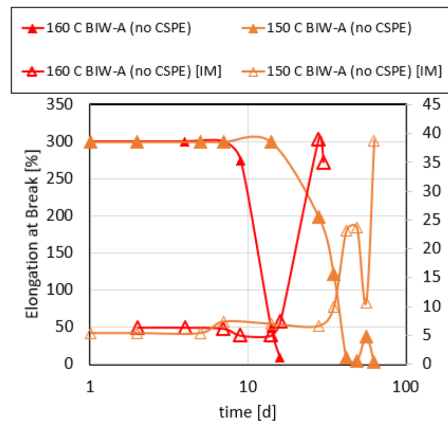


Figure 10. Indenter modulus and EAB as a function of time and temperature for BIW-A EPR insulation without outer CSPE jacket.

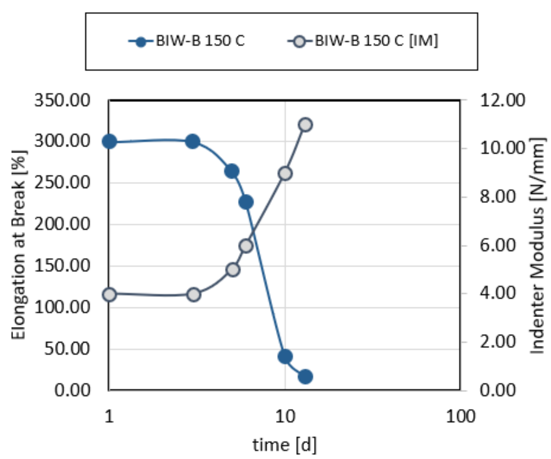


Figure 11. Indenter modulus and EAB as a function of time for accelerated aging at 150°C for BIW-B EPR insulation with outer CSPE jacket.

in harvested BIW-A insulations. While IM is typically measured for cable jackets with larger surfaces, this data would support that IM could be utilized to track degradation in insulations and with additional data could be utilized to estimate activiation energies. In the limited number of density measurements to date, strong correlation between density and EAB is also shown for the case shown in Fig. 12. The correlation between density and EAB is similar to the correlation between IM and EAB with density increasing with degradation. The increase in density is likely tied to the oxidation of the insulation, which will be shown in the FTIR spectra data. More testing needs to be done in order to analyze the full scope of the effect of CSPE on density measurements with separate measurements of outer CSPE jackets. However given the trends found in EAB and IM, it is expected that similar increased should be observed.

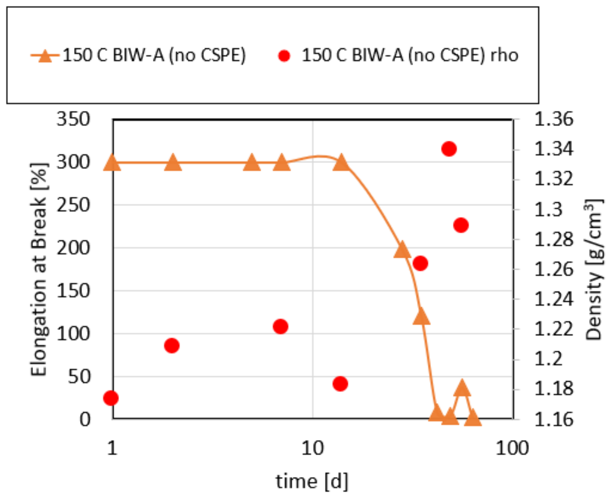


Figure 12. Comparative density measurement data for BIW-A EPR insulation without outer CSPE jacket as a function of time from accelerated thermal aging at 150°C.

3.3 FTIR

Comparison of FTIR spectrum for BIW cable insulations was utilized to study the changes to the chemical bonds of EPR insulation and CSPE outer jacket. While the carbon black filler and the overall black color makes meaningful FTIR measurements difficult due to the limited reflected light, notable changes in the FTIR spectra that seem to correlate to age-related and material-related chemical activity were observed. Figs. 13 and 14 show snapshots of the FTIR spectra for the BIW-A EPR insulation with the outer CSPE jacket removed prior to aging and the BIW-A CSPE outer jacket for the same duration and temperature, 150°C. For the BIW-A EPR insulation and the outer CSPE jacket, oxidation was observed through the decrease in C-H bonds at 530 cm^{-1}, 1460 cm^{-1}, 2850 cm^{-1} & 2920 cm^{-1}. The decrease in the absorbance was more pronounced for the outer CSPE jacket when compared to the EPR insulation. However the EPR insulation did see a growth in C-O bonds as measured near 1060 cm^{-1} and 1710 cm^{-1}. Comparison of the density changes for the outer CPSE jacket and the EPR insulation to these peaks with respect to temperature and time along with oxidation induction time measurements could be beneficial in the future.

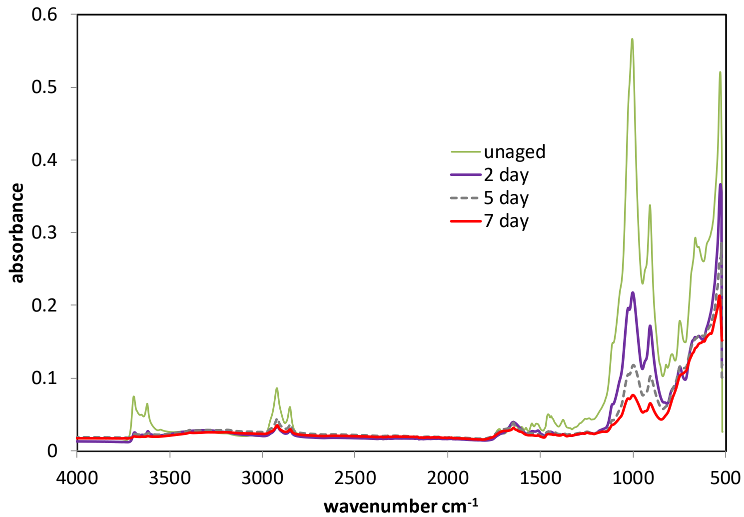


Figure 13. FTIR spectra for BIW-A EPR insulation without outer CSPE jacket as a function of time from exposure to air at 150°C.

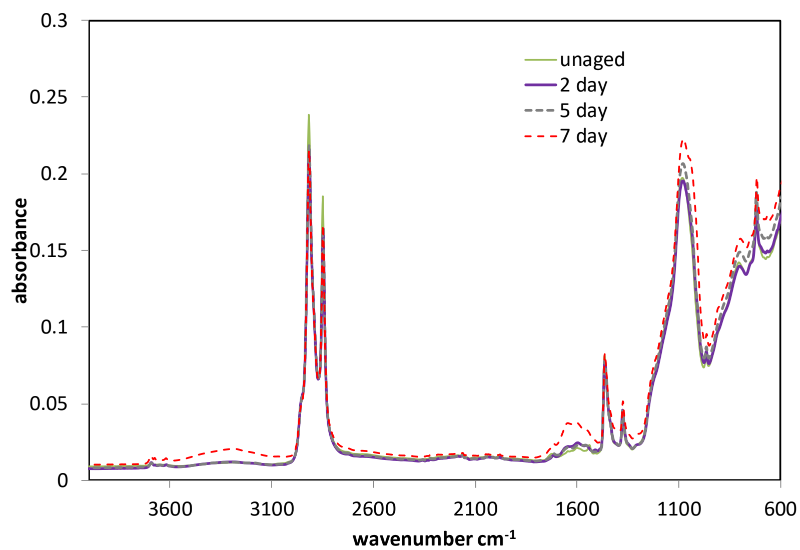


Figure 14. FTIR spectra for BIW-A outer CSPE jacket as a function of time from exposure to air at 150°C.

The FTIR spectra of the BIW-B EPR insulation and outer CSPE cable jacket showed slightly different dependences with respect to the C-H and C-0 bonds. With respect to the outer CSPE jacket, significant drop in the C-H bonds at 665 cm^{-1}, 1460 cm^{-1}, 2850 cm^{-1} & 2920 cm^{-1} was observed. However the peak near 1060 cm^{-1} that is attributed to C-O actually decreased with respect to time for the BIW-B jacket, which is the opposite the expectation from the BIW-A outer CSPE jacket. Another difference in the FTIR spectra can be noted for the EPR insulation C-H bonds near 2850 cm^{-1} and 2920 cm^{-1}. The drop in the absorbance is more pronounced in BIW-B EPR insulation when compared to BIW-A EPR insulation. While the difference in the accelerated aging could be related to the outer CSPE since aging was done with it for the BIW-B

EPR insulation and without it for the BIW-A EPR insulation, additional FTIR measurements are needed for the BIW-A EPR insulation with the outer CSPE jacket aged for a longer period of time to determine the role that the CSPE could play in oxidation or if the differences observed are simply variations in the EPR and CSPE formulations or time of accelerated aging.

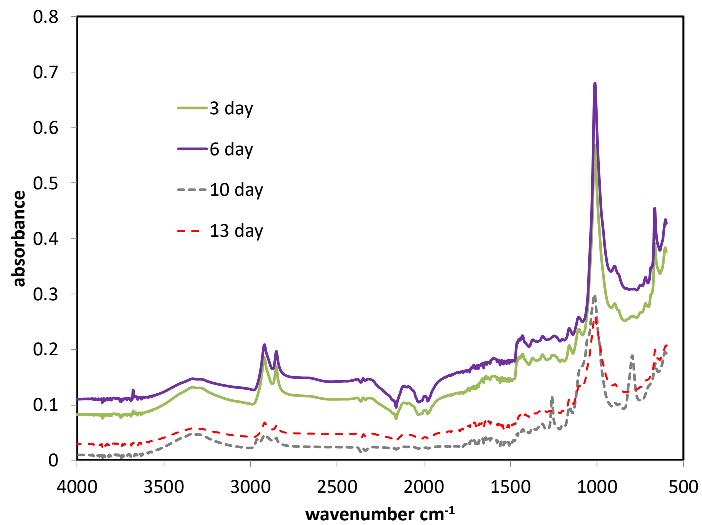


Figure 15. FTIR spectra for BIW-B inner EPR insulation CSPE jacket as a function of time from exposure to air at 150°C.

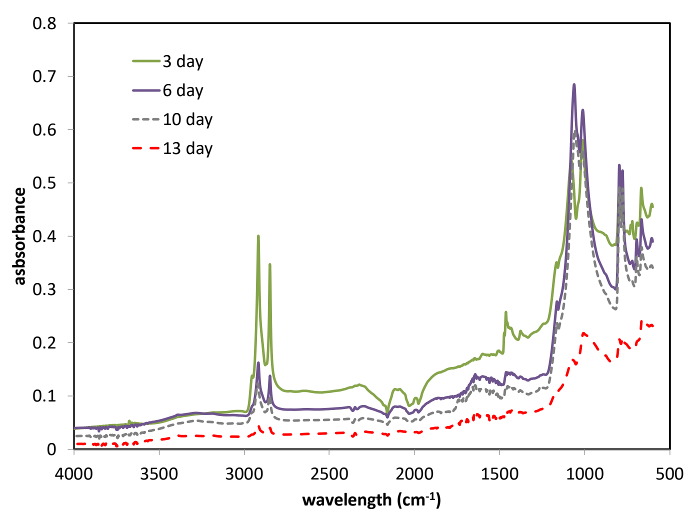


Figure 16. FTIR spectra for BIW-B outer CSPE jacket as a function of time from exposure to air at 150°C.

4 CONCLUSIONS AND FUTURE WORK

Accelerated thermal aging at temperatures between 130°C and 160°C was performed on harvested BIW-manufactured I&C cables to determine the impact of CSPE on aging observed in EPR insulations in support of remaining useful lifetimes. For EAB, IM, and density characterization, degradation appears to occur much sooner with the presences of CSPE. The correlation of IM and density to EAB also suggested that these parameters could also be used effectively in the estimates of activation energy with additional data.

Arrhenius analysis on the mechanical degradation as measured by EAB for the two types of BIW EPR insulations with outer CSPE jackets estimated activation energies slightly different (BIW-A without outer CSPE jacket 1.58 eV, BIW-B with outer CSPE jacket 1.10 eV) than the 1.24 eV found in from analysis of EAB data found in Zion NPP BIW insulation documentation. These values were higher than those previously reported of 0.90 eV to 0.96 eV for CSPE and EPR materials in the literature and additional measurements are needed to further validate the increase in activation energy for these harvested materials and possible impact on remaining useful life estimation.

Finally, FTIR analysis showed differences in the oxidation as measured by decrease in C-H bonds in EPR insulation and CSPE jackets and increase in C-O bonds in certain cases. While there was relationship between the change in the spectra with respect to the presence of the outer CSPE jacket, more systematic measurements with respect to temperature, time, and conditions are needed before determining the nature of the correlation between the FTIR spectra and the mechanical degradation.

In addition to the measurements mentioned above, work is planned on comparison of electrical parameters such as permittivity and dielectric breakdown strength for EPR insulations with outer CSPE jackets. The differences between activation energies as measured mechanical and electrically are important to resolve to increase the effectiveness of activation energy estimates and remaining useful life predictions.

ACKNOWLEDGMENTS

This work was supported under the U.S. Department of Energy – Office of Nuclear Energy Light Water Reactor and Sustainability (LWRS) Program.

The authors would also like to thank the discussion and feedback received from Andrew Mantey at EPRI, Keith Leonard at ORNL, and Leo Fifield at Pacific Northwest Laboratory.

REFERENCES

1. G.J. Toman & A. Mantey, "Cable System Aging Management for Nuclear Power Plants," *2012 IEEE International Symposium on Electrical Insulation (ISEI)*, pp. 315-318 (2012)
2. H.M. Hashemian, "Aging Management of Instrumentation & Control Sensors in Nuclear Power Plants," *Nucl. Engr. Des.,* **240**, pp. 3781-3790 (2010)
3. "Exelon Will Seek License to Run Nuclear Plant for 80 years," Bloomberg News, https://www.bloomberg.com/news/articles/2016-06-06/exelon-said-to-seek-license-to-run-nuclear-plant-for-80-years (2016).
4. R. Bernstein, S. Burnay, C. Doutt, K. Gillen, R. Konnik, S. Ray, K. Simmons, G. Toman, and G. von White, "Expanded Material Degradation Assessment, Volume 5: Aging of Cable and Cable Systems," United States Nuclear Regulatory Commission, NUREG/CR-7153, vol. 5 (2014).

5. EPRI Equipment Reliability Newsletter, http://mydocs.epri.com/docs/Portfolio/P2017/Roadmaps/NUC_ER_02-Cable-Aging-Management.pdf (2017)
6. EPRI, "Low-Voltage Environmentally-Qualified Cable License Renewal Industry Report, Rev. 1," Electrical Power Research Institute, EPRI-TR-103841 (1994).
7. SNL, "Aging Management Guideline for Commercial Nuclear Power Plants Electrical Cable and Terminations," SAND96-0344, (1996).
8. K. T. Gillen, R.A. Assink, and R Bernstein, 2005, "Nuclear Energy Plant Optimization: Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials," SAND2005-7331, (2005).
9. B.D. Shumaker, G.W. Morton, S.D. Caylor, & H. Hashemian, "Online Monitoring Implementation in Boiling Water Reactors," *2012 NPIC/HMIT Conference Proceedings,* **2**, 1314-1324 (2012).
10. D. Mantey, "Long-Term Operations: Initial Findings on Use of Dielectric Spectroscopy for Condition Monitoring of Low Voltage Nuclear Power Plant Cables," EPRI, Palo Alto, CA, Tech. Report No. 3002010403 (2017).
11. J. Groeger, K. Brown, & T. Esselman, "Plant Engineering: Cable Polymer Handbook – Medium Voltage Insulations" EPRI, Palo Alto,CA, Tech. Report No. 3002005322 (2015).
12. F. Foucalt, S. Esnouf, & A. Le Moel, "Irradiation/temperature synergy effects on degradation and ageing of chlorosulphonated polyethylene," *Nucl. Inst. Methods Phys. Res. B*, **185**, pp. 311-317 (2001).
13. V. Gueguen, L. Audouin, B. Pinel, & J. Verdu, "General and Kinetic Aspects of Radiochemical and Thermal Oxidation of a Chlorosulfonated Polyethylene," *Eur. Polym, J.*, **30**, pp. 1157-1164 (1994).
14. K. Anandakumaran & D.J. Stonkus, "Assessment of oxidative thermal degradation of crosslinked polyethylene and ethylene propylene rubber cable insulation," *Polym Eng. Sci.* **32**, p. 1386 (1992).
15. K.T. Gillen, R. Bernstein, & M. Celina, "Non-Arrhenius Behavior for Oxidative Degradation of Chlorosulfonated Polyethylene Materials," *Poly. Deg. Stab.*, **87**, pp. 335-346 (2005).
16. J.V. Gasa, Z. Liu, & M.T. Shaw, "Relationship between Density and Elongation-at-Break of Naturally and Artificially Aged Cable Materials used in Nuclear Power Plants," *Poly. Deg. Stab.,* **87**, pp. 77-85 (2005).
17. J.-F. Chailan, G. Boiteux, J. Chauchard, B. Pinel, & G. Seytre, "Effects of Thermal Degradation on the Viscoelastic and Dielectric Properties of Chlorosulfonated Polyethylene (CSPE) Compounds," *Poly. Deg. Stab.,* **48**, pp. 61-65 (1995).
18. Y. Gong, et. al., "Comparative Study on Degradation of Ethylene-Propylene Rubber for Nuclear Cables from Gamma and Beta Irradiation," *Poly. Test.,* **60**, pp. 102-109 (2017).
19. L.S. Fifield, Q. Huang, M. I. Childers, & A.W. Zwoster, "Progress in Characterizing Naturally-Aged Nuclear Power Plant Cables," U.S Department of Energy, Office of Nuclear Energy, PNNL-25439 (2016).
20. L. Verardi, D. Fabiani, & G.C. Montanari, "Electrical Aging Markers for EPR-based Low Voltage Cable Insulation Wiring of Nuclear Power Plants," *Rad. Phys. Chem.,* **94**, pp. 166-170 (2014).
21. Zion Station Equipment Qualification Binder, BIW Cable Systems Inc. Electrical Instrumentation, Control, & Thermocouple Extension Cables, Sargent & Lundy Engineers, EQ-ZN042 (1991).
22. IEEE, IEEE Standard for Qualification Class 1E Equipment for Nuclear Power Generating Stations, IEEE 323-1974, Institute of Electrical and Electronics Engineers (1974).

23. IEEE, IEEE Standard for Qualifying Electric Cables and Splices for Nuclear Facilities, IEEE 383-2015, Institute of Electrical and Electronics Engineers (2015).

24. ASTM Standard D638-14, “Standard Test Method for Tensile Properties of Plastics,” ASTM International, doi: 10.1520/D0638-14 (2010).

25. IEC/IEEE 62582-3, Nuclear Power Plants—Instrumentation and control important to safety—Electrical equipment condition monitoring methods—Part 3: Elongation at break, International Electrotechnical Commission/IEEE (2012).

26. IEC/IEEE 62582-2, Nuclear power plants—Instrumentation and control important to safety—Electrical equipment condition monitoring methods—Part 2: Indenter modulus, International Electrotechnical Commission/IEEE (2011).

27. L. Küpper, J. V. Gulmine, P. R. Janissek, and H. M. Heise, “Attenuated Total Reflection Infrared Spectroscopy for Microdomain Analysis of Polyethylene Samples after Accelerated Aging within Weathering Chambers,” *Vibrational Spectroscopy*, **34**, pp. 63-72 (2004).

28. T. Kurihara, T. Takahashi, H. Homma, & T. Okamoto, “Oxidation of Cross-linked Polyethylene due to Radiation-thermal Deterioration,” *IEEE Trans. DEI,* **18,** pp. 878-887 (2011).