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Revision 0

Light Water Reactor Sustainability Program

Summary Report on Assessment of electrical breakdown strength relative to mechanical properties in insulations from harvested cable systems from nuclear power plants

April 2019

US Department of Energy

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Summary Report on

Assessment of electrical breakdown strength relative to mechanical properties in insulations from harvested cable systems from nuclear power plants

Robert Duckworth

Oak Ridge National Laboratory

April 2019

Prepared for the

US Department of Energy
Office of Nuclear Energy

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ACRONYMS

AMS	Analysis and Measurements System Corporation
BIW	Boston Insulated Wire
CSPE	Chlorosulfonated Polyethylene
DOE	Department of Energy
EAB	Elongation at Break
EPR	Ethylene Propylene Rubber
EPRI	Electrical Power Research Institute
EQ	Environmental Qualification
I&C	Instrumentation and Control
IPAM	Indenter Polymer Aging Monitor
LOCA	Loss-of-Coolant Accident
LWRS	Light Water Reactor Sustainability
NDE	Nondestructive Evaluation
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PNNL	Pacific Northwest National Laboratory
SLR	Second (or Subsequent) License Renewal
VLF	Very Low Frequency

SUMMARY

As part of the Cable Aging Task within the Material Research pathway of the DOE Light Water Reactor Sustainability (LWRS) program, ORNL is collaborating with Pacific Northwest National Laboratory (PNNL), the Electric Power Research Institute (EPRI), and the US Nuclear Regulatory Commission (NRC) to study cable aging mechanisms. Understanding cable aging mechanisms in cable insulation and jacket material of power and instrumentation and control (I&C) cables will provide existing nuclear power plants (NPPs) with needed information as they seek plant life extensions to 80 years of operation.

This report summarizes the characterization of the electrical breakdown strength in harvested electrical I&C cable insulation as a function of aging and its relationship to other mechanical properties. Often mechanical properties such as elongation at break and indenter modulus that track degradation in the insulation are utilized to determine its remaining useful life with typical values of 10% to 50% elongation at break associated with end of useful life. However, when the mechanical degradation to this value is compared with electrical breakdown strength evaluation in environmental qualification (EQ) documentation, the observed differences to the time to end of life indicate sizeable operating margin. While the electrical breakdown strength is measured in cables with lengths greater than 15 feet after they have been exposed to a loss of coolant accident (LOCA), wound on a mandrel with a diameter 40X the cable diameter, and subjected to a pass/fail AC withstand test, a series of electrical breakdown strength measurements of the insulation after accelerated aging without LOCA or additional EQ level characterization is proposed as a first step to determine the margin in the insulation and determine whether the differences between electrical and mechanical property degradation along the aging and characterization process are meaningful.

Electrical breakdown strength was measured in a series of ethylene propylene rubber (EPR)–insulated wires with chlorosulfonated polyethylene (CSPE) outer jackets that were manufactured by the Boston Insulated Wire (BIW) Company and harvested from NPPs. Two types of BIW insulation were examined to determine whether functional dependencies for the electrical breakdown strength exist with respect to thickness and composition. Thermal accelerated aging of wire insulation was done at temperatures between 130°C and 150°C prior to electrical breakdown measurements. Breakdown measurements were performed in air and transformer oil and used samples with a minimum length of 25 cm, a 2.54 cm long ground in sample center, and voltage provided by a 0.1 Hz, 60 kV power source. This power source, along with the distance between the conductor and ground, was selected to minimize flashover at the end of the samples and ensure that the breakdown occurred in the sample center. After breakdown measurements in air were taken but prior to any breakdown measurements in oil, the indenter modulus of the insulation was measured and compared with the electrical breakdown strength. As expected, the electrical breakdown strength and indenter modulus tracked degradation as a function of temperature and time, and the rate of degradation observed in the breakdown strength was significantly less than the indenter modulus. In fact, the electrical breakdown strength for one type of harvested BIW insulation was high enough to max out the 60 kV voltage source when the samples were immersed in oil. Additional characterization is planned, including, when appropriate, measurement of the insulation in oil with a larger z voltage source and possible immersion of the insulation in water to determine the percentage of difference observed that is a function of the setup or the insulation.

CABLE PROPERTIES UTILIZED IN REMAINING USEFUL LIFE PREDICTIONS

In order to determine the remaining useful life in cables as many in service pass their original 40-year planned operating life, knowledge of long-term, degradation mechanisms in cable insulation and jacket materials and their correlation to cable performance parameters is essential. When this information is coupled with nondestructive evaluation (NDE) techniques and predictive models and enough information is available, cable aging management programs at nuclear power plants (NPPs) can make effective use of financial resources during operations and maintenance during planned outages. Financial management has taken on a greater role as NPPs assess their current operation and future operations beyond 60 years into Second License Renewal (SLR). Groups at the Electric Power Research Institute (EPRI), the US Department of Energy (DOE) Office of Nuclear Energy (NE) Light Water Reactor Sustainability (LWRS) program, and the US Nuclear Regulatory Commission (NRC) work together and with cable aging management programs at NPPs to harvest cable insulations and assess key issues related to closing knowledge gaps in cable aging.

Elongation at break (EAB) is one cable performance parameter that is commonly utilized to gauge the remaining useful life of cable insulation and jacket materials. An acceptable endpoint value for EAB is typically 50% of its original length according to the International Atomic Energy Agency [1]. However, when reviewing Environmental Qualification (EQ) documentation [2], a noticeable gap is observed between the time to failure as predicted by EAB analysis and the other parameters used. Figures 1 and 2 show the temperature dependence of EAB and AC withstand test at 2400 Vac with respect to time for an instrumentation cable manufactured by the Boston Insulated Wire Company (BIW). The AC withstand was conducted on an insulated conductor within a cable after it had been subjected to accelerated aging for the time and temperature shown in Fig. 2 and exposed to a loss-of-coolant-accident (LOCA) scenario consistent with the IEEE 323 and 383 standards [3, 4]. The LOCA included a total accumulated gamma irradiation of 200 MRad and a high-temperature and pressure steam mixture up to 750 kPa and 170°C (110 psig and 340°F), respectively. When compared at the same temperatures, the time to failure for the AC breakdown is considerably longer than the time to reach 50% EAB, which would suggest that there is a sizeable margin with the EAB measurement. While this margin was likely designed to have a high degree of conservatism to benefit NPPs and their cable systems when they were originally deployed in the 1970s for their original 40-year life, it is possible that NDE methods that are benchmarked to 50% EAB could result in the unnecessary removal of cables that could have measurable margin remaining.

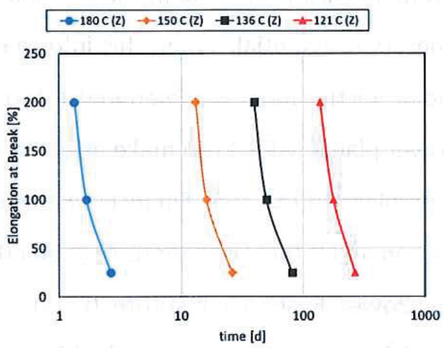

Fig. 1. Elongation at Break for BIW insulated cable from EQ documentation from Zion NPP after accelerated aging at different temperatures.

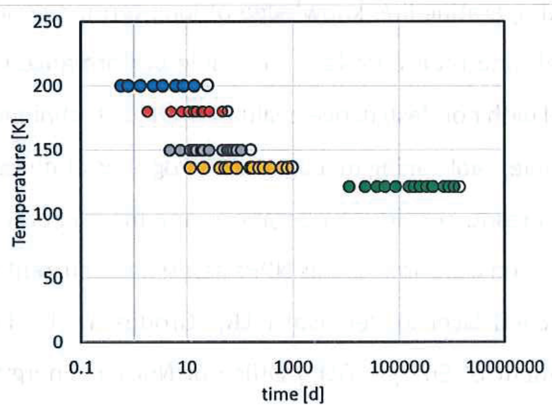

Fig. 2. Time to failure (open circle) Zion NPP EQ documentation BIW insulated cable from 5-minute, 2.4-kV (AC) withstand after accelerated aging at different temperatures and LOCA exposure consistent with IEEE 323-1974 and 383-1974 standards [3,4].

In an attempt to quantify the margin in the remaining useful life of cable insulation and tie it to an electrical performance parameter, this report details an investigation of the relationship of mechanical properties in the insulation to the insulation electrical breakdown strength. The electrical breakdown strength and indenter modulus were measured in two types of harvested BIW insulation that were aged in air. The relationship of these two factors was analyzed as a function of temperature and time. Results indicate that the electrical breakdown strength of insulation could be used to track degradation and that differences were observed in the degradation of two insulation types.

HARVESTED CABLE SPECIFICATIONS AND CHARACTERIZATION

The mechanical and electrical properties of the harvested cable insulations were assessed as a function of accelerated aging temperature and time to determine their ability to track with degradation of the insulation. The harvested cables were obtained from two plant locations. Both cables, originally manufactured by BIW, are still found in current NPPs but are no longer in production. The first harvested location was from conduit connected to motor-operated control valves outside of the missile barrier in the decommissioned Zion NPP as part of the LWRS Zion Harvesting project in cooperation with Energy Solutions and the NRC. Zion NPP was in operation for 25 years prior to decommissioning before its 40-year operation license expired. The second harvested location was from the auxiliary space outside the missile barrier of an existing NPP after 30+ years of operation. The cable was harvested through a collaboration with Analysis and Measurements System Corporation (AMS) and EPRI. Comparing these two types of cable insulation from the same manufacturer can give some indication of variation across a given manufacturer relative to different cables in service.

Both insulations that were aged and characterized consisted of an ethylene propylene rubber (EPR) insulation and an individual chlorosulfonated polyethylene (CSPE) jacket. The insulation from the Zion NPP consisted of an inner EPR insulation 1.0 mm thick and an outer CSPE jacket 0.1 mm thick (Fig. 3). The second cable from the existing power plant was a multi-conductor cable with 22 conductors total, with the 22 AWG conductor insulated with an inner EPR insulation 1.1 mm thick and an outer CSPE jacket 0.4 mm thick (Fig. 4). The thicknesses of the EPR insulation and CSPE insulation differ from those listed in the EQ documentation mentioned earlier, which were an inner EPR insulation 0.64 mm thick and an outer CSPE jacket 0.38 mm thick. While these differences could impact the observed degradation, the insulations are representative of those still in use in NPPs and provide a good starting point for this analysis given their degradation across different mechanical and chemical parameters have been examined previously [5,6].

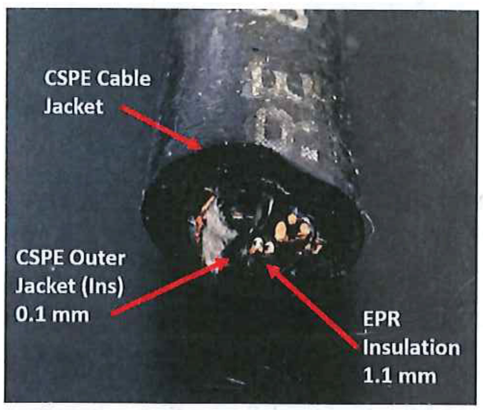

Fig. 3. Cross sections of insulated conductor from BIW cable that was harvested from Zion NPP.

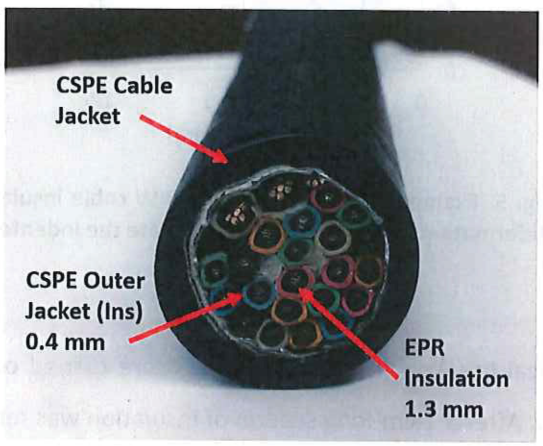

Fig. 4. Cross sections of insulated conductor from BIW cable that was harvested from existing NPP.

ACCELERATED AGING AND CHARACTERIZATION METHODOLOGY

Accelerated aging was carried out on the insulation samples that were harvested from each cable type as a function of temperature and time. Insulation samples including the conductor were nominally 25.4 cm long and were inserted in separate air-circulation ovens to avoid contamination between the two insulation types. Five to six samples were removed periodically, and their insulation performance was measured as function of aging time.

Given that the goal was to preserve the insulation with the conductor for electrical breakdown measurements, mechanical properties were measured initially using an Indenter Polymer Aging Monitor (IPAM) system, which was used to track the insulation indenter modulus and relaxation time. The insulation was centered on the stylus, and force and deformation were measured under load and with the load removed after it reached a peak value of 9 N (Fig. 5).

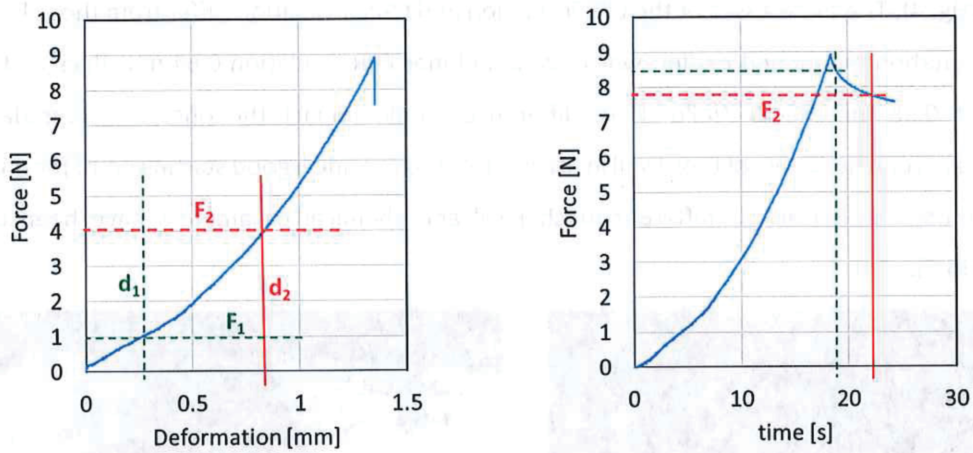

Fig. 5. Examples of data collected BIW cable insulation from IPAM indenter with respect to force, deformation, and time used to calculate the indenter modulus (left) and the relaxation time (right).

Electrical breakdown measurements were carried out using a very low-frequency (VLF) 0.1 Hz power supply. After a 1-cm-long section of insulation was removed to make a lead connection, a narrow strip of conductive aluminum tape, 1 m wide, was placed at the center of the sample to localize the electrical stress away from the end connection to minimize flashover between the ground and the high-voltage connection. The VLF power supply and its frequency were selected to minimize flashover as well as conduct initial testing prior to aging as flashover was observed at or near 10 kV when a 60 kV 60 Hz AC power supply was used in preliminary testing of the insulation. The voltage in the VLF was ramped in 1 kV increments and held for 30 s (0.1 Hz, three cycles) until breakdown was observed. If flashover was observed, the insulation sample was submerged in Univolt N 61 B transformer oil, which has a high dielectric strength (30 kV/mm). Six samples were tested to generate data with respect to the electrical breakdown strength of the insulation.

A two-parameter Weibull analysis was utilized to determine the spread and average of the electrical breakdown strength of the insulation. From IEEE Standard 930-2004 [7], a two-parameter Weibull distribution can be expressed by

$$F(E;\alpha,\beta) = 1 - exp\left\{-\left(\frac{E}{\alpha}\right)^{\beta}\right\}, \quad (1)$$

where *E* is electric field at breakdown (voltage divided by film thickness) and *F*(*t*) is the probability for failure at or below the measured variable. The Weibull scale parameter, α, is the electric field when the failure probability is 63.2%, or 1 − 1/e. This parameter is comparable with the mean of a normal distribution. The shape parameter, β, is a measure of the range of failure and is representative of the variation within the sample set. A small β would indicate a high degree of variation due to defects or other non-uniformities, while large β would support a consistent failure across a given data set. The failure probability, *F*, is calculated for a given number of data points, *n*, in a data set from the expression

$$F(i,n) = {(i-0.44)}\Big/{(n+0.25)}, \quad (2)$$

where *i* is the test number of the data and *n* is the total number of data points collected within the group. The scale and shape parameters, α and β, are calculated from the failure probability and measured variable data, and a regression analysis calculates the statistical accuracy of α and β.

RESULTS AND ANALYSIS

Mechanical / Electrical Degradation

Weibull distribution of the electrical breakdown for the BIW Zion insulations is shown in Fig. 6 for three different aging temperatures as a function of time. The degradation observed from electrical breakdown appears to be comparable with that found in mechanical properties, with degradation increasing at higher aging temperatures. When the scale and the shape parameter from the Weibull distribution were compared directly to the indenter modulus curve (Fig. 7), the scale parameter, α, has the strongest correlation to the indenter modulus. For accelerated aging at 140°C and 150°C, the shape parameter decrease with the increase in indenter modulus would suggest that variation might increase as a function of time, but the data from 130°C did not show a strong correlation between these two factors. This could be the result of the small sample size and is worth considering in future characterization work.

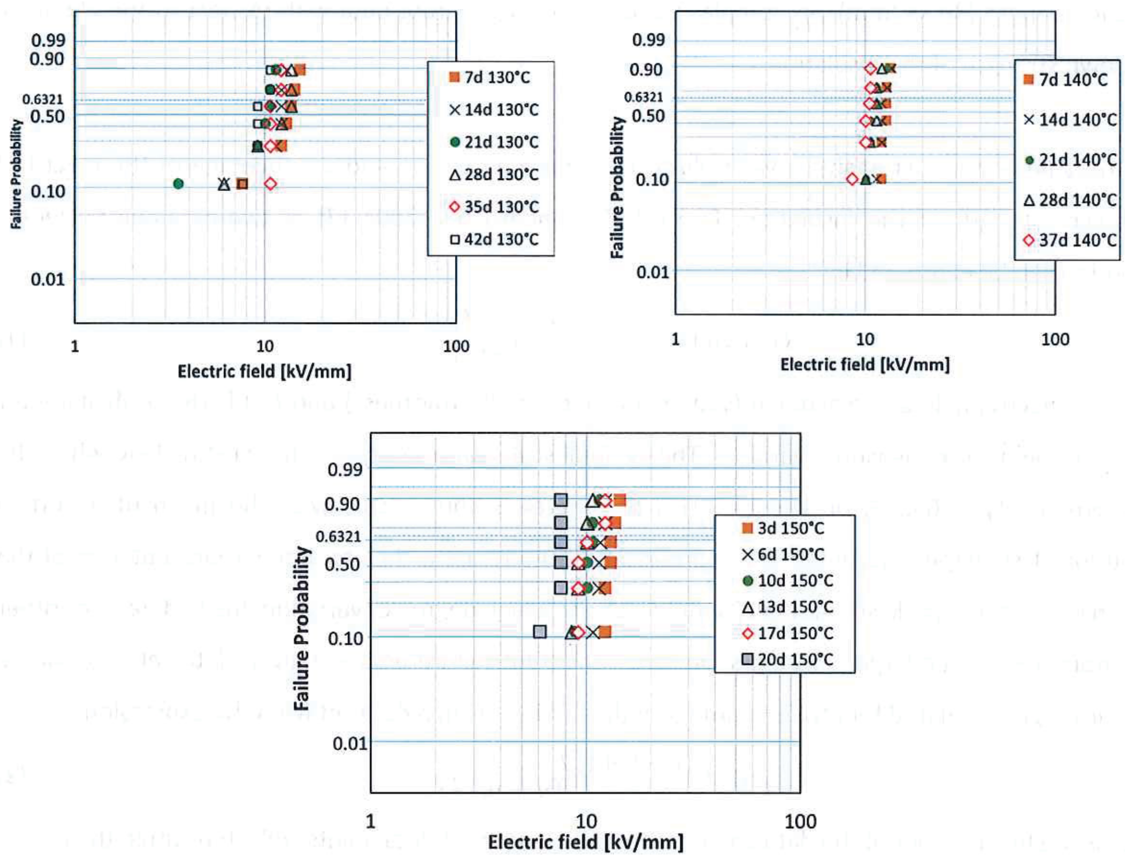

Fig. 6. Weibull distribution of electrical breakdown strength for BIW EPR/CSPE Zion insulation after thermal accelerated aging with respect to temperature and time.

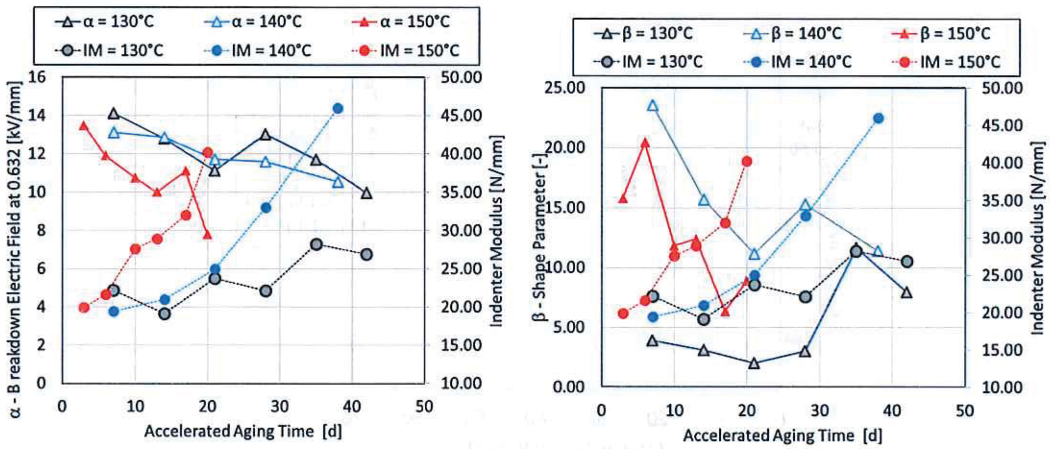

Fig. 7. Comparison of Weibull scale and shape parameters, α and β, for BIW (Zion) EPR/CSPE to indenter modulus data with respect to accelerated aging temperature and time.

The breakdown strength for BIW EPR/CSPE insulation that was harvested from the existing NPP showed no change with respect to aging temperature and time. Figure 8 shows the electrical breakdown strength for BIW EPR/CSPE insulation samples after 70 days at 130°C of accelerated aging. Accelerated aging was carried out for 20 days at 150°C and 35 days at 140°C, which was consistent with the BIW EPR/CSPE insulation from Zion. While degradation was not observed in electrical breakdown strength, the indenter modulus and relaxation time tracked with the time and temperature (Figs. 9 and 10). When comparing these results to the other insulations, several possible conclusions could be drawn. One possibility is that the Zion insulation experienced a higher level of aging based on its installation location. For EPR insulation, the literature puts the dielectric strength of EPR between 35 kV/mm and 45 kV/mm [8]. This would indicate that the dielectric strength for the auxiliary cable EPR/CSPE insulation was higher than expected, but there are differences in breakdown strengths measured at 0.1 Hz and 60 Hz. Another possibility is that thicker CSPE insulation could affect the aging of the insulation, whose impact has been shown in previous work on accelerated aging [5]. However, the increased amount of CSPE thought to be detrimental from the mechanical and chemical properties studied could be a benefit from an electrical property standpoint. Other explanations related to breakdown tests are possible when factors such as the number of samples tested and the test configuration are considered, but because the insulation samples did not experience electrical breakdown using the current test configuration, testing a group of the BIW EPR/CSPE insulations in oil with a higher voltage 60 Hz power supply would be a first step in determining the electrical breakdown strength of the insulation. Additional chemical and mechanical characterizations are planned on the remaining samples to determine whether previously observed degradation tracks with known parameters such as carbonyl index from Fourier-transform infrared spectroscopy (FTIR) and EAB.

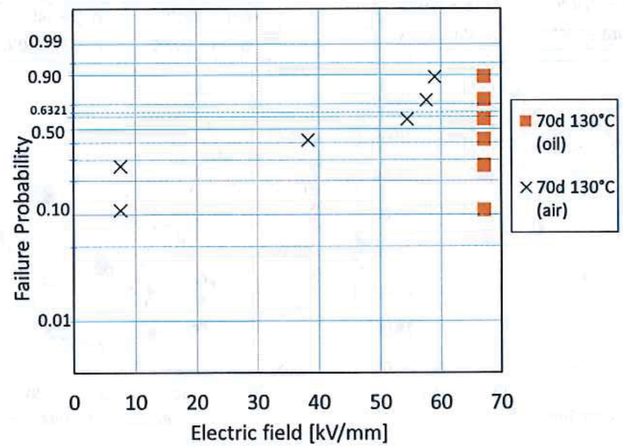

Fig. 8. Comparison of electrical breakdown strength for BIW EPR/CSPE (red) insulation in air and in oil after aging for 70 days at 130°C.

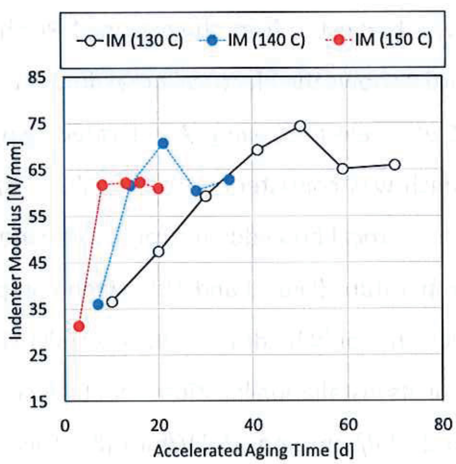

Fig. 9. Indenter modulus as a function of aging time and temperature from accelerated aging of BIW EPR/CSPE (red) insulation.

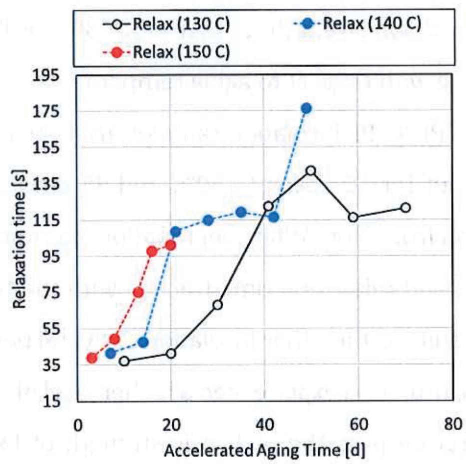

Fig. 10. Relaxation time as a function of aging time and temperature from accelerated aging of BIW EPR/CSPE (red) insulation.

Analysis of Electrical Breakdown Strength for Remaining Useful Life

Based on the degradation that was observed for the Zion BIW EPR/CSPE insulation, an Arrhenius-type analysis was performed relative to the scale parameter, α. The dependence of the scale and shape parameters on temperature and time are given in Fig. 11. An Arrhenius analysis assumes that the rate of degradation, k, with respect to temperature, *T*, can be expressed as

$$k \sim e^{\left[{}^{-E_a}/_{RT}\right]}, \tag{3}$$

where E_a is the activation energy and R is the ideal gas constant 8.314 kJ/kmol-K. Taking the 130°C case as the reference location, the times for the other temperatures were multiplied by a constant, a, and plotted with respect to inverse temperature (Fig. 12) before being fit by a curve (Fig. 13). Assuming a maximum operating temperature of 90°C, the remaining useful life could be found by dividing the time to failure relative to the other aging temperatures by 0.069. The question is then is how best to determine the time to failure relative to the data shown in Fig. 6 to determine the remaining useful life of the insulation.

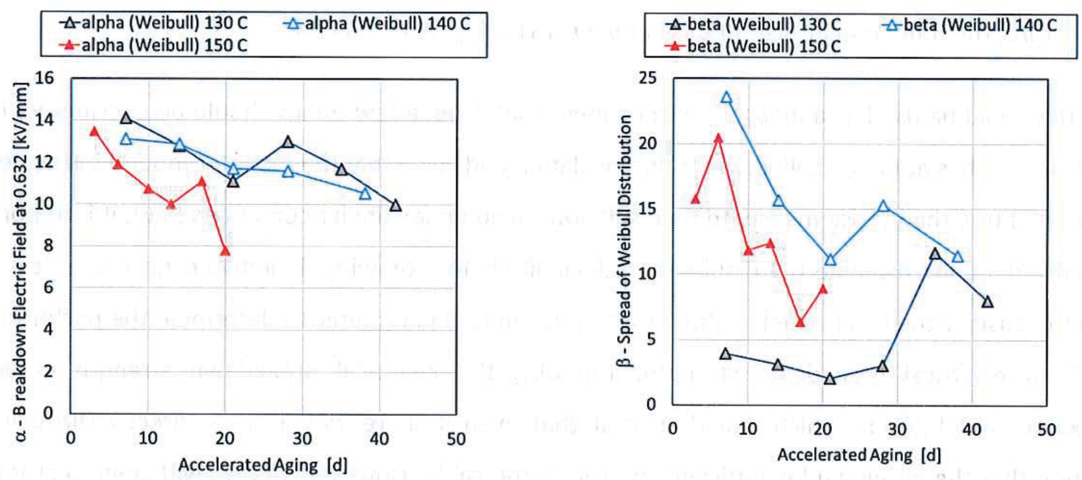

Fig. 11. Weibull shape parameters, α (left) and β (right), for electrical breakdown strength in Zion BIW EPR/CPSE from thermal accelerated aging at different temperatures and time.

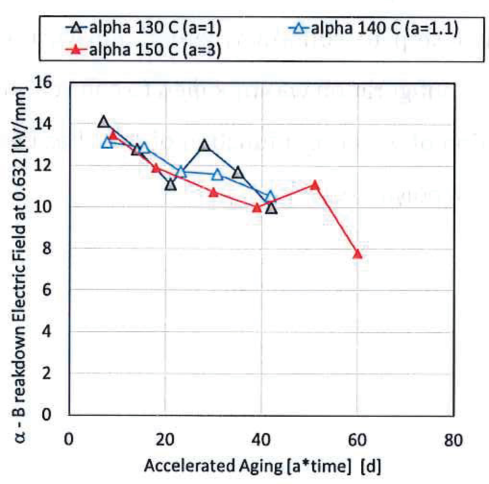

Fig. 12. Arrhenius analysis of Weibull shape parameter, α, for electrical breakdown strength in Zion BIW EPR/CPSE after accelerated aging time multiplied by a constant, a.

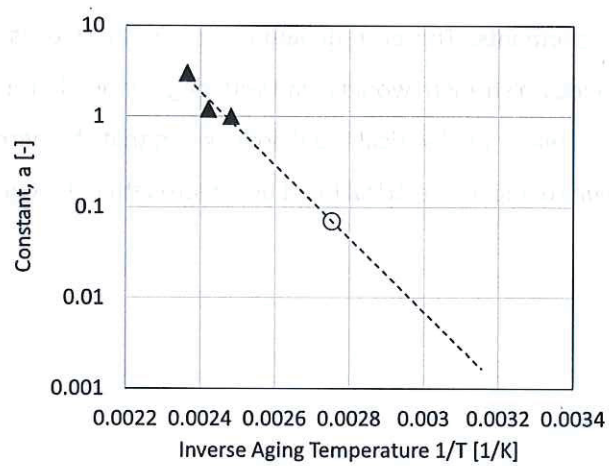

Fig. 13. Arrhenius constant, a, as a function of inverse aging temperature used to extrapolate a value at 90°C with exponential curve fit.

If the electrical breakdown strength follows the Weibull distribution expression in (1), the scale parameter, α, degrades linearly with time, and the shape parameter, β, is held constant at 10, the electrical breakdown was estimated at different values of α (Figs. 14 and 15). Data was only utilized for the 140°C and 150°C given the variation observed in the shape parameter, β, that was observed for the 130°C data. The two curve fits shown in these figures reflect the failure probability Weibull curves at 0.1% and 1.0% at 2.18 kV/mm. This is the electric field for the insulation thickness of 1.1 mm relative to an assumed voltage of 2400 Vac, which was the withstand voltage utilized in the EQ documentation mentioned earlier. For the values of α at 0.1% as the metric to determine the time to failure for each temperature, the time to failure at 90°C is between 1314 days and 2004 days.

While this could be used as a measure of remaining useful life, a few things should be considered. Data relative to EAB has not been collected for this insulation and given that the indenter modulus is higher by a factor of 3 to 4 than those measured on insulations aged under similar conditions [5,6], it is important to get this data and examine the results reproducibility before drawing definitive conclusions. It is also useful to consider the electric field value of 2.18 kV/mm as a parameter to determine the performance limit from electrical breakdown strength. Typically, the electrical breakdown strength in air is approximately 3 kV/mm, which would suggest that even if there was a crack directly through the insulation that the air would be sufficient to protect the cable. However, the AC withstand test for EQ testing was performed in water and not air. This would indicate the importance that water would play in the dielectric strength of the insulation and in future test configurations for electrical breakdown measurements. The current approach was utilized as a first step to confirm whether the electrical breakdown strength would trend with degradation before the configuration was modified to consider the role of water in electrical breakdown given that the permeation of water as a function of time has been shown to impact electrical breakdown strength in EPR and XLPE polymers [9].

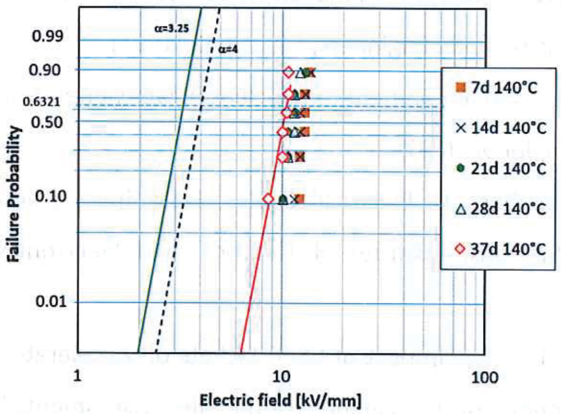

Fig. 14. Electrical breakdown of Zion BIW EPR/CPSE at 140°C along with assumed Weibull curve fits with different values of the shape parameter, α, to estimate at failure probabilities at 0.1% and 1.0% for the withstand voltage of 600 V or 2.18 kV/mm.

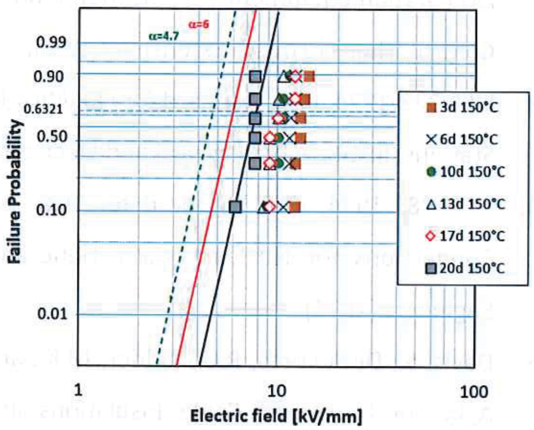

Fig. 15. Electrical breakdown of Zion BIW EPR/CPSE at 150°C along with assumed Weibull curve fits with different values of the shape parameter, α, to estimate at failure probabilities at 0.1% and 1.0% for the withstand voltage of 600 V or 2.18 kV/mm.

CONCLUSIONS

Electrical breakdown strength was measured in a series of ethylene propylene rubber (EPR)–insulated wires with chlorosulfonated polyethylene (CSPE) outer jackets that were manufactured by the Boston Insulated Wire Company (BIW) and harvested from nuclear power plants (NPPs). Two types of BIW insulations were examined to determine whether functional dependencies for the electrical breakdown strength existed with respect to thickness and composition. Thermal accelerated aging of the wires was done at temperatures between 130°C and 150°C prior to electrical breakdown measurements. Degradation in electrical breakdown strength was observed for the BIW EPR/CSPE insulation that was harvested from the motor control area of the Zion NPP, but no degradation was observed for the harvested BIW insulation from the auxiliary room of another NPP. Although this lack of degradation could be indicative of the amount of remaining useful life of the insulation, degradation as observed by the indenter modulus indicated that additional analysis was needed. Possible modification to the test configuration would incorporate the EQ configuration with water and bending the insulation on a similar diameter could be beneficial. Additional characterization relative to EAB and carbonyl content is also planned to understand the degradation or lack thereof relative to other known parameters.

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