

Light Water Reactor Sustainability Program

Evaluation of Inverse Temperature Effects on Cable Insulation Degradation in Accelerated Aging of High Priority Cable Insulation Materials



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Evaluation of Inverse Temperature Effects on Cable Insulation Degradation in Accelerated Aging of High Priority Cable Insulation Materials

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August 30, 2019

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SUMMARY

Electrical cable insulation may degrade over time in service as a result of exposure to elevated temperature and gamma irradiation if the cable is at a location in the plant, such as inside containment, where both stresses occur. Cable polymer insulation generally degrades faster at higher temperatures. The extent of degradation is also generally proportional to the absorbed radiation dose. Accelerated aging at high temperatures and high doses has been used in the laboratory to simulate cable material aging that occurs in the milder temperatures and lower doses experienced by cables in in service over the 40-year or longer life of the reactor. It has been observed, however, that certain materials under particular circumstances undergo more significant damage from radiation at lower temperatures than they do at higher temperatures through what is known as the 'inverse temperature effect' (ITE). Due to idiosyncrasies of certain polymers under particular conditions, such as when comparing radiation degradation rates above and below the melt phase transition of the material, the prediction of long-term degradation from short term accelerated aging can be more complex than the general case.

Accelerated aging of nuclear cables in the historical process of qualification used temperatures from around 109 °C to around 165 °C to replicate in service thermal aging of cable materials which might occur at around 50 °C. Gamma radiation exposure of cables in service may occur at elevated temperature or may occur to cables at mild ambient temperature. Combined thermal/gamma radiation laboratory aging to predict cable performance under milder, long-term conditions may underestimate cable materials degradation if ITE were to exist for the material and for the in-service and laboratory conditions on which the prediction is based.

In this work, Pacific Northwest National Laboratory (PNNL) is exposing a series of nuclear cable polymer insulation samples to gamma radiation at different temperatures to understand ITE in the materials. Insulation from eight different cables was used, representing some of the most prevalent varieties of low voltage cable insulation found in U.S. nuclear power plants (NPPs). A dose rate of 100 Gy/h was selected to be as low as practical to avoid dose rate effects, while still achieving a relevant maximum dose of 300 kGy in a feasible amount of time. Corresponding samples were simultaneously exposed at 26, 50 and 90 °C to identify if degradation of the materials, as tracked by mass change, follows with temperature.

Mass change, the difference between the mass of a polymer sample before exposure and the mass of the sample after exposure, has been observed to track linearly with thermal exposure time for cross-linked polyethylene (XLPE) and ethylene-propylene rubber (EPR) at a series of temperatures. It was therefore explored here as a method to track relative changes in cables insulation material with radiation exposure at different temperatures.

ITE refers to the situation in which polymer material exposed to gamma irradiation is observed to undergo more extensive degradation at lower temperatures than at higher temperatures. This can be due to phase transitions and relative molecular motion differences in polymers with temperature that alter the aging mechanism at contrasting temperatures. A concern with ITE is that accelerated laboratory aging occurs at temperatures much higher than what occurs in service and, with ITE, may underestimate degradation that would occur in the lower service temperature. Expected useful lifetimes for environmentally qualified nuclear cables are largely based on extrapolation of laboratory accelerated aging results to in service environments. As U.S. plants enter operational periods longer than originally envisioned in the qualification process, it is important to refine historical understanding of cable insulation aging in containment to enable efficient and effective cable aging management. This work will inform risk ranking of cable materials for assessment and replacement decisions by identifying which of the common materials are most likely to have degradation rates underestimated in initial qualification experiments.

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CONTENTS

SUMMARY	ii
ACKNOWLEDGMENTS	iii
CONTENTS.....	v
FIGURES	vi
ACRONYMS AND ABBREVIATIONS.....	vii
1. INTRODUCTION.....	8
2. EXPERIMENTAL	9
2.1 Materials.....	9
2.2 Exposure.....	10
3. RESULTS.....	10
4. CONCLUSIONS	14
5. FURTHER WORK.....	15
6. IMPACT OF THS WORK.....	15
7. REFERENCES	16

FIGURES

Figure 1. Mass change of Brand-Rex XPLE (XX28) with time and temperature.	9
Figure 2. Mass change of Anaconda EPR (AE21) with time and temperature.....	9
Figure 3. Mass change with gamma dose for RSCC XLPE (RX82).	11
Figure 4. Mass change with gamma dose for Rockbestos XLPE (RX39).	11
Figure 5. Mass change with gamma dose for Anaconda EPR (AE21).	12
Figure 6. Mass change with gamma dose for Brand-Rex XLPE (XX28).....	12
Figure 7. Mass change with gamma dose for Okonite EPR (OE34).	13
Figure 8. Mass change with gamma dose for Kerite HTK (KH31).	13
Figure 9. Mass change with gamma dose for Samuel Moore (SE79).	14
Figure 10. Mass change with gamma dose for BIW EPR (BE15).	14

TABLES

Table 1. Cable Insulation Materials Studied (PNNL ID in parentheses).....	10
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ACRONYMS AND ABBREVIATIONS

EPR	ethylene-propylene rubber
HEF	High Exposure Facility
ITE	inverse temperature effects
LWRS	Light Water Reactor Sustainability
NPP	nuclear power plant
PNNL	Pacific Northwest National Laboratory
S/E	synergistic effects
SLR	subsequent (or second) license renewal
XLPE	cross-linked polyethylene

1. INTRODUCTION

Electrical cable insulation may degrade over time in service as a result of exposure to elevated temperature and gamma irradiation if the cable is at a location in the plant, such as inside containment, where both stresses occur. Cable polymer insulation generally degrades faster at higher temperatures. The extent of degradation is also generally proportional to the absorbed radiation dose. Accelerated aging at high temperatures and high doses has been used to simulate cable material aging over the milder temperatures and lower doses experienced by cables in service over the 40-year or longer life of a reactor. It has been observed, however, that certain materials under certain circumstances undergo more significant damage from radiation at lower temperatures than they do at higher temperatures through what is known as the 'inverse temperature effect' (ITE) [1]. Due to idiosyncrasies of certain polymers under particular conditions, such as when comparing radiation degradation rates above and below the melt phase transition of the material, the prediction of long-term degradation from short term accelerated aging can be more complex than the general case.

Accelerated aging of nuclear cables in the historical process of qualification used temperatures from around 109 °C to around 165 °C to replicate in service thermal aging of cable materials which might occur at around 50 °C. Gamma radiation exposure of cables in service may occur at elevated temperature or may occur to cables at mild ambient temperature. Combined thermal/gamma radiation laboratory aging to predict cable performance under milder, long-term conditions may underestimate cable materials degradation if ITE were to exist for the material and for the in-service and laboratory conditions on which the prediction is based.

In this work Pacific Northwest National Laboratory (PNNL) is exposing a series of nuclear cable polymer insulation samples to gamma radiation at different temperatures to understand ITE in the materials. Insulation from eight different cables was used, representing some of the most prevalent varieties of low voltage cable insulation found in U.S. nuclear power plants. A dose rate of 100 Gy/h was selected to be as low as practical to avoid dose rate effects, while still achieving a relevant maximum dose of 300 kGy in a feasible amount of time. Corresponding samples were simultaneously exposed at 26, 50 and 90 °C to identify if degradation of the materials, as tracked by mass change, follows with temperature.

Mass change, the difference between the mass of a polymer sample before exposure and the mass of the sample after exposure, has been observed to track linearly with thermal exposure time for cross-linked polyethylene (XLPE) (Fig. 1) and ethylene-propylene rubber (EPR) (Fig. 2) at a series of temperatures [2]. It was therefore explored here as a method to track relative changes in cables insulation material with radiation exposure at different temperatures.

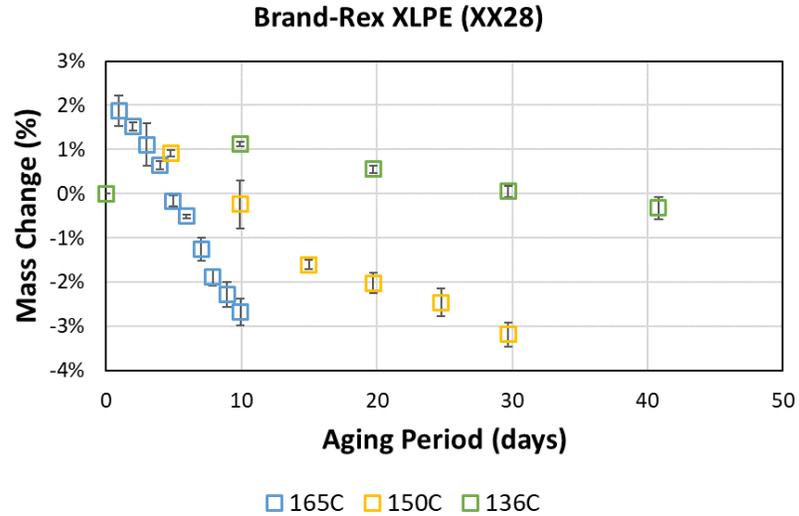


Figure 1. Mass change of Brand-Rex XPLE (XX28) with time and temperature.

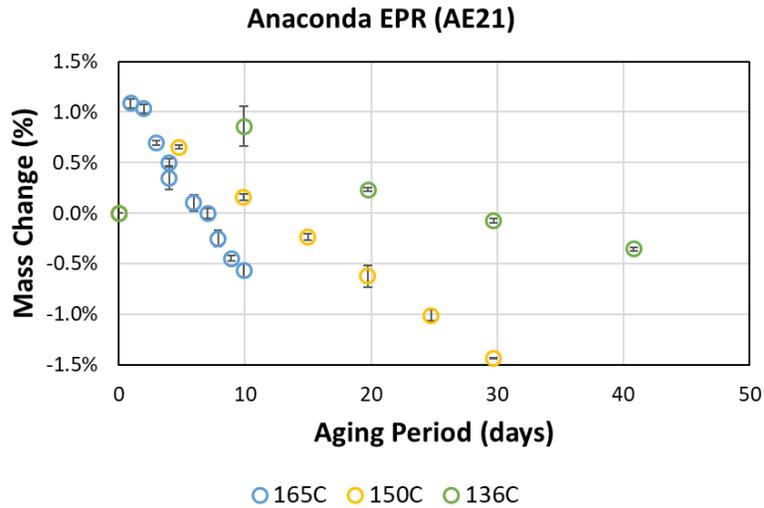


Figure 2. Mass change of Anaconda EPR (AE21) with time and temperature.

2. EXPERIMENTAL

2.1 Materials

The most popular cable insulations employed inside nuclear power plant containments are: Rockbestos Firewall III (XLPE), Anaconda EPR, Brand-Rex XLPE, Okonite EPR, Kerite HTK, Rockbestos Coax, Raychem XLPE, Samuel Moore, BIW Bostrad, and Kerite FR [3]. The materials used in this study correspond with most of the cables on this list of the most common and are described in PNNL-27987 [4]. They include vintage insulation formulations source from harvested Crystal River Unit 3 cables plus one new RSCC XLPE material. Each sample consists of an insulation ‘straw’ with the metal

conductor removed from its center. Average and standard deviation value of sample masses are determined using three straw samples for each variation.

Table 1. Cable Insulation Materials Studied (PNNL ID in parentheses)

RSCC XLPE (RX82) – modern
Rockbestos XLPE (RX39)
Anaconda EPR (AE21)
Brand-Rex XLPE (XX28)
Okonite EPR (OE34)
Kerite HTK (KH31)
Samuel Moore EPDM (SE79)
BIW EPR (BE15)

2.2 Exposure

A cobalt-60 source in the High Exposure Facility (HEF) facility at PNNL was used for gamma exposure. Air circulating mechanical convection ovens were used to hold samples at 50 and 90 °C, respectively, while 26 °C samples were located outside of an oven during exposure. The distance of the samples from the source determined the gamma dose rate and the three racks containing the three set of samples at different temperatures were positioned with respect to the source to achieve a 100 Gy/h dose rate at the midpoint of the samples.

3. RESULTS

In general, for all the materials, mass change tracks with gamma dose. In some cases, mass increases with dose and in some cases it decreases. For most of the materials where trends are observable, the mass change trends with temperature, being most extreme at the most extreme of the three temperatures investigated: 90 °C.

In Fig. 3, the mass of RSCC XLPE increases with exposure under the conditions explored, the greatest increase is for exposure at 26 °C, and the increase is intermediate for the intermediate temperature of 50 °C. This insulation was the only one of contemporary manufacture of those described, with current formulation. The others were harvested from cables installed decades ago and constructed of historical insulation formulations no longer available.

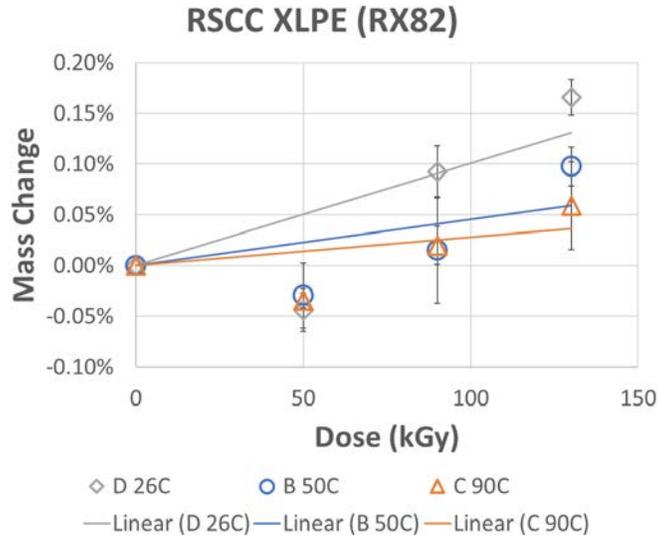


Figure 3. Mass change with gamma dose for RSCC XLPE (RX82).

In Fig. 4, the mass of Rockbestos XLPE (RX39) (that is expected to be similar in formulation to the RSCC XLPE) is also seen to increase with gamma exposure. However, for this material it is the 90 °C samples that experience the greatest mass gain followed by the 26 °C samples.

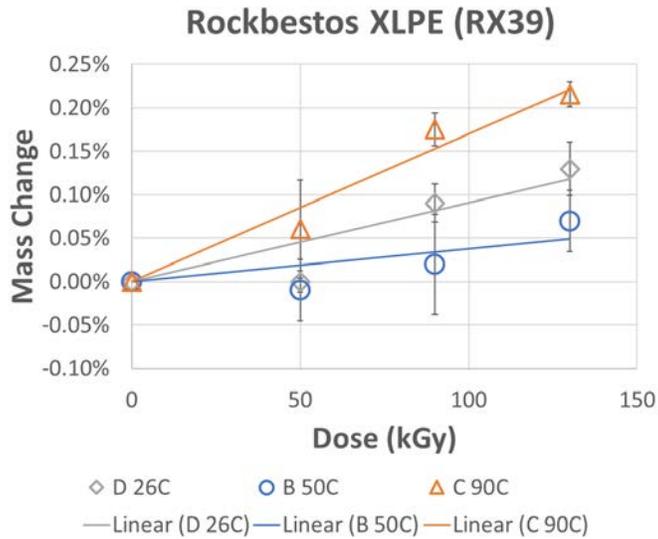


Figure 4. Mass change with gamma dose for Rockbestos XLPE (RX39).

Mass change for the Anaconda EPR (AE21), plotted in Fig. 5, does not exhibit an obvious trend, even with removal of the significant outlier point at 90 °C and 90 kGy. This is unexpected as the same material exhibits very clear mass change with thermal only exposure, seen in Fig. 2.

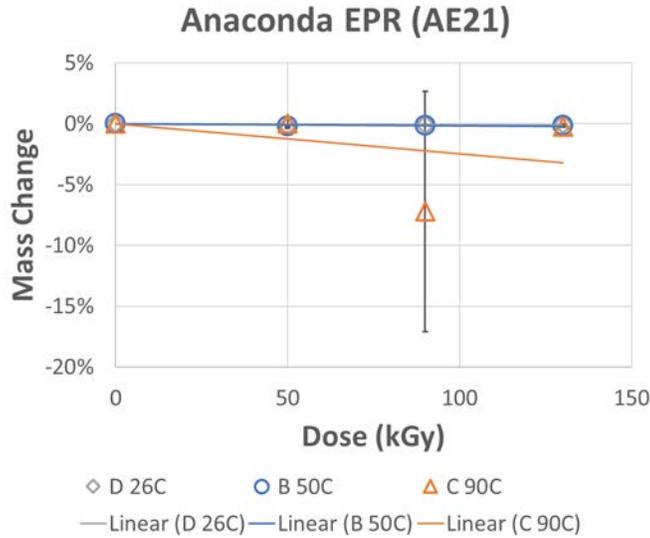


Figure 5. Mass change with gamma dose for Anaconda EPR (AE21).

The Brand-Rex XLPE (XX28) shows unusual mass change behavior with exposure in Fig. 6 in that the mass increases for the 26 °C samples, but decreases for the 50 °C and 90 °C samples. Later exposure time points (in progress) may clarify or reinforce this behavior.

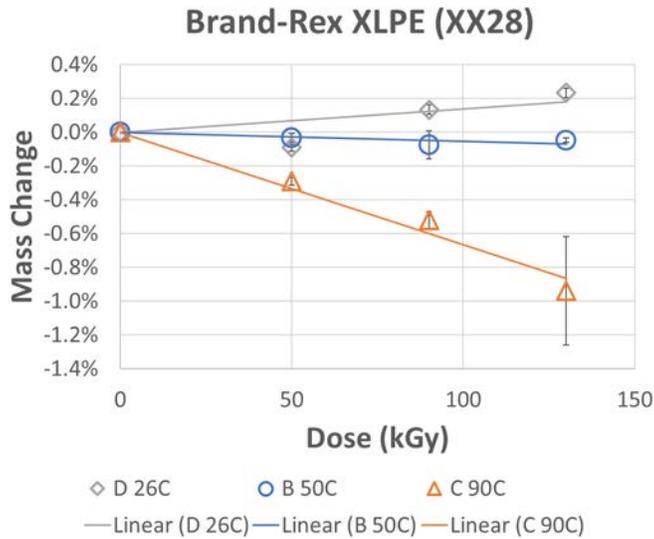


Figure 6. Mass change with gamma dose for Brand-Rex XLPE (XX28).

The Okonite EPR (OE34) material is seen in Fig. 7. to decrease in mass with exposure; mass decrease rate trended with temperature from 26 to 50 to 90 °C.

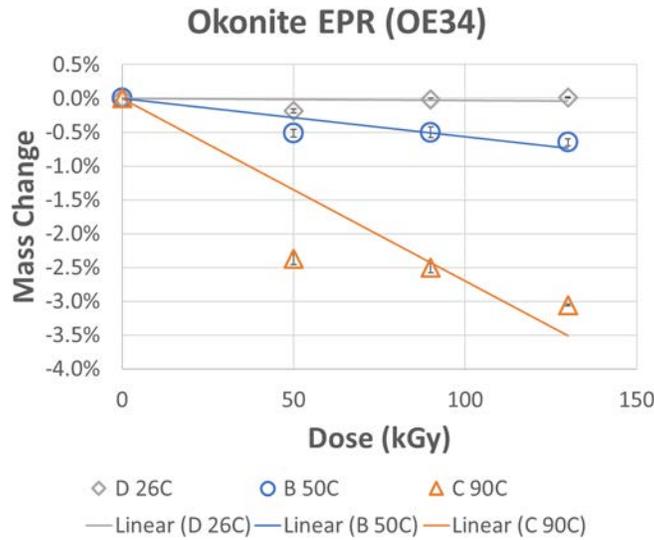


Figure 7. Mass change with gamma dose for Okonite EPR (OE34).

Mass change of Kerite HTK (KH31) in Fig. 8 shows a very similar trend to that of Okonite EPR (OE34) in Fig. 7. HTK is an ‘EPR-like’ material and may perform similarly to EPR under the degradation scenario explored.

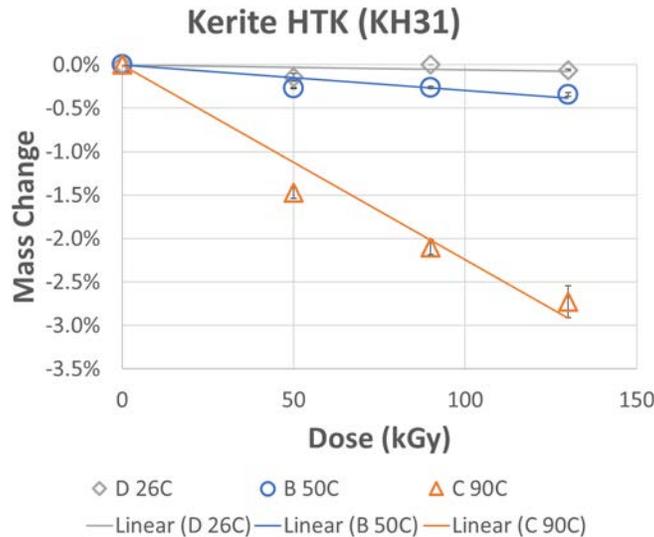


Figure 8. Mass change with gamma dose for Kerite HTK (KH31).

The Samuel Moore EPDM (SE79) material also exhibits mass loss with exposure as seen in Fig. 9, but the order of mass decrease rate is not as clear. Standard deviation of mass change among Samuel Moore samples is greater than that for many of the other materials considered.

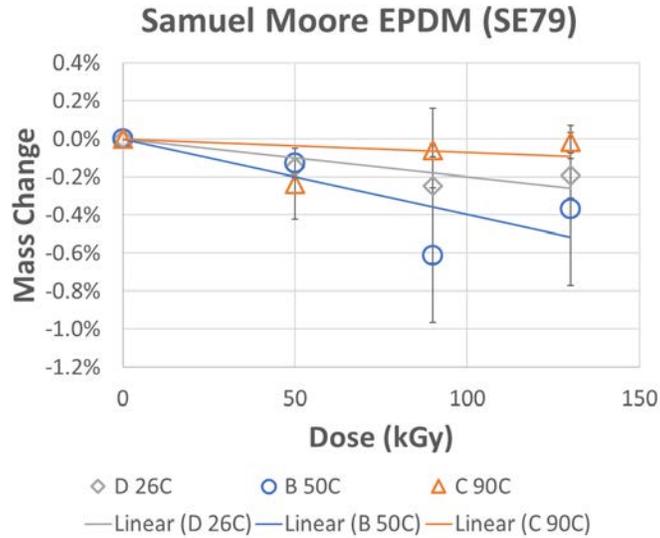


Figure 9. Mass change with gamma dose for Samuel Moore (SE79).

The BIW EPR (BE15), another common EPR material, shows in Fig. 10 very similar degradation behavior to that seen for the Okonite EPR insulation in Fig. 7 and the Kerite EPR insulation in Fig. 8.

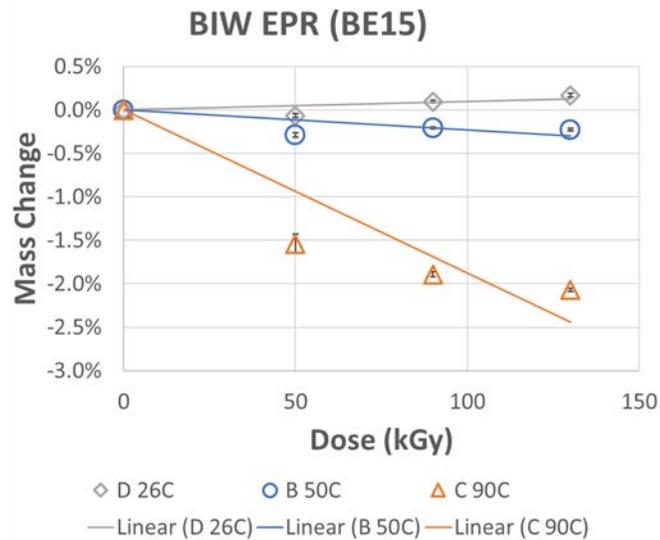


Figure 10. Mass change with gamma dose for BIW EPR (BE15).

4. CONCLUSIONS

The masses of cable insulation ‘straw’ samples are generally observed to change with gamma exposure. This mass change may be due to chain scission of the constituent polymer and volatilization of low molecular weight fragments. It may also be due to loss of lower molecular weight additives within the insulation formulation. Interestingly, while most materials show progressively greater mass loss with temperature increase, some of the materials considered, namely the XLPE-based Rockbestos, RSCC, and Brand-Rex materials, gain mass with exposure. Mass gain may be associated with oxidation reaction in

which oxygen in the air reacts with radicals generated on polymer chains in the material to add oxygen functionalities where there were none and thus increases the weight of the sample.

Completion of additional exposure time data points in the ongoing work will strengthen understanding of the trends observed in the first three dose level points considered.

5. FURTHER WORK

The series of samples described here are half of those utilized in the experiment, with total absorbed gamma doses of 50, 90 and 130 kGy. Samples currently undergoing radiation exposure include those designated for 170, 210, 250 and 300 kGy. Data from these additional exposure points will serve to further reveal trends in material degradation with temperature and with dose more closely corresponding to significant long-term aging.

In addition to analysis of mass change for the remaining samples, a complete set of testing and characterization is planned for these samples to understand ITE in these materials including mechanical, physical and chemical testing. Infrared spectroscopy may reveal the presence of oxidation in the weight-gaining XLPE samples. X-ray diffraction and differential scanning calorimetry may reveal difference in crystallinity and phase change temperatures between the sample types that could be correlated with any temperature dependence observed.

Identification of the presence and extent of ITE in the materials studied will be reported in the context of previous work and the identified ITE knowledge gap.

6. IMPACT OF THIS WORK

ITE refers to the situation in which polymer material exposed to gamma irradiation is observed to undergo more extensive degradation at lower temperatures than at higher temperatures [1]. This can be due to phase transitions and relative molecular motion differences in polymers with temperature that alter aging mechanism at contrasting temperatures. A concern with ITE is that accelerated laboratory aging occurs at temperatures much higher than what occurs in service and, with ITE, may underestimate degradation that would occur in the lower service temperature. Expected useful lifetimes for environmentally qualified nuclear cables are largely based on extrapolation of laboratory accelerated aging results to in service environments. As U.S. plants enter operational periods longer than originally envisioned in the qualification process, it is important to refine historical understanding of cable insulation aging in containment to enable efficient and effective cable aging management. This work will inform risk ranking of cable materials for assessment and replacement decisions by identifying which of the common materials are most likely to have degradation rates underestimated in initial qualification experiments.

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