Advanced Models for Nondestructive Evaluation of Aging Nuclear Power Plant Cables

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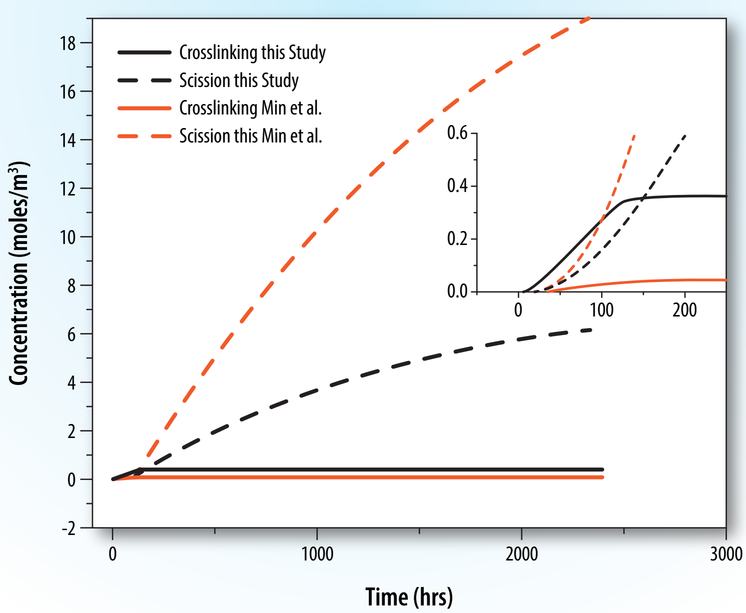
Nuclear power plant cables must function correctly for proper power supply and control of the nuclear reactor under rigorous conditions. This is especially important for public and environmental safety at critical times, such as during postulated design basis events. Over extended periods of service, the cable insulation and plastic jacket suffer from degradation due to environmental exposure in a complex and harsh service environment that can include elevated temperature and gamma radiation.

This Nuclear Energy University Project (NEUP), which concluded in March 2018, linked directly to the LWRS Program goals through several objectives. The first was to develop advanced, validated models relating microstructural and chemical changes due to thermal and gamma radiation exposure of cable insulation polymers to observable changes in physical, mechanical, and electrical properties. The second was to identify, from this information, the most sensitive indicators of microstructural and chemical changes in the polymers. The third was to employ this information to enable the non-destructive determination of the cable material state. To achieve these objectives, a diverse team with expertise in polymer science, materials modeling, materials informatics, electrical properties of materials, and nondestructive evaluation was assembled from Iowa State University, Pacific Northwest National Laboratory (PNNL), and the University of Bologna.

The two most prevalent cable insulation polymers found in U.S. nuclear power plants, cross-linked polyethylene (XLPE) and ethylene propylene rubber, were selected for this study. Accelerated aging was conducted by suspending samples

Figure 4. Comparison of kinetic models presented in this study and those reported by Min et al. [1] for oxygen concentration in polyethylene samples aged with gamma radiation at dose rate 100 Gy/h for 5 days. The inset shows the crossover points of the models.



in an oven that was placed inside the High Exposure Facility of the Radiological Exposures and Metrology Laboratory at PNNL. Simultaneous thermal and radiation aging of XLPE samples was achieved by controlling the oven temperature as it was placed in the gamma-ray field. The dose rate and total radiation dose received by each sample were controlled by the position of the sample within the oven and the number of days of exposure, respectively. Different aging temperatures were achieved by running multiple rounds of the experiment with different oven temperatures.

The first project objective—to develop models of material aging—was approached by developing a kinetic rate model based on a set of likely chemical reactions occurring in polyethylene exposed to elevated temperature and gamma radiation. The results that were obtained from this kinetic model under different radiation conditions (i.e., dose rate, dose duration, and temperature) were used to build an analytical model that predicts the degree of polymer cross-linking and chain scission (e.g., the mechanisms for polymer degradation) occurring during the aging process, as a function of time and radiation rate. The model improves upon a previous one in which the long-time concentration of scission sites continued to increase, as shown in Figure 4.

The second project objective—to identify key indicators of aging—was approached in one of two ways, depending upon whether the data was single-point or spectral data. In the case of single-point data, materials informatics (multivariate analysis) was employed to find the key indicators of degradation of aged XLPE. Several kinds of data that had been measured on the sample set were analyzed: mass loss, elongation-at-break, indenter modulus, mass density, and oxidation induction time. Of these, it was determined that multiple regression analysis models provided a satisfactory result for predicting the outcome of oxidation induction time measurements on XLPE samples whose exposure temperatures and radiation aging conditions were known and fell within the bounds of the radiation conditions studied here.

The third project objective—to support nondestructive evaluation of the cable material state—was approached by making measurements of polymer dielectric parameters that can, in principle, be made nondestructively on in-service cables by a suitable capacitive sensor. Results showed that dielectric loss increases nearly linearly with aging time for samples aged in the presence of gamma radiation, as shown in Figure 5. Capacitive sensing is, therefore, a promising tool for nondestructive evaluation of insulation material state.

The completion of this NEUP provides the nuclear industry with an increased understanding of cable degradation mechanisms in common insulation types and has identified key measurements and potential monitoring techniques for the assessment of cable life. The collaboration effort from this work continues through further development of the modeling and monitoring techniques for cable insulation evaluation under the umbrella of an International Nuclear Energy Research Initiative United States-Euratom Collaboration, "Advanced Electrical Methods for Cable Lifetime Management."

References

1. D. Min, S. Li, N. Hirai, and Y. Ohki, "Modeling of oxidation process and property changes of ethylene-propylene-diene copolymer," IEEE Trans. Dielectr. Electr. Insul., Vol. 23, No. 1, pp. 537–546, February 2016.

Figure 5. Dielectric loss tangent as a function of frequency for XLPE samples aged at 90°C with gamma radiation at dose rate 450 Gy/h, for 0, 5, 10, 15, and 20 days.