Insight into Thermal Aging of Jacket-Bonded Ethylene-Propylene Rubber Cable Insulation

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INTRODUCTION

Electrical cables are integral to nuclear power plant operation and control during power generation, during planned outages, and during design basis events. Polymeric insulation and jacketing used in cable construction does age over time as a function of environmental stresses including heat, moisture, and radiation. Degradation of polymer mechanical properties can lead to breaks in the insulation and consequent electrical shorting. The tensile elongation at break (EAB) has therefore developed as a metric of cable health for elastomeric cable insulation. A conservative estimate of the ability of a cable to perform its safety-related function in the case of a design basis event such as a loss of coolant accident is associated with an EAB value of 50%. The lifetime curve then of cables thus maps exposure over time from initial EAB values of ~300% to approximate end of remaining useful life at 50%. A condition monitoring program for installed cables may correlate non-destructively measured key indicators of aging with corresponding EAB values to place snapshots of cable health on the cable lifetime curve for predictive value. A cable far from the end of its remaining useful life may safely be retained. A cable status corresponding to further along its lifetime curve may need to be scheduled for evaluation more frequently or even scheduled for immediate replacement prior to functional failure.

Key indicators of material aging including EAB can be correlated with aging state using laboratory accelerated aging. So-called lifetime curves plot measured signal versus exposure time from new, unaged material through material state corresponding to end of useful life. These curves can be used to calibrate non-destructive measures of aging with cable functional state. One challenge to the extrapolation of laboratory empirical data to field assessment is the question of how closely laboratory aging approximates long term, in plant aging. For instance, do material changes in a cable exposed to 140°C for a few months mirror those of the same cable exposed to service temperatures of 50°C for a several decades? A second challenge to the validity of this approach is the question of how closely do material changes in free-standing polymer insulation specimens, such as those used for determining tensile EAB, represent changes in polymer material intact in a cable assembly (including semiconducting layers, fillers, metallic shielding, jacket, etc.) exposed to the same environmental conditions?

The interaction of material components within a cable assembly can be a factor in the aging of the polymer insulation that may not be reflected in accelerated aging of the polymer alone. Additives or chemical break-down products from one component such as the jacket of the exposed assembly may affect the aging of the insulation. Also, materials in cable configurations in which a jacket layer is bonded to the insulation during the manufacturing extrusion process may present a new material case whose degradation is distinct from that of the separate components.

In this work we consider the thermal aging behavior of one of the two most common insulation polymer classes in nuclear power plants, ethylene-propylene rubber (EPR), both as an independent material and within a cable in which the EPR is bonded to a chlorinated polyethylene (CPE) jacket. Understanding the changes in these two materials with aging, both independently and in concert, will allow the establishment of aging lifetime curves and enable the development of effective non-destructive methods for tracking the condition of installed cables composed of similar material systems. Additional and more effective methods for monitoring the condition of installed cables are needed as a technical basis for continued safe use of aging cables in long term operation and to minimize operating costs for cable aging management through better informed retain/repair/replace decisions.

EXPERIMENTAL

Materials

EPR-insulated cable, Okoguard®-Okolon® TS-CPE Type MV-90 2.4kV Nonshielded Power Cable (Catalog Number 114-24-2227), was purchased from The Okonite Company. Okoguard® is an EPR-based thermosetting compound with a distinctive red (pink) color. Okolon® TS-CPE is a flame, radiation and oil resistant, vulcanized chlorinated polyethylene-based compound that is black in color. There is no shielding or other material layer between the CPE and the EPR is this cable and we were unable to separate the layers one from another. Incidentally, the insulation is also bonded to an inner extruded semiconducting EPR layer, black in color, between the insulation and the uncoated, compact stranded copper conductor. To obtain tensile behavior of the EPR with exposure, free-standing samples with controlled dimensions were sought.

Pressed mats of similar red-colored Okoguard-type EPR insulation were graciously supplied directly from The Okonite Company. These ~9-in x 9-in x 0.125-in mats are convenient for cutting and stamping specimens from.

Methods

Cable segments of 8-in in length were placed on oven racks for aging. The ends of the cable were covered with aluminum foil secured with O-rings to discourage infiltration of air to the cable interior during aging. Stamped tensile specimens from the EPR mat were held by clamps and hung from hooks during aging. A Heratherm OMH180 (ThermoScientific) advanced protocol oven with mechanical convection for air circulation was used for the accelerated aging. The oven was kept at 140C throughout aging. Samples were all loaded into the oven initially and removed one set at time, approximately once per week for 9 weeks.

As-received and aged dumbbell specimens stamped from the EPR mat were pulled to failure to identify EAB values. Fourier Transform Infrared spectroscopy (FTIR)-based chemical change indexes were calculated from the ratios of absorbance peaks recorded using the attenuated total reflectance (ATR) mode of a Thermo Scientific™ Nicolet™ iS™ 10 FT-IR Spectrometer equipped with a diamond crystal ATR attachment. FTIR spectral results were used to calculate aging indices for the EPR insulation and the CPE jacket. Carbonyl index (CI) is defined as the ratio of absorbance A at 1740 cm^{-1} to absorbance at 2850 cm^{-1}:

$$CI = \frac{A_{C=O}}{A_{C-H}} = \frac{A_{1740cm^{-1}}}{A_{2850cm^{-1}}} \qquad (1)$$

Density measurements were made using the Archimedes method in air and in water. Indenter modulus values of cable segments were evaluated using an Ogden Environmental & Energy Services Indenter Polymer Aging Monitor 2 (IPAM2) instrument

RESULTS

The EAB lifetime curve for the EPR material exposed to 140°C in circulating air is shown in Fig. 1. The photograph inset to the figure illustrates the color change for the red EPR specimens during the aging. The profound darkening within 14-days occurred for these specimens aged in proximity to the jacketed cable segments in the same oven and did not occur to nearly the same extent for specimens aged in an oven without CPE-jacketed cables (not shown).

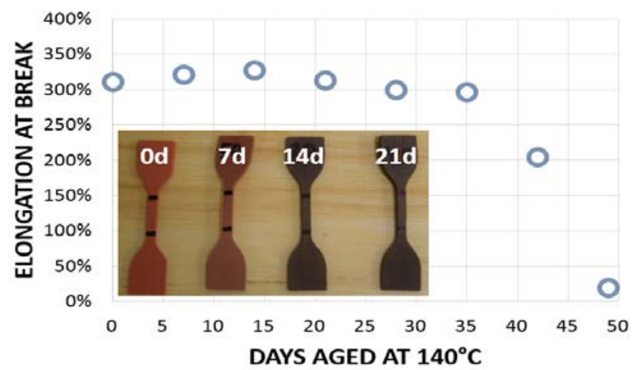

Fig. 1. EAB versus days at 140°C for EPR mat specimens.

FTIR tracking of oxidative aging for the EPR mat material was measured on the red EPR interior of the blackened specimens. Fig. 2 reveals that changes in the carbonyl index (CI) with aging coincide with the EAB changes plotted in Fig. 1. The photo inset to Fig. 2 shows an EPR specimen sliced open to reveal the interior for FTIR measurement.

CI calculated from FTIR spectra of EPR material isolated from the aged cable segments, plotted in Fig. 3, did not reveal the same identifiable oxidation trend as the EPR from the tensile specimens.

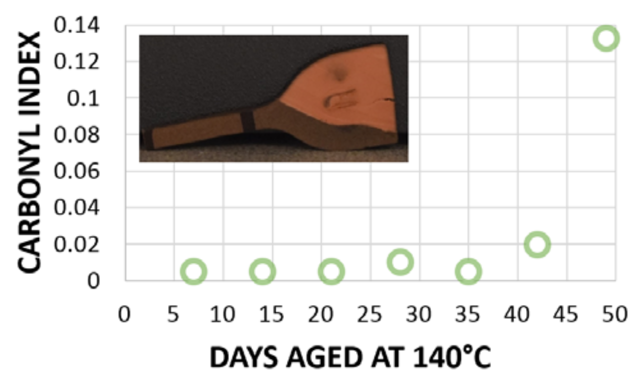

Fig. 2. CI versus days at 140°C for EPR specimen interiors.

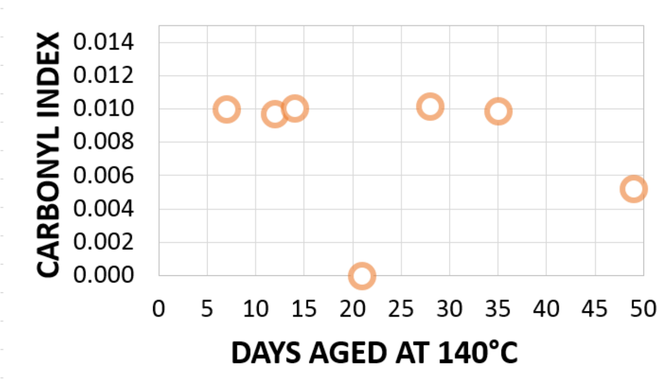

Fig. 3. CI versus days at 140°C for EPR cable material.

The density of EPR samples from the mat tensile specimens and cut from the insulation of the aged cable segments were also measured in an attempt to track aging in both using a method amenable to the form factors of each. The results of density versus aging time shown in Fig. 4 showed similarity in trend between the two materials, but not a clear trend in the density with aging.

It was observed in cable segment cross sections, as seen in the insert of Fig. 5, that the interface between the black CPE jacket and the red EPR insulation grew darker in the course of aging. The thickness of this interfacial layer versus aging time is plotted in Fig. 5.

CI calculated from the FTIR spectra of the black CPE cable segment jacket, plotted in Fig. 6, indicated oxidation after 30 days of exposure at 140°C.

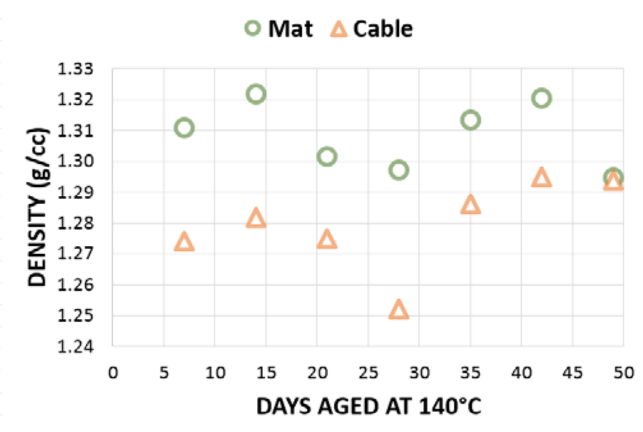

Fig. 4. Density versus days at 140°C for EPR samples.

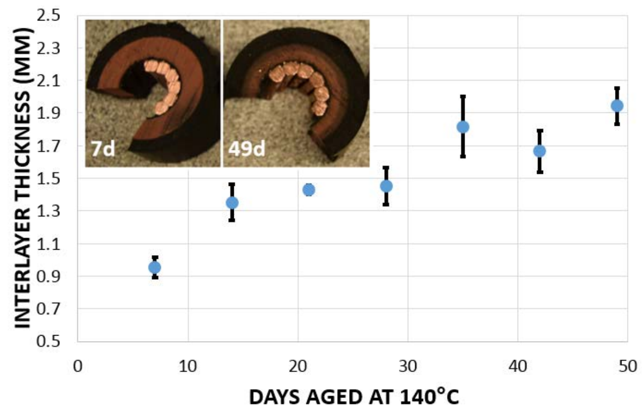

Fig. 5. Interlayer thickness of cable segments aged at 140°C.

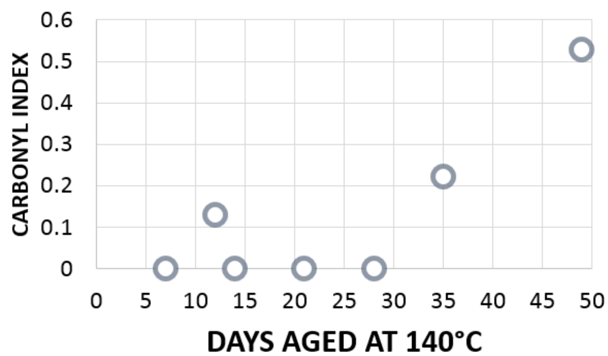

Fig. 6. CI versus days at 140°C for CPE jacket material.

Indenter modulus of the cable segment CPE jacket, plotted in Fig. 7, is more sensitive to the thermal aging, tracking aging after less than 15 days at 140°C.

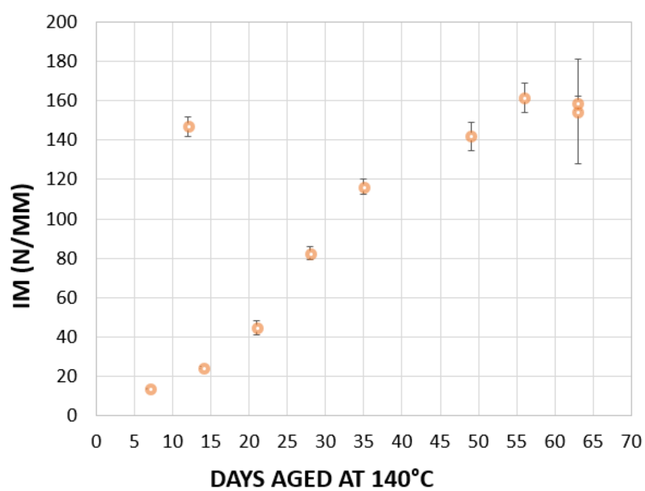

Fig. 7. Indenter modulus (IM) versus days at 140°C for CPE jacket material on cable segments.

CONCLUSIONS AND FUTURE WORK

The lifetime curve observed for EAB versus thermal exposure time for the EPR mat material followed a common trend consisting of an induction period, in which initial EAB values are relatively constant, followed by a precipitous drop in EAB values near end of useful life. The FTIR-derived CI values measured from the interior of the sliced open tensile specimens followed the same trend indicating that oxidation occurred through the thickness of the mat samples.

The CI of EPR from with the aged cable section did not exhibit the same oxidation signature. It may be that the relatively high aging temperature of 140°C contributed to rapid aging of the outer portion of the cable segments which in turn limited diffusion of oxygen through the jacket and into the cable. The relatively thin EPR mat specimens must not have experienced this same resistance to aging of sample interior.

Density values were not seen to trend with aging for either the mat samples or the EPR samples from the cable segments. Previous work indicated a linear trend of density increase with aging for EPR material and it is not clear why that was not observed in this case.

The monotonic increase in growth of the dark colored interlayer at the jacket/insulation interface reveals an additional aging mechanism in the cable system besides simple oxidation. Further analysis of cross-sectional samples of the series of aged cable segments are planned to identify the chemical nature of the interfacial layer. Its growth may be a result of diffusion of reactive chlorine from the jacket into the insulation as the chlorine is released from the CPE during thermal exposure.

The CPE jacket on the exterior of the aged cable segments was observed by CI to undergo thermal oxidation. Similarly, the hardness of the jacket increased with thermal exposure as evidenced by increase in indenter modulus.

Freestanding tensile specimens, such as the stamped EPR mat dumb bells employed here, are often used as witness samples with intact cable during aging to relate cable testing results to material changes in the cable insulation. In this investigation, it appears that the assumption that EPR inside the intact cable is changing at the same rate and in the same way as the EPR in the freestanding witness sample may not be a good one. While it is difficult to produce tensile specimens from the aged insulation within the cable for EAB comparison with the mat samples, alternative indications of aging such as density and CI may be readily applied to the insulation samples from the cable. Density values did not trend for either sample case, but the CI indication of thermo-oxidative aging did track with exposure for the freestanding samples and not for the sample extracted from the cable insulation.

The variance between observed material changes in the witness and in the cable insulation samples might be further investigated with additional analysis of the EPR materials to evaluate and compare changes in each with aging. There may be a useful measure of aging applicable to both other than density and CI. It may be that the 140°C aging temperature does result in an attenuation of aging within the cable due to rapid aging at the cable surface. Similar aging comparison at lower temperatures might confirm whether this is the case. While the EPR in the molded mat and the EPR in the extruded cable insulation may have composition differences corresponding to their formulation for processing, it is not anticipated that the variances observed here in aging are a result of those difference.

These results caution against the simplistic assumption that material changes in freestanding witness directly correlate to material changes within an intact cable system and encourage steps to validate that assumption when it is used to draw intact cable aging behavior conclusions.