

Cable Insulation Testing for Mechanistic Degradation FEA Modeling

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INTRODUCTION

The potential for degradation of the polymer jacket and insulation of medium and low voltage power cables represents a concern for lifetime extension of nuclear power plants. A growing concern especially for medium voltage cables is failures that have been observed in submerged environments. According to a NEI survey, over 50 circuit failures have been reported in 21 nuclear power plants (NPPs), perhaps the result of aqueous impact [1]. Given that the number of cables in submerged environments for a period of greater than 30 years is growing and the majority of reported failures range from 20 to 40 years [2], mechanistic understanding of the degradation process is critical to confidently predict functional properties and safety margins for dielectric breakdown over timeframes of 80 years.

Degradation of cable jackets and insulation with respect to exposure in wet and/or submerged environments is attributed to its possible interaction with pore formation within the polymer. It is hypothesized that solvent escape paths are generated during the polymer extrusion process in cable manufacturing. As solvents and low molecular weight polymer escape at extrusion temperatures and pressures, pores form in the polymer matrix. A combination of oxidation and polymer chains reorientation due to aqueous pressure drives the pore surface to become more hydrophilic and allow greater penetration by water molecules (see Figure 1). The presence of pores is supported by molecular dynamics simulations and positron annihilation [3] and equivalent circuit models of polymer coatings [4] have shown a cyclic dependence on immersion when the thickness and pore contributions are taken into account. While commercial cable jackets and insulation are designed to greatly minimize porosity, thus delaying the initiation of barrier compromise that leads to electrical breakdowns, long-term performance on the order of years would suggest that degradation is enhanced by the presence of electric field. This degradation should be considered as a coupled problem since the higher electric field produced by pores is a driver for ion transport to these pores and thus advance of the pore to the conductor, water treeing.

In order to develop and validate a degradation model that utilizes finite element models to emulate representative environment, predict electrochemical impedance, and measures polymer physics properties, the mechanistic understanding of the degradation and dielectric breakdown properties in aqueous environment in order to predict

catastrophic failure under long-term aging. A Department of Energy (DOE) Nuclear Energy University Partnership (NEUP) project led by University of Minnesota-Duluth is working with Oak Ridge National Laboratory toward development of a mechanistic model through the comparison of degradation of equivalent neat cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR) to harvested commercial cables under similar conditions. The importance of equivalent neat XLPE and EPR polymers is that it provides a template to allow for the systematic study of different additives like those that reduce flammability and reduce oxidation [5-9]. When their chemical, mechanical, and electrical properties are compared to those found in submerged commercially or harvested XLPE and EPR cables, the mechanistic model can be tested directly under the same laboratory stressors alongside the polymer physics test samples, which are jacket/insulation materials in sheet form insulated from the environment on one side.

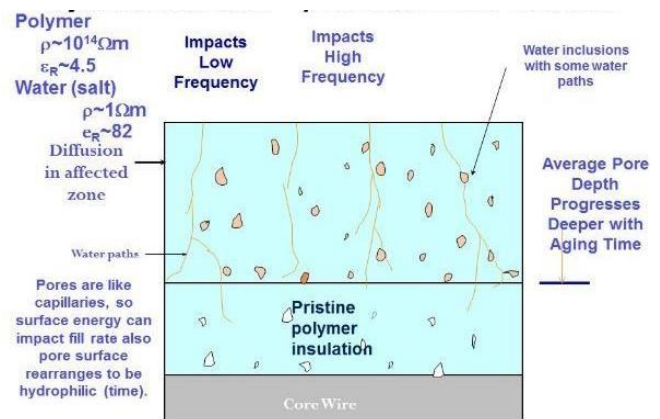


Fig. 1. Evolution of percolating paths from outer aqueous solution connecting polymer low density (pores) for mechanistic model of transport of water and ions in jacket/insulation.

EXPERIMENTAL METHODOLOGY AND RESULTS

With respect to insulation materials, the majority of the cable insulation (95%) that is currently deployed in existing NPPs is either EPR or XLPE [2,10]. While the primary material focus of the project is EPR given the lack of information on fundamental mechanism and current needs in the NPP industry, Work on XLPE will serve as a benchmark for our approach given the extensive work done on degradation in aqueous environments [11-13].

Several different techniques have been implemented to understand the dependence of polymer structure and properties with respect to permeation of water. The mass transport of water is determined over time as the water advance into the hydrophobic polymer matrix phase separates and develops pores and water inclusions. Permeation cups are used to directly investigate the cyclic water transport as shown in Figure 2 for four replicates of polyethylene films at 80C. [Need to add a sentence as what this shows, did things change with the refill.]

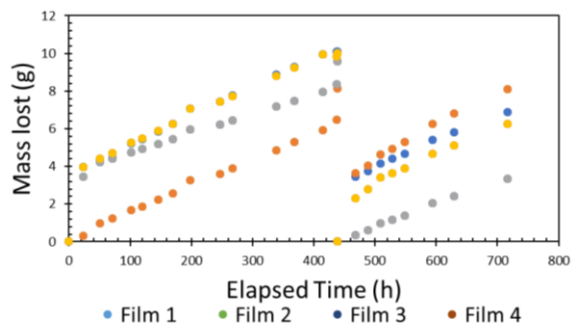


Fig. 2. Polyethylene 50 μm thick films permeability is tracked with respect to mass loss and are tracked until dry, then refilled. The impact of cyclic water permeation on rate are used to estimate pore growth.

Water uptake rate is tracked indirectly using electrochemical impedance spectroscopy, Figure 3 shows the condition of Harrison's solution as one electrolyte and DI water is the other. This figure shows the decrease in low frequency impedance representing pore advance, in the case shown a failure by water pore.

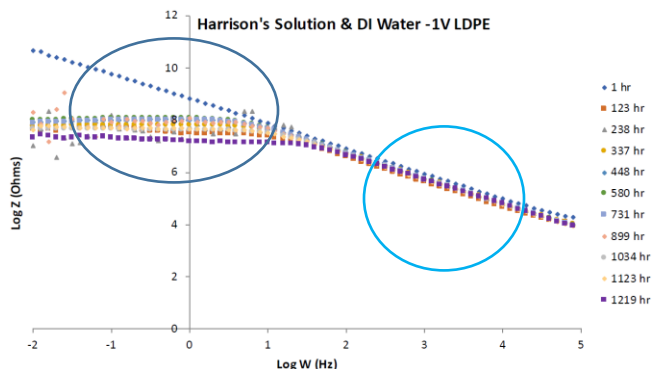


Fig. 3. Polyethylene 50 μm thick films are measured by electrochemical impedance spectroscopy every ~ 8 hours. The low frequency (left circle) tracks pore advance while the right circled area shows the capacitance used to determine water volume fraction.

The spectra in Figure 3 are further analyzed with equivalent circuit modeling. The low frequency is tracked for resistance as the quantification of the pore advance. As

the pores penetrate the electric field increases both driving water and eventually exceeding the dielectric breakdown field at that location. The high frequency regime is the capacitive element which predicts the water volume fraction as a function of time (diffusion) shown in Figure 4. The capacitance is associated with the instantaneous water volume fraction using the effective media theory of Hartshorn as applied in electrochemical impedance spectroscopy through the Brasher-Kingsbury formulation.

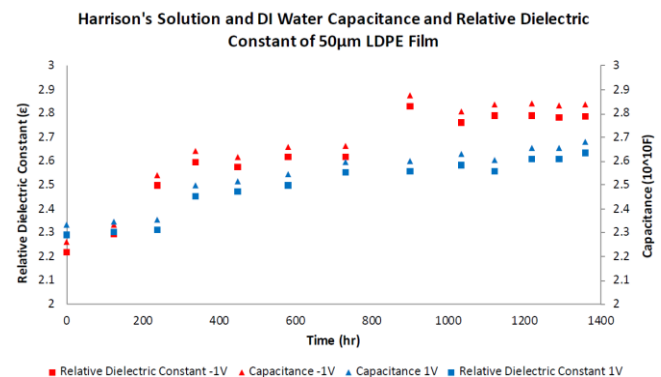


Fig. 4. Polyethylene 50 μm thick films permeability is tracked until dry, then refilled. The impact of cyclic water permeation on rate are used to estimate pore growth.

Further, equivalent circuit modeling is ongoing as the samples continue under thermal accelerated aging. These equivalent circuit values are associated with properties that are needed for finite element analysis. The impact of water chemistry, applied voltage, and binder polymer are fit to determine the impact on activation energy for pore advance and water volume fraction which impacts dielectric breakdown voltage.

CONCLUSIONS AND FUTURE WORK

Developing an accelerated weathering test that accurately ages polymers equivalent to 40 to 80 years of service is challenging. Development of pore advance measurements at high temperatures in thin, high quality films are underway to develop the electronic and mechanical properties necessary for this extended extrapolation. Neat polyethylene and polypropylene barriers of 50 μm have been aged for 6 months at 70 and 90C and show only the initiation of electrical barrier property degradation. The advance of pores in these neat polymer continues to be tracked employing electrochemical impedance spectroscopy. Investigated conditions include Harrison's solution, distilled water, and copper sulfate. Applied voltages and cyclic wet/dry testing continues. Equivalent circuit parameters are used to inform FEA (Comsol Multiphysics) under development. The evolution of resistance and capacitance as a function of time at RT, 45, 70, and 90C is used to determine the activation for water diffusion and pore advance.

Investigations continue with dye, nanoparticle, and fluorescent to image water treeing on both neat and commercial systems. These images will further inform the finite element simulation based on size and geometry of water tree samples in polymers of a given molecular weight distribution.

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