Predictive Model on the Degradation of the Electrical Resistance of Cable Insulation

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Abstract: Cross-linked polyethylene (XLPE) is one of the major materials for cable insulation. The degradation of cable insulation can be safety issues to nuclear power plants. This research has proposed deterministic and probabilistic models quantitatively predicting the decrease of the electrical resistance of the insulation as a function of time in thermal degradation. The activation energy of the degradation reaction has been determined as well. Different from previous studies using one resistivity value to represent the resistance of an entire specimen, our approach models one specimen as the combination of two parts: one degraded part and one non-degraded part possessing disparate resistivity based on Dichotomy Model. The volume ratio of the two parts determines the total resistance. The change of the ratio as a function of time can be calculated by the cumulative density function (CDF) of an exponential distribution. The trend of the total resistance is modeled into three phases: phase 1 with uniform degradation, transition phase caused by percolation, and phase 2 with an insignificant drop-off rate. The experimental data measured in accelerated conditions have been included in this paper to validate the models.

Keywords: Cable insulation, degradation, Bayesian parameter estimation, electrical resistance, resistivity, Dichotomy Model, Cross-linked polyethylene (XLPE or PEX)

1. INTRODUCTION

Cross-linked polyethylene (XLPE or PEX) is a major material for cable insulation [1] because of its high reliability [2]. However, it inevitably degrades when exposed to heat, which can cause safety issues to nuclear power plants. The maximum operating temperature for XLPE insulation is about 90℃ [3-5], but even below this threshold, the degradation persists [6].

XLPE insulation loses its electrical resistance due to ageing [6-8]. The resistivity after degradation can be 1,000 times smaller than that before ageing [7]. Therefore, many experiments have been performed to measure the resistivity of the insulation at different aging temperature [6-8]. Nonetheless, few physics-based models have been developed to quantitatively connect the change of electrical resistance and the effect of ageing temperature.

Based on the Dichotomy Model [9-11], this research has proposed deterministic and probabilistic models representing the decrease of the insulation resistance as a function of time corresponding to different aging temperatures. Unlike the previous study using one resistivity value to represent an entire specimen [6-8], we model the resistance by the combination of one non-degraded part and one degraded part inside a bulk XLPE. Accelerated aging conditions have been applied to obtain the degradation rate and activation energy. Experimental data have been incorporated in this paper to validate the proposed models.

2. MODELING

In thermal degradation, the trend of the electrical resistance or resistivity of XLPE insulation is shown in Figure 1 (a) [6-8]. Curve (A) starts with phase 1, followed by a steeper drop named transition phase, followed by phase 2 with a smaller slope. The start and end time of transition phase are denoted by t_s and t_f, respectively. When aging temperature is raised, each phase of curve (A) becomes steeper, where this process is schematically represented by curve (B), (C), and (D), sequentially. In curve (D), three phases visually merge due to their high slopes and short (t_f - t_s).

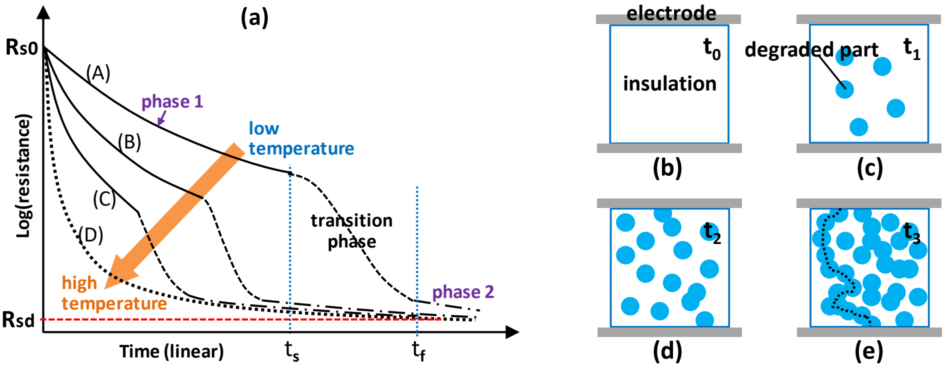

Figure 1. (a) Trend of the resistance modeled into three phases at lower and higher temperatures. (b) ~ (e) Illustration of the formation of percolation

In Figure 1 (b) ~ (d), when aging time is smaller than t_3, the degraded part is scattered. After t_3, the degraded part forms the percolation denoted by the dotted line between the two electrodes in Figure 1 (e). This percolation renders transition phase since the resistivity of the degraded XLPE can be 1,000 times lower than that of the non-degraded XLPE [7].

To model the resistance of phase 1, the degraded part is assumed to be uniformly distributed in the bulk, as shown in Figure 1 (c) and (d). According to the Dichotomy Model [9-11], one unit cube is divided into n^3 subcubes. As time elapses, some of the non-degraded subcubes become degraded subcubes shown by the dark subcubes in Figure 2 (a).

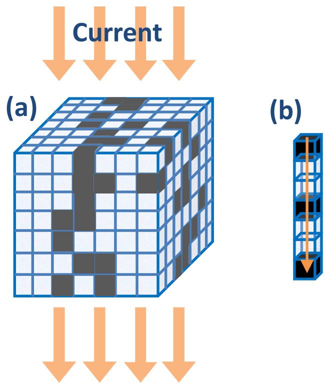

Figure 2. (a) Current uniformly flows through (a) a unit cube, and (b) one of the columns in (a)

The resistance of a non-degraded subcube (R_{s0}) and a degraded subcube (R_{sd}) can be represented by equation (1) and (2), respectively. ρ_0 is the resistivity of the non-degraded part and can be measured via a non-degraded material. ρ_d is the resistivity of the degraded part and can be measured from a well-degraded specimen.

$$R_{s0} = \rho_0 \times \frac{(1/n)}{(1/n)^2} = \rho_0 \times n \tag{1}$$

$$R_{sd} = \rho_d \times \frac{(1/n)}{(1/n)^2} = \rho_d \times n \tag{2}$$

The resistance of a unit cube (R_{tl}) can be calculated by the parallel connection of the columns where Figure 2 (b) shows one of the columns. Set V_d to be the volume ratio of the degraded part in a unit cube (degradation ratio). After calculation, R_{tl} can be denoted by equation (3).

$$R_{tl} = \rho_0 (1 - V_d)^{\frac{1}{3}} + \rho_d (V_d)^{\frac{1}{3}} \quad (3)$$

If the degradation portion per unit time (degradation rate, ν) is constant, V_d can be calculated by equation (4) according to the cumulative distribution function (CDF) of an exponential distribution.

$$V_d(t) = 1 - e^{-\nu t} \quad (4)$$

Therefore, equation (3) can be rewritten into equation (5).

$$R_{tl} = \rho_0 (e^{-\nu t})^{\frac{1}{3}} + \rho_d (1 - e^{-\nu t})^{\frac{1}{3}} \quad (5)$$

Equation (5) represents the degradation of the resistance as a function of time in phase 1. For the simplicity in field application, transition phase is modeled by a straight line connecting the end of phase 1 and the start of phase 2. The change of the resistance in phase 2 is insignificant compared to those in phase 1 and transition phase. Hence, phase 2 can be modeled as a horizontal line.

3. VALIDATION

3.1. Case A

The experimental data of set A samples are from the Figure 3 of the reference [6]. Since the data is in the form of resistivity, it is independent of the geometry of a specimen. Therefore, this research set the specimens to be unit cubes for the simplicity of calculation. In this condition, the values of resistance and resistivity are equal. The discrete patterns in Figure 3 are experimental data [6], which can be used to determine the values of ρ_0 and ρ_d in equation (5); the values are listed in Table 1. The values of ν in equation (5) are tested to fit the experimental data and listed in Table 2. It is worth noting that when equation (5) is used to fit the experimental data, for the data points at 80 and 100℃, only the points in phase 1 are used, while for the data points at 120 and 140℃, all the data points in the three phases are considered.

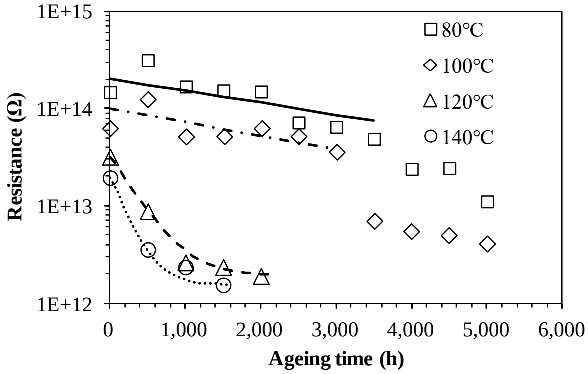

Figure 3. Measured (discrete patterns) and modeled (continuous lines) R_{tl} of the XLPE insulation

Table 1. Parameters for equation (5)

Resistivity (Ω-cm)	80℃	100℃	120℃	140℃
ρ_0	2.0E14	1.0E14	3.2E13	1.95E13
ρ_d	1.0E12	1.0E12	1.9E12	1.54E12

Table 2. Modeled degradation rate (ν)

Temperature (℃)	ν (1/h)
80	8.5E-4
100	1.0E-3
120	9.0E-3

140	1.4E-2

Figure 4 is the Arrhenius plot of Table 2. The slope of its linear fitting can be used to determine the activation energy (ΔG) where ΔG = - slope × (ideal gas constant) = 64 kJ/mol, which is close to the values reported in the reference (62.8 ~ 66.1 kJ/mol) [12].

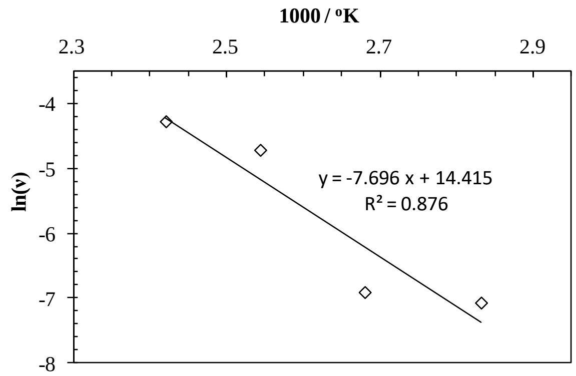

Figure 4. The Arrhenius plot corresponding to Table 2

3.2. Case B

The experimental data in case B are from Figure 1 of the reference [7]. The measured data are denoted by the discrete patterns in Figure 5. Their trends are similar to curve (D) in Figure 1. The values of ρ_0 and ρ_d are read from Figure 5 and listed in Table 3. Corresponding to equation (5), the values of the degradation rate (ν) are tested to fit the experimental data. The result is listed in Table 4. The values of the resistance calculated by equation (5) are represented by the continuous lines in Figure 5.

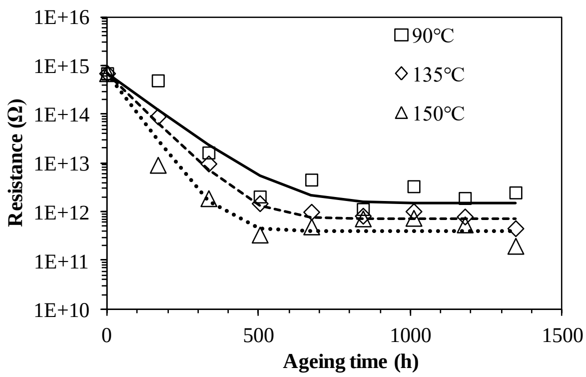

Figure 5. Measured (discrete patterns) and modeled (continuous lines) R_{tl} of the XLPE insulation

Table 3. Parameters for equation (5)

Resistivity (Ω-cm)	90℃	135℃	150℃
ρ_0		7.0E14	
ρ_d	1.5E12	7.0E11	4.0E11

Table 4. Modeled degradation rate (ν)

Temperature (℃)	Degradation rate (1/h)
90	0.031
135	0.042
150	0.057

Figure 6 is the Arrhenius plot of Table 4. The slope of the linear fitting of the plot can be used to determine ΔG where ΔG = - slope × (ideal gas constant) = 1.414 × 8.314 = 12 kJ/mol, which is significantly lower than the ΔG of set A samples. However, this value is expected since the drop-off rate of the resistance shown in Figure 3 is much lower than that in Figure 5.

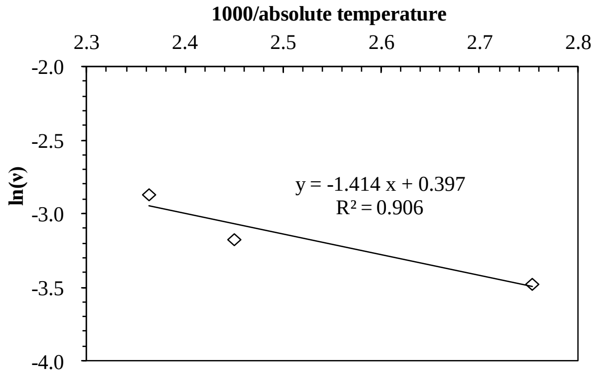

Figure 6. The Arrhenius plot corresponding to Table 4

4. DISCUSSION

The degradation rate (ν) in this model is derived from the trend of the electrical resistance. This ν is not equal to the degradation rate measured by chemical reactions. The degradation ratio (V_d) represented by equation (4) is the integral of ν against time, which can be used to draw the boundaries of each phase. According to the experimental data at 80℃ and 100℃ in Figure 3, the continuous lines plotted by equation (5) can be used to determine the values of V_d at the boundaries. At 80℃ and 100℃, the V_d at the end of phase 1, or the beginning of transition phase, is about 0.95. At the same temperatures, the V_d at the end of transition phase is about 0.97. Therefore, by these V_d values, the t_s and t_f in Figure 1 can be calculated via equation (5).

Since there is always uncertainty between the predicted and measured values as shown in Figure 3 and Figure 5, in addition to the deterministic approach based on equation (5), a probabilistic model has also been developed in this research. Bayesian parameter estimation [13-17], represented by equation (6) where the priors are ν and σ, can be used to obtain the distributions of priors.

$$\Pr(\theta \mid \text{data}) = \frac{\Pr(\text{data} \mid \theta)\,\Pr(\theta)}{\int \Pr(\text{data} \mid \theta)\,\Pr(\theta)d\theta} \tag{6}$$

A measured resistance (y_i) is assumed to be normally distributed around a predicted resistance (μ_y) with the standard deviation (σ), which is represented by equation (7) and (8), where μ_y can be calculated by equation (5) and represented by equation (9).

$$y_i \sim \mathcal{N}(\mu_y, \sigma) \tag{7}$$

$$\Pr\left(y_i \,\middle|\, \mu_y, \sigma\right) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\left(y_i - \mu_y\right)^2}{2\sigma^2}\right) \tag{8}$$

$$\mu_y = \rho_0 (e^{-\nu t})^{\frac{1}{3}} + \rho_d (1 - e^{-\nu t})^{\frac{1}{3}} \tag{9}$$

Take the experimental data at 120℃ in Figure 3 for example, the priors (ν and σ) are both assumed to be uniform distributions ranging from 0 to 0.015 and from 0 to 1E+13, respectively. The distributions of ν and σ calculated by Bayesian parameter estimation are shown in Figure 7. The average and percentiles of ν are listed in Table 5. By plugging the corresponding values of ν into equation (5), the uncertainty of the resistance is plotted in Figure 8.

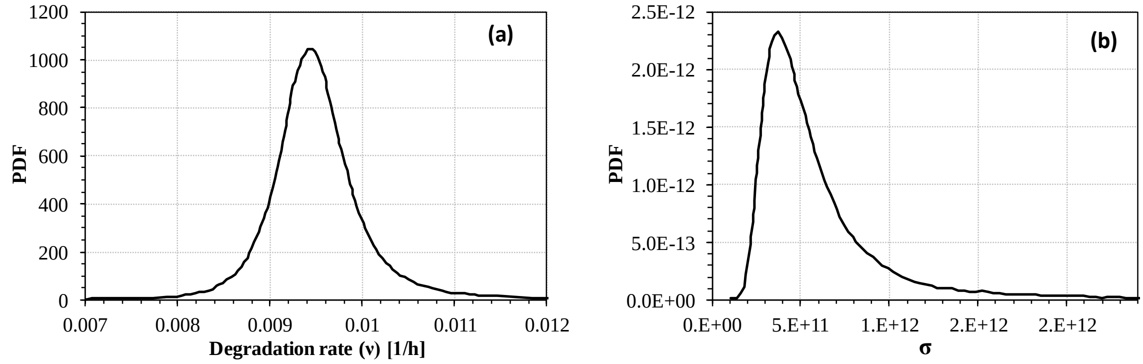

Figure 7. The PDF of ν and σ

Table 5. The average and percentiles of ν [$\times 10^{-3}$ /h]

Average	2.5%	25%	50%	75%	97.5%
9.515	8.537	9.210	9.464	9.747	10.83

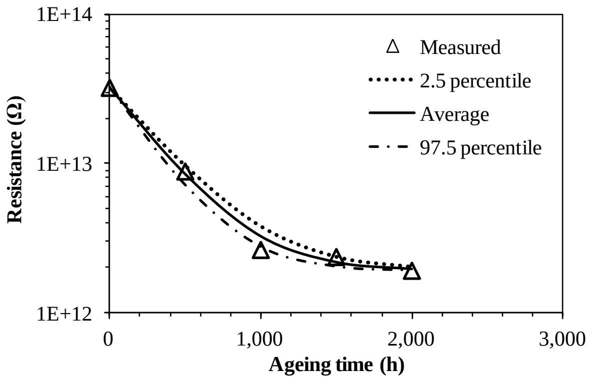

Figure 8. The uncertainty of the resistance at 120°C corresponding to Figure 3

5. CONCLUSION

XLPE is a major material for cable insulation. The degradation of the insulation in nuclear power plants can result in safety issues. Few physics-based models have been developed to predict the degradation. The Dichotomy Model [9-11] has been applied to the decrease of the electrical resistance under thermal aging. It divides an entire material into degraded and non-degraded parts possessing disparate resistivity. The ratio and distribution of the two parts determine the trend of the resistance. The trend of the resistance is modeled into three phases: phase 1 with uniform degradation, transition phase caused by percolation, and phase 2 with an insignificant slope. While the aging temperature is high, the boundaries of the three phases become indiscernible. The development of the degradation rate and degradation ratio based on the Dichotomy Model facilitates the determination of the activation energy, which is an essential parameter in accelerated aging experiments widely used to predict the degradation rate of materials. In addition to the deterministic model, a probabilistic model has also been proposed in this research to model the uncertainty of the degradation according to the Dichotomy Model and Bayesian parameter estimation. Both deterministic and probabilistic models have been validated by experimental data.

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