Thermal and Mechanical Properties
of EPR Cable Compound

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Source of Data

• All data were measured during 2005 at the Institute of Materials Science, University of Connecticut

• DMA, TGA, DSC, and TMA data were measured by the staff member in charge of the Thermal Lab within IMS.

• Thermal conductivities/resistivities were measured in my lab under my supervision.
Source of Materials Measured

• Four EPR compounds were obtained from three companies which compound EPR
• Samples (plaques and cylinders) measured were made by the companies which supplied the compounds
• XLPE samples were obtained from a company which had it in stock and which made the samples used for measurement.
Thermal Data

- Underground transmission of electric power is limited by the ability to dissipate heat from the conductor through the insulation and into the soil.

- The range of Thermal Conductivity:
  - Cu: $390 \text{ W/m-K} \ (0.26 \ ^\circ\text{C-cm/W})$
  - Al: $240 \text{ W/m-K} \ (0.42 \ ^\circ\text{C-cm/W})$
  - BeO dense ceramic: $30 \text{ W/m-K} \ (3.3 \ ^\circ\text{C-cm/W})$
  - ZnO arrester element: $15 \text{ W/m-K} \ (6.7 \ ^\circ\text{C-cm/W})$
  - Good Soils: 2 to 1 W/m-K (50 to 100 °C-cm/W)
  - Polymers: 0.1 to 0.3 W/m-K (300 to 1000 °C-cm/W)
  - Aerogel: 0.02 W/m-K (5000 °C-cm/W)
Measurement of Thermal Conductivity

• If a constant power line heat source is placed in an infinite solid, the temperature of the line heat sources vs time is given by

\[ T(t) = -\frac{q}{4\pi k} \text{Ei}\left(\frac{-r^2}{4\alpha t}\right) \]

Where \( q \) is the power per unit length, \( k \) is the thermal conductivity, \( \alpha \) the thermal diffusivity, \( r \) is the distance from the line heat source, and \( \text{Ei} \) is the “error function”. 
• This can be expanded in the form:

\[
T(t) = \frac{q}{4\pi k} \left( \ln \left( \frac{4\alpha t}{r^2 D} \right) + \frac{r^2}{4\alpha t} - \frac{1}{4} \left( \frac{r^2}{4\alpha t} \right)^2 + \frac{1}{9} \left( \frac{r^2}{4\alpha t} \right)^3 - \frac{1}{16} \left( \frac{r^2}{4\alpha t} \right)^4 + \ldots \right)
\]

• Only the first term is significant at long times, thus:

\[
T(t) = \frac{q}{4\pi k} \left( \ln \left( \frac{4\alpha t}{r^2 D} \right) \right) \quad \text{or} \quad T(t) = \frac{q}{4\pi k} \left( \ln(t) - \ln \left( \frac{r^2 D}{4\alpha} \right) \right)
\]

• Thus if we plot Temperature vs log of time, we can determine the thermal conductivity, \(k\), knowing \(q\), the power dissipation per unit length
\[ T(t) = -\frac{q\rho}{4\pi} \text{Ei}\left(\frac{-r^2}{4\alpha t}\right) \]

\[ T(t) = \frac{q\rho}{4\pi} \left[ \ln t + \ln \frac{4\alpha}{r^2D} \right] \]

\[ \frac{q\rho}{4\pi} \ln \frac{4\alpha}{r^2D} \]
Temperature (°C) vs. Time (s)

- Temperature values: 28.0, 28.5, 29.0, 29.5, 30.0, 30.5, 31.0
- Time values: 50, 100, 150, 200, 250, 300

The graph shows a linear increase in temperature over time.
Thermal Conductivity of EPR’s

![Graph showing thermal conductivity of EPR’s over temperature range.](image)
Thermal Resistivity of EPR’s

[Graph showing thermal resistivity (°C·cm/W) vs. temperature (°C) for different EPR types, including XLPE, EPR3, EPR2, EPR4, and EPR1. The graph illustrates varying thermal resistivity across different temperatures for each type.]
Thermal Diffusivity & Heat Capacity

• Under steady state conditions, only the thermal conductivity is relevant
• Under transient conditions, the thermal diffusivity is relevant
  – Thermal diffusivity, $\alpha$ (m$^2$/s), is the ratio of the thermal conductivity (W/m-K) to the volumetric heat capacity (J/m$^3$-K)
  – The volumetric heat capacity of solids is about the same, 2x10$^6$ J/m$^3$-K
Differential Scanning Calorimetry (DSC)

A thermal analysis tool for measuring thermal properties

- Heat Capacity
- Crystallinity
- Curing
- Oxidation or decomposition
Basic principles

- Applies a programmed temperature ramp to both blank and sample.
- Maintains both temperatures nearly identical at all time.
- Measures the amount of heat flow in and out of the sample relative to the blank.
- During phase transitions, more or less heat will need to go into the sample to keep both temperatures same.
Schematic of a DSC trace

- Heat Flow -> exothermic
- Glass Transition
- Crystallization
- Melting
- Cross-Linking (Cure)
- Oxidation or Decomposition
Heat Diffusion

• The distance heat diffuses in a time, $t$, is given by
  \[ x = \sqrt{\alpha t} \]

• Since the thermal conductivity of EPR insulation is about 0.3 W/m-K and the heat capacity is about $2 \times 10^6$ J/m$^3$-K, the thermal diffusivity is about $1.5 \times 10^{-7}$ m$^2$/s.

• Thus heat diffuses across the ~5 mm dielectric of a 15 kV cable in about
  \[ t = \frac{x^2}{\alpha} = \frac{(5 \times 10^{-3})^2}{1.5 \times 10^{-7} \text{ m}^2/\text{s}} \approx 170 \text{ seconds} \]
Mechanical Properties

- Thermal Expansion of the dielectric is important for reliable high temperature operation, especially that involving repeated excursions to high temperatures.
- If the thermal expansion at high temperatures is too great and if the polymer has a tendency to soften and set at high temperature, the dielectric may distort and/or reduce interfacial pressures within accessories to a degree which results in failure.
Thermal Expansion from 80 to 140 °C

- EPR1 (320 ppm/K)
- EPR2 (340 ppm/K)
- EPR3 (300 ppm/K)
- EPR4 (390 ppm/K)
- XLPE
Dynamic Mechanical Analysis

• A DMA imposes a cyclic displacement on the sample and measures the force as a function of position.
  – From these data, the mechanical tan(δ), storage modulus (capacitance), loss modulus (resistance), etc. can be determined as a function of temperature.
  – The stress (Pa) required to cause the programmed displacement is a good measure of the “stiffness” of the material as a function of temperature.
Themogravimetric Analysis (TGA)

![Graph showing weight loss as a function of temperature for different samples labeled EPR1, EPR2, EPR3, EPR4, and XLPE.](image-url)
Physical Attributes of EPR

- Relatively high thermal conductivity as a result of mineral fillers
- Relatively small and uniform thermal expansion coefficient
- Relatively small variation in “stiffness” with temperature (a factor of 100 from –40 to +150 °C) compared to 1000 for unfilled dielectric.
- “Stiffness” or “Hardness” levels off at very high temperatures