

Thermal and Mechanical Properties of EPR and XLPE Cable Compounds

Key Words: EPR, TRXLPE, thermal conductivity/resistivity, thermal diffusivity, heat capacity, thermal expansion, thermal decomposition

Introduction

Thermal and mechanical properties of four ethylene propylene rubber (EPR) cable dielectrics and a tree-retardant, cross-linked polyethylene (TRXLPE) cable dielectric have been measured from room temperature to 140°C. The measurements were carried out by the Institute of Materials Science, University of Connecticut on samples prepared by cable manufacturers. Dynamic mechanical analyzer (DMA), thermogravimetric analyzer (TGA), differential scanning calorimeter (DSC), and thermomechanical analyzer (TMA) data were measured by professional staff of the Institute, and thermal conductivities were measured by the Electrical Insulation Research Center. In the areas addressed by this contribution, the data update and expand on previous work [1].

The EPR samples took the form of plaques and cylinders, which were prepared by the companies that supplied the compounds, all of which are in commercial production. The commercially available TRXLPE samples were obtained from a company that had stock and made the samples for measurement. The labeling of compounds is consistent throughout the paper, i.e., EPR1 for thermal conductivity measurements is the same compound as EPR1 for the TGA, DSC, etc.

Thermal Data

Underground transmission of electric power is limited by the ability to dissipate heat from the conductor through the insulation of the cable and into the surrounding soil. Table 1 shows the thermal conductivity (or resistivity) for a range of materials.

A. Thermal Conductivity Measurement

If a line heat source which dissipates constant power is placed in an infinite solid, the temperature of the line heat source versus time is given by:

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The mechanical and thermal properties of EPR cable dielectrics are very stable with temperature.

$$T(t) = -\frac{q}{4\pi k} \text{Ei}\left(\frac{-r^2}{4\alpha t}\right) \quad (1)$$

where q is the power per unit length (W/m), k is the thermal conductivity (W/m-K), r is the distance from the line heat source, Ei is the error function, and α is the thermal diffusivity (m^2/s), which is the ratio of the thermal conductivity (W/m-K) to the volumetric heat capacity ($\text{J}/\text{m}^3\text{-K}$). This can be expanded in the form:

$$T(t) = \frac{q}{4\pi k} \left(\ln\left(\frac{4\alpha t}{r^2 D}\right) + \frac{r^2}{4\alpha t} - \frac{1}{4}\left(\frac{r^2}{4\alpha t}\right)^2 + \frac{1}{9}\left(\frac{r^2}{4\alpha t}\right)^3 - \dots \right) \quad (2)$$

where D is Euler's constant. All but the first term go to zero at long times, so that at long times:

Table 1. Thermal Properties for a Range of Materials		
Material	Thermal conductivity	Thermal resistivity
	(W/m-K)	(°C-cm/W)
Cu	390	0.26
Al	240	0.42
BeO Ceramic	30	3.3
ZnO element	15	6.7
Good Soil	1 to 2	50 to 100
Polymers	0.1 to 0.3	300 to 1000
Aerogel	0.02	5000

$$T(t) = \frac{q}{4\pi k} \ln\left(\frac{4\alpha t}{r^2 D}\right) = \frac{q}{4\pi k} \left(\ln(t) - \ln\left(\frac{r^2 D}{4\alpha}\right) \right) \quad (3)$$

Thus if we plot temperature versus $\ln(\text{Time})$, we can determine the thermal conductivity, k , if we know the power dissipation per unit length, q . Figure 1 shows a plot of the relevant equations. Figure 2 shows a plot of temperature versus $\ln(\text{Time})$ for data typical of the present study. Figure 3 shows a linear regression to such data from 60 s to 300 s, from the slope of which the thermal conductivity is determined as above.

B. Thermal Conductivity Data

Figure 4 shows the measured values of thermal conductivity from 20°C to 140°C for the four types of EPR cable dielectric and TRXLPE, and Figure 5 shows the thermal resistivity. The

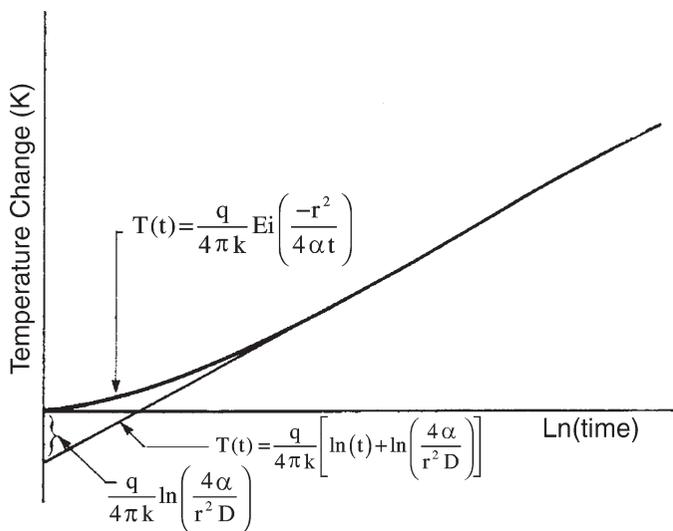


Figure 1. Plot of the equations relevant to measurement of thermal conductivity.

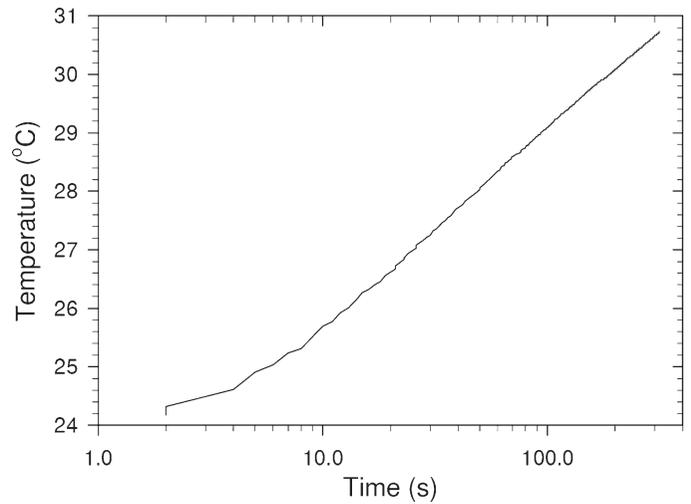


Figure 2. Typical measured data. The temperature becomes a linear function of $\ln(\text{time})$ after about 60 s.

reproducibility of the data is indicated by duplicate measurements at a number of temperatures. The precision of the data appears to be better than 3%.

The thermal properties of the EPR compounds are very stable from 20°C to 140°C with only a slight decrease in the thermal conductivity as a function of temperature. The thermal properties of the TRXLPE are similar to the majority of EPR compounds up to about 80°C. Between 80°C and 120°C, the thermal properties of the TRXLPE are affected by melting of the crystallites over this temperature range. Above about 120°C, the TRXLPE is essentially amorphous and has a lower thermal conductivity than the EPR compounds. The EPR compound with a higher thermal conductivity has a greater filler concentration than the other compounds, as will be seen from the TGA data discussed below.

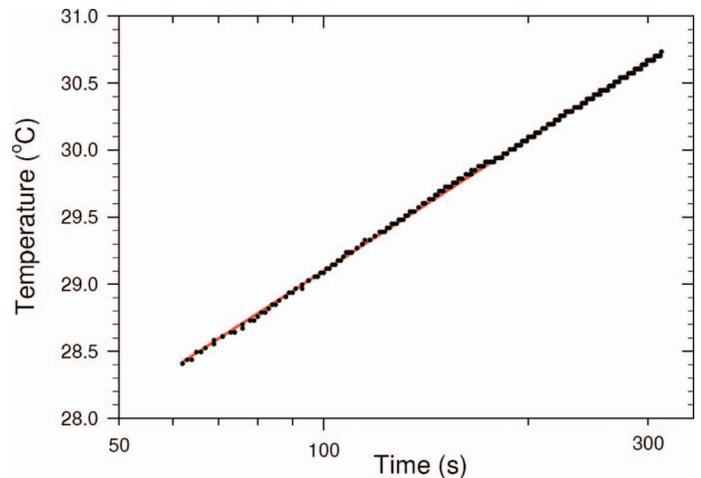


Figure 3. Typical linear regression to measured data from which the thermal conductivity is determined.

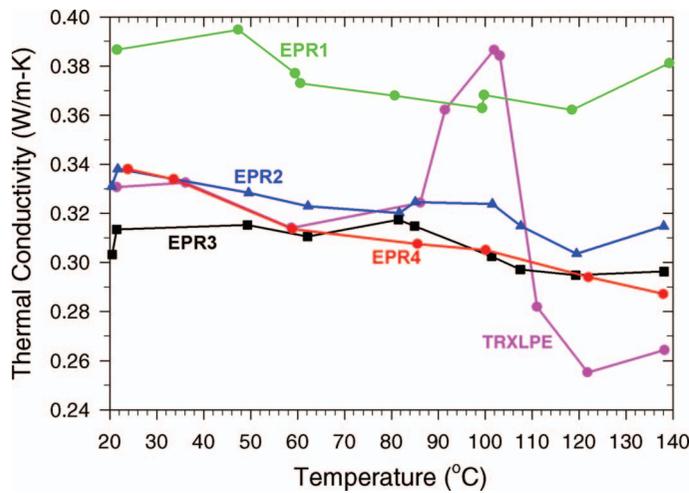


Figure 4. Thermal conductivity as a function of temperature from 20°C to 140°C for four EPR cable dielectrics and TRXLPE. The reproducibility of the data is indicated by duplicate measurements at a number of temperatures.

C. Thermal Diffusivity and Heat Capacity

Under steady-state conditions, only the thermal conductivity is relevant. Under transient conditions, the thermal diffusivity becomes relevant. The thermal diffusivity is the ratio of the thermal conductivity (W/m-K) to the volumetric heat capacity (J/m³-K). The volumetric heat capacity of all solids is about the same, in the range of 2 MJ/m³-K to 3 MJ/m³-K. Thus if we plot thermal conductivity versus thermal diffusivity, we tend to get a straight line, because the thermal diffusivity tends to be proportional to

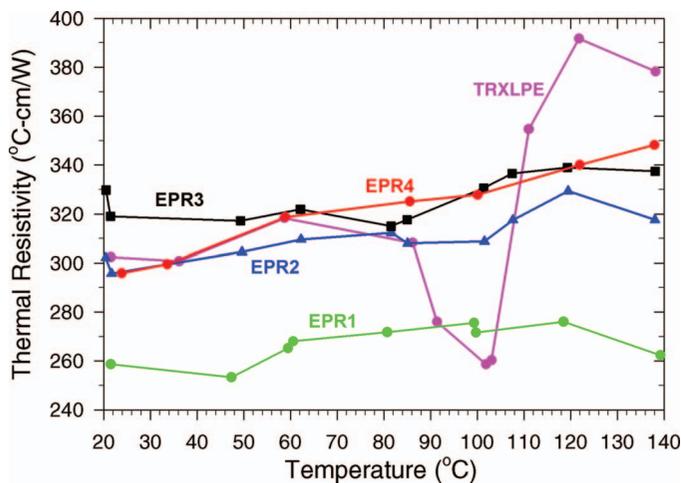


Figure 5. Thermal resistivity as a function of temperature for four EPR cable dielectrics and TRXLPE. The data are the same as plotted in Figure 4, but represented as thermal resistivity rather than thermal conductivity.

the thermal conductivity. The materials that fall well off the line of proportionality tend to be porous, such as cork, polymer foams, etc. Figure 6 shows such a plot [2].

The exception to such proportionality would be when a material is going through a phase transition, at which point the volumetric heat capacity increases greatly, resulting in a large reduction in the thermal diffusivity. The increase in heat capacity means that the material must absorb more heat at one location before the heat can diffuse through that location, which results in a reduction in the rate of diffusion. The time required for heat to diffuse a distance, x in a material with a thermal diffusivity α is given by $x(t) = \sqrt{\alpha t}$. The thermal diffusivity of polymers is about 10^{-7} m²/s [(0.2 W/m-K)/(2x10⁶ J/m³-K)]. Thus in 1 s, heat will diffuse about 0.3 mm. The time for heat to diffuse across the ~5 mm of a 15 kV cable dielectric is about 3 minutes.

Heat capacity typically is measured with a differential scanning calorimeter (DSC) that has been calibrated using indium. The basic principle of a DSC is shown in Figure 7. The instrument has two “pans”, and the materials in the two pans are heated at a constant rate while the heat energy required to achieve this is measured. If one pan is empty and the other contains the sample of interest, the difference in the heat required to heat the two samples is that required to heat the sample of interest. Figure 8 shows typical data that result. Crystallization is exothermic; that is, it gives off heat; melting is endothermic, i.e., requires that heat be added.

Figure 9 shows the heat capacity of the four EPR compounds and TRXLPE as a function of temperature. Because the EPR polymer has very little crystallinity, almost no melting peaks are visible for the EPR compounds. The TRXLPE has substantial crystallinity, which results in a large melting peak between 50°C and 120°C with most of the melting taking place between 80°C and 120°C. As the amorphous polymer has a greater volume than the crystalline polymer, this melting is accompanied by a very large thermal expansion, which is of greater practical significance than the effect on thermal properties.

Mechanical Properties

A. Thermal Expansion

Measurement of the thermal expansion of TRXLPE is difficult because above the melting point of the crystallites, the yield stress becomes very small and the force of the probe on the sample is likely to distort the sample. Figure 10 shows the thermal expansion coefficient of the four EPR compounds and TRXLPE from 20°C to 140°C. The expansion coefficient of the EPR cable dielectrics is given in the legend. As noted above, melting of the crystallites in TRXLPE results in a very large thermal expansion of the cable dielectric. A large interfacial pressure is required for the dielectric integrity of many cable accessories, and the concern is that the large thermal expansion of TRXLPE combined with the low yield stress above the melting point (discussed below) will result in permanent deformation of the cross-linked polyethylene (XLPE) which lowers the interfacial pressure upon cooling. The EPR cable dielectrics do not suffer from such thermal expansion and maintain a more stable yield stress—as will

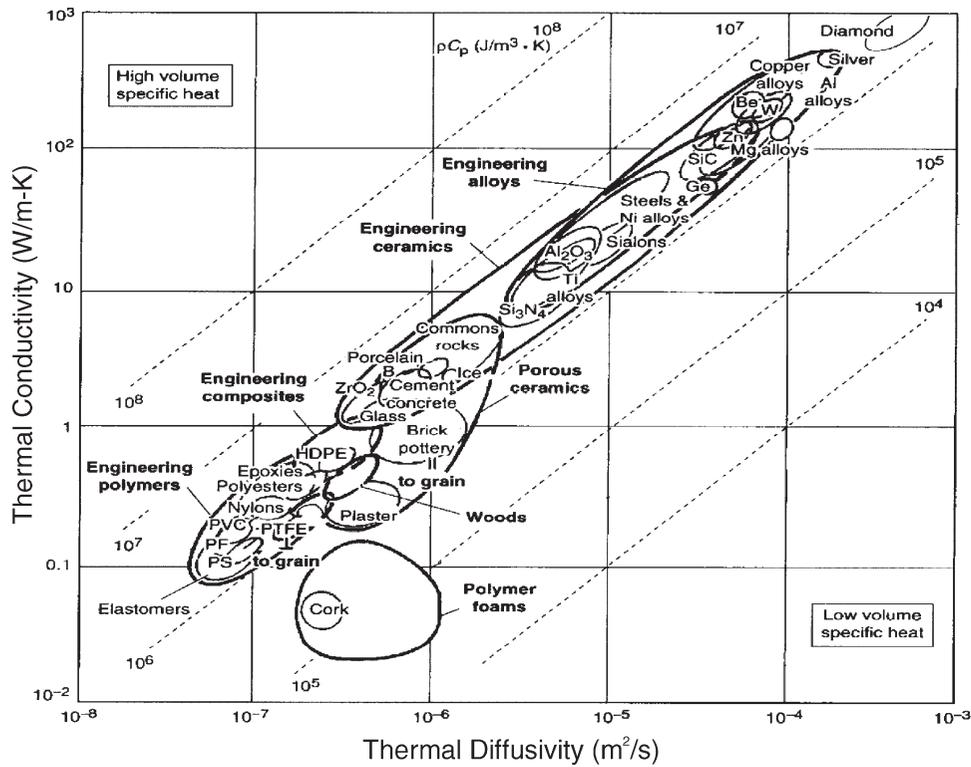


Figure 6. Plot of thermal conductivity versus thermal diffusivity [2]. As the thermal diffusivity is the ratio of the thermal conductivity to the volumetric heat capacity and the latter tends to be constant for solids, the thermal diffusivity tends to be proportional to the thermal conductivity.

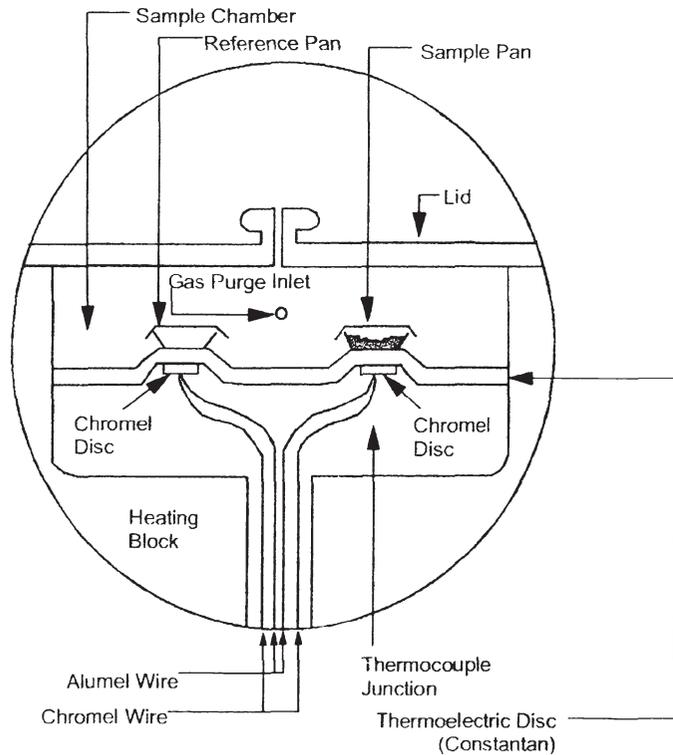


Figure 7. Schematic of a DSC showing the two sample pans, heaters, and temperature measurement. Often one pan is left empty while the sample is placed in the other so that the heat capacity can be measured as a function of temperature [3].

be shown below—thus improving the reliability of the cable system when exposed to very high temperature excursions. This becomes increasingly important given present trends toward increased emergency operating temperature of distribution cables.

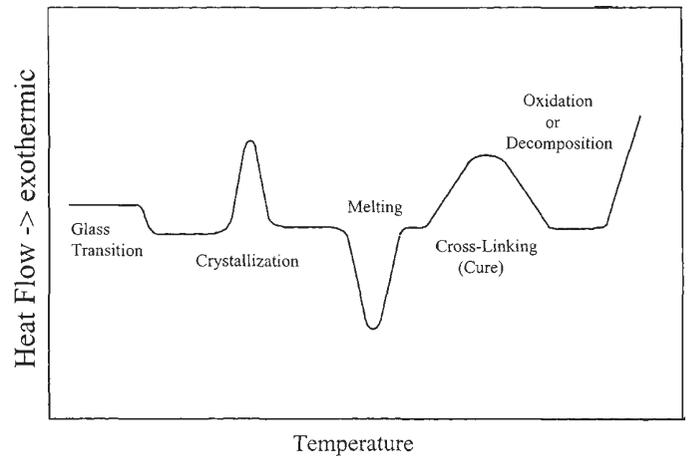


Figure 8. A schematic of DSC data. Crystallization is exothermic (gives off heat); melting is endothermic (absorbs heat) [4].

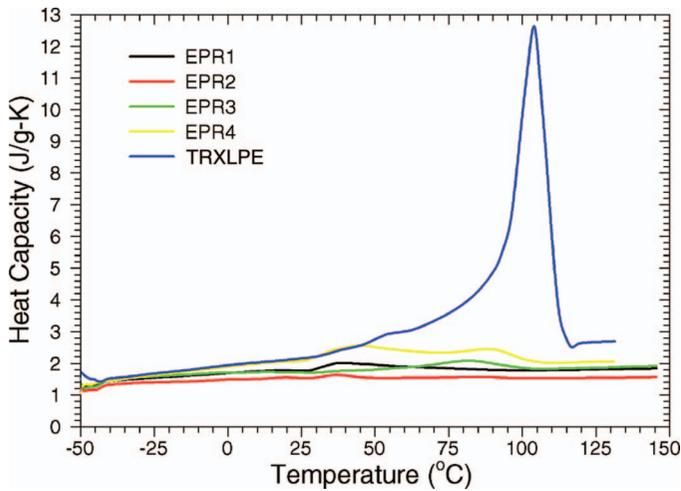


Figure 9. Heat capacity versus temperature of the four EPR compounds and TR-XLPE. As the EPR polymer is essentially amorphous, no melting peak is visible. However the TRXLPE has substantial crystallinity that melts between 50°C and 120°C with most of the melting between 80°C and 120°C.

B. Dynamic Mechanical Analysis

A DMA imposes a cyclic displacement on the sample and measures the force as a function of position. For these data, the mechanical $\tan(\delta)$, storage modulus (capacitance), loss modulus (resistance), etc. can be determined as a function of temperature. The stress (pressure in N/m or Pa) required to cause the programmed displacement is a good measure of the material “stiffness” as a function of temperature. Figure 11 shows the stress during the DMA measurement as a function of temperature. The

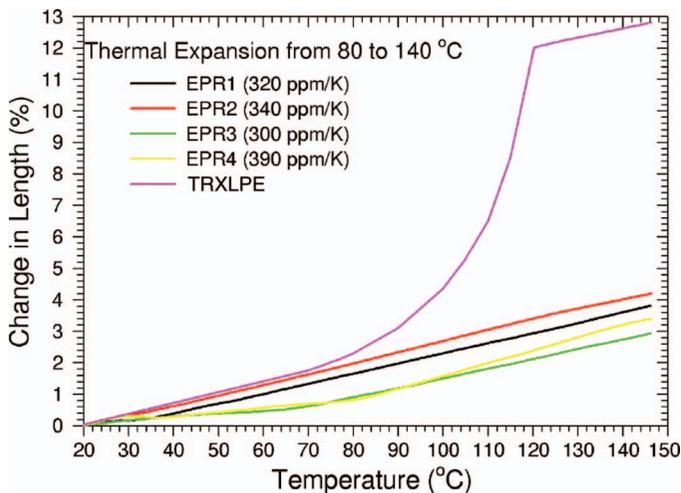


Figure 10. Thermal expansion as a function of temperature for the four EPR cable dielectrics and TR-XLPE. The approximate thermal expansion coefficient for the EPR compounds is given in the legend.

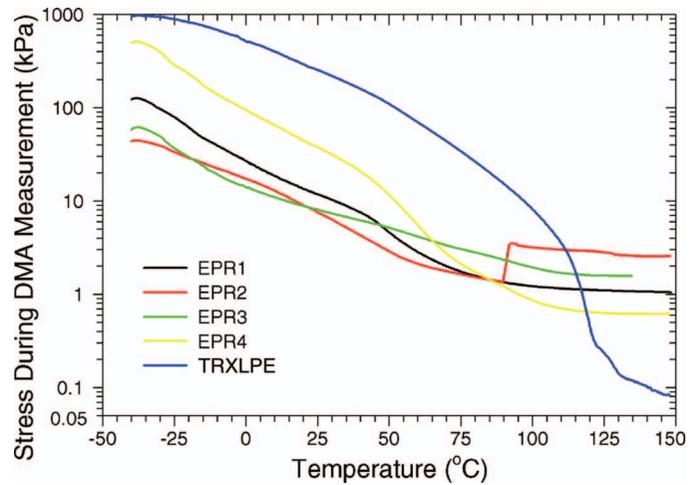


Figure 11. Stress during DMA provides a relative indication of the material stiffness as a function of temperature. The mechanical properties of the EPR compounds are much more uniform as a function of temperature than those of the TR-XLPE, which is an order of magnitude more stiff than the EPR compounds at low temperature and an order of magnitude less stiff at 140°C.

EPR compounds are much less stiff at low temperatures and much stiffer at high temperatures than TRXLPE, i.e., they maintain much more uniform mechanical properties as a function of temperature than TRXLPE.

Thermal Decomposition

Thermal decomposition at elevated temperatures can be determined using thermogravimetric analysis. The sample is heated in oxygen, air, or nitrogen, and the sample weight is measured as a function of temperature. In the case of an unfilled hydrocarbon, the final weight will be about zero, as the polymer is reacted to gas. In the case of a filled compound, the final weight will indicate the inorganic filler content. Figure 12 shows TGA measurements on the four EPR cable dielectrics and TRXLPE as measured in nitrogen. The compounds start to degrade rapidly above about 400°C, and visible degradation starts between 200°C and 300°C. Evidently the inorganic content of the EPR cable dielectrics varies from about 38% to 49%. The compound with 49% inorganic content had the greatest thermal conductivity.

Conclusions

Commercially available EPR and TRXLPE cable dielectrics typically have about the same thermal conductivity, although the thermal conductivity of TRXLPE above the melting point of the crystallites drops below that of the EPR dielectrics. One type of EPR has about 10% greater thermal conductivity than the other compounds, probably as a result of greater inorganic filler content. The mechanical properties of EPR cable dielectrics are

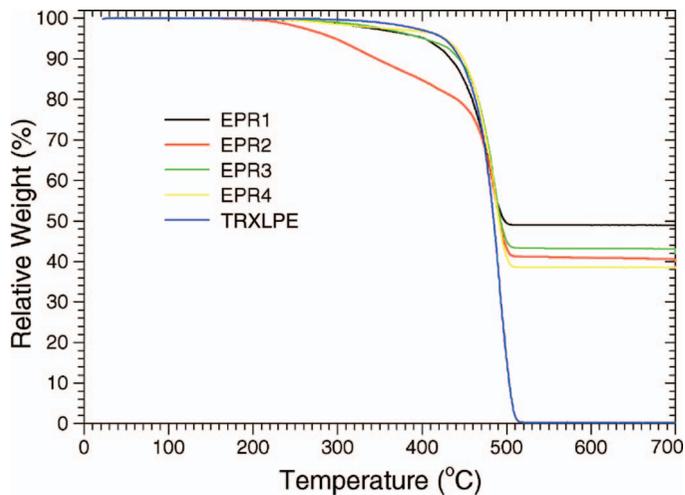


Figure 12. TGA measurements indicate rapid degradation above about 400°C. The filler content of the EPR cable dielectrics varies between 38% and 49%.

much more stable with temperature than those of the TRXLPE, as EPR polymer is essentially amorphous so that EPR cable dielectrics do not suffer from the very large thermal expansion of TRXLPE as its crystallites melt between about 80°C and 120°C. EPR cable dielectrics also have much more uniform stiffness as a function of temperature, with the stiffness varying only by a factor of 100 from -40°C to 140°C, while the stiffness of XLPE varies by a factor of 10,000 over the same temperature range. A combination of large thermal expansion and low stiffness (or yield stress) at elevated temperatures can cause problems with cable accessories, as discussed above. For these reasons the upper temperature limit for operation of XLPE is often limited to 90°C or 105°C, and EPR cable dielectrics can be operated safely to 140°C.

References

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