Electrical Insulation Research Center

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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 W/m-K (0.26 °C-cm/W)
  - Al: 240 W/m-K (0.42 °C-cm/W)
  - BeO dense ceramic: 30 W/m-K (3.3 °C-cm/W)
  - ZnO arrester element: 15 W/m-K (6.7 °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

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

Where q is the power per unit length, k is the thermal conductivity, α the thermal diffusivity, r is the distance from the line heat source, and Ei is the “error function”.

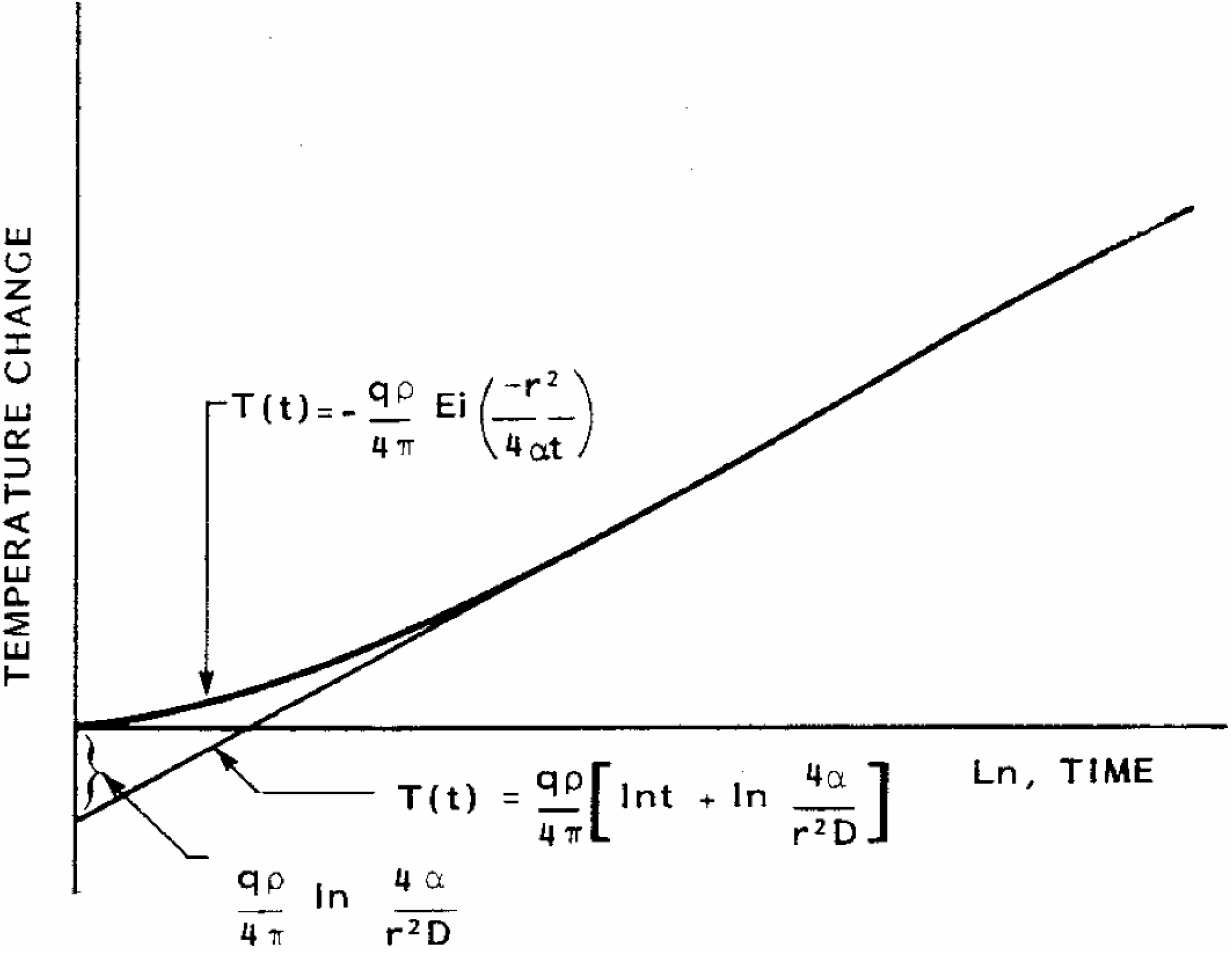
- This can be expanded in the form:

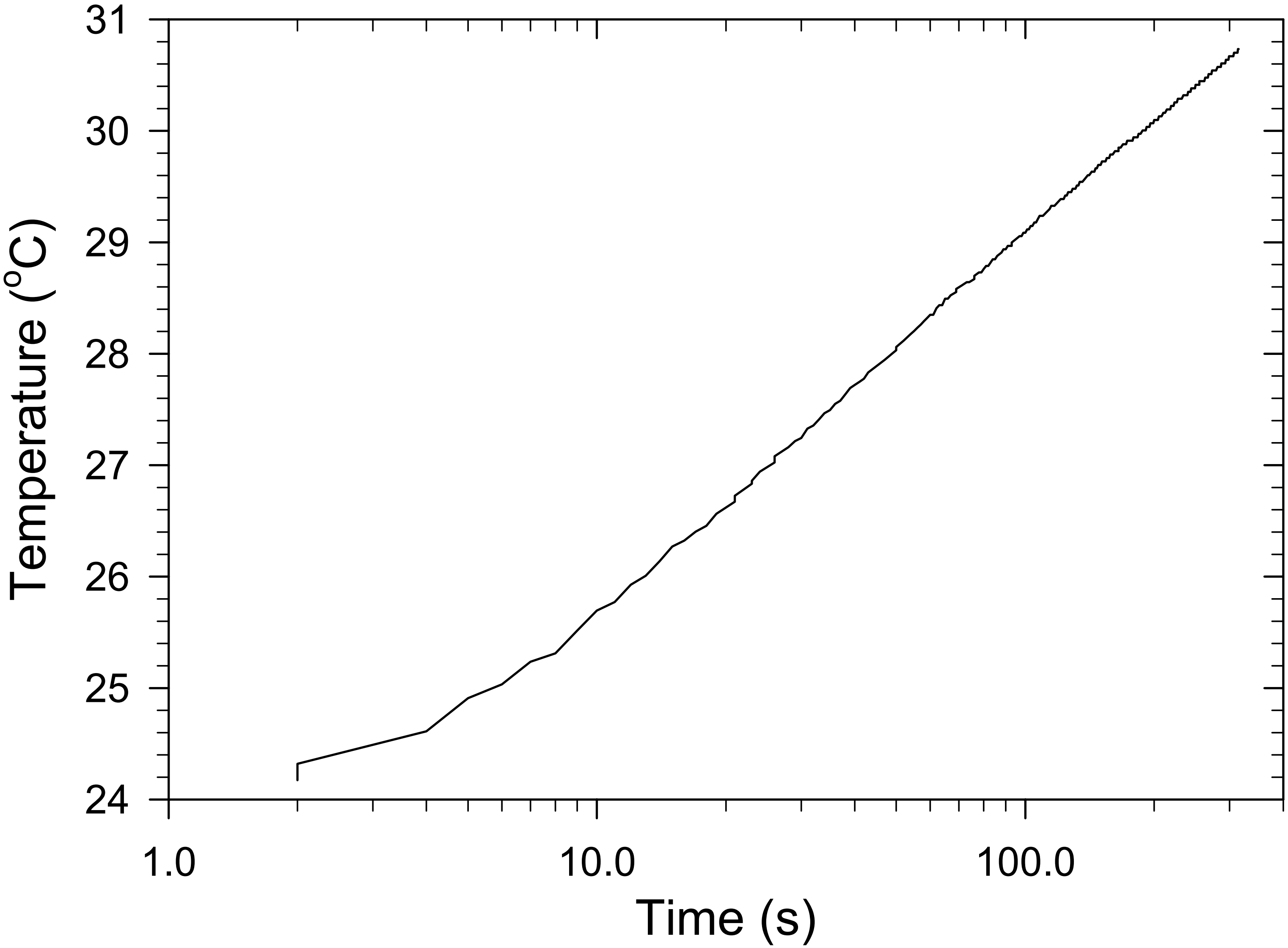
$$T(t)=\frac{q}{4\pi k}\left(\ln\left(\frac{4\alpha t}{r^2 D}\right)+\frac{r^2}{4\alpha t}-\frac{1}{4}\left(\frac{r^2}{4\alpha t}\right)^2+\frac{1}{9}\left(\frac{r^2}{4\alpha t}\right)^3-\frac{1}{16}\left(\frac{r^2}{4\alpha t}\right)^4+\ldots\right)$$

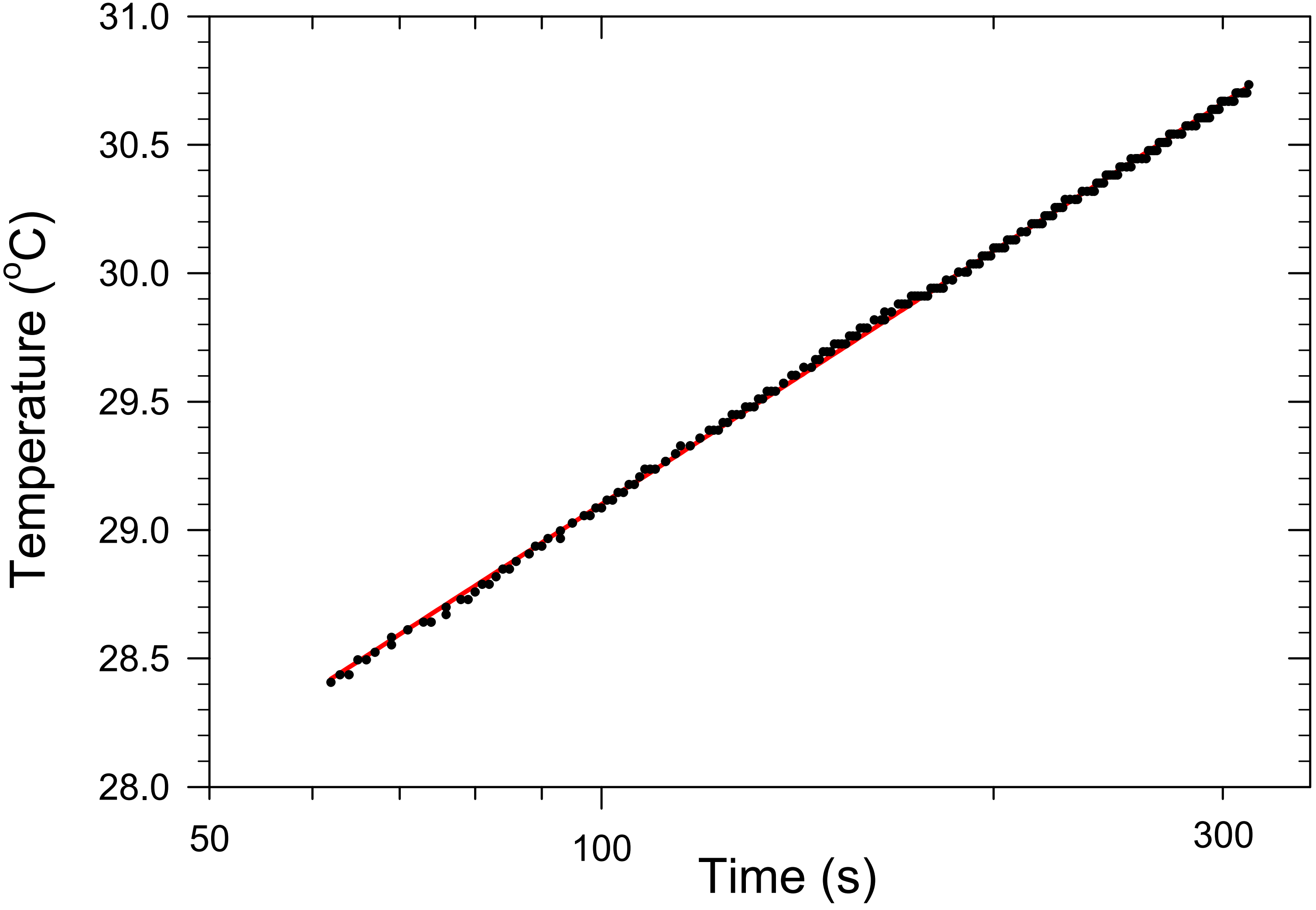
- Only the first term is significant at long times, thus:

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

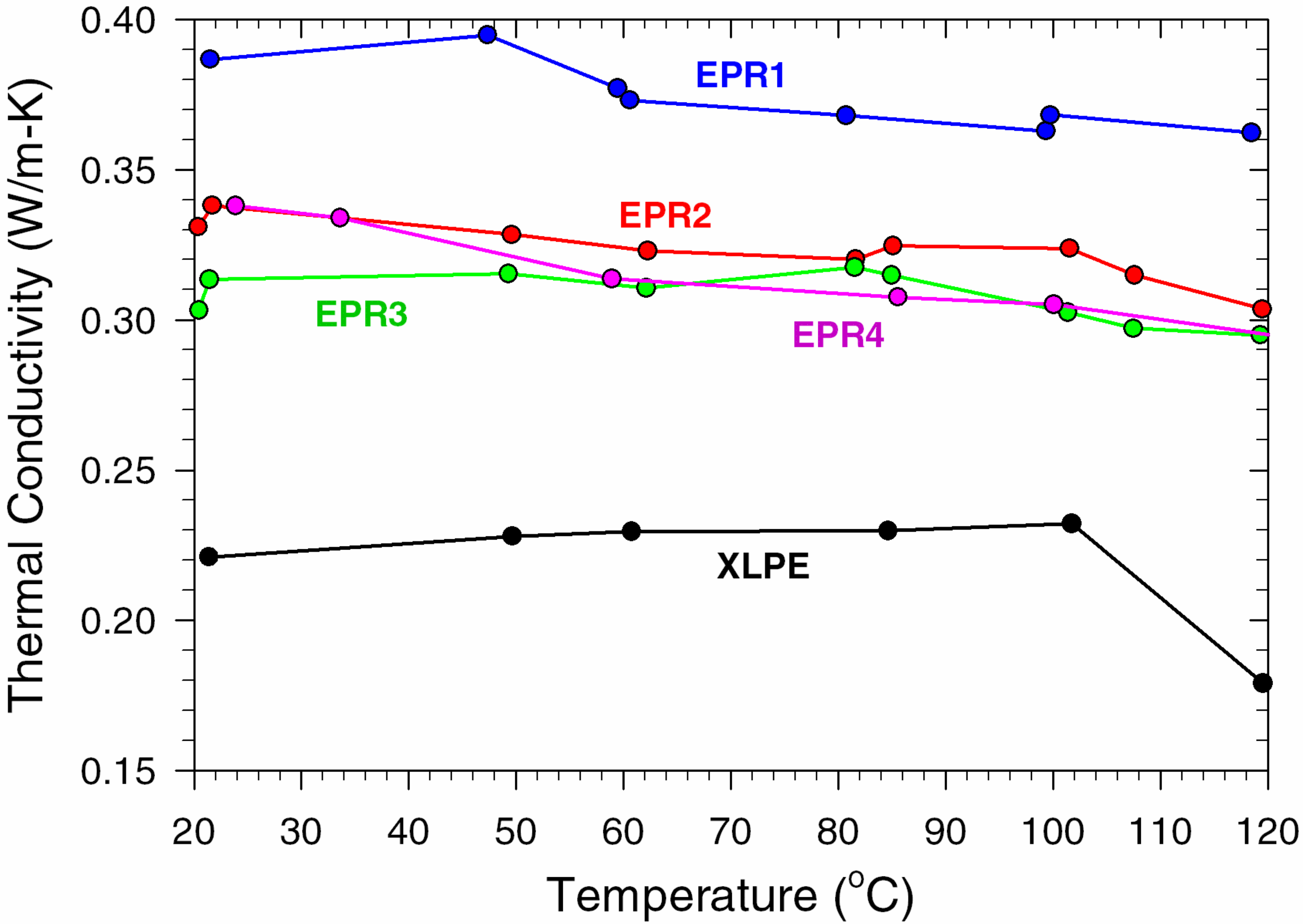
- Thus if we plot Temperature vs log of time, we can determine the thermal conductivity, *k*, knowing *q*, the power dissipation per unit length


TEMPERATURE CHANGE
$T(t) = -\frac{q\rho}{4\pi} \, Ei\left(\frac{-r^2}{4\alpha t}\right)$
$T(t) = \frac{q\rho}{4\pi}\left[\ln t + \ln \frac{4\alpha}{r^2 D}\right]$
Ln, TIME
$\frac{q\rho}{4\pi} \ln \frac{4\alpha}{r^2 D}$

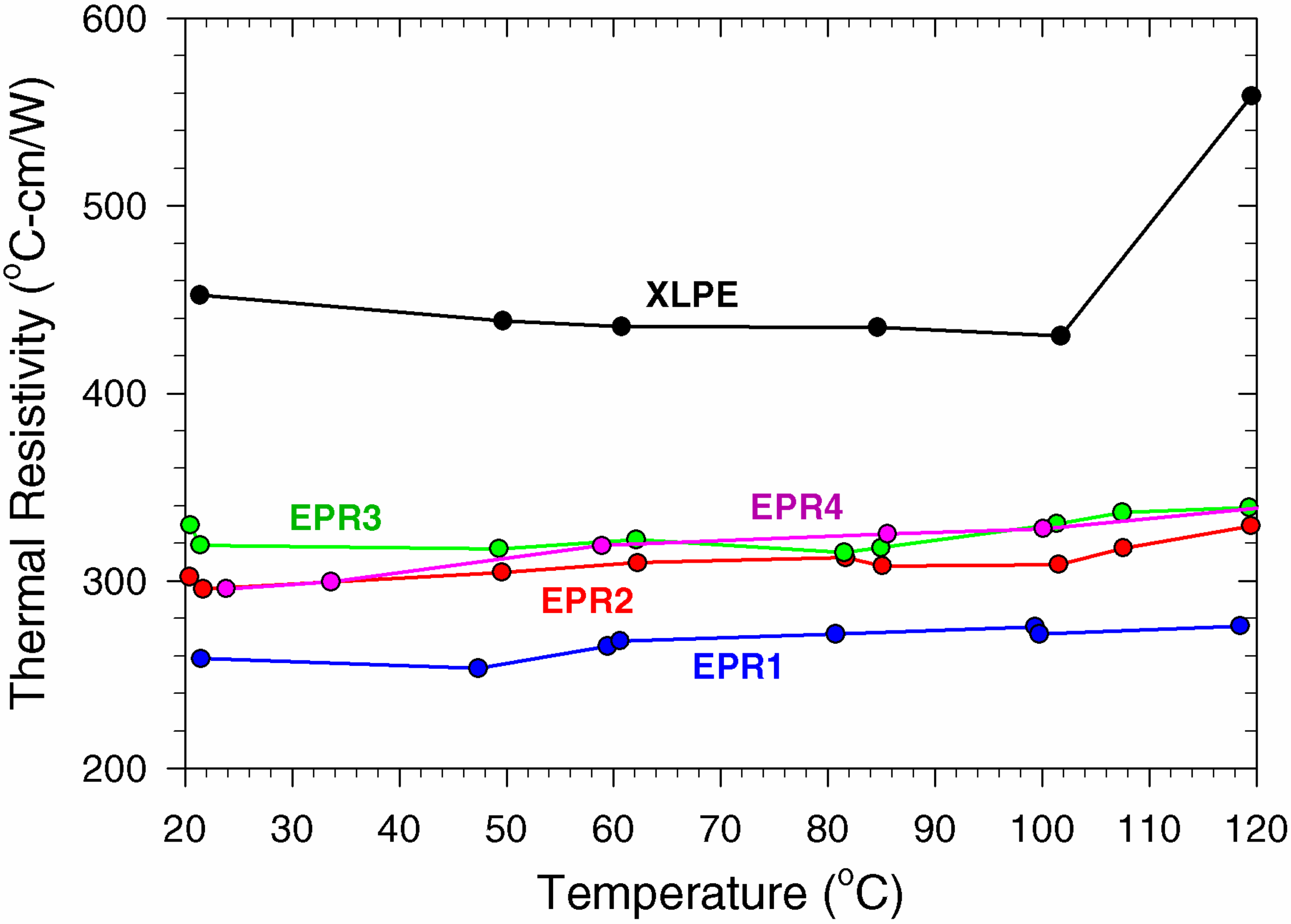

Temperature (°C)
31
30
29
28
27
26
25
24
1.0
10.0
100.0
Time (s)


31.0
30.5
30.0
29.5
29.0
28.5
28.0
Temperature (^{o}C)
50
100
300
Time (s)

Thermal Conductivity of EPR’s

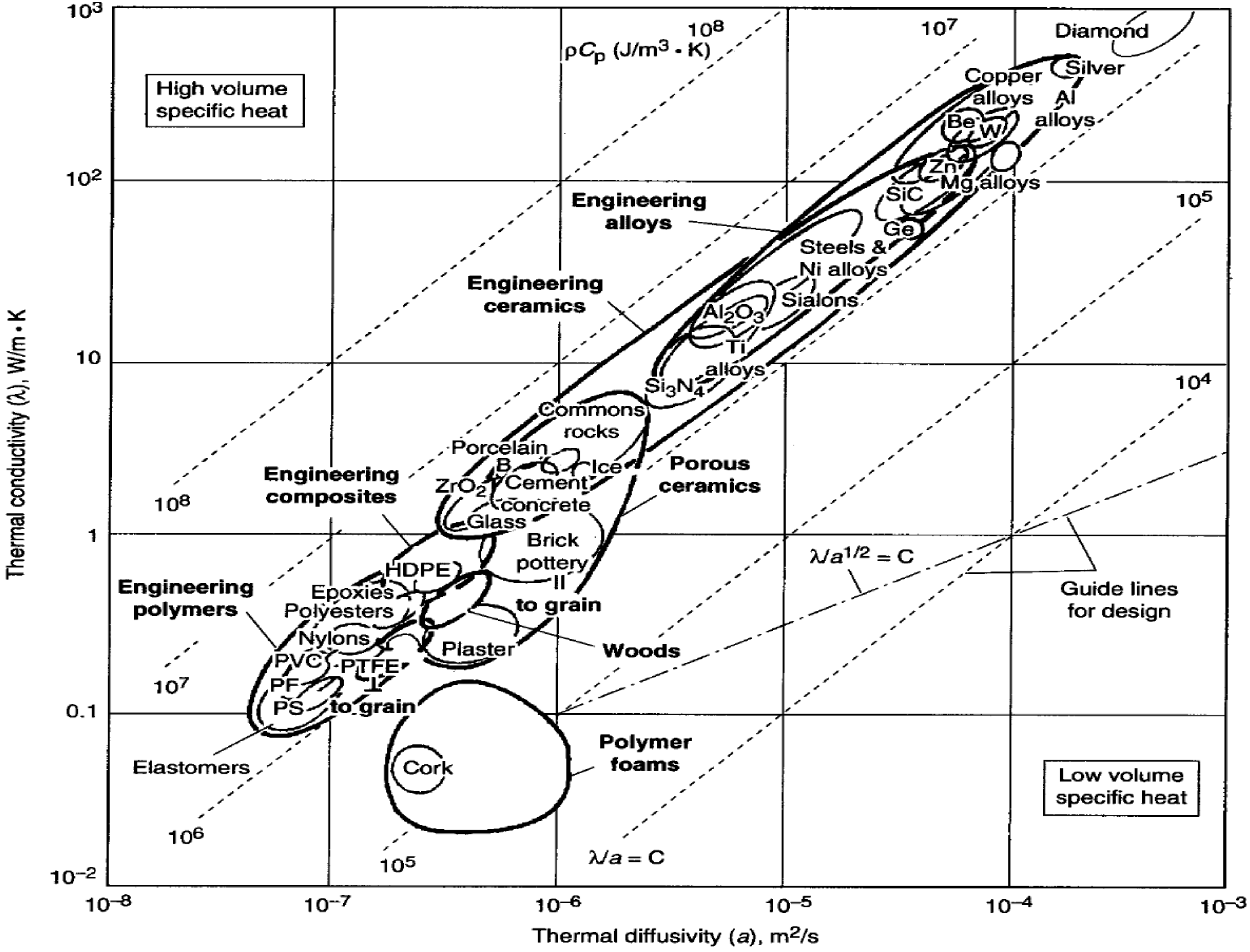


Thermal Resistivity of EPR's



Thermal Diffusivity & Heat Capacity

- Under steady state conditions, only the thermal conductivity is relevant
- Under transient conditions, the thermal diffusivity is relevant
  - Thermal diffusivity, α (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, 2×10^6 J/m^3-K


High volume specific heat
Low volume specific heat
ρC_p (J/m^3 · K)
10^8
10^7
10^6
10^5
10^4
Diamond
Silver
Copper alloys
Al alloys
Be
W
Zn
Mg alloys
SiC
Ge
Engineering alloys
Steels & Ni alloys
Sialons
Engineering ceramics
Al_2O_3
Ti alloys
Si_3N_4
Commons rocks
Porcelain
B
Ice
Porous ceramics
Engineering composites
ZrO_2
Cement concrete
Glass
Brick pottery
∥ to grain
HDPE
Engineering polymers
Epoxies
Polyesters
Nylons
Woods
Plaster
PVC
PTFE
PF
⊥ to grain
PS
Elastomers
Cork
Polymer foams
$\lambda/a^{1/2} = C$
$\lambda/a = C$
Guide lines for design
Thermal conductivity (λ), W/m · K
10^3
10^2
10
1
0.1
10^{-2}
Thermal diffusivity (a), m^2/s
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

Differential Scanning Calorimetry (DSC)

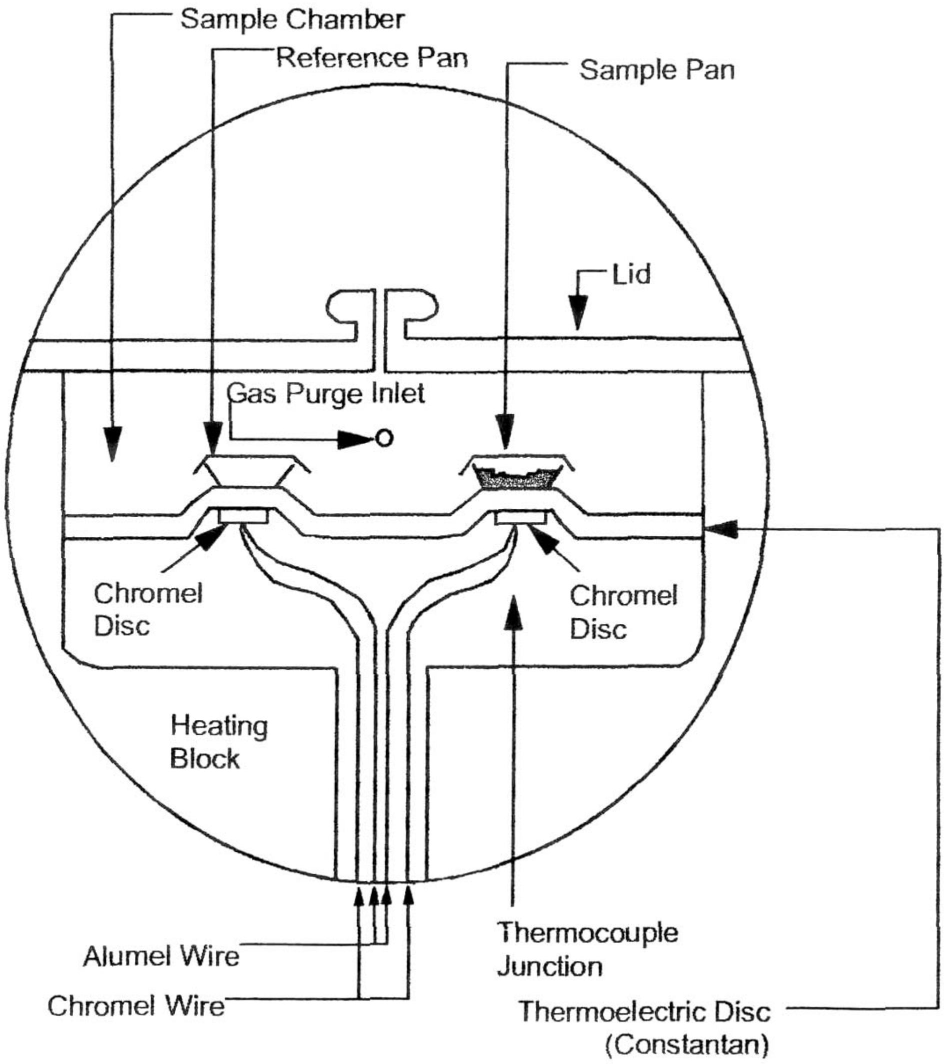
A thermal analysis tool for measuring thermal properties

- Heat Capacity
- Crystallinity
- Curing
- Oxidation or decomposition

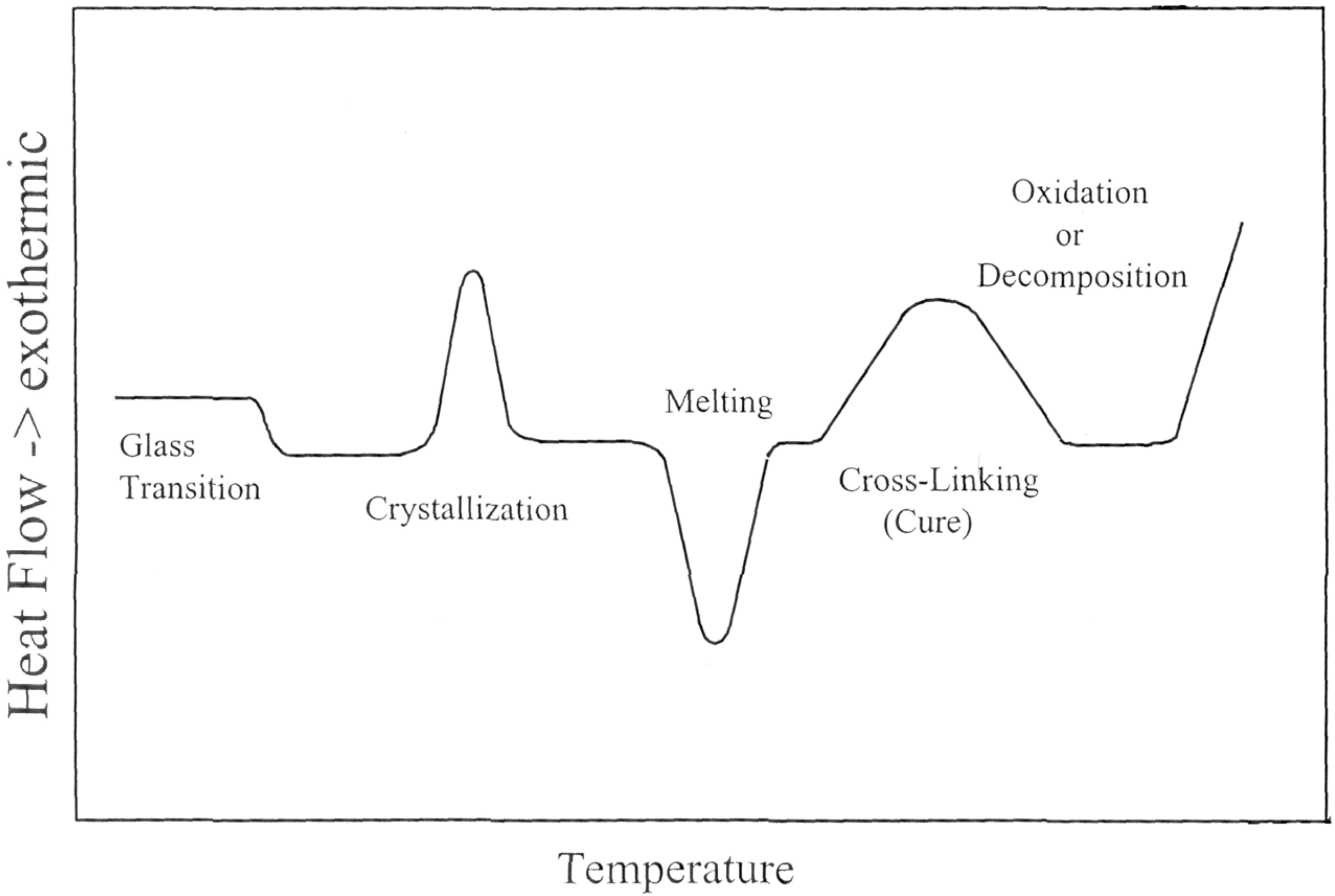
DSC (cont.)

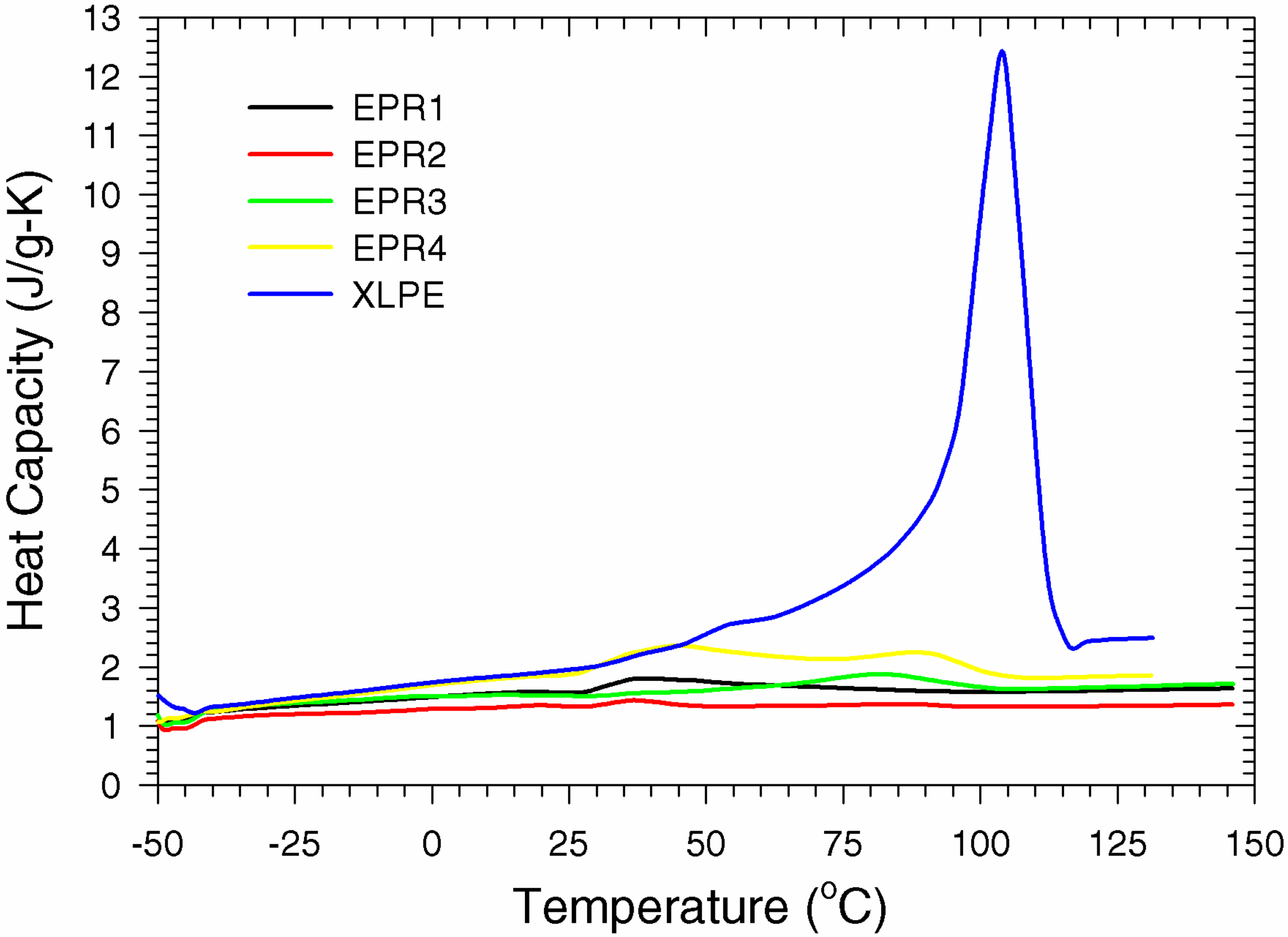
Basic principles

- 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 Capacity (J/g-K)
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-50
-25
0
25
50
75
100
125
150
Temperature (°C)
EPR1
EPR2
EPR3
EPR4
XLPE

Heat Diffusion

- The distance heat diffuses in a time, *t*, is given by

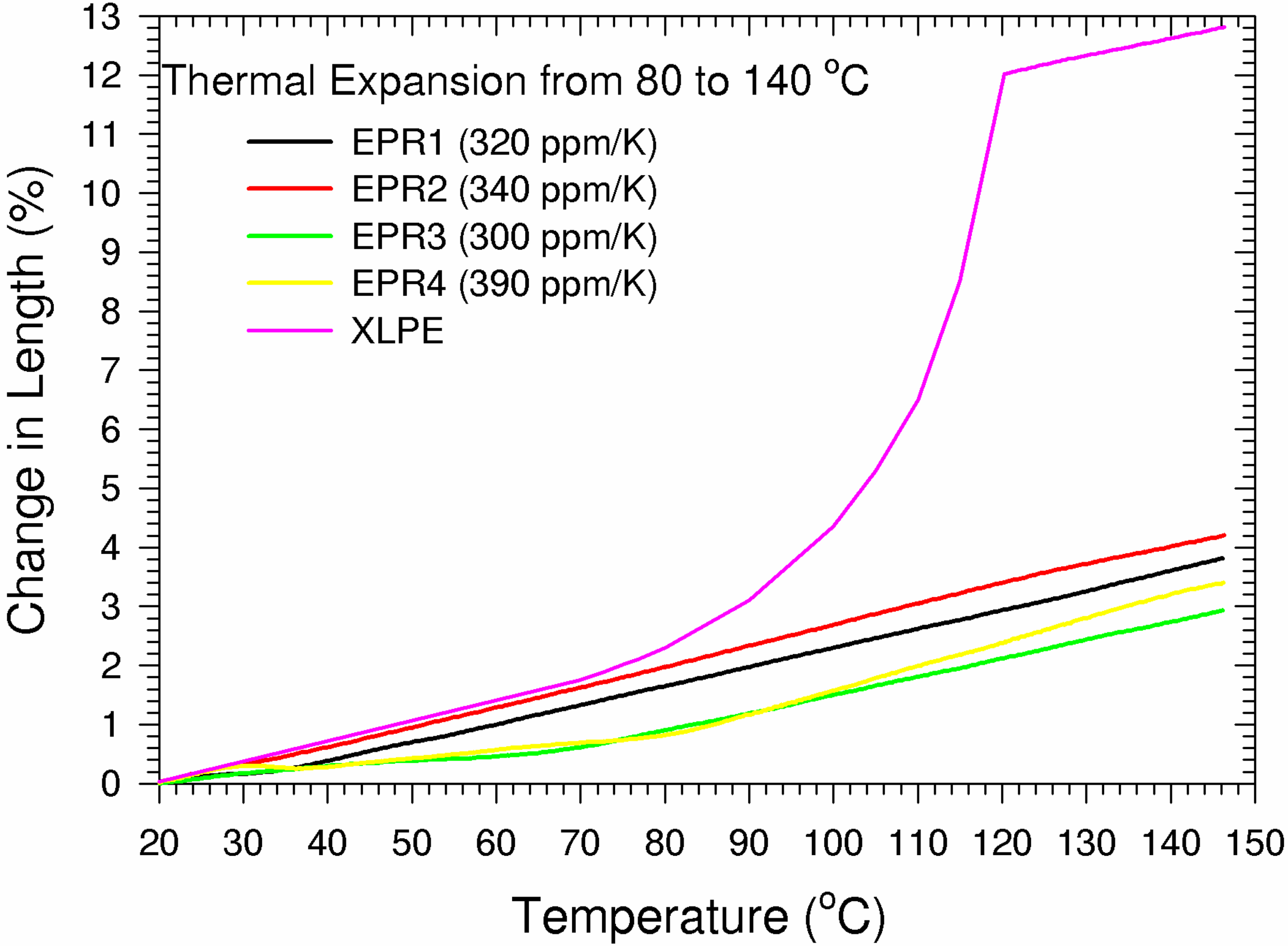
$$x = \sqrt{\alpha t}$$

- Since the thermal conductivity of EPR insulation is about 0.3 W/m-K and the heat capacity is about $2\text{x}10^6$ J/m^3-K, the thermal diffusivity is about $1.5\text{x}10^{-7}$ m^2/s.
- Thus heat diffuses across the ~5 mm dielectric of a 15 kV cable in about

$$t = \frac{x^2}{\alpha} = \frac{\left(5\times10^{-3}\right)^2 \mathrm{m}^2}{1.5\times10^{-7}\ \mathrm{m}^2/\mathrm{s}} \approx 170\,\text{seconds}$$

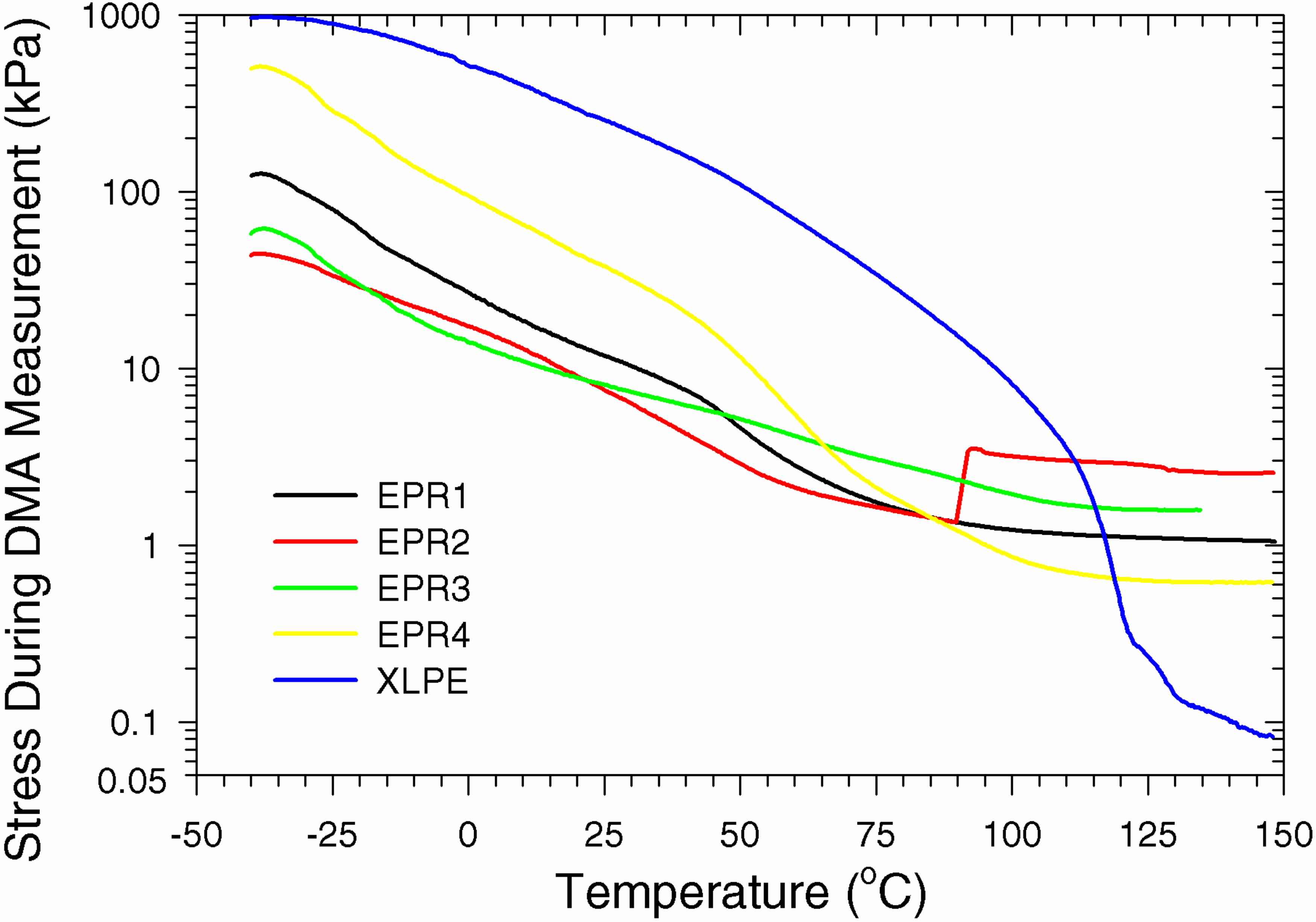
Mechanical Properties

- 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.

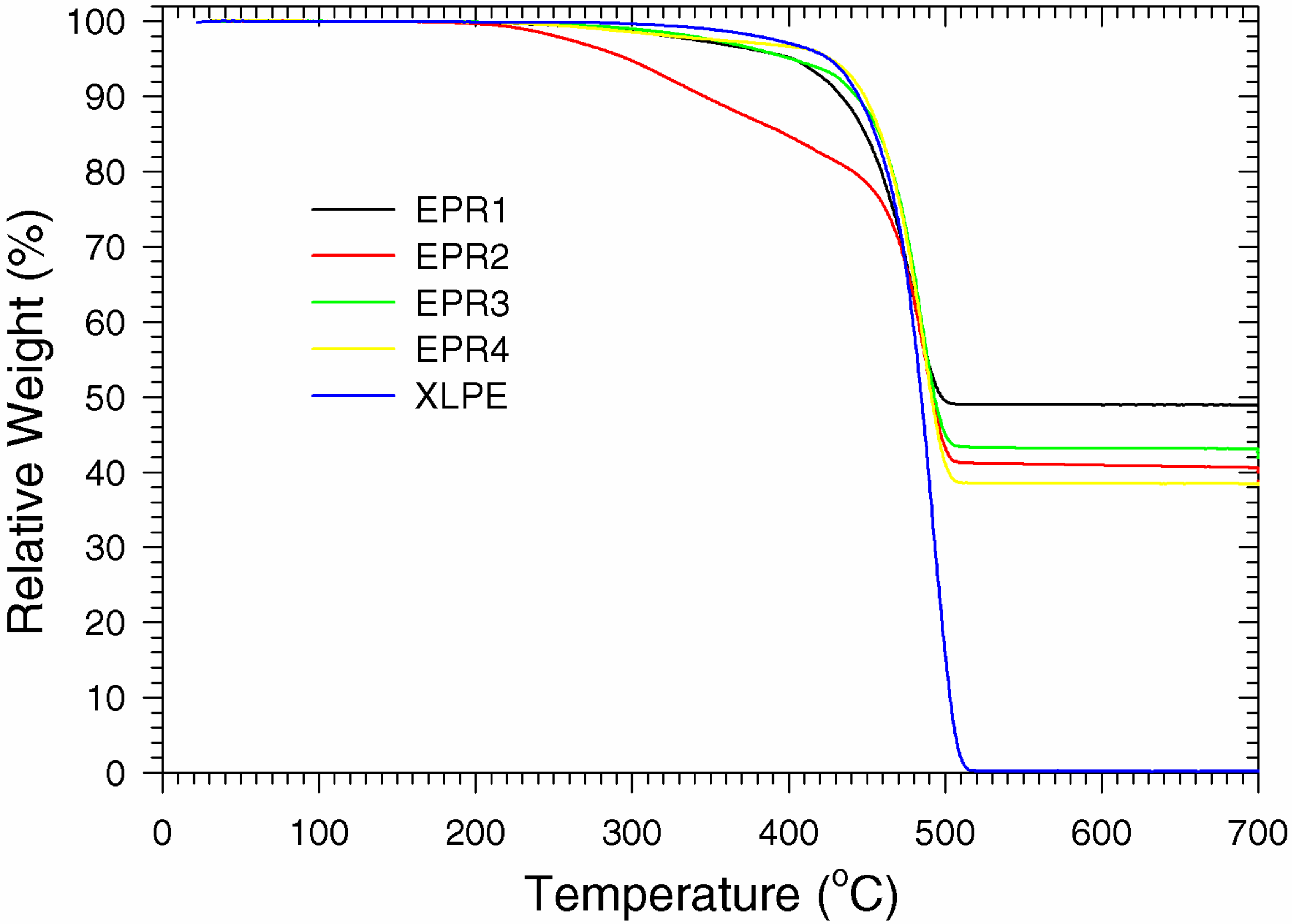

Thermal Expansion from 80 to 140 °C
EPR1 (320 ppm/K)
EPR2 (340 ppm/K)
EPR3 (300 ppm/K)
EPR4 (390 ppm/K)
XLPE
Change in Length (%)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Temperature (°C)
20
30
40
50
60
70
80
90
100
110
120
130
140
150

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.


Stress During DMA Measurement (kPa)
1000
100
10
1
0.1
0.05
-50
-25
0
25
50
75
100
125
150
Temperature (°C)
EPR1
EPR2
EPR3
EPR4
XLPE

Themogravimetric Analysis (TGA)



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 ^{o}C) compared to 1000 for unfilled dielectric.
- “Stiffness” or “Hardness” levels off at very high temperatures