REVIEW

A Critical Comparison Of XLPE And EPR For Use As Electrical Insulation On Underground Power Cables

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ABSTRACT

A summary of previously published technical data is presented with commentary. The purpose is to offer reliable information for use in material selection and cable design in a form which is convenient for reference and use. Since the value of this summary depends upon the quality of the data presented, the most objective sources have been selected. The primary source is the report of EPRI supported work carried out at the IREQ laboratory in Canada [1]. A few results of work by the author are used to fill in for completeness, to facilitate understanding, or when a disagreement exists between other sources [2].

1. INTRODUCTION

Recently some of the failure statistics reported for URD type cables (direct buried, underground distribution cables without continuous moisture impermeable metal sheaths) insulated with PE (polyethylene) and XLPE (cross-linked polyethylene) have caused uncertainty about the wisdom of using these materials for cables which are intended to serve for 40 years [3]. Other statistics lead to optimism for full-wall XLPE insulated cables [4]. At the same time, publications have appeared which report the advantages of filled and cross-linked EPR (ethylene-propylene copolymer rubber) and EPDM (ethylene-propylene-diene terpolymer rubber) in comparison with PE and XLPE. It should be recognized that there are many good, solid dielectrics available today and each has a unique combination of properties. Some have one or more superiorities over all others for certain special applications. In order to make more objective information available for those who must choose between these materials, this summary of data is presented. A commentary is included to point out that most applications require a careful and objective selection of insulation material on the basis of properties and requirements.

While the safe and efficient conduction of electrical energy is the function of a power cable, there are mechanical, thermal, and chemical requirements which the insulation must satisfy as well as high breakdown stength and low dielectric loss. This is because the function of the insulation is not only to separate opposite electrical charges at high potential difference and on closely spaced conductors, but also to support the two conductors and maintain their separation. Furthermore, the insulation must often withstand rough handling and abuse during installation and thermal overloading during its service life. Damage during installation and subsequent dig-ins are the cause of over 90% of all underground cable failures in the US.

It has been shown that the properties of both XLPE and EPR are affected by temperature. Physical properties are in many (but not all) cases more temperature sensitive than electrical properties, and XLPE is often (but not always) more temperature sensitive than EPR. While considering the data presented here, it is important to remember that the mechanical damage which leads to cable failure occurs at low temperatures while the electrical damage which leads to failure usually occurs at operating temperature.

2. MATERIALS AND SPECIMENS USED

Unless otherwise indicated, all specimens used for the measurements and tests reported here were prepared by compression molding and are fully cross-linked. The compression molding procedure was used to eliminate all except material variables. Thus the effects of molecular orientation, residual stress, shrinkage after extrusion, and the presence of moisture-induced microvoids have been excluded. The results characterize the tested materials per se. It is within the province of a cable manufacturer to make cables which realize and emphasize the good intrinsic properties of the materials used in his product.

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The materials used to generate the data reported here are commercially available grades. The XLPE is a chemically cross-linked polyethylene which contains no filler. It is a translucent whitish compound which contains only conventional high-pressure, low-density, branched polyethylene, plus an antioxidant and dicumyl peroxide as cross-linking agent. The optically opaque and colored EPR and EPDM compounds tested are among the best which are commercially available and in use at this time. The exact EPR formulations are proprietary and not disclosed by their manufacturers. However, it is well known that most include (1) ethylene-propylene copolymer (EPR or EPM) or ethylene-propylene-diene terpolymer (EPDM) where the third monomer is often ethylidene norbornene or ethylene norbornadiene, (2) a filler, such as finely-divided surface-treated clay to provide physical properties, (3) zinc oxide and (4) lead oxide as acid acceptors to stabilize the polymer against the effects of residual catalyst, (5) paraffin wax as a processing aid, (6) paraffinic oil as a processing aid and to increase the filler acceptance, (7) an organosilane as surfactant for the solid interfaces, (8) an antioxidant for thermal stabilization, (9) a peroxide for cross-linking, and (10) an accelerator like triallyl cyanurate to increase or advance the cross-linking reaction. Up to five additional components are used by various manufacturers in their proprietary formulations. Consideration of the problems involved in accomplishing uniform and reproducible blends of 10 to 15 different components, some in low concentration, and the number of combinations possible, explains why the acronym EPR cannot specify a unique material. In this paper the name EPR will be understood to include filled formulations based upon either EPR or EPDM. Most curves will show a range of properties measured for the EPR formulations. In studies where only one EPR was used and reported, the material was selected by the original author as either the best one available, or perhaps more often as a typical commerically used insulation.

In recent practice, blends of EPR or EPDM, and PE have been cross-linked together to obtain improved properties and introduce some crystallinity into the compound. The ratio of EPR or EPDM is controlled to accomplish a satisfactory balance between processability and adequate thermal stability [5] as is the oil content. Physical properties of filled and unfilled EPR systems are affected by the fillers used [6,7] and the crystallinity of the polymer [8]. It is well known that most electrical properties of filled EPRs are controlled, but never improved, by the additives used with the polymer, primarily the filler.

3. THERMAL PROPERTIES

Almost all of the physical and chemical properties of XLPE and EPR are affected by and vary reproducibly with temperature. They will be treated in subsequent sections.

The most important thermal properties of organic high polymers used for electrical insulation on flexible power cables are thermal expansion, thermal conductivity, and thermal stability. Fundamental and analytical treatments of these properties have been published [9-14] and can be used to provide background and understanding. Surveys of published data are also available [15,16] if further information is desired.

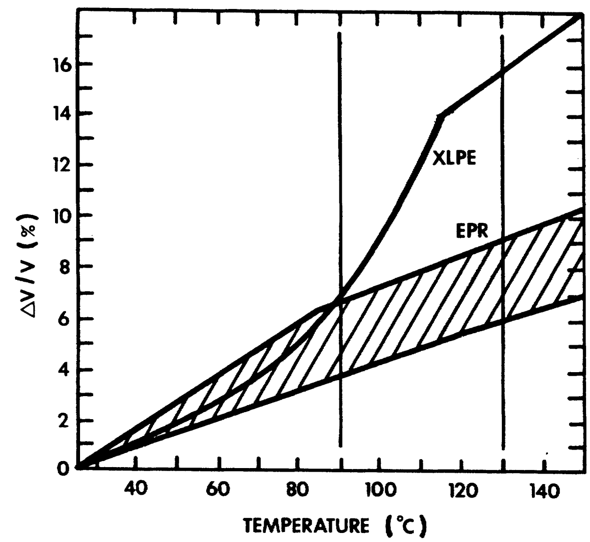

Fig. 1: Relative (thermal) volume expansions [Ref. 1, p. 3-13].

3.1. *Thermal Expansion*

All organic materials expand much more than metals and minerals when their temperatures increase in the 0 to 200°C range. PE and XLPE expand more than mineral-filled EPR or EPDM. This is because the homopolymers are partially crystalline and have melting temperatures around 115°C, also because the fillers have relatively negligible expansion in this range. In the crystalline regions of polymers, segments of long molecules are spatially ordered. This ordering results in higher density and greater strength and stiffness than in the amorphous or disordered regions. Starting in the solid phase, as thermal energy is supplied to the crystalline regions by heating, molecular motion increases until crystallites of polyethylene are disrupted and the molecular segments which had been ordered add to the amorphous fraction. The result of this effect is shown in Fig. 1. The long concave upward portion of the XLPE curve results from the fact that the crystalline regions, called crystallites, have lattice energies or stabilities proportional to their sizes. Hence small crystallites have little stability and their lattice energies are exceeded by the thermal energy of the molecules which decompose them at fairly low temperature. As temperature increases, crystallites of larger and larger size are melted, thus causing the rate of expansion to increase until the largest is melted. After this point, called the thermodynamic melting point (MP), the material is completely amorphous. Thermal expansion with further temperature increase then continues at a constant rate characteristic of the molecular structure.

Similar data obtained by a different laboratory and plotted in different proportion is presented in Fig. 2 [17]. Note that from 20 to 90°C in both figures EPR expands between 3.5 and 6.5% while XLPE expands 6 or 7% depending upon the formulation of the EPR and which data are used. That is a small difference, particularly for the new, higher voltage, partially crystalline EPRs which lie at the top of the EPR range. The literature contains further data on the thermal expansion of polyethylene [10,11,15,16] but little on filled compounds of EPR or EPDM.

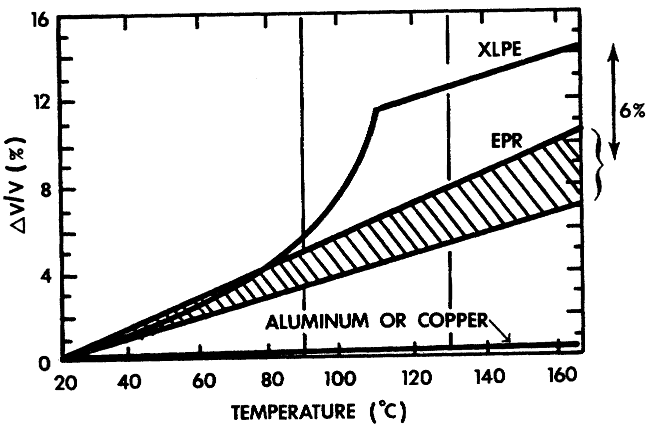

Fig. 2: Relative (thermal) volume expansions [17].

There are two effects of the thermal expansion of electrical insulation on power cables. The first results from the great difference between the expansion of organic insulating materials and metallic conductors. This difference is shown in Fig. 2. The differential can destroy the initially intimate interfacial contact between the conductor and the innermost organic layer. When extruded semiconductive shields are used, this is not a problem. The second effect is that poorly designed cables may be destroyed by the practically irresistable force of expansion of either XLPE or EPR. This problem also involves the bulk modulus and will be considered in detail in section 4-4 on compressibility where P-V-T data are presented.

3.2. *Thermal Conductivity*

The thermal conductivity of the insulation in a buried cable is important because it controls how rapidly the heat generated by conductor and dielectric losses can be passed to the surroundings. Thus it is a major factor, with the nature of the surroundings, in determining ampacity. It is also important because the resistivity of the conductor and the dielectric loss of EPR insulation are themselves temperature sensitive.

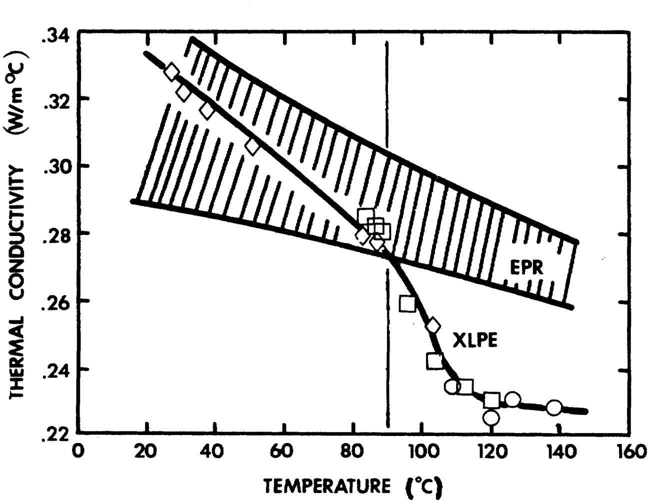

Fig. 3: Thermal conductivity of XLPE and EPR [Ref. 1, pp. 6-3, 6-5].

Fig. 3 presents data comparing the thermal conductivities of XLPE and EPR over a wide temperature range. Fig. 4 presents the same kind of data for the same materials, plus thermoplastic polyethylene (PE) as a reference, carried out with the same method [18], but in a different laboratory [19]. The most significant difference between them is the surprisingly large change in slope in the polyethylene curve through its melting range shown in Fig. 3. Two other good sets of data obtained by use of several different polyethylene resins in each [14,20] are in better agreement with the second XLPE curve, shown in Fig. 4. The several curves presented in ref. [20] are all linear, with no change in slope, from 10 to 100°C, which is the temperature range of the data presented.

Consideration of the data in Fig. 3 shows that XLPE has average thermal conductivity at temperatures in the operating range, below 90°C, while Fig. 4 shows that XLPE has higher conductivity over the whole measured range and ref. [20] verifies the shape of the polyethylene curve in Fig. 4.

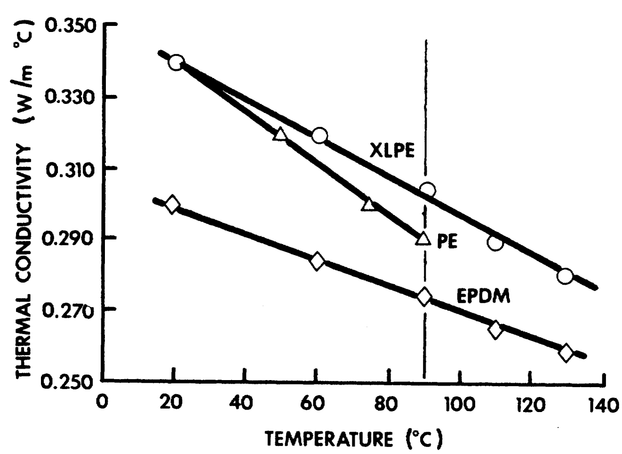

Fig. 4: Thermal conductivity of PE, XLPE, and EPDM compound [19].

The most conservative comparison of the three sets of data would suggest that there may be no difference between the thermal conductivities, or that of XLPE may be slightly higher. If the data in Fig. 4 is accepted, the difference, at temperatures over 90°C, would be less than 10%, while if Fig. 3 is accepted, the maximum difference, at 130°C, is only 20%.

3.3. *Thermal Stability*

The thermal stability of XLPE and EPR has been evaluated in the laboratory at temperatures up to 427°C along with other copolymers of ethylene [9]. Thermal Gravimetric Analysis (TGA) was the technique used and the specimens were held in an inert nitrogen atmosphere. The purpose of the work was to determine the suitability of these materials for high-temperature, dry nitrogen curing. It was observed in a temperature-programmed experiment that degradation commenced at 360°C for a cross-linked EPDM formulation and at 375°C for XLPE, a small difference. In isothermal studies the initial degradation rates for XLPE and EPR at 260°C were 0 and 0.013% wt. loss per minute. At 315°C the rates were 0.013 and 0.121, respectively, while at 370°C, which is above the nitrogen curing temperature range, the rates in the same order were 0.186 and 0.200. These low rates indicate that the thermal stability of EPR, as XLPE, should be satisfactory for the curing process in pure nitrogen.

An interesting comparison can be made with the test results for other copolymers and rubbers. The most stable copolymer studied was ethylene/ethyl acrylate which is close to polyethylene and better than EPR up to 370°C. Ethylene/vinyl acetate copolymer is not as good as EPR but very much better than Hypalon(R) and neoprene rubbers.

Other thermal analysis studies carried on in air, instead of nitrogen [21], showed that the temperatures at which rapid oxidation commenced were 160°C for EPR and 230°C for XLPE.

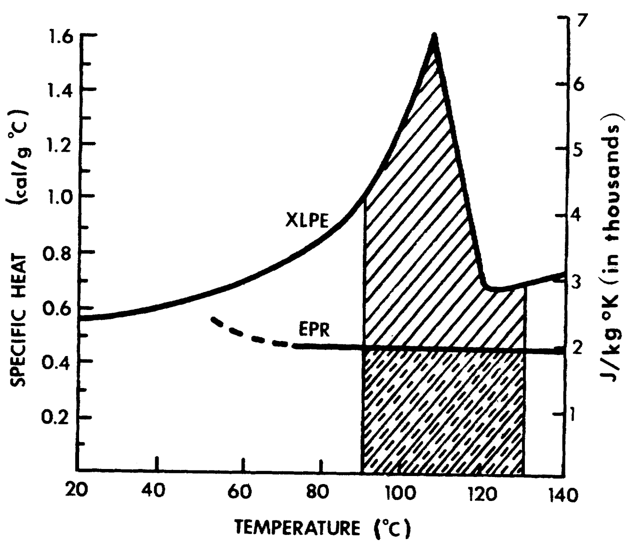

Fig. 5: Heat contents of XLPE and EPR between 90° and 130°C [22,23].

3.4. *The Effect of Melting*

If a cable operating at its maximum permissible continuous conductor temperature of 90°C is suddenly overloaded by a substantial amount, the conductor temperature will rise and the insulation temperature will follow. Under these conditions the EPR insulation will reach the overload temperature of 130°C sooner than the XLPE because the XLPE must be completely melted before its temperature can exceed about 115°C as shown in Figs. 1 and 2.

Fig. 5 shows the specific heats of XLPE [22] and EPR [23] as a function of temperature. Integration of the area under the curves between 90° and 130°C gives the amount of heat required to cause that temperature increase. For the EPR it is about 1760 cal/gm while for XLPE it is about 4400 cal/gm, two and a half times as much. The significance of this result is that given an increased, but constant, heat input the time required to heat XLPE from 90 to 130°C would be two and a half times as long as that for EPR. The effect of thermal conductivity on this estimate has been neglected due to the conflict in data available and the minor effect it would have. When the period of overload is completed, and the cable permitted to cool, the opposite effect would be observed. The EPR would cool faster. Therefore, the seriousness of this effect would depend upon the duration of the overload period.

4. MECHANICAL PROPERTIES

The mechanical properties of XLPE and EPR are affected by temperature and XLPE is more temperature sensitive by a substantial amount. Thus, in order to make a fair comparison, the temperature range of practical importance should be considered first.

Since over 90% of underground cable failures are due to mechanical damage, the temperatures at which such damage occurs is important to consider. This damage happens during installation and from dig-ins, both of which take place when the temperature is low. In the first case it is near ambient because the cable is exposed to the atmosphere and not connected, in the second case because the activities which result in dig-ins are not underway at the times when cables are likely to be overloaded.

It should also be remembered that because the costs for energy increase rapidly, the optimum economic current loading of cables is decreasing. This is because conductor and insulation losses are diminished by decreasing operating temperatures [24,25].

The important properties considered in this section are toughness, hardness, bearing strength, and compressibility. Modulus of elasticity (or stiffness), tensile strength, and elongation are introduced first.

4.1. *Modulus of Elasticity*

Cable insulation is stressed in tension at temperatures below 40°C (105°F) during installation in a trench or when pulling around corners and into ducts. Fig. 6 displays the modulus of elasticity in tension as a function of temperature. There are significant differences at temperatures below 90°C.

The tensile modulus test determines how much force is required to stretch or deform a material by pulling on it. The amount of force required to deform a material by squeezing on it in one direction is called the Elastic Modulus in Compression. (This is not the same as Bulk Modulus or Compressibility which will be

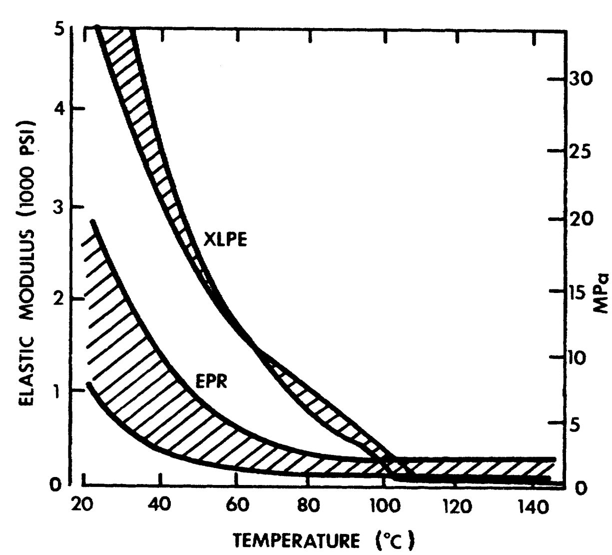

Fig. 6: Modulus of elasticity in tension [Ref. 1, p. 5-4].

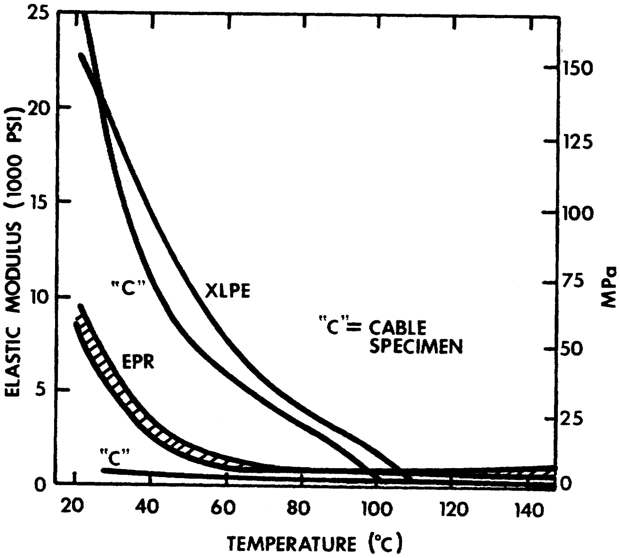

Fig. 7: Modulus of elasticity in compression [Ref. 1, p. 5-10].

treated in a following section.) Fig. 7 presents compression data where the same difference between XLPE and EPR, as shown in the previous figure, is evident.

While the data show clearly that XLPE is stronger and therefore more resistant to mechanical distortion which leads to damage, the EPR is obviously softer, more limp and flexible at low temperatures. Unfortunately these two advantages are incompatible in the same material. Therefore, while moderate heating will soften XLPE sufficiently for training and installation of cable in small spaces, EPR has a real advantage for those applications where permanent flexibility is important.

4.2. *Tensile Strength, Elongation, and Stiffness*

Values of ultimate tensile strength and elongation for "high-voltage" EPR formulations and for XLPE are presented in Table 1. Measurements were made at 23°C and at a strain rate of 0.08 mm/sec for modulus and 8 mm/sec for tensile strength and elongation.

TABLE 1

Mechanical Properties of XLPE and EPR at 23°C

	XLPE	EPR
Ultimate Tensile Strength (MPa)	19.3	8.6 - 11.7
Maximum Elongation (%)	550	250 - 300
Modulus of Elasticity (MPa)	120.7	4.8 - 13.8

Conversion Factor: 6.895 kPa/psi

When comparing the mechanical properties of different materials used for the same applications, it is necessary to insure that measurements are made under identical conditions. These properties are sensitive to temperature, specimen size and geometry, testing rate, even the specimen holder used, as well as thermal and mechanical history.

4.3. *Toughness*

The toughness of a material is defined as the amount of work or energy which it can absorb before failure occurs. Analytically it is given as

$$T = \int F \cdot dl \qquad (1)$$

where F is the applied tensile or compressive force, and dl the incremental change in length which results [26]. Thus the toughness of a material is related to its tensile strength and elongation and is a function of the rate of strain.

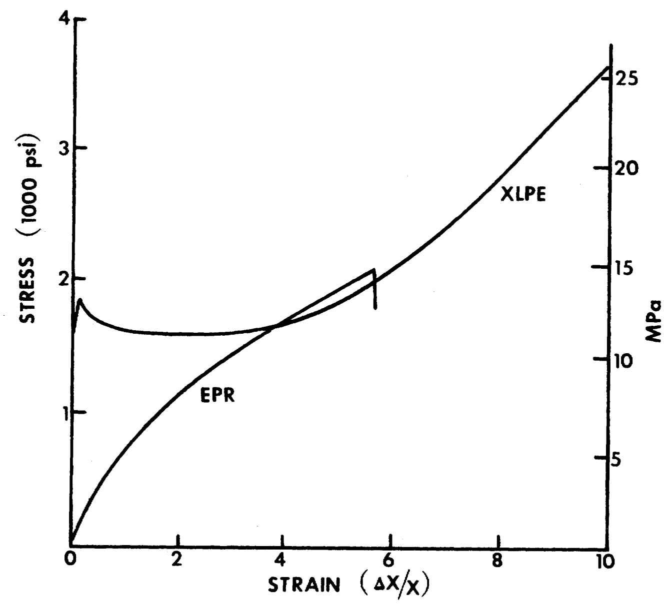

Fig. 8: Stress vs strain curves used for determination of toughness.

For electrical insulation on a cable, the ability to absorb work or energy during pulling would depend upon toughness. An estimation of the amount of work absorbed during tension (extension or stretching) is made by integration of the area under a stress-strain curve as in Fig. 8. Numerical or graphical integration of the areas under the XLPE and EPR curves for a strain rate of 8 mm/sec starting with 25.4 mm long specimens gives toughness values of 143 J/cm^3 for XLPE and 48 J/cm^3 for EPR. The results are similar for tests made at higher rates and are displayed in Table 2.

It is very clear that while EPR is soft and resilient at low stresses, XLPE will absorb much more energy before it breaks.

TABLE 2

Toughness Values for XLPE and EPR at 23°C

Dimension: (Joule/cm^3)

	8 mm/sec	20 mm/sec	Impact
XLPE	143	127	30
EPR	48	38	24

Conversion Factor: 0.0827 (J/cm^3)/(ft pound force/$inch^3$)

Examination of the stress strain curve also shows that at 8 mm/sec extension rate (30%/sec), and at higher speeds, the level of recoverable stress is very low. While XLPE will recover the small strain resulting from 7 MPa stress, EPR cannot recover from stress over about 2.8 MPa. At 20 mm/sec (75%/sec) the difference is greater, about 14 MPa for XLPE and about 3.4 MPa for EPR.

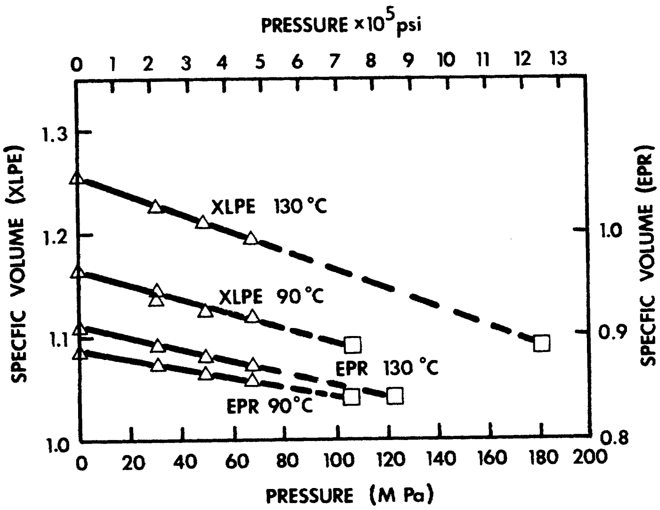

Fig. 9: P-V-T Curves for XLPE and EPR at 90° and 130°C [32].

4.4. *Compressibility*

It was stated earlier that all organic materials expand more than metals or minerals when heated; Figs. 1 and 2 showed that XLPE expands 12.5 or 15% while EPR expands from 5 to 9% between the temperatures of 20 and 130°C. Between 20 and 90°C the difference between the materials is about 2% or less. If cables are not designed to accommodate this expansion it can destroy them because the force of thermal expansion is almost irresistible.

The force required to prevent thermal expansion equals the product of the expansion coefficient α_v, the temperature change ΔT, and the bulk modulus of elasticity at the higher temperature M_T. That is

$$F = M_T \alpha_v \Delta T. \qquad (2)$$

While there is sufficient data easily accessible in the literature to make this calculation for polyethylene [14,15,27-31] this is not true for commercial EPRs which are highly filled and chemically crosslinked by peroxides. Therefore, a series of compressibility measurements was made on XLPE and EPR at temperatures of 90, 110, and 130°C and pressures up to 70 MPa [32]. Fig. 9 shows the *P-V-T* relationships for the two temperatures which are important. Since the curves are all linear it appears entirely valid to estimate the pressure which would be required to prevent the expansion by extrapolating the data back to the 23°C specific volume levels, i.e. to the volume in cm^3 which each gram occupied before heating and expansion started. The extrapolations show that at 90°C the same pressure, 106 MPa (15,375 psi) would be required to prevent the expansion of either XLPE or EPR. The reason, obviously, is that while XLPE expands slightly more it has a lower bulk modulus at elevated temperatures. At 130°C there is a difference: XLPE would require 180 MPa (26,000 psi) while EPR would require 122 MPa (17,700 psi).

To calculate how thick a tight-fitting pipe, made of pure electrical grade copper, would be required to prevent significant radial thermal expansion in a long cable where end effects can be neglected is simple. Setting the expression for hoop stress in the pipe [33,34] equal to the yield strength for copper [35], the thickness can be determined. For a typical URD cable with OD = 2.54 cm, at 90°C the wall thickness required would be about 5 mm (0.2 inch) if hard copper were used or 19 mm (0.75 inch) if soft copper were used. These values are estimates only, calculated to show that the force of thermal expansion is irresistible for any solid organic dielectric and cables must be designed to accommodate the expansion or they will fail when seriously overloaded.

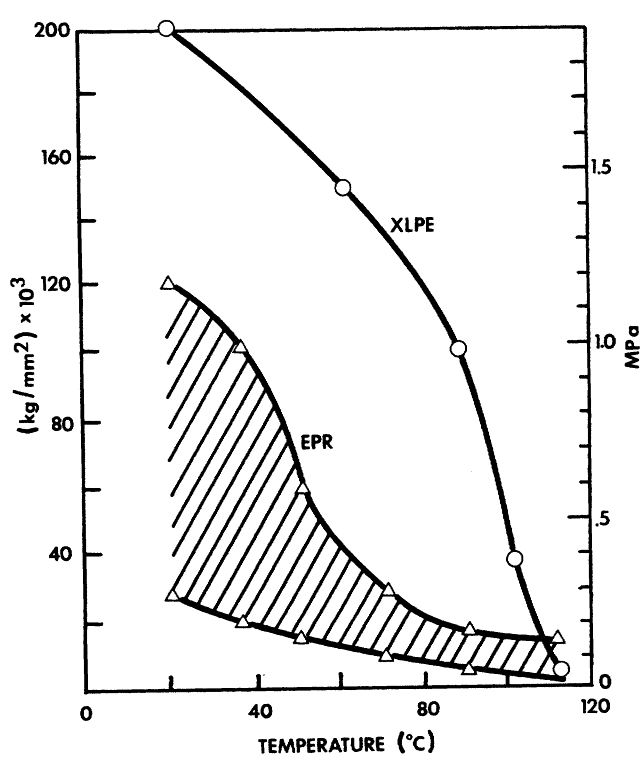

Fig. 10: Hardness [Ref. 1, data replotted]

4.5. *Structural Strength*

A mechanical property which relates directly to possible damage to a cable before or during installation is "hardness." Fig. 10 shows the relation between temperature and the force required to indent the surface of a thick section with a standard indenter. At all important temperatures the hardness of XLPE is about twice that of the hardest EPR, over ten times that of the softest EPR tested.

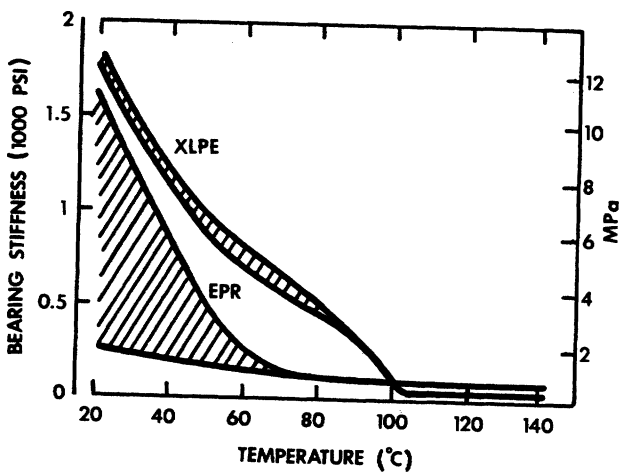

Fig. 11: Bearing Stiffness [Ref. 1, data replotted]

The "Bearing Strength" shown in Fig. 11 and measured by ASTM D-953B (69) is a property similar to deformation. It measures the stress required to produce 4% distortion over a form like a mandrel, or a rigid conductor, in compression; in other words, how much force is required to flatten the insulation.

Now if we consider the mechanical properties presented in Figs. 6 through 11 it is apparent that XLPE is stiffer, stronger, harder, and tougher at temperatures below about 100°C while EPR is slightly stronger above 100°C. EPR is softer and more flexible below 100°C. The important considerations are, how important is the advantage of permanent flexibility, and which material, used as cable insulation, could best withstand the forces of pulling, twisting, and localized compression, which occur during storage, installation, and accidental dig-ins.

4.6. *Retention of Mechanical Properties (Aging)*

It has been shown that the short-time mechanical properties of XLPE are quite sensitive to temperature and that above 90 or 100°C EPR has a higher modulus and a greater deformation resistance. However, it was also shown in 1973 [36], see Figs. 12 and 13, that properly stabilized XLPE resisted thermal degradation better and retained its mechanical properties very well after aging at 135°C in air. The data plotted were measured at 25°C after the thermal aging periods were completed. The EPR tests were terminated by embrittlement as indicated by the asterisks on the Figures. Since then, the properties of EPR have been improved, as shown in Table 1, but comparable aging data have not been found.

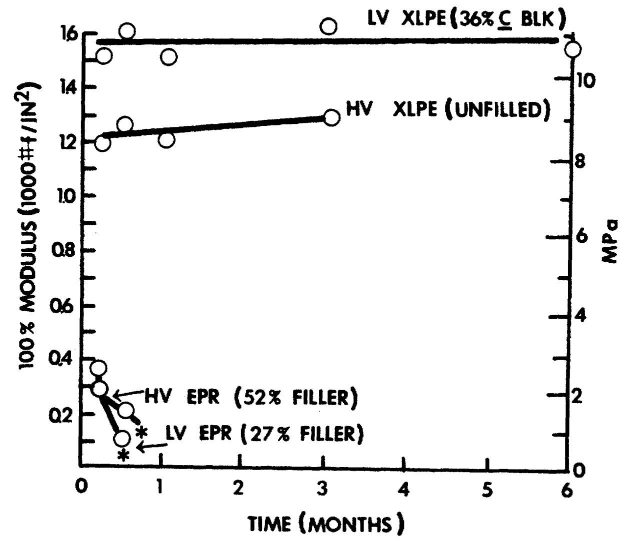

Fig. 12: Retention of 100% modulus after 135°C aging BS 2782:301 D [36].

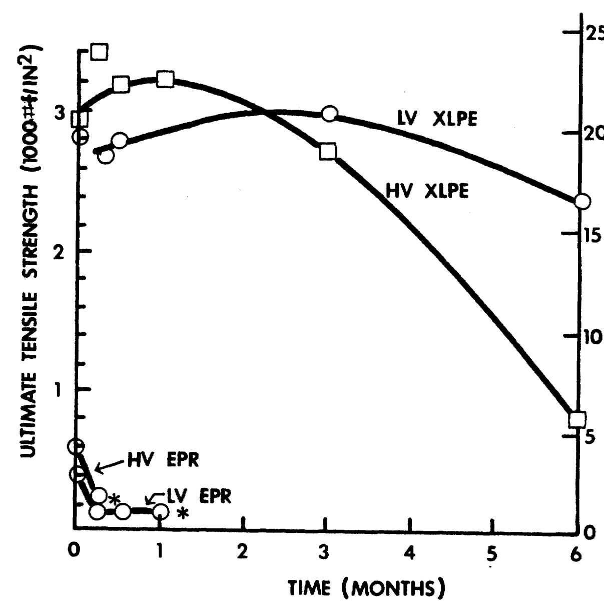

Fig. 13: Retention of ultimate tensile strength after 135°C aging BS 2782:301 D [36].

4.7. *Moisture Penetration*

Fig. 14 shows the effect of fillers on the moisture vapor permeability of PE and compares the rates at which moisture passes through unfilled XLPE and a filled, black EPR compound which was commercially used in 1975. There is no organic material which is impermeable to moisture, and the only commonly used high polymer less permeable than polyethylene is polyvinylidene chloride (SARAN). Further moisture data is presented in Tables 3 and 4 [39]. It has also been reported that EPR absorbs about 1% moisture by weight after two weeks immersion in 80°C water. Upon removal from the water the EPR was observed to dry out much more rapidly than it had been infused with moisture.

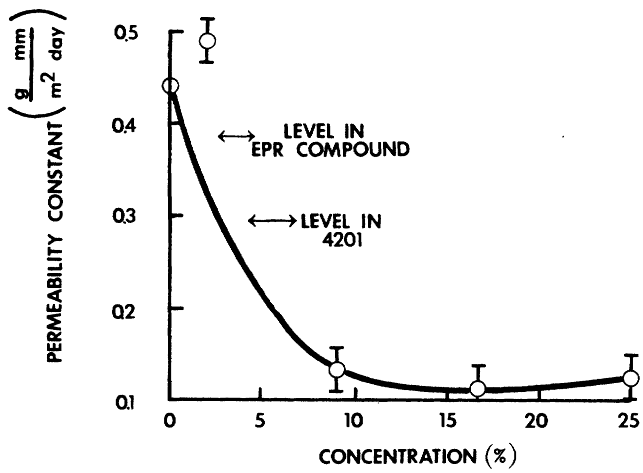

Fig. 14: Penetration of moisture through PE plus surface-treated clay T = 38°C, RH = 90%.

TABLE 3

Water Absorbed by XLPE and EPR

Material	Concentration of HOH	Temperature
Polyethylene	350 ppm (0.035%) Plaque	23°C
	850 ppm (0.085%) Cable	23°C
EPR	1,150 to 3,200 ppm	23°C

These specimens were conditioned in 103 kPa steam for two hours, then cooled, and measured before drying occurred. The data are from [Ref. 1, p. 4-7].

TABLE 4

Effect of Temperature Upon Moisture Permeability of Three Polymers

	Temp., °C	Permeability Constant $\frac{g \cdot mm}{m^2 \cdot day}$
Polyethylene	25	0.15
	30	0.27
Polyvinylidene chloride	25	0.0035
	32	0.0132
	38	0.028
Ethylene Propylene (3-2 molar) (unfilled)	37.5	1.51

Unfortunately, measurements of moisture vapor penetration into and through these materials are not, in general, capable of high precision. Therefore, very good agreement between the results of different investigators who use different methods is rarely observed.

4.8. *Chemical Resistance*

When solid organic materials are exposed to or immersed in organic liquids of lower molecular weight, they are usually observed to swell as they imbibe some of the lower molecular weight material. Table 5 shows this effect for cable oil. The changes in weight and volume for EPR when immersed in oil are surprisingly great. Similar tests with joint box compound (Bitumen) showed smaller changes; +5.1% increase in weight for EPR and +3.6% for XLPE at 60°C [36].

TABLE 5

Chemical Resistance at 23° and 60°C
Swelling of Polymers in Cable Oil
Test Procedure ASTM D-543 [Ref. 36]

	h.v. XLPE	l.v. XLPE	h.v. EPR	l.v. EPR
Increase in Diameter X (%) 23°C	+2.5	+2.5	+30.0	+35.0
Increase in Diameter Y (%) 23°C	+2.5	+2.5	+42.5	+37.5
Increase in Weight (%) 23°C	+7.6	+6.9	+151.3	+100.2
Increase in Diameter X (%) 60°C	+12.0	+20.0	+46.9	+43.8
Increase in Diameter Y (%) 60°C	+13.0	+20.0	+50.0	+46.9
Increase in Weight (%) 60°C	+40.8	+25.8	+232.9	+160.3

A practical example of creosote contamination and chemical attack upon EPR insulated cable which resulted in failures has been reported [37].

5. ELECTRICAL PROPERTIES

The most important properties of a material used for electrical insulation are, by definition, the electrical properties. The electrical properties of XLPE and EPR are presented here as functions of temperature, voltage, moisture content, and time. The differences between materials are fairly obvious and need little explanation.

5.1. *Breakdown Strength*

The dielectric breakdown strengths measured with 60 Hz ac voltage are shown in Figs. 15 and 16. The first Figure shows a threefold difference at 25°C and this difference is verified by others [38]. Other workers have observed that the breakdown strength of XLPE exceeds that of EPR by 50% [37,41]. Fig. 16 shows superiority for XLPE at temperatures up to 90°C.

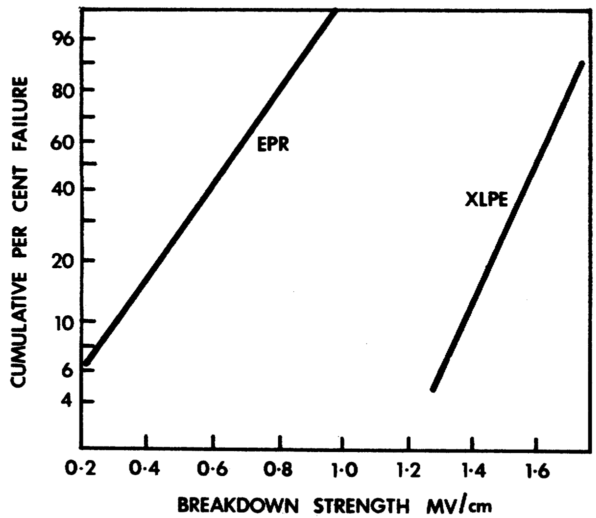

Fig. 15: Short time ac electrical breakdown strength [21].

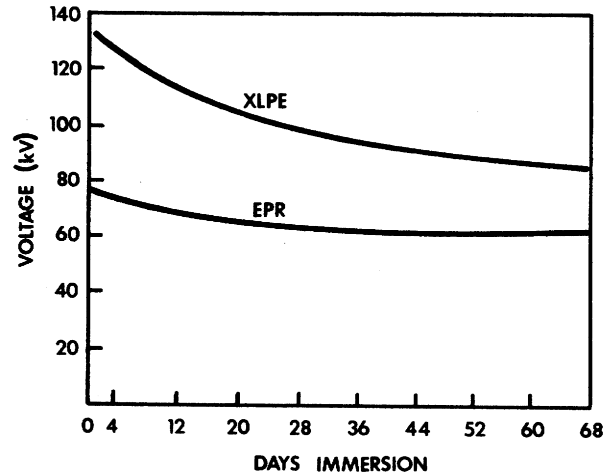

Fig 17: ac breakdown voltage of 11 kV cable immersed in 70°C water [21].

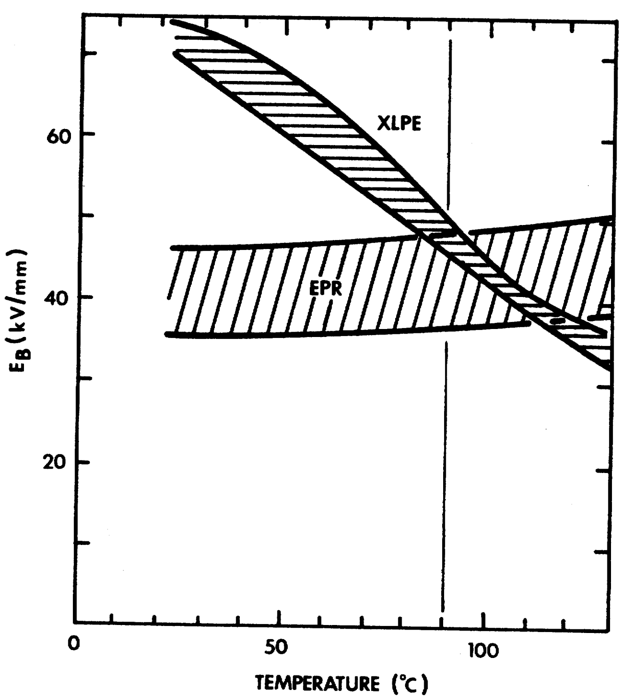

Fig. 16: Variation in ac breakdown strength with temperature [*Ref. 1, p. 4-36*].

The effect of water on ac breakdown strength is shown in Fig. 17. This result is similar to the general degradation of electrical properties which occurs with the absorption of water. Note that after 68 days continuous immersion in 70°C water, XLPE has decreased more but still has a higher breakdown voltage than the dry EPR. The moisture studies reported in [40] show that the breakdown strength of EPR decreases still further when it returns to dryness.

5.2. *Impulse Strength*

The impulse strength of XLPE and EPR is shown in Fig. 18 as a function of temperature. Note that as in Fig. 16 XLPE is superior up to 90°C. The data plotted is verified by reported values typically of 95 and 55 kV/mm for XLPE and EPR respectively at about 25°C on cables. Values of about 87 and 63 kV/mm have been reported in a study for cable insulations up to 10 mm thick [41].

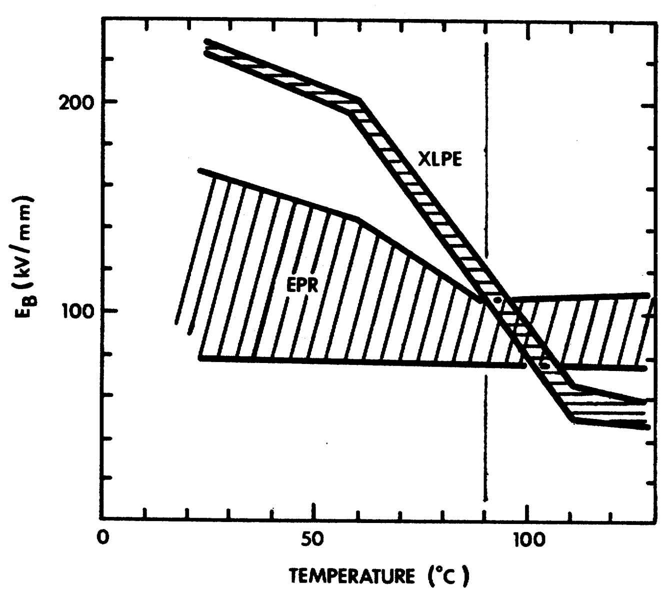

Fig. 18: Impulse strength vs temperature [*Ref. 1, p. 4-39*].

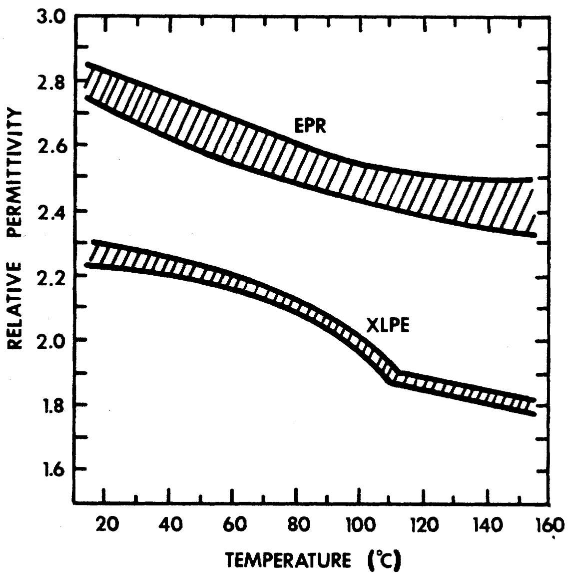

Fig. 19: Relative permittivity vs temperature [Ref. 1, p. 4-21]

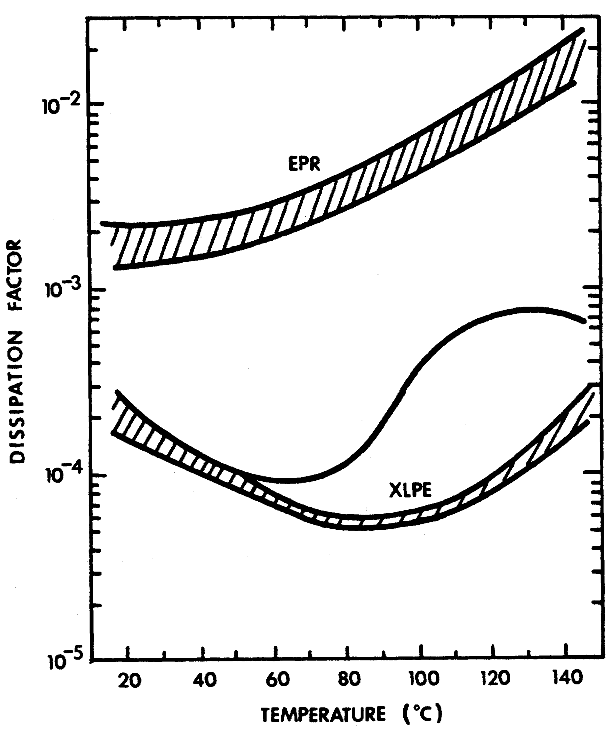

Fig. 20: 60 Hz dissipation factor vs temperature [Ref 1, p. 4-23]

5.3. *Dielectric Loss*

The dielectric losses of XLPE and EPR have been measured and reported by many workers and the effects of temperatures and moisture content are well known. The importance of this comparison results from the increasing cost of energy and therefore the seriousness of the dielectric component of power losses in cables.

The relative permittivity of the best recent EPR formulations and XLPE is shown in Fig. 19 as a function of temperature. Older EPRs had permittivities as high as 3.5.

Values for dissipation factor or $\tan\delta$ from the same laboratory are shown in Fig. 20. The data shown for XLPE is somewhat unusual compared to that reported by other sources. More typical data is shown in Fig. 21 which includes an old XLPE compound which used a staining antioxidant. Although that antioxidant was very effective, the compound has not been manufactured for many years. One effect of very high dielectric losses is to cause further temperature increase and even higher losses. The effect on temperature is given as [43]

$$\Delta T = \pi V^2 f \varepsilon_o \varepsilon_r \, \rho \, \tan\delta \qquad (3)$$

where V is the rms phase to ground voltage in volts, f is the frequency in Hz, $\varepsilon_o = 8.854\ 10^{-12}$ F/m is the permittivity of free space, ε_r is the relative permittivity or dielectric constant of the insulating material, and ρ is the thermal resistance in m°C/W. The temperature obviously is independent of conductor geometry but only small temperature increases can be generated at power frequency.

The power losses which are suffered in the dielectric can be calculated by use of the relation

$$W = 2\ \pi V^2\ f\ \ \varepsilon_o \varepsilon_r\ \tan\delta\ \rho(A/t) \qquad (4)$$

where the symbols have the same meanings and A is cross-sectional area of insulation which has thickness t. Some users calculate that dielectric losses in 69 kV EPR cables can run as high as 130 times those in XLPE and can reduce the current carrying capacity as much as 5% [36,37].

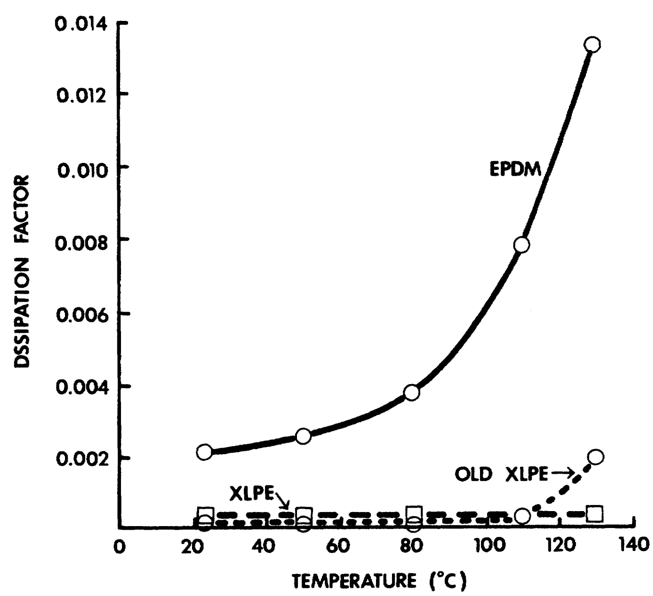

Fig. 21: Dissipation factor vs temperature, 60 Hz

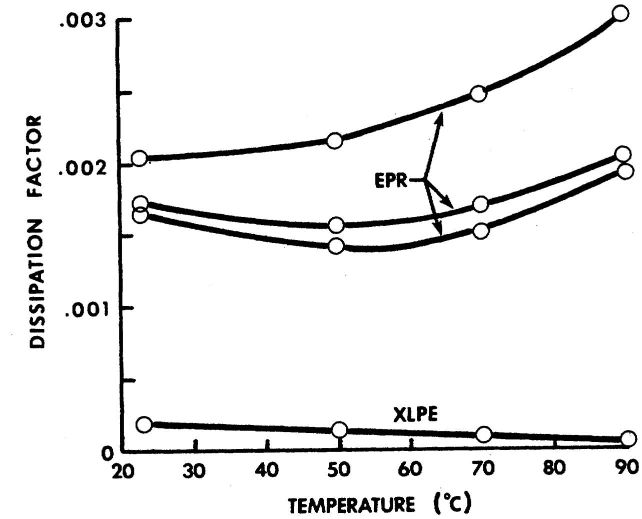

Fig. 22: Dissipation factors of modern dielectrics

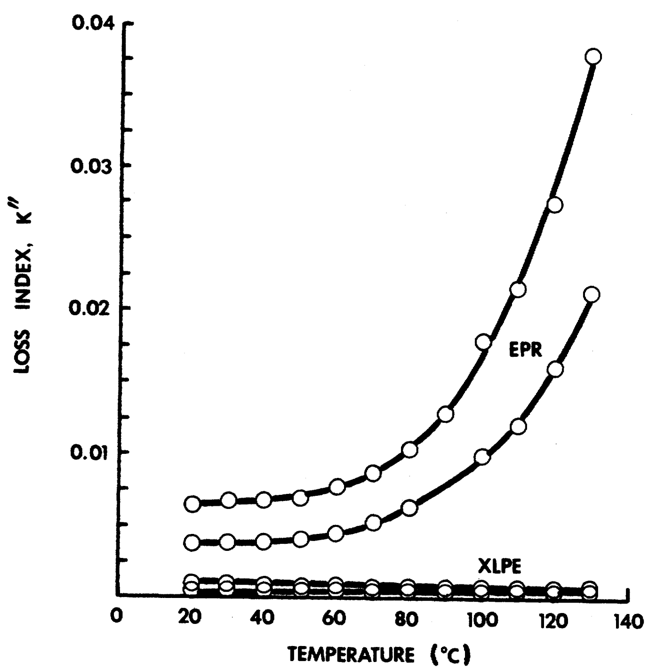

Fig. 23: Dielectric loss index as a function of temperature

As the amount of ethylene in the EPR copolymer or EPDM terpolymer is increased the material becomes more crystalline, more like PE and less like amorphous EPR. The dielectric losses measured for three commercial (high-ethylene) EPRs are shown in Fig. 22. This compromise toward improved electrical properties has other effects as well; other properties approach those of XLPE.

If the results already given are used to calculate the loss index [44], previously called the loss factor, the data of Fig. 23 is obtained. Simple rectangular coordinates are used for plotting since the loss index κ''

$$\kappa'' = \kappa' \tan\delta \qquad (5)$$

appears to the first power in the equation for power loss. It is thus easier to visualize the significance of the data.

The variation of dielectric loss with moisture is well known. It increases, in either material, with the amount of moisture absorbed.

For the purpose of accelerated testing, it is often desirable to use frequencies higher than 60 Hz. But if this is done, it is necessary to prove that there is not a change in the failure mechanism due to frequency effects. Fig. 24 shows that increasing the test voltage frequency up to 10 kHz should not introduce such problems [43] since its effect is the same for both XLPE and EPR.

5.4. *Resistance to Partial Discharge*

There have been many comparative statements made about the resistance of various dielectrics to partial discharge or corona damage. Unfortunately, reliable and quantitative results are scarce. Most are based upon methods which can give spurious and misleading results like the U-Bend test. One excellent study [1] concludes qualitatively "both XLPE and EPR become highly susceptible to corona discharge degradation at temperatures exceeding 25°C ... the lifetime of XLPE and EPR cables would be expected to be significantly reduced under emergency operating conditions in the presence of voids undergoing corona discharge." The only quantitative result found in the literature [21] is presented as Fig. 25 which relates the number of joules of energy required to erode or decompose one kg of the material under test as a function of temperature.

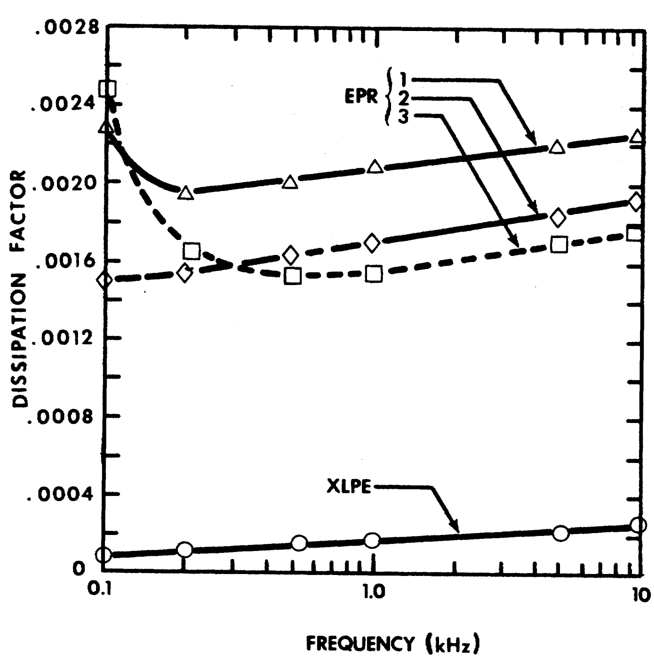

Fig. 24: Dissipation factor at 23°C vs frequency [43]

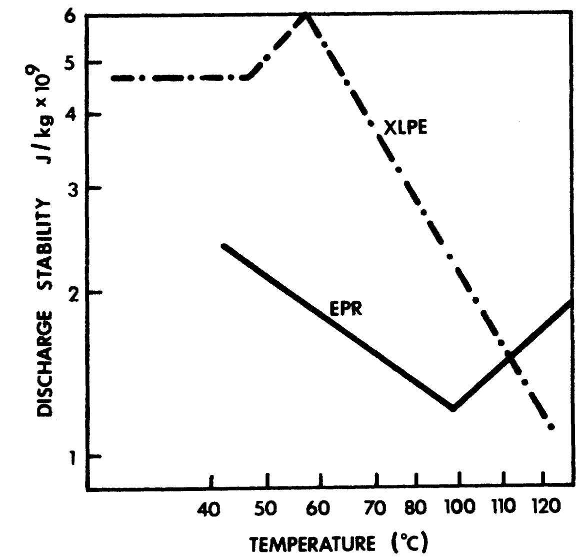

Fig. 25: Partial discharge resistance of XLPE and EPR between 40° and 120°C [21]

5.5. *Treeing*

Since the practical problems related to the growth of trees in polyethylene insulation on URD cables were first reported [45] and subsequently further investigated [46,47], this problem has received great attention among cable users and cable makers. Summaries of the work done have appeared regularly [48-52] and are helpful since the volume of literature has increased very rapidly.

It is now well known that all organic dielectrics are subject to treeing [53] although at one time it was reported that EPR was not. Several papers [54,58] have corrected this misunderstanding which may have resulted from the difficulty in seeing trees in opaque materials.

An interesting observation is that the voltage life of EPR in the ASTM double needle test [59] is only 60% of that measured for XLPE after thermal aging [53]. This seems to correlate with the relative corona resistances [21] mentioned earlier.

TABLE 6

AEIC Specifications for Insulations on 5 to 69 kV Power Cables

	XLPE	EPR
Max. void size	76 μm (3 mils)	127 μm (5 mils)
Max. contaminant size	178 μm (7 mils)	254 μm (10 mils)
Max. power factor	0.1%	1.5%
Five minute ac test voltage (Table C1)	25-33% above Nominal*	Nominal*

*Nominal values are taken as those listed for EPR.

5.6. *AEIC Testing Specifications*

There are two separate specifications issued by the Association of Edison Illuminating Companies (AEIC) for 5 through 69 kV power cables. The first is for cables insulated with thermoplastic and cross-linked polyethylene [60], the second for cables insulated with ethylene-propylene rubber [61]. While the specifications are, in most cases, the same, there are a few differences which require superior properties and construction in the case of polyethylene insulated cables. Table 6 shows the differences.

6. CONCLUSIONS

There are many considerations involved in the decision about the relative acceptability of cables insulated with XLPE or EPR. In this comparison consideration has been concentrated on the properties important to buried power cables for service at 5 kV and higher. It might serve as an appropriate conclusion to note that at the Panel Discussion on Regional Underground Distribution Systems held at the 1979 IEEE T&D Conference in Atlanta, only five U.S. utilities reported satisfaction with EPR cables. The rest were using or switching to XLPE. Some REA utilities are exceptions in that they continue to use thermoplastic PE while others are switching to tree-retardant PE.

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