CONF-781110--3

BNL-24443

Polymeric Films for Use on Superconducting Power Transmission Cables

A. C. Muller

DISCLAIMER

To be Presented at the 71st Annual Meeting of the AICHE, Miami, Florida, Nov. 12-16, 1978

Polymeric Films for Use on Superconducting Power Transmission Cables*

A. C. Muller
Brookhaven National Laboratory
Upton, New York 11973

INTRODUCTION

A flexible superconducting power transmission cable is under development at Brookhaven National Laboratory (BNL). This project was undertaken in 1972 as one means of responding to national power problems. As a result of both growing urbanization and public dissatisfaction with overhead transmission lines, it has become increasingly difficult to acquire the large amount of right-of-way needed for aerial transmission. A further increase in system voltage would require even higher towers and wider tracts of land. In contrast an underground superconducting cable would require only a few feet of right-of-way width and would be able to transmit several thousand megawatts of power at very high efficiencies and with excellent network characteristics.

Initial design studies indicated that a flexible, forced-cooled cable offered the best combination of technical and economic

*Work performed under the auspices of the U.S. Department of Energy.

features.[1] An ac, helium cooled, cable with Nb_3Sn superconductor was chosen for the BNL effort. The operating temperature of this design will be in the range of 6-8 K. The major goal of the BNL program is the construction of a 100 m long, 138 kV outdoor system rated at 1000 MVA. The cryogenic envelope and refrigeration equipment for this cable are already in place.

Many of the design features of the dielectric are governed by the decision to operate the cable at a temperature that is satisfactory for the Nb_3Sn superconductor. The choice was made to form the insulation of many layers of plastic tape applied in a helical pattern since extruded polymer is not a viable mode of insulation application, the very large thermal contraction associated with extruded polyolefins would lead to mechanical failure of the dielectric.

The net thermal contraction of the lapped dielectric medium must be controlled so that the insulation of the cable contracts evenly with the conductor during the cooldown period. Too small a value of dielectric contraction would lead to voids between the inner conductor and the dielectric medium. These voids would permit harmful partial discharges to occur. Too large a contraction would keep the tapes under tensile and compressive load while at operating temperature. This stress to the tapes, if not large enough to cause immediate tape fracture, could contribute to accelerated failure due to other mechanisms.

Additional, critical implications of this design became apparent after the first experimental test cables were built.[2] We learned that our plastic dielectric tapes required very high values of yield strength, tensile strength and tensile moduli in order to be accurately lapped on taping machines originally designed to construct conventional paper-oil cables. Although a tightly wound, hard, cable is desirable if lapped of kraft paper, this property may cause serious problems in the fabrication of a plastic lapped cable. The similar values of tensile and compressive moduli of plastic materials causes high taping tensions to be transformed into high interfacial pressures between layers of tape. During the bending of the completed cable during reeling, these excessive radial pressures can force tapes to wrinkle rather than slide on one another. Wrinkles can result in a lower dielectric strength and shorten the life of the cable. Another feature discovered during electrical testing of small cable samples is that the individual dielectric tapes must be a solid rather than of porous construction. Helium impregnated porous tapes were found to have significantly lower dielectric strengths than solid tapes.[3] Also our desire to minimize refrigerator loading required the selection of a dielectric material that had minimum values of dielectric loss and dielectric constant.

Finally, in order for an underground cable to be cost effective, it should have a life expectancy of 30 to 40 years. Studies of the effects of crazing and fatigue failure on the life of dielectric tapes are being conducted.

Dielectric, mechanical and thermal specifications for the design of dielectric tapes to be used on superconducting cables are shown in Table I.

TAPE DEVELOPMENT

An initial evaluation of all available polymeric films disclosed that none would simultaneously satisfy all of our many dielectric, mechanical, and thermal requirements.[4] Dielectrically acceptable tapes were mechanically weak and mechanically strong tapes had unacceptable dielectric properties. See Table II. During the initial tape selection and evaluation process, emphasis was placed on the possible use of "high temperature" tapes because of their excellent mechanical characteristics at cryogenic temperatures. However, attempts to reduce the 60 Hz, 4.2 K loss tangents of polysulfone and polycarbonate by altering their chemical construction were unsuccessful and these tapes were then eliminated as major candidates. The Teflons, Kaptons, and other exotic tapes had attractive properties but were set aside because of their very high costs. Rather, the decision was made to attempt to modify the dielectric and mechanical characteristics of the less expensive, intrinsically lower loss polyolefins.

Modifications that were made to the tape properties in the course of this work are described in the following sections.

A. Dielectric Properties

In accordance with the concept of a low-loss cable, we placed a great deal of emphasis on the selection of tapes having very low values of both dielectric constant and dissipation factor. A dielectric constant of no greater than 2.5 was chosen to both minimize dielectric losses and to keep the permittivity of the plastic as close as possible to that of the helium impregnant. The goal for the loss tangent of 20×10^{-6} was set so that the dielectric loss at the likely operating voltage would be no greater than either conductor loss or the heat leak through the cryogenic envelope.

The dielectric losses of pure samples of polyethylene and polypropylene are very small at 4.2 K (i.e., $\cong 5 \times 10^{-6}$). The higher values of tan δ measured for commercial polyolefins are due to the presence of additives placed in the polymer during the manufacturing process to protect the polymer in its normal room temperature-air environment. Work by King and Thomas[5] indicated that the antioxidant may be one of the major sources of dielectric loss at temperatures of 6-8 K. A more extensive study of the effects of antioxidant on loss tangent of polyethylene was conducted in a joint cooperative study carried out by Battelle Columbus Laboratories (BCL), the National Bureau of Standards (NBS), and BNL. This work showed that the 60 Hz loss tangent of polyethylene, in the region of 4-10 K, was strongly dependent upon both type and concentration of antioxidant. See Table III. One variety of antioxidant, Topanol, in a concentration of 0.1% was found to result in a loss tangent $<10\times10^{-6}$ over the temperature range 4.2-10 K. See Table III.

B. Mechanical Properties

The most severe problems facing the designer of cryogenic dielectric insulation are those of obtaining satisfactory mechanical properties. The dielectric must be able to withstand the various forces existing during taping, reeling, pulling into the cryogenic envelope, and those present during cooldown to operating temperatures as well as the long term tensile and compressive stress present during the life of the cable. Yield and tensile strengths and tensile moduli must be very high for these plastics. On the other hand, compressive moduli (normal to the tape) must be small, and tape-to-tape friction coefficients should be as low as possible.

B.1. Taping

Plastic lapped cables now under development in this country will probably be fabricated on taping machines originally designed to build conventional "paper-oil" cables that used a dielectric tape that was a stiff, strong variety of kraft paper. Taping tensions of 4-5 pounds are commonly used to ensure that each layer of tape is lapped "out of phase" with the previous layer, so that the small butt gaps between adjacent turns are completely covered by the width of a tape from a subsequent layer. This avoidance of "registrations" or exactly coinciding butt gaps between successive layers is of paramount importance with superconducting cables. Double thick butt spaces would give rise to high partial discharge levels that could ultimately cause tape degradation and dielectric failure.[(2)] Accurate taping precision requires tapes having tensile moduli of greater than $5x10^5$ psi ($35.2x10^3$ kg/cm^2). In order that typical 2 cm wide by 100 μm-thick tapes do not break or suffer plastic deformation during lapping under high tensions, tape yield strengths greater than 1400 psi (100 kg/cm^2) are required. Off-the-shelf polyolefins were found to be too weak to withstand taping loads without stretching or breaking.

Uniaxially oriented polyolefin tapes were found to have superior tensile properties than the nonoriented versions, but these materials often fibrillated during cooldown to operating temperature. Further studies showed that commercially produced, 25 μm-thick, biaxially oriented polypropylene tapes had acceptable tensile properties at all temperatures. See Table II. The desired tape thickness was achieved by cementing several of these together with a 2.5 μm-thick layer of polyurethane adhesive. Two and three ply laminates under evaluation at BNL have thicknesses of 66 μm and approximately 100 μm, respectively. Loss measurements performed by the Polymer Division, NBS, Gaithersburg[6] show that the loss tangent of these tapes meets design considerations of Table I. Dielectric tests on small cable sections of this very high modulus polypropylene tape are being carried out at BNL.

B.2. Cable Bending and Reeling

One of the reasons that plastic tapes have not been commonly used as cable insulation is that large diameter plastic lapped cables are known to have poor bending properties. The first comprehensive study of the bending behavior of lapped, high-voltage paper cables is described in detail in a report prepared by the Pirelli Company of Milan, Italy in 1961.[7] This theory predicts that cables will bend without wrinkling or deformation of tapes when the internal radial pressure ϕ_r is less than some critical pressure, ϕ_{cr}. Simplified versions of the Pirelli equations for highly anistropic tapes were provided for BNL by a study performed by the Phelps Dodge Cable and Wire Co. (PDC&W).[8]

Here ϕ_{cr} and ϕ_r are given as

$$\phi_{cr} = \left(\frac{S^2}{\sqrt{3Wr}}\right)\left[\frac{(4G^2E_1E_2)^{1/4}}{\mu}\right] \qquad (1)$$

$$\phi_r = \frac{T \cdot \sin^2 \alpha}{S \cdot W} \cdot \frac{1}{\sqrt{n-1}} \qquad (2)$$

(See Appendix I for a glossary of symbols.)

Lapped plastic cables usually have poor bending performance because ϕ_{cr} is usually lower, and ϕ_r is usually higher than the corresponding values for a typical, lapped, paper-oil cable. ϕ_{cr} is low because E_1 and E_2 are lower in plastics than in paper and μ is higher than for paper. Also ϕ_r is high in plastics because "n", the measure of the tape anisotropy (E_1/E_3), is usually very low. For paper tapes "n" is commonly 900-1000 but "n" is found to be in the range of 100-300 for typical plastic dielectric tapes. Experimental values of E_1, E_3, n, and μ_s are given in Table IV for several plastics under evaluation at BNL. For comparison purposes, corresponding values are also given for a 178 μm-thick sample of electrical grade kraft paper.

Although ϕ_{cr} can be determined by calculation only, ϕ_r may be either calculated or measured directly using a method developed by the Pirelli Co.[7] In order to quantify the effect of the variables in Eq. 2, a series of radial pressure measurements were performed with this method, on several tapes of interest. In these experiments 2.2 cm-wide tapes were wound concentrically on 2.54 cm-diameter mandrels under a 500 gm taping tension. The materials tested are listed in Table IV. Also the thickness and appropriate "n" value for each material is given in this table. Thirty-five layers of tape were applied to the mandrel. Steel pull-out strips, 0.476 cm-wide by 25 μm-thick were inserted at five layer intervals during winding. Thus there were pull-out strips underlying 5, 10, 15, 20, 25, and 30 layers of tape. The force required to just move the pull-out strip was then measured on the Instron Tensile Testing Machine immediately after winding (≅5-10 min.). If the tape-to-steel strip coefficient of friction is known, radial pressures can be directly calculated. (In future measurements this time interval will be increased to assess the effects of stress relaxation on radial pressure.)

Radial pressure as a function of radial position for the five materials are shown in Fig. 1. The effects of tape anisotropy on radial pressure are evident. Tapes having large values of "n" show small radial pressures and the curves for kraft paper and embossed polycarbonate approach the "plateau" predicted by theory. The effect of tape thickness, S, on radial pressure is also apparent in this figure; the radial pressure for the two-ply polypropylene laminate is considerably higher than the value found for the same material in a three-ply configuration. Finally, it should be noted that embossing causes a significant reduction in radial pressure.

B.3. Embossing

In order to both evaluate the effects of commercial embossing on the effective compressive modulus, E_3, and to become acquainted with the practical problems accompanying this technique, several rolls of 100 μm-thick, Makrofol "G" polycarbonate film were embossed. Temperature control of the operation was found to be critical, and a roller temperature of 160°C was found to produce optimum results. Embossing at lower temperatures was ineffective, and exposure to higher temperatures caused shrinkage and distortion of the film. A fine irregular embossing pattern with a pattern density of approximately 200 marks per square cm was found by Penn at NBS to reduce E_3 by a factor of six and to reduce μ_s by 5%. Pertinent mechanical properties of embossed and plain Makrofol "G" are given in Table IV. This treatment would probably be a very effective means of reducing radial pressures in cable systems where partial discharges were not a problem.

B.4. Friction Measurements

With the very high values of radial pressure associated with plastic cables, it is imperative to keep ϕ_{cr} as high as possible. As shown in Eq. 1, ϕ_{cr} is inversely proportional to the tape friction coefficient, μ_s. Tape-to-tape friction coefficients of plastic films are usually between 0.4 and 0.5. The addition of slip additives to the oriented polypropylene has caused a reduction of μ_s from 0.5 to 0.225 in polypropylene. No noticeable increase in loss tangent at 4.2 K was found to accompany addition of the slip additive.

B.5. Very High Modulus Tapes

The bending behavior of lapped plastic cables fabricated with intermediate modulus, mildly oriented, polypropylene tapes appears to be satisfactory for insulation thicknesses up to 1 cm. However, Fig. 1 shows a dependency of ϕ_r on wall thickness that may require tapes of higher moduli for very high voltage cables that may have insulation thicknesses as great as 2 cm.

One means to improve bending performance is to increase the value of tensile modulus, E_1. A higher value of E_1 will simultaneously increase ϕ_{cr} and decrease ϕ_r. Commercially produced polyethylene films have tensile moduli of approximately only

1×10^{10} dynes/cm^2. Recently, however, very highly oriented polyethylene samples were prepared by Porter[9] and others that have tensile moduli of 7×10^{11} dynes/cm^2. In a joint effort with Battelle Columbus Laboratories, work was started to develop very high modulus (7.0×10^4 kg/cm^2) tapes by a hydrostatic extrusion process. At high degrees of orientation, extrusion provides better control over final product dimensions than does drawing.[10] In the BCL system a molten polymer reservoir feeds a long rectangular channel which precedes the "draw-down" section of the die. The polymer is cooled in the channel so as to be solid prior to area reduction. (The channel thickness is 1.5 mm and the "draw-down" section is 125 μm-thick. This results in an extrusion ratio or draw ratio of 12:1.) The surface of the channel was also Teflon coated to reduce frictional drag. Several tapes one-inch wide, by 125 μm-thick, by several meters long were successfully extruded. Tensile tests revealed tensile moduli of approximately 14×10^4 kg/cm^2 and tensile strengths of 4.6×10^3 kg/cm^2. (The BNL goal for maximum value of tensile modulus is only 7×10^4 kg/cm^2.) Tape lengths are limited at this time due to inadequate temperature control in the one-inch long channel. Poor temperature control permits the liquid-solid interface to move downward in the channel during an extrusion, terminating the run.

An improved die is now under design. The die will have a three-inch long channel with three independent temperature control zones along its length. It is expected that the improved version will provide better temperature control and make it possible to extrude tapes of substantially greater length.

C. Thermal Properties

C.1. Thermal Expansion

The amount of thermal contraction of the dielectric medium upon cooldown to cable operating temperature is critical. The specification of 0.6 to 1.0% was set to ensure that the dielectric would contract evenly with the conductor during cooldown. Many of the earlier polyethylene and polypropylene tape candidates were found to fracture during dielectric strength tests at operating temperature. Measurements of both thermal contraction[11] and total longitudinal elongation revealed that those tapes that fractured had values of contraction that were approximately equal to their total elongations at 4.2 K. Tapes possessing total elongations that were much larger than their contractions remained intact. See Table V. Failure usually occurred when the elongation to contraction ratio, E/C was less than 2:1. Mechanical fracture did not occur when E/C was >2:1.

Oriented tapes were found to withstand thermal contraction better than nonoriented versions. As a general rule it was found that the elongation to fracture usually increased as a result of orientation and the thermal contraction decreased as a result of this treatment. The 293 to 4.2 K contraction of the laminated biaxially oriented tapes was found to be 0.641,[11] and E/C ratios for this material are greater than 12:1. See Table V.

C.2. Thermal Conductivity

Both upper and lower limits apply to thermal conductivity of the dielectric medium of the superconducting cable. See Table I. Calculations made at BNL[12] predicted that a thermal conductivity $<5\times10^{-5}$ W/cm-K could cause local heating of portions of the dielectric and a resulting reduced dielectric strength of the helium impregnant. The upper limit of 3×10^{-4} W/cm-K was set to prevent excessive "thermal coupling" between counterflowing "go" and "return" helium streams. The thermal conductivities of several plastics under evaluation at BNL were measured at BCL and are shown in Table VI. With the exception of polysulfone, most tape candidates meet the thermal conductivity design limits.

CONCLUSIONS

Many, severe design specifications apply to a dielectric tape that is under consideration for use as dielectric on an ac superconducting underground power transmission cable. Off-the-shelf plastic tapes that satisfied mechanical requirements had excessive values of loss tangent and dielectric constant. On the other hand, most tapes that had acceptable dielectric properties were found to possess tensile moduli and yield strengths that were too low at 293 K and too high at 4.2 K. Porous paper-like tapes were found to produce dielectrically-weak cables probably because of stress enhancement in the helium impregnant.

Solid, polyethylene or polypropylene tapes were found to best satisfy dielectric requirements. The antioxidant was found to be the major source of dielectric loss at 100 Hz and 4.2 K, and the selection of the proper type and concentration of antioxidant kept tan δ within design limits. Acceptable values of yield strength and tensile moduli were obtained with several 25 μm-thick, biaxially-oriented, polypropylene films laminated to obtain the required tape thickness. Bixaxial orientation was also found to reduce thermal contraction and increase the 4.2 K elongation of the polypropylene films. Work has been started to develop a very high modulus, single layer polyethylene tape for use with higher voltage superconducting cables.

ACKNOWLEDGMENTS

The author wishes to acknowledge the technical assistance of A. L. Minardi and J. Scrofani in obtaining the results reported in this manuscript. Many other persons have contributed to the design of the experiments described here, in particular D. H. Gurinsky,

A. J. McNerney, K. F. Minati and R. Zoller of Brookhaven National Laboratory, E. D. Eich of Power Technologies, Inc., and J. A. M. Gibbons of the Central Electricity Research Laboratory, England.

REFERENCES

1. E. B. Forsyth, et al., Flexible Superconducting Power Cables, IEEE Trans., PAS 92, No. 2, 494 (1973).

2. E. B. Forsyth, A. J. McNerney, A. C. Muller and S. J. Rigby, Progress in the Development of Gas-Impregnated Lapped Plastic Film Insulation, IEEE Trans., PAS 97, No. 3, 734 (1978).

3. E. B. Forsyth, A. J. McNerney and A. C. Muller, Dielectric Design Considerations for a Flexible Superconducting Power Transmission Cable, Advances in Cryogenic Engineering 22, 296 (1977).

4. A. C. Muller, Mechanical Properties of Insulating Tapes at Cryogenic Temperatures, Revue Generale de l'Electricite 94, 568-72, 1975, Paris, France.

5. C. N. King and R. A. Thomas, Dielectric Loss at Low Temperatures in High Density, Low Density and Spun Bonded Polyethylene, 1974 Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, National Academy of Sciences, 1975.

6. F. I. Mopsik, Low Temperature Dielectric Loss Characteristics of Polypropylene, to be presented at the 1978 ICMC Meeting, July 10-11, Munich, Germany.

7. P. G. Priaroggia, E. Occhini and N. Palmieri, Fundamentals of the Theory of Paper Lapping of a Single Core High Voltage Cable, Pirelli, SPA, Milan, 1961.

8. E. B. Forsyth, A. C. Muller and S. J. Rigby, Some Theoretical Considerations Affecting the Design of Lapped Plastic Insulation for Superconducting Power Transmission Cables, EPRI Research Report No. EL 269, Dec. 1976.

9. R. S. Porter and N. J. Capiatti, J. Poly. Sci.-Phys. Ed. 13, 1177 (1975).

10. T. Williams, J. Mat. Sci. 8, 59 (1973).

11. F. Jelinek and A. Muller, The Study of the Dimensional Behavior of Various Thin-Film Polymers in the Temperature Range 4.2 K to 300 K, Advances in Cryogenic Eng. 22 (1977).

12. G. H. Morgan and J. E. Jensen, Counter-Flow Cooling of a Transmission Line by Supercritical Helium, Cryogenics 17, No. 5, May 1977.

APPENDIX I

List of Symbols

T	Taping Tension	kg
S	Thickness of Tape	cm
W	Width of Tape	cm
α	Taping Angle (The Complement of the Angle with the Cable Axis)	Degree
E_1	Tensile Modulus Lengthwise along Tape	kg/cm^2
E_2	Tensile Modulus Across the Tape (i.e. at Right Angle to E_1)	kg/cm^2
E_3	Compressive Modulus (Normal to the Paper)	kg/cm^2
G	Shear Modulus in the Plane of the Paper	kg/cm^2
n	E_1/E_3	
μ	Static Coefficient of Friction	
r	Cable Radius at which the Pressure is Determined	cm
r_1	Outer Radius of Insulation	cm
r_o	Radius of Conductor	cm
r_x	Radius of the Tensioned Paper Tape	cm
ϕ_{cr}	Upper Limit of Radial Stress	kg/cm^2
ϕ_p	Plateau Pressure	kg/cm^2
F	Factor of Safety Less than 1	
τ	Time Constant of Plastic Flow and Relaxation	sec

Table I

Specifications for Dielectric Tapes for Use in ac Superconducting Cables

A. Dielectric (6-8 K)

1. Dielectric Constant - 2.5 max
2. Dissipation Factor - $2\text{x}10^{-5}$ max

B. Mechanical (293 K)

1. Yield Strength - 100 kg/cm^2-min
2. Tensile Strength - $1.4\text{x}10^3$ kg/cm^2-min
3. Tensile Modulus, E_1-3.5-$7.0\text{x}10^4$ kg/cm^2
4. Compressive Modulus, E_3-$1.0\text{x}10^2$ kg/cm^2-max
5. Friction Coefficient, μ_s - 0.250 max

C. Thermal

1. Total Contraction (293 to 4.2 K) 0.6 to 1.0%
2. Conductivity (4.2 K) - $5\text{x}10^{-5}$ to $3\text{x}10^{-4}$ W/cm-K

Table II

Dielectric and Mechanical Properties of Some Dielectric Tapes

Polymer Type	Diss. Factor* (Tan $\delta x10^6$)	Diel. Constant*	Yield Strength, kg/cm^2 at 293 K	Tensile Modulus, kg/cm^2x10^{-3} at 293 K	Tensile Modulus, kg/cm^2x10^{-3} at 4.2 K
Polyethylene low density non-oriented (100 μm)	15	2.3	21.1	0.929	54.5
Polypropylene low density non-oriented (125 μm)	8	2.2	57.0	3.12	8.30
Polypropylene biaxially oriented laminated (100 μm)	21	2.3	221	19.2	14.4
Polysulfone (125 μm)	60	2.5	398	18.9	45.0
Polyimide, Kapton H (100 μm)	90	3.1	441	28.4	55.0
Polycarbonate, Makrofol "KG" (60 μm)	55	2.9	493	34.8	45.5
Polyester, Mylar (75 μm)	200	2.5	653	40.1	67.4

*(4.2 K and 100 Hz)

Table III

Effect of Antioxidant Type and Concentration on Loss Tangent of Phillips Marlex Type 6006 Polyethylene

BNL Sample No.	Additive Content	Extraction Solvent	Tan δ x 10^6 at 100 Hz 4.2 K	5.1 K	6 K	8 K	10 K
1	None	None	-	7	-	4	5
2	None	Methanol	6	-	3	7	5
3	Ional 0.05%	None	-	26	-	11	9
4	Ional 0.01%	None	-	16	-	11	7
5	Ional 0.01%	Methanol	-	9	-	28	7
6	Ional 0.1%	Cyclohexane	-	2	-	0	0
7	Ional 0.26%	None	-	88	-	4	21
8	Ional 0.5%	None	232	-	126	73	50
9	DLTDP 0.05%	None	25	-	17	15	9
10	DLTDP 0.11%	None	14	-	5	19	2
11	DLTDP 0.11%	Methanol	8	-	6	2	2
12	Topanol 0.5%	None	14	-	10	0	0
13	Topanol 0.1%	Methanol	0	-	0	0	1
14	Topanol 0.1%	None	9	-	9	5	9

Table IV

Values of Factors Affecting Cable Bending Performance

Polymer Type	Tensile Modulus, E_1 ($kg/cm^2 x 10^{-2}$)	Compressive Modulus, E_3^* ($kg/cm^2 x 10^{-2}$)	$n=E_1/E_3$	Coefficient of Friction, μ_s**
Polyethylene, uniaxially oriented, laminated Valeron (100 μm)	89	1.76	50.4	0.418
Polycarbonate, non-embossed, Makrofol "G" (100 μm)	214	1.83	117	0.453
Polypropylene, biaxially oriented, 2 ply laminate (66 μm)	234	1.61	145	0.225
Polypropylene, biaxially oriented, 3 ply laminate (100 μm)	192	0.70	273	0.225
Polycarbonate, embossed, Makrofol "G" (178 μm)	171	0.282	607	0.438
Kraft paper, electrical grade (178 μm)	640	0.64	1000	0.320

*At 1.40 kg/cm^2 load.

**Cross machine direction to cross machine direction.

Table V

Thermal Contraction and Tensile Elongation of Dielectric Tapes

Polymer Type	Contraction, 293K to 4.2K,%		Elongation to Fracture at 4.2K,%	Elongation/Contraction, %
	Longitudinal	Transverse		
Polyethylene low density, non-oriented	2.74	2.69	2.85	1.02
Polyamide, Nylon-11	1.92	1.85	3.13	1.61
Polyethylene, uniaxially oriented, laminated Valeron	1.70	1.26	3.10	1.80
Polysulfone	1.16	1.07	2.98	2.58
Polypropylene, biaxially oriented, 2-ply laminate	0.641	-	8.29	12.9
Polycarbonate, Makrofol "KG"	0.474	0.471	10.8	23.0

Table VI

Thermal Conductivities of Dielectric Tapes*

Temperature, °K	Thermal Conductivity, Watts/cm-K 6	20	100	300
Polymer Tape				
Polysulfone	$2.0x10^{-5}$	$2.5x10^{-5}$	$4.4x10^{-5}$	$1.1x10^{-4}$
Polyethylene, uniaxially oriented, laminated Valeron	$6.0x10^{-5}$	$7.1x10^{-5}$	$1.2x10^{-4}$	$8.1x10^{-4}$
Polypropylene, biaxially oriented, 2-ply laminate, urethane binder	$7.8x10^{-5}$	$1.1x10^{-4}$	$2.9x10^{-4}$	$8.9x10^{-4}$
Polycarbonate, Makrofol "KG"	$9.0x10^{-5}$	$1.2x10^{-4}$	$1.5x10^{-4}$	$6.0x10^{-4}$
Polypropylene, biaxially oriented, 2-ply laminate, polyethylene binder	$9.2x10^{-5}$	$1.3x10^{-4}$	$4.3x10^{-4}$	$1.1x10^{-3}$

*Measurements made in vacuum at 10^{-6} torr.

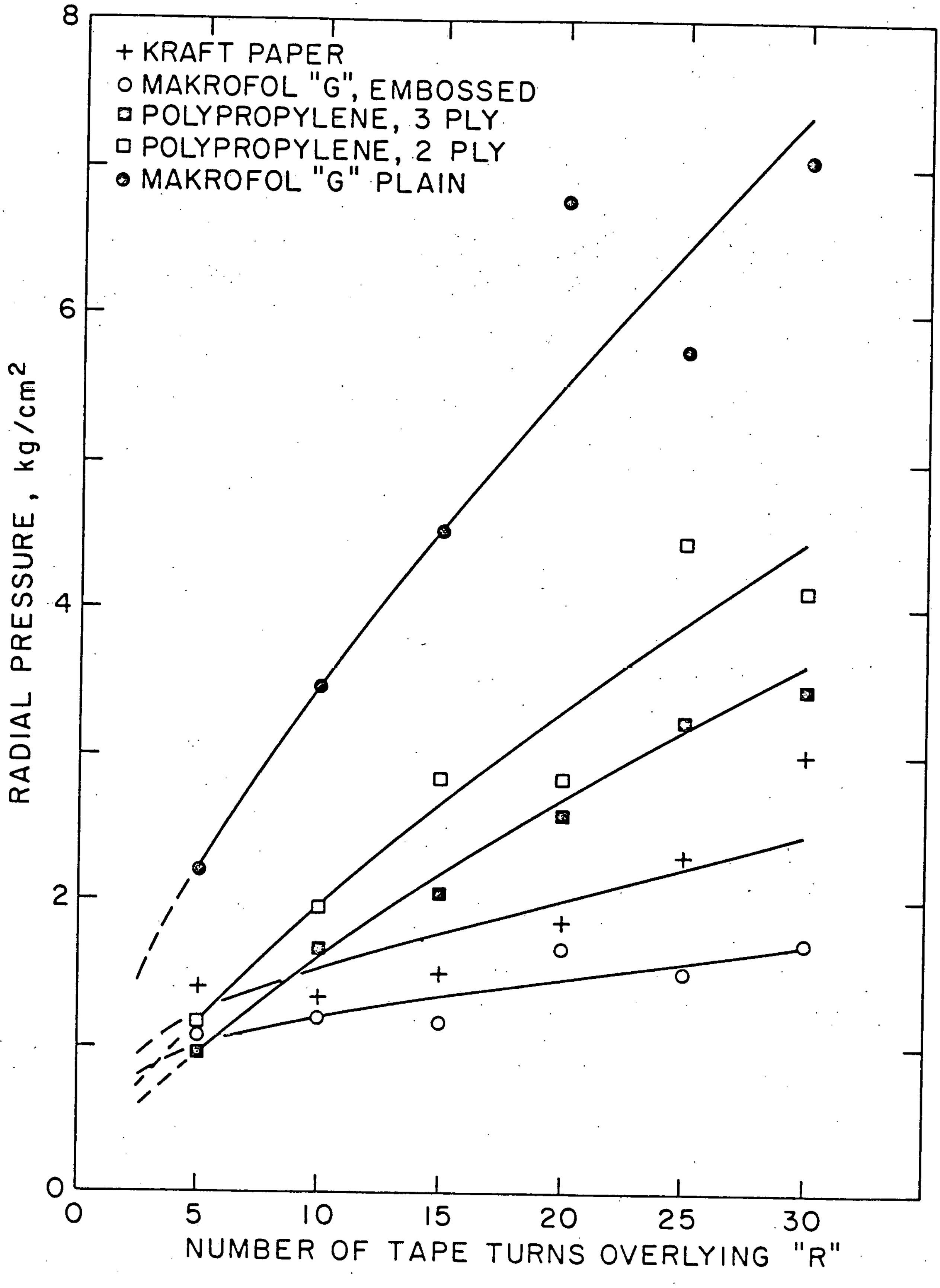

Fig. 1. Radial pressure vs turns overlying "r" for several tape candidates.