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Properties of Plastic Tapes for Cryogenic Power Cable Insulation*

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INTRODUCTION

A superconducting ac power transmission cable is under development at Brookhaven National Laboratory (BNL). This project was undertaken in 1972 in response to growing national power requirements. The goal of this program is to develop an underground power transmission system suitable for transferring bulk quantities of electricity over distances of 16 to 160 km. Both the capital investment and operating costs must be low enough to make the system attractive to the electric utilities.

The superconducting cable shares the advantages with conventional underground cables of needing only a few feet of right-of-way width rather than the large tracts of increasingly expensive land required for conventional aerial transmission. Recent cost analysis studies[1] show that superconducting cables, although more expensive than aerial transmission, will probably be competitive with other methods of underground transmission at loads greater than 2000 MVA. Initial design studies showed that a flexible, forced-cooled cable offered the best combination of technical and economic features.[2] A helium cooled cable with Nb_3Sn superconductor was chosen as the BNL design.

The present goal of the BNL program is the construction of a 100 meter outdoor three-phase ac cable rated at 138 kV and 1000 MVA. The refrigerator and the 100 m-long dewar are already installed. Terminations and cables are under design, and it is planned to begin installation of the first single phase cable in 1979. If the results on this model show promise for eventual commercial use, cables of higher voltage and power rating will be developed. One fundamental phase of this project; the development of the required insulating materials, is the subject of this paper.

TAPE REQUIREMENTS

Many of the design features of the dielectric are governed by the necessity to operate the cable at a temperature suitable for the Nb_3Sn superconductor (6-8 K). Extruded polymer is not a viable mode of insulation application since the very large thermal contraction associated with extruded polyethylene would almost certainly lead to early mechanical failure of this dielectric. Instead, the choice was made to lap many layers of plastic tape and impregnate the butt-gaps with supercritical helium. The major dielectric, mechanical, and thermal specifications for the dielectric tapes are summarized in Table I.

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In order for an experimental cable to be cost-effective the materials should be commonly produced and readily available. Also, fabrication techniques should follow standard practices and technologies wherever possible. The dielectric tapes will be applied to the cable by high-speed taping machines designed many years ago to construct conventional paper-lapped underground cables. Although precise predetermined winding patterns are used during the lapping of a kraft-paper cable, even greater care is required during construction of a plastic-lapped superconducting cable. Each successive layer must be lapped "out-of-phase" with the previous layer, so that the small butt-gaps between adjacent turns are completely covered by the width of the tape from the very next layer. Double-thick butt spaces would reduce the inception stress of partial discharge activity that could ultimately cause tape degradation and dielectric failure. Experience has shown that taping tensions of $2.8\text{-}3.6 \times 10^4$ N/m^2 (4-5 psi) are required to produce tight, accurately wound paper cables. The tapes must possess sufficiently high values of tensile strength and tensile modulus to ensure that they do not break or deform under these tensions.

Additional requirements on the 293 K tape moduli were revealed after several experimental test cables were built for BNL.[3] During cable lapping a component of the taping tension is transformed to a radial pressure directed radially towards the cable core.[4] These radial forces present no problem in conventional cables because of the high compressibility of paper. The more isotropic nature of polymers transforms taping tensions to extremely high values of radial pressures in plastic lapped cables. The pressure increases proportionately to the number of layers of tape applied. During bending of the completed cable in reeling, the radial pressure can force tapes to wrinkle rather than slide on one another as they normally should. Wrinkles will result in a reduced dielectric strength and can shorten the life of the cable.

The net thermal contraction of the dielectric must be designed so that it contracts evenly with the conductor during the cooldown period. Insufficient dielectric contraction would lead to voids between the inner conductor and the dielectric medium. These voids would permit harmful partial discharges to occur. Excessive contraction would keep the tapes under tensile and compressive load while at operating temperature. This stress could either cause immediate tape fracture, or contribute to accelerated failure due to a long-term aging process.

The value of the thermal conductivity is another important consideration in the design of the dielectric. Too small a value could cause local heating of certain portions of the dielectric and produce regions of reduced dielectric strength within the helium impregnant. An upper limit to the conductivity was also established[5] in order to prevent excessive, thermal coupling between counter-flowing "go" and "return" helium coolant streams.

In striving for 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 maximum dielectric constant of 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 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. An important design requirement discovered during electrical testing of small cable samples was that the dielectric tapes must be solid rather than of porous construction. Helium impregnated porous tapes were found to have significantly lower dielectric strengths than solid tapes.[6]

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 environmental stress cracking and fatigue failure on the life of dielectric tapes are being conducted.

Initial evaluation of commercially available plastic films disclosed that none simultaneously satisfied all our requirements.[7] Dielectrically acceptable tapes were mechanically weak and mechanically strong tapes had unacceptable dielectric properties. See Table II. The Teflons, Kaptons, and other exotic tapes had attractive properties but were set aside because of their very high costs. Attempts to reduce the 60 Hz, 4.2 K loss tangents of polysulfone and polycarbonate by altering their chemical construction were unsuccessful. Consequently the decision was made to modify the dielectric and mechanical characteristics of the less expensive, intrinsically lower loss polyolefins. This development work is described in the following sections.

TAPE DEVELOPMENT

A. Dielectric Properties

The intrinsic dielectric losses of pure polyethylene and polypropylene are very small at 4.2 K (i.e., $\cong 5\times10^{-6}$). The higher values of tan δ measured for commercially produced polyolefins are due to the presence of additives placed in the polymer during the manufacturing process to protect the polymer in its intended air environment. Early work by King and Thomas[8] disclosed that the antioxidant may be one of the major sources of dielectric loss at temperatures of 6-8 K. A subsequent study of effects of antioxidant on tan δ carried out jointly by Battelle Columbus Laboratories (BCL), the National Bureau of Standards (NBS) and BNL, also 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. 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.[9]

B. Mechanical Properties

The most severe problems facing the designer of cryogenic dielectric insulation are those of obtaining satisfactory mechanical properties over a wide temperature range. The dielectric must be able to withstand the variety of forces present during construction, installation, and over the normal life of the cable.

B.1 <u>Tensile Measurements</u>. Tape tensile measurements were made at 293, 77, and 4.2 K using an Instron table model testing machine and the associated apparatus shown in Fig. 1. Cryogenic tensile tests were made in the modified 4 liter helium dewar shown in the figure. A pair of grips with cylindrical bearing surfaces were used to hold the specimens. During a cryogenic tensile test the sample was located inside a 6 cm-diameter by 40 cm-long compression cylinder which in turn was submerged in the cryogenic liquid. The compression cylinder was filled with pressurized helium during tests made at 77 K. (Olf[10] has shown that nitrogen gas, at a temperature near its boiling point, can induce crazing and stress cracking in many polymers.) Test specimens were usually 10 cm long by 2 cm wide, and cross-head speeds were (0.05 cm/min). A strip chart record of load versus strain was made of each run. Representative stress-strain curves for both high and low density polypropylene samples are illustrated in Fig. 2.

The initial slopes of the curves were used to compute tensile moduli. The maximum stress reached during a run was used to calculate tensile strength and the strain at fracture was taken as the ultimate elongation. The yield point was defined as the intercept with the stress-strain curve of a straight line parallel to the initial slope and offset 0.2% extension. The tensile data taken at 293, 77 and 4.2 K are summarized in Tables III, IV and V, respectively.

Examination of Table III shows that the nonoriented polyolefins possess 293 K tensile strengths and tensile moduli well below cable specifications. However, oriented polypropylene and polyethylene tapes have superior tensile properties at this temperature.

Tables IV and V illustrate the pattern of dramatically reduced total elongations and increased embrittlement that accompanies most plastics upon cooling to cryogenic temperatures. These changes are most pronounced with the low density, low modulus polyolefins. A high density biaxially oriented laminated polypropylene tape under development at BNL has acceptable tensile properties at all temperatures while also having dielectric and thermal properties that meet cable specifications. This film is manufactured in a thickness of 32 μm and either two or three layers are cemented together with a 2 μm-thick polyurethane binder to produce total tape thicknesses of either 66 or 100 μm, respectively.

B.2 Very High Modulus Tapes. The results of tests made with laminated, intermediate modulus polypropylene show that bending behavior of cables fabricated with this material should be satisfactory for cable insulation thicknesses up to at least 1 cm. However radial pressure is dependent upon insulation thickness[4] and higher voltage cables may require higher ratios of tensile modulus, E_1 to compressive modulus, E_3 to permit reeling without damage to the insulation. Most standard methods of reducing E_3 would probably also degrade the dielectric performance of the tape. However, an increase in the value of E_1 would benefit winding and reeling performance without jeopardizing the electrical properties of the insulation. See Table VI.

Although the tensile moduli of commercial grades of polyethylene are only approximately $1x10^9$ N/m^2 ($1.4x10^5$ psi), the theoretical modulus of highly crystalline oriented polyethylene is $1x10^{11}$ N/m^2. See Fig. 3. Polymers derive their very high moduli from a orientation because the number of tie molecules connecting crystalline regions is greatly increased during orientation. See Fig. 4. The tie molecules are produced as a result of friction between adjacent blocks of lamellae. This causes chain unfolding at the boundaries of these blocks. In drawn material, the resulting higher modulus is almost directly proportional to the draw ratio. See Fig. 5.

There are two major methods used to produce very highly oriented, high modulus polymers; cold drawing and hydrostatic extrusion. Although the highest moduli may be reached by way of the cold-drawing technique, hydrostatic extrusion provides better control over final product dimensions than does drawing.[11]

Working under BNL contract, Battelle Columbus Laboratories (BCL) has begun preliminary work to develop a hydrostatic extrusion process for fabricating ultra-high modulus polyolefin tapes with a tensile modulus of 7×10^9 N/m^2 (1×10^6 psi). (Recently, single fibres of highly oriented polyethylene were prepared by Porter[12] that had moduli of 7×10^{10} N/m^2 (1×10^7 psi). Using the die shown in Fig. 6 molten polymer is fed to a rectangular transition zone which precedes the deformation zone of the die. The polymer is cooled in the transition zone so as to be solid prior to area reduction. The thickness of the transition zone is 1.5 mm and the deformation zone is 125 µm-thick. This geometry 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 have been successfully extruded. Tensile moduli of these tapes were approximately 1.4×10^{10} N/m^2 (2×10^6 psi). Modifications are planned to improve the die temperature control and to reduce the extrusion ratio to 6:1.

C. Thermal Properties

C.1 Thermal Expansion. Early BNL dielectric strength measurements were made with eight to ten layers of tape helically-wound on a 1.27 cm-diameter stainless steel mandrel. Most nonoriented polyethylene and polypropylene tape candidates fractured during these tests which were made at 6-8 K. A comparison of the 293-4.2 K thermal contractions[13] to the elongation to fracture at 4.2 K revealed the probable reason for this problem. See Table VII. Tapes could not contract while wrapped around the metal mandrel and were forced to stretch beyond their maximum elongations. Tapes possessing elongations considerably larger than required contractions remained intact. To avoid future cryofracture problems BNL tape candidates are required to meet an empirical elongation to contraction ratio of ≥2:1. As a general rule it was found that the elongation to fracture usually increased as a result of orientation and the thermal contraction decreased following this treatment. The 293 to 4.2 K contraction of the laminated biaxially oriented tapes was found to be 0.641,[13] and E/C ratios for this material are greater than 12:1. (Details of the BCL thermal expansion technique are described in Appendix I.)

C.2 Thermal Conductivity. Conductivity measurements were made of tape candidates to determine whether or not they would satisfy the cable design requirements listed in Table I. The measurements were made for BNL by Jelinek of BCL using the apparatus illustrated in Fig. 7. The method was a modified steady-state conductivity technique where a temperature gradient was established between two copper plates separated by four layers of polymeric film. (Multilayer measurements were always made so as to approximate the series interfacial resistivity that would be present in lapped cable configurations.) One plate was attached to a controlled heat sink and a measured quantity of heat was added to the other plate by means of an electric heater. With the use of a liquid helium throttling dewar the ambient temperature could be controlled to within one degree Kelvin. (Complete details of the conductivity measurement method are included in Appendix II of this paper.)

The results of the conductivity measurements made in vacuo of several materials are shown in Table VIII. All of the polymers showed increasing values of thermal conductivity with temperature over the range of 6-300 K. The data in Table IX were taken at 6 K as a function of helium gas pressure at several pressures over the range of 0-7.1×10^5 N/m^2 (0-100 psi). This experiment was designed to more closely approximate the composite heat path present in a superconducting cable impregnated with supercritical helium. Although there is a high dependency of conductivity on pressure between 0 and 1.78×10^5 N/m^2 (25 psi), there is no further dependence of conductivity on pressure above this pressure for the polyethylene and polycarbonate films. The polysulfone conductivity appears to increase again as a function of pressure at 7.1×10^5 N/m^2. The conductivities of the three materials at 7.1×10^5 N/m^2 meet the specifications of Table I.

CONCLUSIONS

The development of a suitable polymeric tape for use as insulation on ac superconducting cables is a challenging engineering problem for the designer of plastic films. No commercially available tape simultaneously fulfills all of the dielectric, mechanical and thermal requirements without modification. Porous, paper-like tapes produced dielectrically weak cables.

Uniaxially oriented polyolefin tapes were found to have tensile properties superior to the nonoriented types, but these materials often fibrillated during cooldown to operating temperature. Further studies showed that commercially produced, 32 μm-thick, biaxially oriented polypropylene tapes had acceptable tensile properties at both 4.2 and 293 K. The desired tape thicknesses of 66 μm and 100 μm were obtained by laminating two or three layers together with a 2.0 μm-thick polyurethane adhesive. The loss tangent and permittivity of this laminate meets design considerations. Biaxial 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.

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REFERENCES

1. E. B. Forsyth, Overview of Electric Transmission (Technology and Economics), to be presented at the 1978 Thirteenth Intersociety Energy Conversion Engineering Conference, San Diego, CA, August 20-25, 1978.

2. E. B. Forsyth, et al., Flexible Superconducting Power Cables, IEEE Trans., PAS 92, 494 (1973).

3. 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, 734 (1978).

4. 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.

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

6. 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).

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

8. 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.

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

10. H. G. Olf and A. Peterlin, J. Polymer Sci. 12, 2209 (1974).

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

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

13. 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, 312 (1977).

APPENDIX I

Thermal Expansion Measurement Technique

In preparing the tape samples for measurement the procedure consisted of cutting enough tape strips (1/4" wide x 1 1/2" long) to produce a stack of material 1/4" thick when clamped. Steel clamping jigs were machined to facilitate this stacking procedure. While clamped, the ends of the stack were trimmed to produce a specimen approximately 1 1/4" long, and the longitudinal edge faces of the stack were lightly wiped with Eastman 910 (strain gauge quality) epoxy. The bundles were then unclamped and end-ground on a metallographic polishing wheel. Thermocouples were attached to the specimens with thin strips of masking tape and the beads fastened to the specimen surface with a small drop of electrical varnish.

Measurement Technique. The thermal expansion measurements were performed in a fused silica dilatometer with associated LVDT sensing equipment. The dilatometer has a resolution of .5x10^{-6} in. Temperature is controlled at 10-degree intervals by utilizing a throttling dewar, which uses the sensible heat resulting from vaporized cryogen, and proportional controllers which permit temperature control of ±0.1 K in the entire temperature range.

APPENDIX II

Description of Thermal Conductivity Measurements

In the modified steady-state conductivity method employed in this experiment, a temperature gradient is established between two copper plates separated by the polymeric film. One plate is attached to a controlled temperature heat sink, and a measured quantity of heat is added to the other plate by means of an electric resistance heater. Conductivity is then calculated using a form of the Fourier equation:

$$k = \frac{q}{A} \frac{L}{\Delta T} \quad ,$$

where

k = thermal conductivity
g/A = heat flow per unit across section area
L = film thickness since the conductivity of copper and the bonding agent are orders of magnitude higher
ΔT = temperature gradient across L measured with Keithley 147 nanovoltmeter.

The gradient heater is a 3-lead unit wound of Evanohm wire which has a nearly zero temperature coefficient of resistance. A constant current source is used to power the gradient heater. The temperature gradient set up in the specimen after a steady-state condition has been reached is measured using either gold cobalt versus "normal" silver differential thermocouples, or miniature platinum resistance thermometers. The ambient temperature is precisely controlled (±0.05 K) during a measurement using the output of a Keithley 150 B null detector, the signal to which arises from a copper-constantan thermopile mounted on the specimen container, and a low-temperature modified West controller. The temperature gradient across the specimen is measured by a Keithley 140 nanovoltmeter.

The measurements are carried out in a liquid helium throttling dewar. This dewar provides a degree of ambient temperature control in itself in that by suitably adjusting the throttle value (which admits helium through a capillary to the dewar sample chamber) and the vaporization heater voltage (which allows the liquid helium to vaporize before entering the sample chamber), the cold helium gas flowing past the specimen fixture (which is highly evacuated) can be controlled to within one degree K. This greatly reduces the burden on the independent ambient temperature control device used in the specimen fixture.

For the single film unpressurized experiment, the sample assembly presented no unusual difficulty. For the pressurized conditions a different sample container had to be designed which could convey the required pressure to the film material and at the same time prevent excessive heat loss through the mechanical pressurizing structure. Figure 7 illustrates the technique used. The method was not ideal in that heat losses of 25 to 30% were measured along the top fiber rod. These losses were taken into consideration in calculating the effective thermal conductivity of the film using the equation previously discussed. A load of 70 lbs/in^2 was applied to the fiber rod using an LVDT load measuring device. As the load was applied and held, the setscrew collar was tightened. We estimate the applied load was retained to within 5 lbs/in^2 after cooldown. The glass-metal tube was utilized to further minimize heat losses during the measurement.

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 - $1\text{x}10^{7}$ N/m^2 (minimum)
2. Tensile Strength - $1.4\text{x}10^{8}$ N/m^2 (minimum)
3. Tensile Modulus, E_1 - $3.5\text{-}7.0\text{x}10^{9}$ N/m^2
4. Compressive Modulus, E_3 - $1\text{x}10^{7}$ N/m^2 (maximum)
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 Tensile Properties of Dielectric Tape Candidates

POLYMER TYPE	DISS. FACTOR* (Tan $\delta \times 10^6$)	DIEL. CONSTANT*	YIELD STRENGTH, $N/m^2 \times 10^{-7}$ AT 293 K	TENSILE MODULUS $N/m^2 \times 10^{-9}$ AT 293 K	TENSILE MODULUS, $N/m^2 \times 10^{-9}$ AT 4.2 K
Polyethylene low density non-oriented (100 μm)	15	2.3	0.21	0.093	5.45
Polypropylene low density non-oriented (125 μm)	9	2.2	0.69	0.248	0.830
Polypropylene biaxially oriented laminated (100 μm)	21	2.3	2.21	1.92	1.44
Polysulfone (125 μm)	60	2.5	3.98	1.90	4.47
Polyimide, Kapton H (100 μm)	90	3.1	4.41	2.84	5.50
Polycarbonate, Makrofol "KG" (60 μm)	55	2.9	4.93	3.48	4.55
Polyester, Mylar (75 μm)	200	2.5	6.53	4.01	4.53

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* (4.2 K and 100 Hz)

Table III

TENSILE PROPERTIES OF DIELECTRIC TAPE CANDIDATES AT 293 K*

POLYMER TYPE	ELASTIC ELONGATION, %**	TOTAL ELONGATION, %	YIELD STRENGTH, ** $N/m^2 x10^{-7}$	TENSILE STRENGTH $N/m^2 x10^{-8}$	TENSILE MODULUS $N/m^2 x10^{-9}$
Polyethylene, low density non-oriented (100 μm)	2.48	528	0.21	0.14	0.093
Polypropylene, low density non-oriented (125 μm)	3.1	1118	0.689	0.460	0.248
Polyethlene, uni-axially oriented, laminated, Valeron (100 μm)	0.64	0.402	0.394	0.406	0.889
Polypropylene, bi-axially oriented, laminated (100μm)	1.35	61.8	2.21	1.69	1.90
Polysulfone (125 μm)	2.25	63.6	3.98	0.588	1.88
Polyimide, Kapton H (100 μm)	1.84	55.2	4.41	1.82	2.83
Polycarbonate, Makrofol "G" (100 μm)	2.00	72.2	3.71	1.10	2.13
Polyester, Mylar (75 μm)	2.08	114	6.53	1.50	4.01

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* Measurements made in tape machine direction.

** At 0.2% Offset.

Table IV

TENSILE PROPERTIES OF DIELECTRIC TAPE CANDIDATES AT 77 K*

POLYMER TYPE	ELASTIC ELONGATION, %**	TOTAL ELONGATION, %	YIELD STRENGTH,** N/m^2x10^{-7}	TENSILE STRENGTH N/m^2x10^{-8}	TENSILE MODULUS N/m^2x10^{-9}
Polyethylene, low density, non-oriented (100 μm)	2.60	3.60	10.4	1.04	3.68
Polypropylene, low density non-oriented (125 μm)	2.38	4.55	7.28	0.749	3.40
Polyethylene, uniaxially oriented, Valeron (100 μm)	2.60	10.4	9.31	1.14	3.88
Polypropylene, biaxially oriented, laminated (100 μm)	3.28	17.5	18.3	3.21	1.52
Polysulfone (125 μm)	2.97	4.40	6.69	0.854	2.38
Polyimide, "Kapton H", (100 μm)	2.35	12.0	11.2	2.60	4.93
Polycarbonate, uniaxially oriented 'Makrofol G" (100 μm)	2.85	5.67	9.31	1.47	3.40
Polyester, 'Mylar" (75 μm)	2.75	5.75	17.1	2.76	6.73

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* Measurements made in machine direction of tape.

** At 0.2 % Offset.

Table V

TENSILE PROPERTIES OF DIELECTRIC TAPE CANDIDATES AT 4.2 K*

POLYMER TYPE	ELASTIC ELONGATION, %**	TOTAL ELONGATION, %	YIELD STRENGTH,** $N/m^2 \times 10^{-7}$	TENSILE STRENGTH $N/m^2 \times 10^{-8}$	TENSILE MODULUS, $N/m^2 \times 10^{-9}$
Polyethylene, low density, non-oriented (100 μm)	2.85	2.85	15.0	1.50	5.45
Polypropylene, low density, non-oriented (125 μm)	--	1.175	--	0.383	0.830
Polyethylene, uniaxially oriented "Valeron" (100 μm)	3.1	3.1	12.5	1.25	4.23
Polypropylene, biaxially oriented, laminated (100 μm)	3.26	7.80	20.7	3.23	1.44
Polysulfone (125 μm)	2.62	2.98	11.1	1.21	4.47
Polyimide, "Kapton H", (100 μm)	3.08	5.78	15.4	2.56	5.50
Polycarbonate, uniaxially oriented, "Makrofol G" (100 μm)	4.42	7.25	16.8	2.48	4.10
Polyester, "Mylar" (75 μm)	4.52	10.75	19.0	3.48	4.53

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* Measurements made in machine direction of tape.

** At 0.2% Offset.

Table VI

VALUES OF SOME FACTORS AFFECTING CABLE BENDING PERFORMANCE

POLYMER TYPE	TENSILE MODULUS, E_1 ($N/m^2 x 10^{-7}$)	COMPRESSIVE MODULUS, E_3^* ($N/m^2 x 10^{-7}$)	$m = E_1/E_3$	COEFFICIENT OF FRICTION, μ_s**
Polyethylene, unixially 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)	190	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

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* At $1.40 x 10^5$ N/m^2

** Cross machine direction to cross machine direction.

Table VII

THERMAL CONTRACTION AND TENSILE ELONGATION OF DIELECTRIC TAPES

POLYMER TYPE	CONTRACTION, 293K to 4.2K, %		ELONGATION TO FRACTURE TO 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 Veleron	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 VIII

THERMAL CONDUCTIVITIES OF DIELECTRIC TAPES*

	THERMAL CONDUCTIVITY, WATTS/cm-K			
TEMPERATURE, ^{o}K	6	20	100	300
POLYMER TYPE				
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	$9.2x10^{-5}$	$1.3x10^{-4}$	$4.3x10^{-4}$	$1.1x10^{-3}$

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

Table IX

THERMAL CONDUCTIVITY OF THREE POLYMERS AS A FUNCTION OF HELIUM GAS PRESSURE AT 6K*

POLYMER TYPE	PRESSURE, $N/m^2 x10^{-3}$			
	0	178	532	710
Polysulfone	$2.0x10^{-5}$	$8.4x10^{-5}$	$8.4x10^{-5}$	$9.7x10^{-5}$
Polyethylene, uniaxially oriented, laminated Valeron	$6.0x10^{-5}$	$1.5x10^{-4}$	$1.4x10^{-4}$	$1.6x10^{-4}$
Polycarbonate, Makrofol "KG"	$9.0x10^{-5}$	$2.1x10^{-4}$	$2.5x10^{-4}$	$2.0x10^{-4}$

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* Conductivities in watts/cm K.

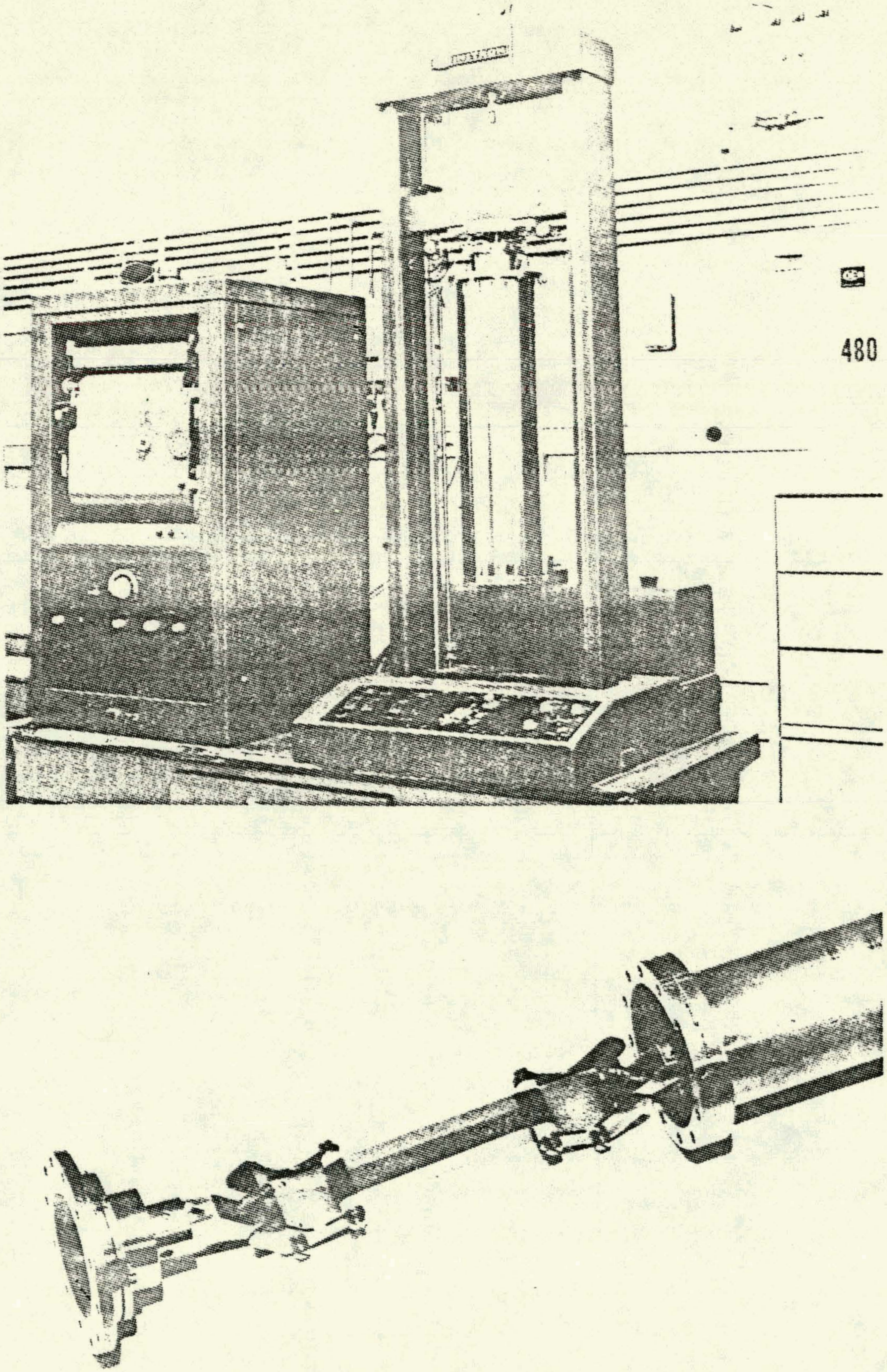

Figure 1. Apparatus used for Tensile Measurements.

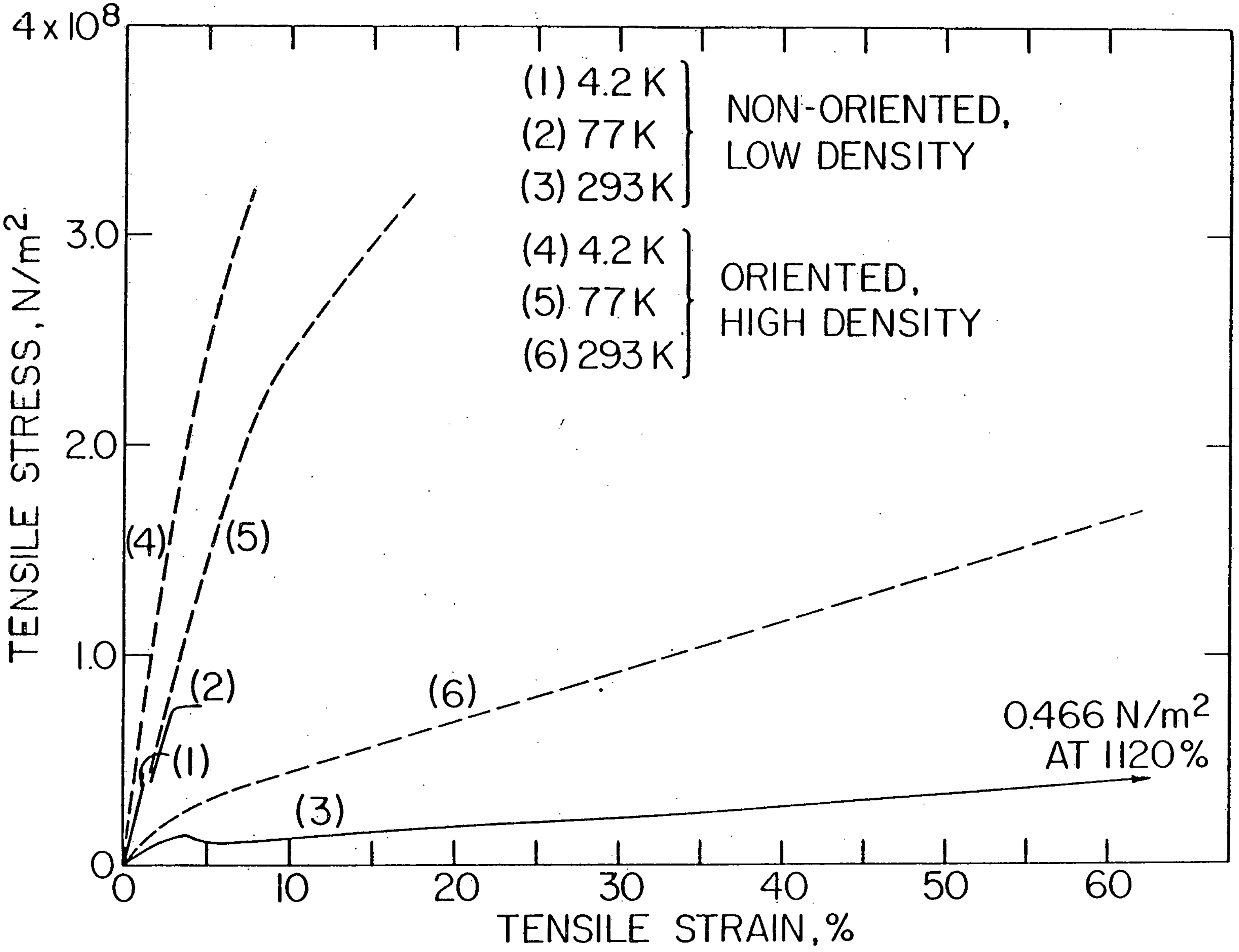

Figure 2. Typical Stress-Strain Curves for Oriented and Non-Oriented Polypropylene Films.

6-1614-78

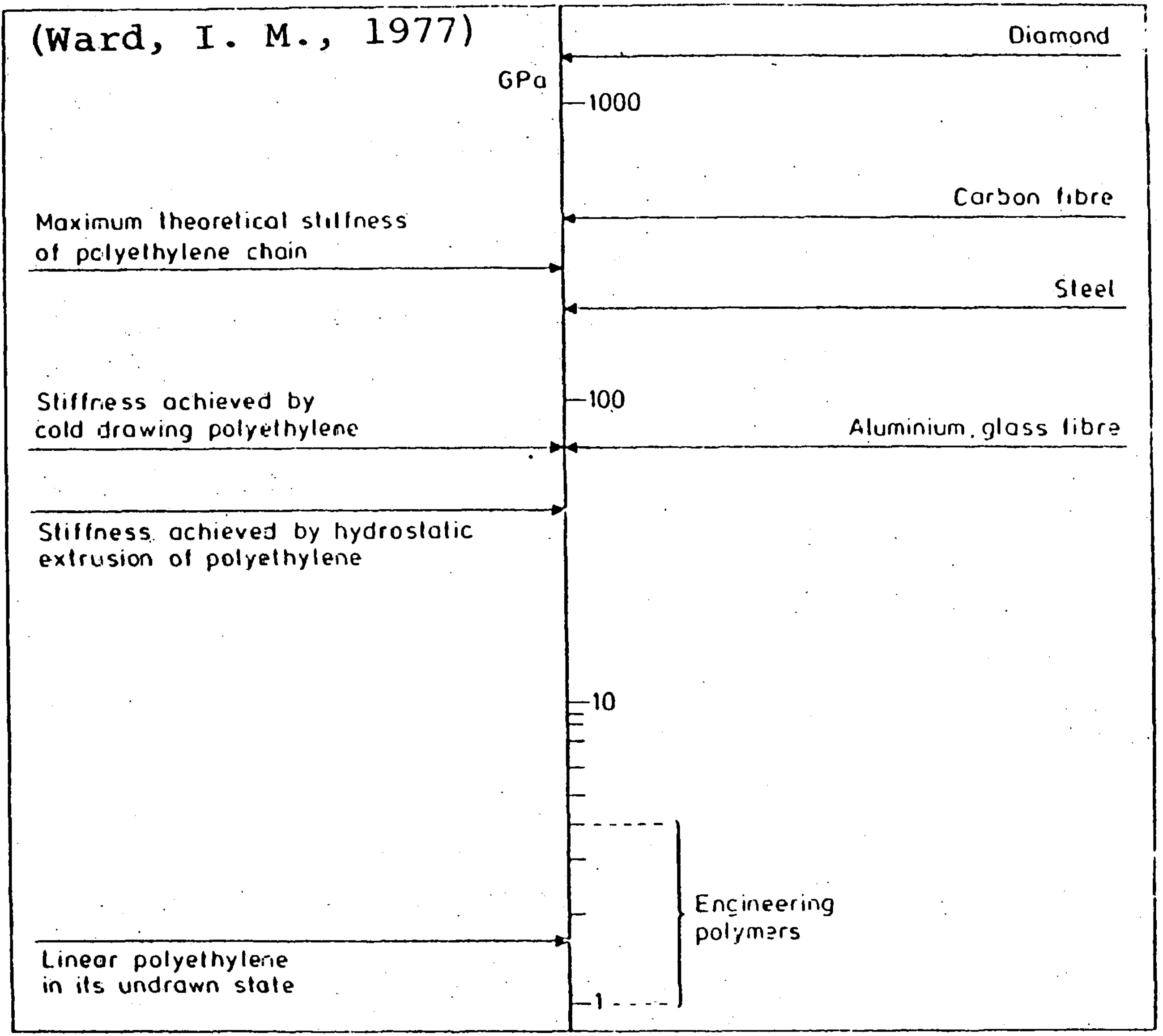
(Ward, I. M., 1977)

Figure 3. The comparative stiffness of some typical materials

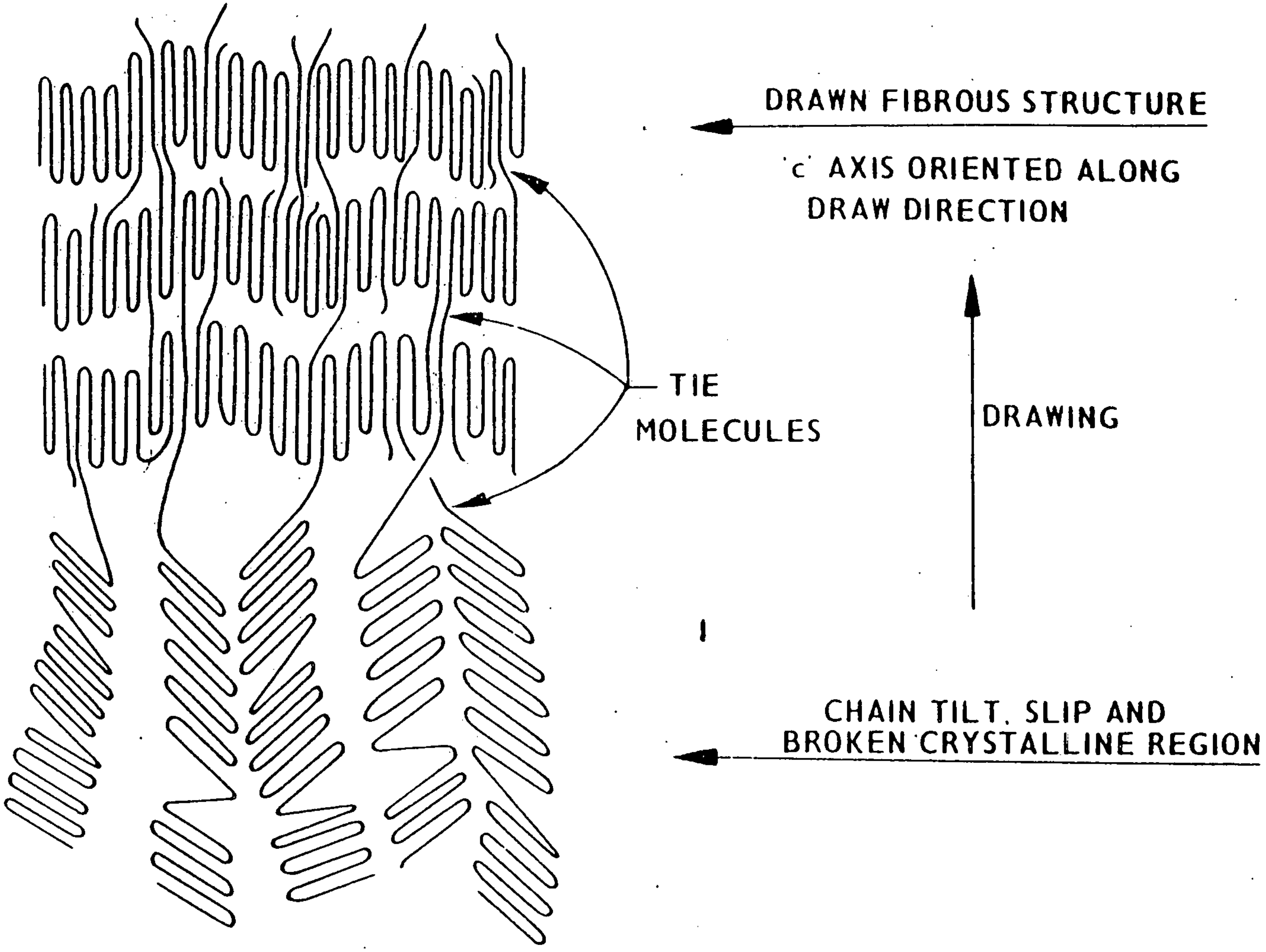

Figure 4. STRUCTURAL CHANGES OCCURRING DURING COLD DRAWING

(Gibbons, 1972)

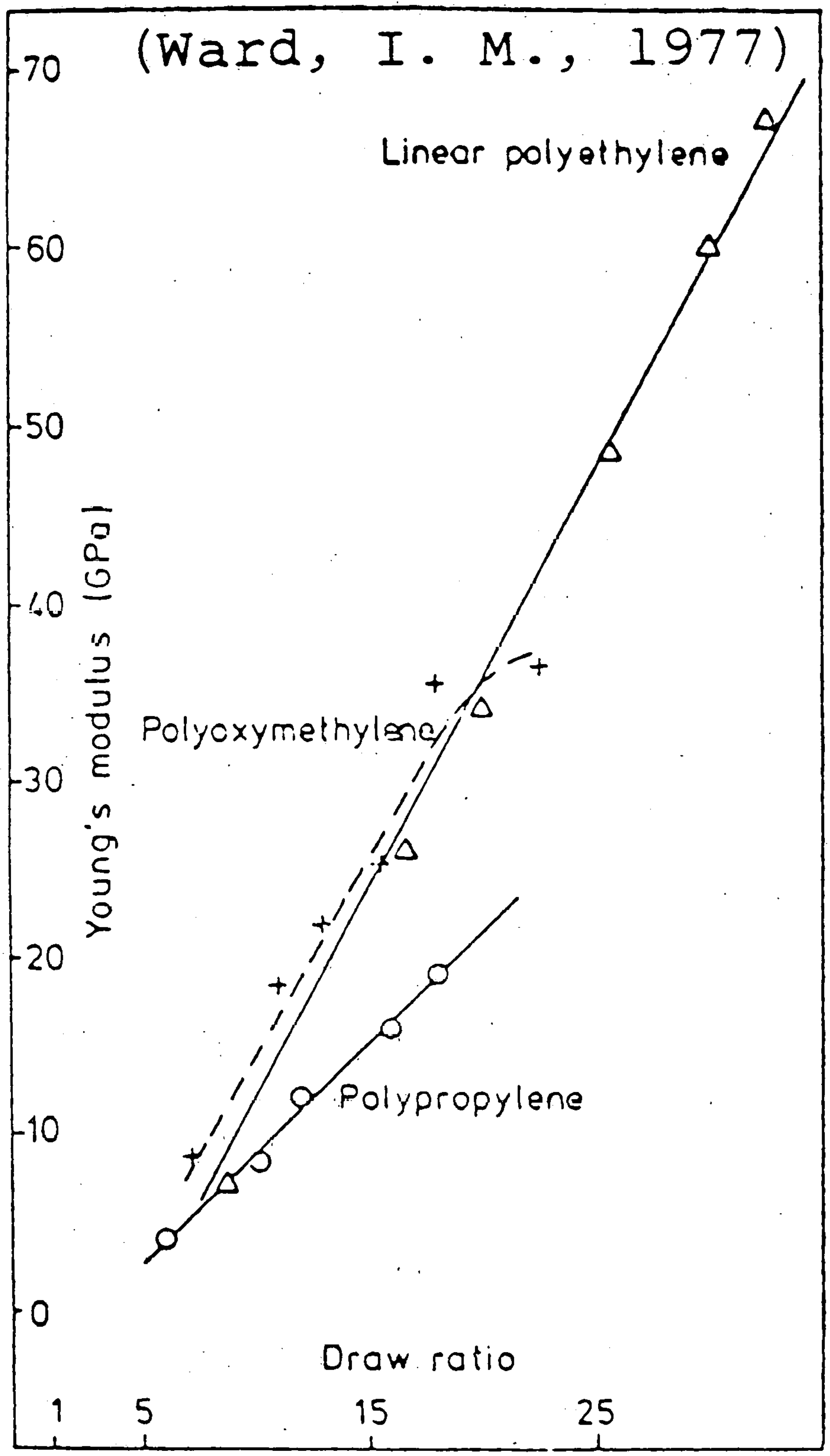

Figure 5. Young's modulus as a function of draw ratio for ultrahigh modulus polymers

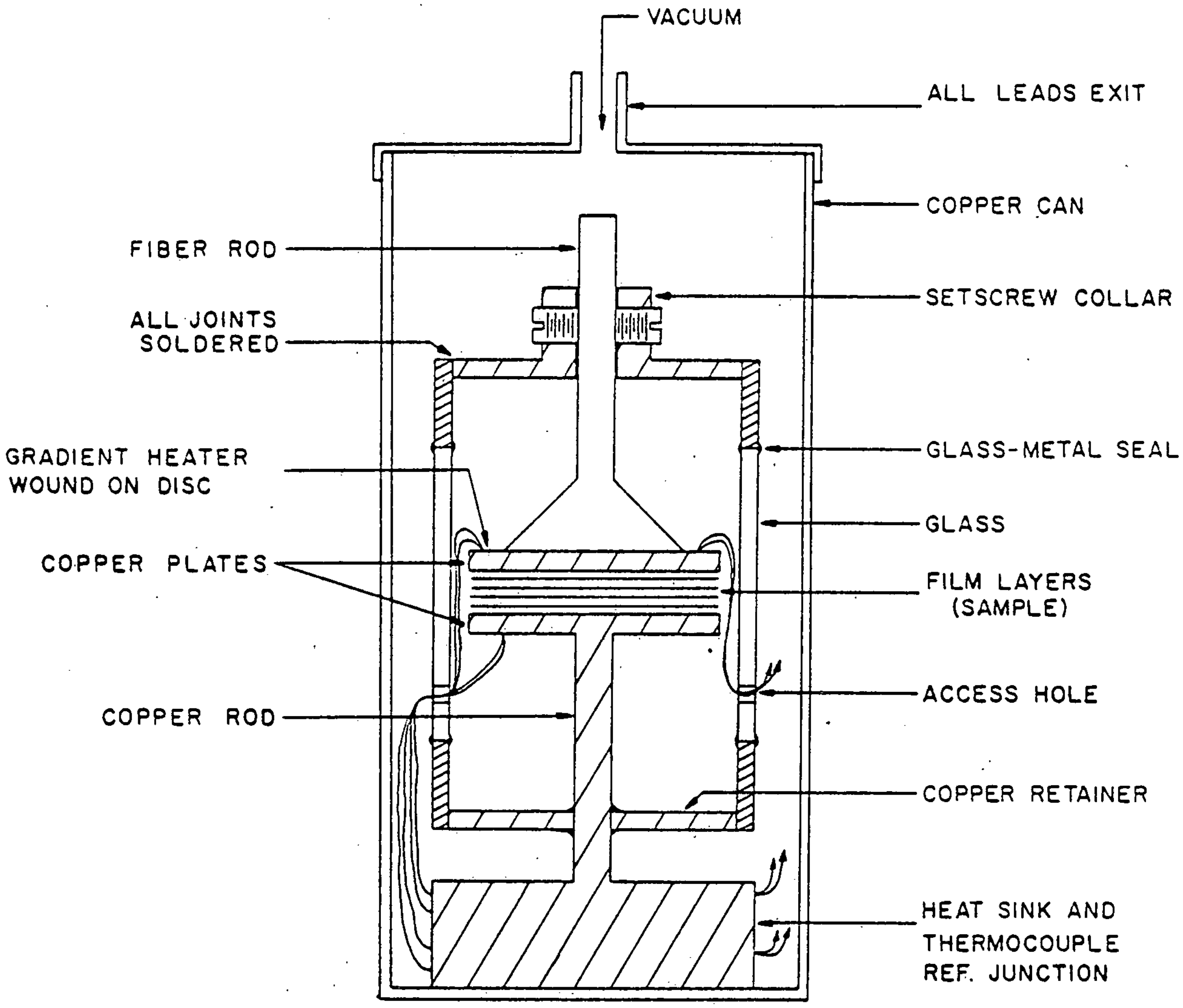

Figure 7. SCHEMATIC OF SAMPLE CONTAINER USED FOR THERMAL CONDUCTIVITY MEASUREMENTS AT 70 LBS/IN^2 APPLIED PRESSURE ON FOUR THICKNESSES OF POLYMERIC FILM

6-1659-78

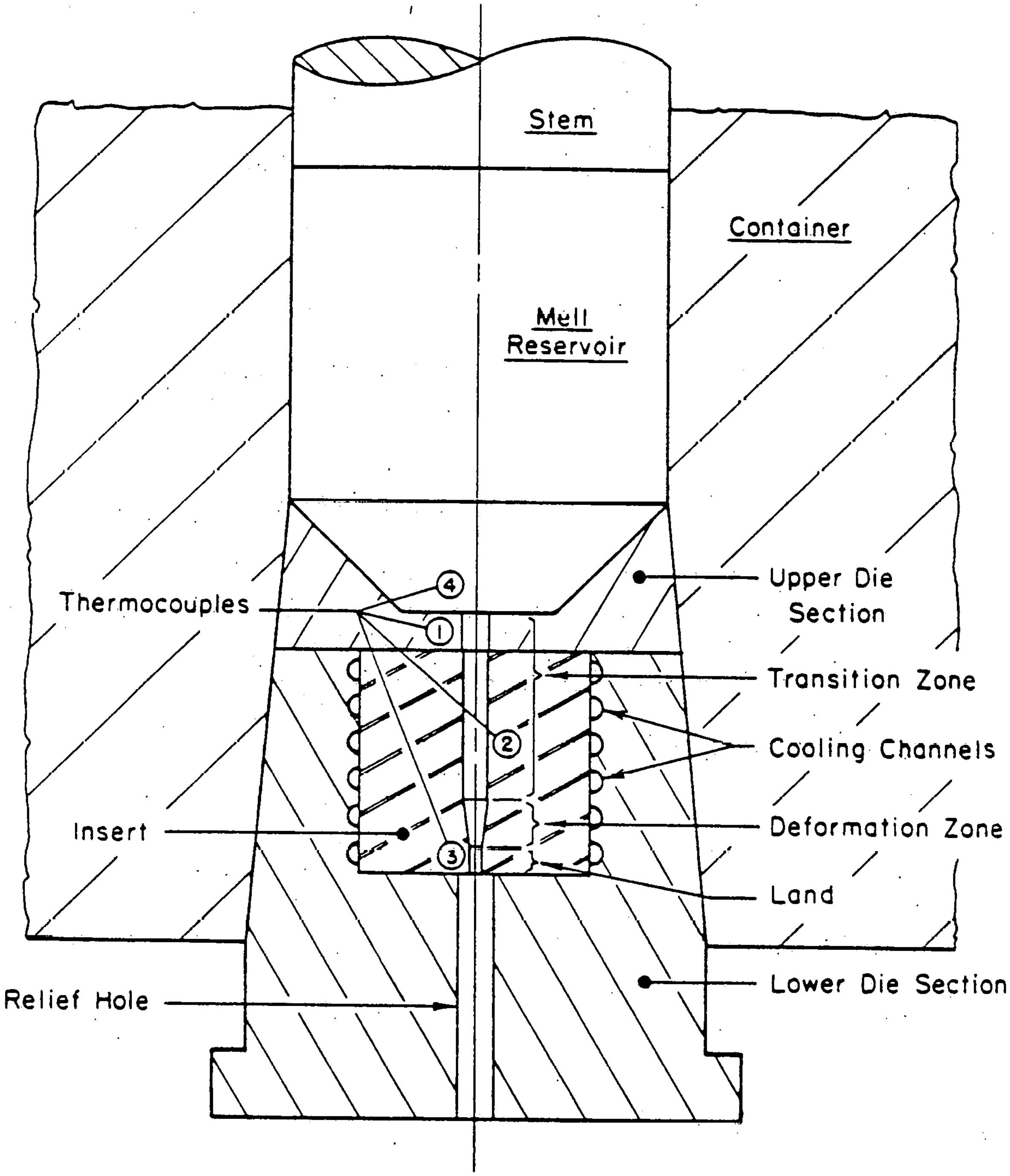

Figure 6. SCHEMATIC CROSS SECTION OF TAPE DIE IN EXTRUSION CONTAINER