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MOLECULAR ORIENTATION
AND MECHANICAL ANISOTROPY IN
POLYETHYLENE, POLYPROPYLENE, AND
POLY(ETHYLENE TEREPHTHALATE) FILMS

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16. Abstract

Sonic-pulse-velocity measurements of the molecular orientation in polyethylene, polypropylene, and poly(ethylene terephthalate) films are presented. The orientation is correlated with the tensile properties which were measured at several angles in the plane of the film. The mechanical anisotropy is shown by the variation of the tensile properties and the stress relaxation modulus with direction in the plane of the film.

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MOLECULAR ORIENTATION AND MECHANICAL ANISOTROPY IN POLYETHYLENE, POLYPROPYLENE, AND POLY(ETHYLENE TEREPHTHALATE) FILMS*

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SUMMARY

Measurements of the molecular orientation and the effect of such orientation on the mechanical properties of polyethylene, polypropylene, and poly(ethylene terephthalate) films are presented. A sonic-pulse-velocity method of detecting orientation is described, and orientation scans of these polymer films are included. The mechanical anisotropy is shown by the variation of the tensile properties and the stress relaxation modulus with direction in the plane of the film. The orientation and anisotropy are compared, and some practical aspects of the anisotropy are reviewed.

INTRODUCTION

That molecular orientation can change the mechanical properties of a polymer and that these properties vary depending on the amount of orientation are well-established facts. Moreover, the properties change with direction relative to the orientation direction; that is, they are anisotropic (refs. 1 to 3). As a result, a considerable amount of work has been done on orientation effects in polymer moldings (refs. 4 to 6), fibers (refs. 7 and 8), sheets (refs. 9 and 10), and films (refs. 11 to 13).

In recent years, the use of polymer films in aerospace structures such as solar concentrators and passive communications satellites (refs. 14 to 16) has increased. In some of these structures, the film may be subjected to sudden or sustained loads in several directions. The mechanical response of the film to such loads can vary depending on the anisotropy that results from molecular orientation. Consequently, it is of value to measure the mechanical anisotropy in films and to investigate means of determining the molecular orientation so that the mechanical load response can be estimated.

One method of estimating orientation is by measuring the velocity of a sonic pulse in the polymer. This method has been used extensively in the study of the sonic modulus and orientation of fibers (refs. 17 to 21). The present paper describes the application of the sonic-pulse-velocity method to polymer films that have been used or have been proposed for use in aerospace structures. The molecular orientation and mechanical anisotropy are reported and compared for a slightly oriented polyethylene film, a uniaxially oriented polypropylene film, and a biaxially oriented poly(ethylene terephthalate) film.

MATERIALS AND TESTS

Materials

Table I lists the polymer films and some of the important characteristics of each. The polyethylene (PE) film had a small amount of transverse orientation that was induced in the normal processing of the film. The polypropylene (PP) film was highly oriented in the transverse direction, and the poly(ethylene terephthalate) (PETP) film was biaxially oriented. X-ray measurements confirmed that all films were crystalline.

Sonic-Pulse-Velocity Tests

The sonic-pulse-velocity tests were performed with a sonic-pulse propagation meter similar to that used in reference 21. The instrument (fig. 1) includes two transducers, one of which produces a longitudinal pulse centered at 8000 Hz. This pulse is generated 194 times each second. When a film (or a fiber) is coupled to the transducers, the pulses generated by one transducer are detected by the other. An electronic clock measures the time required for the pulse to travel the distance between the transducers. Thus, the sonic-pulse velocity is simply the distance between the transducers divided by the pulse transit time. A 6-inch-square (15.24-cm) piece of film was secured to a frame with the longitudinal and transverse directions in known positions. The film was then rotated in its plane to obtain sonic-pulse velocities at different angles. Pulse transit times were measured for each film from 0° (longitudinal or machine direction) to 90° (transverse direction) in 10° increments, plus a measurement at 45°, for each of three transducer spacings. For a particular angle, the measured times were plotted as a function of the transducer spacing and the plot generally provided the expected straight line. The reciprocal slope of the line was the velocity for that particular angle in the film.

Once the sonic-pulse velocity is obtained, the sonic modulus E can be calculated from the expression

$$E = \rho(1 - \mu^2)v^2$$

where ρ is the density, μ is Poisson's ratio (taken as 0.4), and v is the sonic-pulse velocity. This equation is derived from a consideration of the propagation of longitudinal waves in an infinite plate. (See ref. 22.) If the sonic-pulse velocity is measured in a long cylindrical shape, the Poisson effect can be neglected and the equation reduces to

$$E = \rho v^2$$

which is the form frequently used in measuring the sonic modulus of fibers (ref. 23).

Tensile Stress-Strain and Stress Relaxation Tests

The tensile stress-strain tests were performed on 0.5-inch-wide (1.27-cm) strips of film by utilizing a 3.0-inch (7.62-cm) grip separation and a crosshead speed of 2.0 in./min (5.08 cm/min). An integrator associated with the testing machine computed the area under the stress-strain curve so that the energy required to break the strip of film could be measured. From the stress-strain curve, it was possible to determine the initial tangent modulus, the 0.2-percent offset yield strength, and both the tensile strength and the elongation at break.

The stress relaxation tests were conducted on 0.5-inch-wide (1.27-cm) strips of film by using a 5-inch (12.70-cm) grip separation. The test specimens were extended to approximately 10 percent strain at a testing speed of 2.0 in./min (5.08 cm/min). With the specimen in the extended position, the crosshead was stopped and the stress was allowed to relax for 1000 seconds (16 minutes and 40 seconds). The stress at any time during this interval divided by the strain (approximately 10 percent for the present investigation) is referred to as the stress relaxation modulus.

RESULTS AND DISCUSSION

Molecular Orientation

Polymers, such as those described in this paper, consist of molecular chains that are assemblages, or repeat units, of atoms held together by covalent bonds. (See table I.) These intramolecular bonds are considerably stronger than the intermolecular bonds, or Van der Waals forces, between the chains. Typical intramolecular bond strengths may range from 80 to 150 kcal/mole, compared with intermolecular bond strengths of less than 10 kcal/mole (ref. 24). Hence, there is a strength anisotropy that is inherent to a group of molecular chains; that is, the load response of the chains depends partially on whether the load direction is alined to the chain axes.

In addition to the strength anisotropy, the molecular chain has a tendency to assume a kinked and highly contorted configuration that gives it an overall roughly spherical shape (ref. 25). The kinked configuration is the result of the limited number of definite angles

3

that can exist between the atoms in the chain under equilibrium conditions. Although a straight molecular chain is theoretically possible, a folded, twisted, randomly shaped configuration is more probable. The chain can be extended by mechanical force, however, especially if sufficient heat is present to increase the thermal vibrations of the atoms and thereby soften the polymer. The chain extension results in rotation, bending, or stretching of the bonds relative to one another, analogous to the way a folded carpenter's rule may be extended. Bond rotation, rather than bending or stretching, accounts for most of the chain extension (ref. 26). When the chain is extended, the movements that require the least energy take place first. Those movements requiring more energy do not take place until the chain is extended farther. Therefore, if a molecular chain is stretched to remove some of these random kinks, the result is a stiffer chain.

In general, molecular orientation has at least two effects: It changes the absolute value of the mechanical properties and it changes the magnitude of these properties with regard to direction in the polymer.

Sonic-Pulse Velocity

The sonic-pulse-velocity measurements are listed in table II and illustrated in figure 2. Included in table II are values of the sonic modulus.

The PE film, which was slightly oriented, had a relatively low sonic-pulse velocity, on the order of 4×10^3 ft/sec (1.2 km/sec). The film had only a small variation of velocity with angle in the plane of the film, the high value of about 4.5×10^3 ft/sec (1.4 km/sec) occurring at 90° (transverse direction). Because the sonic-pulse velocity and the density of the PE film were low, the sonic modulus (table II) was also low with values ranging from approximately 1.5×10^5 to 2×10^5 psi (1.03 to 1.38 GN/m^2). The orientation scan of the PE film (fig. 2) is illustrative of what may be expected from an unoriented film: The sonic-pulse velocity (and sonic modulus) is low, and there is little variation in the velocity with angle in the plane of the film.

By contrast, the PP film had a large variation in sonic-pulse velocity, a variation that reflected the high degree of uniaxial orientation at 90° (transverse direction). It is remarkable also that the velocity shows little change (less than 10 percent of the 0° value) for angles up to 50° after which it rises sharply to the maximum value at 90°. Such a variation suggests that the film would be useful under unbalanced biaxial loads, such as those occurring in internally pressurized cylinders for which the circumferential or hoop stress is twice the axial stress. The sonic modulus of the PP film is from three to five times the modulus of the PE film (table II).

The orientation scan for the PETP film differed considerably from what might have been expected inasmuch as the film was biaxially oriented. (See fig. 2.) Obviously, biaxial orientation does not necessarily mean the same degree of orientation throughout all

4

directions in the plane of the film. The sonic-pulse velocity varies from approximately 8×10^3 ft/sec (2.4 km/sec) at 0° to 11×10^3 ft/sec (3.4 km/sec) at 90°. The sharp decrease in velocity at 45° may be the result of a high degree of biaxial orientation. The sonic modulus for the PETP film (table II) is the highest for the three films, about 1×10^6 to 2×10^6 psi (6.9 to 13.8 GN/m^2). The high modulus is due to the high sonic-pulse velocity and density. Of considerable importance is the structure of the molecular chain. (See table I.) The inclusion in the PETP chain of the phenylene ring and the carbonyl dipoles adds a relatively stiff segment and enhances the electrostatic intermolecular bonding. As a result, the overall PETP structure is denser and stiffer and has a higher glass-transition temperature (ref. 27) than the less complicated PE and PP structures.

Tensile Properties

The tensile properties of the films are listed in table III and illustrated in figure 3. Each value in table III is the average of 25 tests unless otherwise specified, and the standard deviation follows the ± sign.

The tensile properties of the PE film at 0°, 45°, and 90° are plotted in figure 3(a). As the orientation increases, the tangent modulus and elongation also increase, the tensile strength and energy to break decrease, and the yield strength remains unchanged. The changes are fairly modest, however, being on the order of 10 percent of the 0° values except for the tensile strength and tangent modulus which changed nearly 20 percent. As would be expected, the tangent modulus had a much lower value than the sonic modulus. Because they are measured for short time intervals and at small strains, dynamic moduli, such as the sonic modulus, generally are higher than the essentially static moduli, such as the tangent modulus. Consequently, the PE film would be stiffer under high-velocity or impact loads (by a factor of approximately 2 for the present investigation) than it would be under static loads.

The tensile properties of the PP film are shown in figure 3(b). The changes are larger for this film than for the PE film, ranging from 50 to over 100 percent of the 0° values. In particular, the yield strength, tensile strength, and tangent modulus increase and the elongation and energy to break decrease with increasing orientation. Of importance in impact applications of the film is the sharp drop in energy to break. This property, which is the area under the stress-strain curve and is primarily a function of tensile strength and elongation, is also a qualitative measure of the impact-energy-absorbing ability of the film. Consequently, although the tangent modulus and tensile strength increase with orientation, the impact strength may drop significantly.

The variation of tensile properties with angle in the plane of the PETP film is shown in figure 3(c). Although the film was biaxially oriented, the sonic-pulse velocity generally increased between 0° and 90°, with a low value at 45° (fig. 2). The tangent

modulus shows a similar variation, the elongation varies in essentially the opposite sense, and the yield strength is virtually unaffected. The tensile strength also is unchanged except by high orientation. The energy to break reaches a maximum at 45° where the sonic-pulse velocity and tangent modulus are a minimum. Although little variation of properties might be expected for this film, only the yield strength and energy to break varied less than 10 percent relative to the 0° values. The tensile strength, tangent modulus, and elongation varied from 25 to 35 percent. Obviously, even the biaxially oriented PETP film is mechanically anisotropic.

In general, molecular orientation affects the tensile properties of the test polymer films in the following ways. The yield strength is nearly independent of orientation, except for the very high orientation which exists in the transverse direction (90°) of the PP film. By contrast, the tangent modulus is a function of the orientation, and its value is generally one-half to one-third that of the sonic modulus. The tensile strength and elongation may increase or decrease with increasing orientation. For a given film, if one of these properties increases, the other decreases. To a first approximation, the energy to break varies inversely as the orientation; that is, the energy-absorbing ability of the films tends to be highest where the orientation is lowest. As a result of orientation, a polymer film, such as the uniaxially oriented PP film, may show a large variation in the tensile properties. Although the PETP film was biaxially oriented, it was mechanically anisotropic. The most nearly isotropic film was the slightly oriented PE film.

Stress Relaxation Modulus

The stress relaxation modulus for times up to 1000 seconds is presented in table IV and is plotted in figure 4 in which a logarithmic time axis is used. In figure 4, the values for the PE film are low, as would be expected for a slightly oriented film, and the 45° and 90° curves coincide. For the PP film, there is a slight increase in the relaxation modulus from 0° to 45° and a much larger increase from 45° to 90°. The curves for the PETP film show the beneficial effect of the biaxial orientation (only the data points are shown for the 22.5° and 67.5° tests). At a given time, the relaxation modulus is approximately the same at all angles except 90° where it is 25 to 30 percent higher. If the curves of figure 4 are normalized, then the PE film curves and most of the PETP film curves coincide. By contrast, the PP film curves and the 90° PETP film curve not only have different absolute values but also have different shapes so that they require both a vertical and a horizontal shift to bring them together.

Stress relaxation may be thought of as the change of recoverable elastic strain into irrecoverable plastic strain. In a polymer film, the stress relaxation characteristics are influenced by, among other factors, the number and shape of the molecules that sustain the stress. Segments of the molecular chain, for example, can move or jump from

6

one equilibrium position to another and thereby contribute to the irrecoverable plastic strain. If the normalized stress relaxation curves coincide, the coincidence indicates that the difference in the unnormalized curves is primarily due to the number and distribution of molecular chains rather than to any shape or configuration that might have been given to the chains during orientation. However, the normalized curves may have different shapes. The difference in shapes indicates that the chains have a slightly different configuration and, therefore, the relaxation mechanism is different. More chain segments are available to move and rapidly reduce the imposed stress in a chain that has a large number of kinks (slightly oriented) than in one that is more extended (highly oriented). Consequently, the stress relaxation modulus can be affected by both the molecular chain distribution and chain extension.

CONCLUDING REMARKS

The molecular orientation and the resulting mechanical anisotropy have been determined in three polymer films: slightly oriented polyethylene, uniaxially oriented polypropylene, and biaxially oriented poly(ethylene terephthalate). A sonic-pulse-velocity method has been used to detect orientation and to measure the sonic modulus which varies as the orientation. The investigation has shown that, as the molecular orientation increases, the tangent modulus also increases, the energy to break (an estimate of the impact strength) decreases, and the yield strength is generally unaffected. The stress relaxation modulus generally increases with increasing orientation, and the relaxation mechanism is altered by high orientation.

Langley Research Center,
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TABLE I.- CHARACTERISTICS OF POLYMER FILMS

Polymer film	Thickness, in. (mm)		Specific gravity	Glass-transition temperature, $^\circ$C ($^\circ$K)		Orientation	Molecular repeat unit
Polyethylene	0.0013	(0.0330)	0.950	-120	(153)	Slightly oriented as a result of normal processing	
Polypropylene	0.0006	(0.0152)	0.907	-10	(263)	Uniaxially oriented in transverse direction	
Poly(ethylene terephthalate)	0.001	(0.0254)	1.395	69	(342)	Biaxially oriented	

TABLE II.- SONIC-PULSE VELOCITY AND SONIC MODULUS OF POLYMER FILMS AT DIFFERENT ANGLES IN THE PLANE OF THE FILM

(a) U.S. Customary Units

Angle, deg	Polyethylene film		Polypropylene film		Poly(ethylene terephthalate) film	
	Sonic-pulse velocity, ft/sec	Sonic modulus, psi	Sonic-pulse velocity, ft/sec	Sonic modulus, psi	Sonic-pulse velocity, ft/sec	Sonic modulus, psi
0	3.79×10^3	1.55×10^5	6.94×10^3	4.96×10^5	8.22×10^3	1.07×10^6
10	3.88	1.63	6.85	4.82	8.46	1.13
20	3.79	1.55	6.80	4.70	8.98	1.27
30	3.70	1.48	6.62	4.49	9.25	1.36
40	3.70	1.48	6.94	4.94	9.57	1.45
45	3.79	1.55	7.20	5.31	4.93	.38
50	3.70	1.46	7.58	5.88	10.2	1.65
60	3.85	1.58	8.34	7.08	11.4	2.07
70	4.08	1.78	9.25	8.79	11.0	1.91
80	4.43	2.09	10.1	10.4	10.8	1.84
90	4.49	2.17	10.8	11.9	11.0	1.91

(b) SI Units

Angle, deg	Polyethylene film		Polypropylene film		Poly(ethylene terephthalate) film	
	Sonic-pulse velocity, km/sec	Sonic modulus, GN/m^2	Sonic-pulse velocity, km/sec	Sonic modulus, GN/m^2	Sonic-pulse velocity, km/sec	Sonic modulus, GN/m^2
0	1.16	1.07	2.12	3.42	2.51	7.38
10	1.18	1.12	2.09	3.32	2.58	7.79
20	1.16	1.07	2.07	3.20	2.74	8.76
30	1.13	1.02	2.02	3.10	2.82	9.38
40	1.13	1.02	2.12	3.41	2.92	9.99
45	1.16	1.07	2.19	3.66	1.50	2.62
50	1.13	1.01	2.31	4.05	3.11	11.4
60	1.17	1.09	2.54	4.88	3.47	14.3
70	1.24	1.23	2.82	6.06	3.35	13.2
80	1.35	1.44	3.08	7.17	3.29	12.7
90	1.37	1.50	3.29	8.20	3.35	13.2

TABLE III.- TENSILE PROPERTIES OF POLYMER FILMS AT DIFFERENT ANGLES

IN THE PLANE OF THE FILM[a]

(a) U.S. Customary Units

Polymer film	Angle, deg	Yield strength, psi		Tensile strength, psi		Tangent modulus, psi	Elongation, percent	Energy to break, in-lb/in^3
Polyethylene	0	710 ±	70	3 430 ±	400	$(0.78 \pm 0.25) \times 10^5$	633 ± 51	$(16.7 \pm 2.3) \times 10^3$
	45	740 ±	90	3 140 ±	260	(.76 ± .13)	653 ± 74	(15.4 ± 3.1)
	90	800 ±	90	[b]2 660 ±	110	(.89 ± .15)	[b]720 ± 32	[b](14.6 ± 1.5)
Polypropylene	0	3 720 ±	160	8 680 ± 1 000		$(2.40 \pm 0.20) \times 10^5$	520 ± 63	$(34.9 \pm 0.5) \times 10^3$
	45	3 680 ±	160	12 000 ±	720	(2.60 ± .25)	327 ± 43	(30.9 ± .5)
	90	8 800 ±	320	23 600 ± 1 880		(4.09 ± .30)	110 ± 27	(18.5 ± .7)
Poly(ethylene terephthalate)	0	10 600 ±	800	24 600 ± 3 000		$(5.45 \pm 0.38) \times 10^5$	138 ± 29	$(26.6 \pm 7.2) \times 10^3$
	22.5	11 000 ±	600	24 600 ± 2 800		(5.46 ± .32)	150 ± 27	(28.7 ± 6.4)
	45	10 800 ● 1 000		24 600 ± 2 200		(5.15 ± .45)	157 ± 64	(29.3 ± 5.0)
	67.5	11 000 ±	600	32 600 ± 2 600		(6.32 ± .24)	112 ± 17	(27.6 ± 5.7)
	90	11 600 ±	800	34 000 ± 2 400		(6.89 ± .61)	92 ± 13	(23.9 ± 4.1)

(b) SI Units

Polymer film	Angle, deg	Yield strength, MN/m^2	Tensile strength, MN/m^2	Tangent modulus, GN/m^2	Elongation, percent	Energy to break, MJ/m^3
Polyethylene	0	4.89 ± 0.48	23.6 ± 2.8	0.54 ± 0.17	633 ± 51	115 ± 16
	45	5.10 ± .62	21.6 ± 1.8	.52 ± .09	653 ± 74	106 ± 21
	90	5.52 ± .62	[b]18.3 ± .8	.61 ± .10	[b]720 ± 32	[b]101 ± 10
Polypropylene	0	25.6 ± 1.1	59.8 ± 6.9	1.65 ± 0.14	520 ± 63	241 ± 3
	45	25.4 ± 1.1	82.7 ± 5.0	1.79 ± .17	327 ± 43	213 ± 3
	90	60.7 ± 2.2	163 ± 13	2.82 ± .21	110 ± 27	128 ± 5
Poly(ethylene terephthalate)	0	73.1 ± 5.5	170 ± 21	3.76 ± 0.26	138 ± 29	183 ± 50
	22.5	75.8 ± 4.1	170 ● 19	3.76 ± .22	150 ± 27	198 ± 44
	45	74.5 ● 6.9	170 ± 15	3.55 ± .31	157 ± 64	202 ± 34
	67.5	75.8 ± 4.1	225 ± 18	4.36 ± .17	112 ± 17	190 ● 39
	90	80.0 ± 5.5	234 ± 17	4.75 ± .42	92 ± 13	165 ± 28

[a]Each value is the average of 25 tests unless otherwise specified; the standard deviation follows the ± sign.

[b]Average of 15 tests.

TABLE IV.- STRESS RELAXATION MODULUS OF POLYMER FILMS AT DIFFERENT ANGLES IN THE PLANE OF THE FILM

(a) U.S. Customary Units

Polymer film	Angle, deg	Stress relaxation modulus, psi, at –															
		1 sec	2 sec	3 sec	5 sec	7 sec	10 sec	20 sec	30 sec	50 sec	70 sec	100 sec	200 sec	300 sec	500 sec	700 sec	1000 sec
Polyethylene	0	0.18×10^5	0.17×10^5	0.17×10^5	0.16×10^5	0.16×10^5	0.15×10^5	0.15×10^5	0.14×10^5	0.14×10^5	0.14×10^5	0.13×10^5	0.13×10^5	0.13×10^5	0.13×10^5	0.12×10^5	0.12×10^5
	45	.21	.20	.20	.19	.19	.18	.17	.17	.16	.16	.16	.15	.15	.15	.15	.14
	90	.21	.20	.20	.19	.19	.18	.17	.17	.16	.16	.16	.15	.15	.15	.15	.14
Polypropylene	0	0.44×10^5	0.42×10^5	0.41×10^5	0.40×10^5	0.39×10^5	0.38×10^5	0.37×10^5	0.36×10^5	0.34×10^5	0.34×10^5	0.33×10^5	0.31×10^5	0.30×10^5	0.29×10^5	0.28×10^5	0.27×10^5
	45	.52	.50	.49	.48	.47	.46	.43	.42	.40	.39	.38	.36	.34	.33	.31	.30
	90	.94	.92	.90	.88	.87	.85	.81	.79	.76	.74	.72	.68	.65	.62	.60	.57
Poly(ethylene terephthalate)	0	1.38×10^5	1.34×10^5	1.31×10^5	1.28×10^5	1.26×10^5	1.23×10^5	1.19×10^5	1.17×10^5	1.14×10^5	1.13×10^5	1.11×10^5	1.08×10^5	1.06×10^5	1.04×10^5	1.03×10^5	1.02×10^5
	22.5	1.34	1.30	1.27	1.24	1.22	1.20	1.16	1.14	1.11	1.10	1.08	1.05	1.04	1.02	1.00	.99
	45	1.33	1.29	1.27	1.23	1.21	1.19	1.15	1.13	1.11	1.09	1.08	1.05	1.03	1.01	1.00	.99
	67.5	1.35	1.31	1.29	1.25	1.23	1.21	1.17	1.15	1.12	1.11	1.09	1.06	1.05	1.03	1.01	1.00
	90	1.71	1.66	1.63	1.59	1.57	1.54	1.50	1.48	1.45	1.43	1.41	1.38	1.36	1.34	1.32	1.31

(b) SI Units

| Polymer film	Angle, deg	Stress relaxation modulus, GN/m^2, at –															
		1 sec	2 sec	3 sec	5 sec	7 sec	10 sec	20 sec	30 sec	50 sec	70 sec	100 sec	200 sec	300 sec	500 sec	700 sec	1000 sec
Polyethylene	0	0.124	0.117	0.117	0.110	0.110	0.103	0.103	0.097	0.097	0.097	0.090	0.090	0.090	0.090	0.083	0.083
	45	.145	.138	.138	.131	.131	.124	.117	.117	.110	.110	.110	.103	.103	.103	.103	.097
	90	.145	.138	.138	.131	.131	.124	.117	.117	.110	.110	.110	.103	.103	.103	.103	.097
Polypropylene	0	0.303	0.290	0.283	0.276	0.269	0.262	0.255	0.248	0.234	0.234	0.228	0.214	0.207	0.200	0.193	0.186
	45	.359	.345	.338	.331	.324	.317	.296	.290	.276	.269	.262	.248	.234	.228	.214	.207
	90	.648	.634	.621	.607	.600	.586	.558	.545	.524	.510	.496	.469	.448	.427	.414	.393
Poly(ethylene terephthalate)	0	0.951	0.924	0.903	0.883	0.869	0.848	0.820	0.807	0.786	0.779	0.765	0.745	0.731	0.717	0.710	0.703
	22.5	.924	.896	.876	.855	.841	.827	.800	.786	.765	.758	.745	.724	.717	.703	.689	.683
	45	.917	.889	.876	.848	.834	.820	.793	.779	.765	.752	.745	.724	.710	.696	.689	.683
	67.5	.931	.903	.889	.862	.848	.834	.807	.793	.772	.765	.752	.731	.724	.710	.696	.689
	90	1.179	1.145	1.124	1.096	1.082	1.062	1.034	1.020	1.000	.986	.972	.951	.938	.924	.910	.903
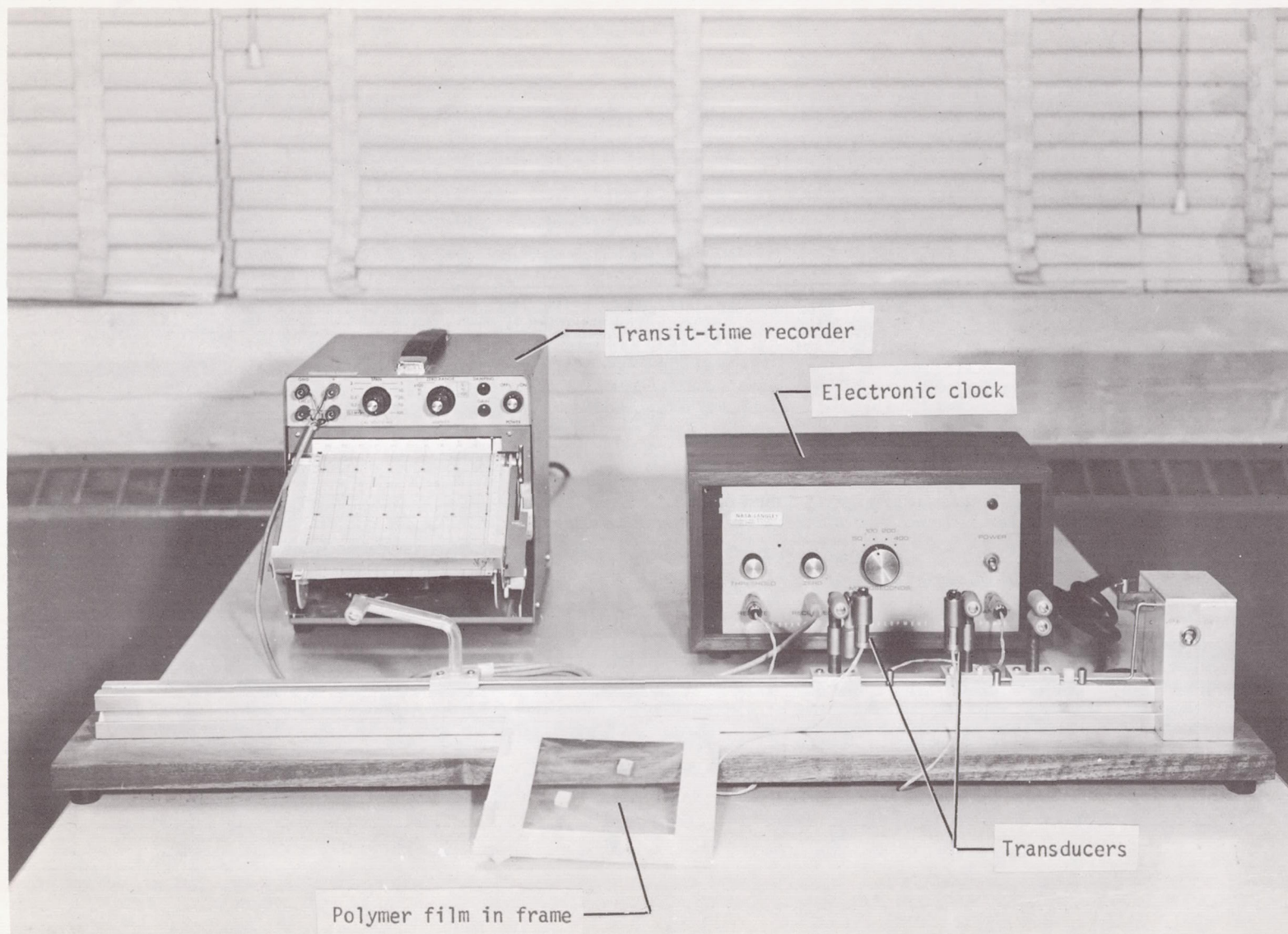
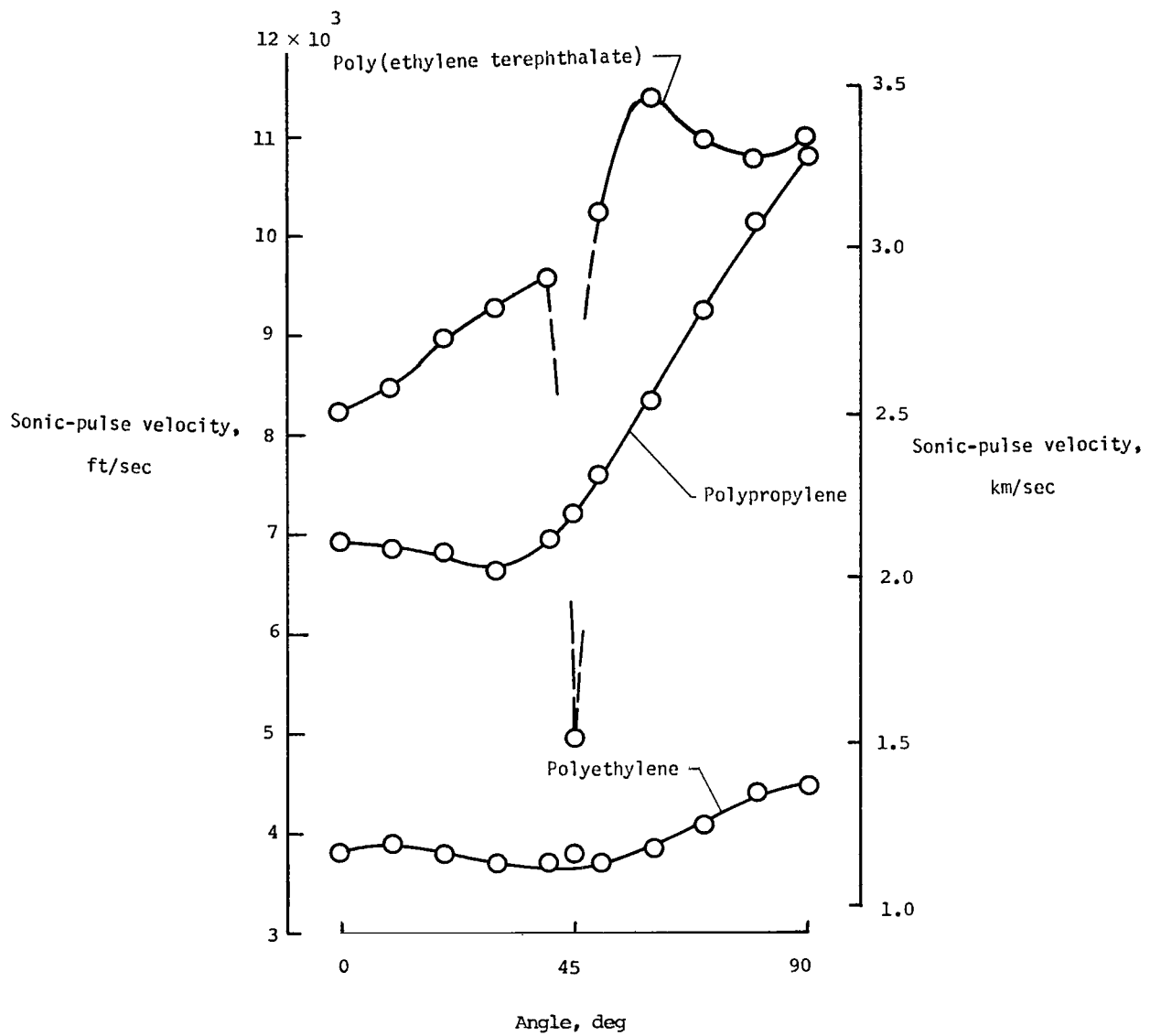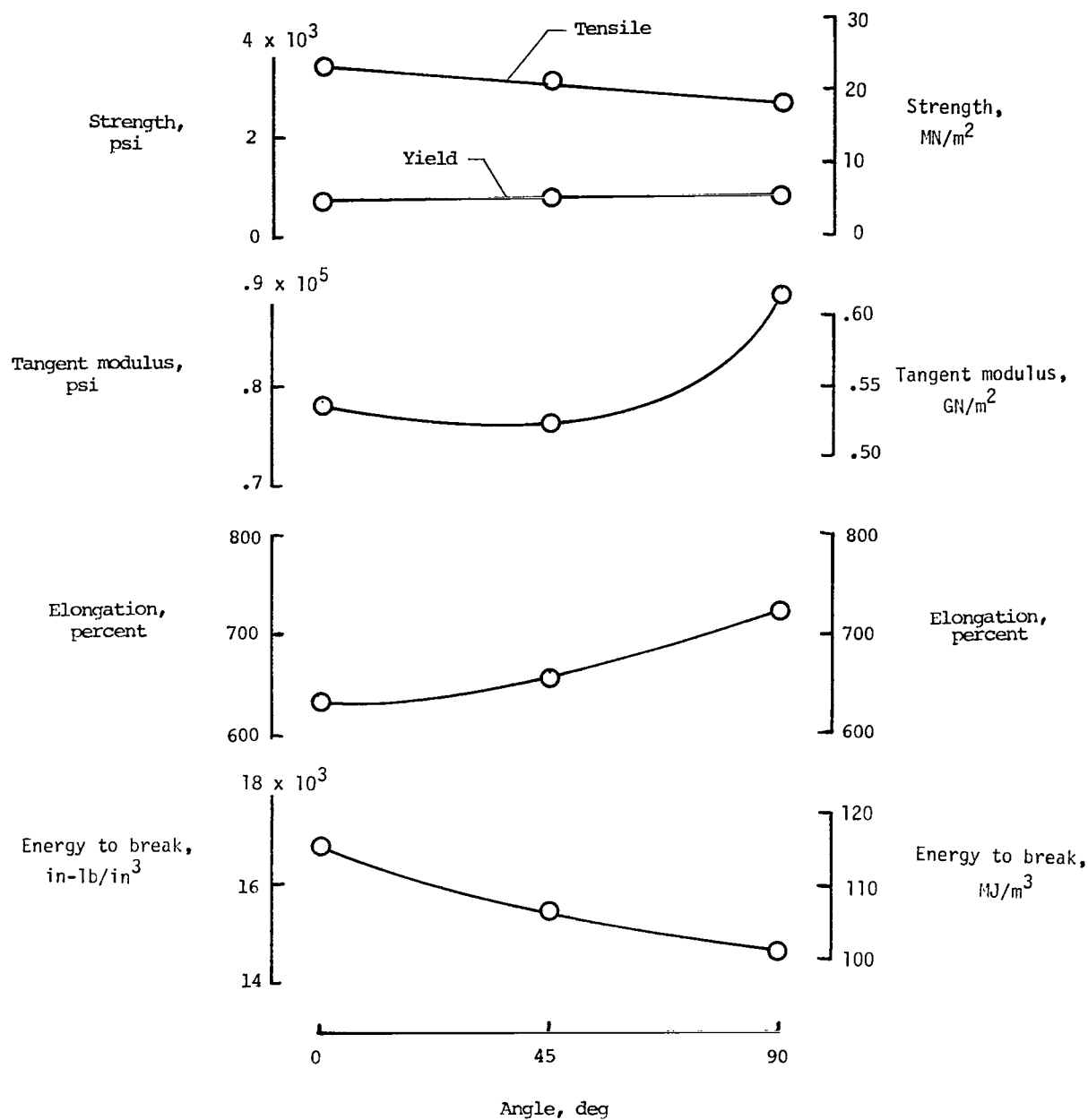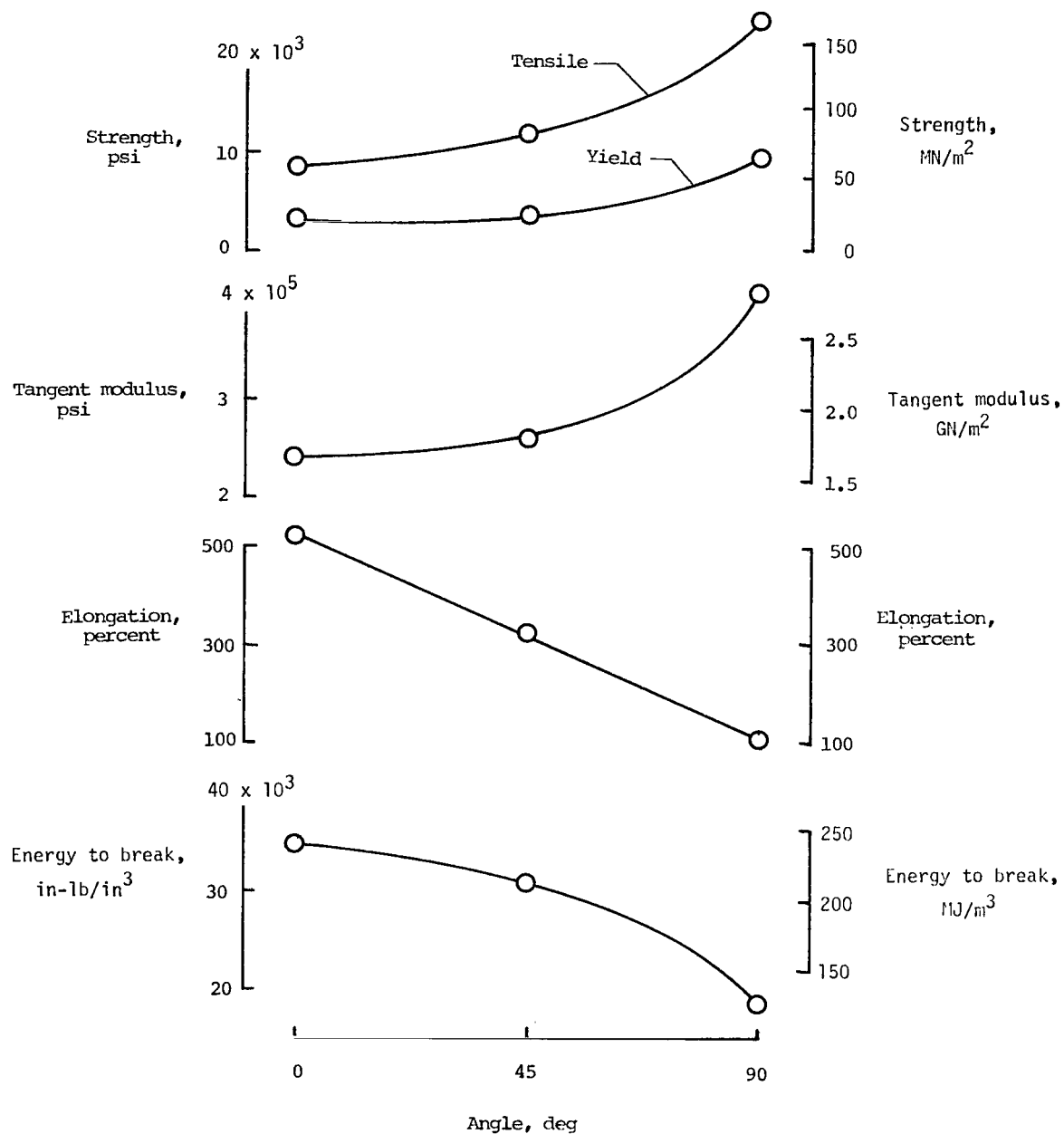Figure 1.- Sonic-pulse propagation meter.

L-66-10200.1

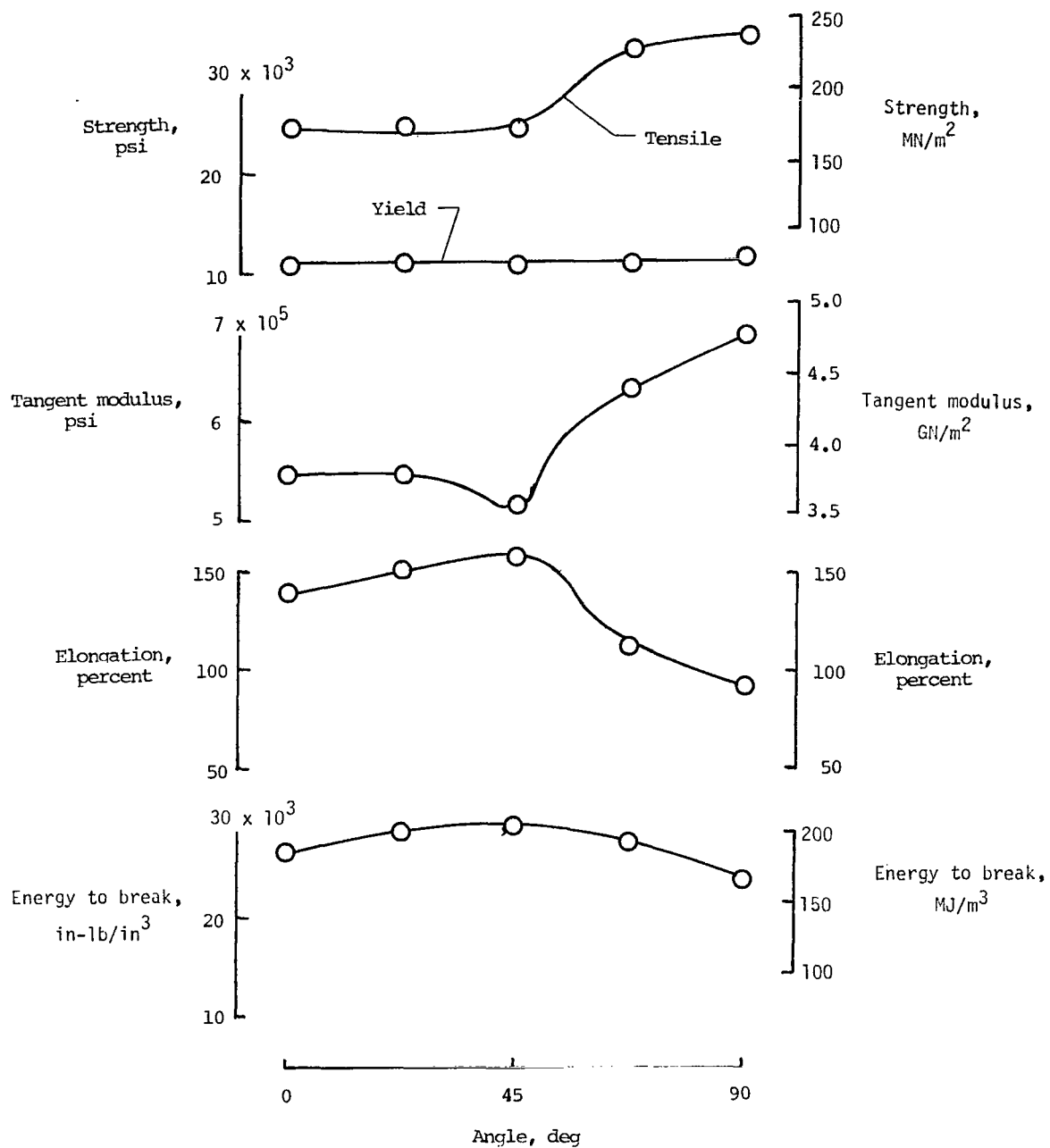Figure 2.- Orientation scans of polymer films.

(a) Polyethylene film.

Figure 3.- Tensile properties of polymer films as a function of direction in the plane of the film.

(b) Polypropylene film.

Figure 3.- Continued.

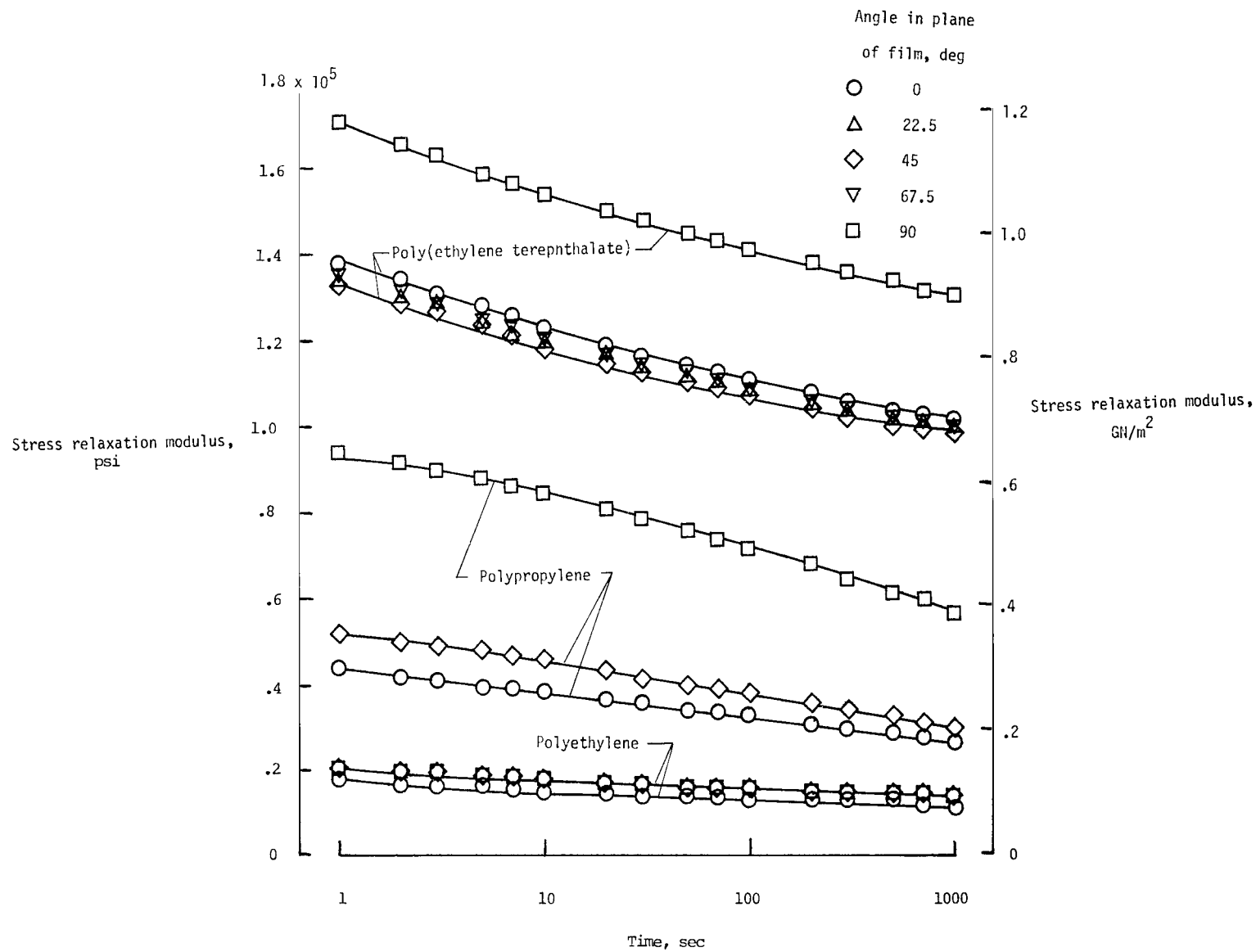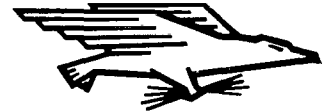(c) Poly(ethylene terephthalate).

Figure 3.- Concluded.

Figure 4.- Stress relaxation modulus of polymer films as a function of time and of direction in the plane of the film. Data points only are shown for the 22.5° and 67.5° relaxation moduli of the poly(ethylene terephthalate) film.

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