DETERMINATION OF MECHANICAL PROPERTIES OF POLYMER FILM MATERIALS

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THE SINGER COMPANY
KEARFOTT DIVISION
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ABSTRACT

Five polymeric film materials, Tedlar, Teflon, Kapton H, Kapton F, and a fiberglass reinforced polyimide, PG-402, in thicknesses ranging from 0.002 to 0.005 inch, were tested over a temperature range of -195° to 200°C in the "machine" and transverse direction to determine: elastic modulus, Poisson's ratio, three percent offset yield stress, fracture stress, and strain to fracture.

Values for the elastic modulus, yield stress and fracture stress decreased with increasing temperature for all the materials. The fracture strain increased as the temperature was raised. Teflon and Tedlar had the greatest temperature dependence and PG-402 the least. At 200°C the Poisson ratio values ranged from 0.39 to 0.5; they diminished as the temperature decreased covering a range of 0.26 to 0.42 at -195°C. The Poisson ratio appeared to drop below 0.5 in the vicinity of the yield region.

Shortening the gauge length from eight inches to one inch increased the strain to fracture and lowered the elastic modulus values. Teflon and Kapton H initially tested at -25°C in carbon dioxide showed anomalous results which were attributed to crazing. This was eliminated by performing all low-temperature tests with liquid nitrogen as the cooling medium. "Machine" and transverse direction properties were nearly the same for the unreinforced materials; the transverse properties of PG-402 were about 75 percent of the "machine" direction values.

ACKNOWLEDGEMENTS

The work described in this report took place during the period August 2, 1974 to January 21, 1975. It was conducted under the overall supervision of Dr. John L. Rutherford, Research Manager-Materials, with Dr. Edward J. Hughes, Principal Scientist, serving as Principal Investigator. Most of the experimental work was performed by William M. Benko and Charles J. Maccia, Research Associates. William B. Swain, Senior Scientist, developed the photographic techniques for determining Poisson's ratio and also made the scanning electron microscope photographs of the specimen edges. The specimen grips were designed by Charles Bing, Manager-Model Shop. Professor Norman Brown, Department of Metallurgy and Materials Science, University of Pennsylvania, was a valued Consultant for the program. William A. Edmiston served as Technical Manager for the Jet Propulsion Laboratory. E.I. DuPont De Nemours and Company donated the Tedlar and Teflon through the cooperation of John Rogers and Gerald J. Arensen.

SUMMARY

The purpose of this experimental investig n was to determine the values of selected mechanical properties of five polymeric film materials ranging in thickness from 0.002 to 0.005 inch: Tedlar, Teflon, Kapton H, Kapton F (a laminate of Teflon and Kapton H), and a fiberglass reinforced polyimide, PG-402. Measurements under tensile loading were made to determine: elastic modulus, Poisson ratio, three percent offset yield stress, fracture stress, and strain to failure, at six temperatures ranging from -195° to 200°C. Specimens were tested in the "machine" direction and the transverse direction.

The elastic modulus values decreased as the temperature was raised for all materials; Tedlar had the strongest temperature dependence and PG-402 the least. PG-402 was the stiffest material and Teflon had the lowest modulus values.

The Poisson ratio measurements were characterized by a large scatter attributed to two sources. The first was a large experimental error. The second was an apparent variation in Poisson's ratio depending upon where the measurement was made. At the lowest stress levels in the purely elastic region the value was close to 0.5; as yielding began the ratio dropped to about 0.3. At 200°C all the measured values fell between 0.39 and 0.51. As the temperature was lowered the Poisson ratio values generally decreased in ragged fashion. At -195°C they ranged from 0.26 to 0.42.

Of the four unreinforced materials, Kapton H had the highest three percent yield stress values and Teflon had the lowest. Raising the test temperature lowered all the yield stress values. There appeared to be a break in the temperature dependence at about 0°C; below that temperature the thermal effect was greater than above it. Due to the small strains in the PG-402, the yield stress values were determined by the first deviation from

elastic loading. PG-402 had no yield stress at 25°C and above due to the specimens fracturing in the elastic region. Yield stresses were observed only below 25°C. The yield stresses of PG-402 were not as strongly influenced by temperature as were the other four polymeric materials.

Fracture stress values became lower as the temperature was raised. Teflon was the weakest material at all temperatures; Kapton H and the PG-402 "machine" direction specimens had the highest strengths.

For all materials the strain to fracture increased as the temperature was increased. Teflon had the greatest ductility of all the materials; PG-402 had, by far, the least extension at fracture. The fracture strains of Kapton H and Kapton F, were relatively insensitive to temperature changes when compared to Teflon and Tedlar.

There were only negligible differences between the "machine" and transverse direction properties for the four unreinforced materials; with PG-402 the transverse property values were about 75 percent of those for the "machine" direction. All property values for Kapton F were intermediate between those of Kapton H and Teflon and could be approximated by the rule of mixtures.

When several of the materials were tested at -25°C using carbon dioxide as the refrigerant, crazing occurred which markedly altered the mechanical properties. Values for the modulus, yield, and fracture stresses were abnormally low and the strains to failure were exceptionally high. When liquid nitrogen was used to cool the specimens and the chamber, the measured properties were consistent with the results obtained at the other test temperatures. Due to size limitations of the environmental chamber, many tests were made using one inch gauge lengths. These results were characterized by larger strains to fracture and, concomitantly, lower modulus values. Correction factors were determined from tests made with longer gauge lengths and measurements of the testing machine "softness" using fiducial-marked specimens. The correction methods used are explained in detail in Section 2.4. Etching Kapton H and Teflon did not produce any strong changes in the measured properties.

LIST OF APPENDICES

TABLE OF CONTENTS

1. INTRODUCTION

The purpose of this test program was to determine selected mechanical properties of polymer film materials at various temperatures. For applications where the materials are to be subjected to stress it is important that the designer know what the properties are, so as to establish design allowables compatible with the material and its intended use. The elastic modulus must be known so that the strain resulting from the applied load can be calculated. Along with the determination of the strain in the loading direction, the designer should be able to calculate the transverse strain; thus, the Poisson ratio must be known. The elastic region in polymeric materials is generally small so that the elastic limit must be known to the designer. Since it is often difficult to determine the exact stress at which a material departs from straight line loading, an offset yield stress is customarily used. To complete the characterization of the mechanical properties of the polymeric materials, values for the fracture stress and strain at fracture are required. If the materials are to be used at temperatures other than room temperature, then the properties must be measured at the temperatures of interest.

Generally, these property values are not available in the literature in complete detail for the temperatures and specimen geometries to meet the designer's needs. Very often, properties are reported for film thicknesses of 0.001 inch with the proviso that thicker films have essentially the same values. Data for the Poisson ratio are exceedingly rare in the literature.

The investigation reported here had the objective of characterizing five polymeric materials at the same time, using the same procedures, with the same experimental variables, having specimen thicknesses the same as those expected to be used in service. Thus, selection of the material to be used could be based on a comprehensive knowledge of the relevant mechanical properties. In order to accomplish these tasks it was necessary to develop several improved test methods. The first was a good method of cutting specimens that guaranteed dimensional integrity and provided cut edges free from flaws that could cause premature failure. Second, specimen grips were designed and built that would not cause failure at the grips, as is often the case with tensile specimens that have no reduced gauge section. Third, special attention was given to the alignment of the specimens through the use of ball-socket joints immediately adjacent to the grips. It was felt that good axiality and concentricity of the grips would result in greater reproducibility of the fracture stress and strain to failure. Furthermore, the reduction of bending stresses in the specimen should provide a more uniform strain pattern in the deformed areas. Finally, a photographic method for measuring the longitudinal and transverse strains was developed, requiring: design of a pattern of fiducial marks, a means for applying marks that would survive temperature excursions and strains up to 500 percent, a method for recording the deformation of the pattern, and a system for measuring the dimensional changes in the fiducial marks.

2. EXPERIMENTAL PROCEDURES

2.1 MATERIALS

Five materials were studied in this program:

a) Kapton H - A polyimide film made by the E.I. DuPont DeNemours and Co.; Type 300H; from Mill Roll No. 04493. It was obtained with a thickness of 0.003 inch in a roll 12 inches wide.

b) Kapton F - a laminated film made by DuPont, consisting of a 0.002 inch layer of Kapton H sandwiched between 2 layers (each 0.0005 inch thick) of Teflon; Type 300F 929; from Mill Roll No. 00809. It was obtained with a total thickness of 0.003 inch in a roll 12 inches wide.

c) Teflon - a fluorinated ethylene propylene film made by DuPont, Type FEP 500A. The material was obtained with a thickness of 0.005 inch in a roll 24 inches wide. It was not possible to determine the mill roll from which it was cut.

d) Tedlar - a poly vinyl fluoride film made by DuPont; Type 200 SG 40 TR; from Slit Roll No. 7E014140. It was obtained with a thickness of 0.002 inch in a roll 12 inches wide.

e) PG-402 0/0 - a fiberglass reinforced polyimide made by the Mica Corporation, Culver City, Cal.; from Lot No. 11974-2028-1. The symbol 0/0 refers to no copper cladding. It was obtained in 36 x 18 inch sheets with a thickness of 0.0025 inch. The 1080 plain weave fiberglass cloth had a warp of 60 and a fill of 47; an amino silane finish was put on the cloth for better wetting during the fabrication of the PG-402.

2.2 CUTTING TEST SPECIMENS

Test specimens, 12 inches long by one inch wide, were cut using a double-bladed tool developed for this program. As shown in Figure 1, the cutting apparatus consists of a double-grooved base plate, a clamping bar, and a block for mounting two razor blades. The grooves in the bottom plate, which accept the razor blade edges, are separated by a distance of one inch. The width of the clamping bar is one inch less the thickness of one razor blade (actually, twice the half-thickness of the blade) so that the cutting edges are one inch apart. Figure 2 shows the cutting apparatus assembled preparatory to cutting a Kapton H specimen. A strip of material several inches wide, is laid on the base plate. The clamping bar is then placed over it, positioned by two locating pins at the ends. The block holding the razor blades is then drawn along the clamping bar with a slow, steady motion. To avoid introducing splits or tears at the edges of the specimens the razor blades were changed frequently. Cut edges were examined with an optical microscope, but the shallow depth of focus prevented satisfactory analysis. Random specimens were then examined in the scanning electron microscope. They were given a thin coating of carbon to render the surfaces electrically conductive. Magnifications were varied from 50X to 500X and the specimens were rotated and tilted to show several views. Typical cut edges are shown in Figures 3-7. Tedlar (Figure 3) had the "cleanest" cut in that it had the smoothest cut face and no burr was formed at the bottom where the blade left the material. Teflon (Figure 4) cut edges were marked by a pronounced burr at the bottom surface and a slightly rough cut face. Figure 5 (Kapton H) shows a somewhat serrated cut edge, with only a very slight burr. The Kapton F (shown in Figure 6) also has a burr at the bottom surface from the outer layer of Teflon. None of the specimens cut from the unreinforced polymer materials showed edge defects that could be considered as sources of premature failure. The cut edge of PG-402 (see Figure 7) was very rough because of the fiberglass content.

"Machine" direction specimens were cut with their longitudinal axis parallel to the direction

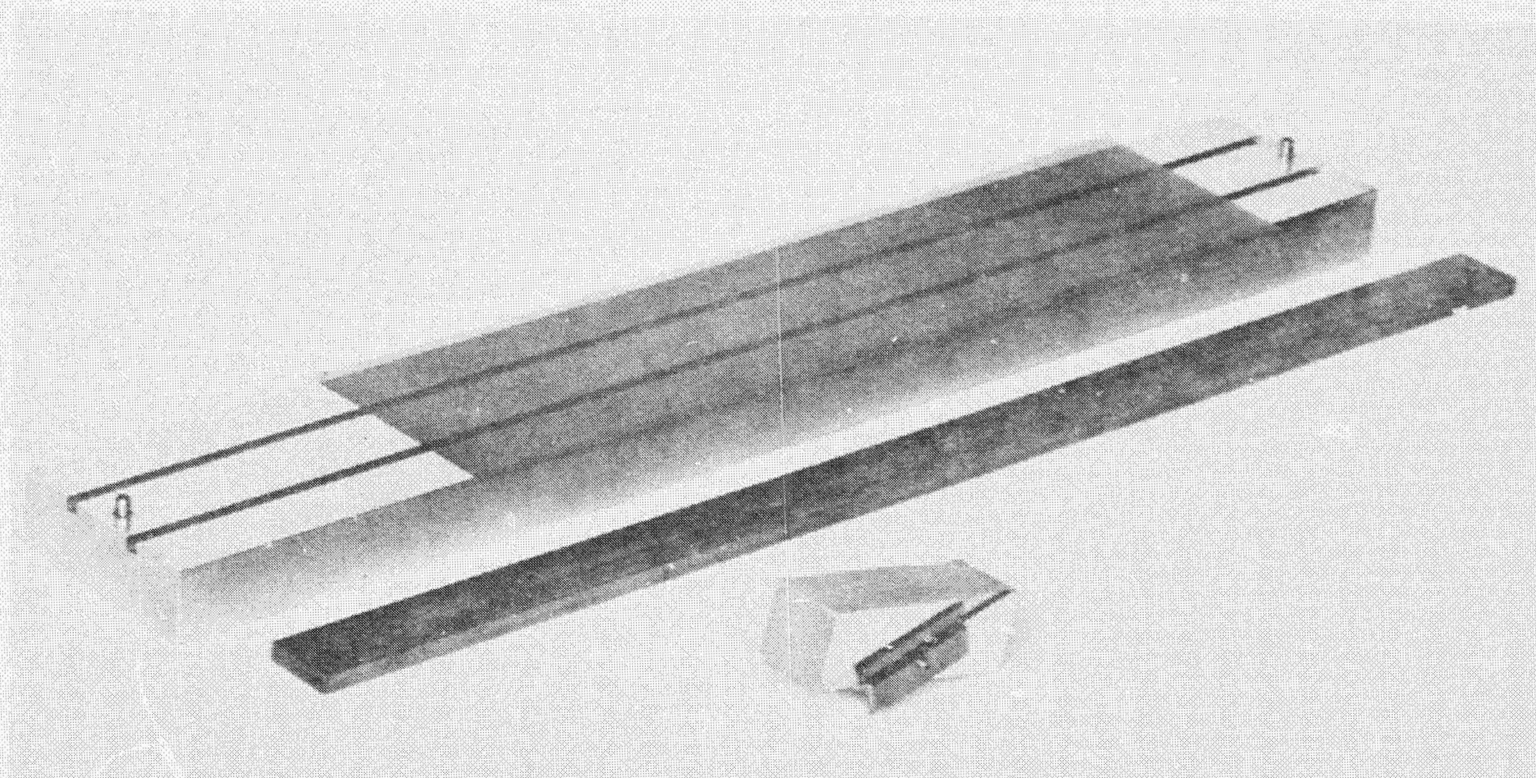

FIGURE 1 - Apparatus for Cutting Specimens, Disassembled

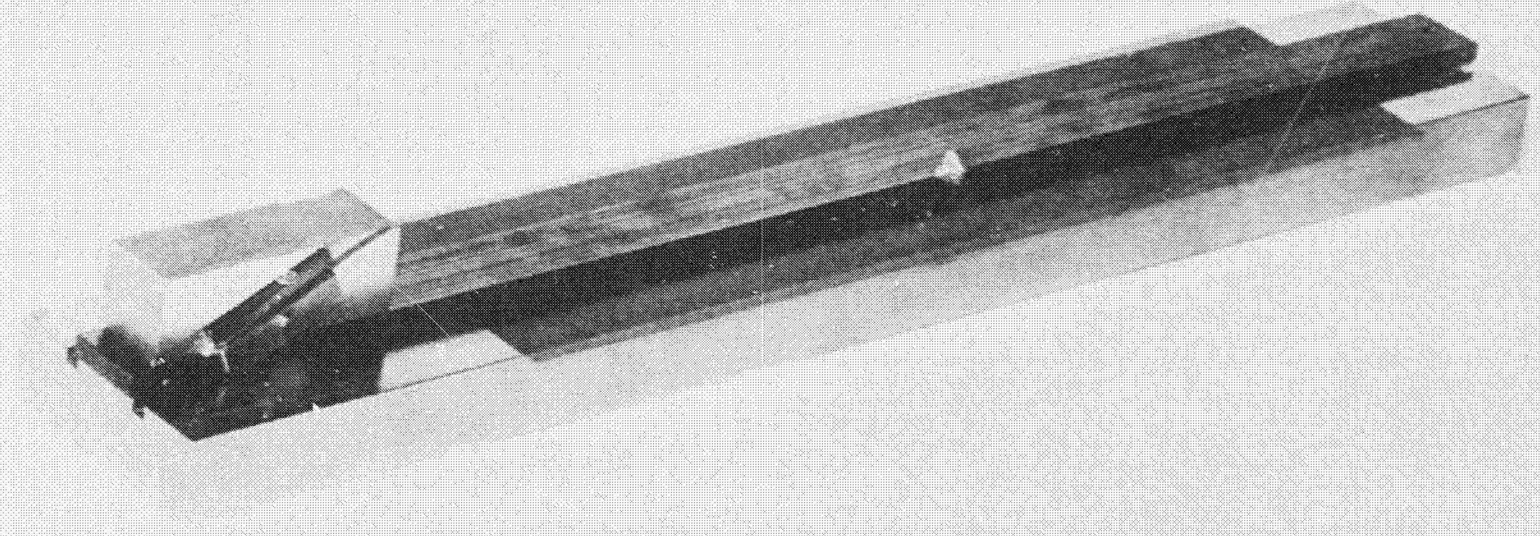

FIGURE 2 - Apparatus for Cutting Specimens, Assembled

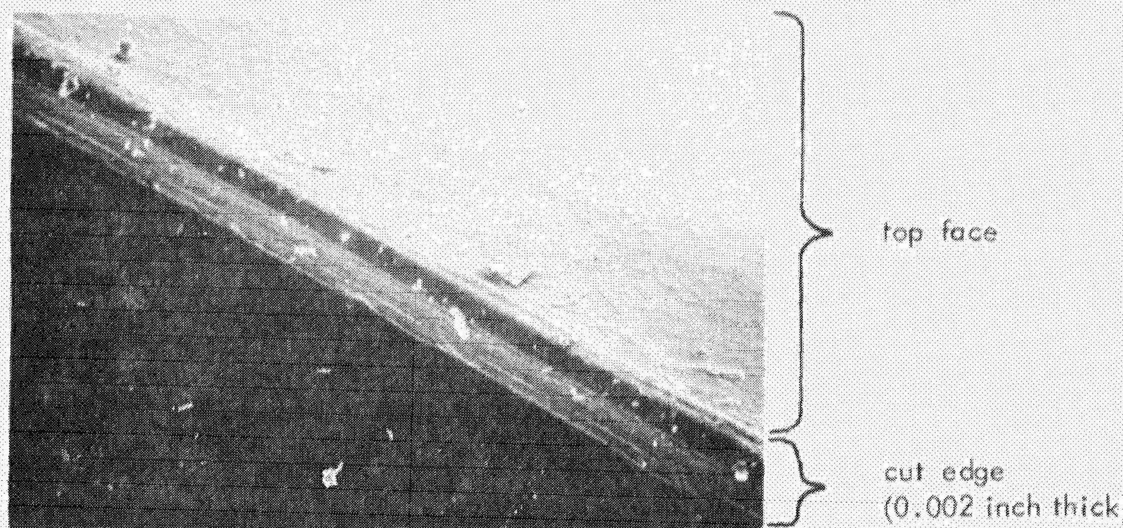

FIGURE 3 - Tedlar Cut Edge of Specimen (scanning electron microscope, 190X)

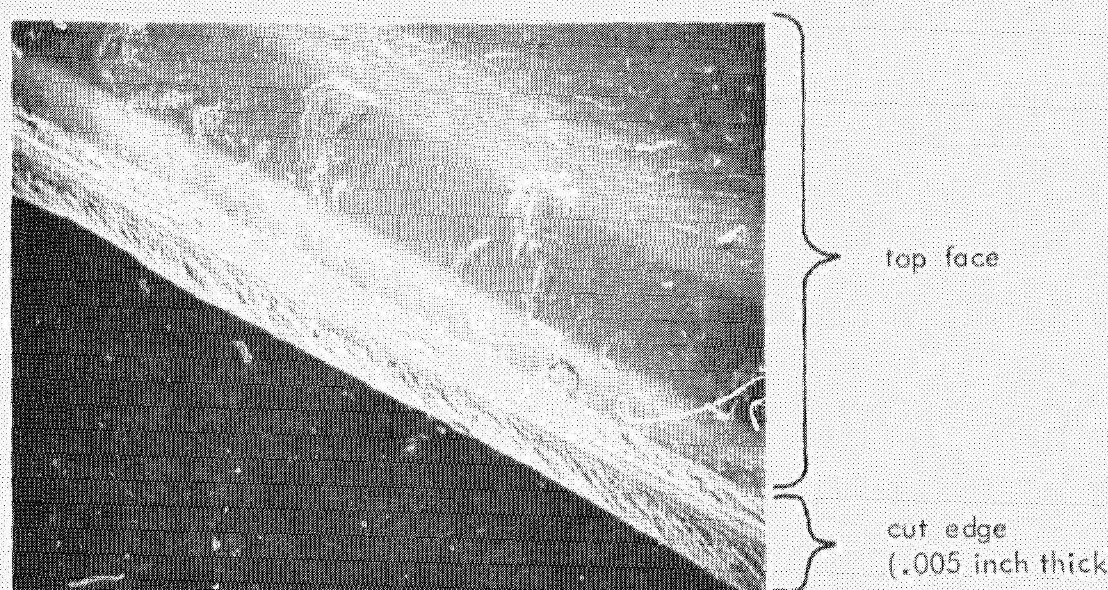

FIGURE 4 - Teflon Cut Edge of Specimen (scanning electron microscope, 250X)

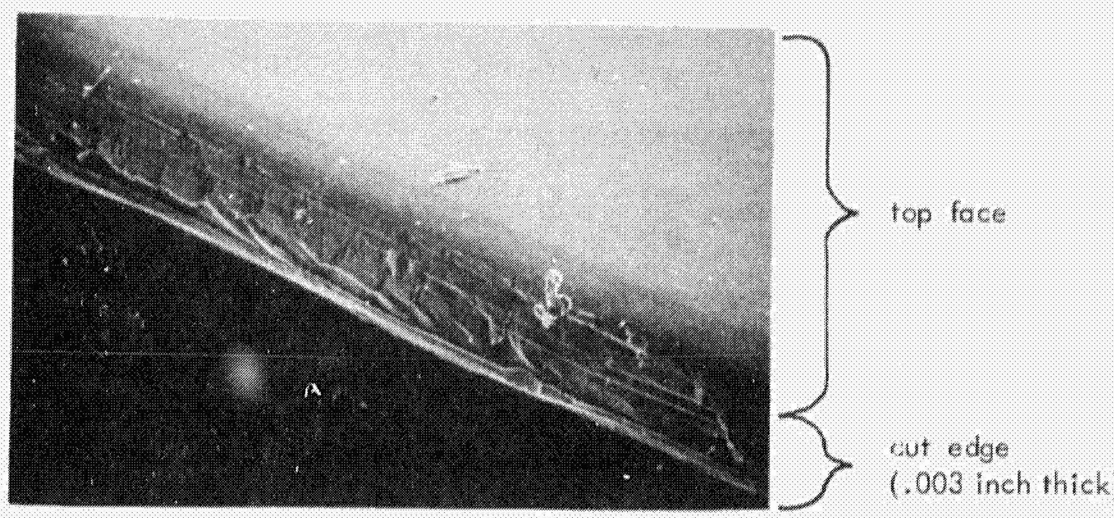

FIGURE 5 - Kapton H Cut Edge of Specimen (scanning electron microscope, 225X)

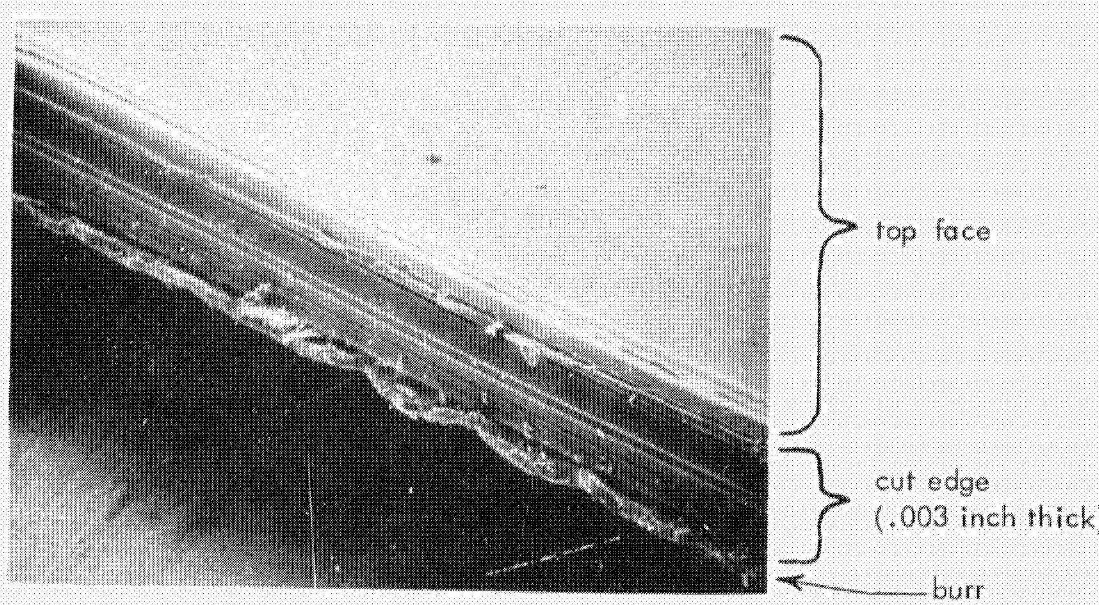

FIGURE 6 - Kapton F Cut Edge of Specimen (scanning electron microscope, 210X)

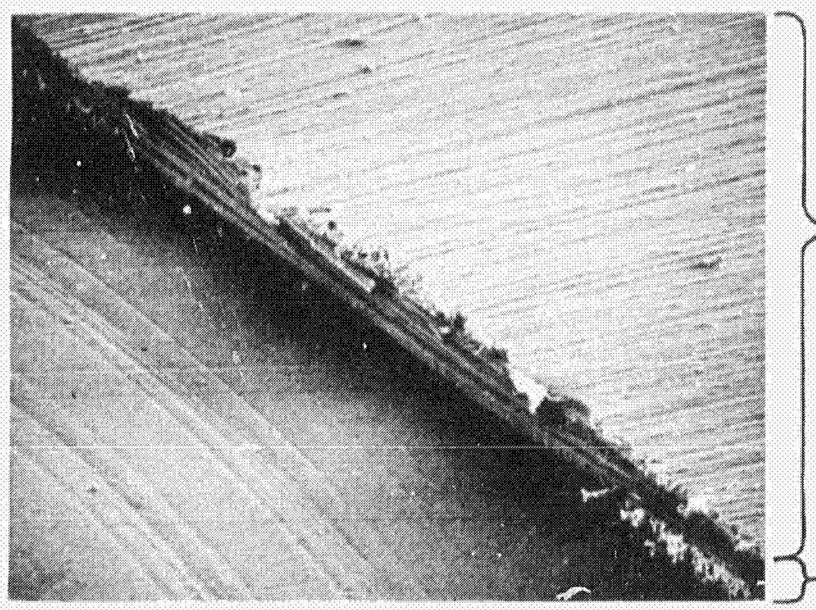

FIGURE 7 - PG-402 Cut Edge of Specimen (scanning electron microscope, 180X)

in which the film was produced and put on the roll. Transverse specimens were cut with their longitudinal axis perpendicular to the "machine", or roll, direction.

2.3 SPECIMEN GRIPS

Special grips were designed and made out of aluminum for applying a tensile load to the test specimens (see Figure 8). About two to three inches (depending upon material thickness) of material was wrapped around a 0.5 inch diameter spool which was inserted in a clamping device. To increase the coefficient of friction the spool surface was sand blasted. The clamps were locked in place by a thumb screw in the bottom grip and by an Allen cap screw in the top grip. The test specimen was in the line of applied force between the crosshead and the load cell in the top of the Instron Tensile Machine.

Each clamping device was fastened to a ball socket joint which provided an effective universal joint immediately adjacent to the specimen grips. From other studies in these laboratories[1] of the precision mechanical properties of materials it was shown that this method of specimen alignment minimizes any bending in the test specimen. A minimum load was always maintained to preserve the axiality of the specimen.

2.4 TEST PROCEDURES

The mechanical tests were made on an Instron Tensile Testing Machine. With the exception of those at room temperature, all tests were made in an environmental chamber bolted to the Instron cross head. Figure 9 shows the interior of the chamber which contained the specimen, grips, ball-socket joints, and extension rods. Behind the specimen is a white panel used to provide greater contrast for photography. A 100-watt bulb is hidden behind the upper extension rod. The fan (partially hidden) is used to circulate the atmosphere in the chamber. A thermocouple is shown attached to the bottom grip assembly.

All room temperature and high temperature tests were made in air. Initially, the -25°C

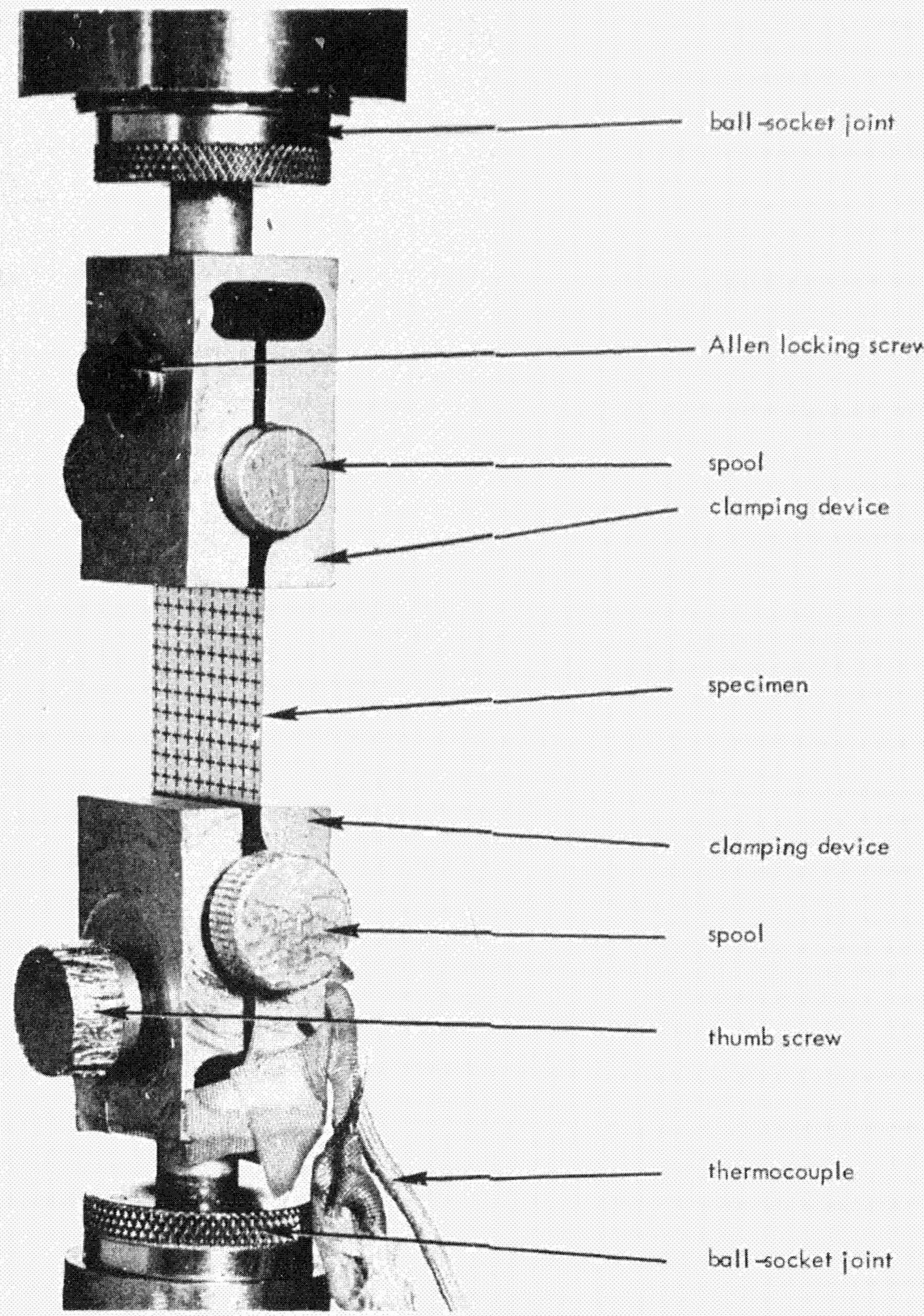

FIGURE 8 - One Inch Gauge Length Specimen Mounted in Grips

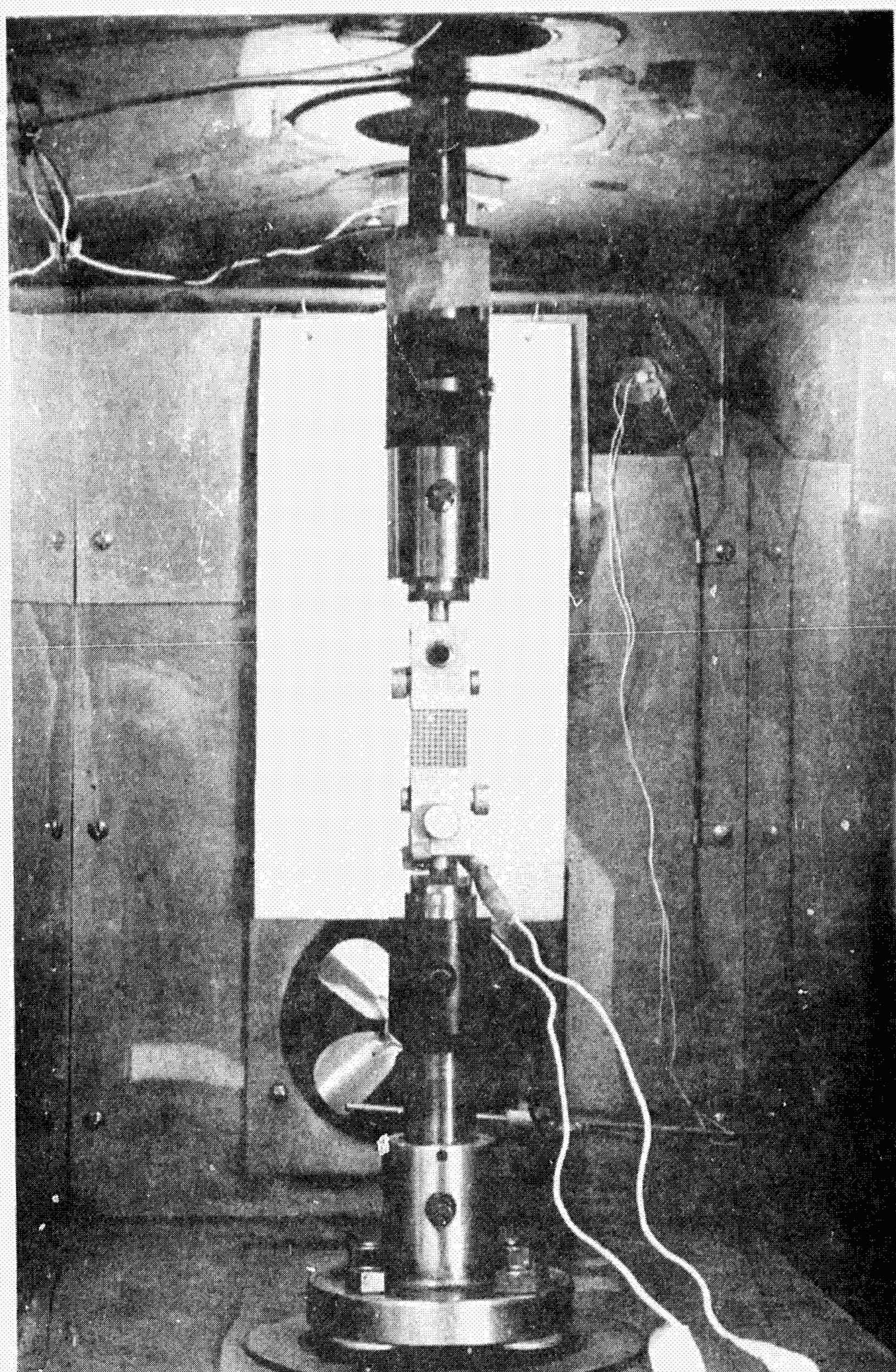

FIGURE 9 - One Inch Gauge Length Specimen Mounted in Testing Chamber

tests were made using compressed carbon dioxide as the refrigerant; however, crazing of the specimens (see Section 2.5) produced anomalous results. Thereafter, all low temperature tests were made using liquid nitrogen as the refrigerant. Specimen temperatures were continually monitored during the 15 minute soak time and during the course of the test.

A minimum of five replicate specimens were used for each set of experimental conditions for the major tests made with specimens cut in the "machine" and transverse directions. Specimens that failed in the grips giving spurious results were discarded. Occasional specimens that yielded anomalous results for no discernible reasons (no obvious flaws nor errors in testing procedures) were included in the results.

Three replicates were used for the Poisson ratio tests which were made at the six temperatures for all materials for "machine" direction specimens only. Each of these specimens had a four inch gauge length. Additional tests were made for the gauge length studies and strain rate effects.

Since the strip chart records all the deformation in the system between the load cell and the cross head it was necessary to correct for the "softness" of the machine. In the present context, softness of the machine is defined as contributions to the apparent strain (measured from cross head motion) arising from extension in the grips and from linkages from the grips to the load cell and cross head. This correction was obtained by comparing the recorded extension for 1 inch specimens with the actual extension determined from photographs of the fiducial patterns. These corrections were made from photographs taken at high strains (near fracture) where additional contributions from non-uniform extension near the grips could be expected to be negligible. The fracture strain was calculated by dividing the corrected extension by the original gauge length.

Modulus values were calculated from the slope of the load/extension recording made on the Instron chart. At these low strains in the elastic region, non-uniform extension in the vicinity of the grips plays a particularly important role. An additional correction for these elastic strains was therefore required. This was determined by comparing the recorded extension in the elastic range for 4 inch gauge length specimens with the extension determined from photographs taken using fiducial marked specimens. Thus when elastic strains were to be determined, the machine softness and non-uniform extension were first subtracted from the recorded extension. Straight line loading, or Hookean behavior, was limited (except for PG-402) to a very short part at the beginning of the curve. This slope was used to calculate Young's modulus.

The three percent offset yield stress was obtained by drawing a line parallel to the initial loading slope but displaced by an extension equivalent to a three percent strain. The yield stress was calculated from the load at which that line crossed the recorded trace. The fracture stress was calculated by dividing the load at fracture by the original cross sectional area.

The majority of the tests were made at a cross head speed of one inch per minute in compliance with ASTM D-882-67 (reapproved 1972) Method A, exercising the option of using a gauge length shorter than ten inches. Because of the great ductility of some of these materials and the limited amount of cross head travel in the environmental chamber it was necessary to use specimens having one inch gauge lengths. To demonstrate the validity of this approach, tests were made at room temperature for the four unreinforced materials using ASTM-acceptable gauge lengths (eight inches for Kapton H, Kapton F, and Tedlar; and four inches for Teflon). In addition, fracture stress and strain to failure data were obtained from the four inch gauge length Poisson ratio specimens. Results for the three different gauge lengths are shown in Table 1 (see Appendix A for specific values for the eight inch gauge length tests). There it can be seen that reducing the gauge length lowered the modulus values and raised the fracture strains (except for Teflon). These two observations are consistent; if the short gauge length specimens are characterized by greater strains (for a given applied stress) than for longer gauge length specimens then the

TABLE 1 - Effects of Gauge Length, 25°C, Machine Direction

Material	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Gauge Length (in.)
Kapton H	531,110	15,680	25,980	35	8
	426,820	14,150	28,940	58	4
	323,280	14,705	30,540	71	1
Kapton F	366,670	9,920	20,690	81	8
	282,850	9,030	19,240	73	4
	208,190	9,280	19,500	90	1
Teflon	68,410	1,950	3,580	351	4
	63,060	1,440	2,590	295	4
	48,710	1,770	2,650	317	1
Tedlar	251,900	5,520	10,940	150	8
	217,870	4,680	10,550	164	4
	170,780	5,100	11,600	224	1
PG-402	1,763,900	-	24,720	2	4
	826,000	26,780	26,780	3.4	1

respective modulus values should be different. According to Table 1 the shorter gauge length specimens had slightly lower values for the yield stress and the fracture stresses were not altered in any consistent fashion. The modulus values in Table 1 have been corrected for machine softness but have not been corrected for the non-uniform deformations occurring in the gauge length.

To determine whether the property variations listed in Table 1 were due to strain rate effects, tests were made at a much slower loading rate. All the tensile tests reported here were made with a cross head speed of one inch per minute and a gauge length of one inch to provide a strain rate of 1.0 per minute. When the gauge length was increased to eight inches the strain rate was reduced to 0.125 per minute. Three specimens of Kapton H having a one inch gauge length were tested with a strain rate of 0.2 per minute (0.2 inch per minute cross head speed). The average results were essentially the same as those shown in Table 1 for the Kapton H, one inch gauge length tests:

modulus	353,820 psi
3% yield stress	15,000 psi
fracture stress	30,330 psi
fracture strain	72%

Thus, strain rate was ruled out as the cause of the property variations shown in Table 1.

2.5 CRAZING

It has been shown by a number of workers[2-5] that at low temperatures approaching the boiling point of the cooling medium, polymers craze in the presence of nitrogen, argon or carbon dioxide. Conversely, in helium or under vacuum, low temperature crazing does not occur. The effects of crazing on the tensile strength is strain rate dependent. At low strain rates the tensile strength is reduced (compared to that in vacuum or helium) in the presence of nitrogen, carbon dioxide, or argon, whereas at higher strain rates the tensile strength in nitrogen approaches that in helium and may eventually exceed it.

Crazing is generally agreed to be nucleated by a cavitation process. Brown[6] has recently developed a theory which explains "(1) the critical temperature above which the phenomenon disappears, (2) the critical stress for nucleating a craze, (3) the effect of strain rate on the yield point and size of the crazes, (4) the drop in load during craze yielding, and (5) the increase in strength of the polymer in nitrogen or argon at high strain rates so that the ultimate strength may exceed that in helium or vacuum." The theory basically uses the fact that nitrogen and argon can significantly lower the surface-free energy of polymers (by up to 75 percent) when adsorbed at -193°C. By considering the stress concentration to produce a cavity, it was shown that the conditions for craze nucleation are favorable the greater the stress concentration at the surface and the greater the reduction in surface energy and yield stress by the nitrogen or argon. Subsequent to craze nucleation, craze yielding and experimentally observed strain rate effects were shown to be determined by diffusion of nitrogen or argon to the tip of the craze and the subsequent "wedging effect" of the gaseous molecules.

In the present work, the initial testing of Kapton H and Teflon at -25°C was carried out in carbon dioxide. Since crazing is usually observed at temperatures close to the boiling point of the cooling medium, it was felt that carbon dioxide could be used at -25°C without causing crazing. The results obtained are summarized in Table 2. The modulus, yield and fracture stress values measured on Kapton H were considerably lower than was expected at this temperature. The tests were therefore repeated using nitrogen as the cooling medium. These properties (presented in Section 3) are also included in Table 2 (see Appendix B for specific values). The values of the elastic modulus, yield stress, and fracture stress for Kapton H specimens tested in carbon dioxide were about 50 percent lower than those tested in nitrogen. The fracture strains observed were about 20 percent greater in carbon dioxide compared to nitrogen. The decrease in yield stress and fracture is typical of crazing, and the slight increase in strain to fracture is not unusual in crazed materials. The decrease in the tensile modulus is not often associated with crazing, since the latter phenomenon is usually associated with surface diffusion into the polymer.

TABLE 2 - Effects of Testing in Carbon Dioxide and in Nitrogen, 1.0 inch Gauge Length, Machine Direction, -25°C

Material	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Refrigerant
Teflon	59,600	3,260	6,400	505	CO_2
Teflon	129,290	2,750	4,530	303	N_2
Kapton H	194,890	8,100	16,150	66	CO_2
Kapton H	295,710	10,340	23,490	96	N_2

The large decrease in the tensile modulus indicates that gross diffusion of the carbon dioxide into the body of the Kapton H had probably occurred and since the specimen thickness was only 0.003 inch, this is not unreasonable. In summary, the behavior of Kapton H at -25°C in a carbon dioxide atmosphere shows typical crazing behavior. It occurs at an unusually high temperature and the reduction in the modulus values indicate possible diffusion into the bulk of the film.

The results obtained on Teflon (Table 2) are unusual in that the values of yield stress, fracture stress and the fraction strain all increased in carbon dioxide compared with nitrogen. The modulus, on the other hand, decreased which indicates diffusion into the bulk of the film; but the increase in the other three parameters is not consistent with crazing theory. Since the scope of the program did not allow for a study of these effects, testing in carbon dioxide was discontinued and all subsequent low temperature testing was performed in nitrogen. The effects of testing in carbon dioxide, as outlined above, should be further studied for a complete explanation of the observed phenomena.

2.6 POISSON RATIO

To calculate the Poisson ratio, a fiducial pattern was photographed during the stress-strain tests. The pattern (see Figure 10) consisted of an orthogonal array of "plus signs" on 0.1 inch centers. Each arm of the "plus signs" was 0.080 inch long. The center line of the first column of "plus signs" was 0.050 inch from the cut edge of the specimen; and the tenth and last column was also 0.050 inch from the other cut edge. The total array of "plus signs" was one inch wide by four inches long.

Several methods of applying the pattern were evaluated. A stainless steel mask, 0.002 inch thick, was used as a stencil for spraying. The resulting pattern was unsatisfactory because the paint was not uniformly deposited and did not replicate the "plus signs" faithfully. Brushing the ink through the stencil also resulted in a poor pattern; in addition, the life of the stencil was only a few transfers. Finally, a silk screen method was

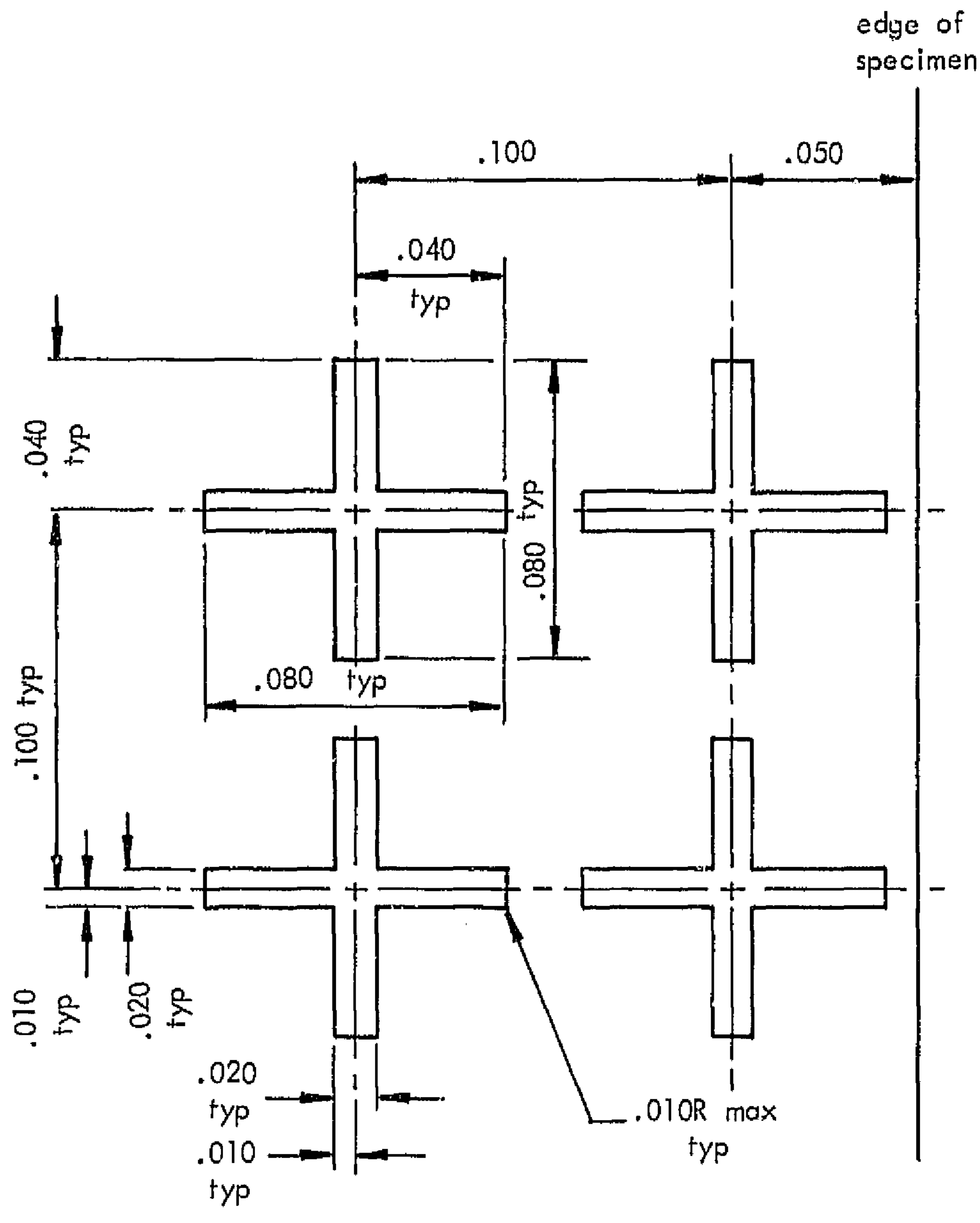

FIGURE 10 - Dimensions of "Plus Signs" Used as Fiducial Pattern

used successfully[7]. Two inks were evaluated (a black epoxy ink[8] and a black screening ink[9]) by applying them to samples of each material and then subjecting the patterns to large extensions and to temperature extremes of -195° and 200°C. The epoxy ink was so strong that the "plus signs" would not stretch with the specimen, rather, they popped off the specimen intact. The adhesion of the regular silk screening ink to the Kapton H, Tedlar and PG-402 was greater than the tensile fracture stress of the ink. Thus, as the specimen stretched, the ink cracked and faithfully followed the deformation of the test specimen. Temperature cycling had no deleterious effect on either of the inks. Adhesion of the inks to Teflon and Kapton F was very weak. Therefore, it was necessary to etch the surface of the Teflon to obtain adequate adhesion of the silk screen ink. Each Poisson ratio specimen of Teflon and Kapton F was etched for 60 seconds in Chemgrip Treating Agent[10]. This treatment did not reduce the thickness of the materials and did not alter the mechanical properties in any significant fashion (see Tables 3 and 4). Etching produced a light frosty appearance and reduced the transparency of the Teflon.

The fiducial array was photographed using a tripod-mounted 35mm Pentax camera fitted with a 100mm f/4 bellow Takumar lens. A shutter speed of 1/8 second was used throughout. Each time a photograph was taken, a signal"pip" was marked on the Instron load/time recording trace so that the deformation patterns could be coordinated with longitudinal strain or stress in the specimen. Kodak Plus X film was used with Acufine developer diluted one-to-three. All tests, except those at 25°C, were made inside an environmental chamber. Photographs were taken through the double glass window with a specimen-to-camera distance of 15 inches. Heater tapes had to be mounted on the inside glass window to prevent the build up of frost at -100°C and -195°C.

A base-line photograph was made for each specimen before applying the load. Two or three photographs were made prior to the estimated three percent yield stress and another three to four were made before fracture occurred. Typical photographs of fiducial patterns are shown in Figures 11 and 12 for the four inch gauge length specimens. Photographs of

TABLE 3 – Effects of Etching Kapton F, 1 inch Gauge Length, Machine Direction, Average Values (3 replicates)

Test Temp. (°C)	Fracture Stress (psi)	Fracture Strain (%)	Etched
200	12,440	139	yes
	12,910	161	no
100	16,280	109	yes
	15,830	100	no
25	21,080	124	yes
	19,500	90	no
-25	26,060	117	yes
	23,490	96	no
-100	27,220	66	yes
	36,120	91	no
-195	45,130	34	yes
	45,130	65	no

TABLE 4 - Effects of Etching Teflon, 1 inch Gauge Length, Machine Direction, Average Values (3 replicates)

Test Temp. (°C)	Fracture Stress (psi)	Fracture Strain (%)	Etched
200	430	327	yes
	510	378	no
100	1,350	463	yes
	1,790	399	no
25	3,490	556	yes
	2,650	317	no
-25	5,530	466	yes
	4,530	303	no
-100	9,480	128	yes
	9,760	132	no
-195	14,500	16	yes
	13,790	15	no

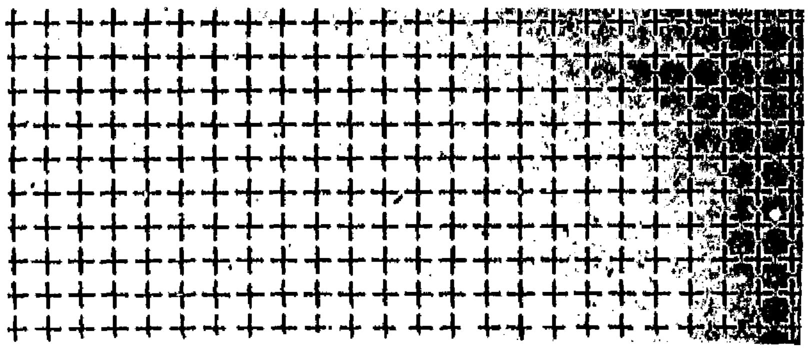

FIGURE 11a - Teflon, 25°C, Base-Line Fiducial Pattern Four Inch Gauge Length (no strain)

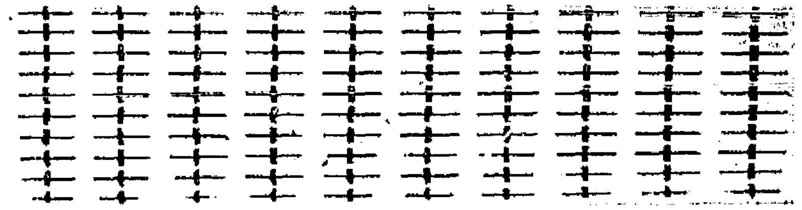

FIGURE 11b - Same Pattern After 145 Percent Strain

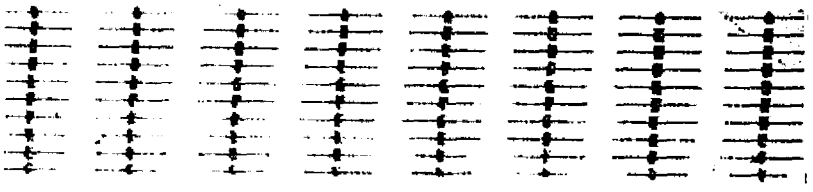

FIGURE 11c - Same Pattern After 192 Percent Strain

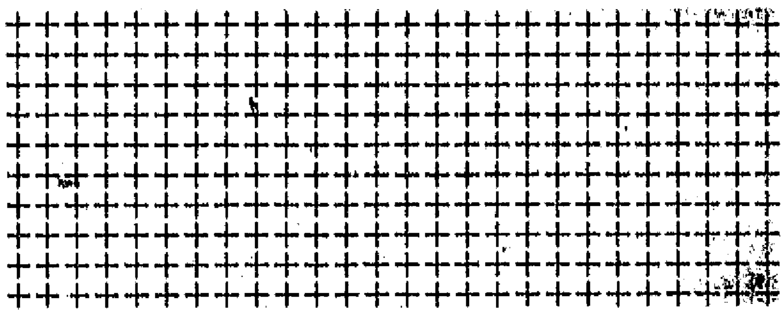

FIGURE 12a - Kapton H, 100°C, Base-Line Fiducial Pattern Four Inch Gauge Length (no strain)

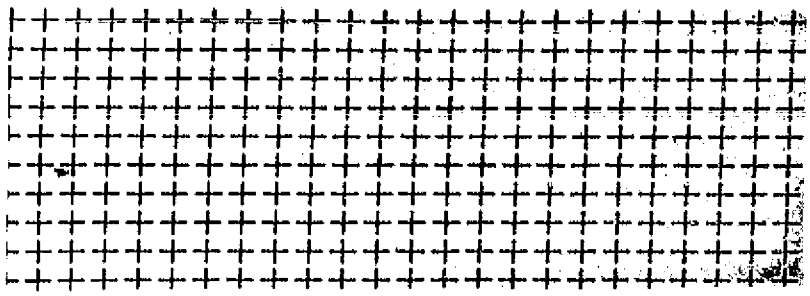

FIGURE 12b - Same Pattern After 14 Percent Strain

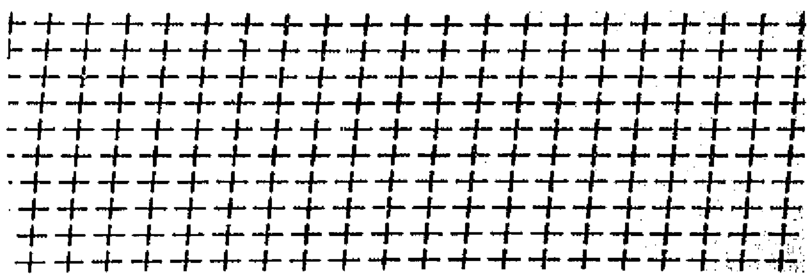

FIGURE 12c - Same Pattern After 32 Percent Strain the fiducial pattern distortion of a one inch gauge length specimen are shown in Figure 13. Each negative to be measured was cut from the strip and placed in a glass-sided frame for projection on a wall. On the specimen the distance between adjacent "plus signs" was 0.1 inch (2.54 mm), when projected that distance was usually about 40 mm. Greater projector-to-wall distances to increase the magnification did not improve the accuracy of the measurements because the increased fuzziness of the edge of the bright "plus signs" made it difficult to see the demarcation between light and dark. The entire four-inch array of "plus signs" was photographed; but only the central 6 x 6 section of "plus signs" was measured. Measurements were made of six "plus signs" in the "machine" and transverse directions. Three measurements were made, alternately, in each direction across the same set of fiducial marks and the individual results averaged. Differences in the measurements between the base-line negative and that of the first negative taken in the elastic region were used to calculate the longitudinal and transverse strains and, then, the Poisson ratio. The distances between adjacent plus signs, in each direction, were used as the respective gauge lengths. The unreinforced specimens were characterized by very low elastic limits so that the first strain measurements often included some plastic flow; however, these stress levels were well below the three percent yield stress. It was often difficult to align the specimens and apply the initial loads at high temperatures without imparting a permanent set to the specimen. This occurence was recognized when the base-line longitudinal and transverse gauge lengths were different.

From the longitudinal strain data and a knowledge of the stress level at which the photograph was made, it was possible to calculate Young's modulus. The ratio of transverse to longitudinal strains was also determined for stress levels greater than the three percent yield stress.

2.7 ERROR ANALYSIS

Errors in the reported stress values can arise from inaccuracies in the load weighing system and in the measurement of specimen dimensions. The load weighing system has an error

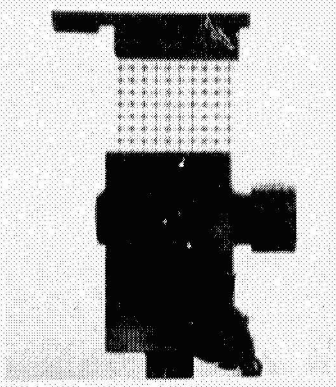

FIGURE 13a – Teflon, -100°C, Base-Line Fiducial Pattern One Inch Gauge Length (no strain)

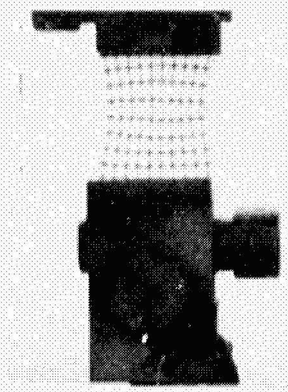

FIGURE 13b – Same Pattern After 43 Percent Strain

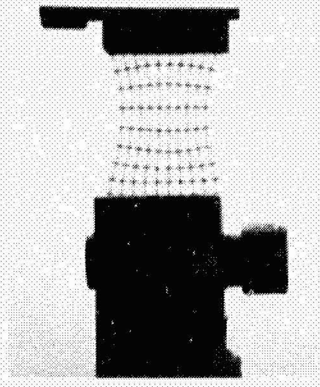

FIGURE 13c – Same Pattern After 65 Percent Strain

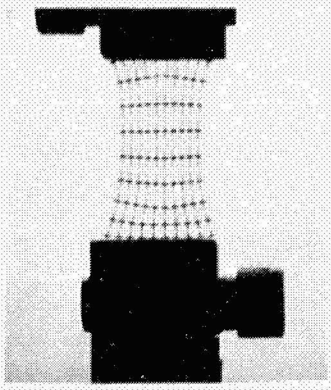

FIGURE 13d – Same Pattern After 89 Percent Strain

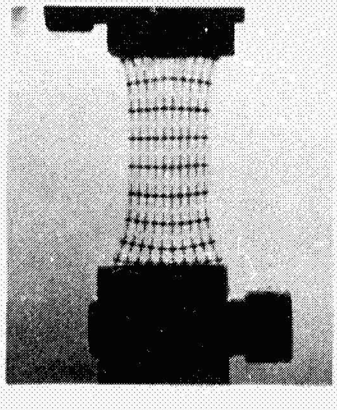

FIGURE 13e – Same Pattern After 99 Percent Strain

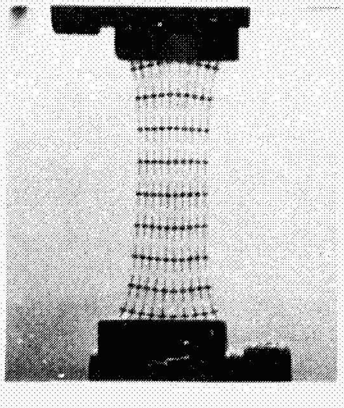

FIGURE 13f – Same Pattern After 125 Percent Strain of ± 1/2 percent of the full scale load and the error in measurement of the dimensions was about ±0.4 percent, resulting in an error in stress values of less than 1 percent.

The strain measurements were obtained from the total extension of the specimen as determined by the cross head movement. Errors in the strain measurements arise from errors in: measurement of the distance between grips (gauge length), the chart and cross head speeds, and the correction factor for "machine softness." Using the ASTM method for determining strain, the elongation of the polymer specimen is taken as the total separation of the grips during loading. In the present method the contributions from "machine softness" were subtracted from the recorded deformation. The remaining errors in the strain measurement therefore arise from errors in the initial gauge length measurements and in the chart and cross head speeds. The chart speed and cross head speeds are accurate to better than 0.1%. The error in the initial gauge length measurement is estimated at about ± 10 percent. Ignoring the small errors in the chart and cross head speeds, the error in the strain measurement is therefore about ± 10 percent.

The error in the Poisson Ratio measurements arise from measurements in the longitudinal and transverse strains. Considering the small changes in the spacing of the fiducial marks in the elastic region, even though the actual measurements at 16X were reproducible to within 0.25 mm in about 250, the small strains involved resulted in quite high errors in the Poisson Ratio. The probable fractional errors in the transverse and longitudinal strains are estimated at ±0.0014 and ± 0.0007, respectively, resulting in an error in the ratio of approximately ± 0.18.

The values of standard deviation (σ) for modulus, yield stress, fracture stress and strain are included in most of the Tables. These values were calculated in the usual manner from

$$\sigma = \sqrt{\frac{\Sigma x^2 - (\Sigma x)^2/n}{n - 1}}$$

where n = number of observations and x = measured variable. Also included in the Tables are values of the standard error of the mean (α) where

$$\alpha = \sigma / n^{1/2}.$$

3. RESULTS AND DISCUSSION

Summary values for the five materials tested at all temperatures using one inch gauge length specimens are shown in Tables 5 to 9. Specific data for each of the test specimens are given in Appendix C. In all of the Tables both "measured modulus" and "corrected modulus" values are given. The former value refers to values not corrected for non-uniform deformation effects. The latter values have been corrected for this effect. For design and analysis purposes the corrected modulus values should be used. In the discussion of the unreinforced polymers that follows, attention will be given to the "machine" direction specimens with the understanding that the results from the transverse tests are essentially the same.

3.1 STRESS-STRAIN CURVES

Typical stress-strain curves at each of the test temperatures are shown in Figures 14 to 18 for Kapton H, Kapton F, Teflon, Tedlar, and PG-402. All of these were "machine" direction specimens with one inch gauge lengths. The temperature dependence of the modulus, yield stress, and fracture stress can be seen; these properties decreased as the test temperature was raised. Generally speaking, the strain to fracture increased as the temperature was increased. There was a smooth transition from the elastic part of the stress-strain curve to the fully plastic region in Kapton H and Kapton F indicating that yielding was a gradual occurence. By contrast, Teflon specimens tested at 25°C and lower had distinct yield points that became more pronounced as the temperature was lowered; tests at -195°C were marked by a precipitious yield drop. There were no sharp yield points at 100° and 200°C in Teflon. Similar behavior was observed with Tedlar; however, at -195°C there was no yield drop because the specimen failed obruptly. The stress-strain curves for PG-402 were composed mainly of nearly straight lines. The load drops seen at -100° and -195°C were attributed to the breaking of individual fibers.

3.2 POISSON RATIO

There was a considerable amount of scatter in the measured Poisson ratio values. The

TABLE 5 - Summary Data, Kapton H, 0.003 inch Thick, 1.0 inch Gauge Length

Test Temp. °C	Measured Elastic Modulus psi (GN/m^2)	Corrected Elastic Modulus psi (GN/m^2)	3% Yield Stress psi (MN/m^2)	Fracture Stress psi (MN/m^2)	Fracture Strain %	Specimen Direction
200	175,050 (1.206)	176,840 (1.218)	11,750 (80.96)	18,285 (125.98)	83	machine
200	176,040 (1.213)	177,800 (1.225)	10,790 (74.34)	17,475 (120.40)	79	transverse
100	303,800 (2.093)	526,330 (3.621)	13,510 (93.77)	23,480 (161.78)	65	machine
100	262,820 (1.811)	454,680 (3.133)	11,530 (79.44)	22,330 (153.85)	74	transverse
25	323,280 (2.227)	520,500 (3.585)	14,705 (101.32)	30,540 (210.42)	71	machine
25	321,970 (2.218)	518,370 (3.571)	14,360 (98.94)	30,200 (208.09)	73	transverse
-25	439,040 (3.025)	654,170 (4.507)	17,170 (118.30)	34,410 (237.08)	54	machine
-25	436,710 (3.009)	650,700 (4.483)	16,920 (116.58)	33,720 (232.33)	58	transverse
-100	533,830 (3.678)	693,980 (4.781)	25,280 (174.18)	45,430 (313.01)	52	machine
-100	529,430 (3.648)	688,300 (4.742)	23,110 (159.23)	39,230 (270.29)	41	transverse
-195	630,730 (4.346)	756,900 (5.215)	33,970 (234.05)	50,870 (350.49)	36	machine
-195	604,980 (4.168)	735,300 (5.002)	32,800 (225.99)	46,030 (317.15)	31	transverse

TABLE 6 - Summary Data, Kapton F, 0.003 inch Thick, 1.0 inch Gauge Length

Test Temp. °C	Measured Elastic Modulus psi (GN/m^2)	Corrected Elastic Modulus psi (GN/m^2)	3% Yield Stress psi (MN/m^2)	Fracture Stress psi (MN/m^2)	Fracture Strain %	Specimen Direction
200	96,140 (0.662)	103,800 (0.715)	7,060 (48.64)	12,910 (88.95)	161	machine
200	95,500 (0.658)	103,100 (0.711)	7,300 (50.30)	12,700 (87.50)	103	transverse
100	196,530 (1.354)	261,400 (1.801)	8,080 (55.67)	15,830 (109.07)	100	machine
100	206,210 (1.421)	274,300 (1.890)	8,320 (57.32)	18,100 (124.71)	97	transverse
25	208,190 (1.434)	314,400 (2.165)	9,280 (63.94)	19,500 (134.36)	90	machine
25	210,440 (1.450)	317,800 (2.190)	9,150 (63.04)	20,315 (139.97)	72	transverse
-25	295,710 (2.037)	422,900 (2.913)	10,340 (71.24)	23,490 (161.85)	96	machine
-25	304,150 (2.096)	435,000 (2.997)	14,120 (97.29)	26,870 (185.13)	77	transverse
-100	451,380 (3.110)	627,100 (4.323)	18,750 (129,19)	36,120 (248.87)	91	machine
-100	447,960 (3.086)	622,700 (4.290)	17,970 (123.81)	34,170 (235.43)	70	transverse
-195	693,440 (4.778)	1,171,900 (8.075)	26,230 (180.72)	45,130 (310.95)	65	machine
-195	668,090 (4.603)	1,128,800 (7.779)	26,430 (182.10)	47,600 (327.96)	62	transverse

TABLE 7 - Summary Data, Teflon, 0.005 inch Thick, 1.0 inch Gauge Length

Test Temp. °C	Measured Elastic Modulus psi (GN/m²)	Corrected Elastic Modulus psi (GN/m²)	3% Yield Stress psi (MN/m²)	Fracture Stress psi (MN/m²)	Fracture Strain %	Specimen Direction
200	2,425 (16.71)	2,790 (19.22)	175 (1.21)	505 (3.48)	378	machine
200	2,290 (15.78)	2,630 (18.15)	160 (1.10)	280 (1.93)	298	transverse
100	8,075 (55.64)	14,050 (96.81)	515 (3.55)	1,790 (12.33)	399	machine
100	7,410 (51.05)	12,900 (88.83)	380 (2.62)	1,210 (8.34)	324	transverse
25	48,710 (335.51)	70,600 (486.49)	1,770 (12.20)	2,650 (18.26)	317	machine
25	50,290 (346.50)	72,900 (502.43)	1,670 (11.51)	2,520 (17.36)	306	transverse
-25	129,290 (890.81)	150,000 (1042.25)	2,750 (18.95)	4,530 (31.21)	303	machine
-25	133,210 (917.82)	155,900 (1073.85)	2,690 (18.53)	4,750 (32.73)	314	transverse
-100	287,780 (1982.8)	348,600 (2478.5)	10,080 (69.45)	9,760 (67.25)	132	machine
-100	286,500 (1974.0)	358,100 (2467.5)	9,880 (68.07)	9,620 (66.28)	81	transverse
-195	477,570 (3290.5)	969,500 (6679.7)	14,250 (98.18)	13,790 (95.01)	15	machine
-195	515,780 (3553.7)	1,047,000 (7214.0)	16,680 (114.93)	15,940 (109.83)	15	transverse

TABLE 8 - Summary Data, Tedlar, 0.002 inch Thick, 1.0 inch Gauge Length

Test Temp. °C	Measured Elastic Modulus psi (GN/m^2)	Corrected Elastic Modulus psi (GN/m^2)	3% Yield Stress psi (MN/m^2)	Fracture Stress psi (MN/m^2)	Fracture Strain %	Specimen Direction
150	4,450 (30.66)	5,070 (34.95)	445 (3.07)	3,030 (20.88)	238	machine
150	5,740 (39.55)	6,540 (45.09)	412 (2.84)	2,705 (18.64)	220	transverse
100	16,575 (114.20)	17,570 (121.05)	1,120 (7.72)	5,620 (38.72)	259	machine
100	15,090 (103.97)	16,000 (110.21)	900 (6.20)	6,980 (48.09)	224	transverse
25	170,780 (1176.7)	348,300 (2388.7)	5,100 (35.14)	11,600 (79.92)	224	machine
25	167,270 (1152.5)	339,560 (2339.6)	4,780 (32.93)	10,920 (75.24)	161	transverse
-25	265,130 (1826.7)	601,530 (4146.6)	10,960 (75.51)	16,020 (110.38)	129	machine
-25	275,760 (1900.0)	625,980 (4313.0)	10,180 (70.14)	18,650 (128.50)	102	transverse
-100	565,430 (3895.8)	1,174,980 (8103.3)	21,590 (148.76)	24,160 (166.46)	38	machine
-100	595,450 (4102.7)	1,237,340 (8533.6)	22,480 (154.89)	28,650 (197.40)	47	transverse
-195	714,430 (4922.4)	1,364,550 (9401.8)	30,940 (213.18)	35,600 (245.28)	7.6	machine
-195	698,280 (4811.1)	1,333,700 (9189.2)	21,900 (150.89)	27,900 (192.23)	7.8	transverse

TABLE 9 - Summary Data, PG-402, 0.0025 Inch Thick, 1.0 Inch Gauge Length

Test Temp. °C	Measured Elastic Modulus psi (GN/m^2)	Corrected Elastic Modulus psi (GN/m^2)	3% Yield Stress psi (MN/m^2)	Fracture Stress psi (MN/m^2)	Fracture Strain %	Specimen Direction
200	787,800 (5.428)	2,111,300 (14.547)	23,290 (160.47)	23,290 (160.47)	3.2	machine
200	548,870 (3.782)	1,471,000 (10.136)	15,030 (103.56)	15,030 (103.56)	3.4	transverse
100	846,380 (5.832)	2,209,000 (15.222)	21,930 (151.10)	21,930 (151.10)	2.7	machine
100	630,220 (4.342)	1,644,900 (11.333)	11,700 (80.61)	11,700 (80.61)	1.7	transverse
25	826,000 (5.691)	2,866,300 (19.748)	26,780 (184.51)	26,780 (184.51)	3.4	machine
25	629,110 (4.335)	2,183,000 (15.042)	17,080 (117.68)	17,080 (117.68)	2.7	transverse
-25	858,640 (5.916)	2,902,200 (19.996)	24,870 (171.35)	29,290 (201.81)	3.7	machine
-25	634,580 (4.372)	2,144,900 (14.777)	15,800 (108.86)	19,030 (131.12)	3.8	transverse
-100	902,710 (6.220)	3,493,500 (24.071)	28,930 (199.33)	45,390 (312.74)	6.7	machine
-100	744,360 (5.129)	2,880,700 (19.849)	15,130 (104.25)	33,070 (227.85)	6.7	transverse
-195	1,078,570 (7.431)	3,343,600 (23.036)	26,330 (181.41)	55,330 (381.22)	7.6	machine
-195	786,480 (5.419)	2,438,100 (16.799)	19,130 (131.81)	35,110 (241.91)	6.3	transverse

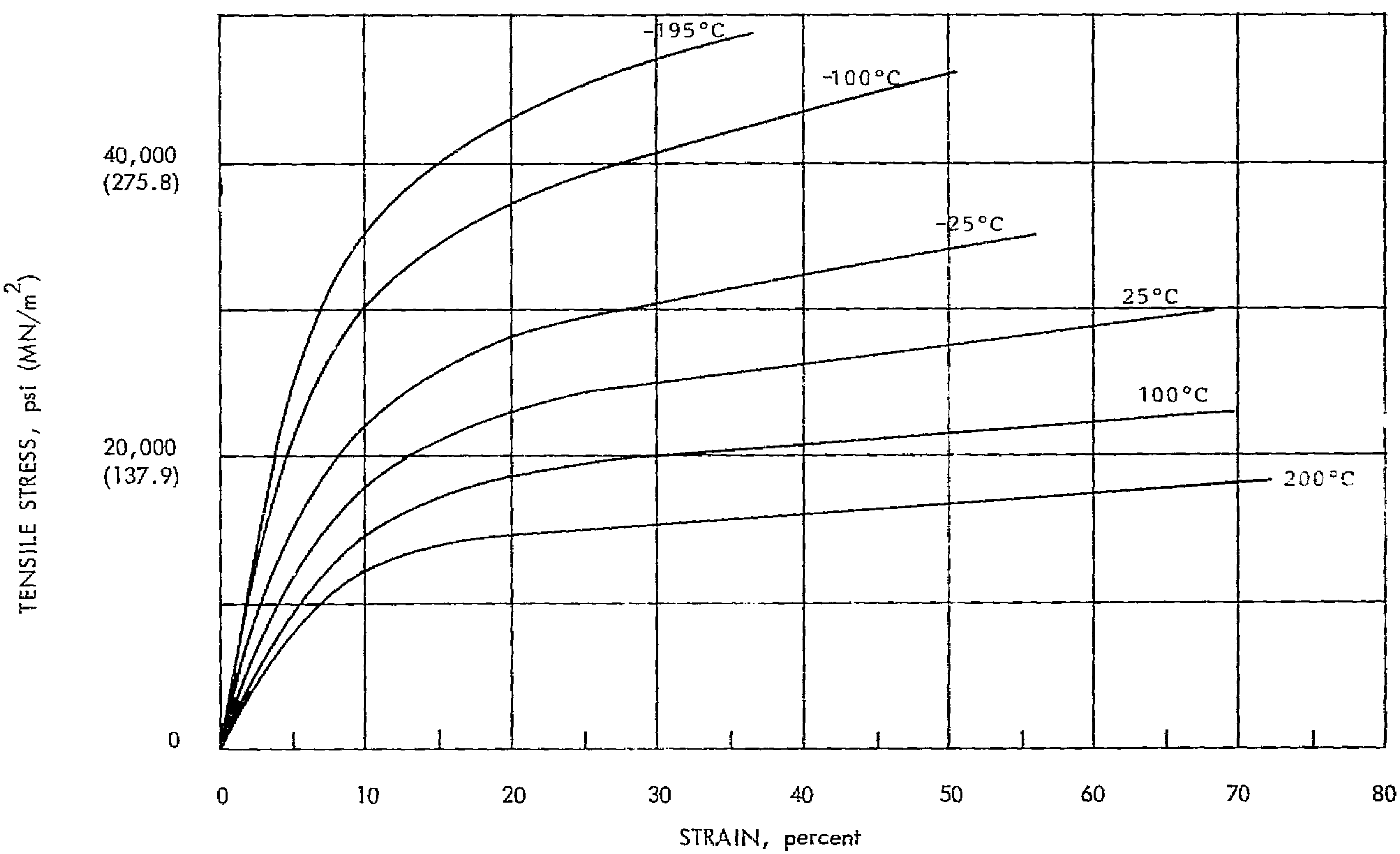

FIGURE 14 – Typical Tensile Stress Strain Curves for Kapton H (0.003 inch thick)

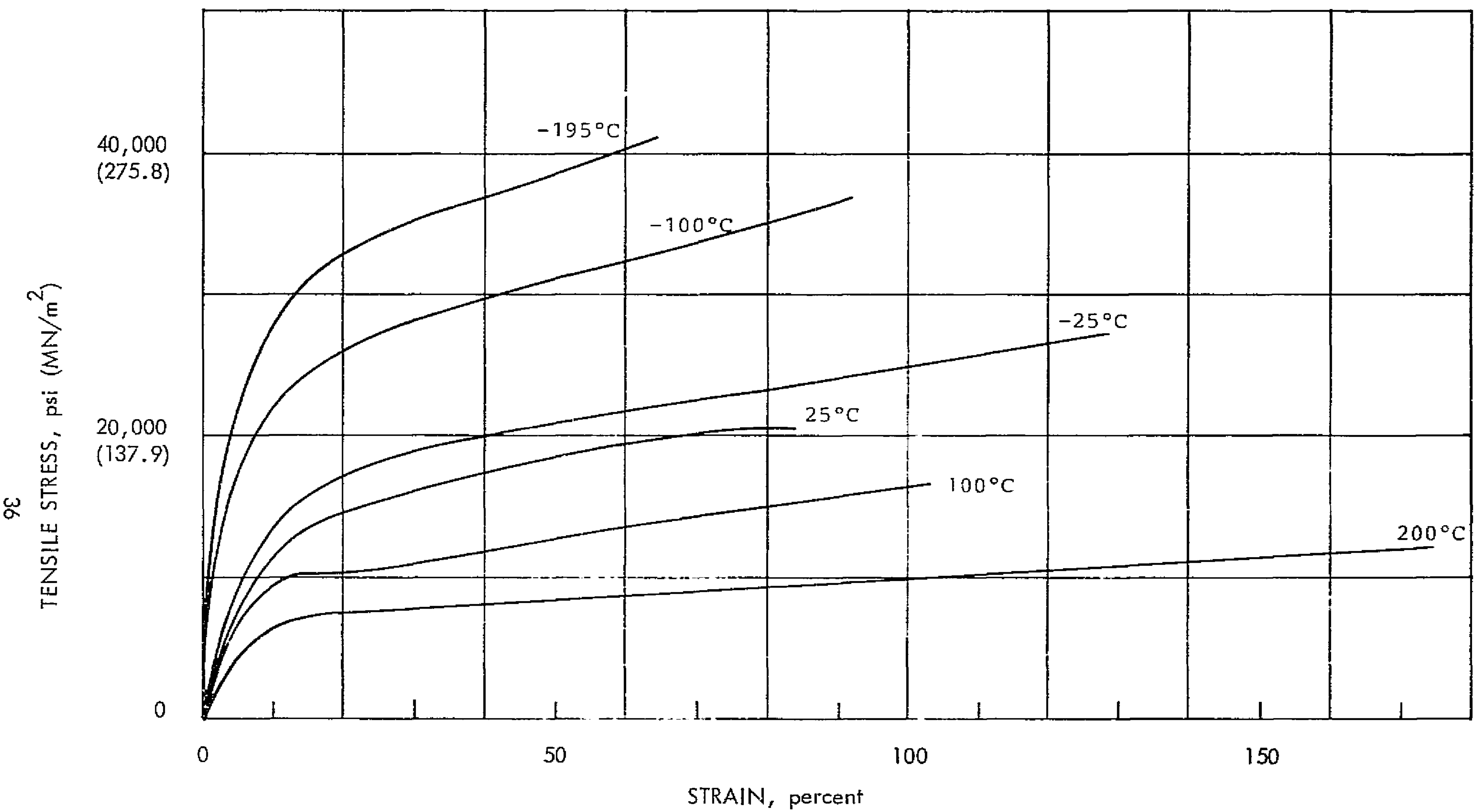

FIGURE 15 - Typical Tensile Stress Strain Curves for Kapton F (0.003 inch thick)

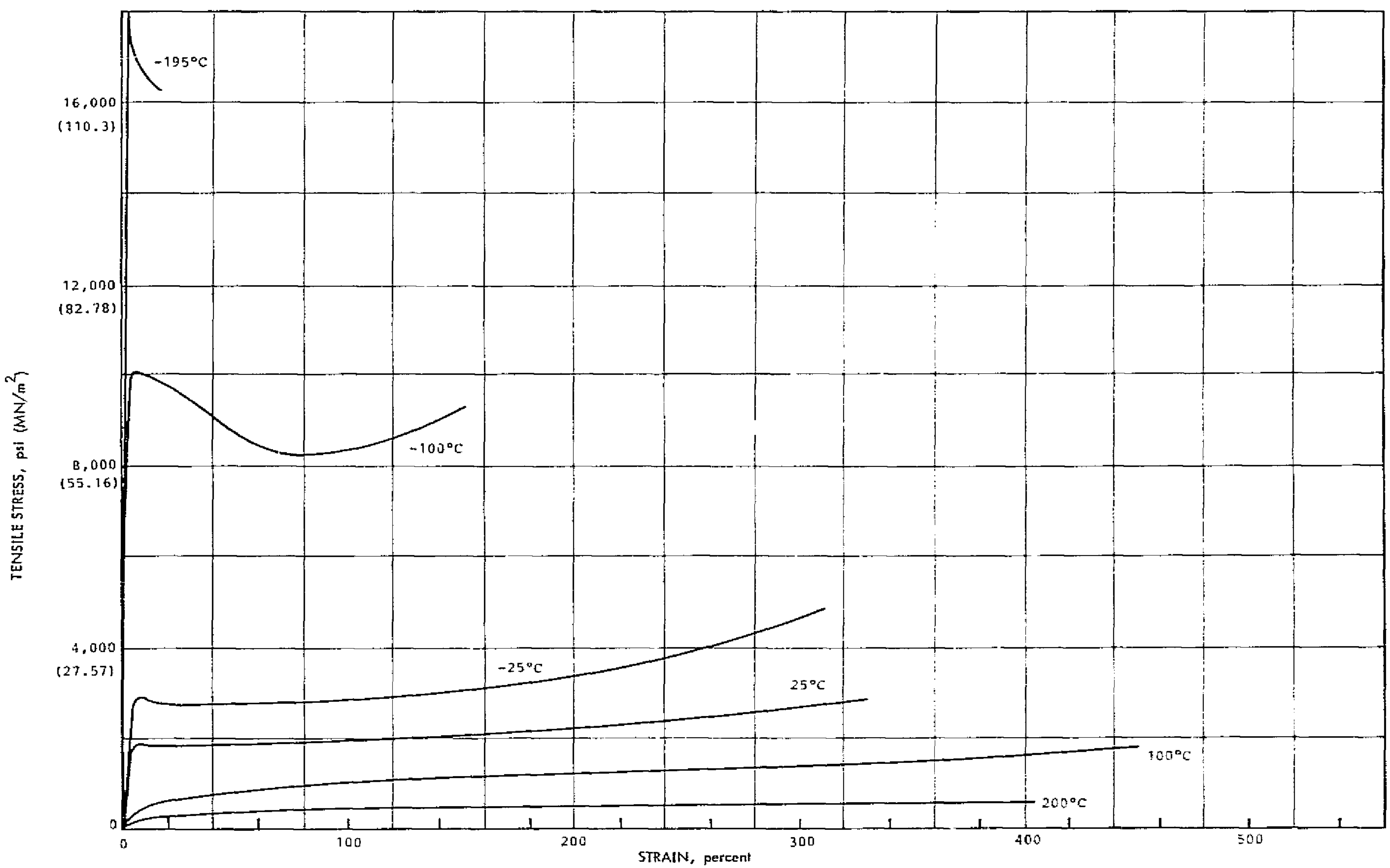

FIGURE 16 - Typical Tensile Stress Strain Curves for Teflon (0.005 inch thick)

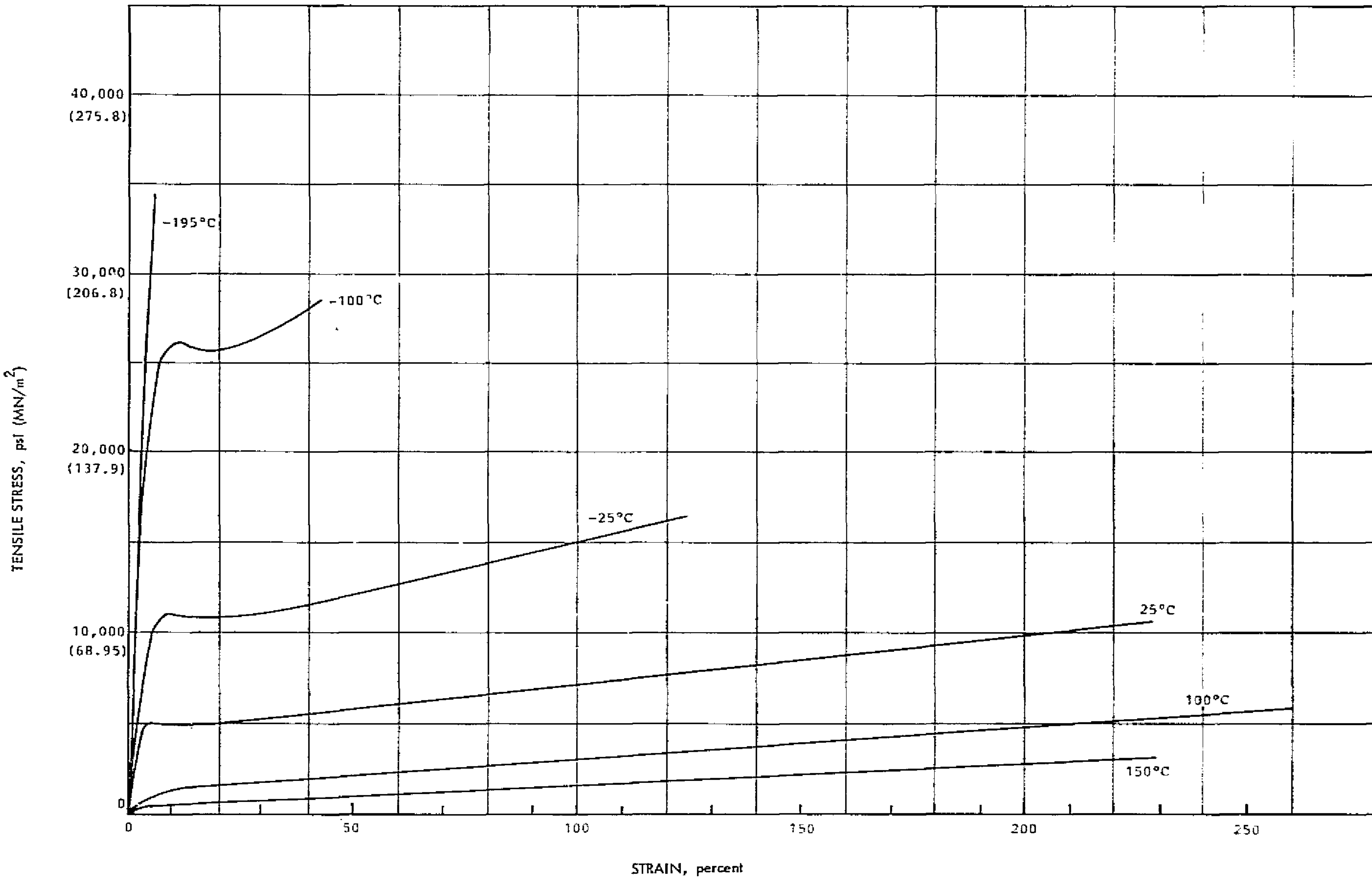

FIGURE 17 - Typical Tensile Stress Strain Curves for Tedlar (0.002 inch thick)

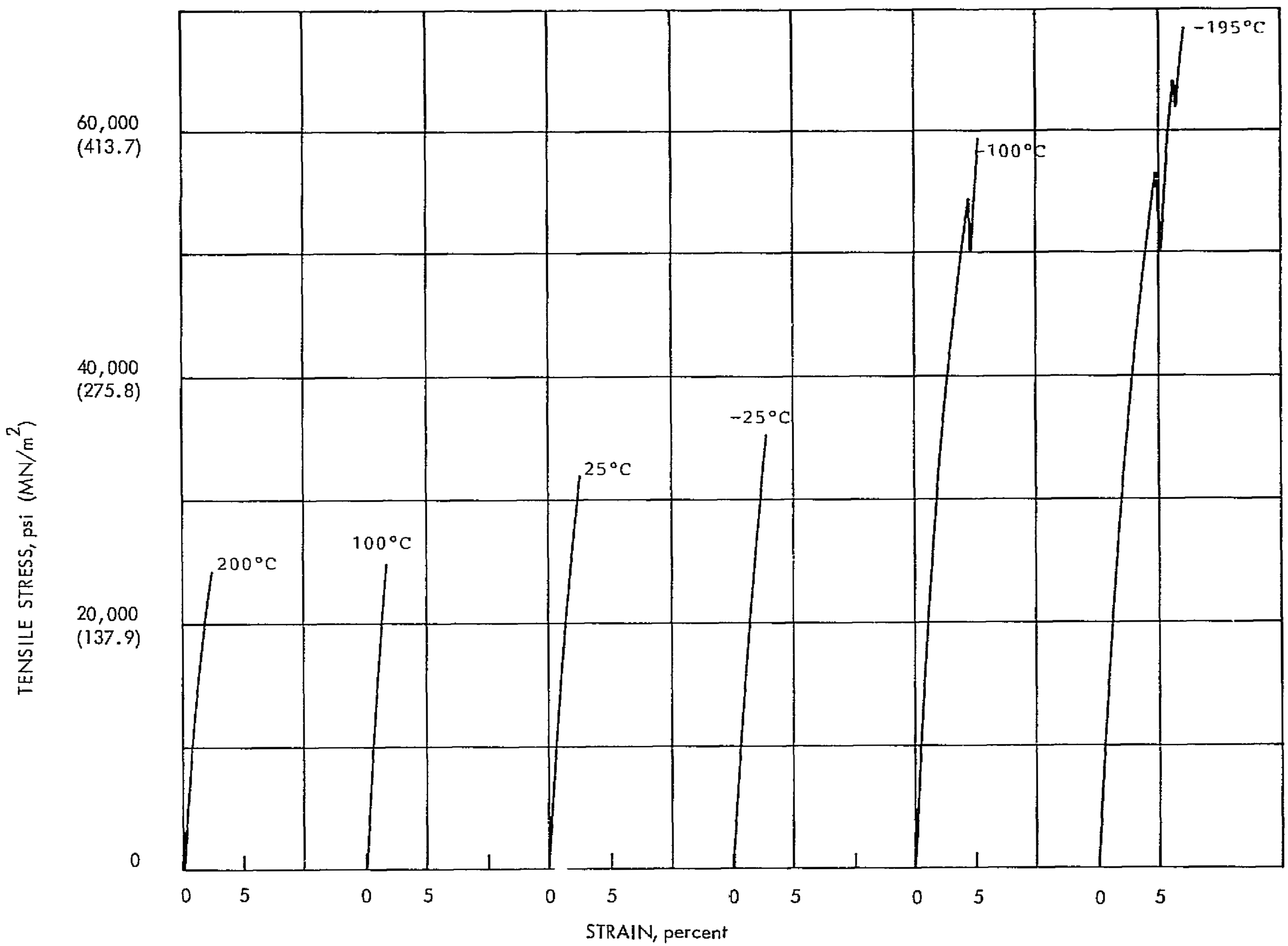

FIGURE 18 – Typical Tensile Stress Strain Curves for PG-402 Fiberglass Laminate (0.0025 inch thick)

experimental error was large because the strains to be measured were so very small. To further complicate interpretation of the results was the limited observation that the Poisson ratio changes rapidly in the initial part of the stress-strain curve. It appeared that, particularly at the higher temperatures, the ratio was close to the theoretical 0.5 when the specimen was still deforming in purely elastic fashion. At stresses close to the three percent offset yield stress, the Poisson ratio appeared to decrease. This phenomenon was not investigated in detail because it was revealed too late in the program to increase the number of pre-yield photographs that were made. When the program was started it was decided to take only two to three photographs in the pre-yield region, which was insufficient for a thorough study of the phenomenon. It should also be noted that measurements made at the lowest stress levels also have the greatest experimental error.

Even with these limitations it is possible to draw conclusions about the Poisson ratios of the five materials. Figure 19 shows the variation in the average Poisson ratios as the test temperature was changed. These values were calculated from photographs taken at the lowest stress levels. In addition, Table 10 lists average values for the Poisson ratio taken from the fiducial pattern photographs. Specific values for individual specimens are presented in Appendix D. At the highest temperatures, 100° and $200^{\circ}C$, Poisson ratio values for all the materials fell between 0.39 and 0.51. At $25^{\circ}C$ the spread in values became greater, and they began to diminish as the temperature was further lowered. At $-195^{\circ}C$ all the Poisson ratio values were between 0.26 and 0.42. Of all the materials, only Kapton H showed a smooth progression in values as the test temperature changed from -195° to $200^{\circ}C$.

3.3 RATIO OF TRANSVERSE TO "MACHINE" DIRECTION STRAINS

From photographs of the fiducial patterns taken after the three percent offset yield stress was reached, calculations were made of the transverse and "machine" direction strains. The ratios of these values for various fractions of the fracture strain are presented in detail in Appendix E. Generally speaking, for Kapton H and Kapton F, the measurements made in

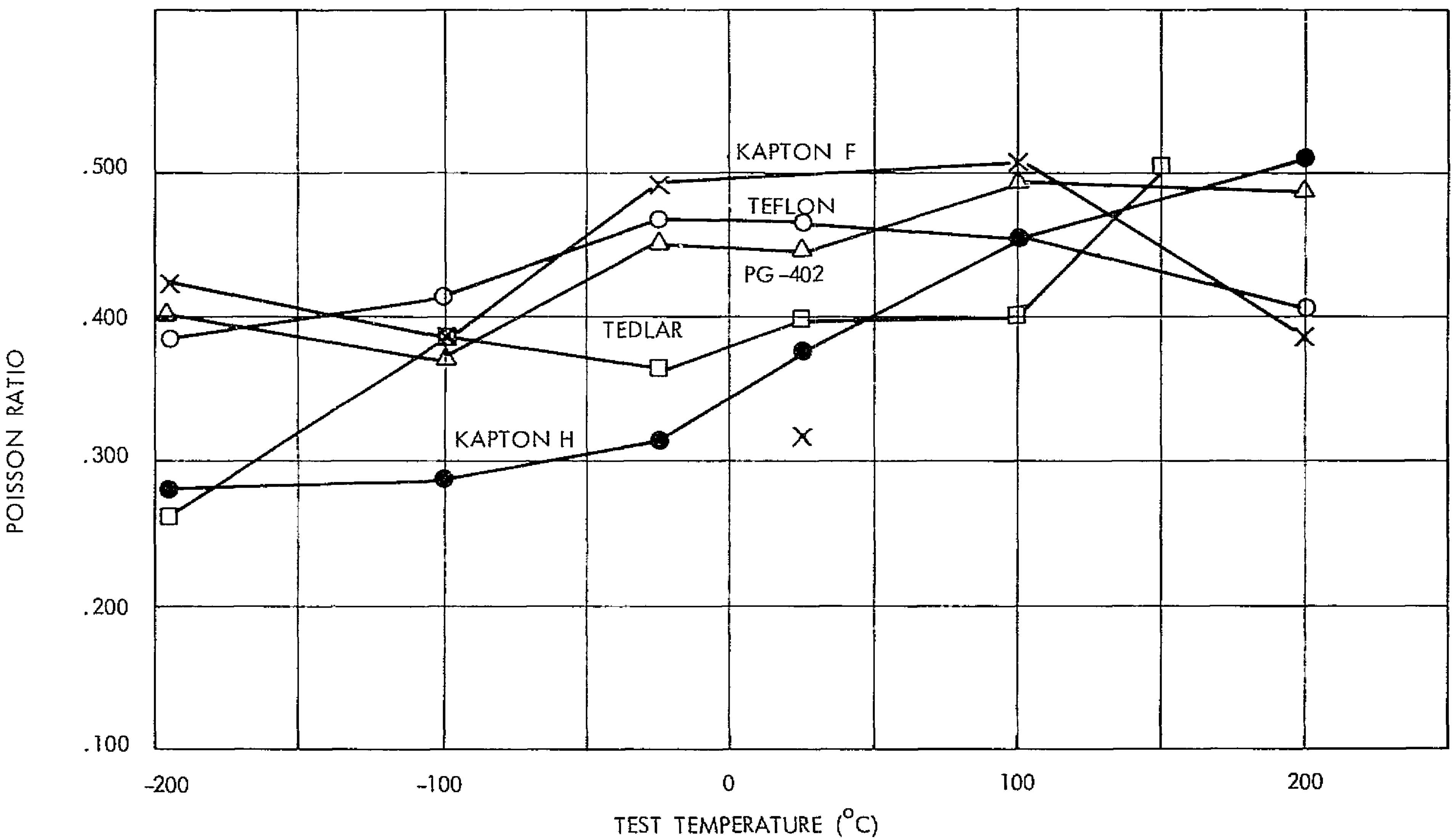

FIGURE 19 - Poisson Ratio vs. Temperature for Five Materials

TABLE 10 - Effect of Temperature on Average Poisson Ratio

Material	Test Temp. (°C)	Poisson Ratio
Kapton H	200	0.50
	100	0.45
	25	0.38
	- 25	0.32
	-100	0.29
	-195	0.28
Teflon	200	0.41
	100	0.46
	25	0.46
	- 25	0.47
	-100	0.41
	-195	0.39
Kapton F	200	0.39
	100	0.51
	25	0.32
	- 25	0.49
	-100	0.39
	-195	0.42
Tedlar	150	0.51
	100	0.40
	25	0.40
	- 25	0.36
	-100	0.39
	-195	0.26
PG-402	200	0.49
	100	0.50
	25	0.45
	- 25	0.45
	-100	0.38
	-200	0.41

the yielding region of the stress-strain curve where plastic flow was becoming dominant showed Poisson ratio values approaching 0.3. With Teflon and Tedlar comparable values were about 0.5. As the strain increased there was a tendency for the Poisson ratio values to increase in Kapton H, and Kapton F, and to decrease in Teflon and Tedlar. Teflon plastic flows had Poisson ratios of about 0.5 just beyond the three percent offset yield stress and decreased to lower values as the fracture point was approached.

3.4 ELASTIC MODULUS

Summary curves for the temperature dependence of the elastic modulus of one inch gauge length specimens are shown in Figures 20 and 21. Tedlar and Teflon had the strongest temperature dependence, while PG-402 had the least. Kapton H data show a break at about 25°C; above room temperature the effect of temperature is greater than below. A similar break was seen in the Kapton F results. This would be expected since two thirds of Kapton F is Kapton H material. At 150° and 200°C the modulus values for Tedlar and Teflon, respectively, are very small. Transverse direction properties in PG-402 were about 75 percent of those in the "machine" direction.

Using measured values of the properties of Kapton H and Teflon, the rule of mixtures was used to predict the properties of the laminate Kapton F as follows:

$$\text{composite property} = .67 \times \text{Kapton H property} + .33 \times \text{Teflon property}.$$

Results for four of the mechanical properties at three temperatures are shown in Table 11. There was good agreement for the modulus values.

3.5 THREE PERCENT OFFSET YIELD STRESS

Figures 22 and 23 are summary curves of the three percent yield stress as a function of test temperature. All of the materials showed a decrease in yield stress as the temperature was raised. The reinforced polyimide, PG-402, had only a modest temperature dependence over the test temperature range. Kapton H and Kapton F showed a break at -25°C similar

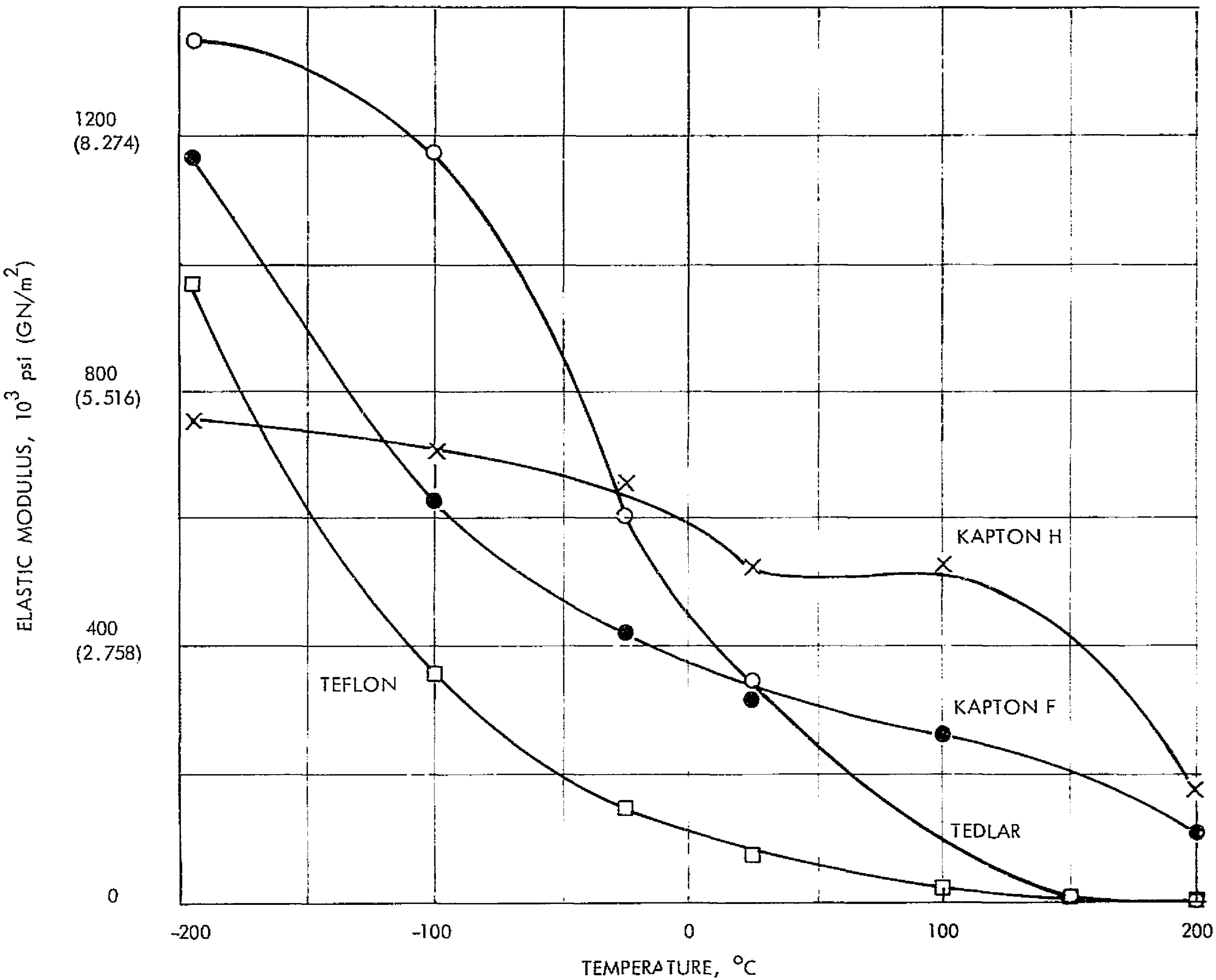

FIGURE 20 - Corrected Elastic Modulus vs Test Temperature for Tensile Loading (materials as marked)

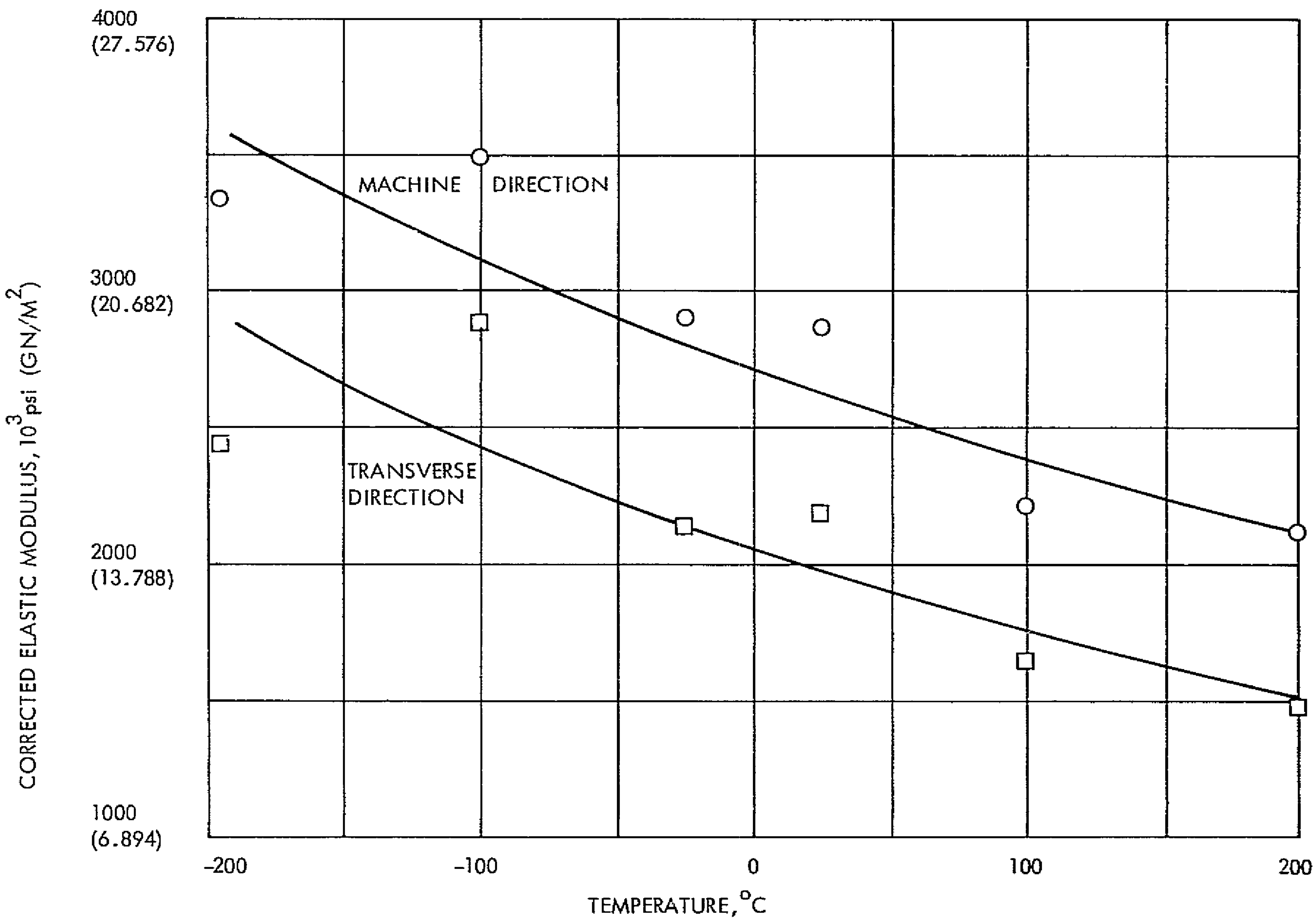

FIGURE 21 - Corrected Elastic Modulus vs Test Temperature for Tensile Loading of PG-402 Fiberglass Laminate (specimen direction as marked)

TABLE 11 - Rule of Mixtures Applied to Kapton F Properties

Property	Test Temp. (°C)	Calculated Value	Measured Value	Difference Between Calculated and Measured Values (%)
Measured Elastic	200	118,808	96,140	19
Modulus	25	232,337	208,190	10
(psi)	-195	581,190	693,440	16
Yield Stress	200	7,938	7,060	11
(psi)	25	10,390	9,280	11
	-195	27,370	26,230	4
Fracture Stress	200	12,368	12,910	4
(psi)	25	21,233	19,500	4
	-195	38,397	45,130	18
Fracture Strain	200	181	161	11
(%)	25	153	90	41
	-195	22	65	195

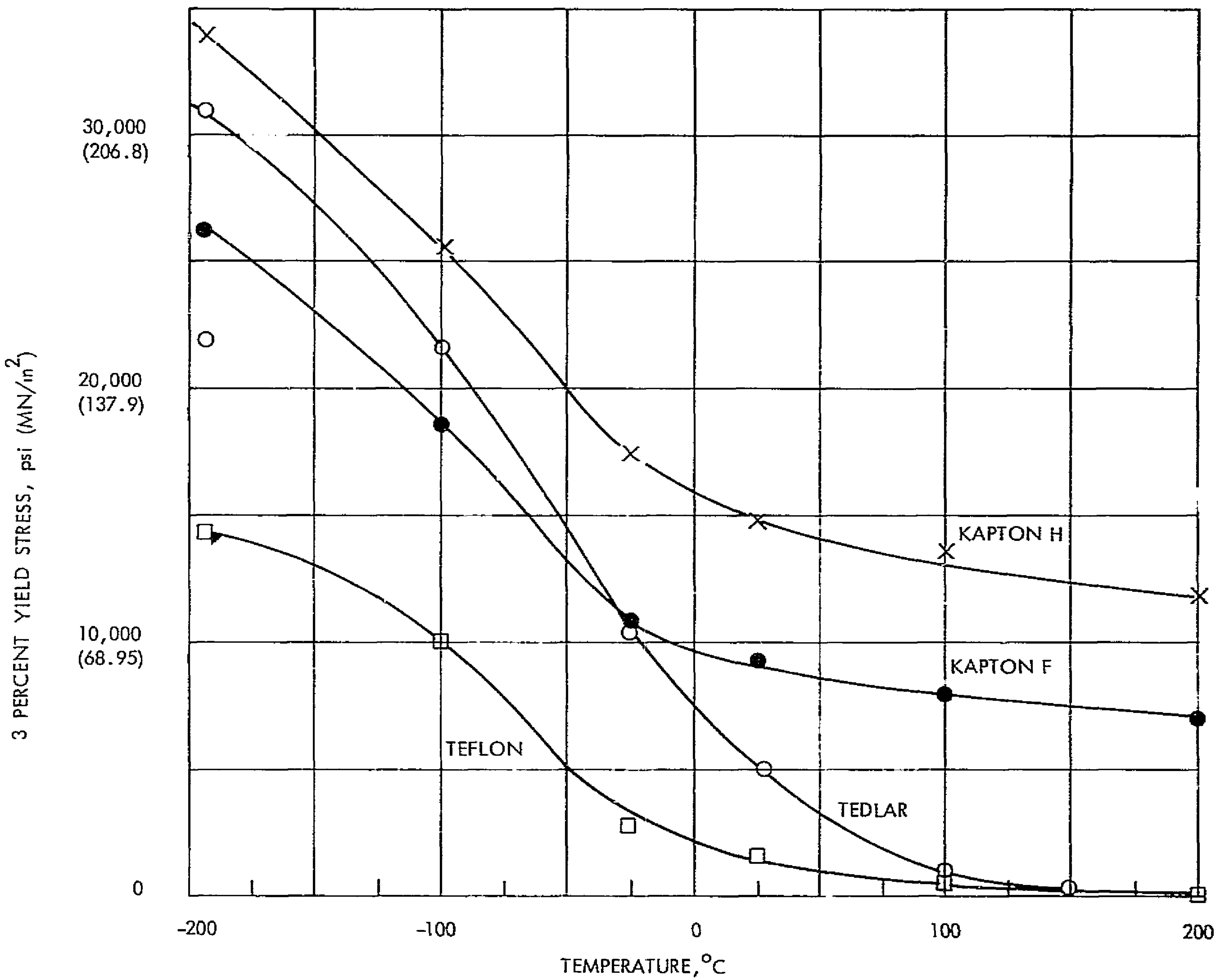

FIGURE 22 - 3 Percent Yield Stress vs Test Temperature for Tensile Loading (materials as marked)

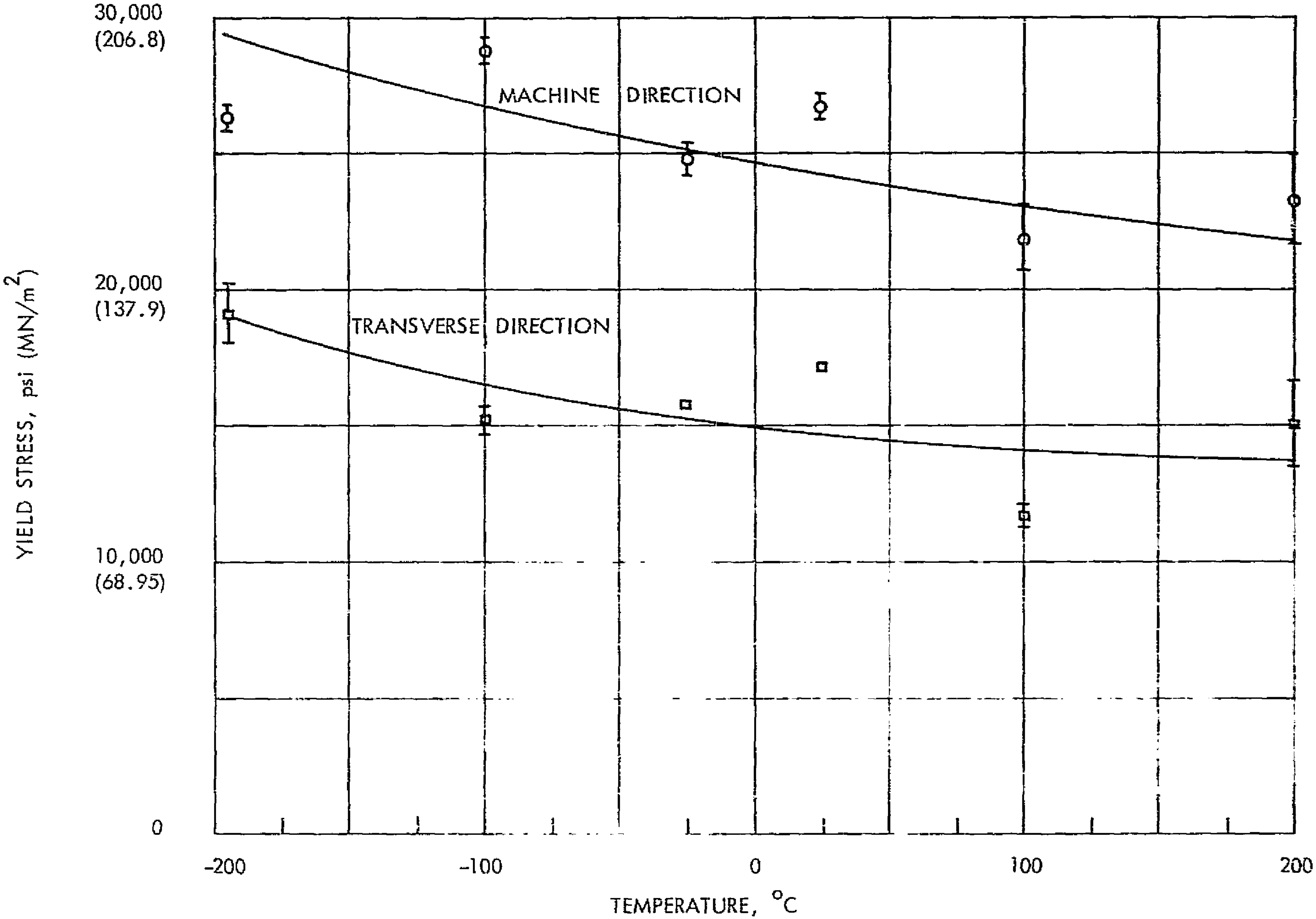

FIGURE 23 - Yield Stress vs Test Temperature for Tensile Loading of PG-402 Fiberglass Laminate (specimen direction as marked)

to that seen at 25°C in the modulus values for those two materials. The rule of mixtures held up well for Kapton F with regard to the yield stresses.

Tests made at 25°C, and above, with PG-402 showed no yield stress; the specimens failed in the elastic region. The first deviation from straight line loading occurred at -25°C at an average value of 24,870 psi while fracture took place at an average stress of 29,290 psi. When the test temperature was lowered even furthe: the yield stress increased by only a few thousand psi while the fracture stress nearly doubled. Thus, much more plastic flow was observed at the lower temperatures as compared to the high temperatures.

3.6 FRACTURE STRESS

The change in fracture stress with test temperature is shown in Figures 24 and 25. All of the materials showed a decrease as the test temperature was raised. Teflon had the lowest strength of all the materials. Results for Kapton H and PG-402, the two strongest materials, were remarkably similar. According to Table 11, the rule of mixtures was valid for the fracture stress values of Kapton F.

3.7 FRACTURE STRAIN

Figure 26 is a plot of the strain to fracture as a function of test temperature for the four unreinforced materials. In all cases the strain to fracture decreased as the temperature was lowered. Kapton H and Kapton F had a relatively shallow temperature dependence as compared to Tedlar and Teflon. The maximum Teflon fracture strain (399 percent) was seen at 100°C. When the test temperature was raised to 200°C, the Teflon strain at fracture diminished to 378 percent. Tedlar also had a maximum fracture strain at 100°C. This may be explained by recognizing that the mechanisms of deformation and fracture are different. That is, deformation is accomplished by stretching, uncoiling, or breaking molecular chains in localized internal areas, while fracture is a gross rupture of the molecular structure, usually starting at a void or a flaw and involves the creation of new surfaces as the crack grows. These mechanisms probably have different temperature de-

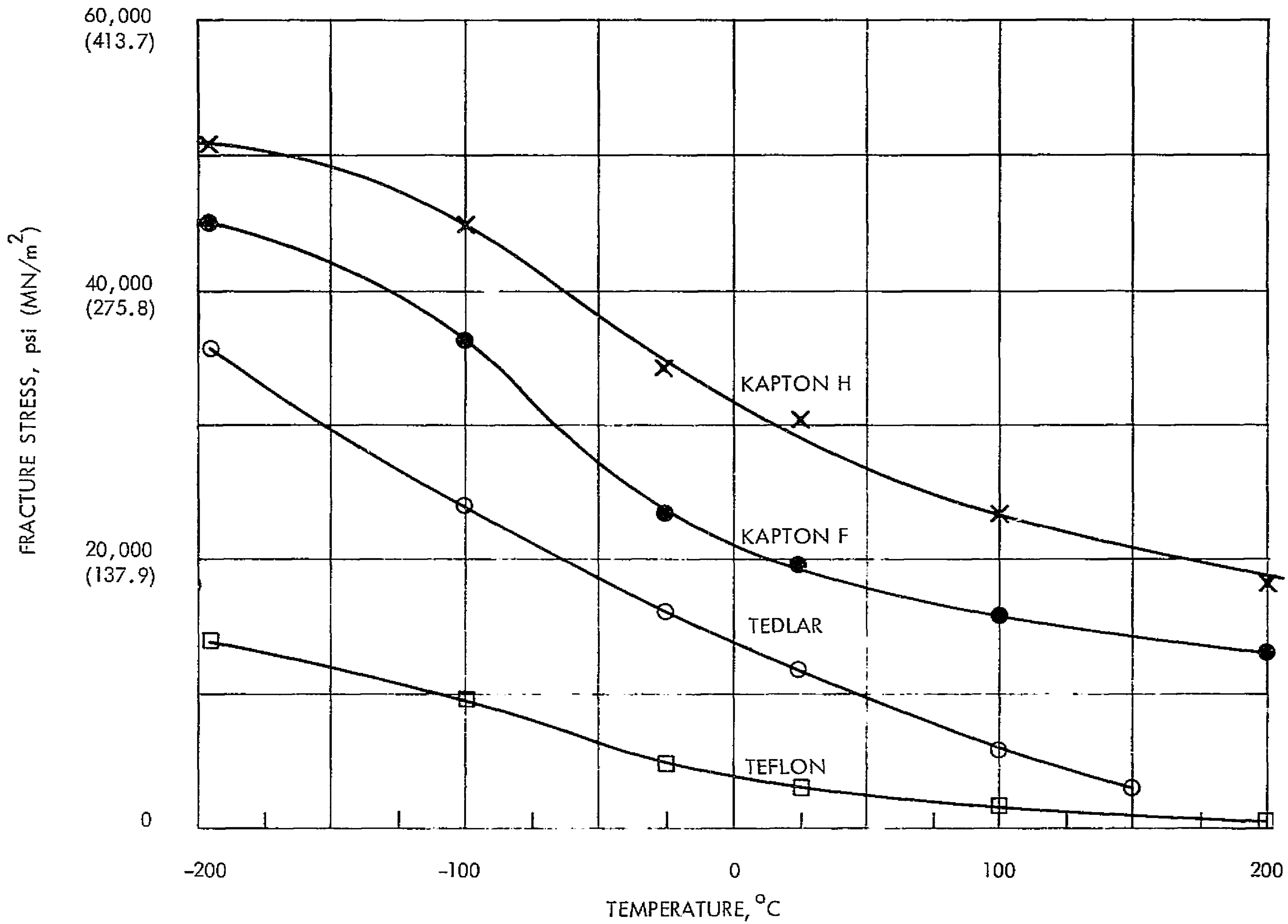

FIGURE 24 - Fracture Stress vs Test Temperature for Tensile Loading (materials as marked)

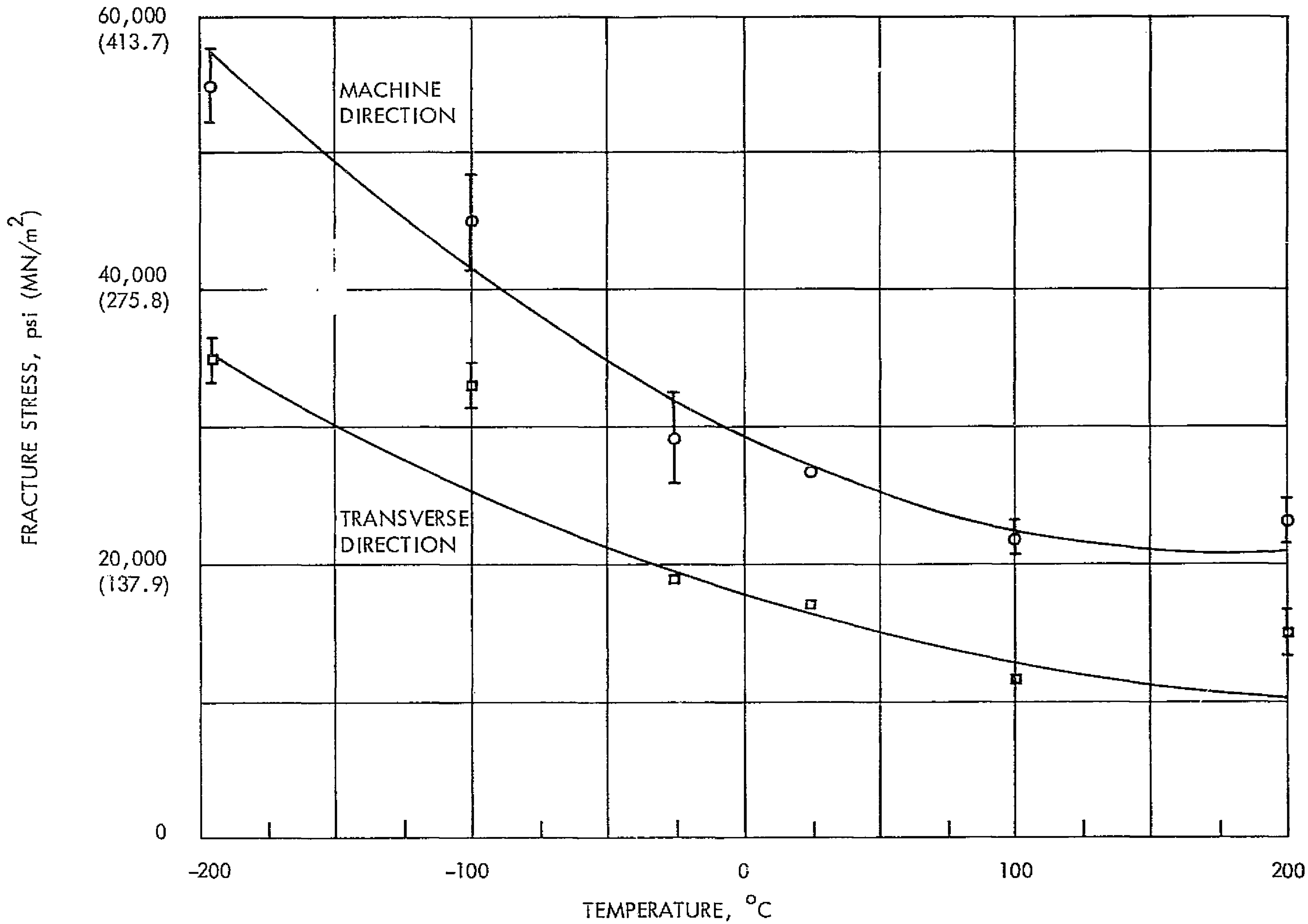

FIGURE 25 - Fracture Stress vs Test Temperature for Tensile Loading of PG-402 Fiberglass Laminate (specimen direction as marked)

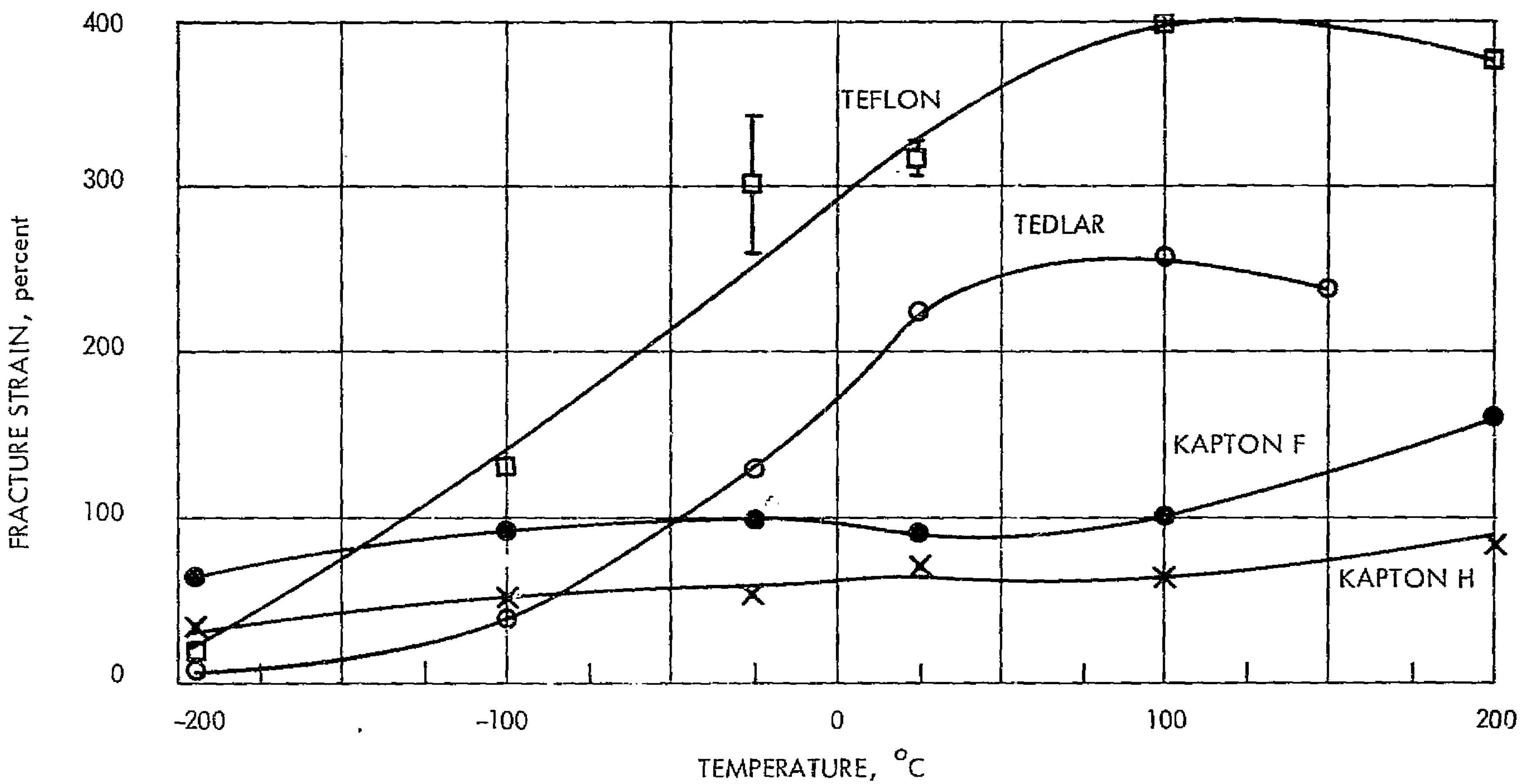

FIGURE 26 - Strain to Fracture vs Test Temperature for Tensile Loading (materials as marked)

pendences. It can be postulated that above 100°C the stress required to nucleate and/or propagate a crack drops to a value less than that required to deform the molecular structure. Thus, fracture would occur before any further deformation took place. The rule of mixtures was not useful for predicting the fracture strain of Kapton F at 25 and -195°C.

In contrast to the unreinforced materials, the PG-402 fracture strain increased at low temperatures. This may be due to one, or both, of the following factors. At high temperatures the fracture strength of the matrix materials is lowered, thus providing opportunities for cracks to develop and grow leading to early fracture. Since the deformation of PG-402 is nearly straight line loading, failure at lower stresses necessitates smaller fracture strains. Strengthening the matrix by lowering the test temperature raises the stress required to initiate cracks thus delaying fracture until greater strains have been realized. The relative loads supported by the matrix and the reinforcing fibers are in proportion to their volume fractions and to the relative modulus values. As the matrix modulus is increased in comparison to that of the fibers the matrix assumes a larger support of the applied load. With a fixed volume of reinforcing fibers, as in the PG-402, lowering the test temperature allows the matrix to support a greater load, thereby reducing the stress on the glass fibers. If failure originates in the reinforcing fibers then lowering the test temperatures should allow the fibers to support a greater load before breaking, thereby increasing the strain at failure.

The instantaneous load drops which occurred at -100° and -195°C (see Figure 18) are believed due to the breaking of individual fibers.

4. REFERENCES

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APPENDIX A

MECHANICAL PROPERTIES OF 8 INCH GAUGE LENGTH SPECIMENS

TABLE A-1 - Kapton H, 8 inch Gauge Length, 0.003 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	1	521,380	15,433	25,267	27	machine direction
	2	542,080	15,700	26,167	36	
	3	525,470	15,733	24,083	21	
	4	524,480	15,667	26,000	35	
	5	535,980	15,766	28,333	50	
	6	522,410	14,900	24,417	35	
	7	528,130	15,767	25,000	31	
	8	531,830	15,700	25,667	31	
	9	531,080	16,400	29,333	57	
	10	548,240	15,733	25,500	30	
standard deviation		8775	367	1655	10.7	
standard error of mean		±2775	±116	± 523	± 3.4	

TABLE A-2 - Kapton F, 8 inch Gauge Length, 0.003 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	1	375,400	9,900	22,250	95	machine direction
	2	360,000	10,100	20,667	80	
	3	358,100	10,060	19,854	72	
	4	380,900	9,800	21,500	86	
	5	351,600	10,030	20,000	77	
	6	335,800	10,000	20,834	85	
	7	375,000	10,000	20,000	76	
	8	383,100	9,733	20,750	87	
	9	380,500	9,800	20,667	78	
	10	366,300	9,867	20,333	75	
standard deviation		15,302	126	737	7	
standard error of mean		±4839	± 40	±233	± 2.2	

TABLE A-3 - Teflon, 4 inch Gauge Length, 0.005 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	1	71,400	1900	3120	318	machine direction
	2	67,600	1950	3360	343	
	3	68,000	1950	3480	349	
	4	70,200	2000	4000	334	
	5	67,600	2050	3800	359	
	6	67,600	1860	3840	393	
	7	67,800	1850	3360	347	
	8	66,700	1900	3680	368	
	9	68,700	1980	3600	355	
	10	68,500	2080	3600	340	
standard deviation		1401	77	263	20.3	
standard error of mean		± 443	± 24	± 83	± 6.4	

TABLE A-4 - Tedlar, 8 inch Gauge Length, 0.002 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	1	257,000	5400	10,750	144	machine direction
	2	244,000	5600	10,500	148	
	3	253,000	5600	10,750	149	
	4	254,000	5500	11,000	151	
	5	249,000	5350	11,250	154	
	6	250,000	5600	11,250	144	
	7	258,000	5250	10,500	138	
	8	250,000	5650	11,250	150	
	9	254,000	5650	11,250	164	
	10	250,000	5550	10,875	156	
standard deviation		4149	138	308	7.2	
standard error of mean		± 1312	± 43	± 97	± 2.3	

APPENDIX B

EFFECT OF CO_2 REFRIGERANT ON MECHANICAL PROPERTIES OF KAPTON H AND TEFLON

TABLE B-1 - Kapton H, 1.0 inch Gauge Length, 0.003 inch Thick, Tested in CO_2

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-25	39	180,550	8200	15,670	61	machine direction
	40	216,670	7870	15,670	61	
	41	216,670	8800	16,670	65	
	42	191,410	8000	16,500	68	
	44	206,350	8730	16,830	69	
	45	188,410	8330	16,830	69	
	46	144,000	7800	15,330	65	
	47	201,550	7670	16,170	69	
	48	206,350	7770	16,000	69	
	49	196,980	7800	15,830	61	
standard deviation		21,370	406	535	3.6	
standard error of mean		± 6757	± 129	±169	±1.1	

TABLE B-2 - Teflon, 1.0 inch Gauge Length, 0.005 inch Thick, Tested in CO_2

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-25	35	58,180	3200	5700	500	machine direction
	36	57,140	3180	7150	519	
	37	66,670	3350	6100	469	
	38	61,540	3370	6650	500	
	39	66,670	3400	5150	450	
	42	59,260	3180	6450	513	
	43	55,170	3360	7200	506	
	44	56,270	3280	6350	553	
	45	55,870	3200	7000	568	
	46	59,260	3140	6200	469	
standard deviation		4172	97	651	37	
standard error of mean		± 1319	± 31	± 206	± 11.6	

APPENDIX C

MECHANICAL PROPERTY VALUES OF INDIVIDUAL 1 INCH GAUGE LENGTH SPECIMENS

TABLE C-1 - Kapton H, 1.0 inch Gauge Length, 0.003 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
200	29	180,570	182,380	13,500	19,330	85	machine direction
	30	173,290	175,020	12,170	18,170	77	
	31	188,370	190,250	11,330	18,830	85	
	32	166,670	168,340	12,830	18,420	88	
	33	166,660	168,330	11,670	18,000	85	
	34	166,660	168,330	11,170	18,000	88	
	35	180,570	182,380	11,330	18,330	85	
	36	166,580	168,250	11,000	17,100	72	
	37	180,570	182,570	11,500	18,670	85	
	38	180,570	182,570	11,000	18,000	77	
standard deviation		8063	8172	836	598	5.4	
standard error of mean		± 2550	± 2584	± 264	± 189	± 1.7	
200	111	173,340	175,070	10,740	17,530	84	transverse direction
	112	180,560	182,370	10,800	18,370	95	
	113	179,050	180,840	10,500	18,330	95	
	114	180,570	182,380	10,800	15,670	45	
	115	166,670	168,340	11,100	17,470	77	
standard deviation		6023	6084	214	1095	20.5	
standard error of mean		± 2693	± 2721	± 96	± 490	± 9.2	

TABLE C-1 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
100	15	290,580	502,700	13,500	22,400	57	machine direction
	16	285,900	494,600	14,433	23,733	69	
	19	307,410	531,820	13,733	23,000	70	
	20	302,560	523,430	12,833	24,333	76	
	22	321,030	555,380	12,733	21,167	44	
	23	299,930	518,880	14,667	25,000	72	
	24	325,420	562,980	11,333	25,000	71	
	25	297,190	514,140	13,733	22,500	54	
	27	308,110	533,030	13,500	24,000	70	
	28	299,930	518,880	14,667	23,667	62	
standard deviation		12,323	22,472	1024	1221	10.0	
standard error of mean		± 3897	± 7106	± 324	± 386	± 3.2	
100	90	270,840	468,550	11,500	22,670	80	transverse direction
	91	254,900	440,980	10,670	21,500	71	
	92	254,900	440,980	12,000	22,830	77	
	93	262,630	454,350	12,000	22,830	77	
	94	270,840	468,550	11,500	21,830	65	
standard deviation		7971	13,786	544	623	6	
standard error of mean		±3565	± 6165	± 243	± 279	± 2.68	
25	126	313,890	505,360	13,730	29,670	73	machine direction
	127	323,390	520,660	14,330	30,170	71	
	128	318,390	512,610	15,670	31,170	72	
	129	327,800	527,760	15,100	29,670	62	
	130	332,930	536,020	14,700	32,000	75	
standard deviation		7511	12,094	738	1022	5.0	
standard error of mean		±3359	± 5409	± 330	± 457	± 2.25	

TABLE C-1 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	131	332,800	535,810	13,970	31,000	84	transverse direction
	132	318,390	512,610	13,800	29,670	72	
	133	318,390	512,610	13,670	30,170	72	
	134	323,440	520,740	15,000	29,330	65	
	135	316,810	510,060	15,370	30,830	74	
standard deviation		6552	10,550	770	720	6.8	
standard error of mean		± 2930	± 4718	± 344	± 322	± 3.06	
-25	74	437,710	652,190	16,600	37,330	62	machine direction
	77	424,840	633,010	18,000	30,580	25	
	78	465,950	694,270	16,930	35,330	57	
	82	433,340	645,680	16,670	32,000	50	
	83	433,340	645,680	17,670	36,830	78	
standard deviation		15,752	23,473	627	2988	19.4	
standard error of mean		± 7045	± 10,497	± 280	± 1336	± 8.7	
-25	75	498,080	742,140	16,670	36,670	59	transverse direction
	76	424,830	633,000	17,470	33,920	53	
	84	433,340	645,680	16,600	30,070	40	
	85	433,340	645,680	16,870	32,530	58	
	86	393,950	586,990	17,000	35,430	79	
standard deviation		37,943	56,533	345	2569	14.1	
standard error of mean		± 16,968	± 25,282	± 154	± 1149	± 6.3	

TABLE C-1 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-100	53	528,400	686,920	25,800	46,000	53	machine direction
	54	534,980	695,470	25,330	46,330	50	
	55	541,660	704,160	25,470	44,000	52	
	56	522,080	678,700	25,470	46,000	54	
	57	548,520	713,100	23,930	46,000	52	
	59	534,980	695,470	25,000	43,670	46	
	60	548,520	713,100	24,100	45,330	52	
	61	534,980	695,470	25,670	45,000	56	
	62	522,080	678,700	26,000	45,330	52	
	63	522,080	678,700	26,000	46,670	52	
standard deviation		10,223	13,299	732	981	2.6	
standard error of mean		±3233	± 4205	± 232	± 310	± 0.8	
-100	100	523,750	680,900	21,670	39,330	44	transverse direction
	101	517,360	672,570	24,170	38,670	37	
	102	533,630	693,720	23,830	40,500	46	
	103	492,410	640,130	23,000	35,670	30	
	104	579,980	753,970	22,900	42,000	47	
standard deviation		32,099	41,727	971	2360	7.2	
standard error of mean		±14,355	± 18,660	± 434	± 1056	± 3.2	

TABLE C-1 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-195	64	627,950	753,540	33,330	52,670	41	machine direction
	65	637,250	764,700	34,330	49,670	35	
	66	623,490	748,200	33,330	47,670	31	
	67	635,380	762,460	35,670	48,330	32	
	68	637,250	764,700	32,000	49,330	37	
	69	610,320	732,380	32,000	48,330	38	
	70	632,590	759,100	34,670	54,000	46	
	71	619,050	742,860	32,330	51,670	37	
	72	637,250	764,700	36,330	53,330	32	
	73	646,760	776,100	35,670	53,670	29	
standard deviation		10,660	12,790	1607	2461	5.1	
standard error of mean		± 3371	± 4045	± 508	± 778	± 1.6	
-195	95	585,590	702,700	32,000	46,000	36	transverse direction
	96	637,250	764,700	33,000	46,830	33	
	97	677,080	812,500	33,670	46,000	25	
	98	593,600	712,320	32,670	44,670	26	
	99	570,170	684,200	32,670	46,670	34	
standard deviation		43,750	52,500	606	852	5.0	
standard error of mean		±19,565	± 23,480	± 271	± 381	± 2.2	

TABLE C-2 - Kapton F, 1.0 inch Gauge Length, 0.003 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
200	25	94,210	101,750	6530	12,330	177	machine direction
	26	98,490	106,370	7200	13,580	192	
	27	90,270	97,500	6940	12,670	135	
	28	98,490	106,370	6930	12,920	150	
	29	96,120	103,800	7200	12,500	178	
	30	103,170	111,400	7270	13,170	154	
	31	94,200	101,740	6930	13,170	152	
	32	92,760	100,180	6670	12,250	149	
	33	98,490	106,370	7470	13,670	165	
	34	95,200	102,800	7500	12,840	154	
standard deviation		3655	3940	321	490	17	
standard error of mean		± 1156	± 1260	± 101	± 155	± 5	
200	108	103,170	111,400	7170	12,500	107	transverse direction
	109	86,670	93,600	8000	12,730	98	
	110	90,270	97,500	7200	12,770	112	
	111	103,170	111,400	7000	12,730	99	
	112	94,200	101,740	7130	12,770	101	
standard deviation		7494	8080	399	114	6	
standard error of mean		± 3352	± 3614	± 178	± 51	± 2	

TABLE C-2 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
100	13	180,990	240,700	8330	17,000	103	machine direction
	15	210,460	279,900	7730	17,000	111	
	16	213,900	284,400	7830	17,670	112	
	17	195,280	259,700	7500	13,830	71	
	18	201,710	268,300	7900	16,900	109	
	19	-	-	-	11,080	-	
	20	192,380	255,870	9000	13,670	67	
	21	180,880	240,600	8330	17,170	114	
	22	199,410	265,200	8070	18,670	130	
	23	-	-	-	13,750	75	
	24	201,410	268,300	7780	18,170	129	
	25	188,860	251,200	8330	15,000	77	
standard deviation		11,149	14,848	432	2313	23	
standard error of mean		± 3526	± 4695	± 137	± 668	± 7	
100	97	196,980	262,000	8730	18,670	108	transverse direction
	98	216,670	288,200	8000	17,170	102	
	99	203,350	270,500	8400	17,330	92	
	100	195,200	259,600	8370	18,000	87	
	101	218,860	291,100	8100	19,330	98	
standard deviation		11,000	14,640	286	909	8	
standard error of mean		±4919	± 6547	± 128	± 407	± 4	
25	122	212,420	320,800	9900	20,830	97	machine direction
	123	210,370	317,700	9600	18,670	71	
	126	207,340	313,100	10,100	20,500	84	
	127	203,970	308,000	8200	18,500	101	
	128	206,830	312,300	8600	19,000	95	
standard deviation		3280	4970	835	1085	12	
standard error of mean		±1467	± 2224	± 373	± 485	± 5	

TABLE C-2 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	85	200,000	302,000	8833	20,070	57	transverse direction
	86	210,050	317,200	9633	20,670	61	
	87	210,530	317,900	8900	21,500	76	
	88	222,230	335,600	9100	21,230	72	
	89	217,340	328,200	9000	21,670	77	
	129	210,400	317,700	9530	19,170	71	
	130	206,180	311,300	8930	19,170	75	
	131	212,230	320,500	9130	19,000	68	
	132	211,060	318,700	9100	20,000	78	
	134	204,360	308,600	9300	20,670	84	
standard deviation		6276	9490	267	991	8	
standard error of mean		±1985	± 3000	± 84	± 313	± 3	
-25	35	270,830	387,300	8,670	15,330	73	machine direction
	36	309,530	442,600	6,670	14,000	77	
	37	287,300	410,800	6,230	14,670	90	
	38	309,530	442,600	6,670	21,830	58	
	39	320,970	459,000	6,420	22,500	65	
	40	316,670	452,800	12,170	26,830	108	
	41	291,650	417,100	11,170	26,330	104	
	42	286,020	409,000	12,330	26,670	112	
	43	305,730	437,200	12,670	26,670	108	
	44	270,840	387,300	12,400	27,200	112	
	45	270,790	387,200	11,900	27,500	127	
	46	313,320	448,000	11,790	27,500	119	
	47	288,930	413,200	11,000	24,000	98	
	48	298,870	427,400	12,740	22,830	80	
	49	313,320	448,000	11,430	26,000	104	
	50	277,090	396,200	11,130	26,000	100	
standard deviation		17,554	25,100	2479	4739	20	
standard error of mean		±4389	± 6274	± 620	± 1185	± 5	

TABLE C-2 (continued)

Test Temp. (^{o}C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-25	78	333,340	476,700	14,500	28,330	83	transverse direction
	79	285,720	408,600	14,400	25,830	75	
	82	288,900	413,100	13,730	27,970	81	
	83	305,170	436,400	13,870	26,930	82	
	84	307,700	440,000	14,100	25,270	64	
standard deviation		18,980	27,120	331	1322	79	
standard error of mean		±8488	± 12,130	± 148	± 591	± 3.5	
-100	51	446,730	621,000	18,660	37,670	108	machine direction
	52	416,660	579,200	19,060	36,330	109	
	54	464,890	642,200	18,460	36,000	72	
	56	459,610	638,900	18,400	36,000	88	
	57	446,730	621,000	19,260	38,330	102	
	58	463,920	644,800	19,260	36,330	87	
	59	446,730	621,000	19,000	37,000	91	
	60	451,390	627,400	19,340	37,330	105	
	61	456,130	634,000	17,800	34,330	82	
	62	460,990	640,800	18,400	31,000	54	
	63	451,390	627,400	18,600	37,000	98	
standard deviation		13,389	18,225	478	1996	16.8	
standard error of mean		± 4037	± 5495	± 144	± 602	± 5.1	
-100	92	446,730	621,000	17,770	35,000	81	transverse direction
	93	471,020	654,700	18,330	35,000	69	
	94	442,170	614,600	17,330	33,330	63	
	95	437,710	608,400	18,330	33,500	67	
	96	442,170	614,600	18,070	34,000	68	
standard deviation		13,280	18,457	424	800	6.8	
standard error of mean		±5939	± 8254	± 190	± 358	± 3.0	

TABLE C-2 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-195	64	722,215	1,220,500	29,130	48,670	66	machine direction
	65	687,830	1,162,400	26,130	47,330	67	
	66	698,920	1,181,200	25,330	43,670	65	
	67	677,080	1,144,300	25,330	41,330	58	
	74	681,170	1,151,200	25,230	44,670	67	
standard deviation		18,081	30,530	1661	2922	3.8	
standard error of mean		±8086	± 13,655	± 743	± 1307	± 1.7	
-195	68	677,080	1,144,300	31,400	51,000	62	transverse direction
	69	687,830	1,161,100	26,600	50,670	63	
	71	656,560	1,109,600	25,130	43,670	55	
	72	652,300	1,102,400	24,670	47,000	65	
	73	666,670	1,126,700	24,330	45,670	63	
standard deviation		14,618	24,257	2912	3183	3.8	
standard error of mean		±6537	± 10,850	± 1302	± 1423	± 1.7	

TABLE C-3 - Teflon, 1.0 inch Gauge Length, 0.005 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
200	25	2410	2770	160	520	404	machine direction
	26	2120	2440	160	440	369	
	27	2600	2990	190	520	377	
	28	2470	2840	190	520	396	
	29	2780	3200	160	500	400	
	30	2220	2550	170	460	335	
	31	2560	2940	180	520	362	
	32	2490	2860	170	530	404	
	33	2440	2810	190	500	347	
	34	2160	2480	190	520	388	
standard deviation		202	239	13.5	30	24.5	
standard error of mean		± 64	± 76	± 4.3	± 9.4	± 7.8	
200	109	2240	2580	160	280	302	transverse direction
	110	2330	2680	160	220	290	
	111	2310	2660	170	290	261	
	112	2220	2550	140	290	338	
	113	2260	2600	130	270	292	
	114	2370	2730	200	330	206	
standard deviation		58	68	24	36	25	
standard error of mean		±24	± 28	± 10	± 15	± 10	

TABLE C-3 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
100	13	-	-	-	-	-	machine direction
	14	7500	13,050	510	1800	433	
	15	7440	12,950	530	1720	425	
	16	8900	15,490	540	1740	350	
	17	7870	13,690	550	1860	418	
	18	7200	12,530	460	1720	417	
	19	8860	15,420	550	1880	349	
	20	8860	15,420	560	1820	361	
	22	7530	13,100	500	1860	415	
	23	8740	15,210	460	1750	404	
	24	7850	13,660	480	1760	421	
standard deviation		687	1200	38	61	33	
standard error of mean		±217	± 378	± 12	± 19	± 10	
100	96	7360	12,810	340	1140	309	transverse direction
	98	7590	13,210	370	1320	378	
	99	7140	12,420	380	1080	240	
	100	7710	13,420	428	1200	333	
	101	7250	12,620	380	1320	361	
standard deviation		236	413	32	107	19	
standard error of mean		± 106	± 185	± 14	± 48	± 8	
25	127	50,990	73,900	1680	2380	308	machine direction
	129	43,330	62,800	1760	2580	319	
	130	50,960	73,900	1820	2780	323	
	131	49,140	71,300	1780	2860	322	
	132	49,140	71,300	1830	2660	314	
standard deviation		3145	4570	60	186	6	
standard error of mean		± 1407	± 2044	± 27	± 83	± 3	

TABLE C-3 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	133	49,500	71,800	1720	2280	281	transverse direction
	134	49,140	71,300	1590	2000	275	
	135	49,960	72,400	1690	2800	324	
	136	49,960	72,400	1620	2360	322	
	137	52,910	76,700	1740	3160	328	
standard deviation		1502	2160	65	459	26	
standard error of mean		± 672	± 967	± 29	± 205	± 12	
-25	159	127,150	148,800	2800	5850	372	machine direction
	74	130,000	152,100	2840	4500	330	
	80	123,810	144,900	2750	4220	281	
	81	130,000	152,100	2760	4880	325	
	83	130,000	152,100	2620	6000	417	
standard deviation		2743	3190	83	799	52	
standard error of mean		± 1227	± 1426	± 37	± 357	± 23	
-25	72	123,810	144,900	2840	3900	251	transverse direction
	78	130,000	152,100	2700	4360	293	
	79	126,830	148,400	2740	5420	378	
	82	136,840	160,100	2520	4480	280	
	84	148,580	173,800	2640	5600	370	
standard deviation		9859	11,508	119	728	57	
standard error of mean		± 4409	± 5147	± 53	± 325	± 25	

TABLE C-3 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-100	47	291,660	364,600	9,800	9,680	140	machine direction
	48	300,050	375,100	11,200	10,900	131	
	49	287,490	359,400	10,360	10,040	141	
	50	283,750	354,700	10,200	9,640	118	
	51	287,490	259,400	10,140	10,000	149	
	53	300,430	375,500	9,760	9,380	129	
	54	262,470	328,100	9,440	8,920	135	
	55	276,350	345,400	9,980	9,600	125	
	56	300,300	375,400	9,800	9,720	119	
standard deviation		12,600	19,230	504	540	11	
standard error of mean		± 4200	± 6410	± 168	± 180	± 3.6	
-100	90	283,690	354,600	9,860	9,500	70	transverse direction
	91	279,520	349,400	9,080	8,700	95	
	92	273,230	341,500	10,160	10,000	95	
	93	293,040	366,300	9,980	9,500	100	
	94	303,030	378,800	10,340	10,400	45	
standard deviation		11,712	14,656	485	638	23	
standard error of mean		± 5238	± 6554	± 217	± 285	± 10	
-195	63	514,730	1,044,900	17,200	16,400	17	machine direction
	64	553,360	1,123,300	17,480	16,600	14	
	65	524,340	1,064,400	11,800	11,400	13	
	66	400,010	812,000	11,700	11,400	14	
	67	372,960	757,100	11,380	11,000	19	
	70	500,000	1,015,000	15,960	15,950	15	
standard deviation		73,170	148,600	2926	2778	2.3	
standard error of mean		± 29,874	± 60,645	± 1194	± 1134	± 0.9	

TABLE C-3 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-195	58	466,660	947,300	16,800	16,000	14	transverse direction
	59	477,820	970,000	15,940	15,400	17	
	68	590,920	1,199,600	17,200	16,000	13	
	69	478,270	970,900	17,480	16,500	13	
	71	565,210	1,147,400	15,960	15,800	20	
standard deviatic ;		57,771	117,300	705	397	3	
standard error of mean		±25,836	± 52,450	± 315	± 178	± 1.4	

TABLE C-4 - Tedlar, 1.0 inch Gauge Length, 0.002 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
150	24	4550	5190	-	2800	234	machine direction
	25	4530	5160	325	2850	237	
	26	4350	4960	550	3100	231	
	27	4650	5300	450	2900	215	
	28	4550	5190	425	3150	250	
	29	4260	4860	425	3100	231	
	31	4210	4800	490	3100	235	
	32	4550	5190	500	3150	235	
	33	4500	5130	475	3000	242	
	34	4440	5060	400	3100	258	
	35	4350	4960	400	3100	246	
standard deviation		139	157	63	125	11	
standard error of mean		±42	± 48	± 20	± 38	± 3	
150	161	5780	6590	500	2430	251	transverse direction
	117	5660	6450	450	2875	217	
	119	5920	6750	360	2550	206	
	120	5420	6180	400	2810	222	
	121	5920	6750	350	2860	205	
standard deviation		209	239	63	202	19	
standard error of mean		± 94	± 107	± 28	± 90	± 8	

TABLE C-4 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
100	13	17,330	18,370	1300	5125	265	machine direction
	14	17,500	18,550	1050	6500	267	
	15	15,870	16,820	1100	5100	242	
	16	16,530	17,520	1050	5700	285	
	17	15,280	16,200	850	4500	229	
	18	16,560	17,550	1050	5950	282	
	19	17,780	18,850	1100	5850	260	
	20	17,050	18,070	1200	5600	250	
	22	16,570	17,560	1180	6000	275	
	23	15,280	16,200	1300	5900	236	
standard deviation		879	931	135	571	19	
standard error of mean		±278	± 295	± 43	± 181	± 6	
100	91	16,130	17,100	1050	6600	212	transverse direction
	92	14,090	14,940	600	6950	238	
	93	16,390	17,370	970	7000	227	
	94	13,260	14,060	825	6100	208	
	95	15,060	15,960	875	7350	231	
	101	15,630	16,570	1100	7900	227	
standard deviation		1218	1288	181	617	12	
standard error of mean		±497	± 526	± 74	± 252	± 5	
25	129	185,700	376,970	6700	13,130	223	machine direction
	130	171,280	347,700	4700	10,750	229	
	131	173,100	351,400	4650	13,130	211	
	132	157,690	328,000	4700	10,250	228	
	133	166,140	337,300	4750	10,750	228	
standard deviation		10,261	18,470	895	1410	8	
standard error of mean		±4589	± 8260	± 400	± 630	± 3	

TABLE C-4 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
25	135	169,390	343,860	4680	12,500	189	transverse direction
	136	164,000	332,920	4950	9,380	184	
	137	169,390	343,860	4850	11,200	148	
	139	167,640	340,300	4730	9,750	118	
	140	165,950	336,880	4700	11,750	168	
standard deviation		2322	4712	115	1323	29	
standard error of mean		±1038	± 2107	± 51	± 592	± 13	
-25	38	270,830	614,780	11,000	15,880	135	machine direction
	39	272,770	619,190	10,850	14,000	113	
	40	250,300	568,180	12,400	16,250	127	
	42	248,750	564,660	11,900	17,000	139	
	43	265,300	602,230	11,300	17,500	135	
	44	270,830	614,780	10,800	16,000	135	
	45	250,300	568,180	10,600	16,000	146	
	46	247,990	562,940	10,450	15,250	135	
	47	268,590	609,700	10,350	15,750	135	
	71	283,300	643,090	10,600	16,450	126	
	72	290,000	658,300	10,800	17,400	131	
	77	266,400	604,730	10,500	16,750	125	
	78	258,100	585,890	11,100	16,700	138	
	79	266,400	604,730	10,800	13,350	80	
standard deviation		12,631	29,113	574	1183	16	
standard error of mean		±3376	± 7780	± 153	± 316	± 4	
-25	69	282,620	641,550	10,650	20,600	101	transverse direction
	70	285,090	647,150	10,700	17,100	87	
	80	262,090	594,940	10,750	20,200	125	
	81	266,400	604,730	10,300	15,600	75	
	83	282,610	641,520	8,500	19,750	122	
standard deviation		10,671	24,224	956	2186	22	
standard error of mean		± 4772	± 10,830	± 427	± 978	± 10	

TABLE C-4 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-100	48	541,510	1,125,300	20,100	21,380	35	machine direction
	49	541,510	1,125,300	22,200	24,300	14	
	50	564,670	1,173,400	24,500	28,500	42	
	51	551,000	1,145,000	20,000	25,250	54	
	52	568,190	1,180,700	20,900	23,500	46	
	53	559,450	1,162,500	21,750	25,000	54	
	54	576,700	1,198,400	20,000	22,500	17	
	55	569,500	1,183,400	20,900	22,630	39	
	56	586,000	1,217,700	22,150	23,000	29	
	57	595,800	1,238,100	23,400	25,500	47	
standard deviation		17,906	37,200	1516	2032	14	
standard error of mean		± 5662	± 11,764	± 479	± 642	± 4	
-100	96	580,360	1,206,000	22,700	27,000	47	transverse direction
	97	590,920	1,227,900	21,550	28,250	48	
	98	613,210	1,274,300	22,600	29,000	49	
	99	590,920	1,227,900	22,650	31,000	50	
	100	601,850	1,250,600	22,900	28,000	41	
standard deviation		12,501	25,992	532	1496	3.5	
standard error of mean		± 5591	± 11,624	± 238	± 669	± 1.6	
-195	63	722,230	1,379,460	31,000	34,375	8	machine direction
	64	730,340	1,394,950	31,000	31,000	6	
	65	706,520	1,349,450	30,000	38,200	8	
	66	706,520	1,349,450	34,700	37,200	7	
	67	706,520	1,349,450	28,000	37,200	9	
standard deviation		11,199	21,392	2433	2939	1	
standard error of mean		± 5008	± 9567	± 1088	± 1314	± 0.5	

TABLE C-4 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elast. Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-195	58	691,500	1,320,770	22,500	27,500	7	transverse direction
	59	691,500	1,320,770	21,400	27,000	7	
	60	706,520	1,349,450	20,750	27,000	9	
	61	738,630	1,410,780	22,250	30,500	8	
	62	663,260	1,266,830	22,600	27,500	8	
standard deviation		27,452	52,430	798	1475	0.8	
standard error of mean		± 12,277	± 23,447	± 357	± 660	± 0.4	

TABLE C-5 - PG-402, 1.0 inch Gauge Length, 0.0025 inch Thick

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
200	62	793,670	2,127,000	24,600	24,600	3.2	machine direction
	63	833,330	2,233,300	27,330	27,330	3.0	
	64	724,650	1,942,100	18,000	18,000	2.7	
	65	793,670	2,127,000	21,800	21,800	2.9	
	66	793,670	2,127,000	24,700	24,700	4.0	
standard deviation		39,256	105,180	3544	3544	0.5	
standard error of mean		± 17,556	± 47,040	± 1585	± 1585	± 0.2	
200	68	537,650	1,440,900	14,930	14,930	3.4	transverse direction
	69	555,570	1,488,900	16,200	16,200	3.0	
	71	574,720	1,540,200	18,930	18,930	4.2	
	72	555,570	1,488,900	9,370	9,370	2.4	
	73	520,840	1,395,900	15,700	15,700	3.9	
standard deviation		20,430	54,700	3503	3503	0.7	
standard error of mean		±9137	± 24,470	± 1566	± 1566	± 0.3	
100	42	833,330	2,175,000	19,670	19,670	2.3	machine direction
	43	833,330	2,175,000	24,830	24,830	3.0	
	44	854,700	2,230,800	19,170	19,170	2.6	
	45	877,190	2,289,500	21,500	21,500	2.8	
	46	833,330	2,175,000	24,500	24,500	3.0	
standard deviation		19,554	51,050	2642	2642	0.3	
standard error of mean		±8745	± 22,830	± 1182	± 1182	± 0.1	

TABLE C-5 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
100	47	500,000	1,305,000	11,670	11,670	2.2	transverse direction
	48	625,000	1,631,300	11,500	11,500	1.8	
	49	666,670	1,740,000	10,500	10,500	1.5	
	50	645,160	1,683,900	12,830	12,830	1.4	
	51	714,280	1,864,300	12,000	12,000	1.6	
standard deviation		80,004	208,800	844	844	0.3	
standard error of mean		±35,779	± 93,385	± 377	± 377	± 0.1	
25	1	793,650	2,754,000	28,580	28,580	3.8	machine direction
	2	833,330	2,891,700	27,080	27,080	3.2	
	3	854,690	2,965,800	26,250	26,250	3.2	
	4	854,690	2,965,800	26,670	26,670	3.6	
	5	793,650	2,754,000	25,330	25,330	3.0	
standard deviation		30,794	106,850	1196	1196	0.3	
standard error of mean		±13,771	± 47,785	± 535	± 535	± 0.1	
25	6	617,280	2,142,000	17,080	17,080	2.8	transverse direction
	7	641,030	2,224,400	17,170	17,170	2.7	
	8	617,280	2,142,000	17,080	17,080	2.7	
	9	641,030	2,224,400	16,920	16,920	2.6	
	10	628,930	2,182,400	17,170	17,170	2.7	
standard deviation		11,875	41,200	102	102	0.07	
standard error of mean		±5311	± 18,425	± 46	± 46	± 0.03	

TABLE C-5 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-25	11	833,330	2,816,700	25,330	34,000	4.6	machine direction
	13	769,230	2,600,000	24,670	25,670	3.6	
	14	784,320	2,651,000	25,670	29,330	2.2	
	15	980,390	3,313,700	24,670	31,000	4.5	
	21	925,930	3,129,600	24,000	26,470	3.6	
standard deviation		91,528	309,350	650	3397	0.6	
standard error of mean		±40,932	± 138,340	± 291	± 1519	± 0.3	
-25	16	579,710	1,959,400	15,670	18,500	3.7	transverse direction
	17	666,670	2,253,300	15,000	19,230	4.0	
	18	740,740	2,503,700	16,000	19,700	4.0	
	19	579,710	1,959,400	15,670	20,630	4.3	
	20	606,060	2,048,500	16,670	17,100	2.8	
standard deviation		69,164	233,775	606	1328	0.6	
standard error of mean		±30,931	± 104,545	± 271	± 594	± 0.3	
-100	22	888,890	3,440,000	30,670	35,670	4.8	machine direction
	23	888,890	3,440,000	29,330	48,270	7.4	
	24	874,320	3,383,600	28,670	53,670	9.0	
	25	909,090	3,518,200	28,000	49,670	7.2	
	26	952,380	3,685,700	28,000	39,670	5.3	
standard deviation		30,397	117,635	1116	7456	1.7	
standard error of mean		±13,594	± 52,610	± 499	± 3334	± 0.8	

TABLE C-5 (continued)

Test Temp. (°C)	Specimen Number	Measured Elastic Modulus (psi)	Corrected Elastic Modulus (psi)	3% Yield Stress (psi)	Fracture Stress (psi)	Fracture Strain (%)	Specimen Orientation
-100	27	784,320	3,035,300	16,000	36,000	7.0	transverse direction
	28	740,740	2,866,700	14,670	35,670	7.3	
	29	666,670	2,580,000	13,330	31,670	6.7	
	30	740,740	2,866,700	15,670	34,670	7.3	
	31	789,320	3,054,700	16,000	27,330	5.3	
standard deviation		49,194	190,390	1146	3634	0.7	
standard error of mean		±22,000	± 85,145	± 513	± 1625	± 0.3	
-195	37	1,111,110	3,444,400	26,670	51,170	7.2	machine direction
	38	1,176,480	3,647,100	27,330	62,000	8.0	
	39	1,052,630	3,263,200	24,670	48,170	7.0	
	40	1,000,000	3,100,000	26,000	47,330	8.0	
	41	1,052,630	3,263,200	27,000	58,000	8.0	
standard deviation		67,387	208,900	1052	6408	0.5	
standard error of mean		±30,137	± 93,420	± 471	± 2866	± 0.2	
-195	32	784,320	2,431,400	16,300	33,300	6.3	transverse direction
	33	740,740	2,296,300	17,300	40,300	7.1	
	34	833,300	2,583,200	21,700	37,670	6.6	
	35	833,300	2,583,200	18,670	32,000	5.7	
	36	740,740	2,296,300	21,700	32,300	6.0	
standard deviation		46,296	143,500	2489	3686	0.5	
standard error of mean		±20,704	± 64,175	± 1113	± 1648	± 0.2	

APPENDIX D

POISSON RATIO VALUES OF INDIVIDUAL SPECIMENS

TABLE D-1 - Kapton H, Poisson Ratios from Fiducial Pattern Tests on 4 inch Gauge Length Specimens

Test Temp. (°C)	Specimen Number	Poisson Ratio	Test Temp. (°C)	Specimen Number	Poisson Ratio
200	136	0.50	100	139	0.43
	137	0.50		140	0.50
	138	0.51		142	0.43
25	141	0.40	-25	145	0.50
	143	0.40		146	0.20
	144	0.33		147	0.25
-100	148	0.28	-195	151	0.38
	149	0.38		152	0.21
	150	0.20		153	0.25

TABLE D-2 - Kapton F, Poisson Ratios from Fiducial Pattern Tests on 4 inch Gauge Length Specimens

Test Temp. (°C)	Specimen Number	Poisson Ratio	Test Temp. (°C)	Specimen Number	Poisson Ratio
200	119	0.50	100	137-A	0.50
	120	0.33		138	0.52
	121	0.33		140	0.51
25	135	0.33	-25	140-A	0.60
	136	0.41		141	0.50
	137	0.20		142	0.38
-100	143	0.50	-195	146	0.48
	144	0.25		147	0.50
	145	0.40		148	0.29

TABLE D-3 - Teflon, Poisson Ratios from Fiducial Pattern Tests on 4 inch Gauge Length Specimens

Test Temp. (°C)	Specimen Number	Poisson Ratio	Test Temp. (°C)	Specimen Number	Poisson Ratio
200	138	0.49	100	145	0.53
	140	0.47		146	0.46
	157	0.27		147	0.38
25	142	0.40	-25	148	0.51
	143	0.60		149	0.50
	144	0.39		150	0.40
-100	151	0.34	-195	154	0.44
	152	0.57		155	0.46
	153	0.33		156	0.26

TABLE D-4 - Tedlar, Poisson Ratios from Fiducial Pattern Tests on 4 inch Gauge Length Specimens

Test Temp. (°C)	Specimen Number	Poisson Ratio	Test Temp. (°C)	Specimen Number	Poisson Ratio
150	141	0.50	100	148	0.50
	142	0.51		149	0.41
	143	0.51		150	0.30
25	144	0.51	-25	151	0.51
	145	0.29		152	0.33
	147	0.40		153	0.25
-100	154	0.50	-195	157	0.22
	155	0.33		158	0.25
	156	0.34		159	0.31

TABLE D-5 - PG-402, Poisson Ratios from Fiducial Pattern Tests on 4 inch Gauge Length Specimens

Test Temp. (°C)	Specimen Number	Poisson Ratio	Test Temp. (°C)	Specimen Number	Poisson Ratio
200	75	0.48	100	82	0.50
	76	0.50		83	0.60
	77	0.50		84	0.39
25	78	0.47	-25	85	0.26
	79	0.33		86	0.58
	80	0.50		87	0.50
	81	0.49			
-100	88	0.50	-195	91	0.33
	89	0.25		92	0.51
	90	0.38		93	0.38

APPENDIX E

VARIATION OF TRANSVERSE/LONGITUDINAL STRAIN RATIOS IN PLASTIC REGION

TABLE E-1 – Kapton H Ratio of Transverse to Longitudinal Strains (ϵ_T/ϵ_L) in the Plastic Region

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain	Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
200	122	0.50	8.6	100	108	0.49	11.0
		0.38	17.1			0.29	38.4
		0.25	34.2			0.36	60.4
		0.36	47.2			0.36	76.9
		0.40	64.4			0.50	98.8
		0.45	77.2				
		0.43	90.1		109	0.16	16.2
						0.29	37.8
	123	0.50	9.4			0.39	70.2
		0.50	18.7			0.26	97.2
		0.37	37.5				
		0.46	60.9		110	0.25	10.8
		0.44	75.0			0.34	31.9
		0.47	89.0			0.45	58.7
						0.44	85.4
	125	0.50	11.9				
		0.40	29.8				
		0.30	53.5				
		0.39	77.2				

TABLE E-1 (continued)

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
25	79	0.50	18.1
		0.42	54.6
		0.44	72.8
		0.50	90.9
	80	0.34	15.1
		0.50	30.0
		0.50	58.0
		0.47	85.4
	82	0.50	23.6
		0.34	35.2
		0.45	64.8
		0.41	100.0
-25	105	0.50	6.3
		0.29	44.8
		0.33	76.9
		0.43	89.7
	106	0.25	22.5
		0.25	45.1
		0.27	62.0
		0.42	67.6
		0.40	84.5
	107	0.33	20.0
		0.24	40.1
		0.38	53.3
		0.45	73.3
		0.46	86.6
		0.47	100.0
-100	116	0.49	14.0
		0.40	34.8
		0.44	62.6
		0.50	83.5
		0.50	97.2
	117	0.49	10.9
		0.40	27.1
		0.50	54.1
		0.46	70.3
		0.47	92.1
	118	0.49	13.7
		0.40	34.2
		0.44	61.5
		0.46	88.7
-195	119	0.17	31.7
		0.20	53.1
		0.28	74.2
		0.33	95.2
	120	0.49	23.3
		0.50	46.3
		0.50	69.6
		0.50	92.9
	121	0.49	52.9

TABLE E-2 – Kapton F Ratio of Transverse to Longitudinal Strains (ϵ_T/ϵ_L) in Plastic Region

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain	Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
200	119	0.50	6.5	100	105	0.49	9.0
		0.34	19.3			0.30	44.5
		0.42	38.6			0.41	75.8
		0.45	57.9			0.41	98.0
		0.45	70.8				
		0.42	83.7		106	0.49	6.8
		0.43	96.5			0.38	27.3
						0.47	51.0
	120	0.33	10.2			0.50	68.1
		0.43	23.9			0.44	85.0
		0.43	47.9			0.46	95.2
		0.45	68.5				
		0.48	78.7		107	0.50	9.0
						0.43	44.6
	121	0.33	10.1			0.50	71.2
		0.25	26.9			0.48	93.5
		0.40	50.4				
		0.40	67.2				
		0.42	80.6				

TABLE E-2 (Continued)

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain	Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
25	74	0.40	20.0	-25	102	0.40	17.1
		0.47	60.1			0.40	34.1
		0.46	96.2			0.40	51.2
						0.45	61.5
	76	0.17	17.6			0.43	78.6
		0.44	46.7			0.39	95.6
		0.42	75.9				
		0.38	99.3		103	0.33	14.0
						0.44	42.0
	77	0.42	30.6			0.54	60.6
		0.42	61.1			0.53	70.0
		0.43	89.2			0.50	93.4
					104	0.50	4.2
						0.50	25.5
						0.45	46.6
						0.47	63.5
						0.45	84.6
-100	113	0.49	15.0	-195	115	0.49	21.3
		0.38	59.7			0.50	31.9
		0.46	96.8			0.34	63.8
						0.37	85.1
	114	0.49	13.8				
		0.40	34.3		116	0.50	11.7
		0.44	61.6			0.49	23.7
		0.42	82.1			0.50	35.4
						0.50	47.1
	115	0.49	12.2			0.50	59.2
		0.50	36.4			0.44	94.6
		0.40	60.5				
		0.40	90.9		118	0.49	18.2
						0.49	37.0
						0.50	55.3
						0.50	73.5
						0.50	92.3

TABLE E-3 – Teflon Ratio of Transverse to Longitudinal Strain (ϵ_T/ϵ_L) in Plastic Region

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain	Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
200	123	0.50	2.3	100	106	0.17	3.1
		0.50	8.1			0.30	20.3
		0.28	37.0			0.29	34.5
		0.24	59.0			0.20	67.1
		0.21	72.9			0.18	84.4
		0.17	98.3				
					107	0.33	2.8
	124	0.33	2.9			0.46	10.2
		0.38	15.5			0.29	31.5
		0.31	28.2			0.22	53.7
		0.23	51.4			0.17	81.5
		0.21	61.1				
			84.4		108	0.43	6.6
						0.44	15.1
	125	0.33	9.1			0.30	31.2
		0.33	36.3			0.24	51.0
		0.33	72.6			0.20	68.0
		0.27	93.7			0.19	76.5

TABLE E-3 (Continued)

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
25	75	0.40	3.4
		0.31	23.7
		0.18	64.5
	76	0.40	3.8
		0.35	28.4
		0.18	84.1
		0.17	94.9
	77	0.50	3.5
		0.24	55.9
		0.18	81.3
		0.17	94.4
		0.16	97.0
-100	116	0.40	7.0
		0.33	25.1
		0.30	37.6
		0.27	47.4
		0.27	51.6
		0.27	57.2
		0.25	72.5
	117	0.43	14.8
		0.33	50.9
		0.30	65.7
		0.26	80.6
		0.25	95.4
	118	0.20	6.0
		0.30	46.1
		0.35	60.1
		0.27	68.0
		0.26	78.1
		0.25	90.1

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
-25	103	0.40	7.9
		0.39	22.6
		0.26	49.0
		0.21	66.7
	104	0.42	11.3
		0.33	25.3
		0.24	55.4
		0.20	70.4
		0.18	82.6
		0.18	88.3
	105	0.40	12.1
		0.36	20.2
		0.23	45.2
		0.19	64.5
-195	120	0.50	2.5
		0.50	5.2
		0.50	7.5
	121	0.50	36.1
		0.50	73.3
		0.42	90.9
	123	0.50	22.6
		0.33	68.4
		0.30	91.7

TABLE E-4 - Tedlar Ratio of Transverse to Longitudinal Strains (ϵ_T/ϵ_L) in Plastic Region

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain	Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
150	125	0.50	17.0	100	109	0.17	4.9
		0.41	55.2			0.43	11.4
		0.45	62.9			0.45	35.8
		0.39	78.1			0.41	55.3
		0.37	93.3			0.36	73.2
						0.40	92.7
	126	0.49	4.1				
		0.50	10.3		110	0.34	.2
		0.50	26.8			-	9.0
		0.50	39.1			0.50	35.9
		0.48	55.7			0.43	59.1
		0.44	70.1			0.36	80.6
		0.40	82.4			0.33	98.5
	127	0.33	5.6		111	0.25	3.2
		0.50	15.0			0.50	9.8
		0.50	24.4			0.50	32.5
		0.46	45.0			0.44	52.0
		0.45	54.4			0.36	71.6
		0.41	69.3			0.33	87.8
		0.38	84.4				

TABLE E-4 (Continued)

Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain	Test Temp. (°C)	Specimen Number	ϵ_T/ϵ_L	Percent of Fracture Strain
25	73	0.50	41.3	-25	103	0.34	9.3
		0.44	64.6			0.25	37.3
		0.43	77.4			0.41	52.8
		0.42	90.4			0.45	68.3
						0.39	86.9
	75	0.57	25.4			0.41	99.4
		0.50	43.5				
		0.45	65.3		106	0.17	9.6
		0.41	79.8			0.46	35.3
		0.39	97.9			0.44	51.3
						0.41	70.6
	76	0.50	30.6			0.40	80.2
		0.45	51.5			0.48	93.0
		0.37	72.6				
		0.35	91.7		107	0.08	7.2
						0.46	46.3
						0.47	60.6
						0.48	74.9
						0.46	92.7
-100	112	0.49	6.6	-195	122	0.50	44.6
		0.50	26.4			0.34	67.6
		0.50	39.5			0.49	90.5
		0.47	56.0				
		0.47	67.5		123	0.50	43.4
						0.50	88.2
	113	0.33	17.2				
		0.42	68.6		124	0.50	46.5
		0.50	20.1			0.50	94.4
		0.47	97.3				
	114	0.33	15.0				
		0.42	60.0				