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Mechanical Properties of Several Neat Polymer Matrix Materials and Unidirectional Carbon Fiber-Reinforced Composites

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PREFACE

This final technical report presents the results of a multi-year effort on NASA-Langley Research Grant NAG-1-277. The NASA-Langley Technical Monitor was Dr. Norman J. Johnston of the Materials Division.

All work was performed by the Composite Materials Research Group (CMRG) within the Department of Mechanical Engineering at the University of Wyoming. Co-Principal Investigators were Mssrs. Scott L. Coguill and Richard S. Zimmerman, Staff Engineers, and Dr. Donald F. Adams, Director.

Making major contributions to the program were Paul D. Evertson, Bill G. Gashler, Mike D. Borgman, Douglas L. McLarty, Craig L. Prokop, Stewart L. Atkinson, Lenard E. Frank, Jerome S. Berg, Robert W. Wakelee, Hal D. Radloff, Joey A. Hunter and Roger R. Powell, undergraduate student members of the Composite Materials Research Group.

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SECTION 1

INTRODUCTION

This report presents the final results of an experimental evaluation of various unreinforced (neat) resin materials being considered for various applications in the aerospace industry. Carbon fiber-reinforced composites data were also generated.

The material properties produced by this effort are providing a much needed data base for fully evaluating these new matrix materials, and composite materials incorporating these neat resins. A total of thirteen neat resins and sixteen carbon fiber-reinforced composites were characterized during the total time period this program was active. As new polymer resin systems were developed during this time, intended to fill needs in the aerospace industry for tough, strong, and stiff matrix materials for use in primary load carrying structures, they were incorporated into the test plan.

The Composite Material Research Group (CMRG) at the University of Wyoming has been an active participant in the screening of candidate polymer matrices for a number of years. Several methods for fabricating neat polymers into test specimens have been developed which have permitted the detailed investigations conducted during the period of this grant.

SECTION 2

SUMMARY OF RESULTS

This report presents the properties of the final three unreinforced (neat) resins and twelve composite material systems tested as part of this continuing program. The first two years were only concerned with neat resins [1,2]. The third year effort involved two additional neat resins and four carbon fiber-reinforced composites [3]. In this final phase of the project, three more neat resin systems were chosen for detailed mechanical property characterization. Also, twelve carbon fiber-reinforced unidirectional composite materials incorporating previously studied neat resin systems were chosen for mechanical property characterization.

The three final neat resins chosen for study were PEEK (polyetheretherketone) thermoplastic, Hexcel F155 rubber-toughened epoxy, and Hercules 8551-7 rubber-toughened epoxy. The twelve unidirectional carbon fiber composite systems tested were AS4/2220-1, AS4/2220-3, T500/R914, IM6/HX1504, T300/4901A (MDA), T700/4901A (MDA), T300/4901B (MPDA), T700/4901B (MPDA), APC2 (AS4/PEEK,ICI), APC2 (AS4/PEEK,Langley Research Center), AS4/8551-7, and AS4/$PISO_2$-TPI. The properties of the resin systems contained in the first eleven of these composites were determined during earlier phases of the study; the properties of the TPI resin system were not determined.

The PEEK matrix system was the only thermoplastic evaluated in the study, while the Hexcel F155 and the Hercules 8551-7 were rubber-toughened epoxies. All resin systems were supplied by

NASA-Langley; the epoxies were supplied in uncured bulk form and the PEEK thermoplastic in pellet form. The PEEK pellets were approximately 0.08 inch in diameter and averaged 0.12 inch long. All resin systems were cast into the various shapes required to prepare neat test specimens. Casting of the epoxy resin was performed using the same techniques developed previously by the Composite Materials Research Group, as discussed in detail in the first-year report [1]. The thermoplastic was formed into specimen blanks using a heated press method described in this report. These blanks were then machined into the required specimens.

All test results are reported in the tables of individual results in Appendix A. The tables of average values only include the values that satisfied the outlier rule. That is, if the coefficient of variation(s) for a group of results was greater than 10 percent, all values outside the range $\bar{x} \pm s$, were not included in the average.

2.1 Neat Resin Properties

Extensive mechanical characterization was completed on the three neat resin systems. The PEEK thermoplastic and the Hercules 8551-7 epoxy underwent testing at six different environmental conditions. Dry and moisture-saturated specimens were tested at 23°C (73°F), 82°C (180°F), and 121°C (250°F). These are the same conditions used to test the previous neat resins in this continuing study. Testing performed during the present study included tensile, Iosipescu shear, single-edge notched-bend (SEN) fracture toughness, coefficient of thermal expansion, and coefficient of moisture expansion tests. These tests allowed a comparison of material properties for all the resin systems studied. The testing of the Hercules 8551-7 epoxy also incorporated miniaturized tension and torsion rod specimens. The miniaturized testing was performed to evaluate the possibility of using specimens containing less material. The same tests, except for miniaturized testing, were used for the Hexcel F155 epoxy, but at slightly different environmental conditions. Dry, four percent moisture weight gain, and moisture-saturated specimens were tested at -54°C (-65°F), 23°C (73°F), and 71°C (160°F). The study of the Hexcel F155 epoxy was initiated as an add-on task by NASA-Langley, with distinctly different testing condition requirements. These data are included here for documentation purposes, and to permit comparisons with the other matrix systems. All of the neat resins tested as part of the entire study are listed and described in Table 1.

Tables 2 through 4 are repeated from Reference [3], with the addition of the PEEK thermoplastic and Hercules 8551-7 epoxy property averages for each of the six environmental conditions. Table 5 lists separately the material property averages for the Hexcel F155 neat epoxy. Tables 6 and 7 report the average material data derived from the miniaturized testing of the Hercules 8551-7 neat resin. These tables also compare the miniaturized specimen test results with those results obtained with full-sized specimens. Tables 1 through 7 thus provide a complete record of all material properties for the thirteen neat resins tested.

The PEEK thermoplastic performed very well at elevated temperature and moisture-saturated conditions. This material exhibited the highest tensile strength, tensile modulus and ultimate tensile strain of any resin tested at the 121°C, moisture-saturated condition. The shear

Table 1

Descriptions of Polymer Matrix Materials Tested

Resin System	Manufacturer	Description
3502	Hercules	Epoxy
5245-C	Narmco	Bismaleimide with Small Amount of Epoxy Additive for Tack, Drape and Toughness
BP807	American Cyanamid	Modified Epoxy-Multiphase Epoxy
CYCOM 1806	American Cyanamid	Toughened Epoxy
2220-1	Hercules	Toughened Epoxy
2220-3	Hercules	Toughened Multiphase Epoxy
R914	Ciba-Geigy Fibredux	Rubber-Toughened Epoxy
HX-1504	Hexcel	MY720 Epoxy with Hexcel Proprietary Catalyst/Hardener
4901A(MDA)	Union Carbide	Cycloaliphatic Epoxy Cured with 4, 4'-Methylenedianiline
4901B(MPDA)	Union Carbide	Epoxy Cured with Metaphenylene-Diamine
PEEK	Imperial Chemical	High Temperature Semi-Crystalline Thermoplastic
8551-7	Hercules	Rubber-Toughened Epoxy
F155	Hexcel	Rubber-Toughened Epoxy
$PISO_2$-TPI	Langley Research Center	Polyimide Sulfone/Polyimide Thermoplastic Blend

Table 2

Average Material Properties for Twelve Neat Resin Systems Tested at Room Temperature

Neat Resin System*	Moisture Condition	Tensile Strength (MPa)	Tensile Strength (ksi)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio
3502	DRY	41	6.0	3.8	0.55	1.0	0.36
	WET	36	5.2	3.5	0.51	1.2	0.43
5245-C	DRY	74	10.7	3.7	0.54	2.1	0.39
	WET	47	6.8	4.0	0.58	4.9	0.39
BP907	DRY	86	12.5	3.2	0.47	3.7	0.42
	WET	59	8.4	2.9	0.42	5.6	0.43
1806	DRY	88	12.8	3.1	0.44	3.2	0.39
	WET	78	11.2	3.0	0.44	5.1	0.46
2220-1	DRY	43	6.3	3.0	0.43	1.4	0.36
	WET	68	9.9	3.1	0.45	2.8	0.41
2220-3	DRY	46	6.7	3.0	0.44	1.5	0.36
	WET	67	9.7	3.1	0.45	3.3	0.43
R914	DRY	28	4.0	4.0	0.58	0.7	0.36
	WET	48	7.0	3.1	0.45	1.7	0.43
HX-1504	DRY	77	11.2	3.9	0.57	2.0	0.37
	WET	51	7.4	3.5	0.51	1.6	0.40
4901A (MDA)	DRY	109	15.8	4.8	0.70	2.1	0.41
	WET	79	11.5	3.6	0.52	4.6	0.40
4901B (MPDA)	DRY	97	14.1	5.6	0.81	1.7	0.33
	WET	9	1.3	0.8	0.11	0.8	0.48
PEEK	DRY	50	7.3	4.1	0.60	1.2	0.41
	WET	62	9.1	4.8	0.70	1.5	0.45
8551-7	DRY	88	12.7	3.1	0.45	5.2	0.36
	WET	68	9.8	2.8	0.40	3.1	0.36

* The properties for the first ten resin systems are repeated from Reference [3].

Table 2 (cont.)

Average Material Properties for Twelve Neat Resin Systems Tested at Room Temperature

Neat Resin System*	Moisture Condition	Shear Strength (MPa)	Shear Strength (ksi)	Ultimate Shear Modulus (GPa)	Ultimate Shear Modulus (Msi)	Shear Strain (percent)
3502	DRY	60	8.7	1.8	0.26	3.6
	WET	50	7.2	1.6	0.23	3.3
5245-C	DRY	56	8.1	1.0	0.14	5.9
	WET	68	9.8	1.4	0.20	4.9
BP907	DRY	41	5.9	1.2	0.17	3.3
	WET	44	6.4	1.1	0.16	5.6
1806	DRY	93	13.4	1.2	0.18	17.1
	WET	73	10.6	1.1	0.15	14.1
2220-1	DRY	77	11.1	1.5	0.22	6.2
	WET	68	9.9	1.5	0.22	6.7
2220-3	DRY	68	9.9	1.4	0.20	6.5
	WET	76	11.1	1.5	0.22	13.1
R914	DRY	80	11.6	1.5	0.22	5.9
	WET	69	10.0	1.4	0.21	6.3
HX-1504	DRY	98	14.2	1.8	0.26	8.1
	WET	66	9.6	1.5	0.22	5.8
4901A (MDA)	DRY	123	17.8	2.0	0.29	8.0
	WET	74	10.7	1.7	0.24	7.7
4901B (MPDA)	DRY	127	18.4	2.2	0.32	5.3
	WET	46	6.7	1.3	0.18	3.3
PEEK	DRY	62	9.3	1.6	0.23	4.3
	WET	71	10.4	1.6	0.24	>10.2
8551-7	DRY	57	8.3	1.4	0.20	5.1
	WET	49	7.1	1.2	0.17	5.8

* The properties for the first ten resin systems are repeated from Reference [3].

Table 2 (cont.)

Average Material Properties for Twelve Neat Resin Systems
Tested at Room Temperature

Neat Resin System*	Moisture Condition	Coefficient of Thermal Expansion ($10^{-6}/°C$)	Coefficient of Moisture Expansion ($10^{-3}/\%M$)	Equilibrium Moisture Content (%M)
3502	DRY	50.5	2.70	5.0
	WET	55.5		
5245-C	DRY	48.0	1.52	2.1
	WET	50.2		
BP907	DRY	54.8	2.29	5.1
	WET	58.0		
1806	DRY	58.2	2.53	2.9
	WET	63.2		
2220-1	DRY	55.6	2.51	3.8
	WET	58.6		
2220-3	DRY	53.6	2.96	4.0
	WET	57.5		
R914	DRY	58.4	3.02	7.0
	WET	62.6		
HX-1504	DRY	50.8	2.07	3.8
	WET	54.7		
4901A (MDA)	DRY	57.8	1.55	7.2
	WET	60.9		
4901B (MPDA)	DRY	61.6	1.00	10.2
	WET	94.1		
PEEK	DRY	50.8	7.73	0.5
	WET	54.6		
8551-7	DRY	46.7	3.09	2.0
	WET	70.0		

* The properties for the first ten resin systems are repeated from Reference [3].

Table 3

Average Material Properties for Twelve Neat Resin Systems Tested at 82°C

Neat Resin System*	Moisture Condition	Tensile Strength (MPa)	(ksi)	Tensile Modulus (GPa)	(Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio
3502	DRY	42	6.1	3.1	0.45	1.6	0.37
	WET	25	3.6	2.6	0.37	1.0	0.42
5245-C	DRY	62	9.0	3.4	0.50	2.1	0.40
	WET	57	8.2	3.1	0.45	3.9	0.42
BP907	DRY	67	9.7	2.8	0.40	5.4	0.42
	WET	2	0.3	0.1	0.01	8.2	0.43
1806	DRY	76	10.9	2.5	0.36	5.0	0.46
	WET	36	5.2	1.7	0.24	10.5	0.44
2220-1	DRY	73	10.6	2.6	0.38	2.1	0.36
	WET	46	6.7	2.1	0.30	3.7	0.43
2220-3	DRY	70	10.2	2.5	0.36	2.4	0.35
	WET	44	6.4	2.1	0.30	4.8	0.47
R914	DRY	32	4.6	3.2	0.46	1.2	0.37
	WET	32	4.6	2.1	0.30	1.6	0.40
HX-1504	DAY	71	10.3	3.3	0.48	2.4	0.36
	WET	48	6.9	2.8	0.40	2.0	0.41
4901A (MDA)	DRY	57	8.2	2.8	0.41	8.2	0.44
	WET	3	0.4	0.1	0.01	7.9	0.42
4901B (MPDA)	DRY	73	10.5	3.9	0.56	2.6	0.41
	WET**						
PEEK	DRY	78	11.3	3.8	0.55	5.0	0.44
	WET	66	9.5	3.9	0.56	1.9	0.39
8551-7	DRY	62	9.0	2.4	0.35	4.6	0.39
	WET	46	6.7	2.3	0.34	4.6	0.43

*The properties for the first ten resin systems are repeated from Reference [3].
**Property not measured at this environmental condition

Table 3 (cont.)

Average Material Properties for Twelve Neat Resin Systems Tested at 82°C

Neat Resin System*	Moisture Condition	Shear Strength		Shear Modulus		Ultimate Shear Strain
		(MPa)	(ksi)	(GPa)	(Msi)	(percent)
3502	DRY	70	10.2	1.6	0.23	5.5
	WET	46	6.6	1.0	0.14	4.5
5245-C	DRY	66	8.1	1.0	0.14	5.9
	WET	65	9.4	1.4	0.10	5.8
BP907	DRY	46	6.7	1.0	0.14	>6.0
	WET	5	0.7	0.2	0.03	>6.0
1806	DRY	65	9.5	1.0	0.14	15.0
	WET	45	6.5	0.7	0.10	20.7
2220-1	DRY	74	10.8	1.2	0.17	14.5
	WET	55	8.0	1.2	0.18	9.5
2220-3	DRY	66	9.6	1.1	0.16	12.8
	WET	50	7.2	1.3	0.19	12.8
R914	DRY	75	10.9	1.4	0.20	6.1
	WET	39	5.6	1.2	0.17	4.5
HX-1504	DAY	77	11.1	1.5	0.22	11.0
	WET	62	9.0	1.0	0.15	8.8
4901A (MDA)	DRY	74	10.8	1.4	0.21	7.5
	WET	5	0.7	0.1	0.02	11.5
4901B (MPDA)	DRY	95	13.8	2.1	0.30	5.0
	WET	2	0.3	0.1	0.01	14.8
PEEK	DRY	59	8.6	1.4	0.21	>12.0
	WET	55	8.0	1.6	0.23	>10.2
8551-7	DRY	48	7.0	1.2	0.17	> 8.4
	WET	35	5.1	0.9	0.14	10.5

*The properties for the first ten resin systems are repeated from Reference [3].

Table 4

Average Material Properties for Twelve Neat Resin Systems
Tested at 121°C

Neat Resin System*	Moisture Condition	Tensile Strength (MPa)	(ksi)	Tensile Modulus (GPa)	(Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio
3502	DRY	54	7.8	2.8	0.40	1.9	0.46
	WET	15	2.2	1.9	0.28	0.9	0.45
5245-C	DRY	76	11.0	3.1	0.45	5.0	0.40
	WET	28	4.0	0.9	0.13	8.2	0.49
BP907	DRY	1	0.1	2.6	0.38	8.2	0.41
	WET**						
1806	DRY	63	9.1	2.4	0.35	4.8	0.44
	WET	11	1.7	0.3	0.05	13.4	0.38
2220-1	DRY	60	8.7	2.2	0.32	4.3	0.42
	WET	23	3.4	1.0	0.15	5.2	0.49
2220-3	DRY	62	9.0	2.1	0.31	4.8	0.39
	WET	21	3.0	0.9	0.13	7.5	0.49
R914	DRY	19	2.8	0.7	0.10	6.9	0.44
	WET	8	1.2	0.3	0.04	7.0	0.49
HX-1504	DAY	62	9.0	2.7	0.39	3.5	0.37
	WET	16	2.3	0.9	0.13	7.9	0.49
4901A (MDA)	DRY	10	1.4	0.5	0.07	8.2	0.35
	WET**						
4901B (MPDA)	DRY	10	1.4	0.1	0.02	15.2	0.45
	WET**						
PEEK	DRY	58	8.4	3.5	0.51	6.3	0.44
	WET	56	8.1	3.4	0.49	>8.6	0.35
8551-7	DRY	48	6.9	2.2	0.32	5.6	0.37
	WET	17	2.6	0.8	0.12	7.8	0.65

*The properties for the first six resin systems are repeated from Reference [3].
**Material not tested due to highly degraded properties at this environmental condition

Table 4 (cont.)

Average Material Properties for Twelve Neat Resin Systems
Tested at 121°C

Neat Resin System*	Moisture Condition	Shear Strength (MPa)	Shear Strength (ksi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Ultimate Shear Strain (percent)
3502	DRY***					
	WET***					
5245-C	DRY	67	9.7	1.0	0.15	7.6
	WET	34	4.9	0.9	0.13	14.1
BP907	DRY	1	0.1	1.4	0.20	>6.0
	WET**					
1806	DRY	46	6.7	0.9	0.13	15.7
	WET	23	3.4	0.2	0.03	13.0
2220-1	DRY***					
	WET***					
2220-3	DRY***					
	WET***					
R914	DRY***					
	WET***					
HX-1504	DAY	54	7.8	1.1	0.16	11.7
	WET	37	5.4	6.8	0.98	7.9
4901A (MDA)	DRY	32	4.6	1.0	0.15	6.0
	WET**					
4901B (MPDA)	DRY	24	3.5	0.5	0.07	14.3
	WET**					
PEEK	DRY	50	7.3	1.4	0.21	>11.8
	WET	46	6.7	1.4	0.21	>10.2
8551-7	DRY	34	5.0	0.8	0.12	>10.0
	WET	20	2.9	0.8	0.12	>10.7

*The properties for the first ten resin systems are repeated from Reference [3].

**Material not tested due to highly degraded properties at this environmental condition

***Property not measured at this environmental condition

Table 5

Average Material Properties for Hexcel F155 Neat Epoxy

Moisture Condition	Test Temperature (°C)	Tensile Strength (MPa)	Tensile Strength (ksi)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)	Poisson's Ratio	Shear Strength (MPa)	Shear Strength (ksi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Ultimate Shear Strain (percent)
DRY	-54	72	10.5	4.1	0.60	1.9	0.38	53	7.6	1.8	0.26	3.0
	23	76	11.0	3.3	0.50	2.8	0.40	55	8.0	1.3	0.18	5.7
	71	67	9.7	2.7	0.39	4.2	0.41	43	6.3	1.0	0.14	6.5
4W%M	-54	68	9.9	4.1	0.60	1.7	0.36	37	5.4	1.7	0.25	2.7
	23	67	9.7	2.8	0.41	3.5	0.41	41	6.0	1.0	0.15	4.9
	71	22	3.2	1.0	0.14	3.1	0.38	22	3.2	0.7	0.10	9.9
SATURATED	-54	58	8.4	4.1	0.60	1.4	0.35	46	6.7	1.6	0.23	3.1
	23	58	8.4	2.8	0.41	3.2	0.38	41	5.9	1.0	0.14	5.9
	71	12	1.7	0.5	0.08	5.1	0.37	14	2.0	0.4	0.06	>5.9

Moisture Condition	Test Temperature (°C)	Coefficient of Thermal Expansion (10^{-6}/°C)	Coefficient of Moisture Expansion (10^{-3}/%M)	Equilibrium Moisture Content (%M)
DRY	23	64.3	3.14	4.9
4W%M	23	78.9		
SATURATED	23	84.8		

Table 6

Average Tensile Properties for 8551-7
Neat Epoxy Tested in the Dry Condition

Specimen Size	Test Temperature (°C)	Tensile Strength (MPa)	Tensile Strength (ksi)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Ultimate Tensile Strain (percent)
MINI	23	80	11.6	3.3	0.48	4.0
FULL	23	88	12.7	3.1	0.45	5.2
MINI	82	61	8.8	2.4	0.35	3.9
FULL	82	62	9.0	2.4	0.35	4.6
MINI	121	39	5.7	2.1	0.30	3.3
FULL	121	48	6.9	2.2	0.32	5.6

Table 7

Average Shear Properties for 8551-7
Neat Epoxy at Dry Test Conditions

Specimen Size	Test Temperature (°C)	Shear Strength (MPa)	Shear Strength (ksi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Shear Strain (percent)
MINI	23	79	11.5	1.1	0.16	>14.5
FULL	23	57	8.3	1.4	0.20	3.1
MINI	82	48	7.0	1.3	0.18	6.7
FULL	82	48	7.0	1.2	0.17	> 8.4
MINI	121	36	5.2	1.4	0.20	3.6
FULL	121	34	5.0	0.8	0.12	>10.0

strength and shear modulus average values at the hot/wet condition were also some of the highest recorded in this test program.

The Hexcel F155 epoxy, when compared to the other resins, exhibited material properties in the median range. The exceptions included the high temperature ultimate tensile strain values, which were above average. On the other hand, the shear test results were well below average. The shear strength values were some of the lowest yet achieved, while the shear modulus and shear strain values were well below average.

The 8551-7 epoxy tensile properties at the elevated temperature dry condition were below the average of the other resins tested. The moisture-saturated condition, both at room and elevated test temperatures, resulted in data in the midrange. All the 8551-7 shear test results were below the average of the other resins.

Tension and torsion tests were also performed on sets of miniaturized 8551-7 neat epoxy specimens. These tests produced results, for strength and modulus, equivalent to those of the full size specimens, although the strain results differed significantly. This testing successfully demonstrated the potential for reducing the amount of neat resin needed to perform mechanical characterization tests.

Coefficient of thermal expansion (CTE) testing was performed on both dry and moisture-saturated specimens. CTE's were measured over a wide temperature range, using a computer-controlled quartz glass tube dilatometer with an LVDT (linear variable differential transducer). The Hexcel F155 and the Hercules 8551-7 resins were tested over the temperature range of -40°C to 121°C (-40°F to 250°F), while the PEEK thermoplastic experienced a test temperature range of -40°C to 200°C

(-40°F to 392°F). In the dry condition, the Hexcel F155 and Hercules 8551-7 epoxies displayed a linear CTE over the test temperature range, while the PEEK was bilinear. As expected, at moisture saturation conditions the epoxies exhibited an increase in CTE. The 8551-7 remained linear but the Hexcel F155 became nonlinear. Moisture had little effect on the CTE response of the PEEK.

Coefficient of moisture expansion (CME) testing was performed on all three neat resin systems, from dry to saturation at 65°C (150°F). Moisture saturation levels were also measured, the Hexcel F155 equilibrium value being 4.9 percent by weight compared to 2.0 percent by weight for the 8551-7 epoxy and only 0.5 percent by weight for the PEEK thermoplastic.

The PEEK thermoplastic and the Hexcel F155 epoxy came closer to satisfying the isotropic relation between E, ν, and G than any of the resins tested in the first three studies [1,2,3]. The satisfaction was best for the PEEK material at all temperatures in the dry condition. The Hexcel F155 epoxy agreed best at the room temperature, dry condition. The Hercules 8551-7 epoxy only exhibited good agreement at the high temperature, dry condition.

Single-edge notched-bend (SEN) fracture toughness testing was also performed on the PEEK thermoplastic and 8551-7 neat resin systems. Variations in specimen quality had a distinct effect on the PEEK test values. The PEEK thermoplastic exhibited relatively high Mode I Critical Energy Release Rates (G_{IC}) when compared to values obtained for resins tested in previous studies [2,3]. The 8551-7 results were even higher for the room temperature dry, and moisture-saturated conditions. Average G_{IC} values are reported in Table 8.

Table 8

Average Fracture Toughness Values for Two Neat Polymer Resins

Resin System	Moisture Condition	Test Temperature (°C)	Mode I Strain Energy Release Rate, G_{IC} (J/m^2)	($in\text{-}lb/in^2$)
PEEK	Dry	23	751*	4.3
		82	4958	28.4
		121	7795	44.2
	Moisture-Saturated	23	541*	3.1*
		82	494*	2.8*
		121	9918	56.8
8551-7	Dry	23	1124	6.4
	Moisture-Saturated	23	1040	6.0

* Specimen failure surfaces had a granular appearance; all others had a homogenous appearance

Specimen fabrication and test methods are presented in Section 3. All experimental results are presented in detail in Sections 4 and 5 of this report. Scanning electron microscope photographs are presented in Section 6, and conclusions in Section 7. Appendix A contains tables of individual test specimen results for all tests. Individual stress-strain curves are presented in Appendix B.

2.2 Unidirectional Composite Properties

Table 9 shows the average material properties for the twelve carbon fiber-reinforced composite materials tested. All of the composite testing was conducted at the 23°C and 100°C dry conditions indicated in Table 9. Additional testing was performed on the AS4/8551-7 and the AS4/$PISO_2$-TPI composites at moisture-saturated conditions. Table 10 lists the dry and moisture-saturated specimen average test results for these last two composites.

Table 9

Average Properties of the Twelve Carbon Fiber, Polymer Matrix Unidirectional Composite Materials (Tested in the Dry Condition)

Material System	Test Temp. (°C)	Axial Tensile Strength (MPa)	Axial Tensile Strength (ksi)	Axial Tensile Modulus (GPa)	Axial Tensile Modulus (Msi)	Ultimate Axial Tensile Strain (percent)	Poisson's Ratio
AS4/2220-1	23	1931	280	118	17.1	1.3	0.32
	100	2060	299	136	19.7	1.5	0.46
AS4/2220-3	23	1946	282	123	17.8	0.4	0.16
	100	1855	269	144	20.9	1.3	0.59
T500/R914	23	1441	209	126	18.3	0.3	0.35
	100	1586	230	140	20.4	1.1	0.53
IM6/HX1504	23	2712	393	156	22.7	0.7	0.26
	100	3172	460	155	22.5	1.6	0.46
T300/4901A (MDA)	23	1964	285	133	19.4	1.2	0.21
	100	1752	254	145	21.0	1.2	0.61
T700/4901A (MDA)	23	2634	382	150	21.8	1.7	0.24
	100	2166	314	154	22.3	1.5	0.56
T300/4901B (MPDA)	23	1853	269	138	20.0	0.9	0.26
	100	1256	182	123	17.8	1.9	0.46
T700/4901B (MPDA)	23	1624	236	129	18.6	1.2	0.31
	100	1225	178	109	15.8	1.2	0.25
APC2(AS4/ PEEK,ICI)	23	2070	300	142	20.6	1.3	0.25
	100	2008	291	131	18.9	1.3	0.50
APC2(AS4/ PEEK,LaRC)	23	2550	370	160	23.2	1.6	0.31
	100	1134	164	149	21.6	0.8	0.45
AS4/8551-7	23	1825	265	128	18.6	0.8	0.47
	100	1888	275	139	20.2	1.4	0.30
AS4/PISO$_2$-TPI	23	1762	256	120	17.4	1.4	0.31
	100	1650	239	135	19.6	1.1	0.30

Table 9 (Continued)

Material System	Test Temp. (°C)	Transverse Tensile Strength (MPa)	(ksi)	Transverse Tensile Modulus (GPa)	(Msi)	Ultimate Transverse Tensile Strain (Percent)
AS4/2220-1	23	30	4.3	9.4	1.4	0.3
	100	28	4.0	7.4	1.1	0.4
AS4/2220-3	23	48	7.0	9.6	1.4	0.5
	100	34	4.9	7.7	1.1	0.4
T500/R914	23	48	6.9	8.8	1.3	0.6
	100	26	3.8	6.5	1.0	0.4
IM6/HX1504	23	55	7.9	8.9	1.3	0.6
	100	48	7.0	7.8	1.1	0.8
T300/4901A (MDA)	23	74	10.8	10.8	1.6	0.7
	100	38	5.4	5.9	0.9	1.1
T700/4901A (MDA)	23	67	9.7	11.0	1.6	0.6
	100	27	3.9	6.1	0.9	0.5
T300/4901B (MPDA)	23	60	8.7	11.1	1.6	0.5
	100	17	2.5	1.6	0.2	2.1
T700/4901B (MPDA)	23	60	8.8	12.0	1.7	0.5
	100	24	3.5	3.8	0.6	1.6
APC2(AS4/ PEEK,ICI)	23	79	11.4	9.6	1.4	0.9
	100	66	9.6	8.6	1.2	1.1
APC2(AS4/ PEEK,LaRC)	23	82	12.0	10.3	1.5	0.9
	100	14	2.0	1.9	0.3	0.8
AS4/8551-7	23	66	9.6	9.2	1.3	0.7
	100	58	8.4	7.4	1.1	0.9
AS4/$PISO_2$-TPI	23	33	4.8	8.5	1.2	0.4
	100	44	6.4	9.2	1.3	0.5

Table 9 (Continued)

Material System	Test Temp. (°C)	Shear Strength (MPa)	Shear Strength (ksi)	Shear Modulus (GPa)	Shear Modulus (Msi)	Ultimate Shear Strain (Percent)
AS4/2220-1	23	110	15.9	5.2	0.75	>11.7
	100	81	11.7	4.3	0.62	>11.7
AS4/2220-3	23	99	14.4	5.1	0.74	>11.7
	100	76	11.1	4.3	0.62	>11.7
T500/R914	23	101	14.6	5.5	0.79	9.1
	100	71	10.3	3.9	0.57	> 9.3
IM6/HX1504	23	119	17.3	5.8	0.84	>11.7
	100	93	13.5	5.0	0.72	>11.7
T300/4901A (MDA)	23	102	14.8	7.1	1.02	4.4
	100	56	8.1	3.5	0.51	>11.7
T700/4901A (MDA)	23	106	15.3	6.9	1.00	8.3
	100	55	7.9	3.4	0.50	>11.7
T300/4901B (MPDA)	23	98	14.2	7.4	1.07	5.2
	100	34	4.9	0.8	0.10	>10.3
T700/4901B (MPDA)	23	108	15.6	8.3	1.20	5.2
	100	39	5.8	2.3	0.34	> 8.2
APC2 (AS4/ PEEK,ICI)	23	115	16.7	6.0	0.87	>11.7
	100	91	13.2	4.8	0.75	>11.7
APC2 (AS4/ PEEK,LaRC)	23	113	16.4	4.9	0.71	>11.8
	100	83	12.0	5.2	0.76	>11.5
AS4/8551-7	23	90	13.0	4.0	0.58	> 2.3
	100	76	11.1	4.4	0.63	>10.2
AS4/$PISO_2$-TPI	23	132	19.1	6.5	0.95	> 6.9
	100	110	16.0	5.4	0.78	>13.6

Table 9 (Continued)

Material System	Test Temp. (°C)	Transverse Coefficient of Thermal Expansion (10^{-6}/°C)	Transverse Coefficient of Moisture Expansion (10^{-3}/%M)
AS4/2220-1	23	36.2	2.92
	100	42.4	
AS4/2220-3	23	36.4	4.49
	100	42.6	
T500/R914	23	37.5	3.65
	100	42.9	
IM6/HX1504	23	32.1	2.96
	100	36.7	
T300/4901A	23	35.4	4.37
(MDA)	100	46.9	
T700/4901A	23	37.8	6.38
(MDA)	100	49.3	
T300/4901B	23	32.2	*
(MPDA)	100	85.2	
T700/4901B	23	34.2	*
(MPDA)	100	60.0	
APC2 (AS4/	23	40.2	3.76
PEEK,ICI)	100	40.2	
APC2 (AS4/	23	33.2	3.10
PEEK,LaRC)	100	33.2	
AS4/8551-7	23	31.4	4.10
	100	31.4	
AS4/$PISO_2$-TPI	23	22.3	*
	100	22.3	

*Data not available

Table 10

Average Properties of Two Carbon Fiber, Polymer Matrix Unidirectional Composite Materials Tested at Moisture-Saturated Conditions

Material System	Test Temp.	Axial Tensile Strength		Axial Tensile Modulus		Ultimate Axial Tensile Strain	Poisson's Ratio	Transverse Tensile Strength		Transverse Tensile Modulus	
	(°C)	(MPa)	(ksi)	(GPa)	(Msi)	(percent)		(MPa)	(ksi)	(GPa)	(Msi)
AS4/8551-7	23	1931	280	118	17.1	1.3	0.32	30	4.3	9.4	1.4
	100	2060	299	136	19.7	1.5	0.46	28	4.0	7.4	1.1
AS4/$PISO_2$-TPI	23*										
	100	1565	227	120	17.3	1.3	0.44	27	3.9	9.7	1.4

Material System	Test Temp.	Ultimate Transverse Tensile Strain	Shear Strength		Shear Modulus		Ultimate Shear Strain
	(°C)	(Percent)	(MPa)	(ksi)	(GPa)	(Msi)	(Percent)
AS4/8551-7	23	0.3	110	15.9	5.2	0.75	>11.7
	100	0.4	81	11.7	4.3	0.62	>11.7
AS4/$PISO_2$-TPI	23*						
	100	0.3	102	14.7	5.7	0.82	>18.6

*Material not tested at this condition.

SECTION 3

SPECIMEN FABRICATION AND TEST METHODS

3.1 Introduction

An in-depth test program was completed for the three unreinforced (neat) resin systems and the twelve carbon fiber-reinforced composite materials identified in Sections 1 and 2. Table 11 shows the PEEK and Hercules 8551-7 neat resin test matrix and associated environmental conditions. Six combinations of temperature and moisture were used for neat resin mechanical characterization testing. Table 12 shows

Table 11

Neat Resin Test Matrix

Test Method	Moisture Condition	Test Temperature 23°C	82°C	121°C
Tension	Dry	5	5	5
	Moisture-Saturated	5	5	5
				30 total
Shear	Dry	5	5	5
	Moisture-Saturated	5	5	5
				30 total
Fracture Toughness	Dry	5	5	5
	Moisture-Saturated	5	5	5
				30 total
Coefficient of Thermal Expansion	Dry	3	-40°C to 205°C	
	Moisture-Saturated	3	-40°C to 205°C	
				6 total
Coefficient of Moisture Expansion	98%RH	65°C, Dry to Saturation		
				6 total
		102 Specimens for Each Resin System		

Table 12

Hexcel F155 Neat Resin Test Matrix

Test Method	Moisture Condition	Test Temperature -54°C	23°C	71°C
Tension	Dry	5	5	5
	4W%M	5	5	5
	Moisture-Saturated	5	5	5
			45 total	
Shear	Dry	5	5	5
	4W%M	5	5	5
	Moisture-Saturated	5	5	5
			45 total	
Coefficient of Thermal Expansion	Dry	3	-40°C to 121°C	
	4W%M	3	-40°C to 121°C	
	Moisture-Saturated	3	-40°C to 121°C	
			9 total	
Coefficient of Moisture Expansion	98%RH	65°C, Dry to Saturation		
			6 total	
		105 Specimens for this Resin System		

the test matrix for the Hexcel F155 rubber-toughened epoxy. These tests were performed at different test temperatures than for any previous resin system. The testing of the Hexcel F155 epoxy was originally a separate project. The Hexcel F155 epoxy project was combined with this project in order to increase the number of different resins being compared.

Miniaturized tension and torsion tests were also performed on the 8551-7 neat epoxy. Dry specimens were tested at three temperatures, viz., 25°C, 82°C, and 121°C.

Table 13 shows the carbon fiber-reinforced composite test matrix. The composite mechanical characterization testing was performed in the dry condition at two temperatures.

Table 13

Carbon Fiber-Reinforced Unidirectional Composite Test Matrix

Test Method	Test Temperature* 23°C	100°C
Axial Tension	3	3
Transverse Tension	3	3
Iosipescu Shear	3	3
Transverse Coefficient of Thermal Expansion	3 (-40°C to 121°C)	
Transverse Coefficient of Moisture Expansion	6 (65°C, Dry to Saturation)	
	27 Specimens of Each Composite System	
Total for Twelve Composite Systems:	324 Specimens	

*All testing performed on dry specimens

testing was performed on moisture-saturated specimens for two of the twelve composite systems.

Neat resin specimens were cast into test configurations from bulk resin. Composite test specimens were cut from unidirectional plates supplied by NASA-Langley. Dry test specimens were stored in desiccators prior to testing. Wet test specimens were suspended over distilled water in sealed containers at 74°C until fully moisture saturated. Periodic weighing of these specimens was performed to monitor weight gain versus time, to determine when moisture saturation was achieved.

All static testing was performed using an Instron Model 1125 electromechanical universal testing machine. A BEMCO Model FTU 3.8 environmental chamber was used to maintain the desired elevated test temperatures during testing. A Hewlett-Packard Model 21 MX-E minicomputer was used to record and reduce all test data. A Control Data Corporation CYBER 760 mainframe computer system was used to generate all plots of material properties and groupings of stress-strain plots. The summary bar charts were produced on the DEC VAX 11/750 using the Proplot graphics software.

3.2 Cure Cycles for Neat Resins

Molding procedure is a better term to describe the process for preparing specimens using the PEEK thermoplastic compound. The PEEK specimen blanks were prepared using a specially built compression mold. Figure 1 shows the unassembled view of this mold. To form a specimen blank, the mold was first filled with PEEK pellets that had been washed in acetone. The mold was bolted together and the piston was loaded with weights to produce an approximately 50 psi mold pressure. A vacuum line was attached to the mold cavity and the assembly was placed into a 370°C oven. When the piston quite moving the oven temperature and vacuum were shut off. The mold was allowed to cool overnight before disassembly. After some experimentation, this method produced homogenous, void-free specimen blanks. These blanks were then machined into test specimens.

The Hexcel F155 and Hercules 8551-7 neat resin specimens were cast using the same types of steel molds used in the first three years of this study [1,2,3]. The cure cycle recommended by the resin manufacture was used. This included, for the Hexcel F155 epoxy, melting the frozen resin at 60-70°C for two hours in an air circulating oven under 20-24 in Hg vacuum. The molten epoxy was then poured into steel molds preheated to 70°C. The filled molds were then placed in a vacuum oven at 65°C and

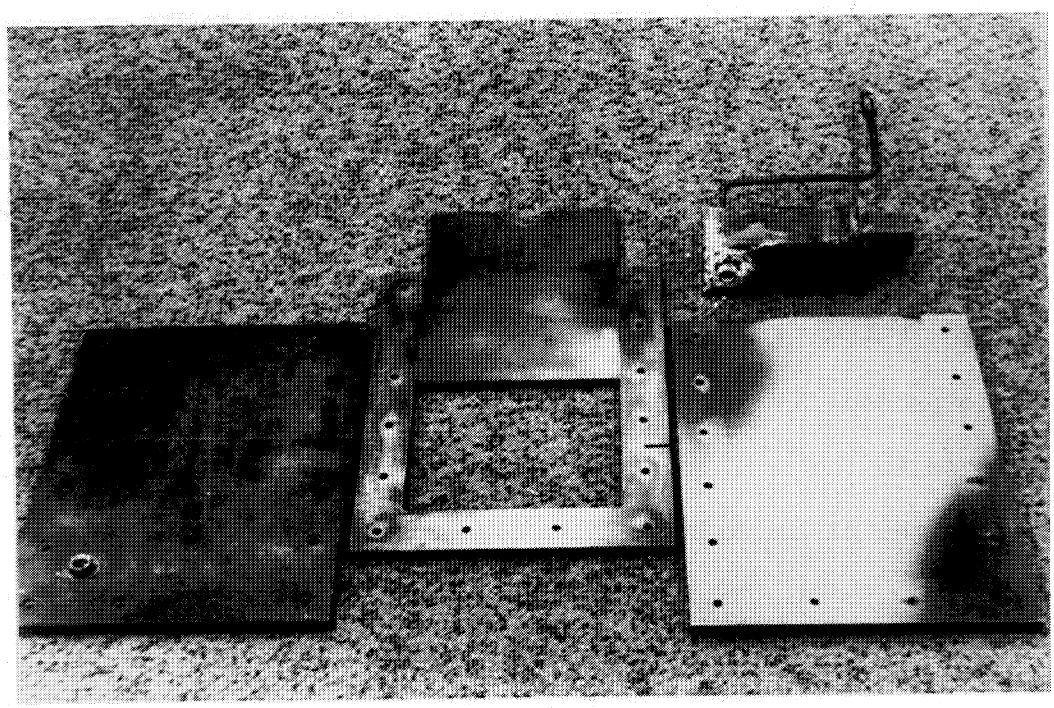

Figure 1. Steel Mold Used to Form the PEEK Thermoplastic Specimen Blanks.

20-24 in Hg for 15 to 30 minutes; until all bubbles in the epoxy were removed or existed only on the top of the mold. The epoxy was then cured in the same oven at 127°C for 90 minutes. The vacuum was discontinued when the oven temperature reached 77°C. The mold was allowed to cool in the oven before removing the specimens.

The Hercules 8551-7 epoxy was subjected to repeated 30 second microwave bursts until molten. The resin was degassed once by applying 20-24 in. Hg vacuum for several minutes. The resin was then poured into steel molds preheated to 100°C. The filled molds were then placed in a vacuum oven at 100°C and full vacuum was repeatedly applied and released for one hour. The epoxy was then cured in the same oven at 177°C for 120 minutes. Vacuum was discontinued when the oven temperature reached 100°C. The molds were allowed to cool in the oven before removing the specimens.

3.3 Neat Resin Specimen Fabrication

A standard dogbone-shaped specimen was used for all neat resin tensile testing. Specimens were nominally 152 mm (6 in) long by 5.1 mm (0.20 in) wide in the gage section, and 2.5 mm (0.1 in) thick. Each specimen was instrumented with a longitudinal extensometer to measure axial strain. This enabled the generation of complete stress-strain curves. A second extensometer was used to measure the transverse strain. Poisson's ratio was then calculated using the measured longitudinal and transverse strains. Figure 2 shows the extensometer arrangement used on each neat resin tensile specimen.

The Iosipescu shear test method as described in References [4,5] was used for all neat resin shear testing. Specimens were nominally

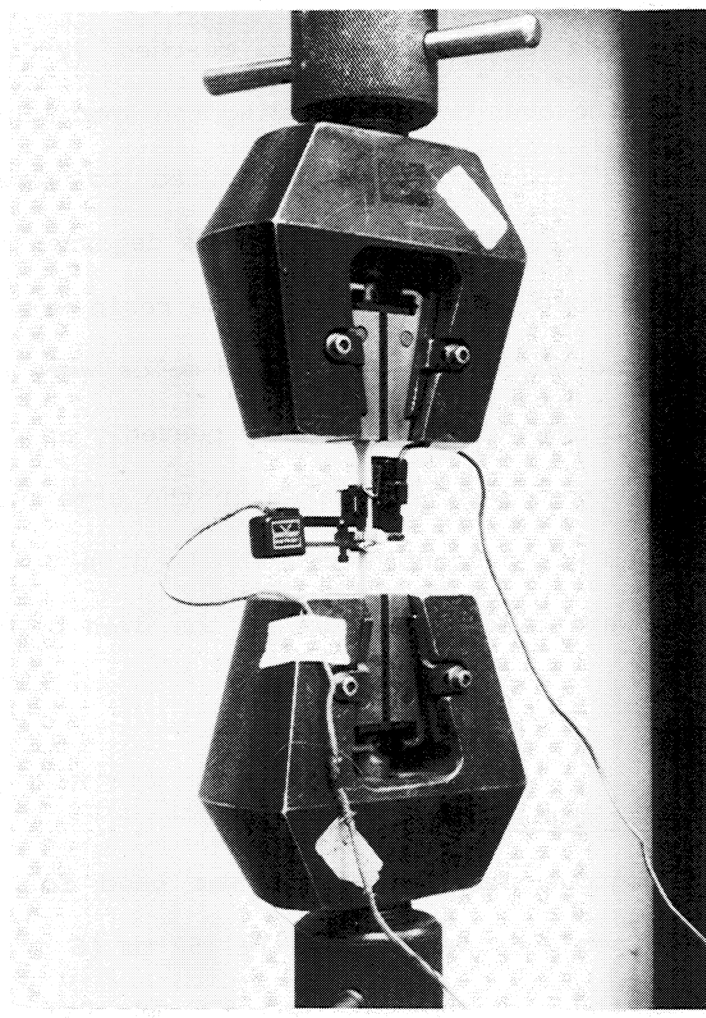

Figure 2. Typical Extensometer Arrangement on a Neat Resin Tension Specimen.

76 mm (3.0 in) long by 19 mm (0.75 in) wide by 2.5 mm (0.1 in) thick. Figure 3 shows a typical specimen mounted in the Iosipescu shear test fixture. A 90° notch was ground in each edge of the specimen and then a two-element strain gage rosette was bonded in the gage section to measure shear strain.

Neat resin fracture toughness testing was performed on the neat resins using the Single-Edge Notched-Bend (SEN) test method described in ASTM Standard E399 [6]. Test specimen blanks were molded the same way as the tensile specimen blanks. The test specimens were machined to size, being nominally 152 mm (6.0 in) long, 15.2 mm (0.6 in) wide, and 7.6 mm (0.3 in) thick. This thickness was three times the tensile specimen thickness, allowing the assumption of plane strain in the G_{IC} calculation. Three evenly spaced notches were cut along one edge of each specimen. This enabled one 15.2 mm (6.0 in) long rectangular specimen to be used for three fracture toughness tests. A water cooled abrasive blade was used for this operation. Figure 4 shows the three-point bend fixture used to test the fracture toughness specimens. Just prior to testing each specimen, a razor blade cooled in liquid nitrogen was used to produce the small crack tip in the root of the sawcut notch. The crack tip, produced by a light tap on the razor blade, was required for this test to be valid. Some experimentation is required each time a new resin system is tested, to acquire a feel for the proper tapping force on the razor blade. Too hard of a tap will result in a broken specimen while too soft a tap will result in an unsatisfactory crack tip and an abnormally high apparent toughness value.

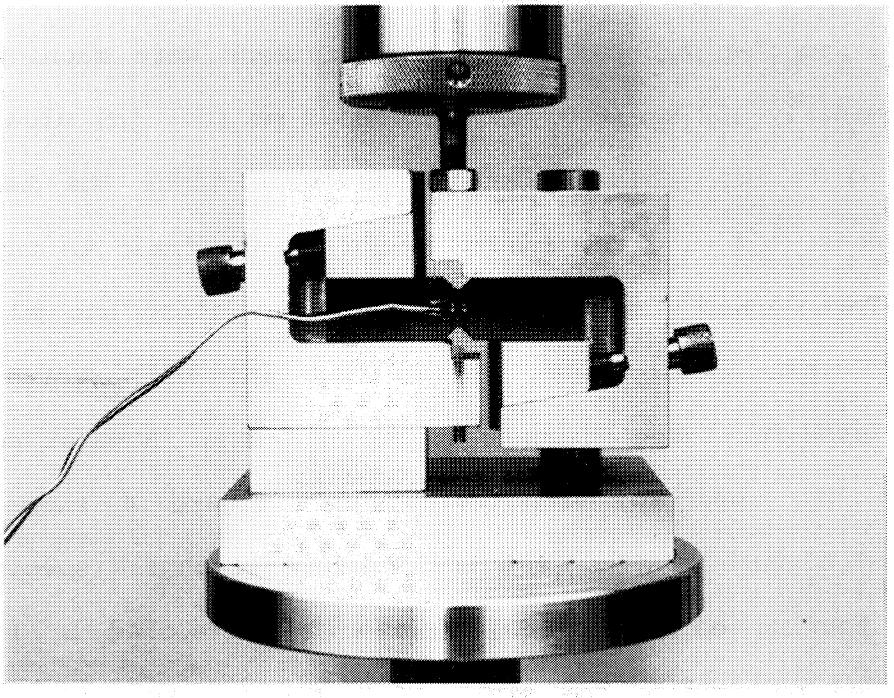

Figure 3. Iosipescu Shear Specimen Mounted in the Test Fixture.

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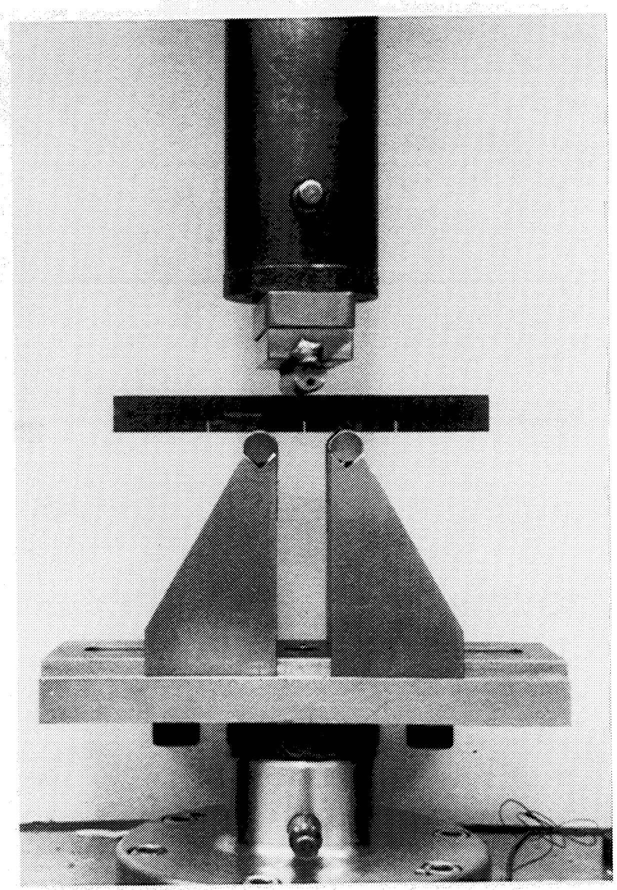
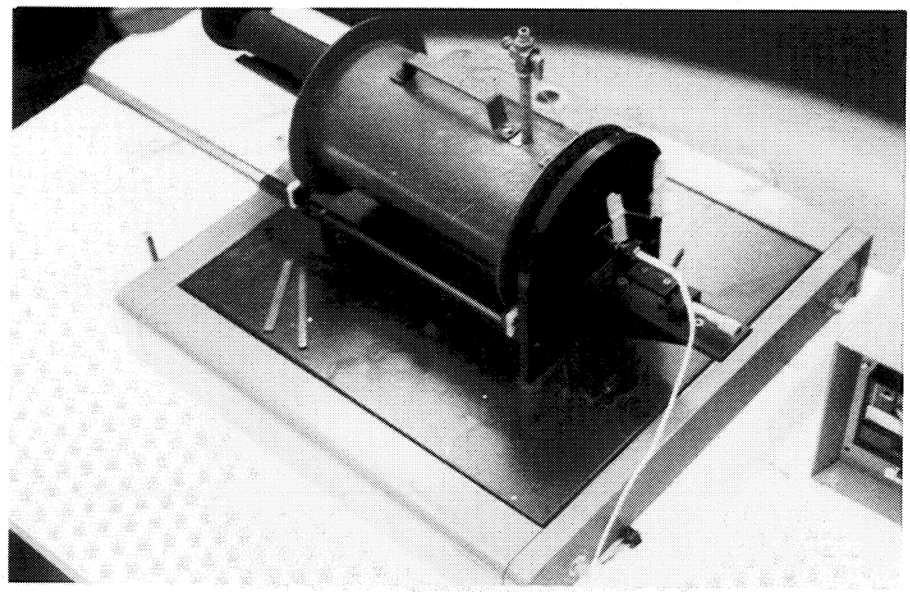
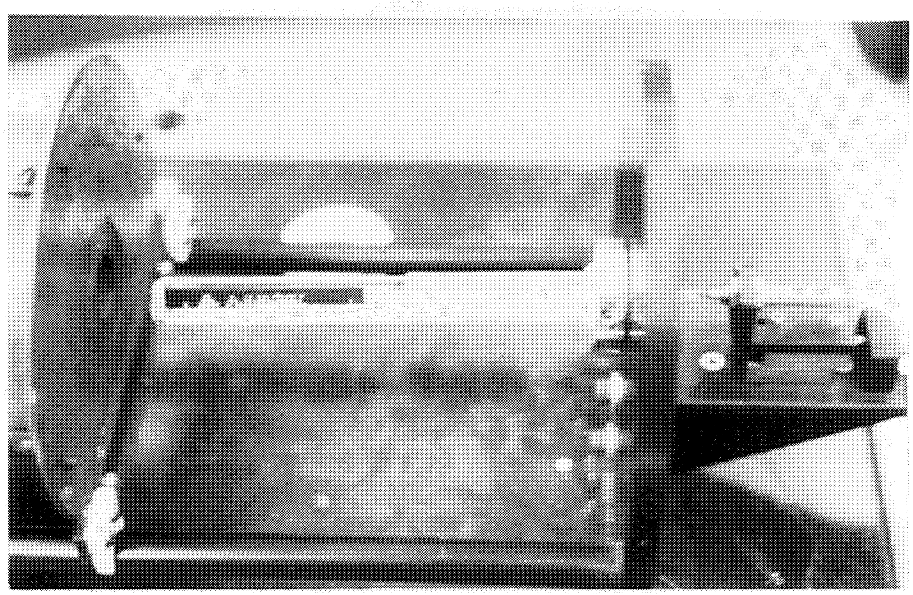


Figure 4. Three Point Bend Fixture Used for Single-Edge Notched-Bend Fracture Toughness Testing.



a) Overall View



b) Close-up of Installed Specimen

Figure 5. Quartz-Tube Dilatometer Thermal Expansion Apparatus.

At least three specimens of each neat resin system were used to measure coefficients of thermal expansion (CTE). Specimens were 127 mm (5.0 in) long by 9.5 mm (0.375 in) wide. All testing was performed using a microprocessor-controlled quartz-tube dilatometer with an LVDT. Figure 5 shows the CTE test apparatus. Data were acquired on 5 1/4" floppy disks and later transferred to a CYBER 760 computer for reduction and plotting. A minimum of two thermal excursions of each dry or moisture-saturated specimen were performed, to verify reproductibility. Only the data from the second thermal excursion are reported here. The PEEK thermoplastic was subjected to a thermal excursion of -40°C to 205°C, while the Hexcel F155 epoxy experienced a thermal excursion of -50°C to 70°C and the Hercules 8551-7 epoxy was exposed to a thermal excursion of -40°C to 120°C. A linear regression curve-fit was performed on the length change versus temperature data to obtain the CTE for the specimen tested.

Coefficient of moisture expansion (CME) measurements were performed on the three neat resin systems, from dry to moisture saturation at 65°C. A constant relative humidity of 98 percent was maintained using distilled water in plexiglass moisture chambers. All CME tests were conducted using the automated moisture expansion test facility shown in Figure 6. CME measurements were accomplished by using two identical specimens for each test. Both specimens were 70 mm (2.75 in) square, surface ground to a thickness of 0.9 mm (0.035 in). This large square specimen of very small thickness is used to allow the assumption of one-dimensional diffusion during the moisture absorption process (i.e., edge effects are negligible). One specimen was suspended from an electronic balance, to monitor the weight gain due to moisture uptake as

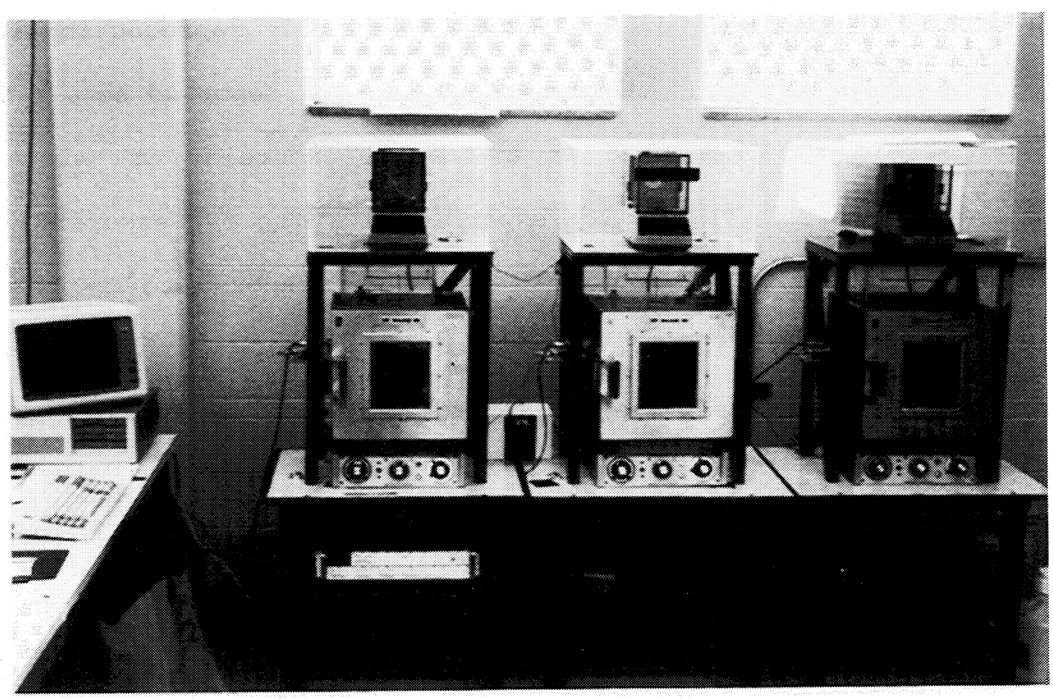


Figure 6. Typical Moisture Expansion Coefficient Chambers with Electronic Balances on Top and LVDT's Mounted on the Side.

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a function of time. A second identical specimen was placed in a quartz-tube dilatometer with an LVDT to measure the in-plane linear expansion.

Miniaturized tension and torsion tests were also performed on the Hercules 8551-7 neat epoxy. Since there are often only limited amounts of experimental resins available for preliminary material characterization, specimen miniaturization was evaluated here as a method of maximizing the amount of information obtained.

A miniaturized dogbone-shaped specimen was used for tensile testing of neat 8551-7 epoxy. Specimens were nominally 76 mm (3 in) long by 2.5 mm (0.1 in) wide in the gage section, and 2.5 mm (0.1 in) thick. Each specimen was instrumented with a longitudinal extensometer to measure strain. This enabled the generation of complete stress-strain curves. A full-size tensile specimen has a nominal weight of 4 grams compared to only 1.5 grams for the miniature specimen.

A miniaturized version of the torsional shear method described in Reference [1] was used for the 8551-7 neat resin shear testing. Specimens were nominally 102 mm (4 in) long with a 51 mm (2 in) gage section. The gage section had a nominal diameter of 5.0 mm (0.2 in). The angle of twist of the gage section was measured using a RVDT (rotary variable differential transducer). This enabled the generation of complete shear stress-shear strain curves. The full-sized torsion rod used in previous studies nominally weighed 20 grams, compared to only 3 grams for the miniaturized torsion specimen.

3.4 Composite Specimen Fabrication

The twelve carbon fiber-reinforced composites tested during this program were cut from plates supplied by NASA-Langley. A water-cooled abrasive saw was used to cut the panels into 0° tension, 90° tension, 0° Iosipescu shear, 90° coefficient of thermal expansion, and 90° coefficient of moisture expansion specimens. All specimens were stored in desiccators prior to testing. Moisture-saturated specimens were suspended over distilled water in sealed containers at 74°C until fully saturated. Periodic weighing of these specimens was performed to monitor weight gain versus time, to determine when moisture saturation was achieved.

All static testing was performed using an Instron Model 1125 electromechanical testing machine. A BEMCO Model FTU 3.8 environmental chamber was used to maintain the desired elevated test temperatures. A Hewlett-Packard Model 21 MX-E mini-computer was used to record and reduce all data. A CDC Cyber 760 mainframe computer was used to generate all plots of material properties and groupings of stress-strain plots. The summary bar charts were generated on a DEC VAX 11/750 with VMS operating system, using the Proplot graphics package.

A standard straight-sided tabbed specimen, as described in ASTM Standard D3039 [7], was used for all longitudinal tension testing. The specimens were 300 mm (9 in) long by 12.7 mm (0.5 in) wide by 1.0 mm (0.04 in) thick. Each specimen had glass fabric/epoxy tabs 64 mm (2 1/2 in) long bonded on each end to ensure adequate gripping during testing. Instrumentation for each test included two extensometers, one to measure axial strain and a second to measure transverse strain. Complete stress-strain curves were generated. Poisson's ratio was calculated using the measured longitudinal and transverse strains. Figure 7 shows the typical extensometer arrangement used on the longitudinal tensile specimens.

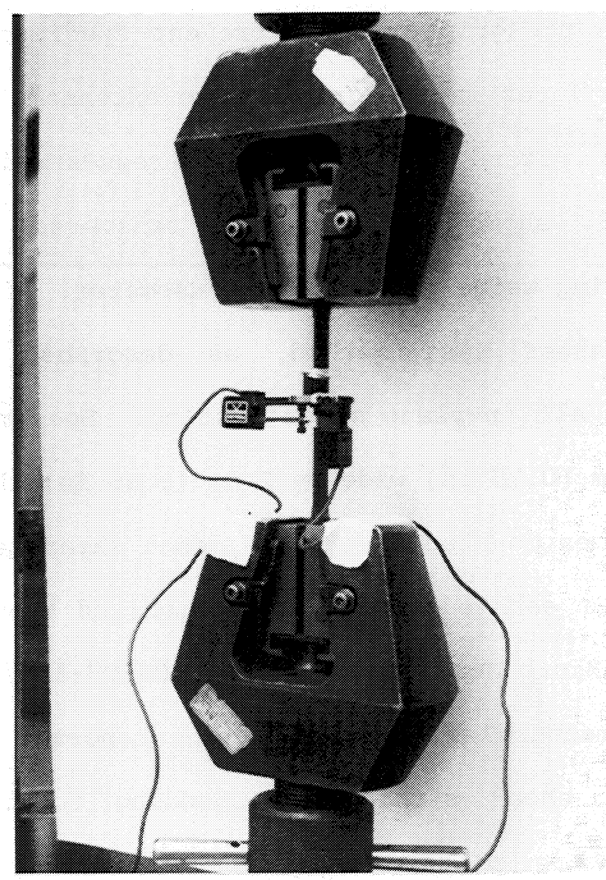

Figure 7. Typical Extensometer Arrangement used on the Unidirectional Composite Longitudinal Tension Test Specimens.

Standard, straight-sided, untabbed specimens, as described in ASTM Standard D3039 [7], were used for all transverse tension testing. Specimens were 127 mm (5.0 in) long by 25 mm (1.0 in) wide by 2.0 mm (0.08 in) thick. Strips of 120 grit emery cloth were placed between the specimen and grips in the grip areas to prevent specimen damage and to preclude premature failures in the grips. One extensometer was mounted on each specimen to record the complete stress-strain response to failure. Figure 8 shows a typical transverse tension test configuration, including wedge grips and extensometer.

The Iosipescu shear test method, as described in References [4,5,8], was used for all in-plane shear testing. Specimens were 76 mm (3.0 in) long by 19 mm (0.75 in) wide by 2 mm (0.08 in) thick. Figure 9 shows a typical specimen mounted in the Iosipescu shear test fixture. A 90° notch was ground in each edge of the specimen and then a two-element strain gage rosette, Micro-Measurements, EA-06-062TV-350, was bonded in the gage section to measure shear strain. The reported ultimate shear strain value is the shear strain corresponding to the peak shear strength. For the more plastic materials, strain gage saturation occasionally occurred before the ultimate strength was reached and therefore no ultimate shear strain could be reported.

Transverse coefficient of thermal expansion (CTE) test specimens were 127 mm (5.0 in) long by 9.5 mm (0.375 in) wide by 2.0 mm (0.08 in) thick. Testing was performed using a microprocessor-controlled quartz tube dilatometer with an LVDT. The apparatus is shown in Figure 5. Axial thermal expansion tests were not performed because of the very low values of CTE expected, these being below the reasonable sensitivity of the dilatometer apparatus. Two thermal excursions

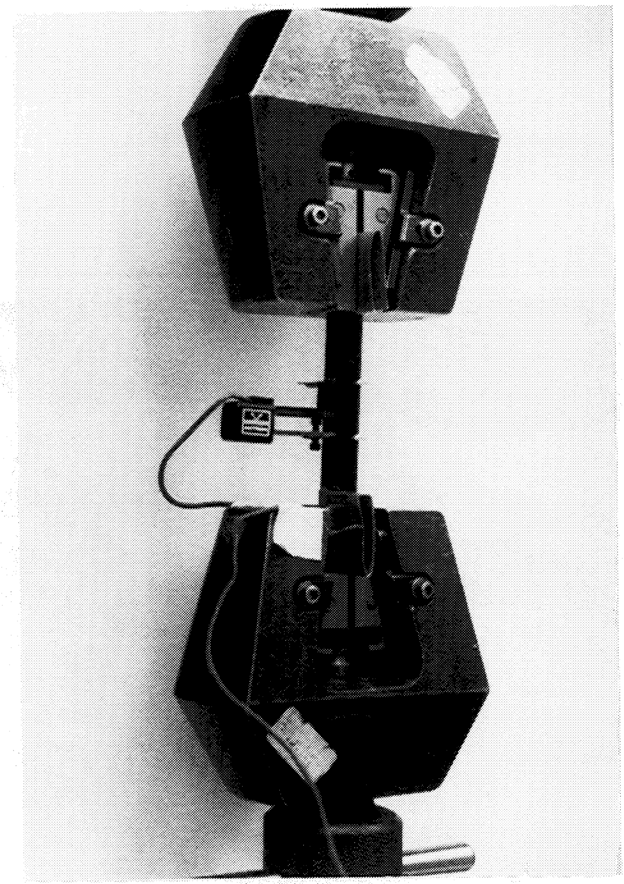

Figure 8. Composite Transverse Tension Test Configuration.

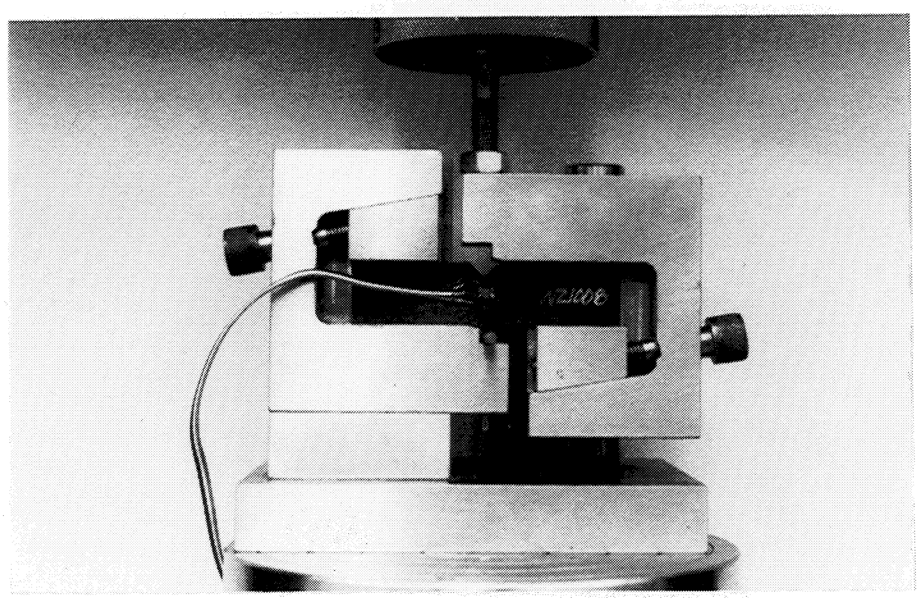

Figure 9. Iosipescu Shear Specimen Mounted in the Test Fixture.

between -40°C and 121°C were performed on each of three test specimens for each material. The one exception was the APC2 material, which was subjected to thermal excursions of -40°C to 205°C. Data were acquired only on the heat up portion of the cycle. A linear regression curve-fit was performed on the length versus temperature data to obtain a CTE value for each specimen.

Transverse coefficient of moisture expansion specimens were 70 mm (2.75 in) square by 0.9 mm (0.035 in) thick. Only transverse CME tests were performed on the composites because of the limited sensitivity of the quartz tube dilatometer, as previously discussed. All CME tests were performed at 98% relative humidity and 65°C, from dry to saturation. The procedure is described in Section 3.3 of this report.

SECTION 4

NEAT RESIN TEST RESULTS

4.1 Neat Resin Tensile Test Results

Properties measured included Young's modulus, E, ultimate stress, σ_u, ultimate strain, ε_u, and Poisson's ratio, ν. Complete stress-strain curves to failure were recorded. Individual test results and stress-strain curves are included in the Appendices. Summary tables were presented in Section 2. This section details the average results obtained for the three resin systems. First, the test results for the PEEK (polyetheretherketone) thermoplastic are presented; then the test results for the Hercules 8551-7 and Hexcel F155 rubber-toughened epoxies will be discussed.

Average tensile strengths for the PEEK neat resin are shown in Figure 10 for the three test temperatures and two moisture conditions. It should be noted that all mechanical testing was performed at test temperatures below the 143°C glass transition temperature for neat PEEK. The PEEK thermoplastic maintained strength with increasing temperature both when dry and when moisture-saturated. Moisture saturation did not appear to affect tensile strength significantly. At the 23°C test temperature, the moisture-saturated specimen results were 20 percent higher than the dry specimen results at that temperature. But at the 82°C test temperature,the results of the dry testing were 16 percent higher then the moisture-saturated testing, while at 121°C, the moisture-saturated and dry results were within 4 percent of each other.

Compared to the previously tested resins, the PEEK neat resin tensile strengths were average. The 23°C, dry results were below

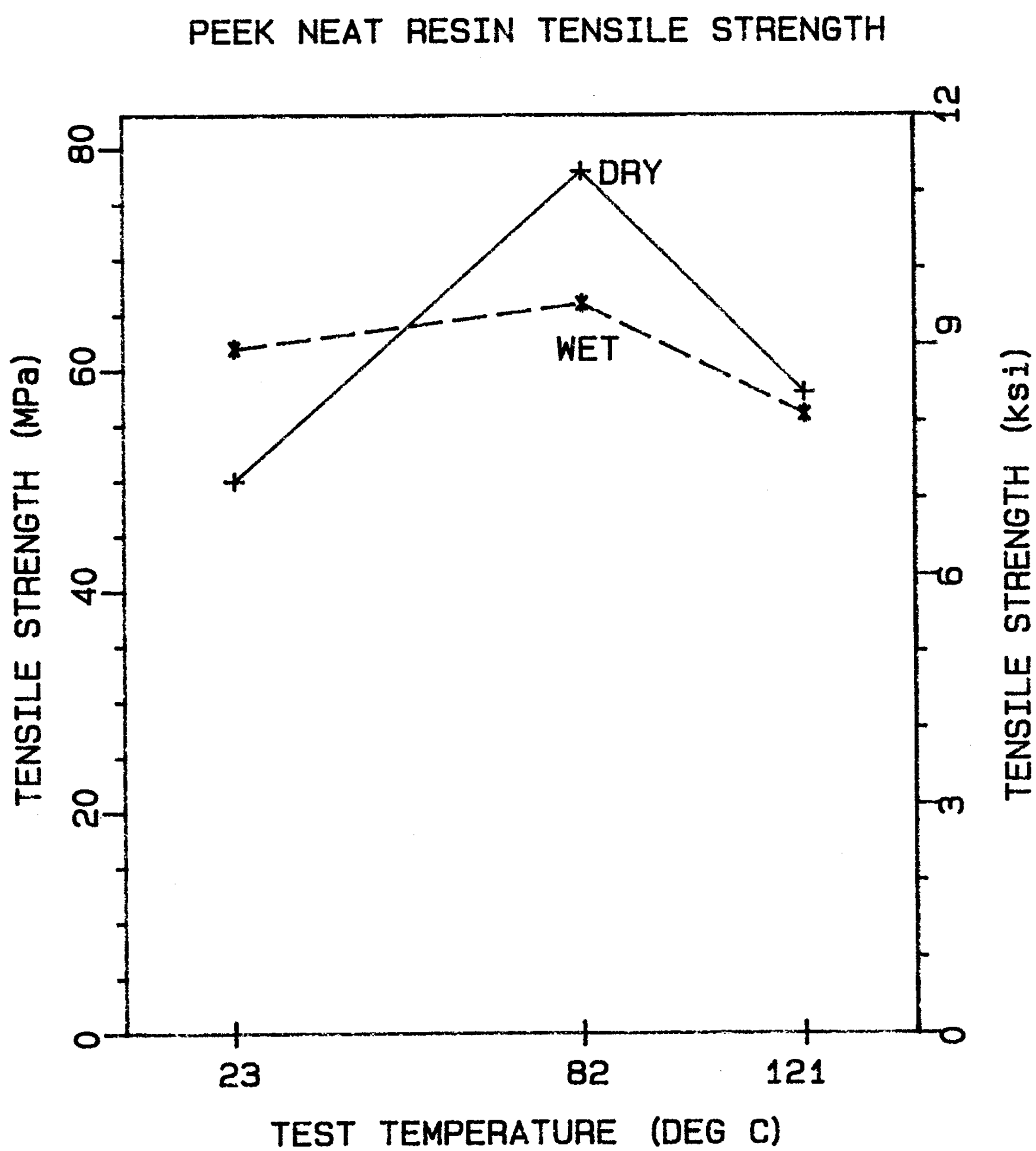

Figure 10. Neat Resin Tensile Strength As a Function of Temperature and Moisture.

average but the 82°C and 121°C results were above average. For the moisture-saturated condition, the 23°C results were below average but the elevated temperature results were the highest yet achieved. The 121°C average tensile strength results were 30 percent higher then any other resin tested (see Tables 1 through 5).

Tensile moduli average values are shown in Figure 11. The stiffness of the PEEK thermoplastic decreased with increasing temperature. The dry modulus dropped by 15 percent and the moisture-saturated modulus decreased by 30 percent. Moisture condition had less than a 4 percent effect at the elevated temperatures.

When compared to previous resin stiffness data, all the PEEK results were above average. All the moisture-saturated results were higher than for any other materials tested at this condition. The 121°C moisture-saturated specimen results were 43 percent higher than any previous results (see Tables 1 through 5).

Ultimate tensile strain average values are shown in Figure 12. The ultimate strain increased with increasing temperature. The increase for both dry and moisture-saturated specimens was over 80 percent. Moisture had an inconclusive effect. At 23°C there was only a slight difference between wet and dry values, but at 82°C the dry value was 62 percent higher than the wet value, and at 121°C the wet value was 36 percent higher than the dry value.

When the PEEK results were compared to other resins previously tested in this program, the 23°C tensile strains were below average, while the 82°C and 121°C strains were average. For the moisture-saturated condition, the 23°C and 82°C ultimate strain results

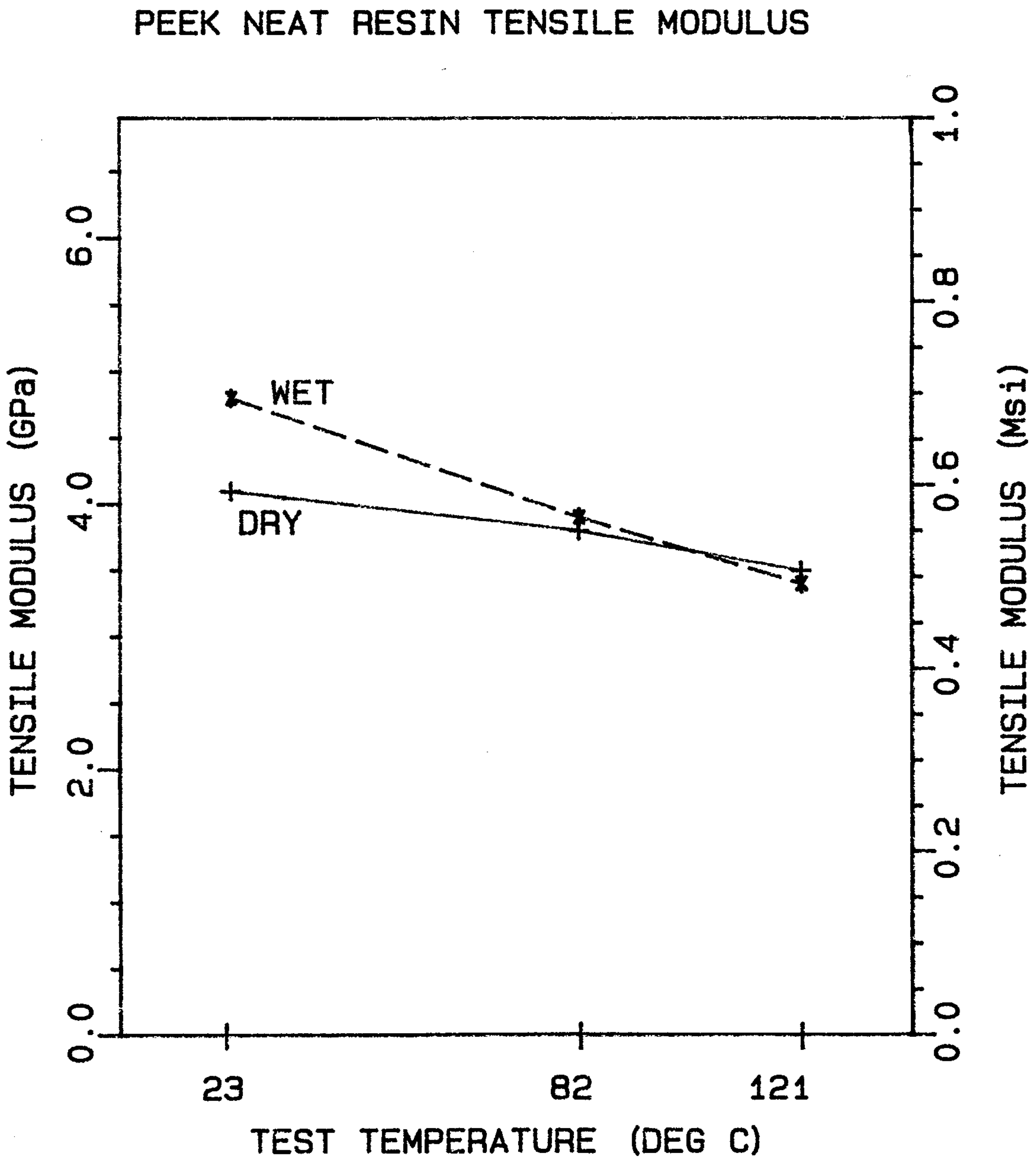

Figure 11. Neat Resin Tensile Modulus As a Function of Temperature and Moisture.

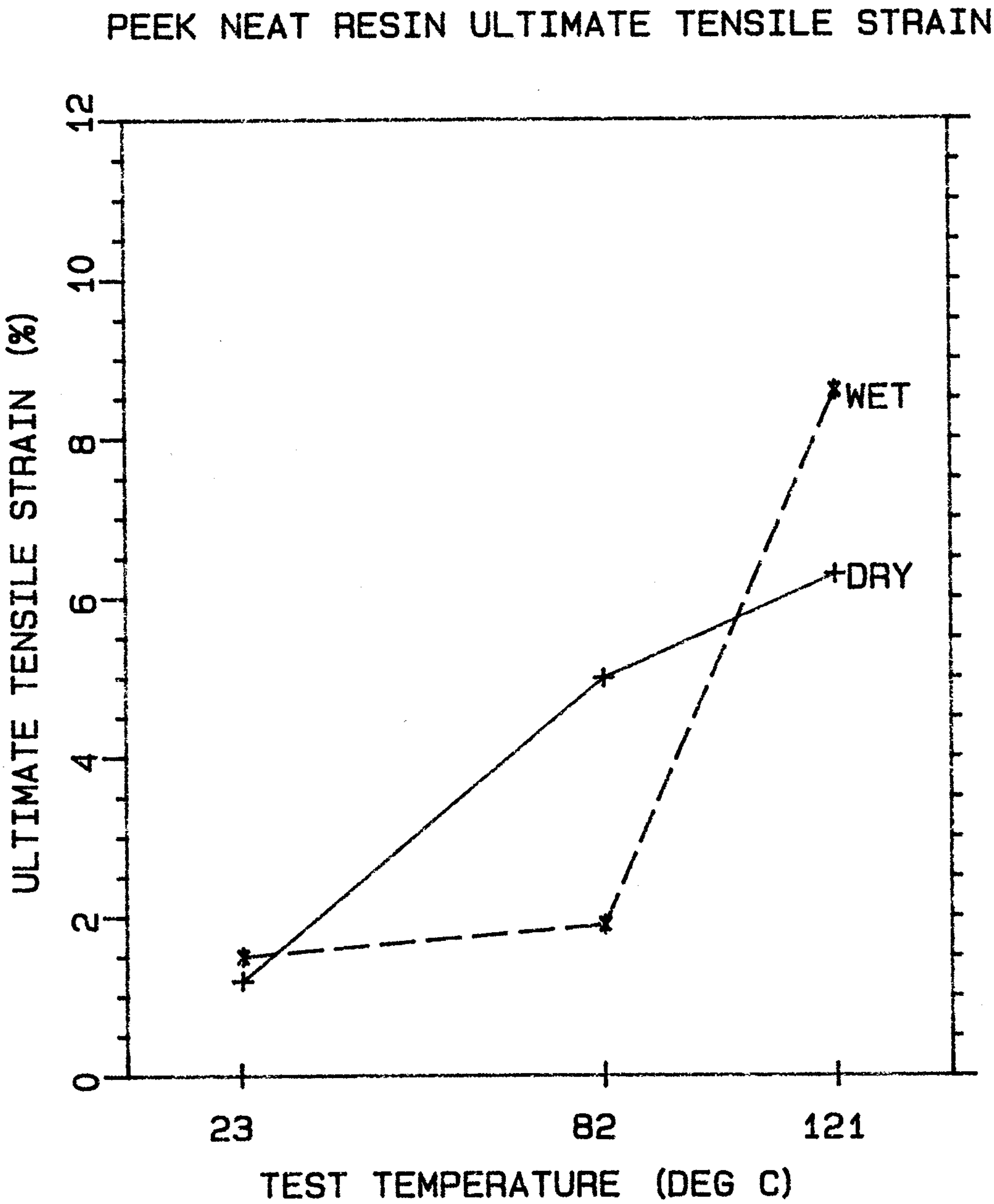

Figure 12. Neat Resin Tensile Strain As a Function of Temperature and Moisture.

were below average. But the 121°C average ultimate strain results were next to the highest of any resin tested (see Tables 1 through 5).

The Hercules 8551-7 neat epoxy average tensile strengths are shown in Figure 13. This bar chart illustrates how tensile strength is affected by test temperature and specimen moisture content. As expected, the strength decreased with increasing test temperature for both the wet and dry specimens. The dry test results yielded a 45 percent decrease in strength between the 23°C and 121°C test temperatures. The corresponding wet data decreased more severely, with a strength loss of 75 percent over the same temperature range.

The 8551-7 neat epoxy average tensile modulus values are depicted in Figure 14 for the various environmental conditions. All modulus values decreased with increasing test temperature. Between 23°C and 82°C there was little change in modulus for either wet or dry specimens. But at 121°C the wet specimens exhibited a much lower modulus than the dry specimens tested at this same temperature. From 23°C to 121°C the average modulus for the dry specimens decreased by 29 percent. Over the same temperature range the wet specimens experienced an average decrease in modulus of 71 percent.

Ultimate tensile strain average results for the 8551-7 neat epoxy are depicted in Figure 15. For the dry specimens there was only a small increase in strain with increasing test temperature. For the wet specimens there was a more substantial increase in strain at the elevated temperatures. The dry specimen strains remained at approximately 5 percent over the entire test temperature range. The wet specimen strain values increased from 3.1 percent to 7.8 percent with increasing test temperature.

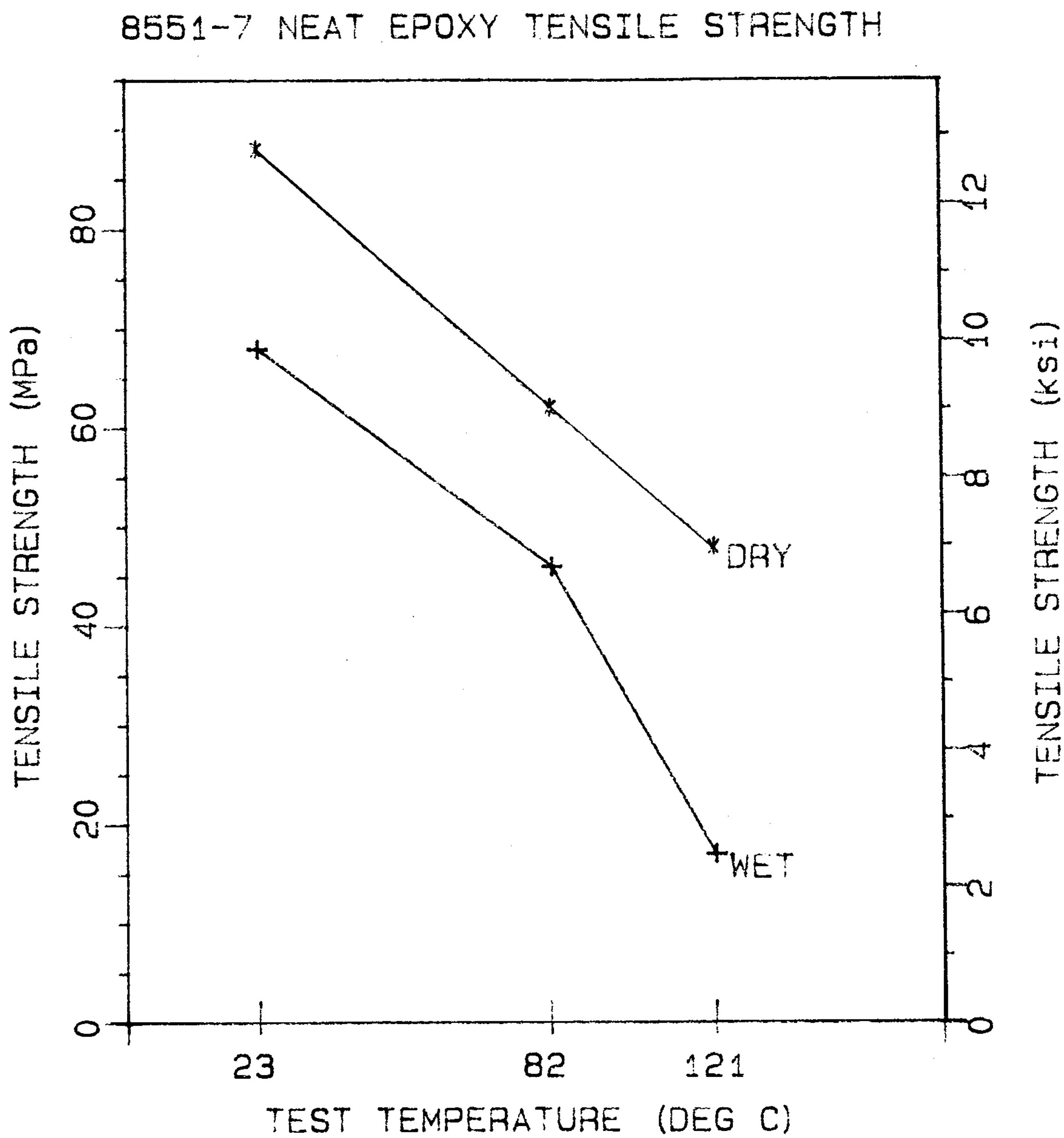

Figure 13. Neat Resin Tensile Strength As a Function of Temperature and Moisture.

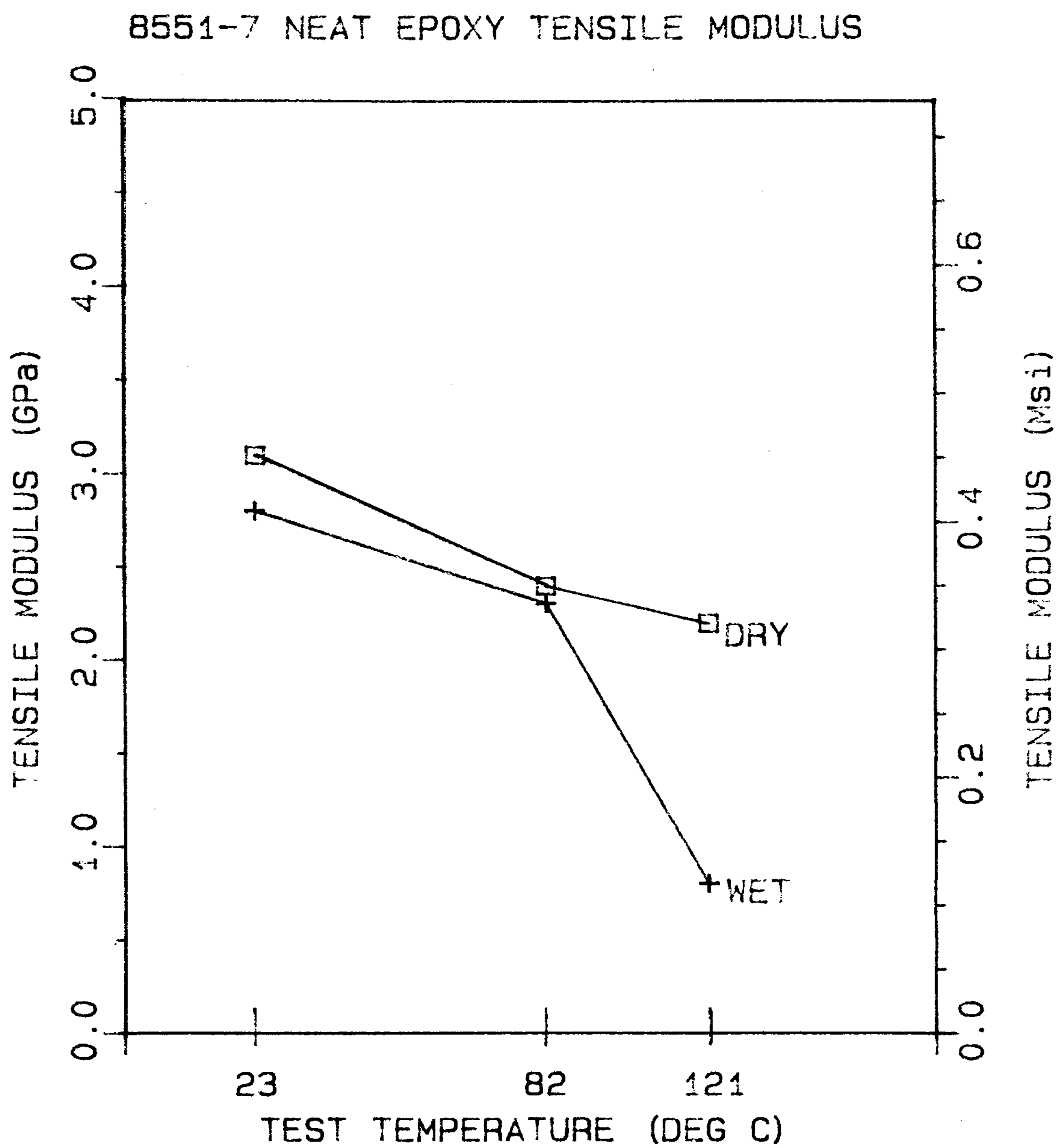

Figure 14. Neat Resin Tensile Modulus As a Function of Temperature and Moisture.

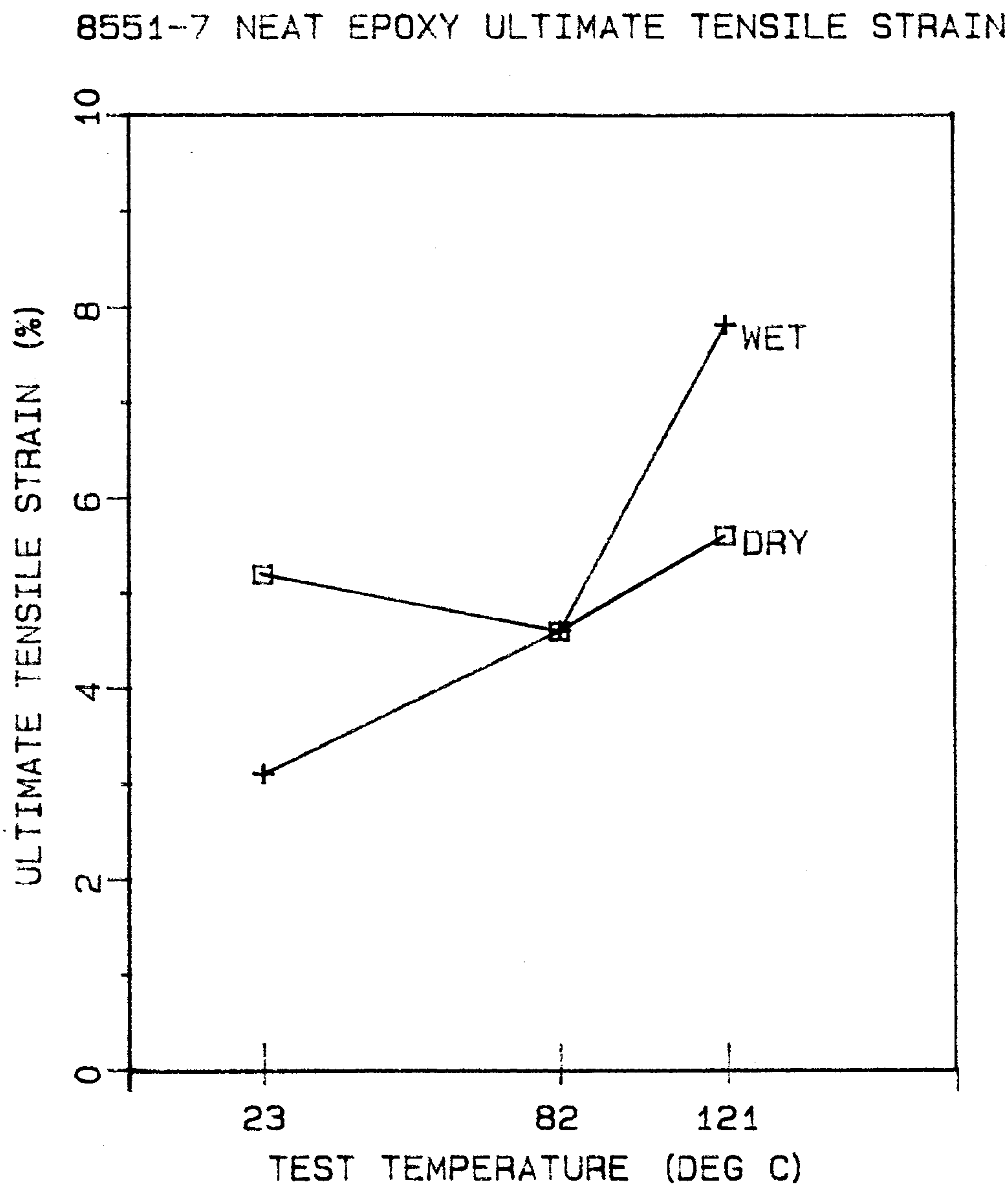

Figure 15. Neat Resin Tensile Strain As a Function of Temperature and Moisture.

Table 6 in Section 2 lists the results of the 8551-7 miniaturized tension testing, and compares these results with those obtained using full-sized specimens. The tensile strength and modulus values compare well, but as shown in the table, the strain results differed significantly. Both specimen sizes used the same extensometer and gage length, but tensile testing produced higher strains in the full-sized specimens at all test temperatures.

The Hexcel F155 neat epoxy was tested at slightly different conditions than any other resin system in this study. Originally the Hexcel F155 neat resin mechanical characterization was designed as a separate study, with different requirements. The results of the Hexcel F155 testing were included in the present report for documentation purposes. Testing was performed at -54°C, 23°C, and 71°C, at three moisture conditions, viz., dry, 4% moisture weight gain, and fully moisture-saturated. As it turned out, the fully moisture-saturated condition occurred at 4.9% moisture weight gain.

Figure 16 illustrates the effect of temperature and moisture on the F155 neat epoxy average tensile strength. At 23°C and below, the F155 epoxy appeared unaffected by temperature. The moisture-conditioned specimens yielded lower strengths. At the elevated test temperature there was a large decrease in average tensile strength for the moisture-conditioned specimens, but only a slight drop in average strength for the dry specimens. The fully moisture-saturated specimens lost 80 percent of their tensile strength between 23°C and 71°C. The dry F155 neat epoxy only lost 12 percent of its strength between 23°C and 71°C.

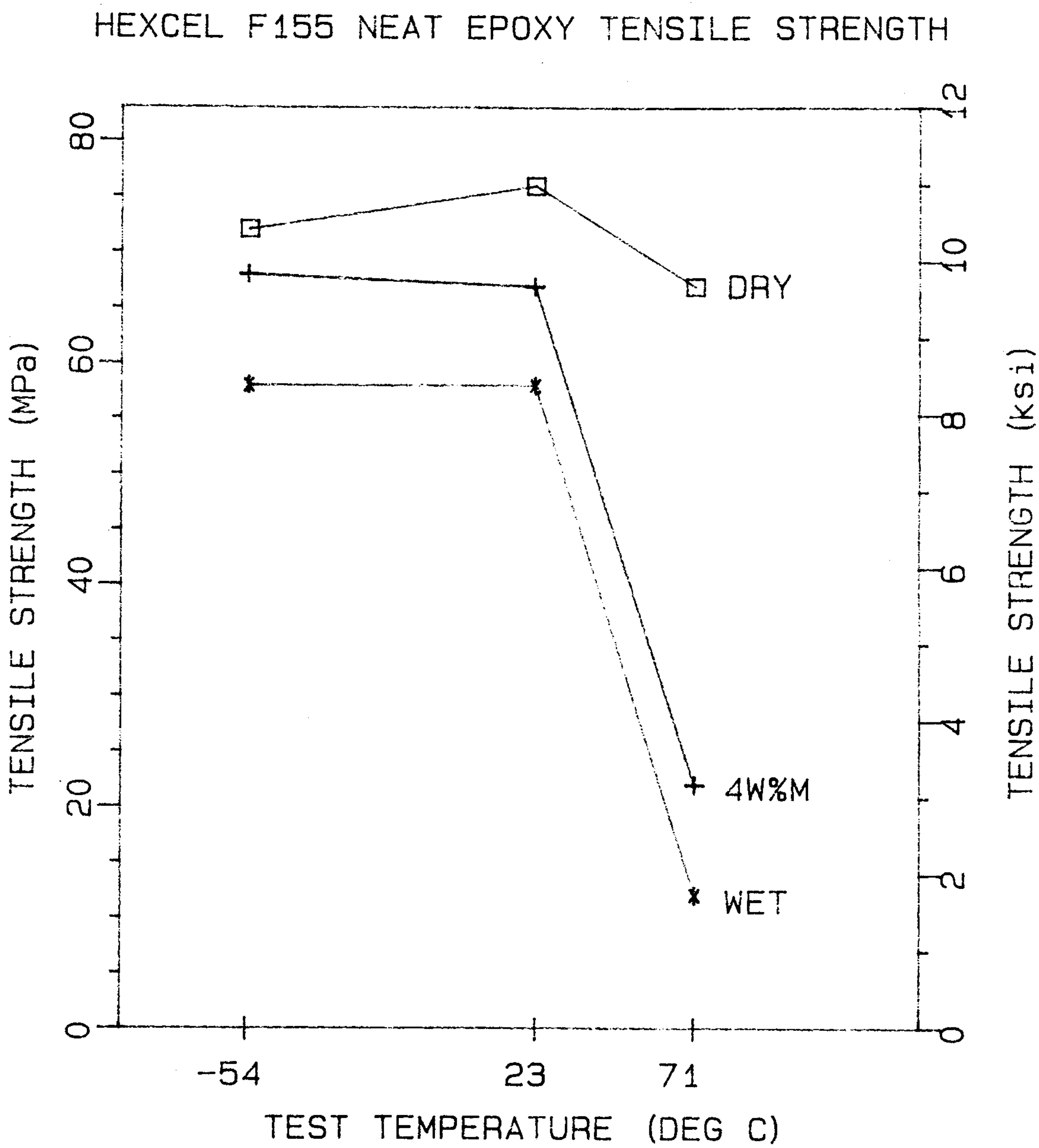

Figure 16. Neat Resin Tensile Strength As a Function of Temperature and Moisture.

Figure 17 shows the average tensile modulus values for the F155 epoxy at the various temperature and moisture conditions. All modulus values decreased with increasing test temperature. This was more significant with the moisture-conditioned specimens than with the dry specimens. Between 23°C and 71°C the moisture-saturated average stiffness dropped 79 percent, while in the dry condition this material exhibited only an 18 percent decrease in tensile modulus.

Ultimate tensile strain average results are depicted in Figure 18. With an increase in test temperature there was a corresponding increase in tensile strain. The fully moisture-saturated condition at 71°C had the highest average ultimate tensile strain, viz., 5.04 percent. The high temperature tensile strains for the F155 epoxy were above average when compared to test results for other neat resin systems (Tables 1 through 5).

4.2 Neat Resin Shear Test Results

Shear properties measured included shear modulus, G, shear strength, τ_u, and ultimate shear strain, γ_u. Complete shear stress-strain curves to failure were recorded. Individual test results and shear stress-strain curves are included in the Appendices. Summary tables were included in Section 2.

Figure 19 represents the average shear strengths at the various temperature and moisture conditions for the PEEK thermoplastic neat resin. Shear strength decreased with increasing temperature. Moisture-saturation appeared to have little effect on strength. The strength dropped 30 percent over the temperature range from 23°C to

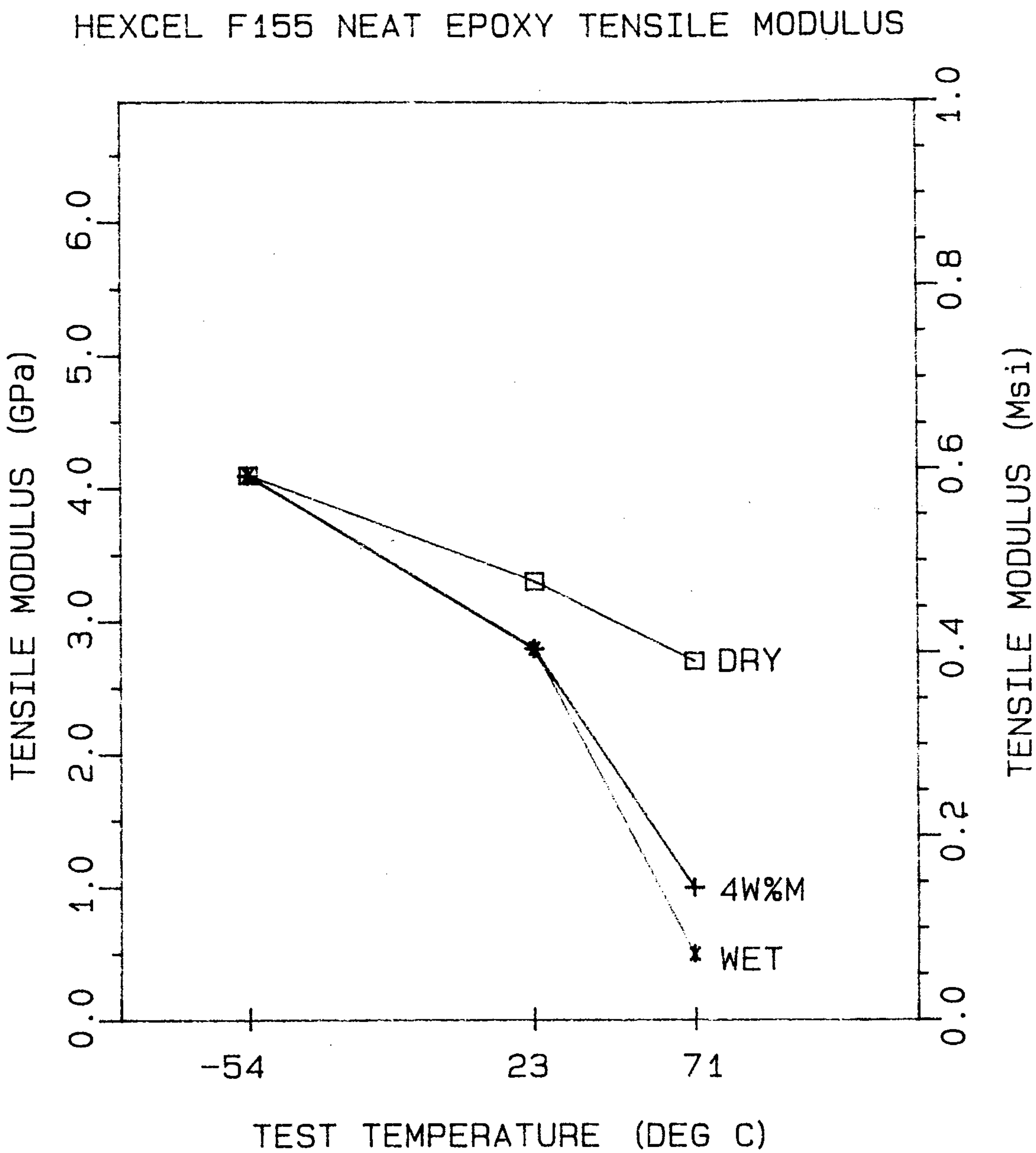

Figure 17. Neat Resin Tensile Modulus As a Function of Temperature and Moisture.

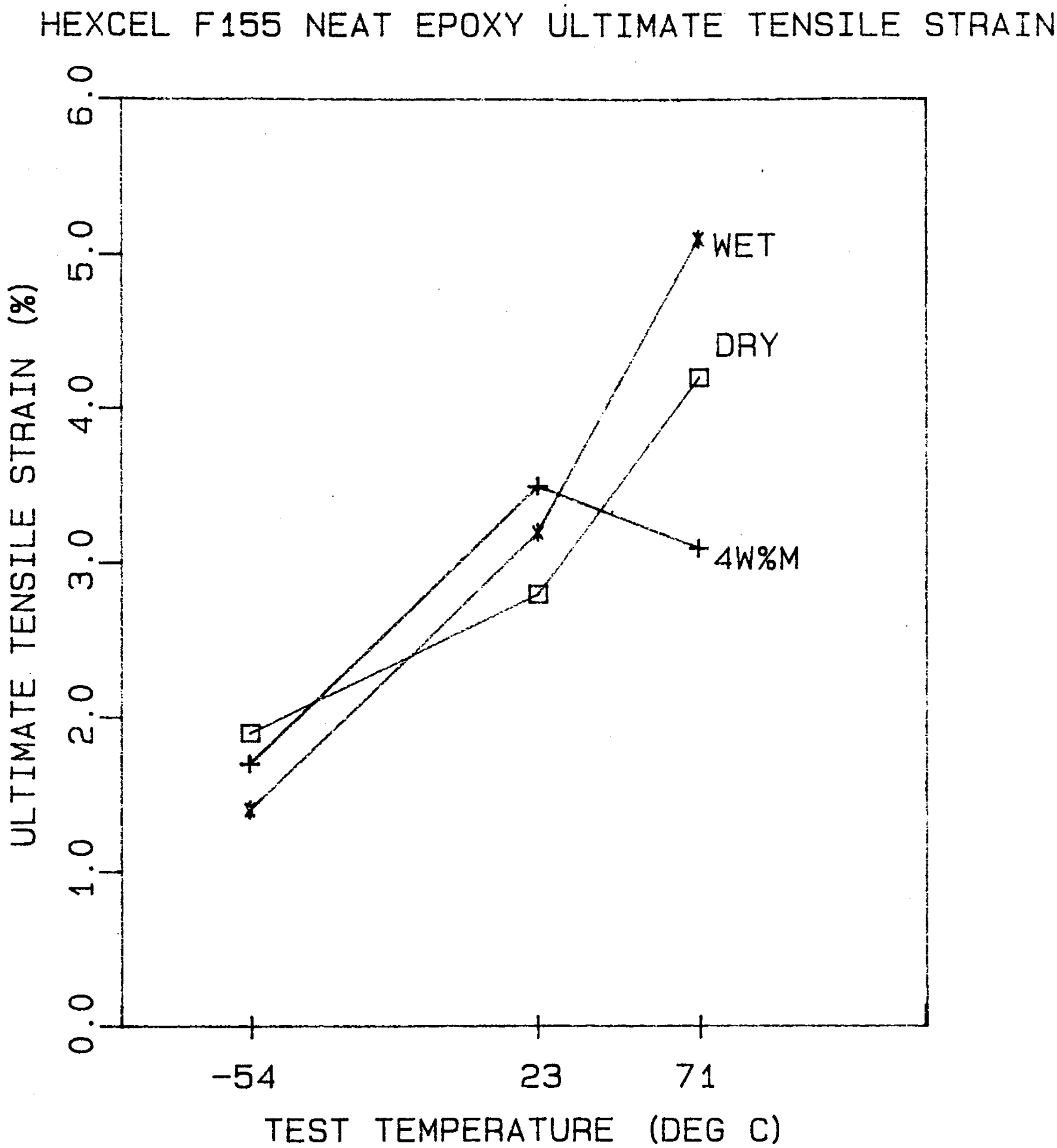

Figure 18. Neat Resin Tensile Strain As a Function of Temperature and Moisture.

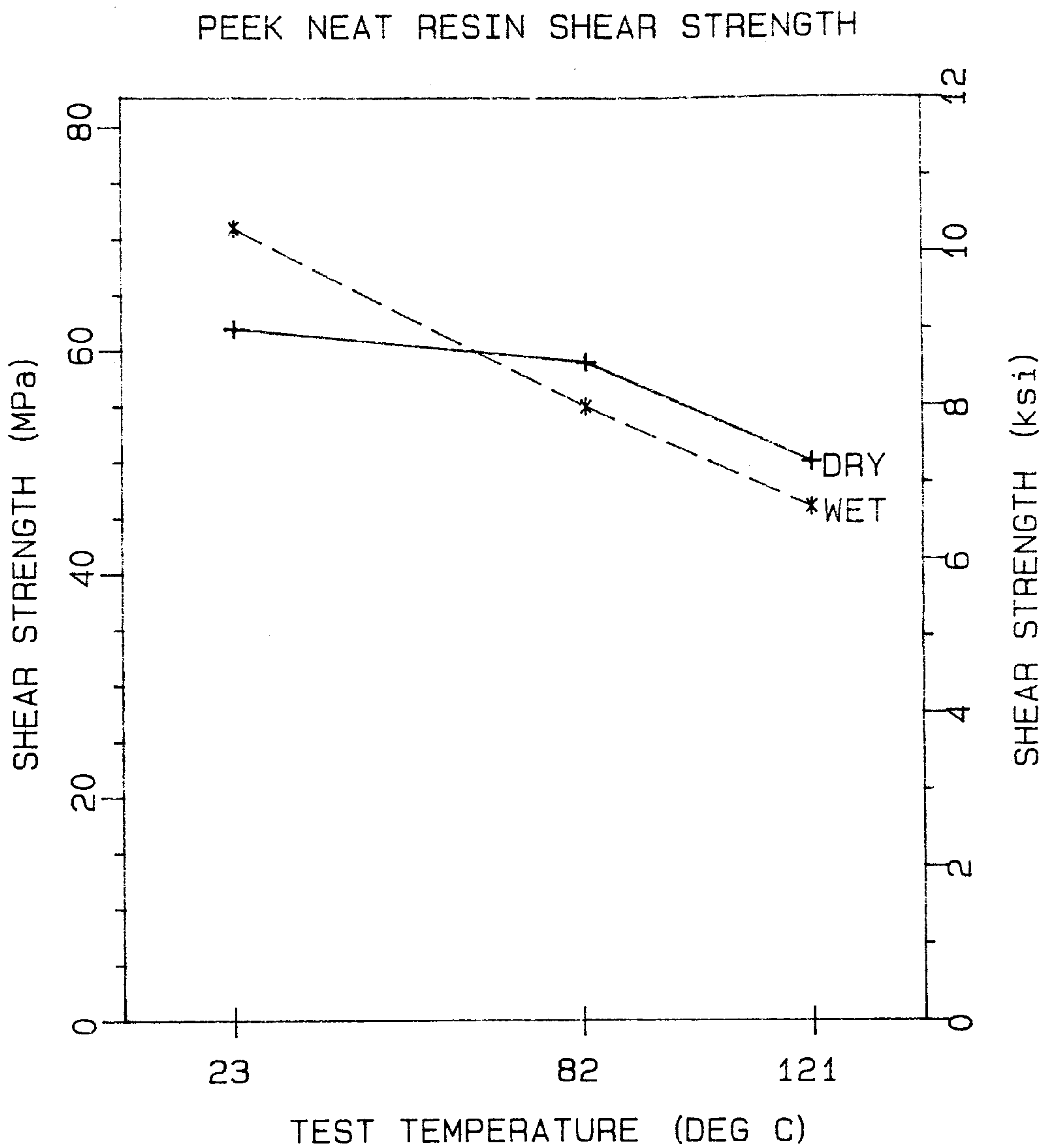

Figure 19. Neat Resin Shear Strength As a Function of Temperature and Moisture.

121°C for the dry tests, and only dropped an additional 8 percent for the moisture-saturated tests.

For the dry condition, the 23°C and the 82°C average shear strength results were some of the lowest measured for the last thirteen resins tested, but the 121°C results were above average. For the moisture-saturated condition, the 23°C and 82°C results were average. The shear strength of the PEEK thermoplastic neat resin at 121°C, moisture-saturated condition, was higher than any of the twelve resins tested at the same conditions (Table 4).

Figure 20 shows the average shear modulus values for the PEEK thermoplastic. The shear modulus decreased only slightly with increasing temperature. Also, moisture did not have a significant effect on the stiffness. When compared to the previously tested resins, all the moisture-saturated results were among the highest yet recorded (see Tables 1 through 5).

A plot of shear strain is not shown. The strain gage rosettes became saturated at approximately 10 percent strain, although the PEEK continued to strain to failure. Therefore a value for ultimate shear strain was not obtained.

The neat PEEK room temperature, dry, tensile and shear strengths were well below the manufacturer's reported values. In the present study an average tensile strength of 50 MPa (7.3 ksi) and an average shear strength of 72 MPa (10.4 ksi) was obtained. The manufacturer, ICI Americas, Inc., reports values of 92 MPa (13.3 ksi) for tensile strength and 95 MPa (13.8 ksi) for shear strength [9]. A careful attempt was made to mold the PEEK thermoplastic specimens at the optimum processing conditions. Per the advice of Reference [10], the newly cast PEEK

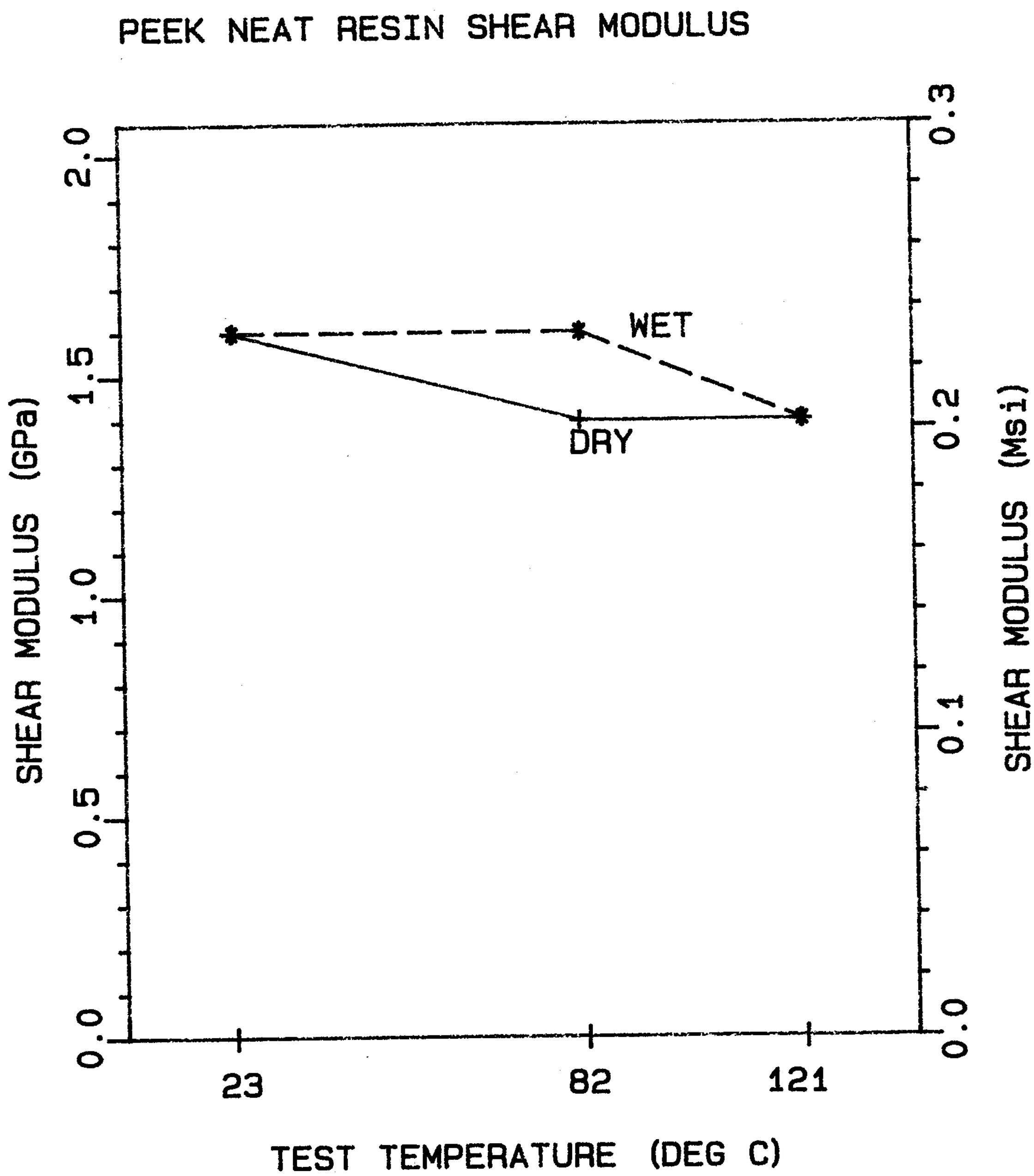

Figure 20. Neat Resin Shear Modulus As a Function of Temperature and Moisture.

specimen blanks were allowed to slowly cool from melt to approximately 200°C at a rate of 1.6 °C/min., than allowed to continue to cool to room temperature overnight. Samples of three of the specimen blanks were sent to NASA-Langley for crystallinity analysis. The results are given in Table 14. The calibration graph and individual diffractograms are presented in Appendix B.

Table 14

Crystallinity of Neat PEEK Thermoplastic Specimens
by the Method of Vonk [11]

Sample	Ia	Ic	Ic / (Ia + Ic)	Percent Crystallinity *
PP4	843077	549261	0.3945	36
PP13	855146	537192	0.3858	35
PP14	928180	464158	0.3334	29

* A derived expression from Ic regressed on Ia:
Percent Crystallinity = (1.0 - (7.651E-07)(Ia))(100%)

Shear strength average values for the 8551-7 neat epoxy are shown in Figure 21. The moisture-saturated specimens consistently produced lower strengths than the dry specimens over the entire test temperature range. Both the dry and wet specimens lost between 40 and 60 percent of their strength when the test temperature was increased from 23°C to 121°C. The dry specimen average strength value decreased from 57 MPa (8.3 ksi) to 34 MPa (4.9 ksi), while the moisture-saturated specimens had a decrease in average strength from 49 MPa (7.1 ksi) to 20 MPa (2.9 ksi).

Shear modulus values for the 8551-7 neat epoxy are depicted in Figure 22. As expected, both the wet and dry specimens yielded lower test results with increased test temperature. Interestingly enough, the

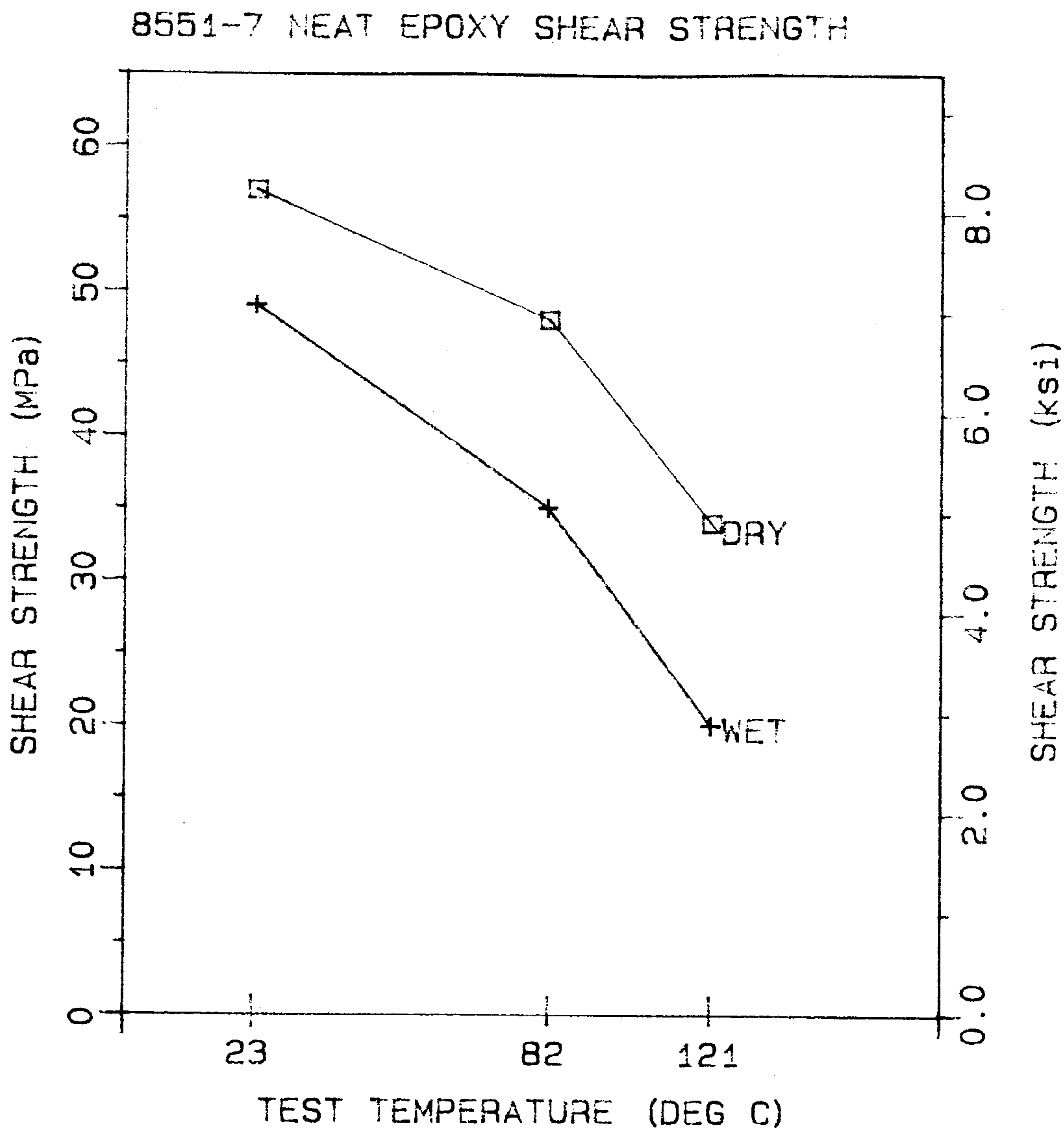

Figure 21. Neat Resin Shear Strength As a Function of Temperature and Moisture.

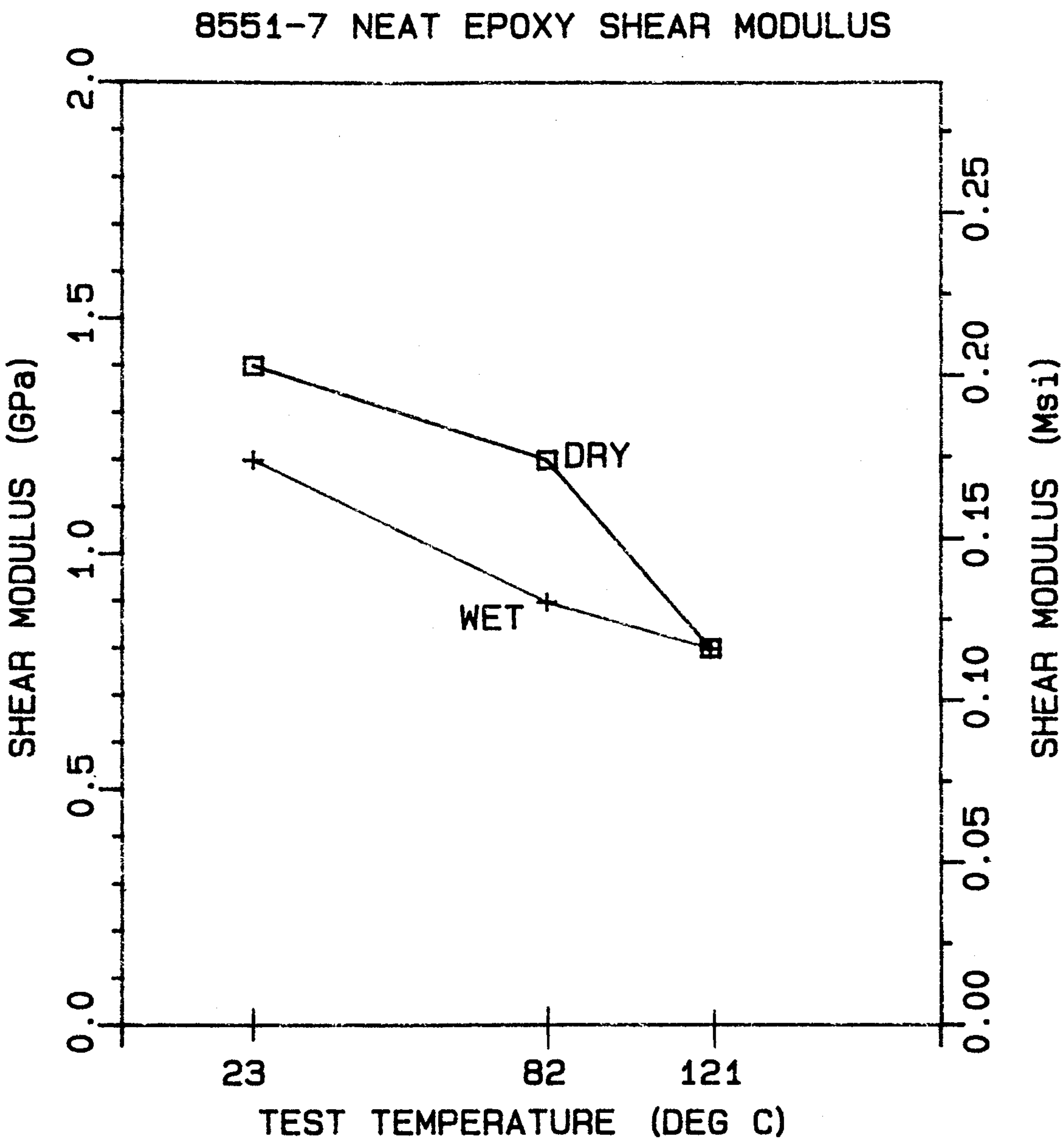

Figure 22. Neat Resin Shear Modulus As a Function of Temperature and Moisture.

wet and dry test results were quite similar. Both sets of specimens had an average shear modulus at 121°C of 0.8 GPa (0.12 Msi). This was a decrease from 1.4 GPa (0.02 Msi) for the dry specimens and a drop from 1.2 GPa (0.17 Msi) for the moisture-saturated specimens.

A graph depicting 8551-7 average shear strain values is not shown. The strain gage rosettes became saturated at approximately 10 percent strain, although the 8551-7 continued to strain to failure. Therefore a value for ultimate shear strain was not obtained.

Table 7 in Section 2 lists the results of the 8551-7 miniaturized torsion testing and compares them to the results obtained with the Iosipescu shear test. These results compare well for shear strength and modulus at most of the environmental test conditions. There was a difference of greater than 20 percent between the two test types for the room temperature shear strength and modulus results. Also, at 121°C there was a difference of 40 percent or more between the two test type modulus values. The remainder of the shear strength and modulus values were within 10 percent of each other for the two test types. The ultimate strain values did not compare well. An RVDT was used to measure strain for the miniaturized torsion specimens while the Iosipescu specimens were mounted with strain gages.

The Hexcel F155 neat epoxy was tested at conditions different than any other resin system in this study. Testing was performed at -54°C, 23°C, and 71°C, at three moisture conditions, viz., dry, 4% moisture weight gain, and fully saturated. It was found that the fully moisture-saturated condition occurred at 4.9 percent weight gain.

Shear strength average values for the F155 epoxy are shown in Figure 23. Below 23°C the shear strength of the epoxy was only affected

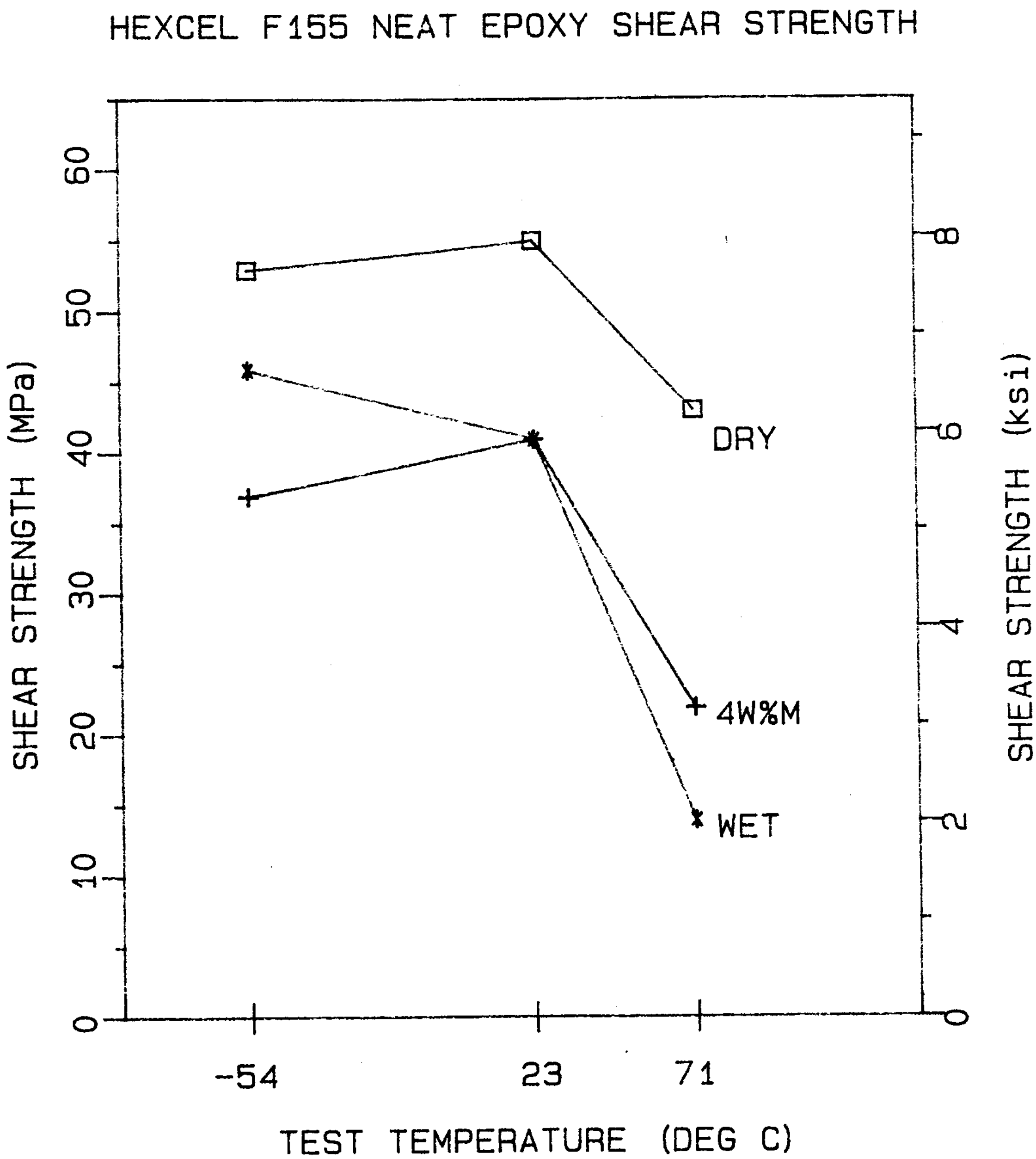

Figure 23. Neat Resin Shear Strength As a Function of Temperature and Moisture.

by the moisture condition; the higher the moisture content the lower the shear strength became. Above 23°C there was a combined temperature-moisture effect that more severely lowered the shear strength. The shear strength of the moisture-saturated material dropped the most, from 41 MPa (5.9 ksi) at 23°C to 14 MPa (2.0 ksi) at 71°C. On the other hand, the dry condition average values only decreased from 55 MPa (8.0 ksi) at 23°C to 43 MPa (6.3 ksi) at 71°C. The Hexcel F155 neat epoxy resin system yielded some of the lowest shear strength values of any resin tested in this program (see Tables 1 through 5).

Shear modulus average values are shown in Figure 24. All conditions exhibited a near linear drop in stiffness with increasing test temperature. The dry condition values dropped by 43 percent, from 1.8 GPa (0.26 Msi) at -54°C to 1.02 GPa (0.15 Msi) at 71°C. The moisture-saturated specimens indicated a decrease in shear modulus of 75 percent, from 1.6 GPa (0.23 Msi) at -54°C to 0.4 GPa (0.06 Msi) at 71°C. The Hexcel F155 displayed below average shear modulus values when compared to any resin tested to date (see Tables 1 through 5).

Figure 25 depicts the average ultimate shear strain values for the Hexcel F155 neat epoxy. The response below 23°C was very similar for the dry and moisture-saturated conditions. Between -54°C and 23°C the strain increased from 3 percent to 6 percent. At elevated test temperatures, the dry condition yielded no increase in shear strain. The moisture-conditioned specimens showed a marked increase in strain at the elevated test temperatures. Strain values for the fully moisture-saturated condition are unavailable since the strain gages were calibrated with too low a full range. This resulted in the strain signal saturating at 5.9 percent. It can be assumed that the fully

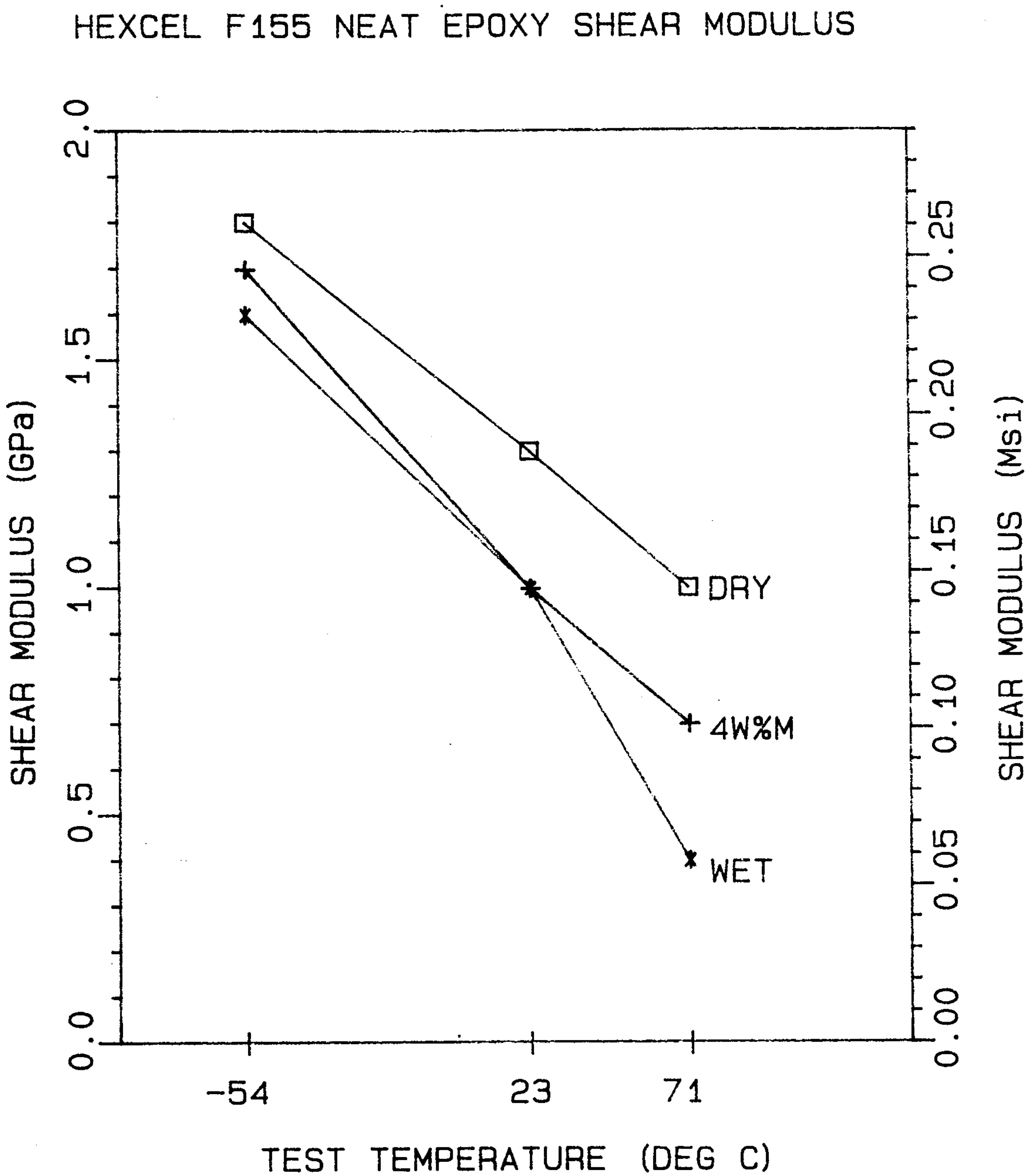

Figure 24. Neat Resin Shear Modulus As a Function of Temperature and Moisture.

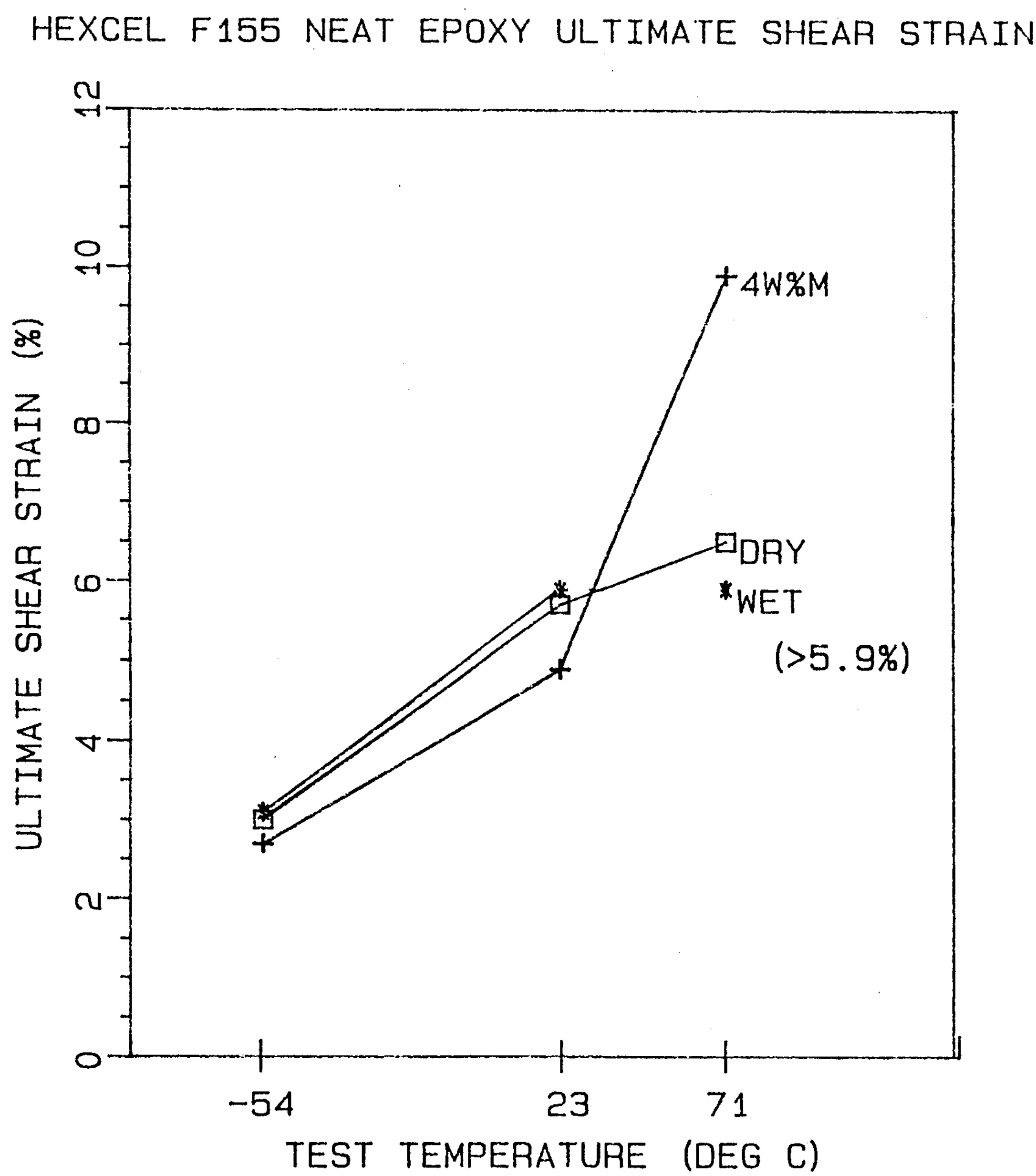

Figure 25. Neat Resin Shear Strain As a Function of Temperature and Moisture.

moisture-saturated condition would yield nearly the same or higher shear strains than the 4 percent by weight moisture content condition. This nearly moisture-saturated condition yielded an average strain at 71°C of 10 percent. These shear strain values are low when compared to shear strains for other neat resins.

4.3 Neat Resin Fracture Toughness Test Results

Mode I strain energy release rate values were measured for the PEEK thermoplastic at six environmental conditions. Average G_{IC} values are plotted in Figure 26. The specimen blanks from which the test specimens were machined had two different appearances. Some were homogenous in appearance and others had a granular look. The granular appearance was most likely due to an incomplete melt of the PEEK pellets during the formation of the specimen blanks. The specimen quality had a definite effect on the Mode I strain energy release rate. The homogenous specimens consistently yielded higher values. Specimen nature is indicated in the tables of average and individual values.

Mode I strain energy release rate values were also obtained for the 8551-7 rubber-toughened epoxy at two environmental conditions. A total of 21 tests were performed at the room temperature, dry test condition. Twelve tests were performed at the room temperature, moisture-saturated test condition. The large sample populations yielded very reliable results. The average result for the room temperature, dry specimens was 1124 J/m^2 (6.4 $in\text{-}lb/in^2$). The room temperature, moisture-saturated specimen average G_{IC} result was very similar at 1040 J/m^2 (6.0 $in\text{-}lb/in^2$). All the individual test values are listed in Appendix A.

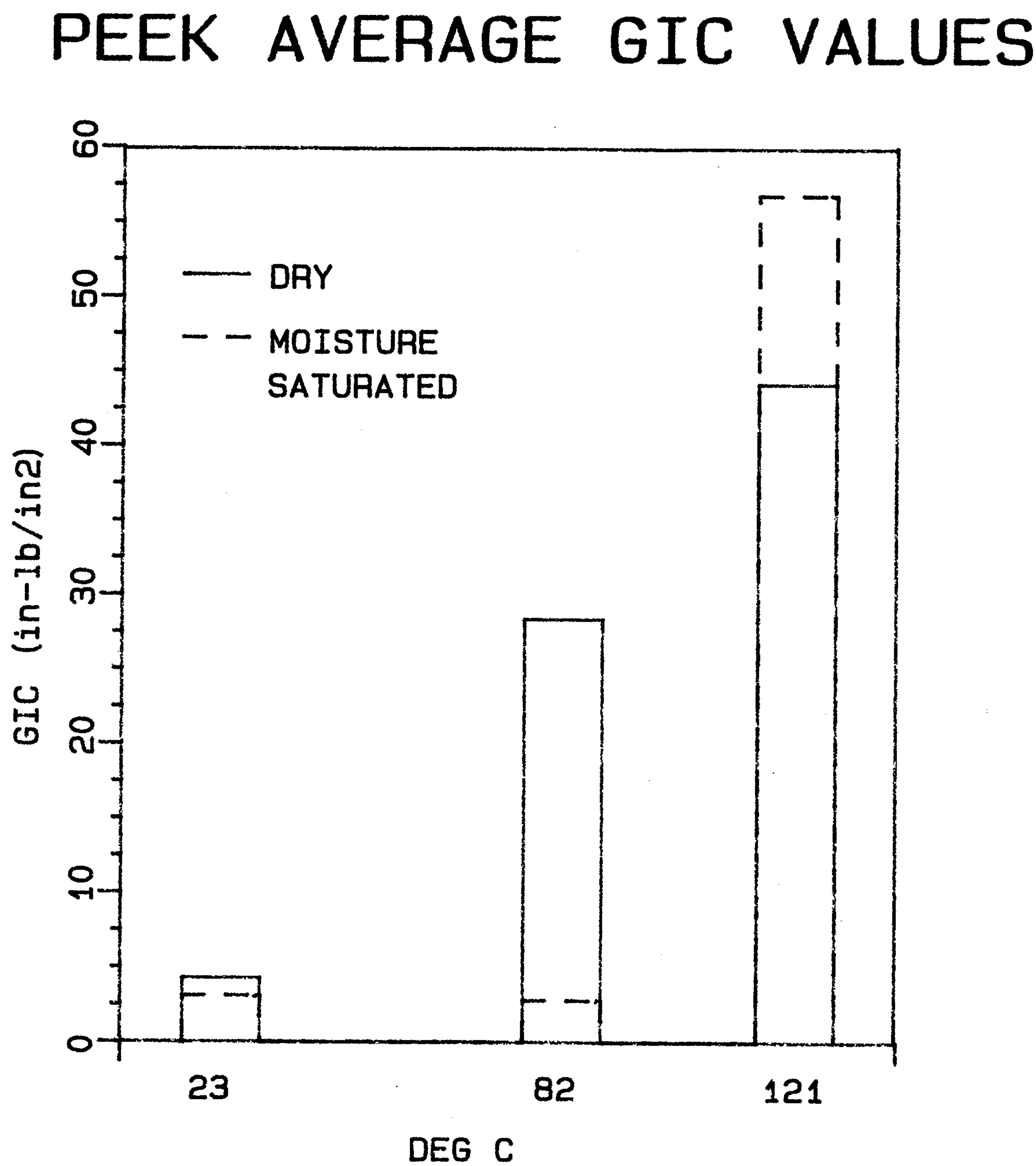

Figure 26. PEEK Fracture Toughness Values As a Function of Temperature and Moisture.

4.4 Neat Resin Coefficient of Thermal Expansion Results

Table 15 lists the average CTE results for the three neat resins. The Hercules 8551-7 exhibited linear expansion behavior, yielding a constant value of CTE over the test temperature range, for both the dry and the moisture-saturated specimens. The Hexcel F155 epoxy only exhibited linear behavior for the dry specimens. The behavior was not linear for the moisture-saturated condition. The PEEK exhibited nonlinear expansion behavior for all the temperature and moisture conditions. Table 15 includes the constant CTE values and the calculated CTE values at three temperatures for the PEEK and the moisture-saturated Hexcel F155, as well as the equations used for the calculations. Using these equations, the CTE at any temperature of interest can be calculated.

All resin systems showed an increase in CTE after being moisture-saturated, as observed in all previous neat resin testing [1,2,3]. Individual curves and data are included in Appendices A and B of this report.

4.5 Neat Resin Coefficient of Moisture Expansion Results

Average coefficients of moisture expansion and moisture saturation weight gains are given in Table 2. The measured CME of the Hexcel F155 and the Hercules 8551-7 were higher than that of the 3502 baseline epoxy. The F155 exhibited about the same equilibrium moisture content as the 3502 epoxy while the 8551-7 was considerably less. On the other hand, the PEEK CME was significantly higher than the 3502 epoxy baseline and recorded the lowest moisture saturation value of any of the resin systems tested to date.

Table 15

Average Coefficients of Thermal Expansion For the Three Neat Resin Systems Tested

$$CTE = C_1 + C_2 T \quad (10^{-6}/°C)$$

Resin System	Moisture Condition	Temperature Range (°C)	Coefficients C_1	C_2
8551-7	Dry	-40 to 120	46.7	0.00
	Wet	-40 to 120	70.0	0.00
Hexcel F155	Dry	-50 to 70	64.3	0.00
	Wet	-50 to 70	76.4	0.37
PEEK	Dry	-40 to 205	43.4	0.32
	Wet	-40 to 205	49.1	0.24

4.6 Relationships Between Elastic Constants

Lack of satisfaction of the isotropic relation

$$G = \frac{E}{2(1+n)}$$

was not as severe for the three resin systems tested here as it has been in previous studies [1,2,3]. Table 16 lists the elastic constants measured and calculated for the epoxy and thermoplastic resin systems.

From Table 16 it is clear that the calculated shear modulus, G, is in most cases lower than the measured shear modulus. The calculated G values are based on the Young's modulus, E, and Poisson's ratio, ν, measured in tensile tests of the neat resins. This behavior is identical to that observed for the previous ten neat resin systems

Table 16

Measured Versus Calculated Shear Moduli
For Two Neat Resin Systems

Neat Resin System	Measured Young's Modulus (GPa)	Measured Poisson's Ratio	Measured Shear Modulus (GPa)	Calculated Shear Modulus (GPa)	$\frac{G_{meas}-G_{calc}}{G_{meas}}$ (percent)
-54°C, Dry					
Hexcel F155	4.1	0.40	1.8	1.58	18
23°C, Dry					
Hexcel F155	3.3	0.40	1.3	1.2	6
8551-7	3.1	0.36	1.4	1.1	21
PEEK	4.1	0.44	1.6	1.4	9
71°C, Dry					
Hexcel F155	2.7	0.41	1.0	1.0	7
82°C, Dry					
8551-7	2.4	0.39	1.2	0.9	25
PEEK	3.8	0.44	1.4	1.3	9
121°C, Dry					
8551-7	2.2	0.44			
PEEK	3.5	0.44	1.4	1.2	16
-54°C, Moisture-Saturated					
Hexcel F155	4.1	0.35	1.6	1.5	1
23°C, Moisture-Saturated					
Hexcel F155	2.8	0.38	1.0	1.0	-6
8551-7	2.8	0.36	1.2	1.0	17
PEEK	4.8	0.45	1.6	1.7	-1
71°C, Moisture-Saturated					
Hexcel F155	0.6	0.37	0.4	0.2	53
82°C, Moisture-Saturated					
8551-7	2.3	0.43	0.9	0.8	11
PEEK	3.9	0.39	1.6	1.4	13
121°C, Moisture-Saturated					
8551-7	0.8	0.35	0.8	0.3	62
PEEK	3.4	0.35	1.4	1.3	13

tested [2,3]. However, in almost all instances the Hexcel F155, Hercules 8551-7 epoxy and PEEK thermoplastic correspond to a higher degree to the isotropic relationship than any material tested in the previous three studies.

The only exceptions were the 71°C, moisture-saturated Hexcel F155 specimens and the 121°C, moisture-saturated 8551-7 specimens. Both epoxies appear to have had a radical loss in Young's modulus at these conditions, which probably resulted in the high error in the calculation between G measured and G calculated.

Further study of this phenomenon would be required before a reasonable explanation could be offered. No additional bulk modulus measurements have been completed on any of the neat resins of interest, to allow an additional independent check of the elastic constants.

SECTION 5

CARBON FIBER REINFORCED UNIDIRECTIONAL COMPOSITE RESULTS

5.1 Introduction

All testing during the first two years of this grant had been performed on only neat resin materials. In the third year, testing of four carbon fiber-reinforced composites was conducted. Now, in the final phase of this grant, twelve more carbon fiber-reinforced composites were supplied by NASA-Langley to allow more testing. Sufficient material was supplied to perform longitudinal tension, transverse tension, in-plane shear, transverse coefficient of thermal expansion, and transverse coefficient of moisture expansion testing. Engineering constants measured included axial and transverse moduli, E_{11} and E_{22}, shear modulus, G_{12}, axial and transverse tensile strengths, σ_1 and σ_2, shear strength, τ_{12}, Poisson's ratio, ν_{12}, and ultimate strains, ε_1, ε_2 and γ_{12}. Also measured were transverse thermal and moisture expansion coefficients, α_2 and β_2, respectively.

5.2 Composite Fiber Volume and Void Volume Measurement Results

Fiber volume and void volume measurements were performed on ten of the twelve carbon fiber-reinforced composites received from NASA-Langley. Nitric acid was used to dissolve the matrix resin in the ten composites. Three replicates were digested for each composite. The fiber volume was calculated for the other two of the twelve composites since their PEEK thermoplastic matrix materials could not be dissolved by nitric acid. The average values are reported in Table 17. Individual fiber volume and void volume results are given in Appendix A.

Table 17

Average Fiber Volume and Void Volume Determinations for the Twelve Carbon Fiber-Reinforced Composites

Material System	Fiber Volume (percent)	Void Volume (percent)
AS4/2220-1	58.4	0.5
AS4/2220-3	59.2	0.0
T500/R914	57.2	0.0
IM6/HX1504	59.5	0.0
T300/4901A(MDA)	65.1	0.0
T700/4901A(MDA)	64.6	0.0
T300/4901B(MPDA)	61.8	0.0
T700/4901B(MPDA)	56.5	1.3
AS4/PEEK (APC-2,ICI)	63.0*	0.0
AS4/PEEK (APC-2,LaRC)	63.0*	0.0
AS4/8551-7	59.7	0.9
AS4/$PISO_2$-TPI	54.0*	0.0

* Calculated value

Some of the composite materials exhibited a large enough variation in fiber volume to influence the mechanical properties, especially the longitudinal properties. Most of the void volumes were essentially zero. Void volumes in similar aerospace materials are typically less than 1 percent. The void volumes measured here were probably too small to effect the results of this program.

It is also interesting to note that the twelve composites tested did not all contain the same type of carbon fiber. Table 18 gives the typical fiber properties for the fibers used. The differences in tensile strength and moduli affected the final composite properties.

Table 18

Typical Carbon Fiber Properties

Fiber	Tensile Strength (MPa)	Tensile Strength (ksi)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Elongation at Break (percent)
T300 *	3450	500	230	33.5	1.5
AS4 **	3590	520	235	34.0	1.5
T500 *	3960	575	245	35.5	1.6
T700 *	4550	660	255	37.0	1.8
IM6 **	4380	635	280	40.4	1.5

* AMOCO Performance Products, Inc., Thornel Product Information Sheet
** Hercules, Incorporated, Product Data Sheet

5.3 <u>Composite Longitudinal Tensile Test Results</u>

Axial tension average test results were given previously in Table 9 of Section 2.2. Individual test results are included in Appendix A.

Figure 27 is a plot of the axial tensile strengths for the twelve composite systems. The solid lines represent the room temperature, dry results while the dotted lines represent the results at 100°C, dry. Axial tensile strength is strongly dependent on the fiber properties. Therefore, fiber volume and fiber strength will dictate the composite

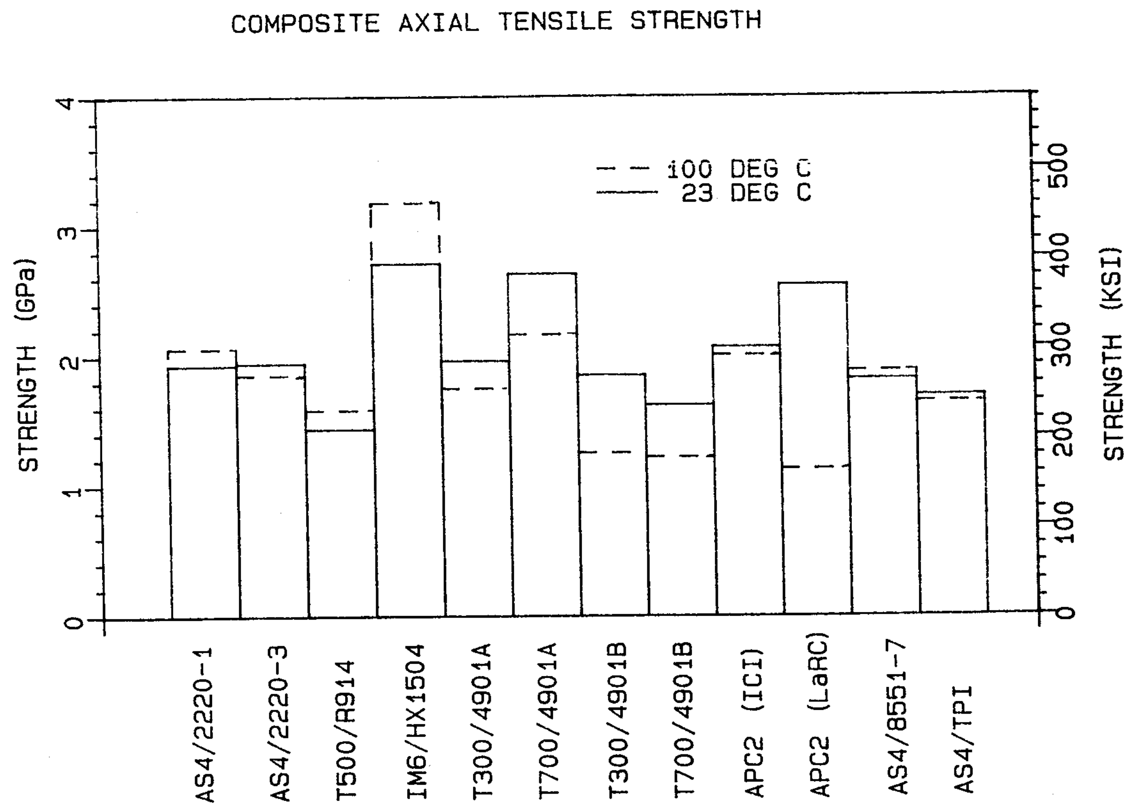

Figure 27. Unidirectional Carbon Fiber-Reinforced Composite Axial Tensile Strengths.

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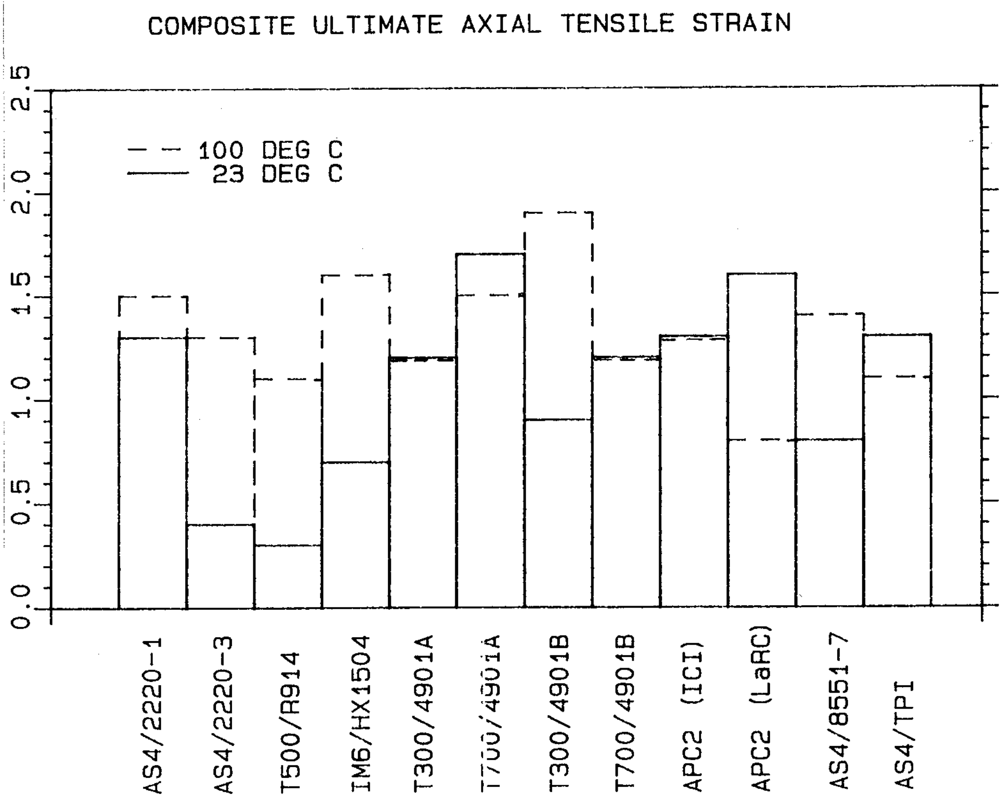

gure 29. Unidirectional Carbon Fiber-Reinforced Composite Axial Tensile Ultimate Strains.

materials, IM6/HX1504 and AS4/PEEK (LaRC), were exceptions. The ɪs pulled free of the AS4/PEEK (LaRC) specimens prior to specimen ilure. Therefore, the specimens were retested without tabs, gripped irectly by the fixture wedge grips. This resulted in longitudinal plits and lower axial tensile strength values. On the other hand, the IM6/HX1504, 100°C tests resulted in higher strengths than the room temperature tests. Working under the premise that strength values can not be artificially increased, the elevated test temperature appeared to allow the IM6/HX1504 material to achieve more of its potential axial strength.

Axial tensile modulus values are shown in Figure 28. As expected, all the composites tested had about the same modulus since all but two of the carbon fibers have approximately the same modulus (see Table 18). The IM6 and the T700 carbon fibers have slightly higher moduli and this was reflected in Figure 28 for the IM6/HX1504 and T700/4901A materials. The T700/4901B composite had a fiber volume lower than any other material and therefore a lower composite tensile modulus. Elevated test temperature had little effect on the modulus since this is a fiber-dominated behavior in the axial direction.

Axial tensile strains are shown in Figure 29. This property is dominated by the fiber used in the composite. Table 18 shows that all the fibers used had an ultimate strain value of at least 1.5 percent. At room temperature, many of the neat resins have an ultimate strain less than the fiber, but at the 100°C test temperature the resin ultimate strain is well above that of the fiber (see Tables 3 and 4). The elevated test temperature allows the composite ultimate strain to approach the fiber value. This characteristic explains most of the

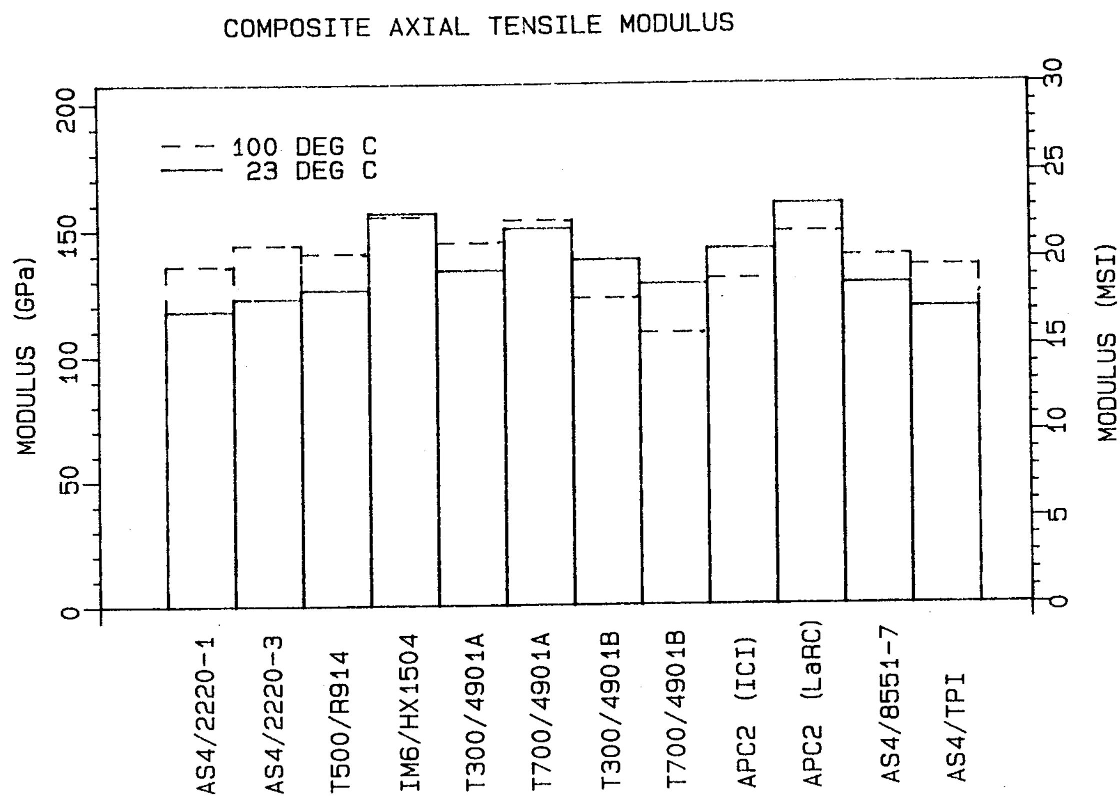

Figure 28. Unidirectional Carbon Fiber-Reinforced Composite Axial Tensile Moduli.

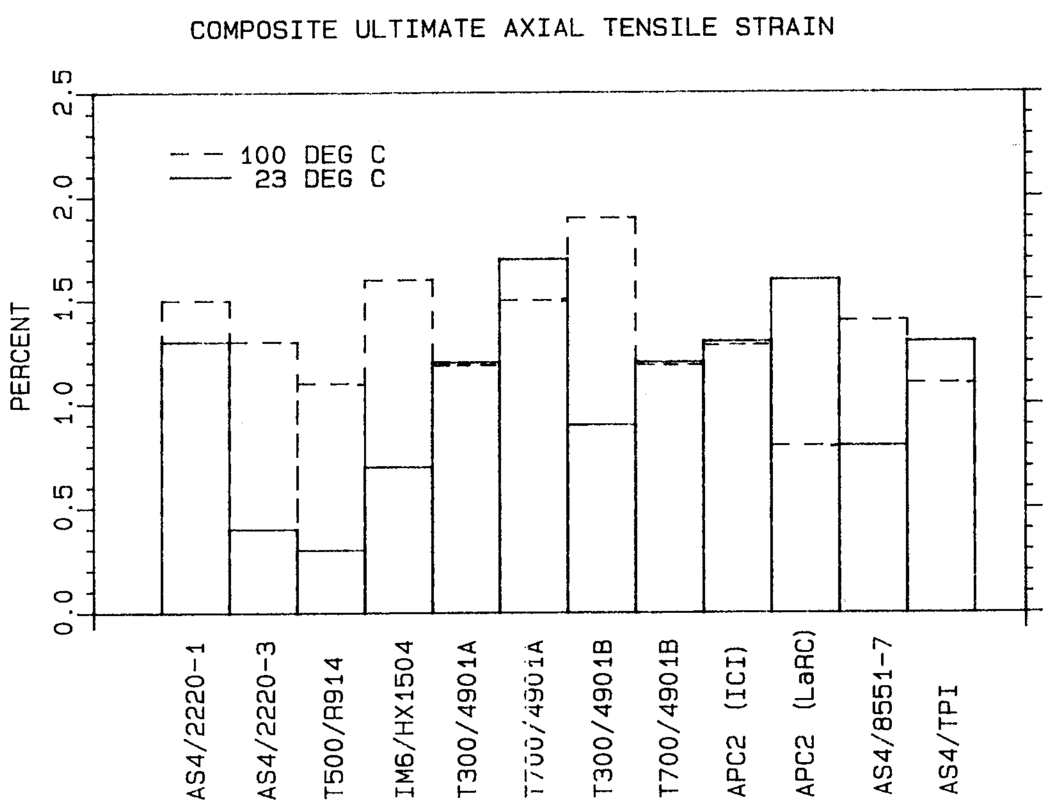

Figure 29. Unidirectional Carbon Fiber-Reinforced Composite Axial Tensile Ultimate Strains.

response seen in Figure 29. The one exception is the AS4/PEEK (LaRC) material. Since the high temperature AS4/PEEK (LaRC) test specimens prematurely failed, the high temperature strains were lower.

5.4 Composite Transverse Tensile Test Results

Average transverse tensile properties were given in Table 9 of Section 2.2. Complete stress-strain curves to failure were recorded for the transverse tensile tests. Individual stress-strain curves and test results are given in Appendices A and B.

Figure 30 is a bar chart of transverse tensile strengths, at both room temperature and 100°C, for the twelve composite systems. This property is highly dominated by the matrix performance, and also by the interaction between fiber and matrix. The room temperature transverse tensile strength values met expectations based upon the matrix strengths (see Table 2) in all but one case. Although no neat resin testing had been done in this project for the $PISO_2$-TPI thermoplastic blend, the exceedingly low transverse tensile strength was not expected. The PEEK thermoplastic matrix composites performed much better. This anomaly in behavior was further investigated by obtaining SEM photographs of the failed test specimens. These photos are presented in Section 6 of this report. The microphotographs indicate a very weak interface between the fiber and the thermoplastic matrix. This would explain the low transverse tensile strength results experienced by the AS4/$PISO_2$-TPI composite. At 100°C, the biggest drop in transverse tensile strength occurred in the composite systems using either 4901A or 4901B resins, with one exception. Transverse tensile specimens cut from AS4/PEEK

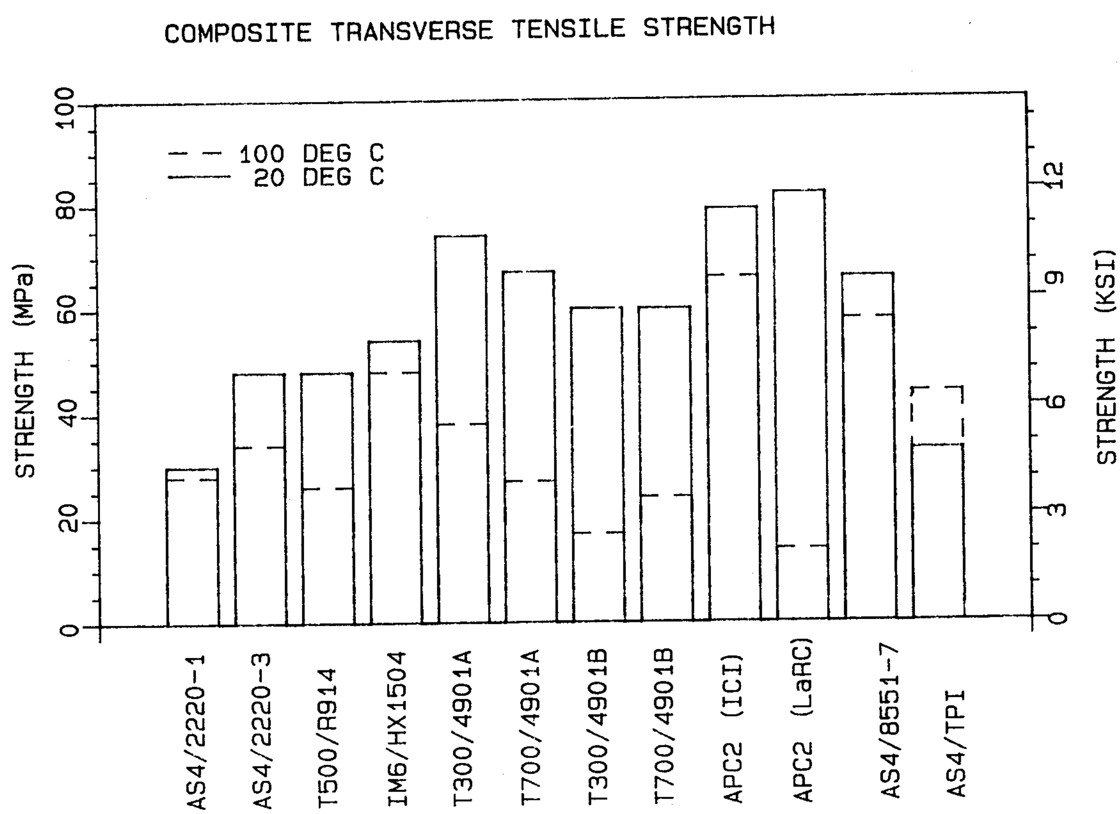

Figure 30. Unidirectional Carbon Fiber-Reinforced Composite Transverse Tensile Strengths.

composite laminate panels fabricated by NASA-Langley had the largest overall drop in strength at elevated temperature. This result is inconsistent with that for specimens cut from AS4/PEEK composite laminate panels fabricated by ICI. Specimens from both panel suppliers were tested in identical fashion. The laminate panel used for transverse tension specimens was 12 plies thick for ICI and 16 plies thick for NASA-Langley. The NASA-Langley panels were fabricated at 370°C (700°F) for 5 minutes and 300 psi. The panels were than cooled to 200°C (400°F) and held at that temperature for 30 minutes before cooling was resumed. The rate of cooling was not specified. No cure cycle information was supplied with the ICI panels.

Transverse tensile failure was characterized by a straight line fracture across the specimen, as seen in Figure 31.

Transverse tensile moduli are shown in bar chart form in Figure 32. All the room temperature moduli were at least twice as high as the neat resin values. This was expected since the transverse modulus of the fiber is greater than the resin modulus. Also, the presence of the fibers in the composite, especially at high fiber volumes, constrain the deformation of the matrix, resulting in increased composite transverse modulus [12].

At the 100°C test condition, the moduli of the 4901A and the 4901B composites were reduced considerably. This was expected based upon the neat resin behavior between 82 and 121°C. The R914 neat resin is also known to exhibit a dramatic drop in modulus between 82 and 121°C. This is reflected in the T500/R914 composite data. The other composites retained their stiffness quite well, with one exception. The

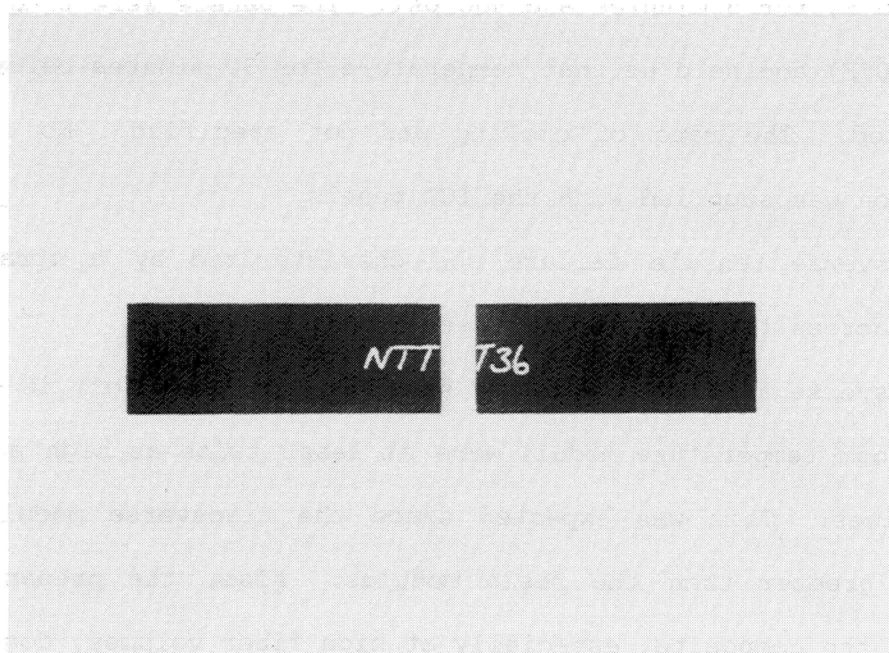

Figure 31. Typical Unidirectional Composite Transverse Tensile Failure.

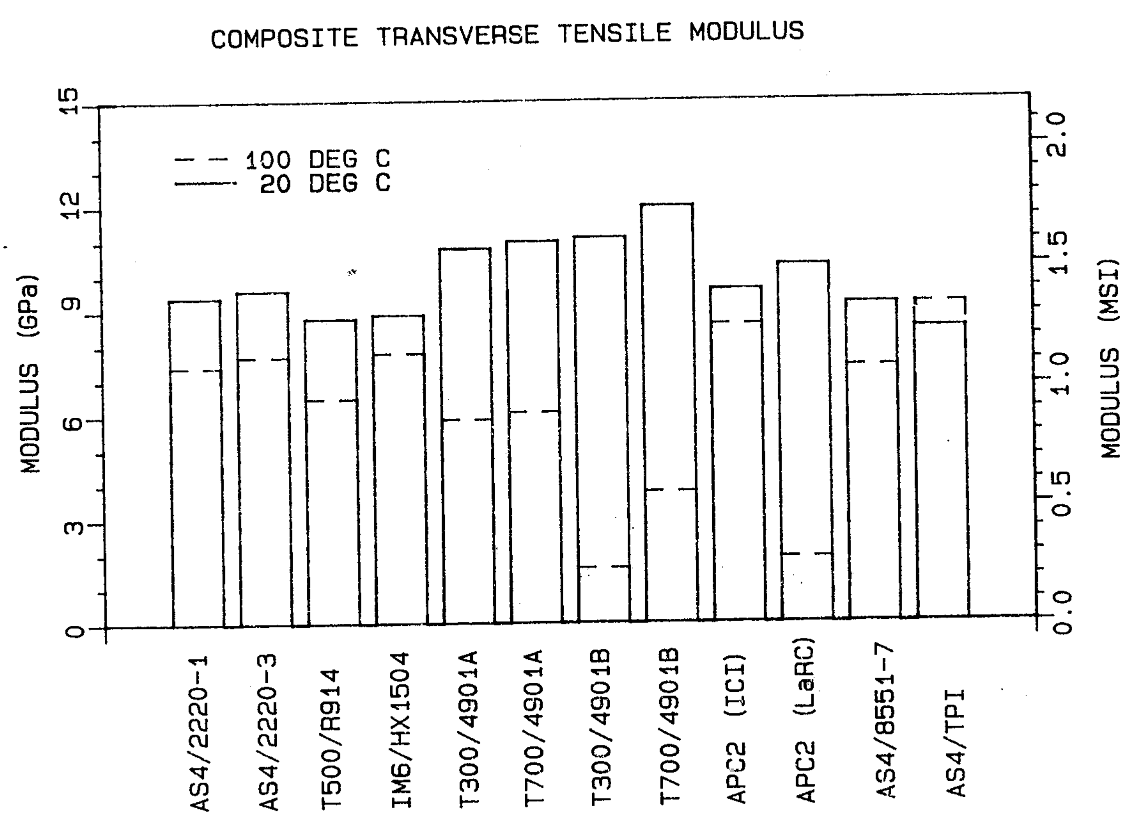

Figure 32. Unidirectional Carbon Fiber-Reinforced Composite Transverse Tensile Moduli.

AS4/PEEK composite fabricated by NASA-Langley exhibited a very large drop in modulus, as did the transverse tensile strength.

Transverse tensile strains are shown in Figure 33. The room temperature strains were all similar, being well below the neat resin values. This was expected since the constraints placed on the matrix by the presence of fibers induces stress and strain concentrations in the matrix adjacent to the fiber. This results in composite failure at lower strains than the strain at which the neat resin material fails [12]. At 100°C the transverse tensile strain value remained nearly the same, with the exception of the the T300/4901B and T700/4901B materials. These two exceptions experienced strain increases three times the corresponding room temperature values, a result of the large decrease in transverse tensile modulus for these two materials.

5.5 Composite In-Plane Shear Test Results

Average in-plane shear properties were listed previously in Table 9 of Section 2.2. Complete shear stress-shear strain curves to failure were recorded for all the composite in-plane shear tests. Individual shear stress-shear strain curves and test results are given in Appendices A and B.

Figure 34 is a bar chart of the in-plane shear strengths of the twelve carbon fiber-reinforced composites tested. Only small differences will be noted between the twelve composites at the room temperature condition, but a much larger variance was observed at the 100°C test temperature. At the elevated test temperature, the T300/4901A and T700/4901A materials degraded to 52 and 60 percent of their original values, respectively, and the T300/4901B and T700/4901B

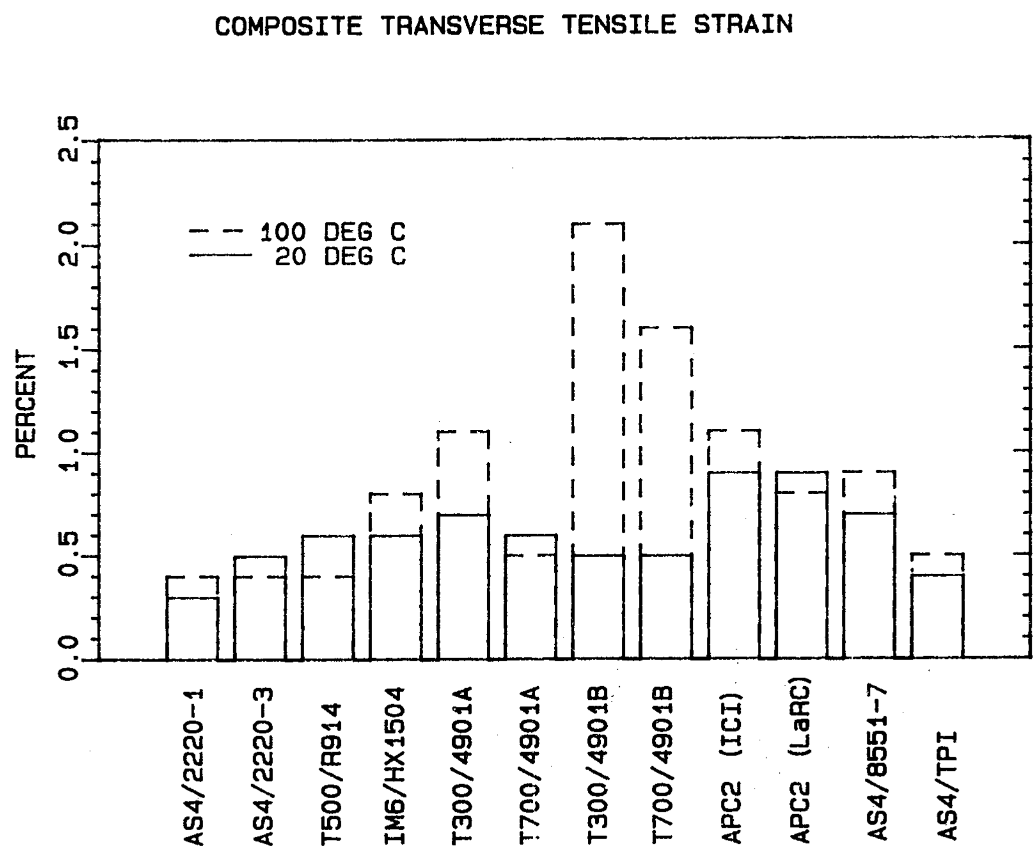

Figure 33. Unidirectional Carbon Fiber-Reinforced Composite Transverse Tensile Ultimate Strains.

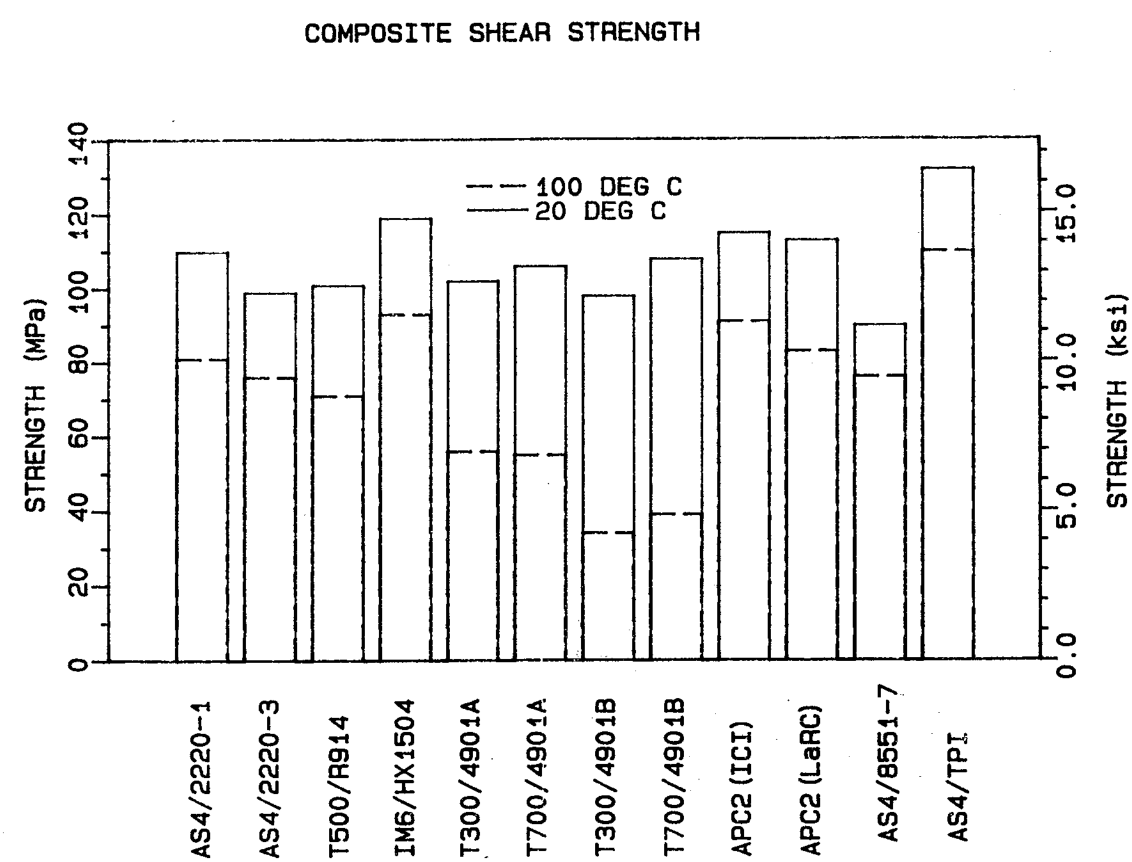

Figure 34. Unidirectional Carbon Fiber-Reinforced Composite In-Plane Shear Strengths.

materials degraded even more, to only 30 and 35 percent of their original room temperature shear strengths, respectively. The remainder of the materials retained approximately 70 to 85 percent of their shear strength. In-plane shear of a unidirectional composite is a matrix-dominated property; thus, these results could be expected after viewing the neat resin behavior (Tables 1 to 4).

A typical failed shear specimen is shown in Figure 35. The displacement between the right and left halves of the specimen, and the faint horizontal cracks between the notches, which are typical shear failure surfaces, will be noted. The large horizontal cracks near the notches act as stress concentration relievers and assist in maintaining a uniform shear strain field in the gage section [5]. The AS4/PISO$_2$-TPI specimens exhibited the highest shear strengths at both room and elevated test temperatures. This is a significant anomaly since in the SEM examinations these same specimens appeared to have a very weak fiber-matrix interface.

Shear modulus values are presented in bar chart form in Figure 36. The shear modulus tended to follow the axial tensile modulus, i.e., the higher axial tensile modulus materials exhibited higher shear modulus values than the materials with lower axial tensile moduli. The exceptions were the 4901A and 4901B matrix composite materials, which had higher room temperature shear moduli than expected. The elevated temperature results were similar to the room temperature shear moduli for all but the 4901A and 4901B composite materials. The relative drop in modulus for the four composite materials containing 4901A and 4901B resin matrices was somewhat predictable based upon the neat resin results.

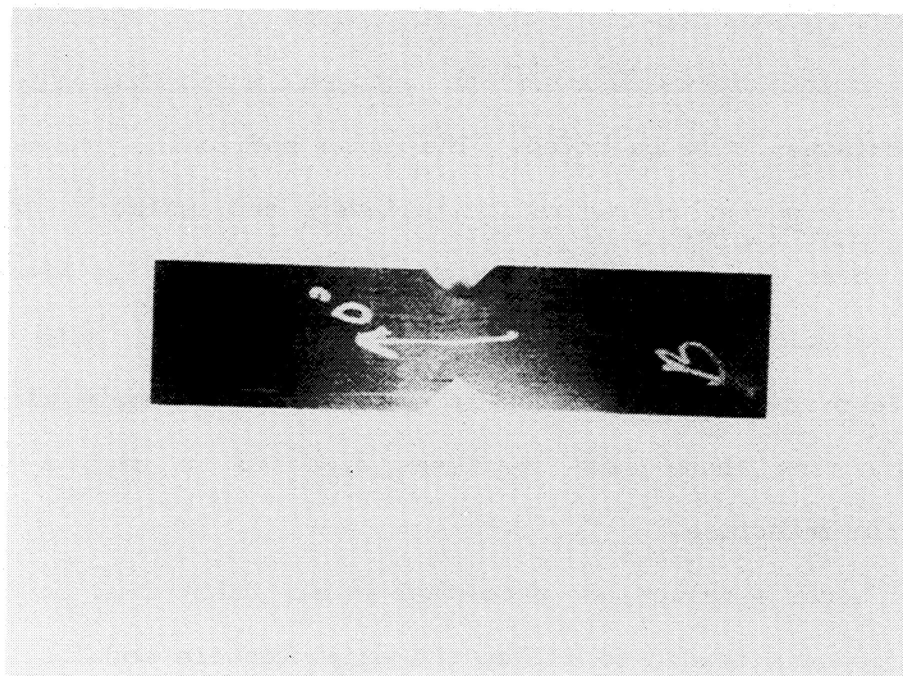

Figure 35. Typical Failed Iosipescu Shear Test Specimen.

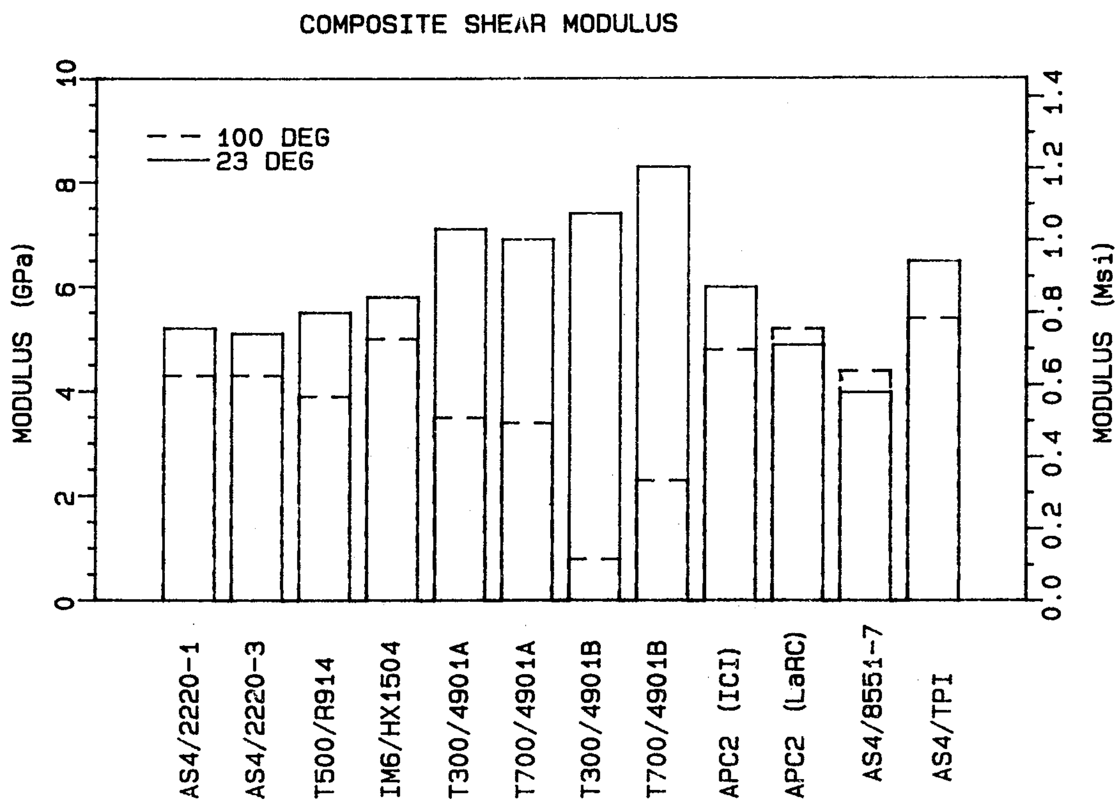

Figure 36. Unidirectional Carbon Fiber-Reinforced Composite In-Plane Shear Moduli.

A bar chart showing the ultimate shear strain values for the twelve composites is not shown because of the strain gage range limitations previously noted. Over half the tests resulted in shear strains beyond the strain gage capacity of 11.7 percent. Therefore, it is not possible to say which composite systems had the highest shear strains. As can be seen in Table 9, the lowest shear strain was 4.4 percent, achieved by the T300/4901A composite at room temperature.

5.6 Composite Transverse Coefficient of Thermal Expansion Tests

Transverse coefficient of thermal expansion (CTE) tests were performed on all twelve composite material systems. Average curve-fit parameters for all the composite systems are listed in Table 19.

Eight of the twelve systems displayed only a slight nonlinearity over the test temperature range. An example of this behavior is shown in Figure 37. Each test specimen was subjected to two thermal cycles. Both thermal cycles were plotted every 10°C, with the curve-fit line being drawn on top of the data points. Only the data from the second cycle was used to determine the CTE, as discussed below.

The CTE plots for four of the composite systems displayed a bilinear behavior, i.e., the plots were linear over two distinct temperature regions. Figure 38 shows an example of the bilinear nature of T300/4901-B. T700/4901B and both AS4/PEEK materials also displayed similar plots for CTE. This resulted in a pair of CTE constants for these materials. Each constant value is valid only over a specified temperature range. Both temperature cycles that the specimens were subjected to are depicted in Figure 38, the upper plot being the first cycle. A drop-off in expansion is quite noticeable at the high

Table 19

Average Composite Transverse Thermal Expansion Test Results

$$CTE = C_1 + C_2T \quad (10^{-6}/°C)$$

Material System	Temperature Range (°C)	Coefficients* C_1	C_2
AS4/2220-1	-40 to 120	34.4	0.08
AS4/2220-3	-40 to 120	34.6	0.08
T500/914	-40 to 120	35.9	0.07
IM6/1504	-40 to 120	30.7	0.06
T300/4901-A	-40 to 120	31.9	0.15
T700/4901-A	-40 to 120	34.3	0.15
T300/4901-B	-40 to 60	32.2	0
	60 to 120	85.2	0
T700/4901-B	-40 to 60	34.2	0
	60 to 120	60.0	0
AS4/PEEK (ICI)	-40 to 120	40.2	0
	120 to 205	82.6	0
AS4/PEEK (LaRC)	-40 to 120	33.2	0
	120 to 205	64.0	0
AS4/8551-7	-40 to 120	31.4	0
AS4/$PISO_2$-TPI			
Dry	-40 to 120	22.3	0
Moisture-Saturated	-40 to 120	21.5	0

* Second cycle

C-2

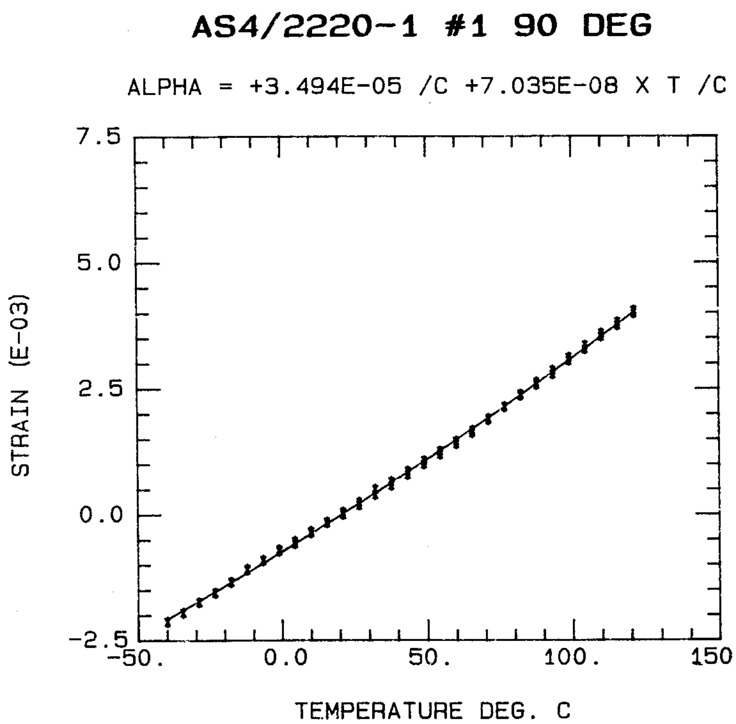

Figure 37. Typical Transverse Coefficient of Thermal Expansion Plot for the AS4/2220-1 Composite Including Both Sets of Temperature Cycle Data.

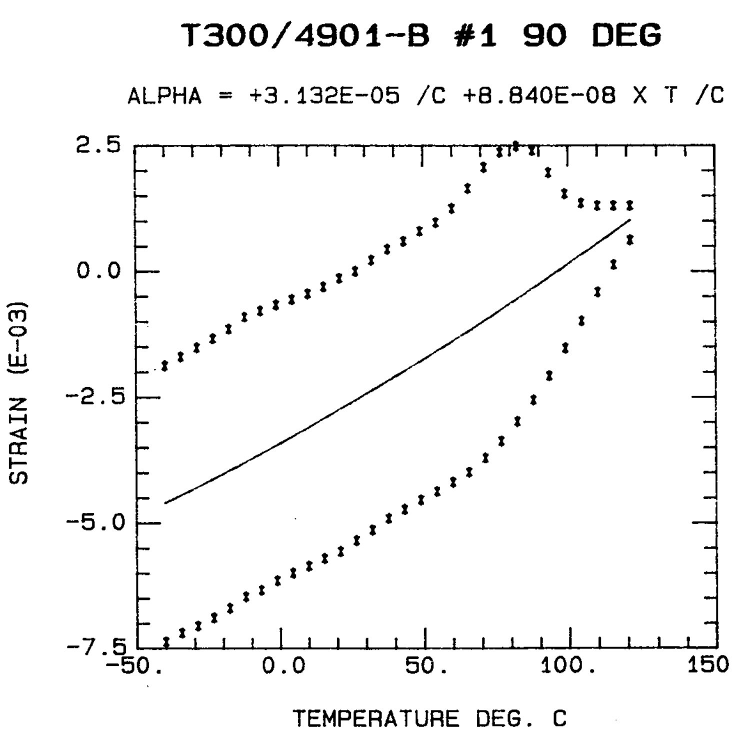

Figure 38. Typical Transverse Coefficient of Thermal Expansion Plot for the T300/4901B Composite, Including Both Sets of Temperature Cycle Data, Displaying Bilinear Behavior.

temperature end. This drop-off was due to shrinkage of the test specimen above 80°C for the T300/4901-B composite system. This same type of drop-off occurred above 110°C for the AS4/PEEK (LaRC) composite system. Shrinkage was verified by measuring and comparing the specimen lengths before and after testing. Table 20 shows the initial, final, and change in length for all composite CTE specimens.

In the figures shown, the second thermal cycle data points are plotted as the lower row of asterisks. The initial slopes of the two cycles were similar, as shown in the plots. The second cycle data demonstrate a continuous smooth curve, without any drop-off at the higher temperature portion of the test. This implies that the test specimens had stabilized after only one thermal cycle, and that the second cycle curve is probably a better measure of actual material behavior. The values given in Table 19 for CTE were thus taken only from the second thermal cycle data points. Individual test results and test plots are given in Appendices A and B, respectively.

5.7 Composite Transverse Coefficient of Moisture Expansion Tests

Transverse coefficient of moisture expansion (CME) tests were also performed on many of the carbon fiber-reinforced composites, using the same test apparatus as used for the neat resin, as described in Section 3.3 and shown in Figure 39.

The slopes of the transverse strain vs moisture curves for the composites were typically constant; the average coefficient of moisture expansion values are presented in Table 21. These are averages of three to six individual tests per material. Individual CME values are given in Appendix A. Plots for individual test specimens are given in

Table 20

Lengths of Individual Thermal Expansion Specimens Before and After Testing

Material System	Specimen No.	Initial Length (in)	Final Length (in)	Change in Length (in)
AS4/2220-1	1	5.108	5.104	-0.004
	2	5.106	5.105	-0.001
	3	5.108	5.104	-0.004
AS4/2220-3	1	5.010	5.008	-0.002
	2	5.011	5.007	-0.004
	3	5.010	5.006	-0.004
T500/R914	1	5.101	5.098	-0.003
	2	5.102	5.098	-0.004
	3	5.102	5.097	-0.005
IM6/1504	1	5.093	5.094	0.001
	2	5.095	5.094	-0.001
	3	5.094	5.095	0.001
T300/4901A	1	5.010	4.975	-0.035
	2	5.010	4.991	-0.019
	3	5.000	4.999	-0.001
T700/4901A	1	5.006	5.005	-0.001
	2	5.003	4.996	-0.007
	3	5.003	4.999	-0.004
T300/4901B	1	5.011	4.989	-0.022
	2	5.011	4.982	-0.029
	3	5.023	4.986	-0.037
T700/4901B	4	5.109	5.082	-0.027
	6	5.104	5.072	-0.032
	7	2.454	2.454	0.000
	8	2.361	2.360	-0.001
	9	2.445	2.444	-0.001
AS4/PEEK (ICI)	1	5.007	5.001	-0.006
	2	4.993	4.991	-0.002
	3	5.008	5.004	-0.004
AS4/PEEK (LaRC)	1	5.004	4.981	-0.023
	2	5.004	4.981	-0.023
	3	5.004	4.977	-0.027
AS4/8551-7*				

Table 20 (cont.)

Material System	Specimen No.	Initial Length (in)	Final Length (in)	Change in Length (in)
$AS4/PISO_2$-TPI Dry	1	4.840	4.840	0.000
	2	4.838	4.838	0.000
	3	4.836	4.836	0.000
$AS4/PISO_2$-TPI Moisture-Saturated	1	2.470	2.470	0.000
	2	2.221	2.221	0.000
	3	2.462	2.462	0.000

*Information not available

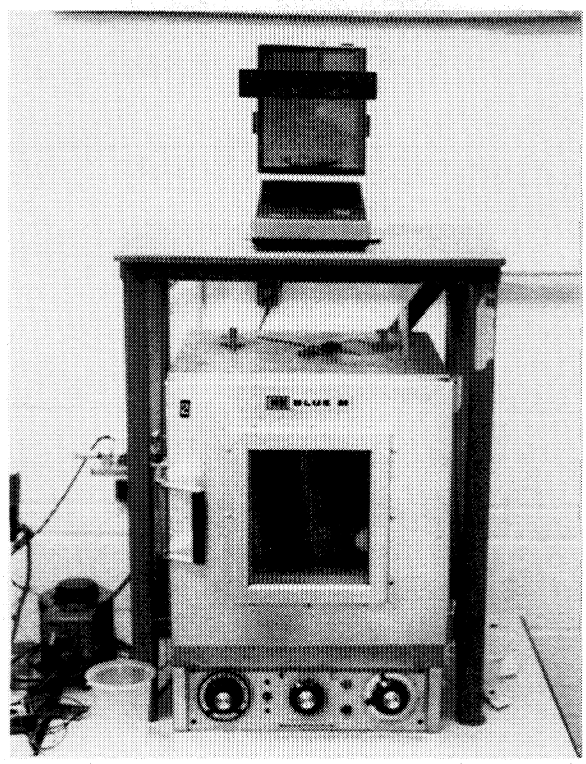

Figure 39. Typical Moisture Expansion Coefficient Chamber with Electronic Balance on Top and LVDT Mounted on the Side.

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Table 21

Average Composite Transverse Moisture Expansion Coefficient Test Results

Material System	Transverse CME (10^{-3}/%M)
AS4/3502	4.67
AS4/2220-1	2.92
AS4/2220-3	4.49
T500/R914	3.65
IM6/1504	2.96
T300/4901A	4.37
T700/4901A	6.38
T300/4901B	*
T700/4901B	*
AS4/PEEK (ICI)	3.76
AS4/PEEK (LaRC)	3.10
AS4/8551-7	4.10
AS4/$PISO_2$-TPI	*

* Data not available
Properties of the first four systems are repeated from Reference [3].

Appendix B. With a few exceptions, the composite transverse CME was similar to the AS4/3502 baseline of 4.67×10^{-3}/%M. Besides the twelve composites in this report, only four other composites in this project had CME measurements. Those previously measured values range from 2.59×10^{-3}/%M to 4.67×10^{-3}/%M.

SECTION 6

SCANNING ELECTRON MICROSCOPY

6.1 Introduction

Scanning electron microscopy (SEM) was performed on selected failed AS4/$PISO_2$-TPI test specimens. The Composite Materials Research Group (CMRG) has utilized the SEM for many years to study both composite material fractures and unreinforced (neat) resin fractures. The SEM provides a large depth of field at high magnification and is thus much more useful than the optical microscope in the study of the rough fracture surfaces seen in composite materials. A JEOL-35C scanning electron microscope was used for all the work in this report. This unit has a magnification range from 10X to 180,000X, a depth of field of 30μ at 1000X, and a resolution of 60Å. Magnifications between 10X and 1000X are particularly informative when examining composite material fractures.

The specimens scanned were a carbon fiber-reinforced thermoplastic blend composite. The fiber was an unsized, 12K, Hercules AS4 graphite fiber while the matrix material was a 2:1 blend of polyimide sulphone ($PISO_2$) and LaRC polyimide (TPI) with an additional 5 percent of a low molecular weight monomer that improved melt flow characteristics.

6.2 Specimen Preparation

Specimens were cut from failed AS4/$PISO_2$-TPI test specimens using a Bueller No. 4150 silicon carbide abrasive cutoff blade. All specimens were then cleaned in an ultrasonic cleaning tank to remove any surface debris. Duco cement was used to bond the specimens to the 25.4 mm between the brass disk and specimens along the bond line to ensure a good conducting path between the two. Gold was vapor-deposited on all specimens to make them electrically conductive, thus preventing the accumulation of electrons on the fracture surface during SEM viewing. Any accumulation of electrons on the surface of a specimen, when exposed to the high energy electron beam, causes flaring and results in a poor viewing image.

6.3 Explanation of SEM Photographs

Failed longitudinal tensile and Iosipescu shear specimens were viewed and photographed. A brief description of each SEM photograph is given below each figure.

The SEM records information directly across the bottom of each photograph. Referring to Figure 41 as an example, the caption reads: 25KV X90 0008 100.0U UW 88. The interpretation is as follows:

25KV	Electron beam accelerating voltage, in kilovolts
X90	Magnification
0008	Photograph number
100.0U	Length of scale bar, in microns
UW 88	The SEM unit identification number, i.e., University of Wyoming and the current year, 1988.

6.4 Longitudinal Tension

A representative failed AS4/$PISO_2$-TPI longitudinal tension specimen was viewed and photographed. This specimen had been tested at room temperature, dry conditions. Figure 40 illustrates the orientation of the SEM sample with respect to the tensile specimen. Figures 41 through 45 are various views of the fracture surface.

6.5 Iosipescu Shear

A representative failed AS4/PISO$_2$-TPI Iosipescu shear specimen was viewed and photographed. This specimen had been tested at room temperature, dry conditions. Figure 46 illustrates the orientation of the SEM sample with respect to the shear specimen. Figures 47 through 50 are various views of this orientation, and primarily display the crack opening. Figure 51 illustrates another orientation of the shear SEM sample. This position of the sample allows a view of the sheared surface. These views are depicted in Figures 52 through 55.

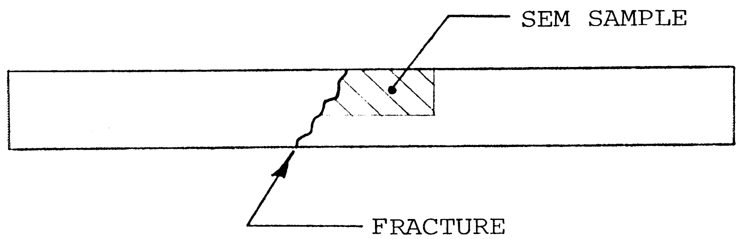

Figure 40. Geometry of SEM Sample in Reference to the Longitudinal Tension Test Specimen.

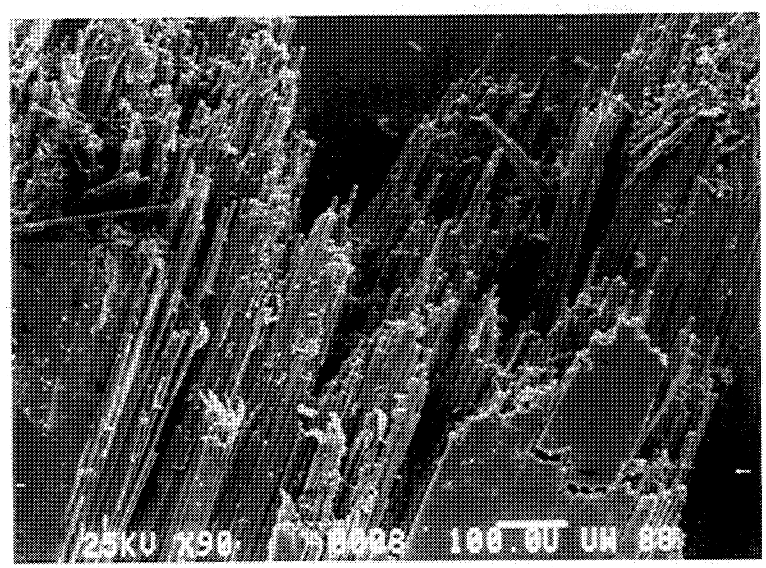

Figure 41. Side View of the Fracture Surface of an AS4/$PISO_2$-TPI Longitudinal Tension Specimen, 23°C, Dry.

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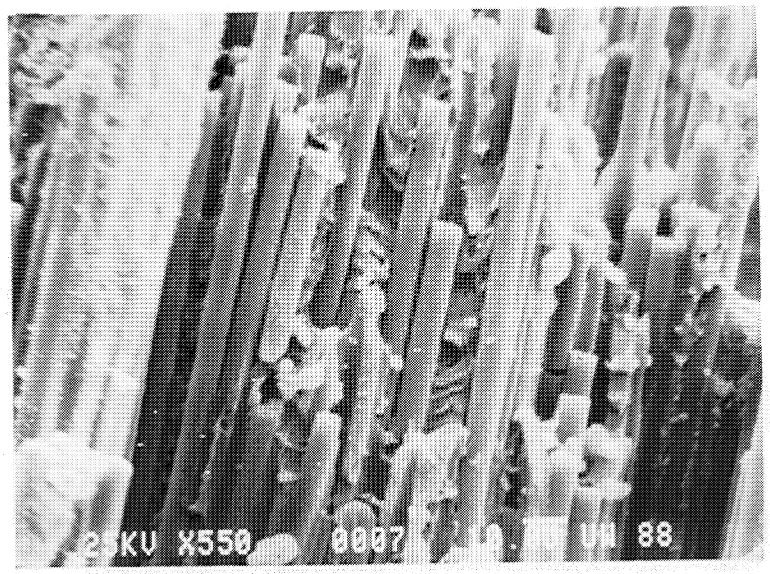

Figure 42. Higher Magnification of View in Figure 41.

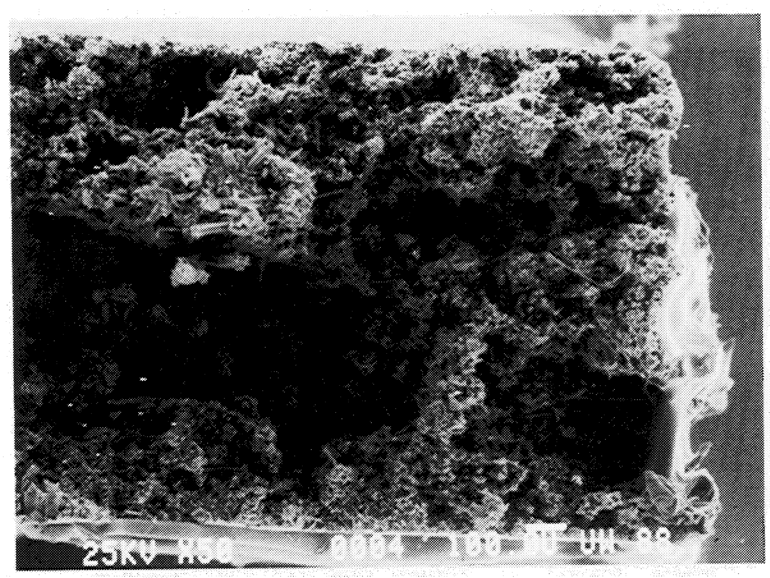

Figure 43. End View of the Fracture Surface of an AS4/$PISO_2$-TPI Longitudinal Tension Specimen, 23°C, Dry.

Notice the area near the upper left of the photograph. This area has the largest degree of fiber pullout.

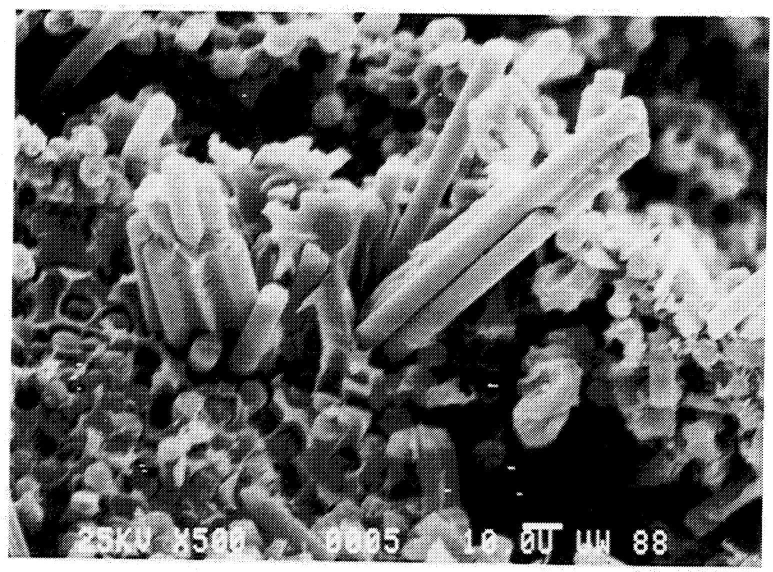

Figure 44. Higher Magnification of Fiber Pullout Area Noted in Figure 43.

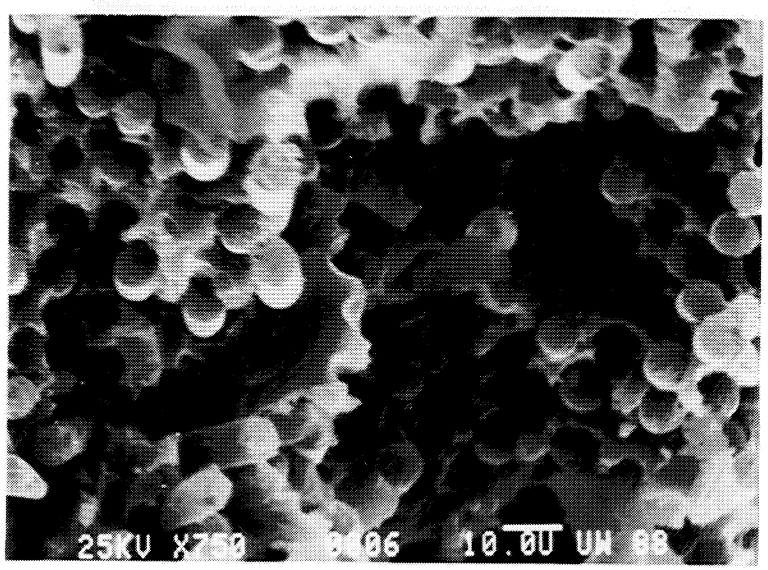

Figure 45. Typical Appearance of Most of the Fracture Surface from Figure 43.

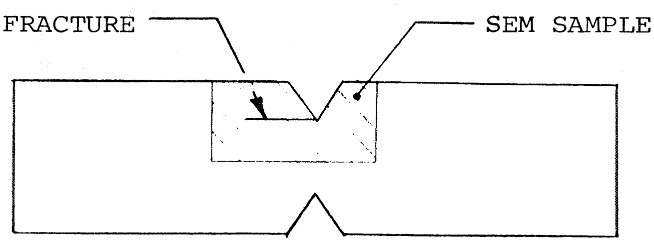

Figure 46. Geometry of the SEM Sample in Reference to the Iosipescu Shear Test Specimen.

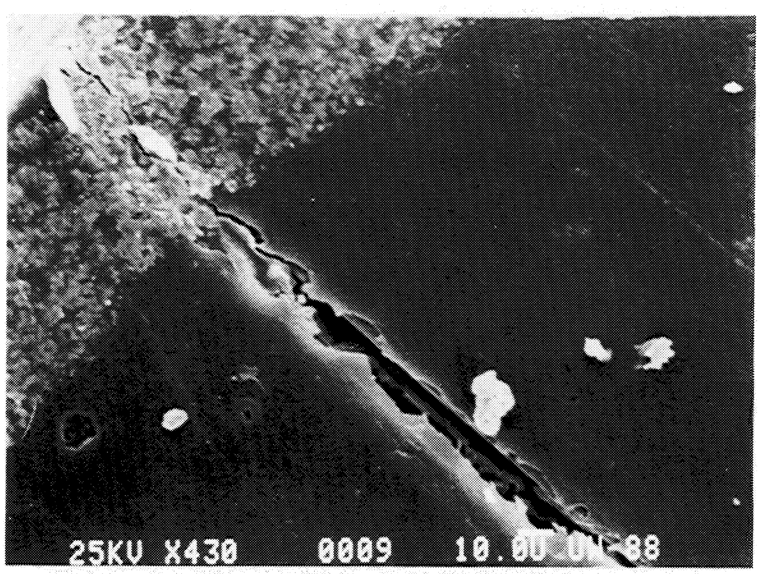

Figure 47. AS4/PISO$_2$-TPI Iosipescu Shear Specimen, 23°C, Dry. View of the Extreme End of the Fracture Away from the Notch.

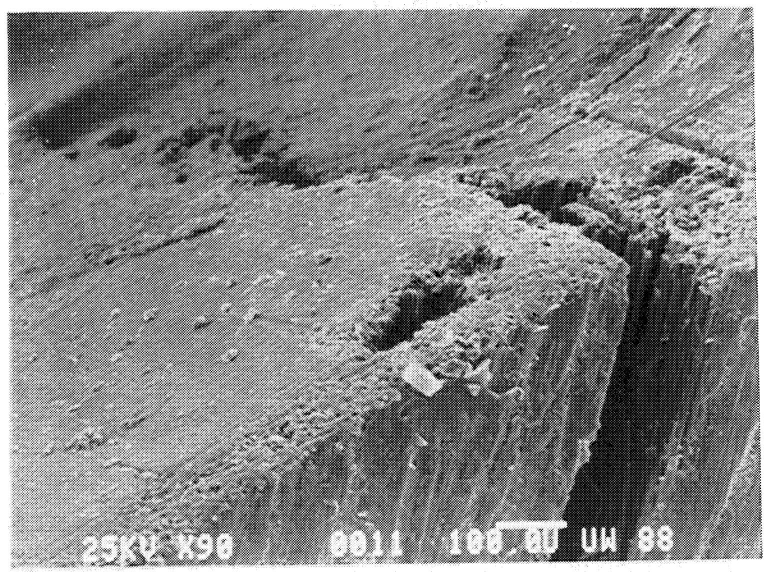

Figure 48. View of the Fracture at the Notch Surface.

The defect below the crack is probably due to handling of the specimen, not testing.

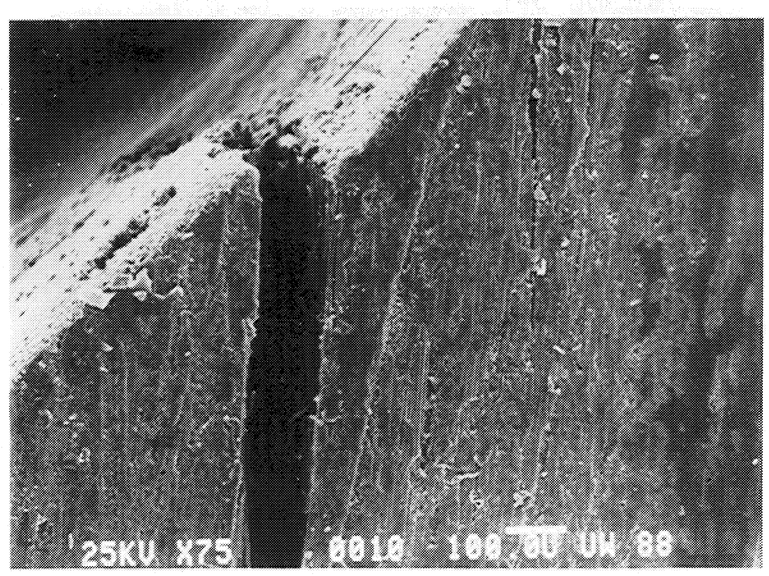

Figure 49. Side View of the Fracture in Figure 47.

Notice the parallel cracks at upper right of the photograph.

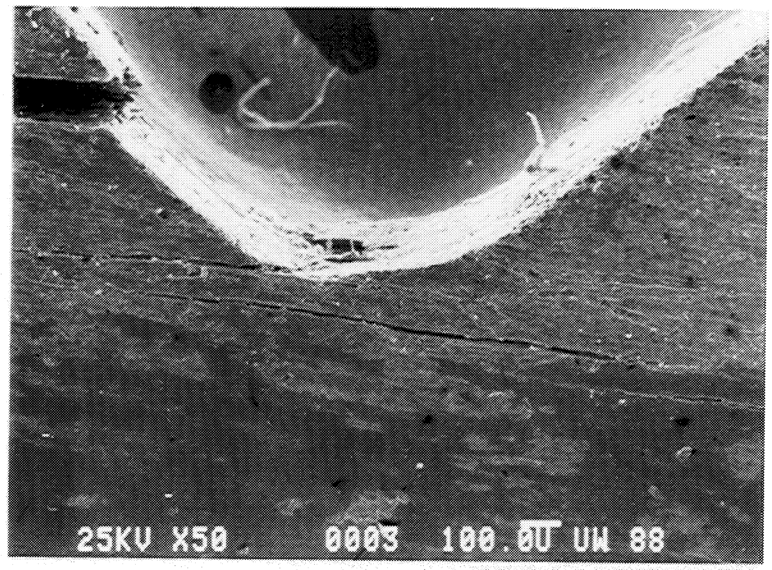

Figure 50. Side View of the Notch Tip.

Note the beginning of the large fracture (upper left) and also the two cracks below the notch.

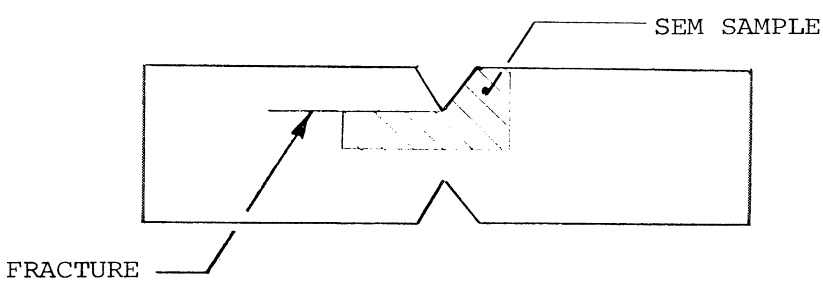

Figure 51. Geometry of SEM Sample in Reference to the Iosipescu Shear Test Specimen.

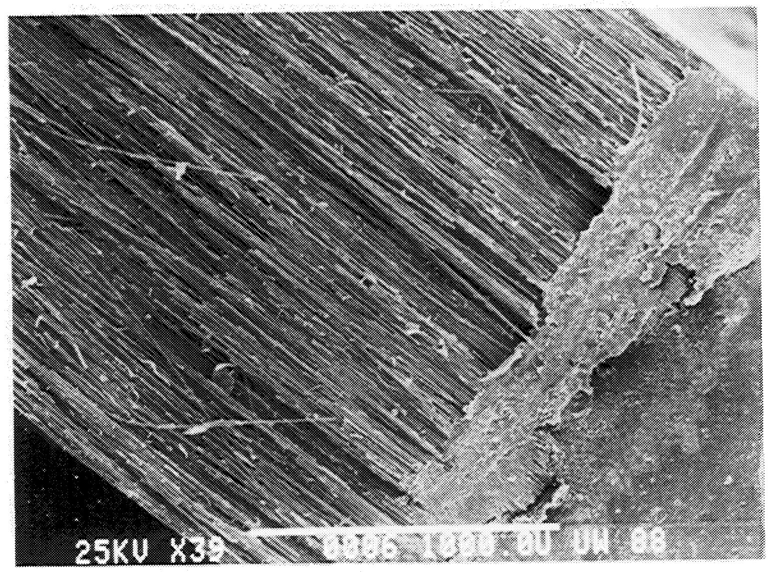

Figure 52. AS4/$PISO_2$-TPI Iosipescu Shear Test Specimen, 23°C, Dry. View of Fracture Surface Along Which Shear Crack Propagated; Notch Surface Appears at the Lower Right.

Notice the apparent defect in the center of the photograph.

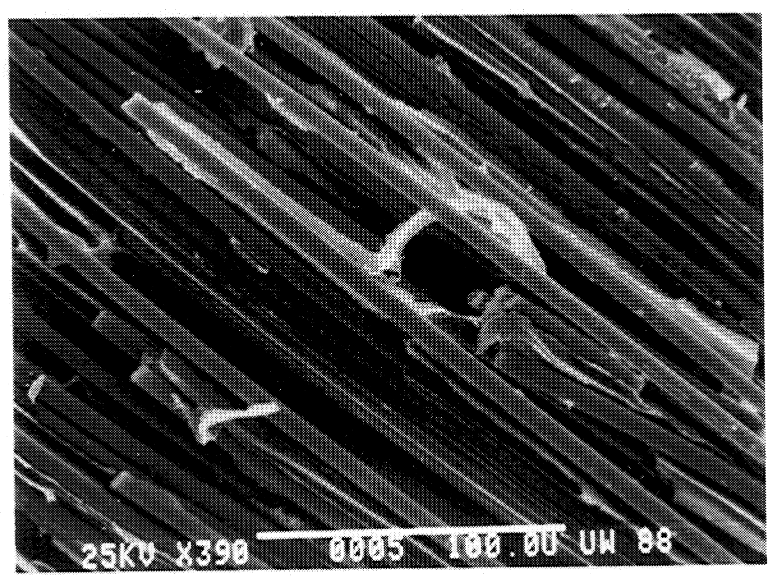

Figure 53. Increased Magnification of Defect Noted in Figure 52.

Notice the lack of material adhering to the fibers.

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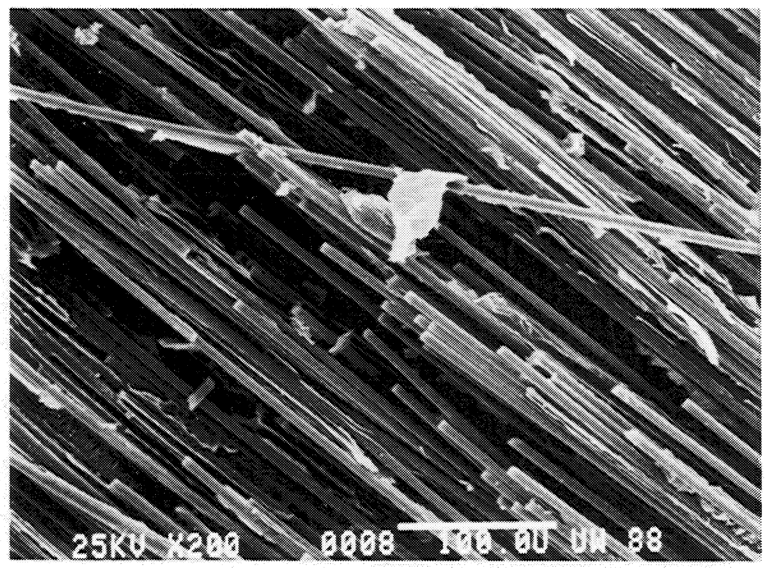


Figure 54. Fiber Fracture Near the Notch End of the Sample.
Again note how clean the fibers appear.

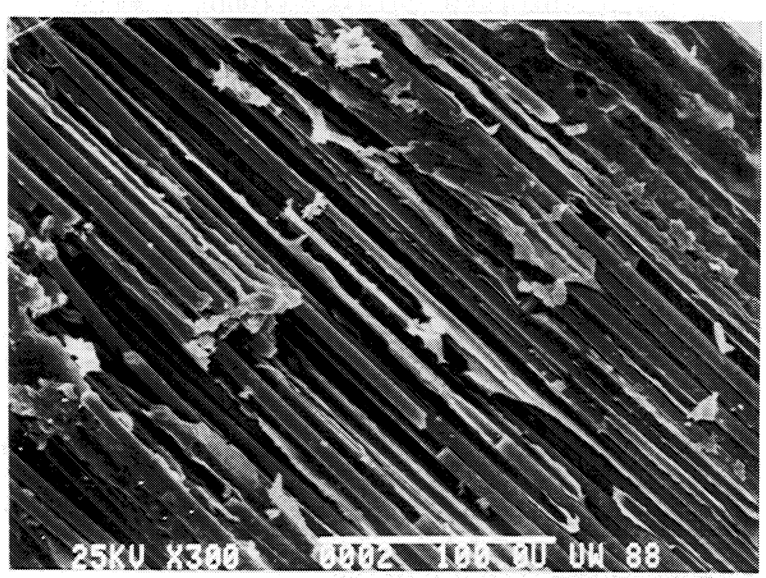


Figure 55. Fracture Surface at the End Furthest from the Notch.

SECTION 7

CONCLUSIONS

Three more neat resin systems, PEEK (polyetheretherketone) thermoplastic, Hexcel F155 epoxy and Hercules 8551-7 epoxy, were successfully cast into various test specimens and mechanically characterized. Tension, Iosipescu shear, single-edge, notched-bend fracture toughness, coefficient of thermal expansion, and coefficient of moisture expansion tests were conducted to generate mechanical properties as functions of temperature and moisture. Properties generated for these neat resins were Young's modulus, E, Poisson's ratio, ν, shear modulus, G, tensile ultimate strength, σ_u, shear ultimate strength, τ_u, coefficient of thermal expansion, α, coefficient of moisture expansion, β, and Mode I strain energy release rate, G_{IC}.

Twelve carbon fiber-reinforced unidirectional composites were also tested. The composite systems were as follows: AS4/2220-1, AS4/2220-3, T500/R914, IM6/HX1504, T300/4901A (MDA), T700/4901A (MDA), T300/4901B (MPDA), T700/4901B (MPDA), AS4/PEEK (APC2, ICI), and AS4/PEEK (APC2, Langley Research Center), AS4/8551-7, and AS4/PISO$_2$-TPI. Flat panels were supplied by NASA-Langley in sufficient quantities to perform various mechanical tests on these twelve composites. Many of the panels had been supplied to NASA-Langley by the primary manufacturer of the fiber/resin system. All specimens were machined and prepared by the CMRG in their own fabrication laboratories.

Longitudinal and transverse tensile, in-plane shear, transverse coefficient of thermal expansion, and transverse coefficient of moisture expansion tests were conducted to generate mechanical properties as a function of temperature. Properties generated for the twelve composite materials were axial and transverse moduli, E_{11} and E_{22}, major Poisson's ratio, ν_{12}, longitudinal shear modulus, G_{12}, axial and transverse tensile strengths, σ_1 and σ_2, shear strength, τ_{12}, and ultimate strains, ε_1, ε_2 and γ_{12}. Also measured were transverse coefficient of thermal expansion, α_2, and transverse coefficient of moisture expansion, β_2.

Processability of the epoxy matrix systems and the thermoplastic neat resin systems were quite different. The PEEK thermoplastic required the development of an entirely new fabrication method. The Hexcel F155 and the Hercules 8551-7 epoxies were processed the same as epoxies in previous years [1-3].

The neat PEEK thermoplastic performed as well or better then any neat resin tested to date [1-3]. It exhibited some of the highest Young's modulus and shear modulus results, especially at the elevated temperature and moisture-saturated conditions, as expected. The tensile and shear strength values also compared well with previous results.

The 8551-7 epoxy tensile properties at the elevated temperature and dry condition were below the average of the other resins in this project. The moisture-saturated condition at both room and elevated test temperatures resulted in data in the midrange of the previous resin test data. All the 8551-7 shear test results were below the average of the other resins.

Tension and torsion tests were also performed on sets of miniaturized 8551-7 neat epoxy specimens. These tests gave equivalent results for strength and modulus, but differed significantly in strain. This testing successfully demonstrated the potential for reducing the amount of neat resin needed to perform mechanical characterization tests.

The Hexcel F155 Young's modulus and shear modulus as well as the tensile and shear strength fell significantly with increased temperature and moisture. The Hexcel F155 specimens were tested at different temperatures than those used with the previous resins in this study. Direct comparisons can thus only be made with the room temperature results.

The Hexcel F155 epoxy reached a moisture saturation level of 4.9 percent, the 8551-7 saturated at 2.0 percent moisture weight gain, and the PEEK thermoplastic only absorbed 0.5 percent moisture at saturation. The PEEK specimens appeared to be relatively unaffected by the moisture conditioning.

The twelve carbon fiber-reinforced composites tested indicated a variety of responses to the 100°C test temperature. Since the twelve composites incorporated five different fibers, direct comparisons are difficult to make.

Lack of complete satisfaction of the isotropic relation relating the neat resin experimental parameters E, ν, and G was again noted. However, in almost all cases the Hexcel epoxy and the PEEK thermoplastic provided a higher degree of agreement with the isotropic relationship than any material tested in the previous three studies [1-3].

REFERENCES

1. R. S. Zimmerman and D. F. Adams, "Investigation of the Relations Between Neat Resin and Advanced Composite Mechanical Properties," NASA CR-172303, Volume I-Results, Volume II-Appendices; November 1984.

2. R. S. Zimmerman and D. F. Adams, "Mechanical Properties Testing of Candidate Polymer Matrix Materials for Use in High Performance Composites," NASA CR-177970, December 1985.

3. R. S. Zimmerman and D. F. Adams, "Mechanical Properties of Neat Polymer Matrix Materials and Their Unidirectional Carbon Fiber-Reinforced Composites," NASA CR-181631, December 1988.

4. D. E. Walrath and D. F. Adams, "Analysis of the Stress State in an Iosipescu Shear Test Specimen," Report No. UWME-DR-301-102-1, Department of Mechanical Engineering, University of Wyoming, June 1983.

5. D. E. Walrath and D. F. Adams, "Verification and Application of the Iosipescu Shear Test Method," Report No. UWME-DR-401-103-1, Department of Mechanical Engineering, University of Wyoming, June 1984.

6. "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials," ASTM Standard E399, American Society for Testing Materials, 1981.

7. "Standard Test Methods for Tensile Properties of Oriented Fiber Composites," ASTM Standard D3039, American Society for Testing Materials, 1985.

8. D. E. Walrath and D. F. Adams, "Iosipescu Shear Properties of Graphite Fabric/Epoxy Composite Laminates," Report No. UWME-DR-501-103-1, Department of Mechanical Engineering, University of Wyoming, June 1985.

9. ICI Americas Inc., "Victrex PEEK, A Guide to Grades for Injection Moulding," Literature Reference VK2/0586, 1986.

10. P. Cebe, S. Hong, S. Chung, and A. Gupta, "Mechanical Properties and Morphology of Poly(etheretherketone)," Jet Propulsion Laboratory, Pasadena, California, August 1985.

11. Challa, Hermans, and Weidinger, Makromo, Chem., Vol. 56, p. 169 (1962).

12. B. D. Agarwal and L. J. Broutman, Analysis and Performance of Fiber Composites, John Wiley & Sons, New York, 1980.

APPENDIX A

Tables of Individual Test Specimen Results for the Three Neat Resins and Twelve Carbon Fiber-Reinforced Composites

Table A1

Individual Tension Test Results for Polyetherether Ketone (PEEK)
Thermoplastic Resin at Dry Conditon

Specimen No.	Test Temperature (°C)	Ultimate Stress (ksi)	Ultimate Stress (MPa)	Ultimate Strain (percent)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Poisson's Ratio
PETD 11	23	12.7*	87.6*	2.4*	0.61	4.2	**
2		9.4	64.8	1.6	0.60	4.1	**
3		7.8	53.8	1.3	0.58	4.0	**
4		6.1	42.1	1.0	0.60	4.1	**
5		5.8	40.0	1.0	0.61	4.2	0.41
	Average--	7.3	50.2	1.2	0.60	4.1	0.41
	Standard Deviation--	1.7	11.5	0.3	0.01	0.07	----
PETD 21	82	11.3	77.9	>8.2*	0.53	3.7	0.44
2		11.7	80.7	4.4	0.54	3.7	0.43
3		11.7	80.7	3.6	0.55	3.8	0.44
4		11.6	80.0	6.9	0.55	3.8	0.43
5		10.0	69.0	2.1*	0.56	3.9	0.44
	Average--	11.3	77.6	5.0	0.55	3.8	0.44
	Standard Deviation--	0.7	5.0	1.7	0.01	0.7	0.01
PETD 31	121	8.3	57.2	4.8	0.48	3.3	0.42
2		9.0	62.1	8.5	0.51	3.5	0.50
3		7.3	50.3	1.4*	0.56	3.9	0.47
4		8.5	58.6	5.6	0.50	3.4	0.42
5		9.1	62.7	16.4*	0.52	3.6	0.41
	Average--	8.4	58.2	6.3	0.51	3.5	0.44
	Standard Deviation	0.7	5.0	1.9	0.03	0.2	0.04

*Not included in average
**Data not available

Table A2

Individual Tension Test Results for Polyetherether Ketone (PEEK)
Thermoplastic Resin at Moisture Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Stress (ksi)	(MPa)	Ultimate Strain (percent)	Tensile Modulus (Msi)	(GPa)	Poisson's Ratio
PEKWL 1	23	10.4	71.7	1.6	0.68	4.69	0.41
2		13.6*	93.8	2.4	0.69	4.76	0.51*
3		7.9	54.5	1.1	0.71	4.90	0.47
4		7.2	49.6	1.1	0.69	4.76	0.45
5		7.3	50.3	1.1	0.71	4.90	0.46
6		12.5	86.2	3.4*	0.53*	3.65*	0.30*
	Average--	9.1	62.5	1.5	0.70	4.80	0.45
	Standard Deviation--	2.3	16.0	0.6	0.01	0.09	0.03
PEKWM 1	82	5.6*	38.6*	1.0	0.59	4.07	0.40
2		7.3	50.3	1.4	0.56	3.86	0.38
3		9.7	66.0	4.1*	0.54	3.72	0.38
4		4.8*	33.1*	0.9	0.59	4.07	0.39
5		9.7	66.9	2.5	0.57	3.93	0.41
6		10.2	70.3	3.9	0.53	3.65	0.36
7		10.6	73.1	4.1	0.53	3.65	0.40
	Average--	9.5	65.5	1.9	0.56	3.86	0.39
	Standard Deviation--	1.3	8.9	1.3	0.03	0.21	0.02
PEKWH 1	121	8.1	55.89	>5.1	0.55	3.7	0.38
2		8.1	55.81	>6.1	0.48	3.3	0.33
3		8.1	55.88	>10.2	0.49	3.3	0.34
4		7.7	53.15	>10.2	0.50	3.4	0.32
5		8.3	57.25	8.5	0.50	3.4	0.36
6		8.1	55.80	>10.2	0.42	2.9	0.34
7		8.2	56.59	>10.2	0.52	3.5	0.39
	Average--	8.1	55.8	>8.6	0.49	3.4	0.35
	Standard Deviation	0.2	1.4		0.04	0.3	0.03

*Not included in average

Table A3

Individual Iosipescu Shear Test Results For Polyetherether Ketone (PEEK) Thermoplastic Resin at Dry Conditon

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (ksi)	Ultimate Shear Stress (MPa)	Ultimate Shear Strain (percent)	Shear Modulus (Msi)	Shear Modulus (GPa)
PEKD 10	23	10.4	71.7	5.9	0.24	1.7
11		7.9	54.5	3.2	0.25	1.7
12		8.9	61.4	4.4	0.24	1.7
13		9.7	66.9	5.8	0.22	1.5
14		5.7*	39.3*	2.4	0.22	1.5
15		10.5	72.4	11.8*	0.22	1.5
16		8.5	58.6	4.0	0.23	1.6
17		10.9*	75.2*	11.8*	0.22	1.5
	Average--	9.3	64.2	4.3	0.23	1.6
	Standard Deviation--	1.1	7.3	1.4	0.01	0.1
PEKD 20	82	8.6	59.3	11.5	0.20	1.4
1		8.5	58.6	>12.0	0.21	1.4
2		8.4	57.9	>12.0	0.22	1.5
3		8.7	60.0	>12.0	0.21	1.4
4		8.4	57.9	>12.0	0.19	1.3
5		8.8	60.7	>12.0	0.24	1.7
	Average--	8.6	59.3	>12.0	0.21	1.4
	Standard Deviation--	0.2	1.4	---	0.02	0.1
PEKD 30	121	7.3	50.3	>11.9	0.20	1.4
1		7.6	52.4	>11.8	0.24	1.7
2		7.4	51.0	>11.8	0.22	1.5
3		7.3	50.3	>11.8	0.20	1.4
4		7.0	48.3	>11.8	0.20	1.4
	Average--	7.3	50.3	>11.8	0.21	1.4
	Standard Deviation	0.2	1.4	---	0.02	0.1

*Not included in average

Table A4

Individual Iosipescu Shear Test Results For Polyetherether Ketone (PEEK) Thermoplastic Resin at Moisture Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (ksi)	Ultimate Shear Stress (MPa)	Ultimate Shear Strain (percent)	Shear Modulus (Msi)	Shear Modulus (GPa)
PEKWR 1	23	10.4	71.7	>10.2	0.24	1.6
2		10.0	69.0	>10.2	0.24	1.6
3		10.3	71.0	>10.2	0.25	1.7
4		10.3	71.0	>10.2	0.24	1.6
5		10.8	74.5	>10.2	0.24	1.6
	Average--	10.4	71.4	>10.2	0.24	1.6
	Standard Deviation--	0.3	2.0		0.00	0.0
PEKW8 1	82	6.8	46.5	2.02	0.47*	3.2*
2		8.4	57.6	>10.2	0.24	1.6
3		8.1	55.7	>10.2	0.24	1.6
4		8.2	56.9	>10.2	0.21	1.4
5		8.6	59.6	>10.2	0.24	1.6
	Average--	8.0	55.3	>10.2	0.23	1.6
	Standard Deviation--	0.7	5.1		0.02	0.1
PEKWH 1	121	7.2	49.4	>10.2	0.20	1.4
2		6.6	45.6	>10.2	0.20	1.4
3		6.4	44.1	>10.2	0.22	1.5
4		6.3	43.6	>10.2	0.21	1.4
5		7.2	49.5	>10.2	0.22	1.5
	Average--	6.7	46.4	>10.2	0.21	1.4
	Standard Deviation	0.4	2.8		0.01	0.1

*Not included in average

Table A5

Individual Tension Test Results For Hexcel F155 Neat Resin at Dry Condition

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NNTD61	-54	66.9	9.7	1.74	4.00	0.58	0.40
62		81.3	11.8	2.17	4.07	0.59	0.39
63		76.5	11.1	1.88	4.48	0.65	0.39
64		73.8	10.7	2.04	4.00	0.58	0.36
65		69.6	10.1	1.78	4.20	0.61	0.38
66		66.9	9.7	1.73	4.00	0.58	0.36
Average		72.5	10.5	1.89	4.13	0.60	0.38
Standard Deviation		5.8	0.8	0.18	0.19	0.03	0.02
NNTD71	23	75.8	11.0	3.14	3.00	0.43	0.39
72		82.0	11.9	3.49	3.31	0.48	0.42
73		77.2	11.2	3.13	3.17	0.46	0.36
74		79.3	11.5	2.15	3.58	0.52	0.38
75		73.8	10.7	2.07	3.31	0.48	0.39
76		70.3	10.2	2.61	3.17	0.46	0.34
Average		76.4	11.0	2.77	3.30	0.50	0.40
Standard Deviation		4.1	0.6	0.58	0.20	0.03	0.03
NNTD11	71	65.5	9.5	4.27	2.69	0.39	0.40
12		68.2	9.9	4.16	2.83	0.41	0.44
13		66.9	9.7	4.31	2.62	0.38	0.41
14		67.6	9.8	3.82	2.69	0.39	0.42
15		66.2	9.6	4.22	2.62	0.38	0.37
Average		66.9	9.7	4.16	2.69	0.39	0.41
Standard Deviation		1.2	0.2	0.20	0.09	0.01	0.03

Table A6

Individual Tension Test Results For Hexcel F155 Neat Resin at 4% Moisture Weight Gain

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	(ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	(Msi)	Poisson's Ratio
BN4T21	-54	66.2	9.6	1.74	4.00	0.58	0.36
22		71.0	10.3	1.93	4.07	0.59	0.35
23		68.9	10.0	1.84	4.20	0.61	0.38
24		53.8*	7.8*	1.24	4.48	0.65	0.32
25		67.6	9.8	1.84	3.79	0.55	0.39
Average		68.4	9.9	1.72	4.11	0.60	0.36
Standard Deviation		2.0	0.3	0.28	0.26	0.04	0.03
BN4T13	23	69.6	10.1	3.74	2.76	0.40	0.39
14		67.6	9.8	3.97	2.76	0.40	0.43
15		66.2	9.6	3.48	2.76	0.40	0.44
16		63.4	9.2	3.11	2.83	0.41	0.41
17		67.6	9.8	3.31	3.10	0.45	0.39
Average		66.9	9.7	3.52	2.84	0.41	0.41
Standard Deviation		2.3	0.3	0.34	0.15	0.02	0.02
BN4T31	71	23.4	3.4	2.98	1.38*	0.20*	0.43
32		20.7	3.0	2.83	0.90	0.13	0.37
33		20.0	2.9	3.15	1.03	0.15	0.35
34		22.7	3.3	3.28	1.10	0.16	0.36
35		15.2*	2.2*	3.20	0.90	0.13	0.39
Average		21.7	3.2	3.09	0.98	0.14	0.38
Standard Deviation		1.6	0.2	0.18	0.10	0.02	0.03

* Not included in the average

Table A7

Individual Tension Test Results For Hexcel F155 Neat Resin at Moisture Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)	Poisson's Ratio
NNTW61	-54	55.4	8.03	1.42	3.99	0.58	0.35
62		44.0*	6.38*	0.97*	4.47	0.65	0.37
63		57.0	8.27	1.42	4.10	0.60	0.34
64		61.2	8.87	1.48	4.14	0.60	0.31
65		56.7	8.22	1.39	3.98	0.58	0.35
Average		57.6	8.35	1.43	4.14	0.60	0.35
Standard Deviation		2.5	0.36	0.04	0.20	0.03	0.02
NNTW71	23	52.4	7.60	2.82	2.62	0.38	0.38
72		62.6	9.08	3.26	2.76	0.40	0.39
73		59.1	8.57	3.50	2.81	0.41	0.38
74		58.7	8.51	3.39	2.92	0.42	0.10*
75		56.6	8.21	2.88	3.04	0.44	0.37
Average		57.8	8.39	3.17	2.83	0.41	0.38
Standard Deviation		3.7	0.54	0.30	0.16	0.02	0.01
NNTW11	71	10.2	1.48	4.86	0.53	0.08	0.40
12		13.7	1.99	3.97*	0.59	0.09	0.36
13		16.3*	2.37*	4.37	0.79*	0.11*	0.38
14		8.1*	1.18*	5.95	0.48	0.07	0.39
15		11.7	1.70	6.05*	0.41	0.06	0.33
Average		11.9	1.72	5.06	0.50	0.08	0.37
Standard Deviation		1.8	0.36	0.81	0.08	0.01	0.03

*Not Included In Average

Table A8

Individual Iosipescu Shear Test Results For Hexcel F155 Neat Resin at Dry Condition

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NFSAD1	-54	55.1	8.0	3.70*	1.93	0.28
2		55.1	8.0	3.46	1.79	0.26
3		43.4	6.3	2.46	1.79	0.26
4		56.5	8.2	3.09	1.86	0.27
5		53.1	7.1	2.43*	1.65	0.24
Average		52.7	7.6	3.00	1.81	0.26
Standard Deviation		5.3	0.8	0.51	0.10	0.01
NFSBD1	23	55.8	8.1	5.76	1.24	0.18
2		56.5	8.2	5.76	1.24	0.18
3		53.8	7.8	5.48	1.17	0.17
4		59.3	8.6	5.76	1.24	0.18
5		51.7	7.5	5.79	1.38	0.20
Average		55.4	8.0	5.71	1.26	0.18
Standard Deviation		2.9	0.4	0.13	0.08	0.01
NFSCD1	71	43.4	6.3	2.61*	1.03	0.15
2		43.4	6.3	5.76	0.97	0.14
3		42.0	6.1	6.19	1.03	0.15
4		43.4	6.3	6.87	1.03	0.15
5		44.1	6.4	7.33	1.03	0.15
Average		43.3	6.3	6.54	0.97	0.14
Standard Deviation		0.8	0.1	0.70	0.03	0.00

*Not included in the average

Table A9

Individual Iosipescu Shear Test Results For Hexcel F155 Neat Resin at 4% Moisture Weight Gain

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NFSAF1	-54	48.3*	7.2*	3.48*	1.70	0.25
2		35.2	5.1	2.02*	1.77	0.26
3		37.9	5.5	2.43	1.76	0.26
4		48.9*	7.1*	3.28	1.65	0.24
5		37.9	5.5	2.35	1.69	0.25
Average		37.0	5.4	2.69	1.74	0.25
Standard Deviation		1.6	0.2	0.52	0.06	0.01
NFSBF1	23	39.8	5.8	4.72	1.02	0.15
2		37.5	5.4	4.54	1.00	0.14
3		42.2	6.1	5.01	1.01	0.15
4		43.0	6.2	3.09*	1.00	0.14
5		40.1	5.9	5.29	0.96	0.14
Average		41.0	6.0	4.89	1.00	0.15
Standard Deviation		1.2	0.2	0.33	0.01	0.00
NFSCF1	71	25.5	3.7	6.27**	0.69	0.10
2		20.0	2.9	2.63**	0.69	0.10
3		31.7*	4.6*	3.01	0.69	0.11
4		21.4	3.1	11.77	0.69	0.10
5		22.1	3.2	11.77	0.69	0.10
Average		22.2	3.2	9.94	0.69	0.10
Standard Deviation		2.3	0.3	3.18	0.00	0.00

**Strain Gage Failed Early, Not Included In Average
*Not Included in the Average

Table A10

Individual Iosipescu Shear Test Results For Hexcel F155 Neat Resin at Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NFSAW1	-54	43.0	6.23	2.77	2.62*	0.38*
2		51.5	7.47	3.71*	1.54	0.22
3		45.7	6.63	3.19	1.45	0.21
4		49.4	7.16	3.47	1.54	0.22
5		40.5	5.88	2.56*	1.69	0.25
Average		46.0	6.67	3.14	1.55	0.23
Standard Deviation		4.5	0.65	0.35	0.10	0.02
NFSBW1	23	40.1	5.81	5.92	1.03	0.15
2		42.0	6.09	5.89	0.94	0.14
3		39.3	5.70	5.80	0.94	0.14
4		43.1	6.25	5.93	1.01	0.15
5		39.0	5.65	5.93	0.93	0.14
Average		40.7	5.90	5.89	0.97	0.14
Standard Deviation		1.8	0.26	0.06	0.04	0.01
NFSCW1	71	16.3	2.37	>5.9	0.43	0.06
2		14.4	2.09	>5.9	0.44	0.06
3		12.5	1.81	>5.9	0.43	0.06
4		15.4	2.23	>5.9	0.53*	0.08*
5		10.8	1.56	>5.9	0.31*	0.05*
Average		14.1	2.04	>5.9	0.43	0.06
Standard Deviation		1.5	0.21	--	0.01	0.00

*Not Included In Average

Table A11

Individual Tension Test Results for Hercules 8551-7 Rubber-Toughened Epoxy at the Dry Condition

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Poisson's Ratio
NL50L 1	23	91	13.2	5.1	3.3	0.48	0.38
2		89	12.9	4.9	3.1	0.44	0.33
3		94	13.7	5.1	3.2	0.47	0.36
4		74	10.7	3.4*	2.9	0.42	0.35
5		91	13.2	5.8	3.2	0.46	0.37
	Average--	88	12.7	5.2	3.1	0.45	0.36
	Standard Deviation--	8	1.2	0.4	0.2	0.02	0.02
NL50M 1	82	60	8.7	3.7	2.4	0.35	0.38
2		59	8.5	3.5*	2.4	0.34	0.34*
3		63	9.2	5.1	2.4	0.35	0.38
4		65	9.4	5.7*	2.5	0.37	0.41
5		64	9.3	5.0	2.4	0.35	0.46*
	Average--	62	9.0	4.6	2.4	0.35	0.39
	Standard Deviation--	3	0.4	0.8	0.0	0.01	0.02
NL50H 1	121	46	6.7	4.6*	2.2	0.32	0.29
2		49	7.1	6.4	2.2	0.33	0.40
3		49	7.2	5.3	2.2	0.32	0.73*
4		46	6.6	6.5*	2.1	0.31	0.43
5		48	7.0	5.1	1.6*	0.23*	0.37
	Average--	48	6.9	5.6	2.2	0.32	0.37
	Standard Deviation	2	0.3	0.7	0.0	0.01	0.06

*Not included in average

Table A12

Individual Tension Test Results for Hercules 8551-7 Rubber-Toughened Epoxy at the Moisture Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Poisson's Ratio
N5WOR 1	23	66	9.6	2.9	2.8	0.40	0.36
2		67	9.7	3.1	2.7	0.39	0.36
3		73	10.6	4.4*	2.8	0.40	0.40
4		68	9.9	3.1	2.8	0.41	0.33
5		64	9.3	3.1	2.7	0.39	0.36
	Average--	68	9.8	3.1	2.8	0.40	0.36
	Standard Deviation--	3	0.5	0.1	0.1	0.01	0.02
N5WOM 1	82	46	6.7	4.7	2.2	0.32	0.36*
2		46	6.7	5.0	2.3	0.34	0.56*
3		47	6.8	3.6	2.4	0.35	0.44
4		47	6.8	5.2	2.2	0.33	0.40
5		46	6.7	3.5*	2.3	0.34	0.44
	Average--	46	6.7	4.6	2.3	0.34	0.43
	Standard Deviation--	1	0.1	0.7	0.0	0.01	0.02
N5WOH 1	121	19	2.8	5.1	0.5	0.07	0.98*
2		26*	3.8*	3.9*	1.5*	0.22*	0.53
3		25*	3.7*	4.9	1.6*	0.24*	0.72
4		19	2.8	6.4	1.4	0.20	0.73
5		17	2.5	10.2	1.0	0.15	0.69
6		12*	1.7*	10.2	0.6	0.08	0.31*
7		14	2.1	10.2	0.6	0.09	0.33*
8		11*	1.6*	15.2*	0.3*	0.05*	0.56
	Average--	17	2.6	7.8	0.8	0.12	0.65
	Standard Deviation	2	0.8	2.6	0.4	0.06	0.09

*Not included in average

Table A13

Individual Iosipescu Shear Test Results For Hercules 8551-7
Rubber-Toughened Epoxy at the Dry Condition

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NS5DR 1	23	65	9.4	6.7*	1.4	0.20
2		61	8.9	6.0	1.4	0.21
3		54	7.8	4.6	1.4	0.21
4		52	7.6	4.5	1.4	0.20
5		55	8.0	5.3	1.3	0.20
	Average--	57	8.3	5.1	1.4	0.20
	Standard Deviation--	5	0.8	0.7	0.0	0.01
NS5DM 1	82	49	7.1	9.4	1.2	0.18
2		49	7.1	>10.0	1.2	0.17
3		47	6.8	7.0	1.1	0.16
4		48	6.9	7.2	1.2	0.17
	Average--	48	7.0	> 8.4	1.2	0.17
	Standard Deviation--	1	0.2	---	0.0	0.01
NS5DH 1	121	36	5.2	>10.0	0.6	0.08
3		34	5.0	>10.0	1.0	0.14
4		33	4.8	>10.0	0.9	0.13
	Average--	34	5.0	>10.0	0.8	0.12
	Standard Deviation	2	0.2	---	0.2	0.03

*Not included in average

Table A14

Individual Iosipescu Shear Test Results For Hercules 8551-7
Rubber-Toughened Epoxy at the Moisture-Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
NNRIR 1	23	50	7.2	5.8	1.2	0.17
2		48	7.0	5.9	1.5*	0.22*
3		50	7.2	5.6	1.2	0.18
4		52	7.5	6.7*	1.1	0.16
5		45	6.5	4.3*	1.2	0.18
	Average--	49	7.1	5.8	1.2	0.17
	Standard Deviation--	3	0.4	0.2	0.0	0.01
NNRIM 1	82	37	5.3	9.9	1.0	0.15
2		36	5.2	9.6	0.9	0.14
3		36	5.2	8.4*	0.9	0.14
4		35	5.1	13.1*	1.2*	0.18*
5		33	4.7	12.0	0.9	0.14
	Average--	35	5.1	10.5	0.9	0.14
	Standard Deviation--	2	0.2	1.3	0.0	0.00
NNRIH 1	121	23*	3.4*	>14.2	0.9	0.13
2		21	3.1	12.3	0.8	0.12
3		19	2.7	10.1	0.9	0.13
4		20	2.9	6.0	1.2*	0.18*
5		16*	2.3*	10.8	0.7	0.11
	Average--	20	2.9	>10.7	0.8	0.12
	Standard Deviation	1	0.2	---	0.1	0.01

*Not included in average

Table A15

Individual Miniature Tension Test Results For Hercules 8551-7
Rubber-Toughened Epoxy at the Dry Condition

Specimen No.	Test Temperature (°C)	Ultimate Stress (MPa)	Ultimate Stress (ksi)	Ultimate Strain (percent)	Tensile Modulus (GPa)	Tensile Modulus (Msi)
MINOR 1	23	72	10.4	2.8	3.7	0.53
2		68*	9.8*	2.5*	3.5	0.51
3		90*	13.1*	4.8	3.2	0.46
4		86	12.5	4.5	3.1	0.45
5		83	12.0	4.1	3.0	0.44
	Average--	80	11.6	4.0	3.3	0.48
	Standard Deviation--	7	1.1	0.9	0.3	0.04
MINOM 1	82	61	8.8	3.6	2.5	0.36
2		61	8.9	3.8	2.5	0.36
3		63	9.2	4.2	2.5	0.36
4		61	8.8	4.0	2.3	0.33
5		57	8.3	3.8	2.3	0.33
	Average--	61	8.8	3.9	2.4	0.35
	Standard Deviation--	2	0.3	0.2	0.1	0.02
MINOH 1	121	40	5.8	3.8*	2.0	0.29
2		40	5.8	3.2	2.2	0.32
3		37	5.3	2.8*	2.0	0.29
4		41	5.9	3.0	2.1	0.31
5		39	5.7	3.7	2.1	0.30
	Average--	39	5.7	3.3	2.1	0.30
	Standard Deviation	2	0.2	0.4	0.1	0.01

*Not included in average

Table A16

Individual Miniature Torsion Rod Shear Test Results For Hercules 8551-7 Rubber-Toughened Epoxy at the Dry Condition

Specimen No.	Test Temperature (°C)	Ultimate Shear Stress (MPa)	Ultimate Shear Stress (ksi)	Ultimate Shear Strain (percent)	Shear Modulus (GPa)	Shear Modulus (Msi)
N6NRR 2	23	77	11.2	15.4	1.0	0.15
3		74	10.8	10.5	1.2	0.17
4		33	4.8*	3.2*	1.2	0.17
5		79	11.5	14.2	1.2	0.17
6		85	12.3	>16.3	1.0	0.15
7		81	11.7	16.0	1.2	0.17
	Average--	79	11.5	>14.5	1.1	0.16
	Standard Deviation--	4	0.6	---	0.1	0.01
NNRTM 1	82	50	7.3	6.5	1.4	0.20
2		50	7.3	5.3*	1.1	0.16
3		50	7.2	6.8	1.2	0.17
4		45	6.5	8.8*	1.4	0.21
5		45	6.5	6.9	1.2	0.17
	Average--	48	7.0	6.7	1.3	0.18
	Standard Deviation--	3	0.4	0.2	0.1	0.02
NNRTH 1	121	37	5.4	4.0	1.2	0.17
2		34	5.0	5.0*	1.2	0.18
3		35	5.1	3.1	1.6	0.23
4		34	4.9	3.6	1.4	0.20
5		39	5.7	2.7*	1.4	0.20
	Average--	36	5.2	3.6	1.4	0.20
	Standard Deviation	2	0.3	0.4	0.2	0.02

*Not included in average

Table A17

Individual Fracture Toughness Values for Polyetheretherketone Thermoplastic at the Dry Condition

Specimen Number	Test Temperature (°C)	Mode I Strain Energy Release Rate, G_{IC} (J/m^2)	($in\text{-}lb/in^2$)
NPFDR1**	23	2376*	13.6*
2**		510	2.9
3**		1136	6.5
4**		557	3.2
5**		802	4.6
	Average	751	4.3
	Std. Dev.	287	1.6
NPFDM1**	82	1431*	8.2*
2		5402	30.9
3		5551	31.8
4		3922	22.4
5**		406*	2.3*
	Average	4958	28.4
	Std. Dev.	901	5.2
NPFDH1**	121	1173*	6.7*
2**		541*	3.1*
3		7872	45.1
4		7031	40.3
5		8483	48.6
	Average	7795	44.7
	Std. Dev.	729	4.2

* Not included in the average
**Fracture surface had granular appearance

Table A18

Individual Fracture Toughness Values for Polyetheretherketone Thermoplastic at the Moisture-Saturated Condition

Specimen Number	Test Temperature (°C)	Mode I Strain Energy Release Rate, G_{IC} (J/m²)	(in-lb/in²)
NPFWR1**	23	1430*	8.2*
2**		523	3.0
3**		349	2.0
4**		628	3.6
5**		663	3.8
	Average	541	3.1
	Std. Dev.	140	0.8
NPFWM1**	82	367	2.1
2**		571	3.3
3**		1488*	8.5*
4**		544	3.1
5		10,168*	58.3*
	Average	494	2.8
	Std. Dev.	111	0.6
NPFWH1	121	11,355	65.1
2		107*	0.6*
3		7817	44.8
4		8417	48.2
5		12,081	69.3
	Average	9918	56.8
	Std. Dev.	2114	12.2

* Not included in the average
**Fracture surface had granular appearance

Table A19

Individual Fracture Toughness Values for Hercules 8551-7 Rubber-Toughened Epoxy at the Dry Condition

Specimen Number	Test Temperature (°C)	Mode I Strain Energy Release Rate, G_{IC} (J/m²)	Mode I Strain Energy Release Rate, G_{IC} (in-lb/in²)
FTD851-1	23	593*	3.4*
1-2		902	5.2
1-3		767*	4.4*
2-1		1226	7.0
2-2		1318	7.6
2-3		1327	7.6
3-1		1329	7.6
3-2		853	4.9
3-3		1324	7.6
4-1		1256	7.2
4-2		1193	6.8
4-3		1423*	8.2*
5-1		1259	7.2
5-2		1376*	7.9*
5-3		1374*	7.9*
6-1		961	5.5
6-2		938	5.4
6-3		569*	3.3
7-1		912	5.2
7-2		945	5.4
7-3		773*	4.4*
	Average	1124	6.2
	Std. Dev.	191	1.3

* Not included in the average

Table A20

Individual Fracture Toughness Values for Hercules 8551-7 Rubber-Toughened Epoxy at the Moisture-Saturated Condition

Specimen Number	Test Temperature (°C)	Mode I Strain Energy Release Rate, G_{IC} (J/m^2)	($in\text{-}lb/in^2$)
FTW851-1	23	436*	2.5*
1-2		1175	6.7
1-3		753	4.3
2-1		1045	6.0
2-2		1155	6.6
2-3		258*	1.5*
3-1		977	5.6
3-2		778	4.5
3-3		1038	6.0
4-1		1174	6.7
4-2		1325	7.6
4-3		975	5.6
	Average	1040	6.0
	Std. Dev.	179	1.0

* Not included in the average

Table A21

Individual Coefficient of Thermal Expansion Results at Three Moisture Conditions for Hexcel F155 Neat Epoxy

Specimen No.	Moisture Condition	CTE* (10^{-6}/°C) -57°C	23°C	71°C
DF155D1	Dry	64.2	64.2	64.2
D2		64.9	64.9	64.9
D3		63.9	63.9	63.9
	Average	64.3	64.3	64.3
	Standard Deviation	0.5	0.5	0.5
DF155W1	4% Moisture	53.4	77.3	91.6
W2		54.3	73.7	85.4
W3		47.6	79.8	99.1
W4		52.6	84.7	104.0
	Average	52.0	78.9	95.0
	Standard Deviation	3.0	4.6	8.2
DF155S1	Fully Saturated	55.8	84.7	101.0
S2		48.7	83.2	104.0
S3		60.2	85.5	101.0
S4		57.1	86.5	104.0
	Average	55.5	84.8	103.0
	Standard Deviation	4.9	1.5	2.0

*Individual values were calculated from Table A14

Table A22

Individual Coefficient of Thermal Expansion Equations at Three Moisture Conditions for Hexcel F155 Neat Epoxy

Specimen No.	Moisture Condition	CTE* $C_1 \times 10^{-5}$	$C_2 \times 10^{-7}$
DF155D1	Dry	64.2	0.0
D2		64.9	0.0
D3		63.9	0.0
DF155W1	4% MOISTURE	7.04	2.99
W2		6.81	2.43
W3		7.05	4.02
W4		7.55	4.02
DF155S1	Fully Saturated	7.60	3.53
S2		7.33	4.31
S3		7.82	3.16
S4		7.81	3.68

* $CTE = C_1 \times 10^{-5}/°C + (C_2 \times 10^{-7}/°C)\ T(°C)$

Table A23

Individual Coefficient of Thermal Expansion Results at Two Moisture Conditions for PEEK Thermoplastic

Specimen No.	Moisture Condition	CTE* (10^{-6}/°C) 23°C	82°C	121°C
#1	Dry	51.4	69.3	81.1
#2		49.9	70.1	83.5
#3		51.0	69.4	81.5
#4		50.3	68.3	80.3
	Average	50.6	69.3	81.6
	Standard Deviation	0.7	0.7	1.4
#1	Fully Saturated	55.8	67.8	75.7
#2		54.5	69.6	79.6
#3A		53.8	67.0	75.7
#4		54.4	71.0	82.0
	Average	54.6	68.8	78.2
	Standard Deviation	0.8	1.8	3.1

*Individual values were calculated from Table A16

Table A24

Individual Coefficient of Thermal Expansion Equations at Two Moisture Conditions for PEEK Thermoplastic

Specimen No.	Moisture Condition	CTE* $C_1 \times 10^{-5}$	$C_2 \times 10^{-7}$
#1	Dry	4.44	3.03
#2		4.20	3.43
#3		4.39	3.11
#4		4.32	3.06
#1	Fully Saturated	5.11	2.03
#2		4.86	2.56
#3A		4.87	2.23
#4		4.79	2.82

* $CTE = C_1 \times 10^{-5}/°C + (C_2 \times 10^{-7}/°C)\ T(°C)$

Table A25

Individual Coefficient of Thermal Expansion Results at Two Moisture Conditions for Hercules 8551-7 Epoxy

Specimen Number	Moisture Condition	CTE ($10^{-6}/°C$)
NL85D1	Dry	46.1
2		47.4
3		46.7
	Average	46.7
	Std. Dev.	0.6
NL85W1	Moisture-Saturated	70.5
2		70.1
3		69.5
	Average	70.0
	Std. Dev.	0.5

Table A26

Individual Coefficients of Moisture Expansion
of the Three Neat Resin Systems Tested

Resin System	Specimen Number	Coefficient of Moisture Expansion (x 10^{-3}/ %M)
Hexcel F155	DF155N1	3.01
	N2	3.47
	N3	2.73
	N4	3.07
	N5	3.59
	N6	3.00
	Average	3.14
	Standard Deviation	0.32
PEEK	1&2 T1	6.18*
	3&4 T1	12.43*
	5&6 T1	6.25
	7&8 T1	7.75
	9&10 T1	9.18
	11&12 T1	11.69*
	Average	7.73
	Standard Deviation	1.45
Hercules 8551-7	NL5N1	2.78
	NL5N2	2.79
	NL5N3	3.70
	Average	3.09
	Standard Deviation	0.53

*Not included in the average

Table A27

Individual AS4/2220-1 Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
N2LT01	23	265	1826	15.2	105	1.2	0.27
2		293	2017	20.0	138	1.5	0.24
3		271	1871	16.2	112	0.7*	0.38
7		291	2008	16.9	116	1.3	0.40
	Average--	280	1931	17.1	118	1.3	0.32
	Std. Dev.--	12	84	2.1	14	0.2	0.07
N2LT04	100	293	2022	19.1	132	1.5	0.48
5		314	2167	19.8	137	1.6	0.54
6		289	1991	20.1	138	1.4	0.37
	Average--	299	2060	19.7	136	1.5	0.46
	Std. Dev.--	11	76	0.4	3	0.1	0.09

Table A28

Individual AS4/2220-3 Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
N3LT01	23	295	2035	17.7	122	0.43	0.09
2		259	1787	17.5	121	0.56	0.21
3		293	2017	18.1	124	0.12	0.18
	Average--	282	1946	17.8	123	0.37	0.16
	Std. Dev.--	16	113	0.2	1	0.18	0.07
N3LT04	100	274	1890	22.0	152	1.2	0.61
5		275	1897	18.3	126	1.4	0.68
6		258	1779	22.3	154	1.2	0.48
	Average--	269	1855	20.9	144	1.3	0.59
	Std. Dev.--	8	55	1.4	9	0.1	0.10

Table A29

Individual T500/R914 Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
NCLT01	2°	218	1507	18.7	129	0.30	0.36
2		202	1390	18.0	124	1.10*	0.27*
3		202	1391	18.1	125	0.30	0.38
7		214	1476	18.2	126	0.34	0.32
	Average--	209	1441	18.3	126	0.31	0.35
	Std. Dev.--	8	52	0.3	2	0.02	0.03
NCLT04	100	230	1589	20.2	139	0.65*	0.54
5		216	1489	18.9	130	1.15	0.53
6		240	1653	21.2	146	1.14	0.52
8		233	1608	21.1	146	1.10	0.60*
	Average--	230	1584	20.4	140	1.13	0.53
	Std. Dev.--	9	60	1.0	7	0.02	0.01

*Not included in the average

Table A30

Individual IM6/HX1504 Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
NTLT01	23	401	2764	20.1	139	1.65*	0.30
2		278*	1914*	25.4	175	0.65	0.08*
3		396	2733	22.5	155	0.45	0.23
7		383	2641	22.6	156	1.08	0.26
	Average--	393	2712	22.7	156	0.72	0.26
	Std. Dev.--	9	64	1.9	13	0.32	0.03
NTLT04	100	366	2521	23.5	162	1.56	0.38
5		512	3532	22.9	158	1.56	0.59
6		502	3462	21.1	145	1.57	0.40
	Average--	460	3172	22.5	155	1.56	0.46
	Std. Dev.--	82	565	1.2	9	0.00	0.12

*Not included in the average

Table A31

Individual T300/4901A (MDA) Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
NTCAT1	23	290	2002	18.9	130	1.24	0.16
2		281	1935	18.4	127	1.08	0.20
3		288	1985	19.2	132	0.92	0.20
4		280	1931	21.0	145	1.34	0.28
	Average--	285	1964	19.4	133	1.15	0.21
	Std. Dev.--	4	31	1.1	8	0.16	0.04
NTCAT5	100	242	1665	20.9	144	1.16	0.67
7		259	1784	20.0	138	1.32	0.42
6		262	1806	22.2	153	1.20	0.73
	Average--	254	1752	21.0	145	1.23	0.61
	Std. Dev.--	9	62	0.9	6	0.07	0.16

*Not included in the average

Table A32

Individual T700/4901A (MDA) Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
N201T1	23	371	2558	22.3	154	1.57	0.42*
2		401	2764	22.3	154	1.78	0.20
3		395	2723	23.0	159	1.72	0.26
7		360	2482	19.5	134	1.58	0.27
	Average--	382	2634	21.8	150	1.66	0.24
	Std. Dev.--	17	116	1.4	9	0.09	0.04
N201T5	100	312	2151	20.0	138	1.46	0.95
6		318	2193	22.3	154	1.46	0.39
N20T10		296	2040	17.4*	120*	1.80	0.73
11		330	2279	24.5	169	1.33	0.17
	Average--	314	2166	22.3	154	1.51	0.56
	Std. Dev.--	12	86	2.3	16	0.17	0.34

*Not included in the average

Table A33

Individual T300/4901B (MPDA) Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
T349B1	23	282	1942	20.1	138	1.03	0.25
2		262	1808	19.3	133	0.83	0.28
3		262	1808	20.7	142	0.97	0.26
	Average--	269	1853	20.0	138	0.94	0.26
	Std. Dev.--	9	63	0.5	4	0.08	0.01
T349B4	100	181	1246	18.2	126	1.82	0.35
5		168	1155	17.4	120	1.75	0.46
6		190	1312	22.1*	152*	2.21	1.52*
7		190	1309	17.7	122	1.77	0.57
	Average--	182	1256	17.8	123	1.89	0.46
	Std. Dev.--	9	64	0.4	3	0.19	0.11

*Not included in the average

Table A34

Individual T700/4901B (MPDA) Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
T749B1	23	243	1674	18.3	126	1.36	0.31
2		229	1577	16.9	117	0.27*	0.30
3		230	1583	20.0	138	1.13	0.33
4		241	1661	19.4	134	1.24	0.31
	Average--	236	1624	18.6	129	1.24	0.31
	Std. Dev.--	6	44	1.2	8	0.09	0.09
T749B6	100	182	1251	15.7	108	1.21	0.28
7		180	1244	16.1	111	1.10	0.26
8		171	1179	15.5	107	1.17	0.21
	Average--	178	1225	15.8	109	1.16	0.25
	Std. Dev.--	5	33	0.3	2	0.04	0.03

*Not included in the average

Table A35

Individual AS4/PEEK (APC2, ICI) Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
PEEK41	23	278	1920	16.8	116	***	1.77*
2		318	2190	20.4	141	1.20	0.22
5		284	1960	21.5	148	1.38	0.13
6		253*	1746*	***	***	0.80*	0.24
7		331*	2285*	22.8	157	1.31	0.30
8		321	2212	21.5	148	1.53*	0.36
	Average--	300	2070	20.6	142	1.30	0.25
	Std. Dev.--	22	152	2.0	14	0.09	0.08
PEKLT4	100	294	2027	20.1	138	1.28	0.40
6		302	2080	18.1	125	1.16	0.55
PEKT10	100	278	1919	18.7	129	1.43	0.55
	Average--	291	2008	18.9	131	1.29	0.50
	Std. Dev.--	10	67	0.8	6	0.11	0.05

*Not included in the average
***Data not available

Table A36

Individual AS4/PEEK (APC2, LaRC) Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
TEPE01	23	386	2660	22.4	154	1.72	0.29
2		372	2564	23.0	159	1.59	0.33
3		352	2426	24.2	167	1.44	0.31
	Average--	370	2550	23.2	160	1.58	0.31
	Std. Dev.--	14	96	0.8	5	0.11	0.02
TEPE07	100	166	1144	20.7	143	0.80	0.42
8		168	1159	22.0	152	0.76	0.34
9		159	1098	22.1	152	0.73	0.58
	Average--	164	1134	21.6	149	0.76	0.45
	Std. Dev.--	4	26	0.6	4	0.03	0.10

*Not included in the average

Table A37

Individual AS4/8551-7 Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
NL5D11	23	256	1738	18.3	126	1.3	0.62
2		269	1855	18.3	126	0.6	0.38
3		273	1882	19.2	132	0.6	0.40
	Average--	265	1825	18.6	128	0.8	0.47
	Std. Dev.--	11	77	0.5	3	0.4	0.13
NL5D21	100	284	1958	20.2	139	1.4	0.37
2		283	1951	21.1	145	1.4	0.21
3		259	1756	19.3	133	1.3	0.32
	Average--	275	1888	20.2	139	1.4	0.30
	Std. Dev.--	14	115	0.9	6	0.1	0.08

Table A38

Individual AS4/8551-7 Axial Tension Test Results at the Moisture-Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
NL5W11	23	297	2048	19.4	134	1.5	0.32
2		270	1862	19.3	133	1.5	0.35
3		276	1903	18.0	124	1.4	0.25
	Average--	281	1938	18.9	130	1.5	0.31
	Std. Dev.--	14	98	0.8	6	0.0	0.05
NL5W21	100	264	1820	20.4	140	1.4	0.39
2		273	1882	20.5	141	1.4	0.30
3		284	1958	20.9	144	1.4	0.13
	Average--	274	1887	20.6	142	1.4	0.27
	Std. Dev.--	10	69	0.3	2	0.0	0.13

Table A39

Individual AS4/$PISO_2$-TPI Axial Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
NLODR1	23	250	1724	16.3	112	1.4	0.37
2		239	1648	17.8	123	1.3	0.25
3		249	1717	17.6	121	1.3	0.27
NLTST1		272	1875	18.2	125	1.4	0.30
2		267	1841	17.2	119	1.4	0.28
3		256	1765	17.5	121	1.4	0.39
	Average	256	1762	17.4	120	1.4	0.31
	Std. Dev.	12	84	0.6	4	0.1	0.06
NLODH1	100	228	1572	19.8	137	1.1	0.33
2		247	1703	19.8	136	1.2	0.27
3		243	1675	19.2	132	1.1	0.74*
	Average--	239	1650	19.6	135	1.1	0.30
	Std. Dev.--	10	69	0.3	3	0.1	0.04

*Not included in the average, bad transverse strain gage

Table A40

Individual AS4/$PISO_2$-TPI Axial Tension Test Results at the Moisture-Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)	Poisson's Ratio
NJTHW4	100	238	1641	15.5	107	1.5	0.41
5		223	1538	18.4	127	1.2	0.49
6		220	1517	18.1	125	1.2	0.43
	Average--	227	1565	17.3	120	1.3	0.44
	Std. Dev.--	10	66	1.6	11	0.2	0.04

Table A41

Individual AS4/2220-1 Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NTTA51	23	3.5	24	1.4	9.6	0.2
2		4.2	29	1.5	10.2	0.3
3		4.6	32	1.4	9.4	0.3
4		5.0	34	1.2	8.6	0.4
	Average--	4.3	30	1.4	9.4	0.3
	Std. Dev.--	0.6	4	0.1	0.7	0.1
NTTA55	100	4.2	29	1.1	7.3	0.4
6		4.0	28	1.1	7.7	0.4
7		3.8	26	1.1	7.7	0.3
8		4.1	28	1.0	7.1	0.4
	Average--	4.0	28	1.1	7.4	0.4
	Std. Dev.--	0.2	1	0.0	0.3	0.0

Table A42

Individual AS4/2220-3 Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NTTA31	23	3.9*	27*	1.4	9.9	0.3
2		6.6	46	1.3	8.7	0.5
3		6.4	44	1.5	10.2	0.4
4		7.9	54	1.2*	7.9*	0.7
	Average--	7.0	48	1.4	9.6	0.5
	Std. Dev.--	0.8	5	0.1	0.8	0.2
NTTA35	100	4.6	32	1.1	7.4	0.4
6		6.0	42	1.1	7.6	0.6*
7		5.4	37	1.1	7.4	0.5
8		3.6	25	1.2	8.5	0.3
	Average--	4.9	34	1.1	7.7	0.4
	Std. Dev.--	1.0	7	0.0	0.5	0.1

*Not included in the average

Table A43

Individual T500/R914 Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NTTR91	23	5.9	41	1.3	8.9	0.5
2		8.3	57	1.3	8.7	0.6
3		6.6	46	1.3	8.8	0.5
	Average--	6.9	48	1.3	8.8	0.6
	Std. Dev.--	1.0	7	0.0	0.1	0.1
NTTR94	100	4.7	32	1.0	6.8	0.5
5		1.6*	11*	0.8	5.9	0.2
6		2.2	15	1.0	6.8	0.2
7		3.6	24	0.9	6.4	0.4
8		4.5	31	1.1	6.7	0.5
	Average--	3.8	26	1.0	6.5	0.4
	Std. Dev.--	1.1	8	0.1	0.4	0.2

*Not included in the average

Table A44

Individual IM6/HX1504 Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NTTHX1	23	8.8	61	1.3	9.2	0.6
2		6.2	43	1.2	8.5	0.5
3		8.7	60	1.3	9.1	0.6
	Average--	7.9	55	1.3	8.9	0.6
	Std. Dev.--	1.5	10	0.1	0.4	0.1
NTTHX4	100	5.0	35	1.1	7.5	0.8
5		7.9	54	1.2	8.6	2.1*
6		8.2	56	1.1	7.3	0.9
	Average--	7.0	48	1.1	7.8	0.8
	Std. Dev.--	1.4	10	0.1	0.6	0.0

*Not included in the average, extensometer slipped

Table A45

Individual T300/4901A (MDA) Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	(MPa)	Tensile Modulus (Msi)	(GPa)	Ultimate Strain (percent)
NTTT31	23	12.0	83	1.5	10.6	0.8
2		9.6	66	1.5	10.5	0.6
3		10.7	74	1.6	11.3	0.6
	Average--	10.8	74	1.6	10.8	0.7
	Std. Dev.--	1.0	7	0.0	0.3	0.1
NTTT37	100	5.1	35	0.8	5.8	1.1
8		5.7	40	0.9	6.0	1.0
	Average--	5.4	38	0.9	5.9	1.1
	Std. Dev.--	0.3	2	0.0	0.1	0.0

Table A46

Individual T700/4901A (MDA) Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
N2TT01	23	9.2	63	1.4	9.9	0.6
2		9.0	62	1.6	11.1	0.6
3		10.9	75	1.7	11.9	0.6
	Average--	9.7	67	1.6	11.0	0.6
	Std. Dev.--	0.9	6	0.1	0.1	0.0
N2TT04	100	3.7	26	0.8	5.8	0.5
5		4.0	27	0.9	6.3	0.5
6		4.0	27	0.9	6.1	0.5
	Average--	3.9	27	0.9	6.1	0.5
	Std. Dev.--	0.1	1	0.0	0.2	0.0

Table A47

Individual T300/4901B (MPDA) Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
TT3491	23	9.0	62	1.6	11.0	0.5
2		6.7*	46*	1.6	11.4	0.4
3		9.8	68	1.6	10.8	0.6
4		7.4	51	1.6	11.2	0.4
5		11.4*	79*	1.6	10.9	0.7*
	Average--	8.7	60	1.6	11.1	0.5
	Std. Dev.--	1.2	9	0.0	0.2	0.1
TT3496	100	2.5	16.9	0.2	1.2	2.1
7		2.4	16.3	0.2	1.5	2.1
8		2.6	18.2	0.3	2.3	2.1
	Average--	2.5	17	0.2	1.6	2.1
	Std. Dev.--	0.1	1	0.1	0.5	0.0

*Not included in the average

Table A48

Individual T700/4901B (MPDA) Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
TT7491	23	9.1	62	1.8	12.7	0.5
2		8.6	59	1.6	11.3	0.5
3		8.6	59	1.8	12.1	0.5
	Average--	8.8	60	1.7	12.0	0.5
	Std. Dev.--	0.2	1	0.1	0.6	0.0
TT7494	100	3.3	22	0.4	2.8	1.9
5		3.3	23	0.5	3.4	1.6
6		4.0	27	0.8	5.4	1.2
	Average--	3.5	24	0.6	3.8	1.6
	Std. Dev.--	0.3	2	0.2	1.1	0.3

Table A49

Individual AS4/PEEK (APC2, ICI) Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
PEKTT1	23	12.4	85	1.7	11.6	0.8
2		11.0	76	1.3	9.0	0.9
3		10.9	75	1.2	8.3	1.0
	Average--	11.4	79	1.4	9.6	0.9
	Std. Dev.--	0.7	5	0.3	1.7	0.1
PEKTT4	100	9.2	63	1.3	8.8	1.0
5		10.2	70	1.3	9.2	1.3
6		9.6	66	1.1	7.9	1.0
	Average--	9.6	66	1.2	8.6	1.1
	Std. Dev.--	0.4	3	0.1	0.6	0.2

Table A50

Individual AS4/PEEK (APC2, LaRC) Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
TTEPE3	23	11.9	82	1.6	10.7	0.8
5		12.2	84	1.4	9.5	0.9
6		11.9	82	1.5	10.6	0.8
	Average--	12.0	82	1.5	10.3	0.9
	Std. Dev.--	0.1	1	0.1	0.1	0.6
TTEPE7	100	2.0	14	0.3	1.9	0.8
8		2.0	14	0.3	1.9	0.7
9		2.0	14	0.3	1.9	0.8
	Average--	2.0	14	0.3	1.9	0.8
	Std. Dev.--	0.0	0	0.0	0.0	0.5

Table A51

Individual AS4/8551-7 Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NTTDR1	23	9.1	63	1.2	8.3	0.7
2		8.3	57	1.5	10.5	0.6
3		11.3	78	1.3	8.7	0.9
	Average--	9.6	66	1.3	9.2	0.7
	Std. Dev.--	1.6	11	0.2	1.2	0.2
NTTDH1	100	8.3	57	1.0	7.2	0.9
2		8.3	57	1.1	7.5	0.9
3		8.7	60	1.1	7.4	1.0
	Average--	8.4	58	1.1	7.4	0.9
	Std. Dev.--	0.2	2	0.0	0.2	0.0

Table A52

Individual AS4/8551-7 Transverse Tension Test Results at the Moisture-Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NTTWR1	23	6.2	43	1.2	8.5	0.5
2		5.7	39	1.3	9.0	0.4
3		5.1	35	1.4	9.6	0.4
	Average--	5.7	39	1.3	9.0	0.4
	Std. Dev.--	0.6	4	0.1	0.6	0.1
NTTWH1	100	4.6	32	1.1	7.7	0.7
2		4.1	28	1.2	7.9	0.6
3		4.2	29	1.1	7.4	0.7
	Average--	4.3	30	1.1	7.7	0.6
	Std. Dev.--	0.3	2	0.0	0.3	0.1

Table A53

Individual AS4/$PISO_2$-TPI Transverse Tension Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NLTDR8	23	6.1*	42*	1.2	8.3	0.5
9		4.3	30	1.2	8.3	0.3
0		5.3	37	1.2	8.3	0.4
1		4.8	33	1.3	9.0	0.4
	Average--	4.8	33	1.2	8.5	0.4
	Std. Dev.--	0.5	4	0.1	0.4	0.1
NLTDH2	100	5.9	41	1.2	8.3	0.5
3		5.8	40	1.4	9.7	0.4
4		7.4	51	1.4	9.7	0.5
	Average--	6.4	44	1.3	9.2	0.5
	Std. Dev.--	0.9	6	0.1	0.8	0.1

Table A54

Individual AS4/$PISO_2$-TPI Transverse Tension Test Results at the Moisture-Saturated Condition

Specimen No.	Test Temperature (°C)	Ultimate Strength (ksi)	Ultimate Strength (MPa)	Tensile Modulus (Msi)	Tensile Modulus (GPa)	Ultimate Strain (percent)
NJ6TT4	100	4.0	28	1.6	11.0	0.3
5		4.1	28	1.3	9.0	0.3
6		3.7	26	1.3	9.0	0.3
	Average--	3.9	27	1.4	9.7	0.3
	Std. Dev.--	0.2	1	0.2	1.2	0.0

Table A55

Individual AS4/2220-1 Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
N2I001	23	16.1	111	0.7	5.0	>11.7
2		16.0	110	0.7	5.1	>11.7
3		15.6	108	0.8	5.4	>11.7
	Average--	15.9	110	0.7	5.2	>11.7
	Std. Dev.--	0.3	2	0.0	0.2	---
N2I004	100	11.8	82	0.6	4.4	>11.7
5		11.1	77	0.6	4.1	>11.7
6		12.1	84	0.6	4.4	>11.7
	Average--	11.7	81	0.6	4.3	>11.7
	Std. Dev.--	0.5	4	0.0	0.2	---

Table A56

Individual AS4/2220-3 Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
N3I001	23	14.5	100	0.8	5.6	>11.7
2		14.6	101	0.7	5.0	>11.7
3		14.1	97	0.7	4.7	>11.7
	Average--	14.4	99	0.7	5.1	>11.7
	Std. Dev.--	0.3	2	0.1	0.5	---
N3I004	100	10.8	75	0.6	4.2	>11.7
5		10.8	74	0.6	4.4	>11.7
6		11.6	80	0.6	4.3	>11.7
	Average--	11.1	76	0.6	4.3	>11.7
	Std. Dev.--	0.4	3	0.0	0.1	---

Table A57

Individual T500/R914 Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
NCI001	23	14.6	100	0.8	5.4	7.8
2		14.7	101	***	***	9.6
3		14.4	99	0.8	5.3	6.5*
4		14.9	103	0.5	.7	9.8
	Average--	14.6	101	0.8	5.5	9.1
	Std. Dev.--	0.2	2	0.0	0.2	1.1
NCI005	100	6.6	45	0.6	4.1	2.1
6		10.6	73	0.6	4.0	>11.7
7		9.6	66	0.5	3.7	>11.7
8		10.5	72	0.6	3.9	>11.7
	Average--	10.3	71	0.6	3.9	> 9.3
	Std. Dev.--	0.4	3	0.0	0.1	---

*Not included in the average
***Data not available

Table A58

Individual IM6/HX1504 Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
NTI001	23	17.7	122	0.8	5.8	>11.7
2		16.5	114	0.8	5.8	7.1
3		17.6	121	0.8	5.8	4.4
	Average--	17.3	119	0.8	5.8	> 7.7
	Std. Dev.--	0.6	4	0.0	0.0	---
NTI004	100	13.6	94	0.7	5.1	>11.7
5		13.7	94	0.7	5.1	>11.7
6		13.2	91	0.7	4.8	>11.7
	Average--	13.5	93	0.7	5.0	>11.7
	Std. Dev.--	0.3	2	0.0	0.2	---

Table A59

Individual T300/4901A (MDA) Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	(MPa)	Shear Modulus (Msi)	(GPa)	Ultimate Shear Strain (percent)
NICA04	23	15.7	108	1.0	7.0	7.2
5		14.2	98	1.0	7.3	3.5
6		12.0*	82*	0.7*	4.9*	2.1
7		14.6	100	1.0	6.9	4.7
	Average--	14.8	102	1.0	7.1	4.4
	Std. Dev.--	0.8	5	0.0	0.2	2.2
NICA01	100	8.3	57	0.5	3.4	>11.7
2		6.8	47	0.5	3.8	>11.7
3		9.1	63	0.5	3.4	>11.7
	Average--	8.1	56	0.5	3.5	>11.7
	Std. Dev.--	1.2	8	0.0	0.2	---

*Not included in the average

Table A60

Individual T700/4901A (MDA) Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
N20I01	23	15.6	108	1.0	7.2	11.3
5		15.0	103	1.0	6.8	5.2
6		15.2	107	1.0	6.8	---
	Average--	15.3	106	1.0	6.9	8.3
	Std. Dev.--	0.3	3	0.0	0.3	4.3
N20I02	100	8.3	57	0.5	3.5	>11.7
3		8.0	55	0.5	3.7	>11.7
4		7.5	52	0.5	3.1	>11.7
	Average--	7.9	55	0.5	3.4	>11.7
	Std. Dev.--	0.4	3	0.0	0.3	---

Table A61

Individual T300/4901A (MPDA) Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
T349R1	23	12.9	89	1.1	7.5	2.2
2		14.8	102	1.0	7.2	6.5
3		14.9	103	1.1	7.4	6.9
	Average--	14.2	98	1.1	7.4	5.2
	Std. Dev.--	0.9	6	0.0	0.1	2.6
T349R4	100	7.7	53	0.1	0.4	>12.0
5		4.3	30	0.1	0.8	>12.0
6		2.7	19	0.2	1.3	7.0
	Average--	4.9	34	0.1	0.8	>10.3
	Std. Dev.--	2.5	18	0.1	0.4	---

Table A62

Individual T700/4901A (MPDA) Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
T749R1	23	16.3	112	1.3	8.8	4.8
2		15.4	106	1.2	8.0	5.7
3		15.0	103	1.2	8.0	5.1
	Average--	15.6	108	1.2	8.3	5.2
	Std. Dev.--	0.5	4	0.0	0.3	0.5
T749R4	100	7.9	54	0.3	2.3	>11.5
6		5.0	34	0.4	2.4	5.6
7		4.4	30	0.3	2.3	7.5
	Average--	5.8	39	0.3	2.3	> 8.2
	Std. Dev.--	1.9	13	0.1	0.1	---

Table A63

Individual AS4/PEEK (APC2,ICI) Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
PEEK05	23	17.6	121	0.8	5.8	>11.7
6		16.6	114	0.9	6.0	>11.7
7		15.8	109	0.9	6.2	>11.7
	Average--	16.7	115	0.9	6.0	>11.7
	Std. Dev.--	0.9	6	0.0	0.2	---
PEEK01	100	13.1	90	0.6	4.1	>11.7
2		12.2	84	0.7	4.9	>11.7
3		14.2	98	0.8	5.5	>11.7
	Average--	13.2	91	0.7	4.8	>11.7
	Std. Dev.--	1.0	7	0.1	0.7	---

Table A64

Individual AS4/PEEK (APC2,LaRC) Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
ASPKR1	23	16.6	114	0.8	5.2	>11.8
2		16.3	113	0.7	4.6	>11.8
3		16.4	113	***	***	***
4		16.3	112	0.7	4.8	>11.8
	Average--	16.4	113	0.7	4.9	>11.8
	Std. Dev.--	0.1	1	0.0	0.3	---
ASPKR5	100	12.0	83	0.8	5.2	>11.5
6		11.8	81	0.8	5.2	>11.5
7		12.1	83	0.8	5.3	>11.5
	Average--	12.0	83	0.8	5.2	>11.5
	Std. Dev.--	0.2	1	0.0	0.1	---

***Data not available, strain gage malfunction

Table A65

Individual AS4/8551-7 Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
NS5DR1	23	14.8	102	0.7	5.0	> 2.3
2		15.6	108	0.5	3.4	> 2.3
3		8.7	60	0.5	3.7	> 2.3
	Average--	13.0	90	0.6	4.0	> 2.3
	Std. Dev.--	3.8	26	0.1	0.9	---
NS5DH1	100	11.5	79	0.6	4.5	>10.2
2		11.2	77	0.6	4.2	>10.2
3		10.5	72	0.6	4.4	>10.2
	Average--	11.1	76	0.6	4.4	>10.2
	Std. Dev.--	0.5	4	0.0	0.2	---

Table A66

Individual AS4/8551-7 Iosipescu Shear Test Results at the Moisture-Saturated Condition

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
NS5WR1	23	13.7	94	0.8	5.2	>10.2
2		13.0	90	0.7	4.8	>10.2
3		12.9	89	0.8	5.2	>10.2
	Average--	13.2	91	0.7	5.1	>10.2
	Std. Dev.--	0.4	3	0.0	0.2	---
NS5WH1	100	7.9	54	0.6	3.9	>10.2
2		8.0	55	0.6	3.9	>10.2
3		9.0	62	0.5	3.7	>10.2
	Average--	8.3	57	0.6	3.8	>10.2
	Std. Dev.--	0.6	4	0.0	0.1	---

Table A67

Individual AS4/$PISO_2$-TPI Iosipescu Shear Test Results at Dry Conditions

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
NLIDR1*	23	19.4	134	0.78	5.4	> 3.0
2*		20.0	138	0.86	5.9	>10.0
3*		18.0	124	1.21	8.3	7.7
	Average--	19.1	132	0.95	6.5	> 6.9
	Std. Dev.--	1.0	7	0.23	1.6	---
UNLIDR1	23	14.3	99	0.84	5.8	3.5
2		15.3	105	0.96	6.6	3.5
	Average--	14.8	102	0.90	6.2	3.5
	Std. Dev.--	0.7	4	0.08	0.6	0.0
NLIDH1*	100	16.8	116	0.75	5.2	14.7
2*		16.2	112	0.77	5.3	>15.0
3*		14.9	103	0.80	5.5	10.5
4*		15.9	110	0.82	5.7	14.2
	Average--	16.0	110	0.78	5.4	>13.6
	Std. Dev.--	0.8	5	0.03	0.2	---

*Specimens had fiberglass tabs mounted in the load bearing areas to prevent localized crushing.

Table A68

Individual AS4/$PISO_2$-TPI Iosipescu Shear Test Results at the Moisture-Saturated Condition

Specimen No.	Test Temperature (°C)	Shear Strength (ksi)	Shear Strength (MPa)	Shear Modulus (Msi)	Shear Modulus (GPa)	Ultimate Shear Strain (percent)
NJIHW1*	100	14.6	101	0.68	4.7	>20.0
2*		15.3	105	0.97	6.7	>20.0
3*		14.3	99	0.81	5.6	15.9
	Average--	14.7	102	0.82	5.7	>18.6
	Std. Dev.--	0.5	3	0.15	1.0	---

*Specimens had fiberglass tabs mounted in the load bearing areas to prevent localized crushing.

Table A69

Individual Transverse Coefficient of Thermal Expansion Test Results for Twelve Carbon Fiber-Reinforced Composites at Dry Conditions

Material System	Specimen Number	Temperature Range (°C)	CTE = $C_1 + C_2(T)$ $C_1(10^{-6}/°C)$	$C_2(10^{-6}/°C)$
AS4/2220-1	D22191		34.9	0.07
	2		34.3	0.09
	3		33.9	0.07
		Average	34.4	0.08
		Std. Dev.	0.5	0.01
AS4/2220-3	D22391	*	35.8	0.11
	2	*	34.6	0.07
	3	*	33.3	0.07
		Average	34.6	0.08
		Std. Dev.	1.2	0.02
T500/R914	T59191	*	36.1	0.06
	2	*	36.0	0.07
	3	*	35.7	0.08
		Average	35.9	0.07
		Std. Dev.	0.2	0.01
IM6/1504	IM1591	*	30.3	0.06
	2	*	30.3	0.06
	3	*	31.6	0.06
		Average	30.7	0.06
		Std. Dev.	0.8	0.00
T300/4901A (MDA)	D34991	*	31.3	0.12
	2	*	32.2	0.16
	3	*	32.3	0.18
		Average	31.9	0.15
		Std. Dev.	0.6	0.31
T700/4901A	D74991	*	33.8	0.15
	2	*	34.7	0.15
	3	*	34.5	0.16
		Average	34.3	0.15
		Std. Dev.	0.5	0.01

Table A69 (cont.)

Material System	Specimen Number	Temperature Range (°C)	CTE = $C_1 + C_2(T)$ $C_1(10^{-6}/°C)$	$C_2(10^{-6}/°C)$
T300/4901B (MPDA)	T34991	-40 to 60	31.7	---
	2	-40 to 60	32.9	---
	3	-40 to 60	32.1	---
		Average	32.2	
		Std. Dev.	0.6	
	T34991	60 to 120	85.5	---
	2	60 to 120	86.0	---
	3	60 to 120	84.0	---
		Average	85.2	
		Std. Dev.	1.0	
T700/4901B (MPDA)	D74994	-40 to 60	33.6	---
	6	-40 to 60	35 2	---
	7	-40 to 60	34.4	---
	8	-40 to 60	36.1	---
	9	-40 to 60	31.5	---
		Average	34.2	
		Std. Dev.	1.8	
	D74994	60 to 120	59.0	---
	6	60 to 120	56.0	---
	7	60 to 120	61.5	---
	8	60 to 120	67.3	---
	9	60 to 120	56.0	---
		Average	60.0	
		Std. Dev.	4.7	
AS4/PEEK (ICI)	1	-40 to 120	39.8	---
	2	-40 to 120	41.1	---
	3	-40 to 120	39.7	---
		Average	40.2	
		Std. Dev.	0.8	
	1	120 to 205	80.3	---
	2	120 to 205	81.3	---
	3	120 to 205	86.1	---
		Average	82.6	
		Std. Dev.	3.1	

Table A69 (cont.)

Material System	Specimen Number	Temperature Range (°C)	CTE = $C_1 + C_2(T)$ $C_1(10^{-6}/°C)$	$C_2(10^{-6}/°C)$
AS4/PEEK (LaRC)	ASPL91	-40 to 120	32.4	---
	2	-40 to 120	33.9	---
	3	-40 to 120	33.3	---
		Average	33.2	
		Std. Dev.	0.8	
	ASPL91	126 to 205	64.6	---
	2	126 to 205	65.9	---
	3	126 to 205	61.6	---
		Average	64.0	
		Std. Dev.	2.2	
AS4/8551-7	1	-40 to 120	30.5	---
	2	-40 to 120	31.5	---
	3	-40 to 120	32.1	---
		Average	31.4	
		Std. Dev.	0.8	
AS4/PISO$_2$-TPI Dry	1	-40 to 120	22.8	---
	2	-40 to 120	21.9	---
	3	-40 to 120	22.2	---
		Average	22.3	
		Std. Dev.	0.5	
AS4/PISO$_2$-TPI Moisture-Saturated	1	-40 to 120	23.8	---
	2	-40 to 120	20.9	---
	3	-40 to 120	19.7	---
		Average	21.5	
		Std. Dev.	2.1	

Table A70

Individual Transverse Coefficient of Moisture Expansion
Test Results for Twelve Carbon Fiber-Reinforced Composites

Material System	Specimen Number		Transverse Coefficient of Moisture Expansion (10^{-3}/%M)
AS4/2220-1	1		2.39
	2		3.80
	3		2.56
		Average	2.92
		Std. Dev.	0.77
AS4/2220-3	1		4.54
	2		4.72
	3		4.20
		Average	4.49
		Std. Dev.	0.26
T500/R914	1		4.00
	2		3.80
	3		3.14
		Average	3.65
		Std. Dev.	0.45
IM6/1504	1		3.64
	2		1.82*
	3		2.33
	4		4.39*
	5		3.06
	6		2.81
		Average	2.96
		Std. Dev.	0.55
T300/4901A	1		4.25
	2		4.77
	3		4.08
		Average	4.37
		Std. Dev.	0.36

Table A70 (cont.)

Material System	Specimen Number		Transverse Coefficient of Moisture Expansion (10^{-3}/%M)
T700/4901A	1		7.53
	2		2.28*
	3		6.44
	4		3.12
	5		7.21
	6		7.59
		Average	6.38
		Std. Dev.	1.88
T300/4901B	***		
T700/4901B	***		
AS4/PEEK (ICI)	1		4.04
	2		4.20
	3		2.75
	5		11.14*
	6		10.04*
	7		4.05
		Average	3.76
		Std. Dev.	0.68
AS4/PEEK (LaRC)	1A		3.61
	2A		1.67
	3A		1.73
	1B		6.10*
	3B		5.37
		Average	3.10
		Std. Dev.	1.76
AS4/8551-7	1		5.03
	2		4.32
	3		3.54
	4		5.83*
	5		2.98*
	6		3.53
		Average	4.10
		Std. Dev.	0.72
AS4/$PISO_2$-TPI	***		

* Data not included in average

*** Data not available

Table A71

Individual Fiber Volume and Void Volume Determinations for Twelve Carbon Fiber-Reinforced Composites

Material System	Sample Number	Carbon Fiber Volume (percent)	Void Volume (percent)
AS4/2220-1	7	59.0	0.4
	8	57.6	0.4
	9	58.7	0.7
	Average	58.4	0.5
	Std. Dev.	0.7	0.2
AS4/2220-3	1	58.2	0.0
	2	60.1	0.0
	3	46.4*	0.0
	Average	59.2	0.0
	Std. Dev.	1.3	0.0
T500/R914	1	56.4	0.0
	2	57.1	0.0
	3	58.2	0.0
	Average	57.2	0.0
	Std. Dev.	0.9	0.0
IM6/1504	1	62.6	0.0
	2	57.9	0.0
	3	58.0	0.0
	Average	59.5	0.0
	Std. Dev.	2.7	0.0
T300/4901A	1	65.2	0.0
	2	64.6	0.0
	3	65.3	0.0
	Average	65.0	0.0
	Std. Dev.	0.4	0.0
T700/4901A	1	64.6	0.0
	2	64.5	0.0
	3	64.8	0.0
	Average	64.6	0.0
	Std. Dev.	0.2	0.0

C-3

Table A71 (cont.)

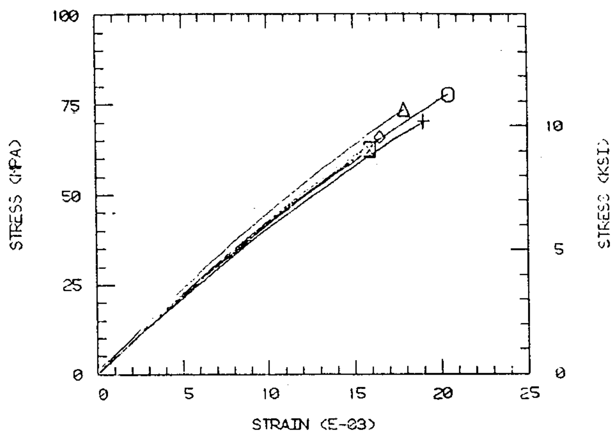
Material System	Sample Number	Carbon Fiber Volume (percent)	Void Volume (percent)
T300/4901B	4	62.3	0.0
	5	62.6	0.0
	6	60.2	0.0
	Average	61.7	0.0
	Std. Dev.	1.3	0.0
T700/4901B	10	57.9	1.4
	11	58.2	1.0
	12	53.4	1.5
	Average	56.5	1.3
	Std. Dev.	2.7	0.3
AS4/PEEK, ICI**	8	63.1	0.0
	9	64.1	0.0
	Average	63.6	0.0
	Std. Dev.	0.7	0.0
AS4/PEEK, LaRC**	10	63.3	0.0
	11	61.9	0.0
	12	63.9	0.0
	Average	63.0	0.0
	Std. Dev.	1.0	0.0
AS4/8551-7	1	62.0	0.7
	2	56.1	1.0
	3	61.2	0.9
	Average	59.8	0.9
	Std. Dev.	3.2	0.2
AS4/$PISO_2$-TPI**	GD-805	51.8	---
	GD-806	52.2	---
	GD-818	56.0	---
	GD-819	56.0	---
	Average	54.0	
	Std. Dev.	2.3	

*Not included in the average, beaker broke.
**Calculated values, did not use acid digestion.

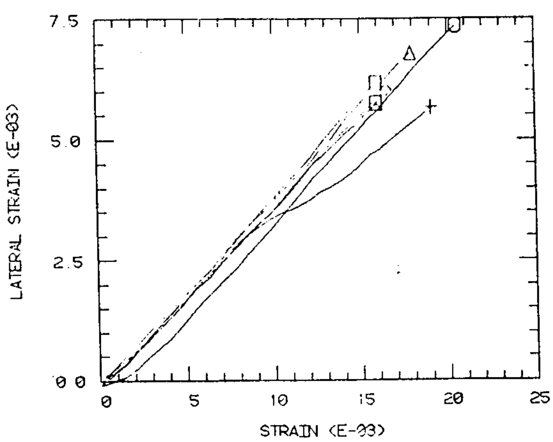
APPENDIX B

Individual Test Specimen Stress-Strain Curves for the Three Neat Resins and Twelve Carbon Fiber-Reinforced Composites

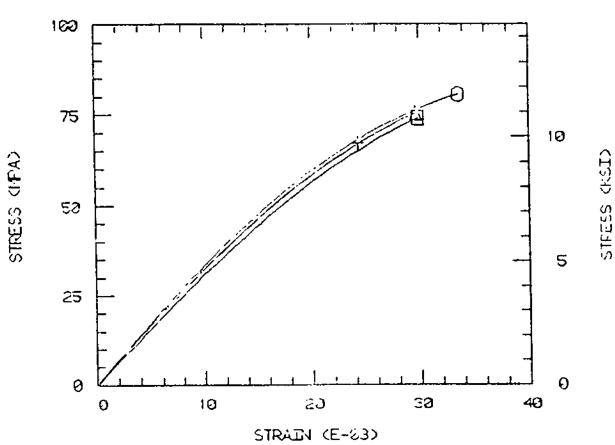
F155 TENSION -54 DEG C, DRY



F155 TENSION -54 DEG C, DRY



F155 TENSION 23 DEG C, DRY



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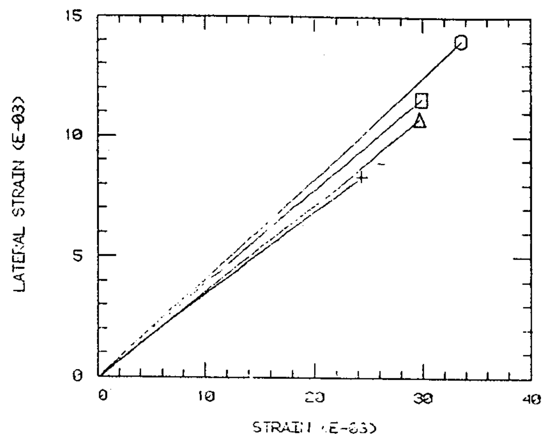
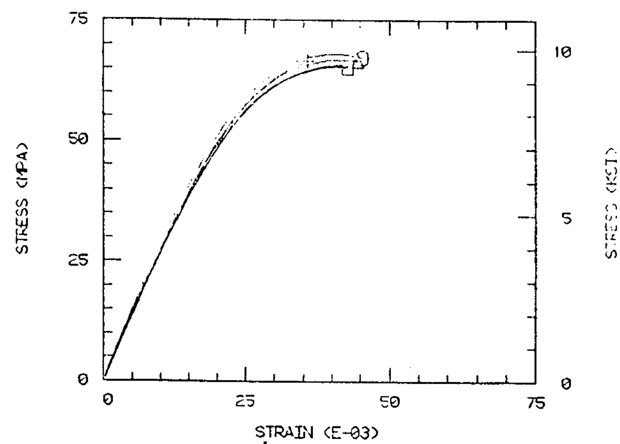


F155 TENSION 71 DEG C, DRY



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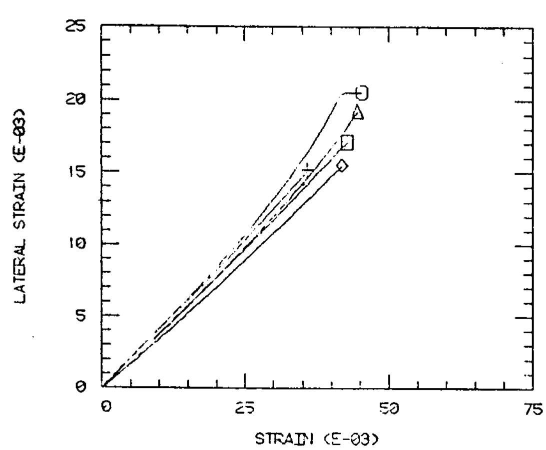
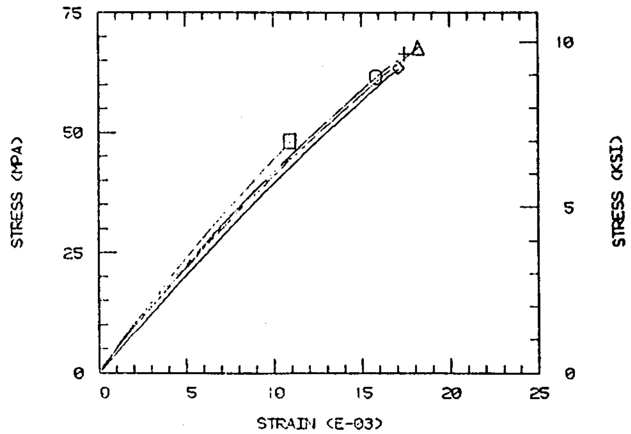


F155 TENSION -54 DEG C, 4% MOISTURE



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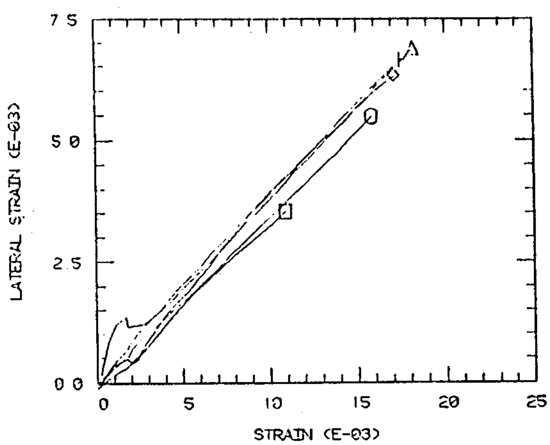

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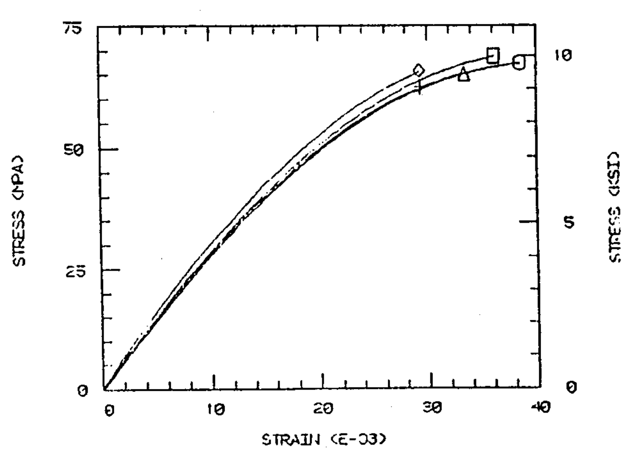

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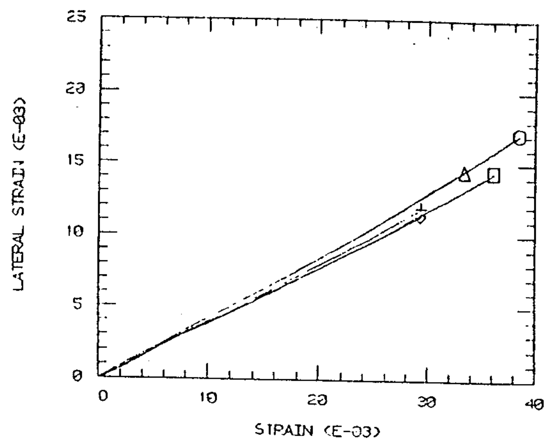

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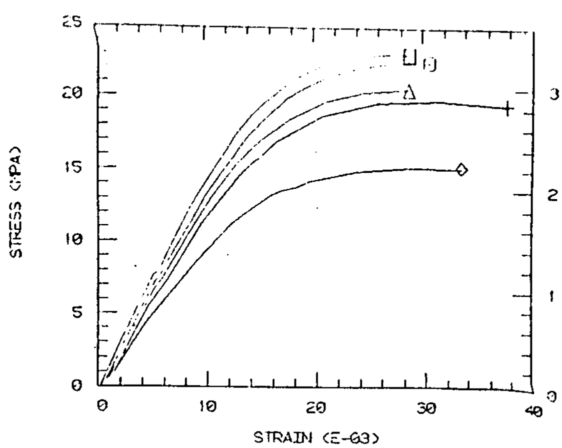

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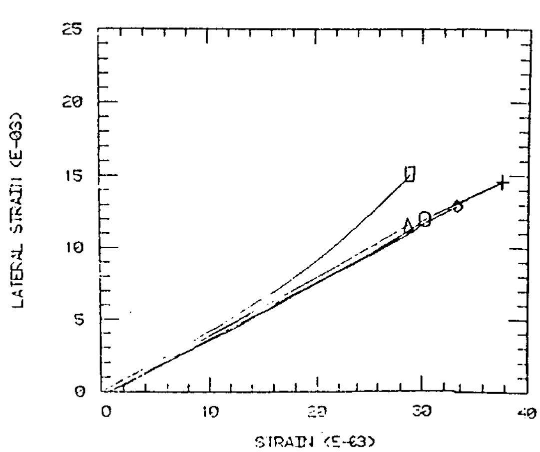
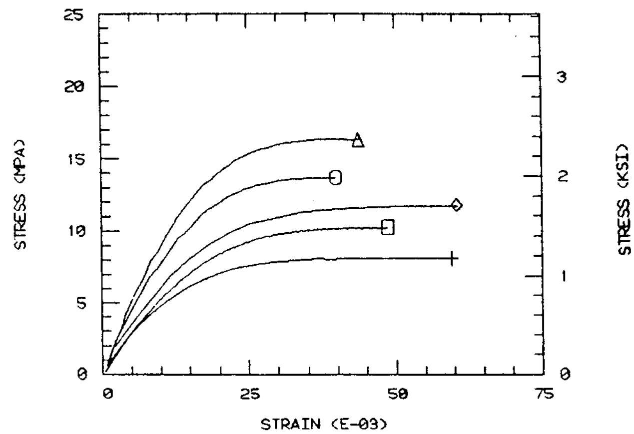
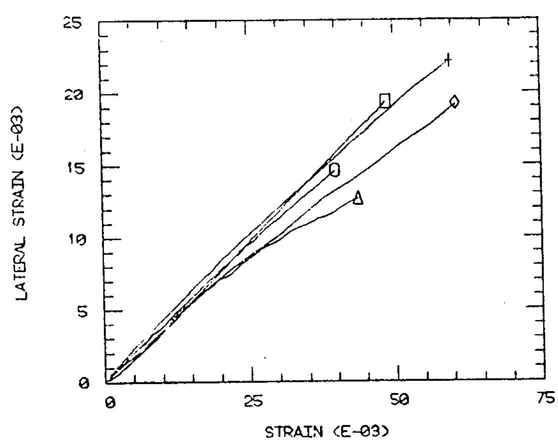


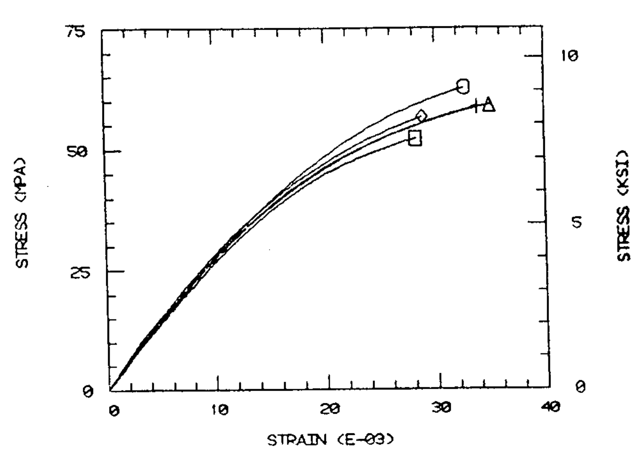
F155 TENSION 71 DEG C, SATURATED



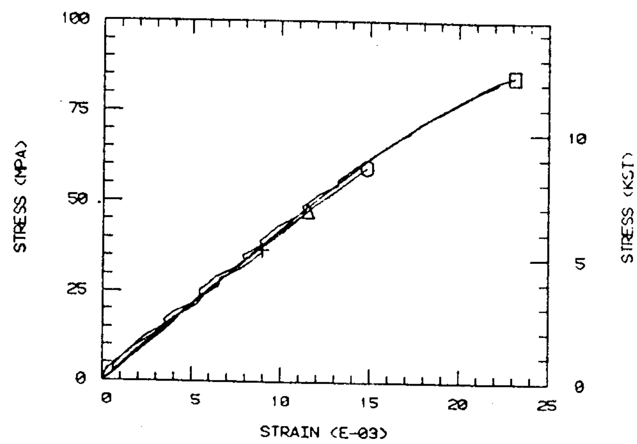
F155 TENSION 71 DEG C, SATURATED



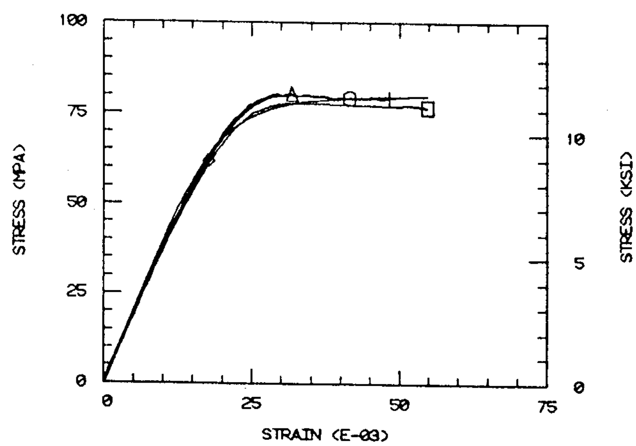
F155 TENSION 23 DEG C, SATURATED



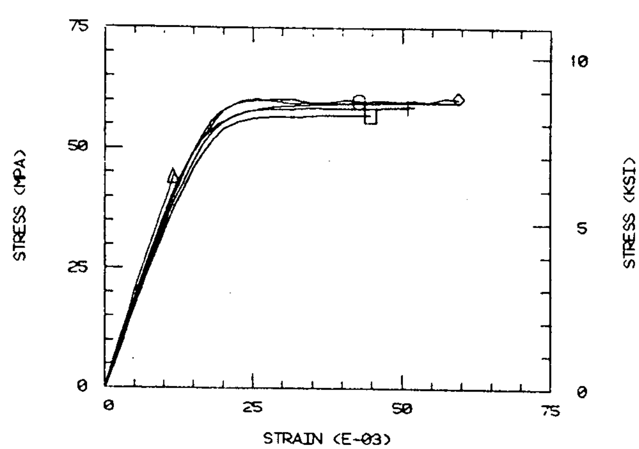
NEAT PEEK DRY TENSION 23 DEG C



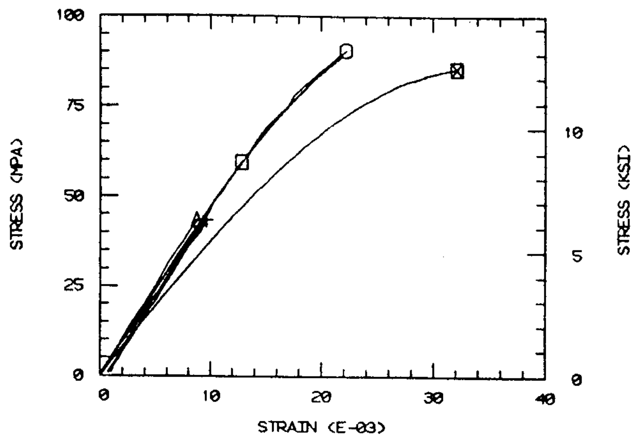
NEAT PEEK DRY TENSION 82 DEG C



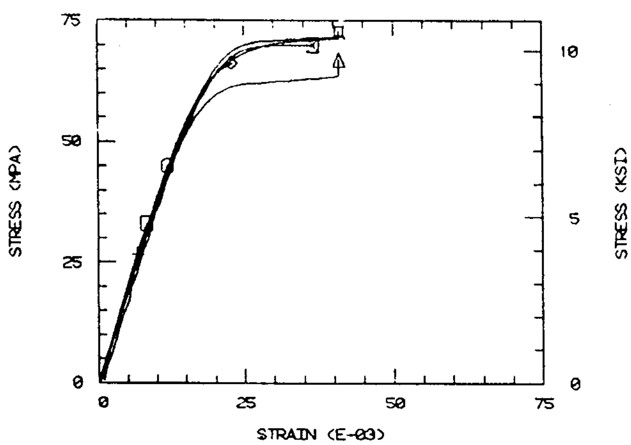
NEAT PEEK DRY TENSION 121 DEG C



NEAT PEEK WET TENSION 23 DEG C



NEAT PEEK WET TENSION 82 DEG C



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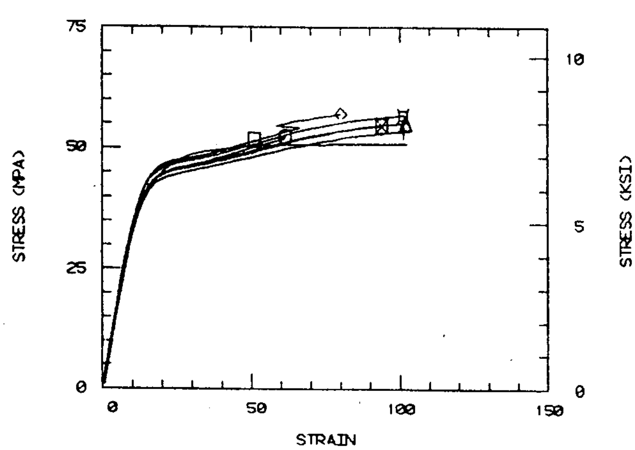
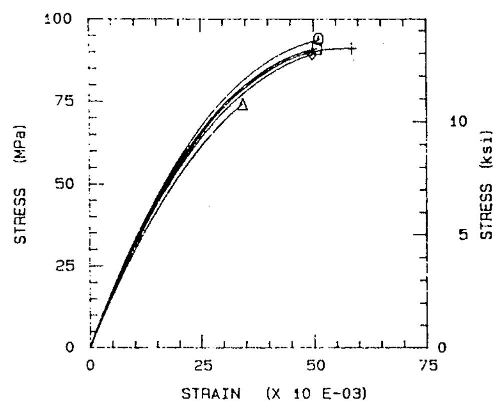


NEAT 8551-7 LONG TENSION 23 DEG DRY



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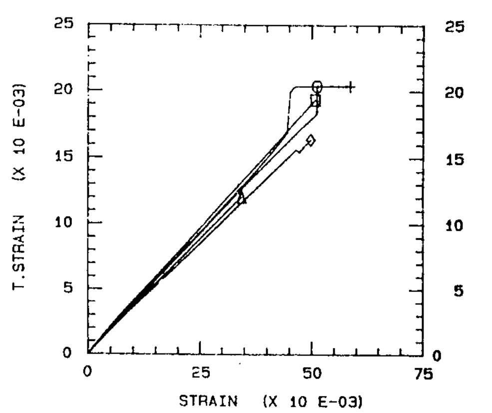
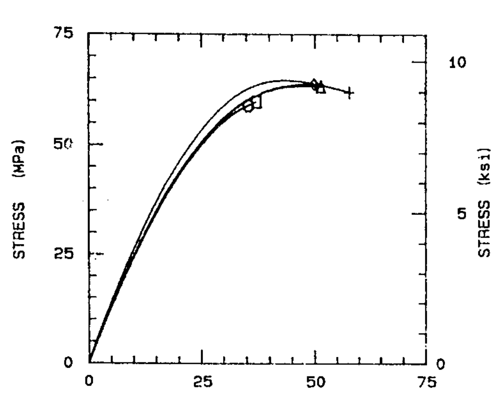
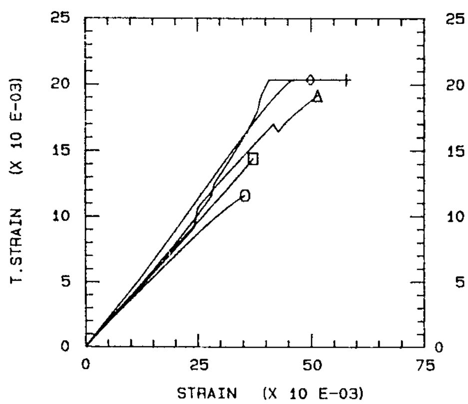


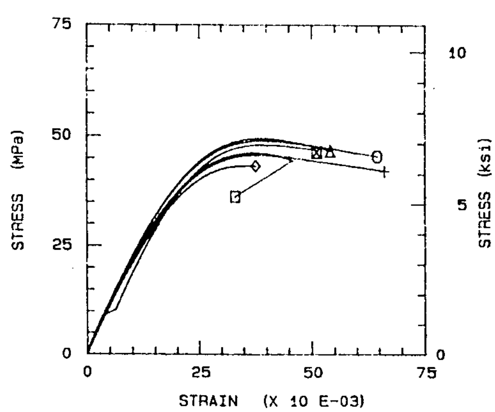
NEAT 8551-7 TENSION 82 DEG C DRY



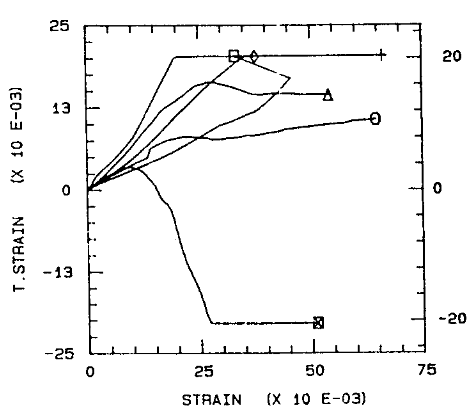
NEAT 8551-7 TENSION 82 DEG C DRY



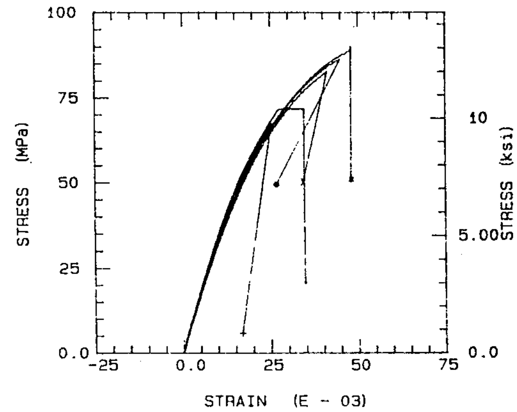
NEAT 8551-7 TENSION 121 DEG C DRY



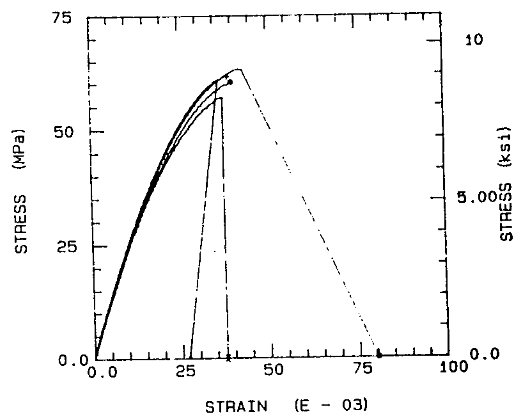
NEAT 8551-7 TENSION 121 DEG C DRY



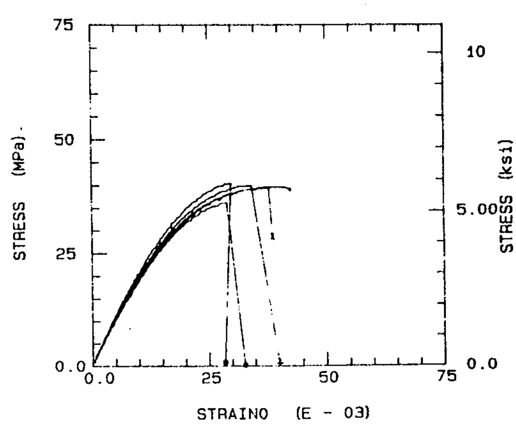
8551-7 MINI-TENSION 23 DEG C



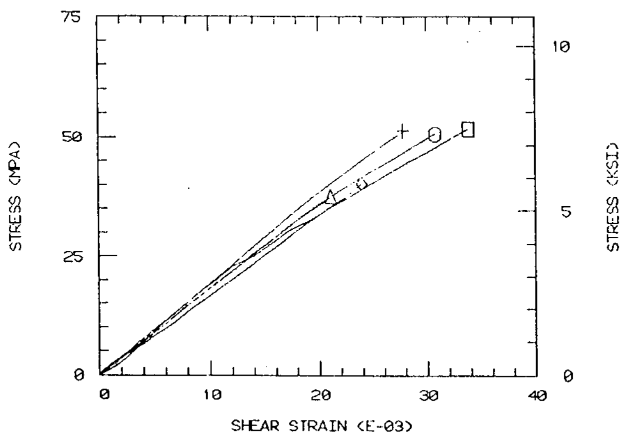
8551-7 MINI-TEN 82 DEG C



8551-7 MINI-TENSION 121 DEG C



F155 IOSIPESCU SHEAR -54 DEG C, DRY



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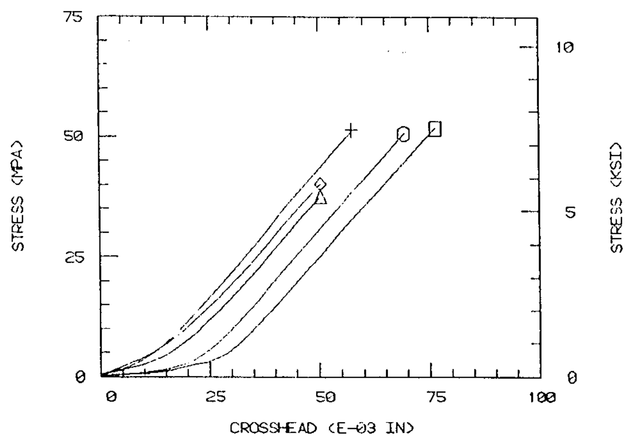

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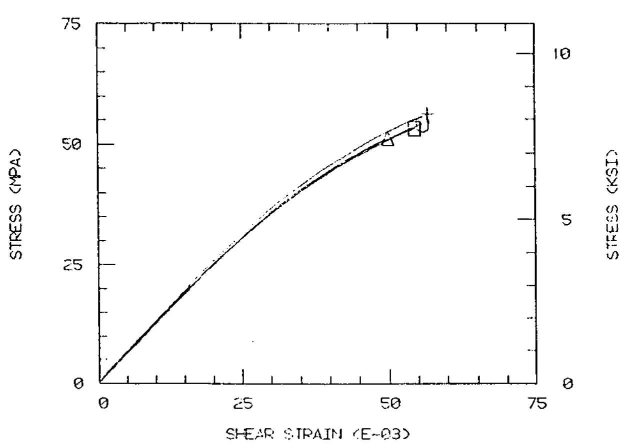

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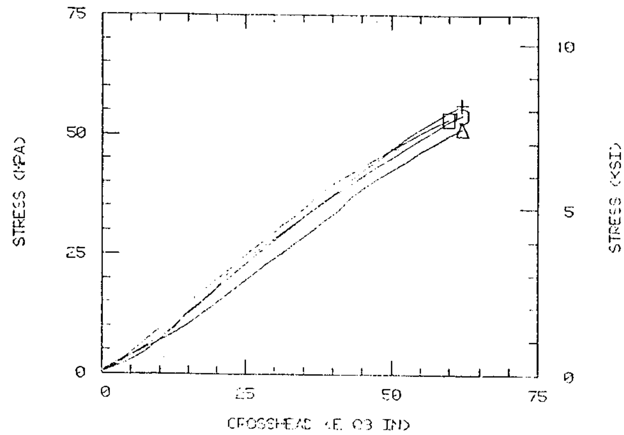
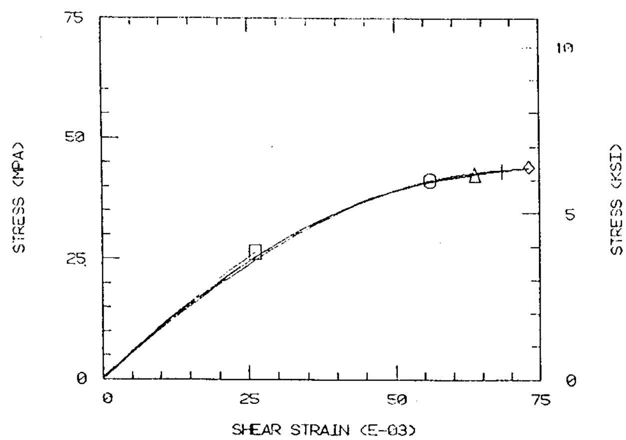


F155 IOSIPESCU SHEAR 71 DEG C, DRY



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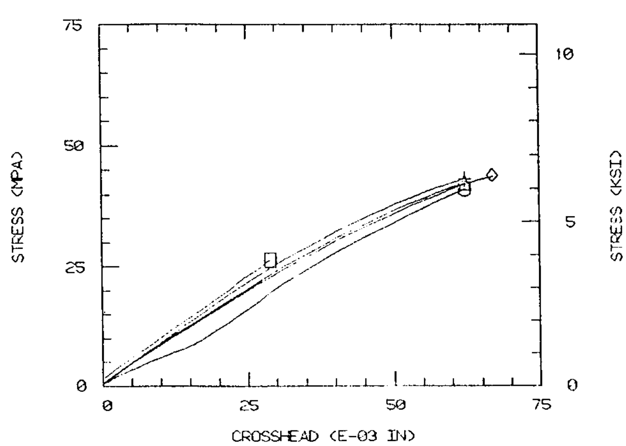
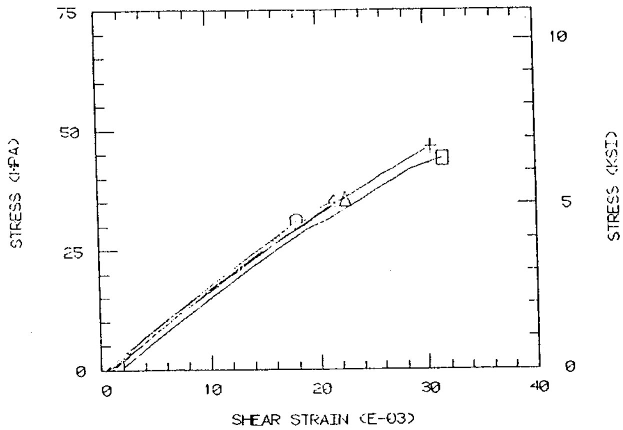
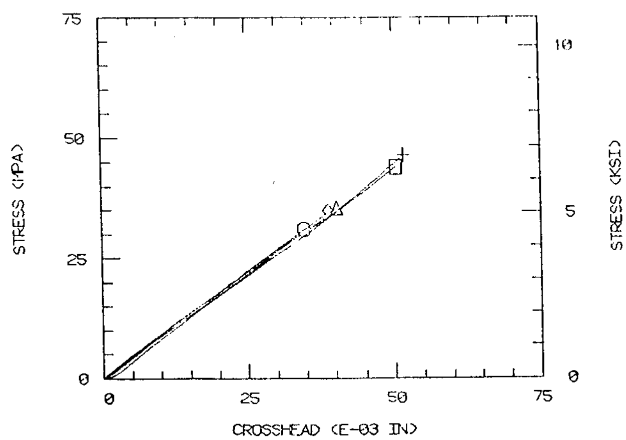


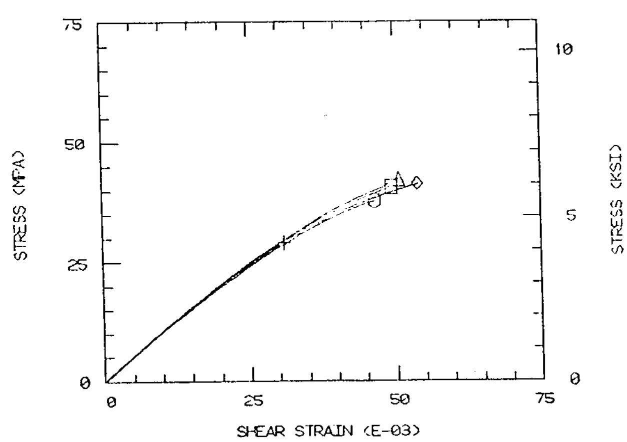
F155 IOS SHEAR 54 DEG C, 4% MOISTURE



F155 IOS SHEAR -54 DEG C, 4% MOISTURE



F155 IOS SHEAR 23 DEG C, 4% MOISTURE



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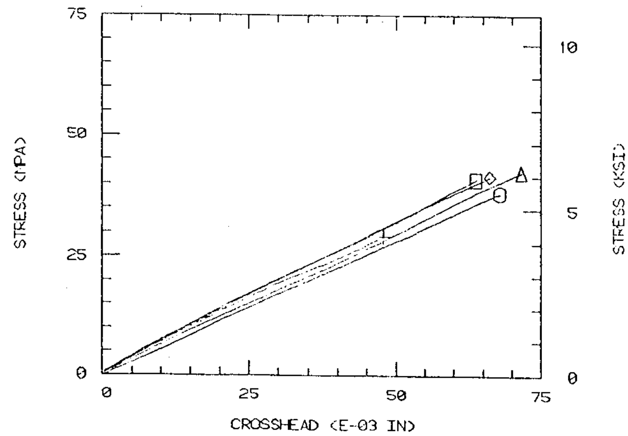
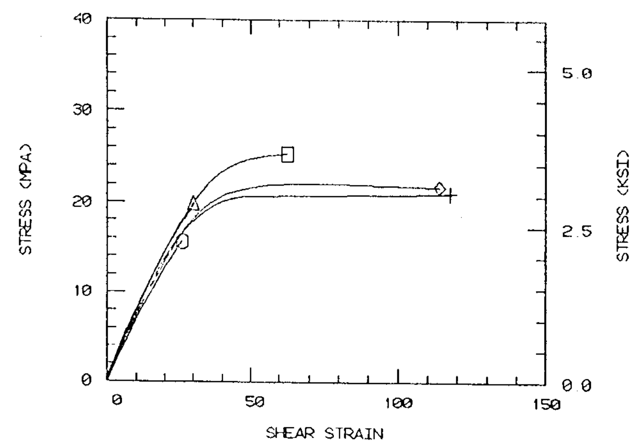
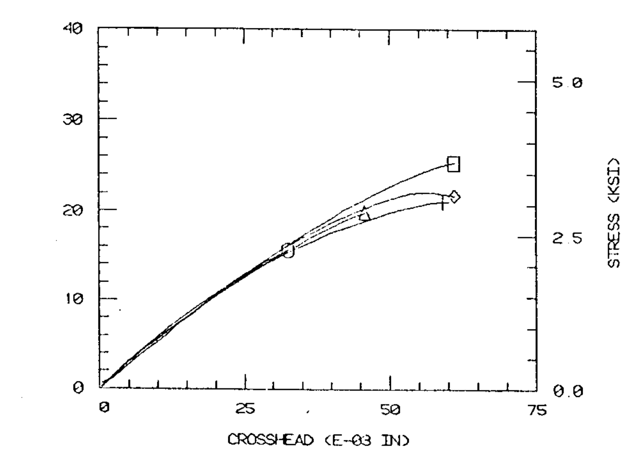
F155 IOS SHEAR 23 DEG C, 4% MOISTURE



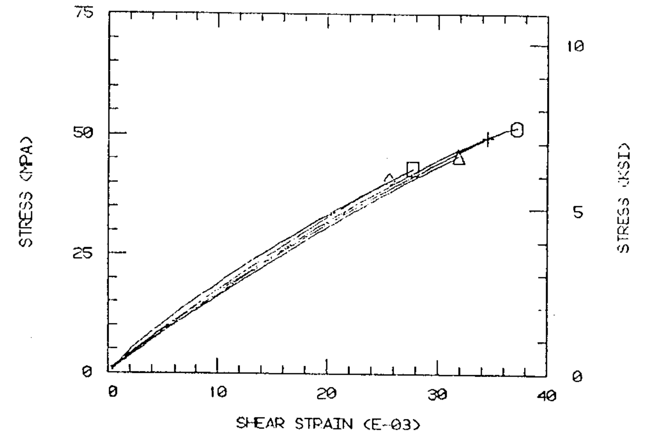
F155 IOS SHEAR 71 DEG C, 4% MOISTURE



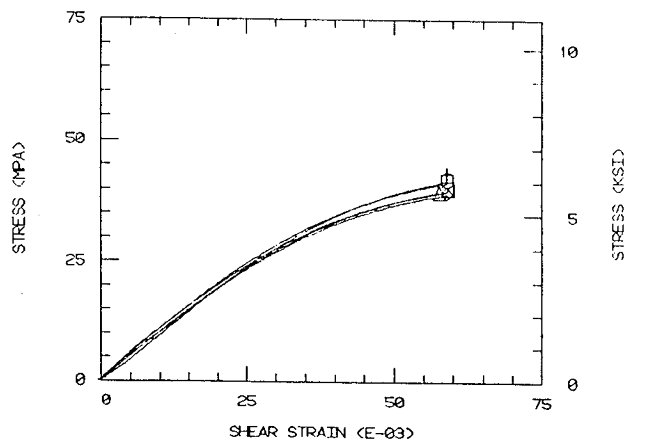
F155 IOS. SHEAR 71 DEG C, 4% MOISTURE



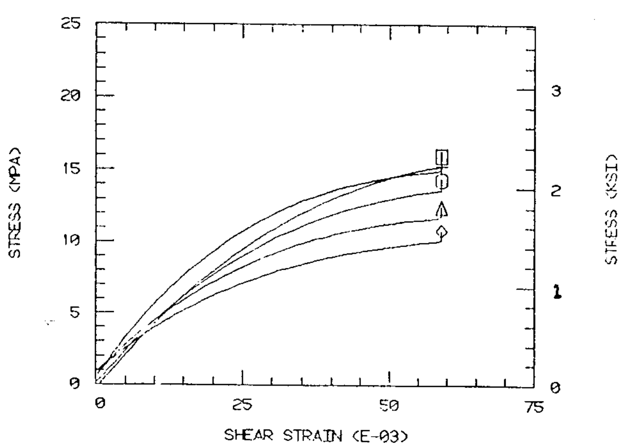
F155 IOS SHEAR -54 DEG C, SATURATED



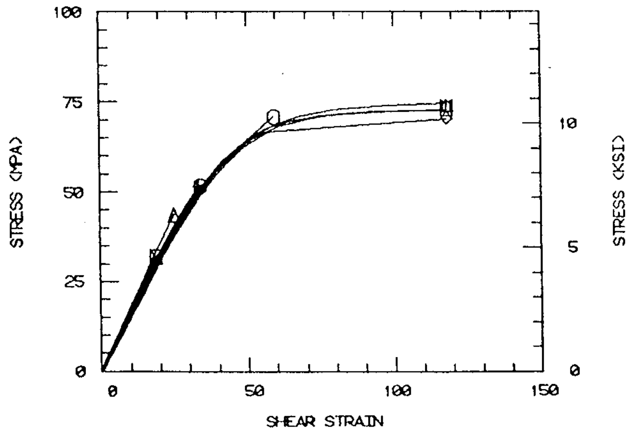
F155 IOS SHEAR 23 DEG C, SATURATED



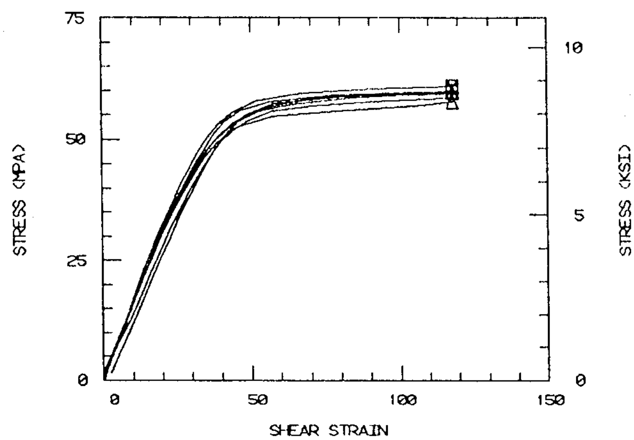
F155 IOS SHEAR 71 DEG C, SATURATED



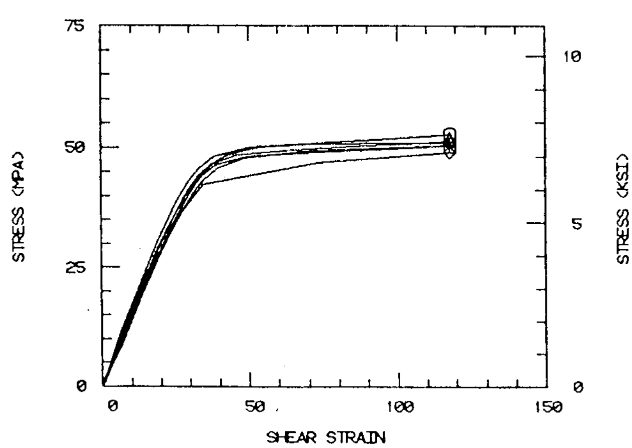
NEAT PEEK DRY IOS SHEAR 23 DEG C



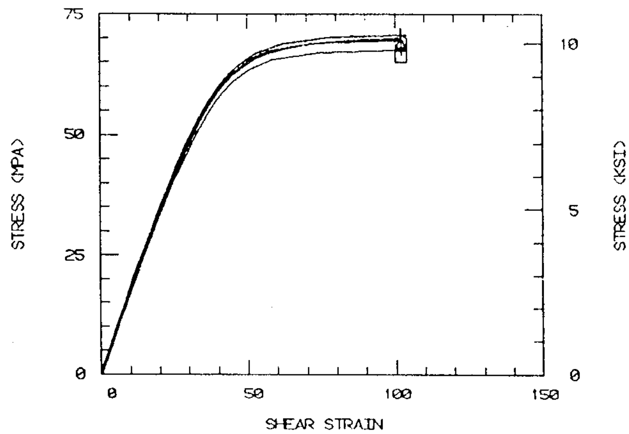
NEAT PEEK DRY IOS SHEAR 82 DEG C



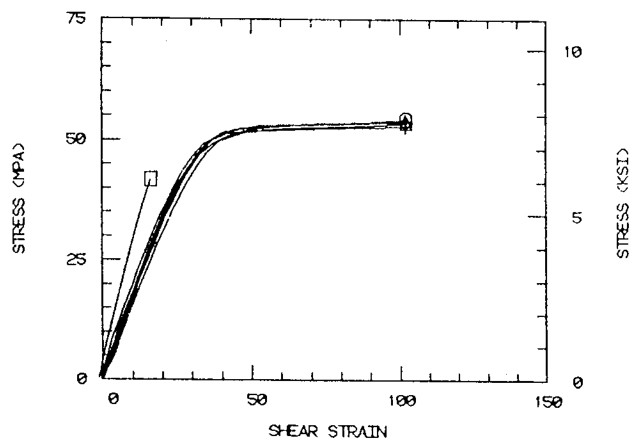
NEAT PEEK DRY IOS SHEAR 121 DEG C



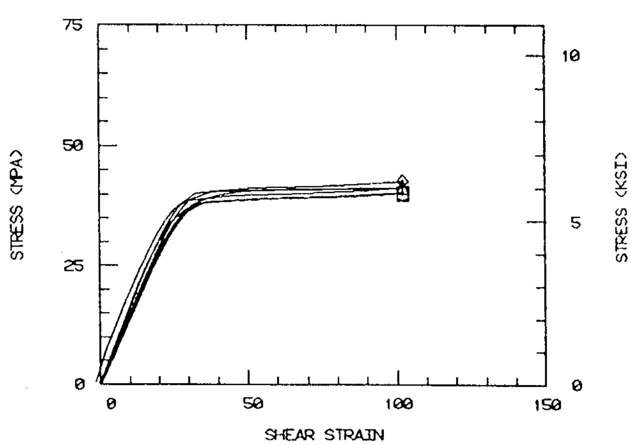
NEAT PEEK WET IOS SHEAR 23 DEG C



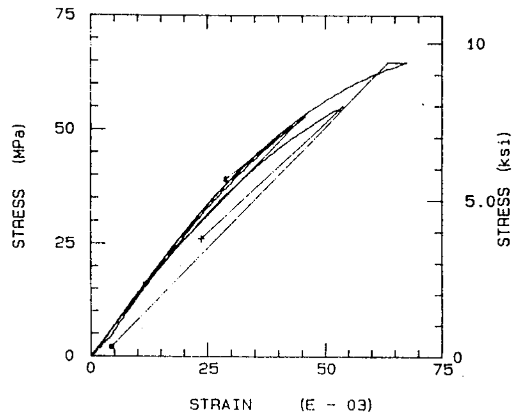
NEAT PEEK WET IOS SHEAR 82 DEG C



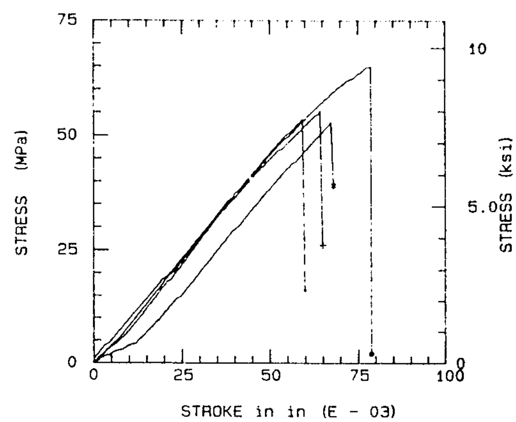
NEAT PEEK WET IOS. SHEAR 121 DEG C



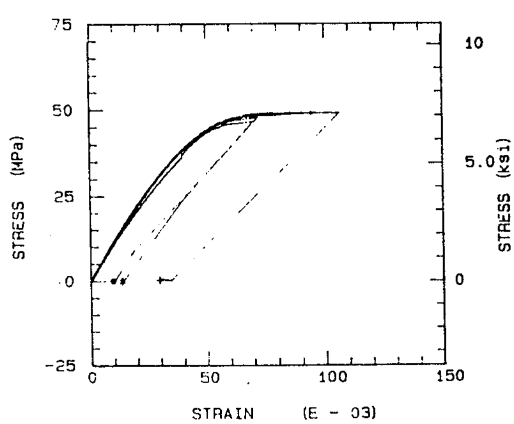
NEAT 8551-7 IOS SHEAR 23 DEG C DRY



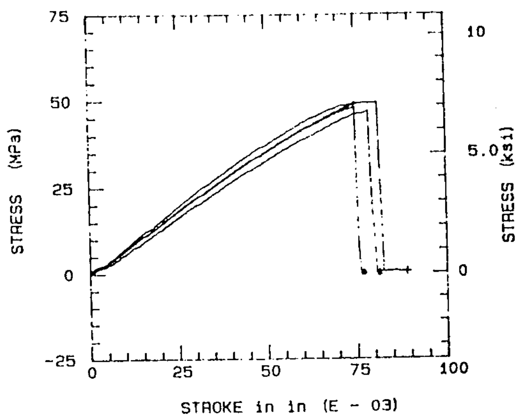
NEAT 8551-7 IOS SHEAR 23 DEG C DRY



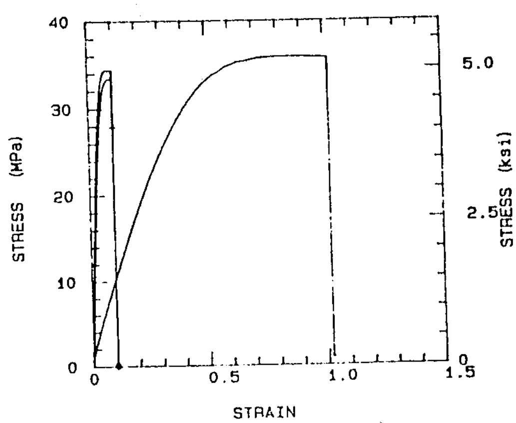
NEAT 8551-7 IOS SHEAR 82 DEG C DRY



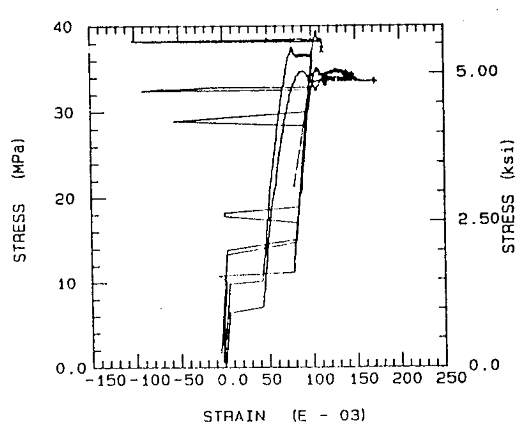
NEAT 8551-7 IOS SHEAR 82 DEG C DRY



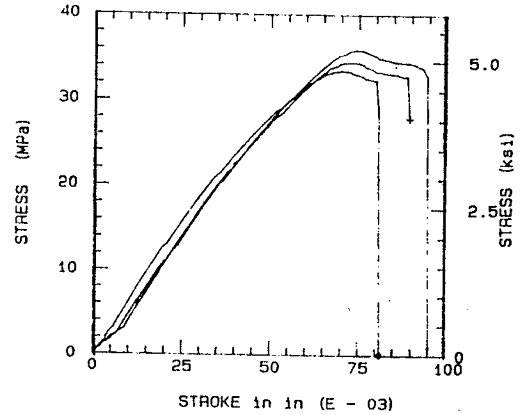
NEAT 8551-7 IOS SHEAR 121 DEG C DRY



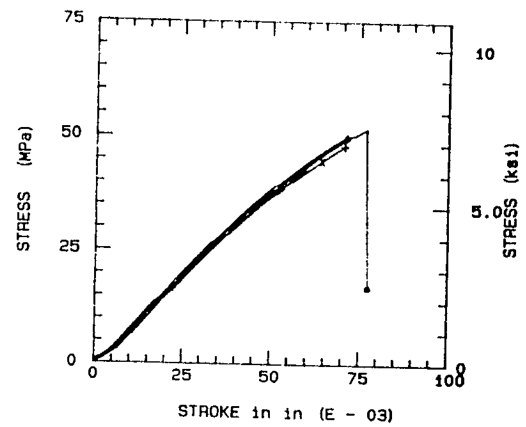
8551-7 MINI-TORSION 121 DEG C



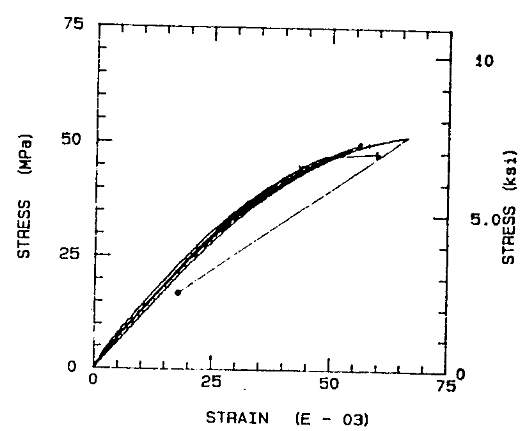
NEAT 8551-7 IOS SHEAR 121 DEG C DRY



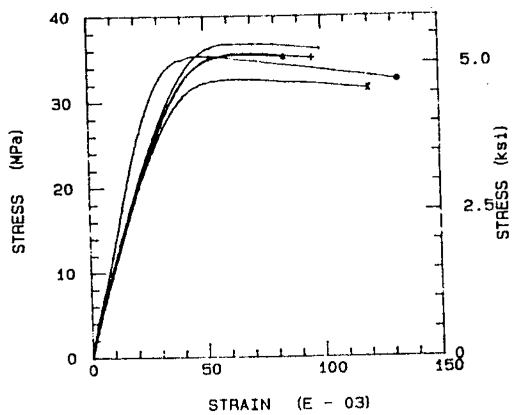
NEAT 8551-7 IOS SHEAR 23 DEG C WET



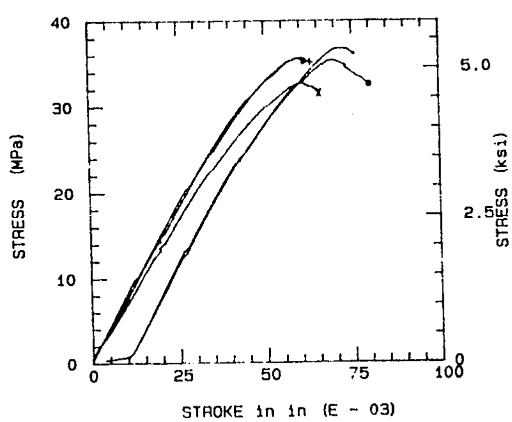
NEAT 8551-7 IOS SHEAR 23 DEG C WET



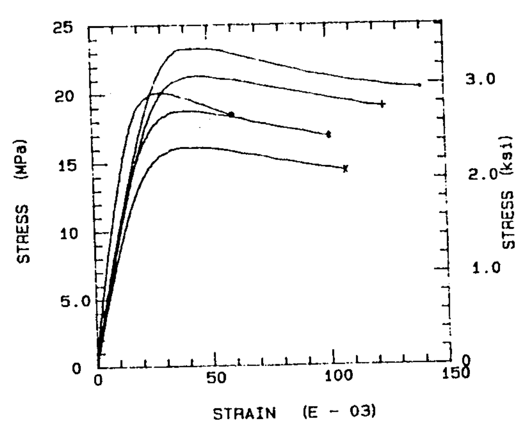
NEAT 8551-7 IOS SHEAR 82 DEG C WET



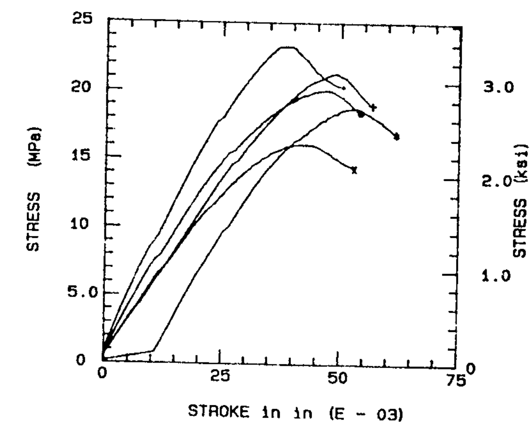
NEAT 8551-7 IOS SHEAR 82 DEG C WET



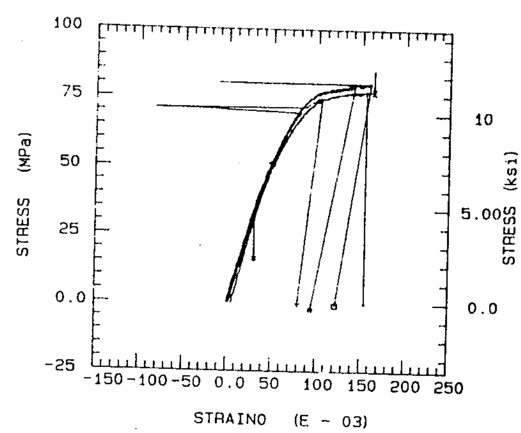
NEAT 8551-7 IOS SHEAR 121 DEG C WE



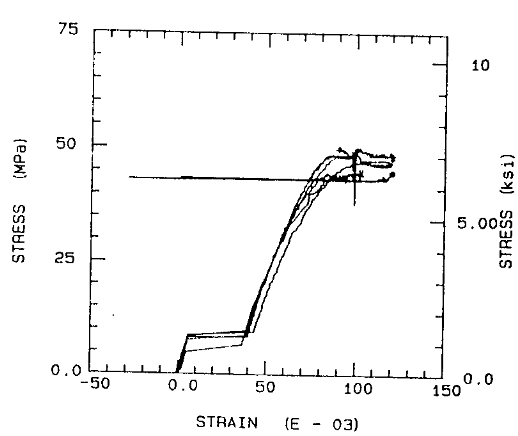
NEAT 8551-7 IOS SHEAR 121 DEG C WET



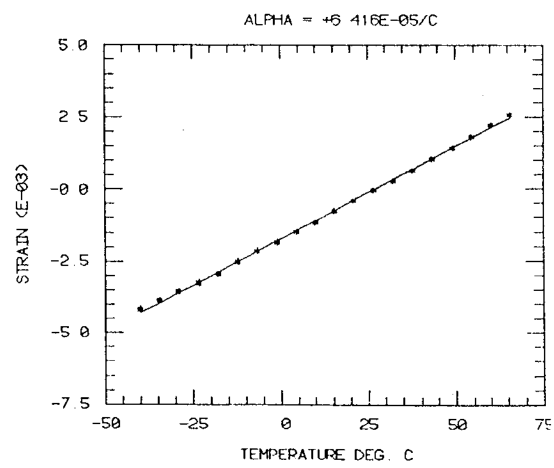
8551-7 MINI-TORSION 23 DEG C



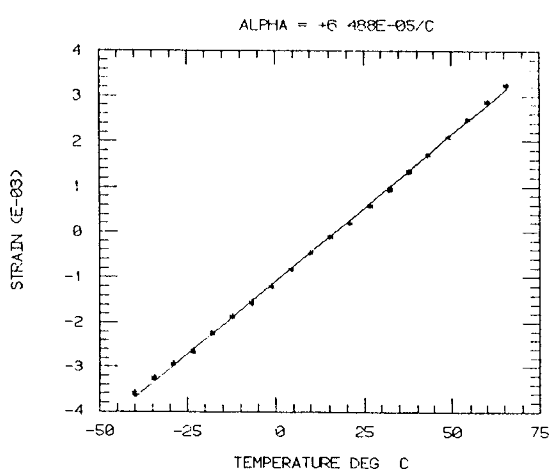
8551-7 MINI-TORSION 82 DEG C



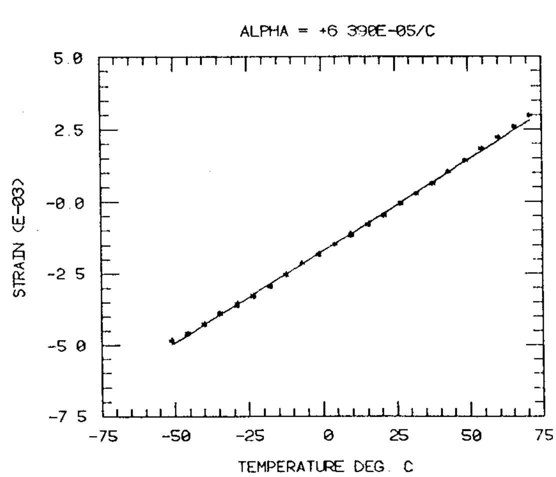
F155 NEAT EPOXY DRY NO 1



F155 NEAT EPOXY DRY NO 2



F155 NEAT EPOXY DRY NO 3



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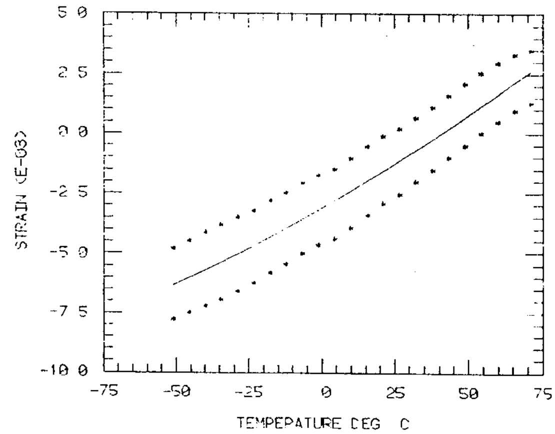
OF POOR QUALITY

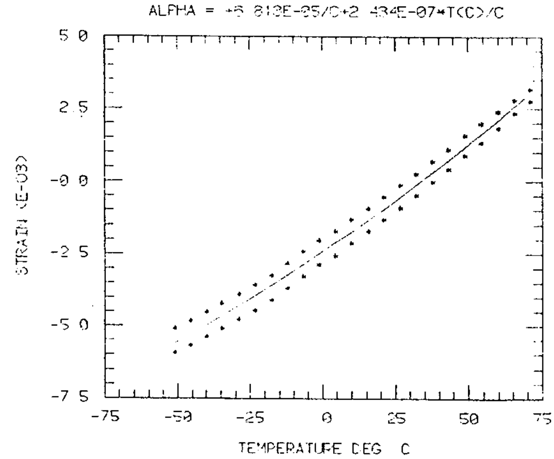
F155 NEAT EPOXY 4% MOISTURE NO 1

ALPHA = +7 041E-05/C+2 985E-07*T(C)/C



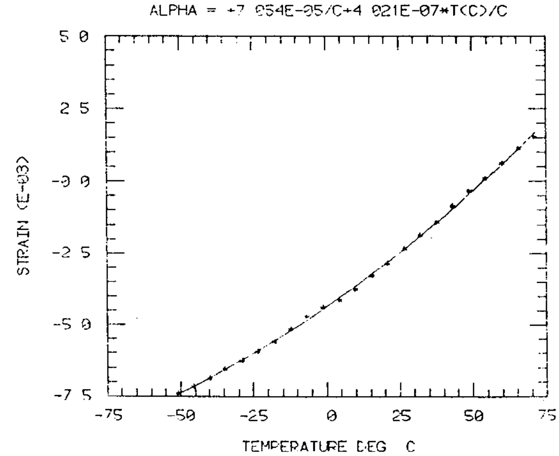
F155 NEAT EPOXY 4% MOISTURE NO 2

ALPHA = +6 812E-05/C+2 434E-07*T(C)/C

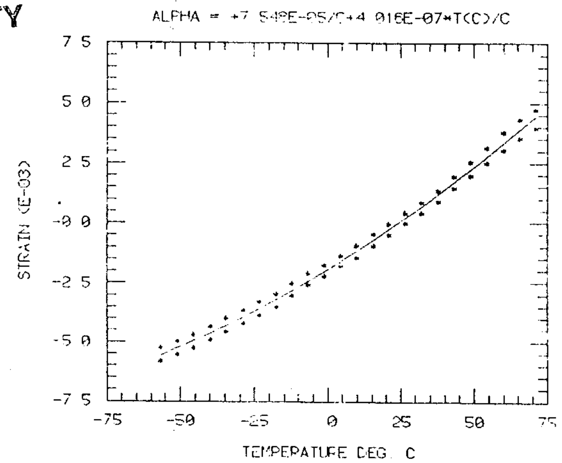


F155 NEAT EPOXY 4% MOISTURE NO 3

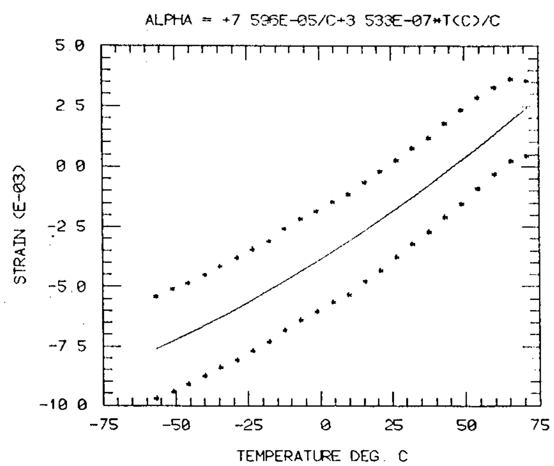
ALPHA = +7 054E-05/C+4 021E-07*T(C)/C



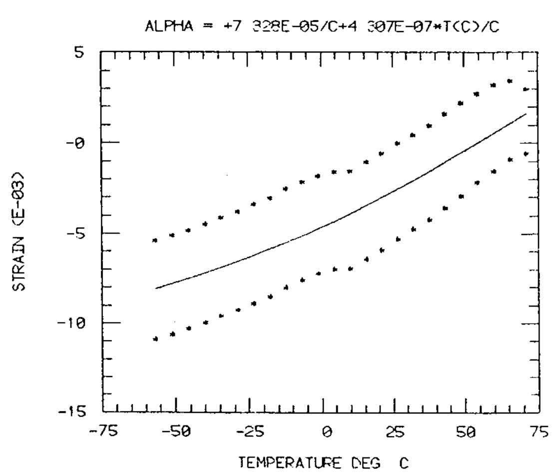
F155 NEAT EPOXY 4% MOISTURE NO. 4



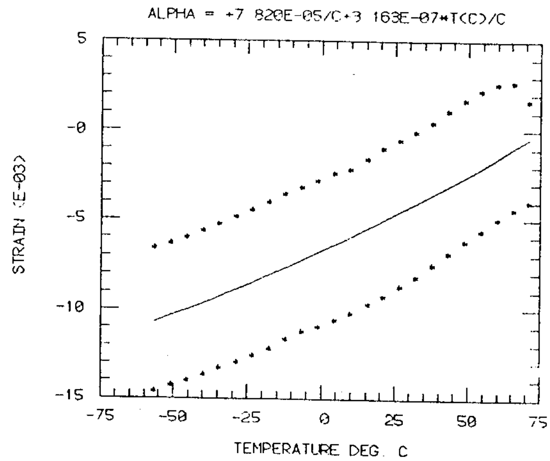
F155 NEAT EPOXY SATURATED #1



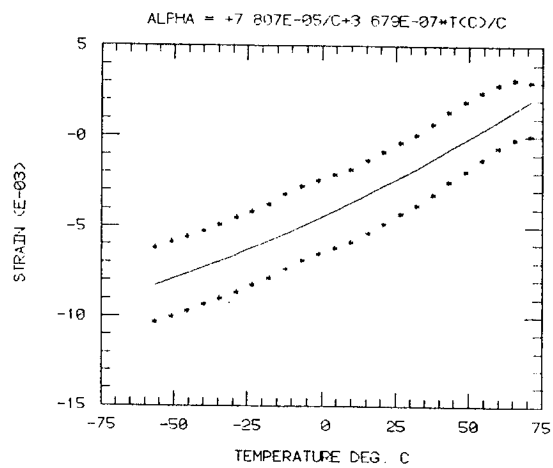
F155 NEAT EPOXY SATURATED #2



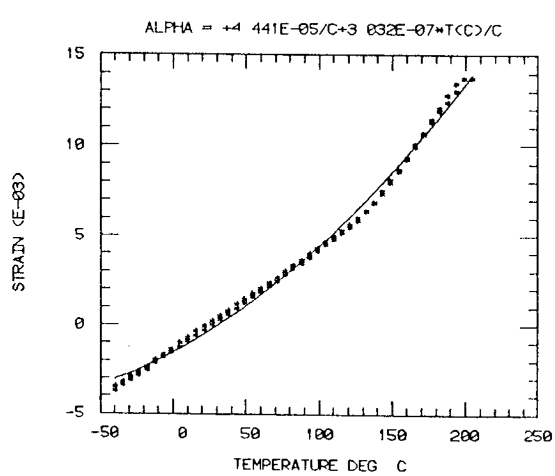
F155 NEAT EPOXY SATURATED #3



F155 NEAT EPOXY SATURATED NO 4



PEEK NEAT THERMOPLASTIC DRY NO. 1



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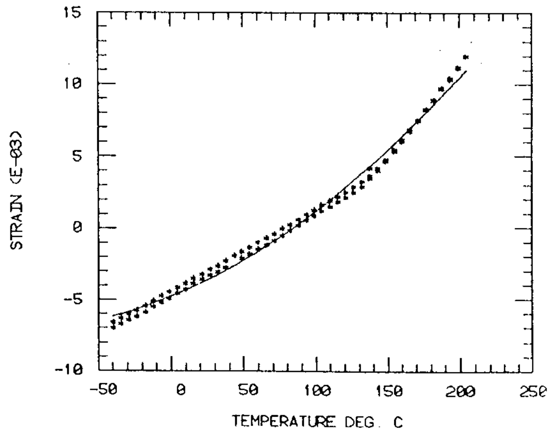
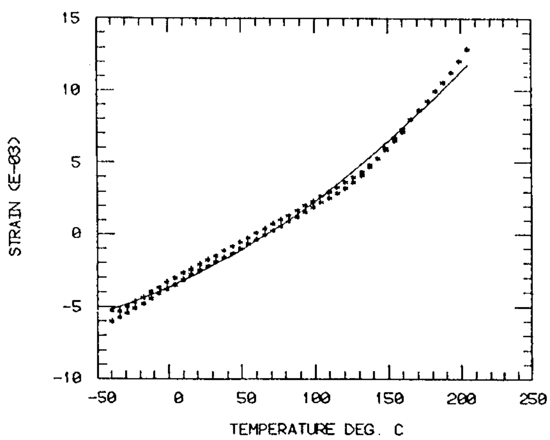
PEEK NEAT THERMOPLASTIC DRY NO 2

ALPHA = +4 201E-05/C+3 426E-07*T(C)/C



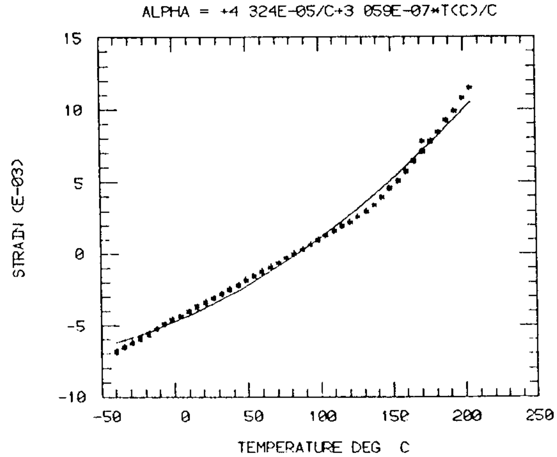
PEEK NEAT THERMOPLASTIC DRY NO 3

ALPHA = +4 388E-05/C+3 111E-07*T(C)/C



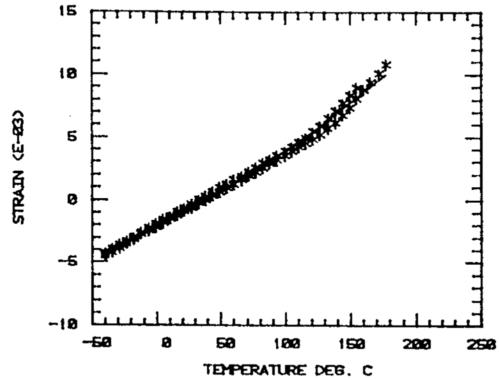
PEEK NEAT THERMOPLASTIC DRY NO 4

ALPHA = +4 324E-05/C+3 059E-07*T(C)/C



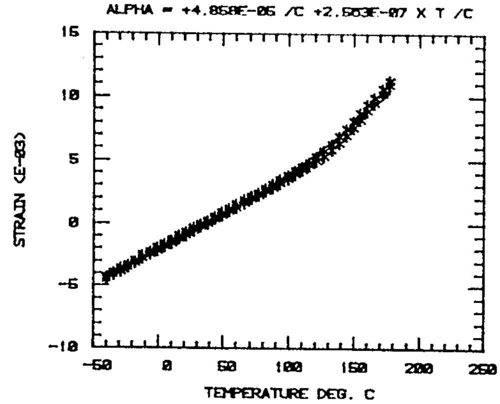
NEAT WET PEEK NO. 1

ALPHA = +5.114E-05 /C +2.031E-07 X T /C



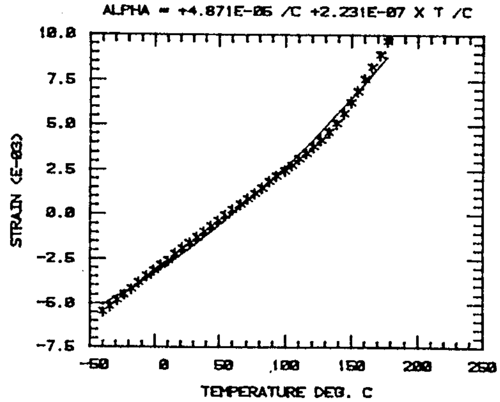
NEAT WET PEEK NO. 2

ALPHA = +4.858E-05 /C +2.583E-07 X T /C

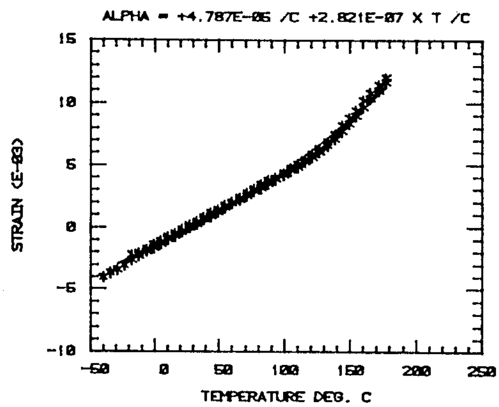


NEAT WET PEEK NO. 3A

ALPHA = +4.871E-05 /C +2.231E-07 X T /C



NEAT WET PEEK N0. 4



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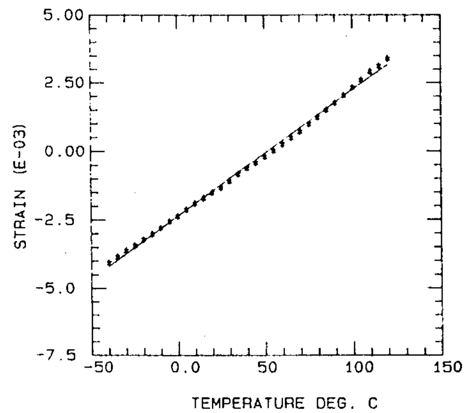
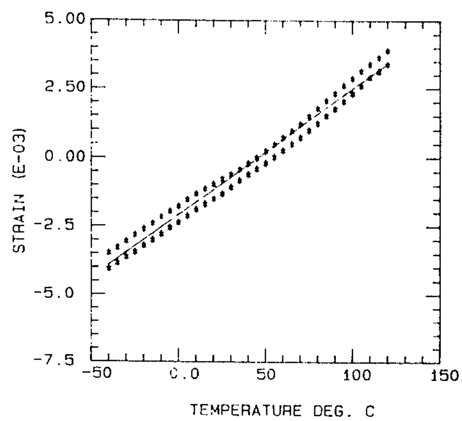
8551-7 NEAT EPOXY DRY CYCLE 2 #1

ALPHA = +4.607E-05 /C



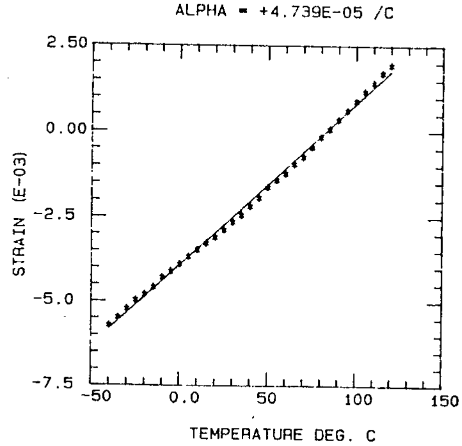
8551-7 NEAT EPOXY DRY #1

ALPHA = +4.578E-05 /C



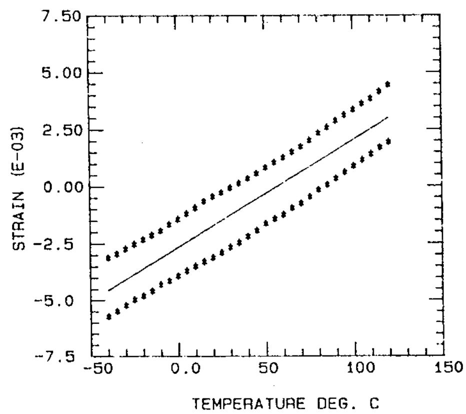
8551-7 NEAT EPOXY DRY 2nd CYCLE #2

ALPHA = +4.739E-05 /C



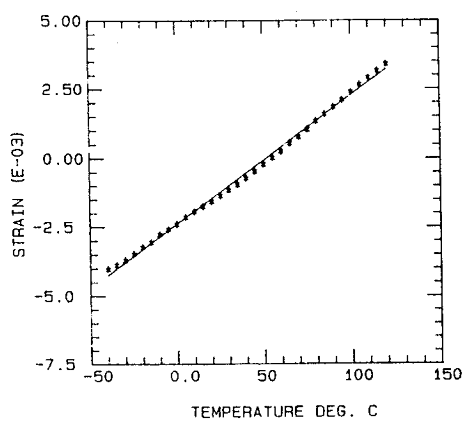
8551-7 NEAT EPOXY DRY #2

ALPHA = +4.727E-05 /C



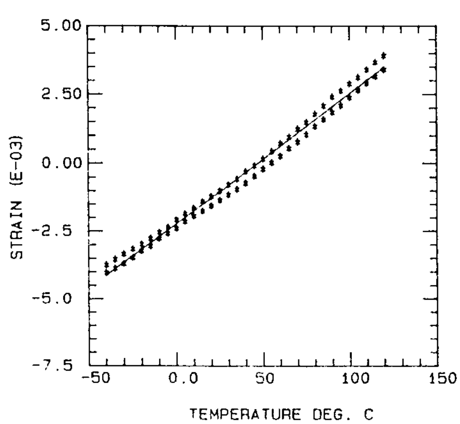
8551-7 NEAT EPOXY 2nd CYCLE #3

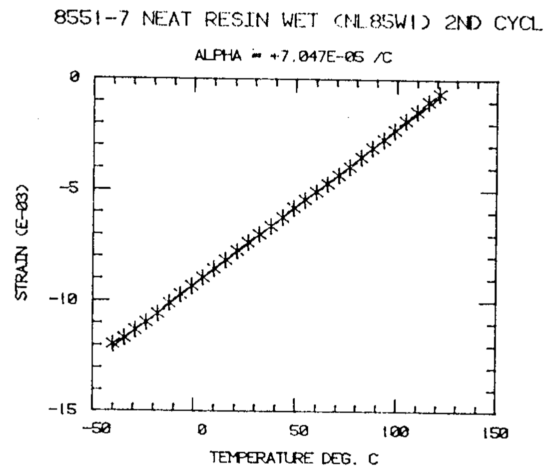
ALPHA = +4.671E-05 /C

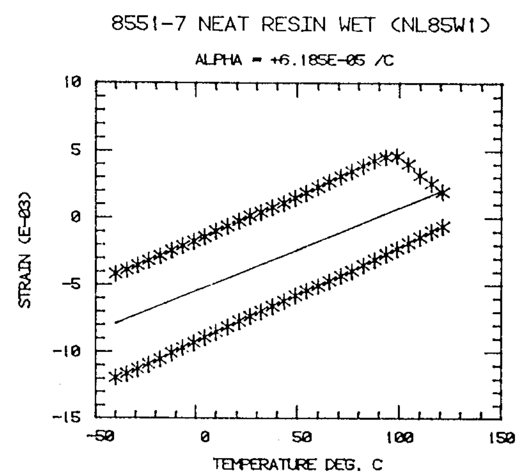


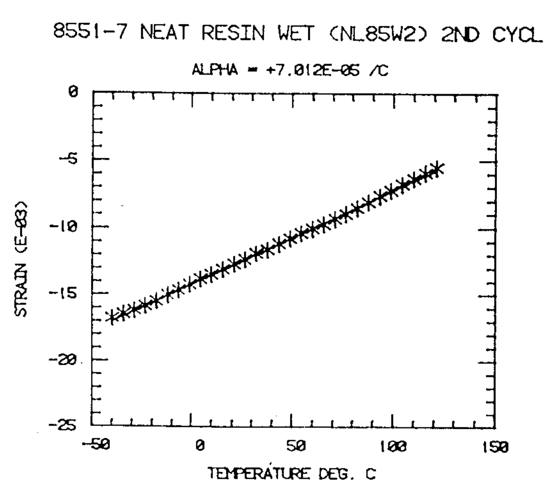
8551-7 NEAT EPOXY #3

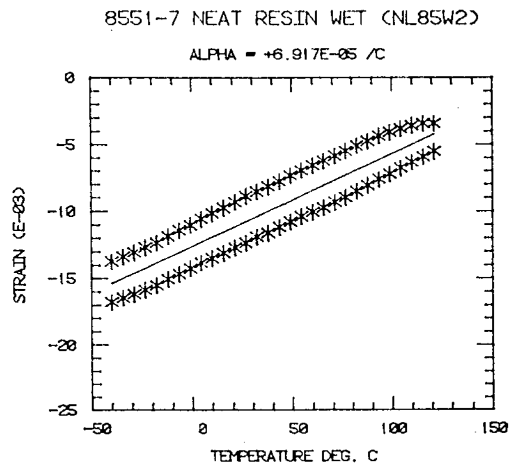
ALPHA = +4.757E-05 /C

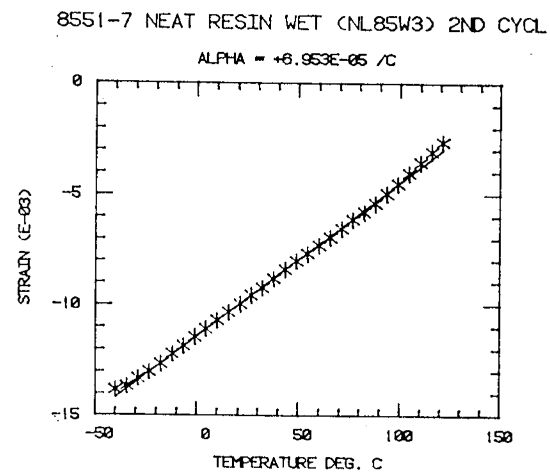


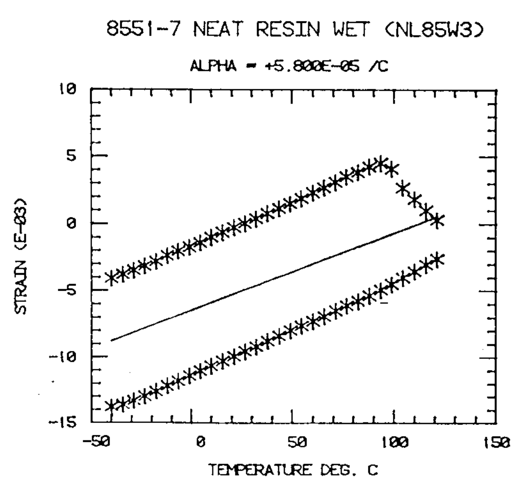

8551-7 NEAT RESIN WET (NL85W1) 2ND CYCL
ALPHA = +7.047E-05 /C
STRAIN (E-03)
0
-5
-10
-15
-50
0
50
100
150
TEMPERATURE DEG. C


8551-7 NEAT RESIN WET (NL85W1)
ALPHA = +6.185E-05 /C
STRAIN (E-03)
10
5
0
-5
-10
-15
-50
0
50
100
150
TEMPERATURE DEG. C

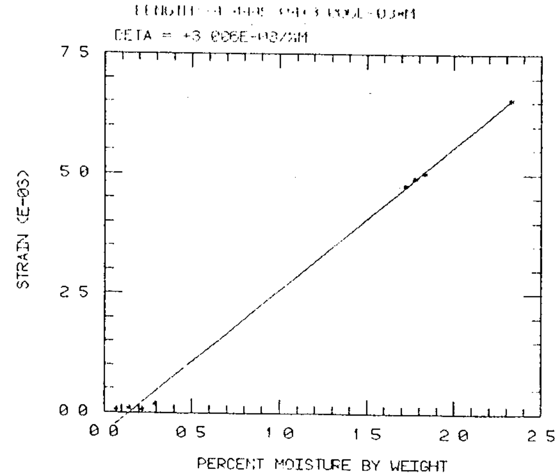

8551-7 NEAT RESIN WET (NL85W2) 2ND CYCL
ALPHA = +7.012E-05 /C
STRAIN (E-03)
0
-5
-10
-15
-20
-25
-50
0
50
100
150
TEMPERATURE DEG. C


8551-7 NEAT RESIN WET (NL85W2)
ALPHA = +6.917E-05 /C
STRAIN (E-03)
TEMPERATURE DEG. C

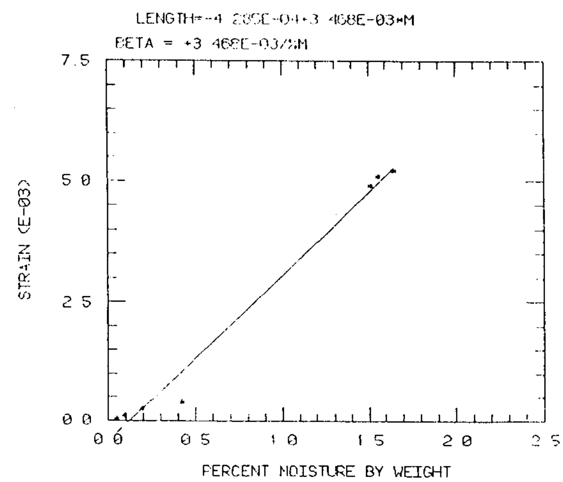

8551-7 NEAT RESIN WET (NL85W3) 2ND CYCL
ALPHA = +6.953E-05 /C
STRAIN (E-03)
TEMPERATURE DEG. C


8551-7 NEAT RESIN WET (NL85W3)
ALPHA = +5.800E-05 /C
STRAIN (E-03)
TEMPERATURE DEG. C

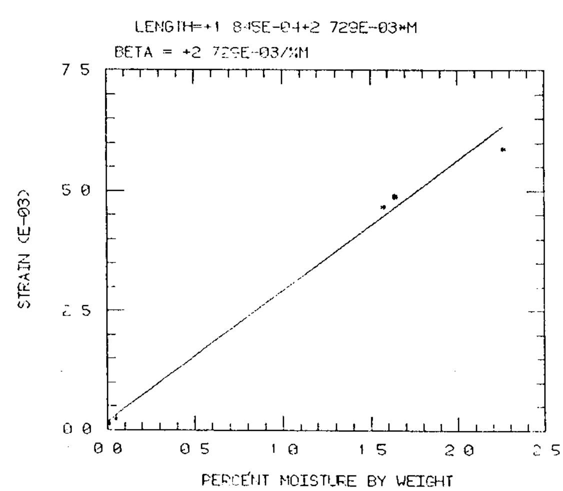
F155 NEAT RESIN NO 1



F155 NEAT RESIN NO 2



F155 NEAT RESIN NO. 3



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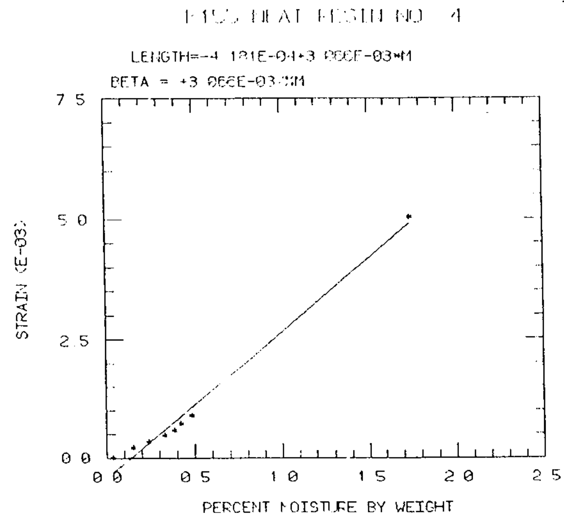
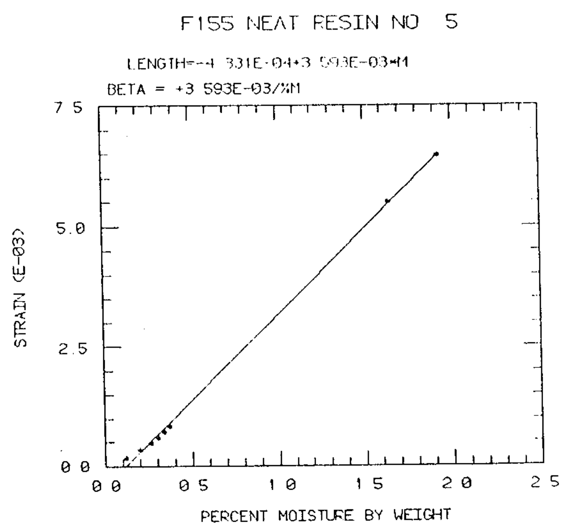
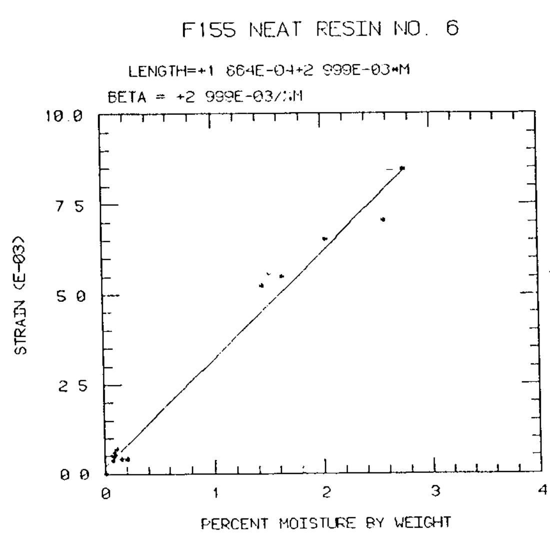
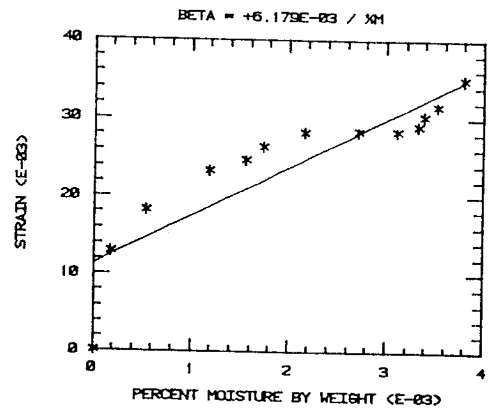

STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT
7 5
5 0
2 5
0 0
0 0
0 5
1 0
1 5
2 0
2 5

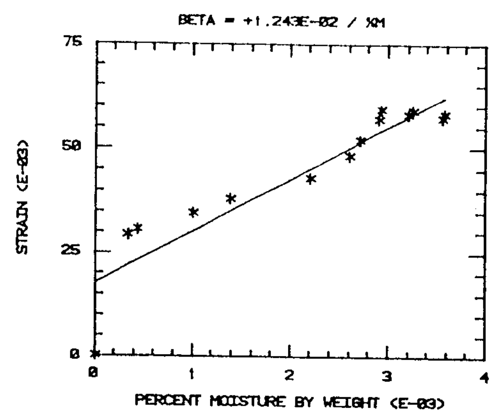

F155 NEAT RESIN NO 5
LENGTH=-4 331E-04+3 593E-03*M
BETA = +3 593E-03/%M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT
7 5
5.0
2.5
0 0
0 0
0 5
1 0
1 5
2 0
2 5


F155 NEAT RESIN NO. 6
LENGTH=+1 664E-04+2 999E-03*M
BETA = +2 999E-03/%M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT
10.0
7 5
5 0
2 5
0 0
0
1
2
3
4

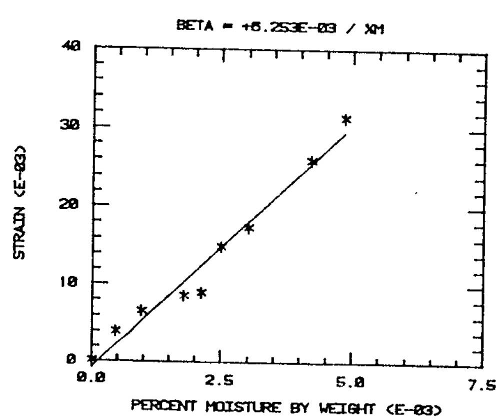
PEEK RESIN NOS. 1 & 2(EXP)T1



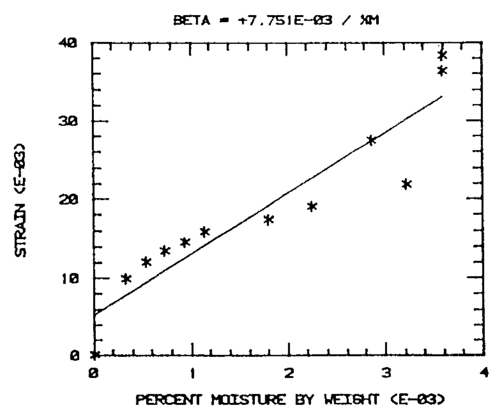
PEEK RESIN NOS. 3 & 4(EXP)T1



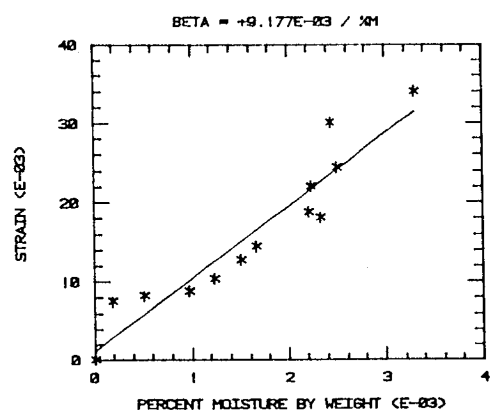
PEEK RESIN NOS. 5 & 6(EXP)T1



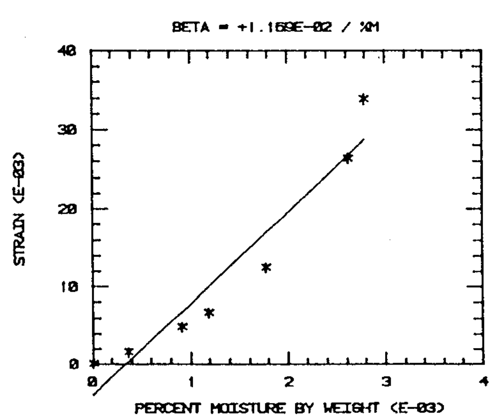
PEEK RESIN NOS. 7 & 8(EXP)T1



PEEK RESIN NOS. 9 & 10(EXP)T1

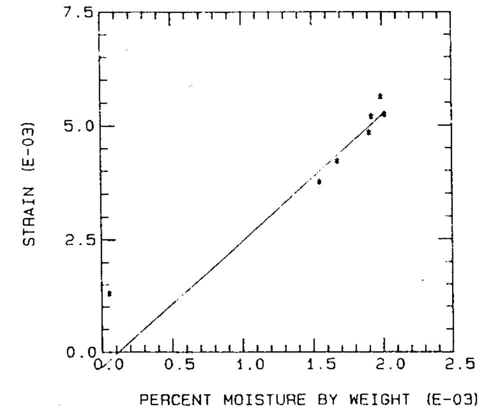


PEEK RESIN NOS. 11 & 12(EXP)T1



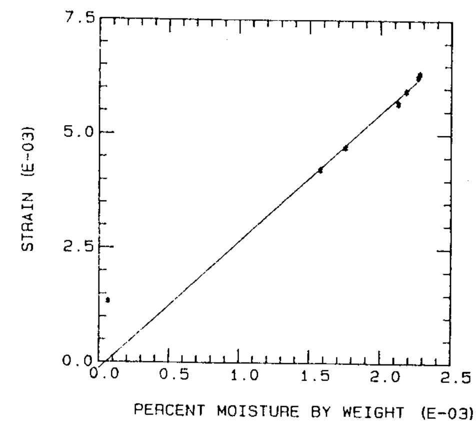
NASA JOHNSON 8551-7 NEAT RESIN NL5N1

BETA = +2.778E-03 / %M



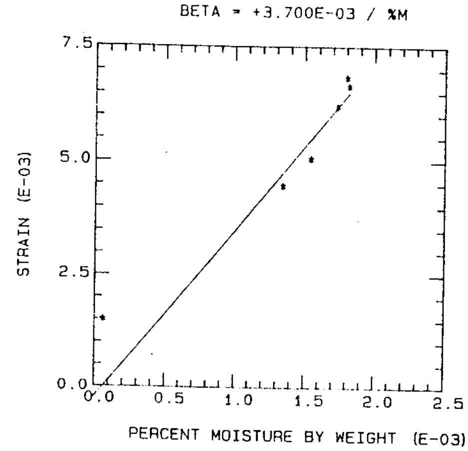
NASA JOHNSON 8551-7 NEAT RESIN NL5N2

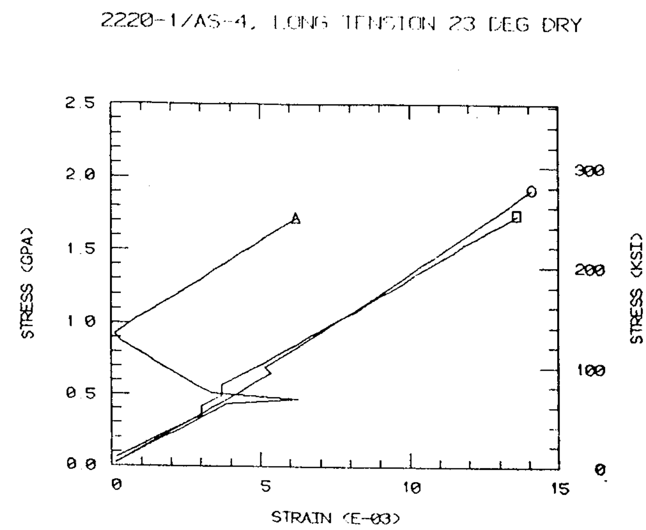
BETA = +2.790E-03 / %M

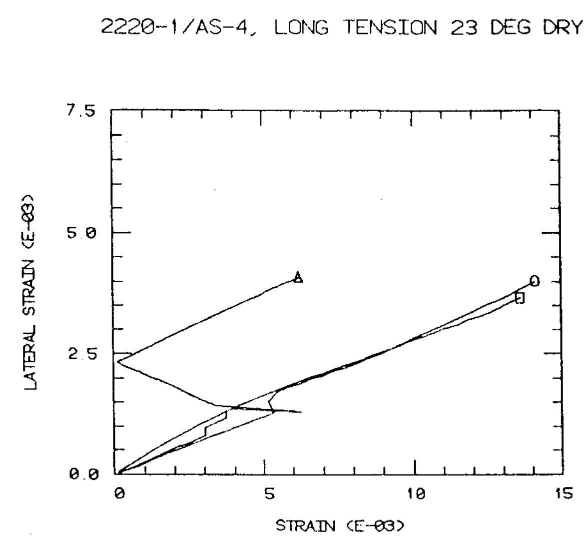


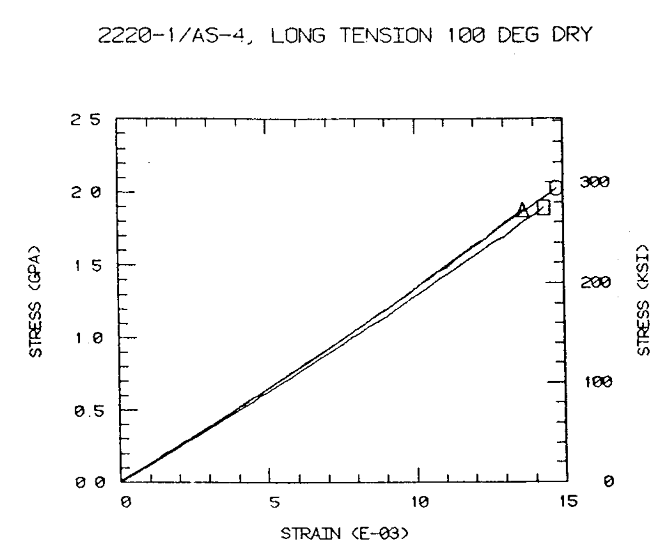
NASA JOHNSON 8551-7 NEAT RESIN NL5N3

BETA = +3.700E-03 / %M

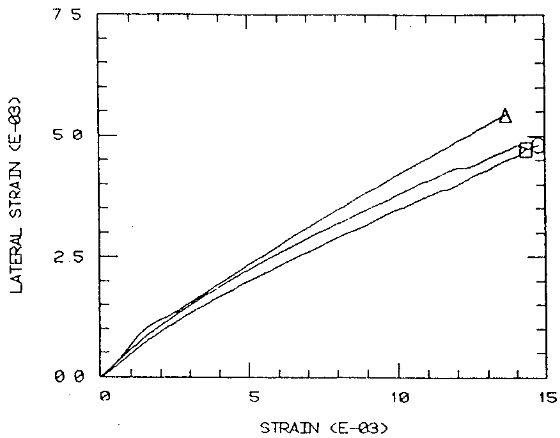



2220-1/AS-4, LONG TENSION 23 DEG DRY
STRESS (GPA)
STRESS (KSI)
STRAIN (E-03)
2.5
2.0
1.5
1.0
0.5
0.0
300
200
100
0
5
10
15

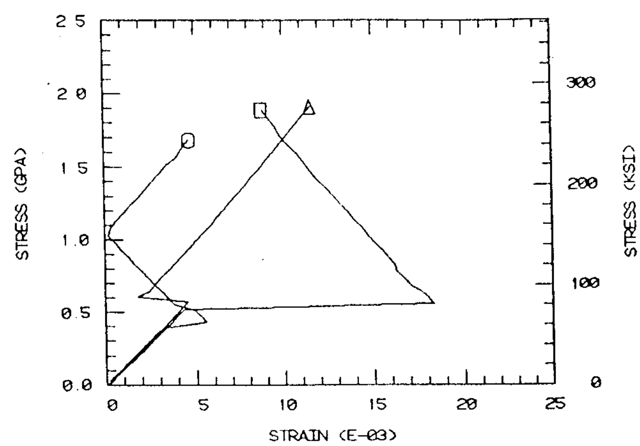

2220-1/AS-4, LONG TENSION 23 DEG DRY
LATERAL STRAIN (E-03)
STRAIN (E-03)
7.5
5.0
2.5
0.0
0
5
10
15


2220-1/AS-4, LONG TENSION 100 DEG DRY
STRESS (GPA)
STRESS (KSI)
STRAIN (E-03)
2.5
2.0
1.5
1.0
0.5
0.0
300
200
100
0
5
10
15

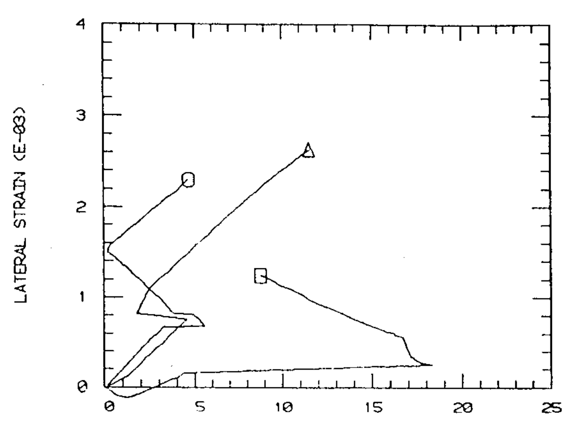
2220-1/AS-4, LONG TENSION 100 DEG DRY



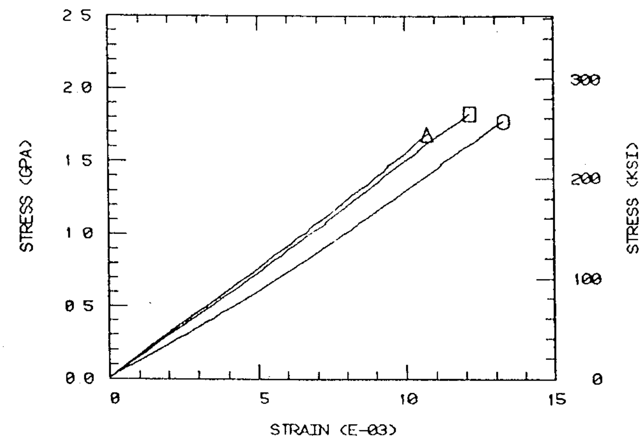
2220-3/AS-4, LONG TENSION 23 DEG DRY



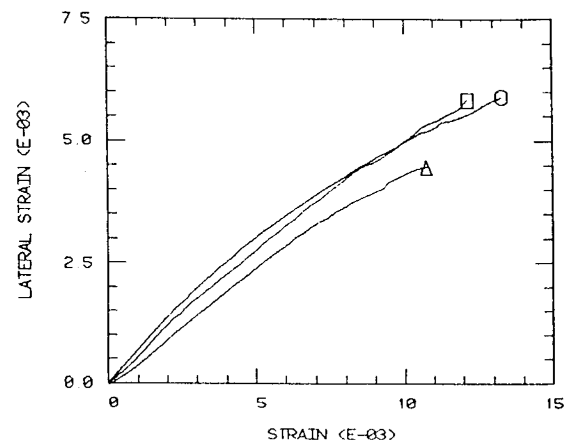
2220-3/AS-4, LONG TENSION 23 DEG DRY



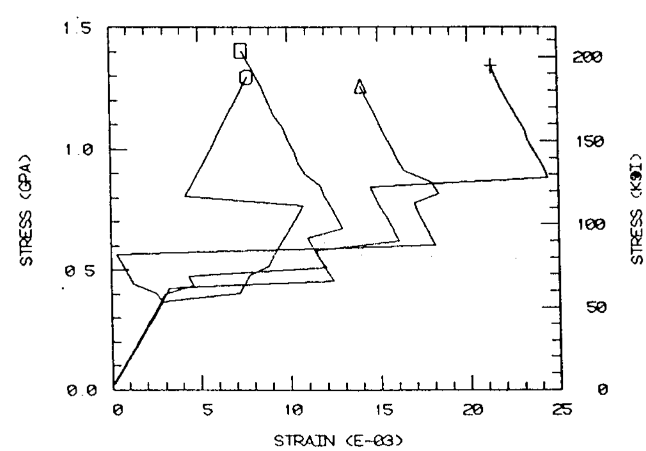
2220-3/AS-4, LONG TENSION 100 DEG DRY



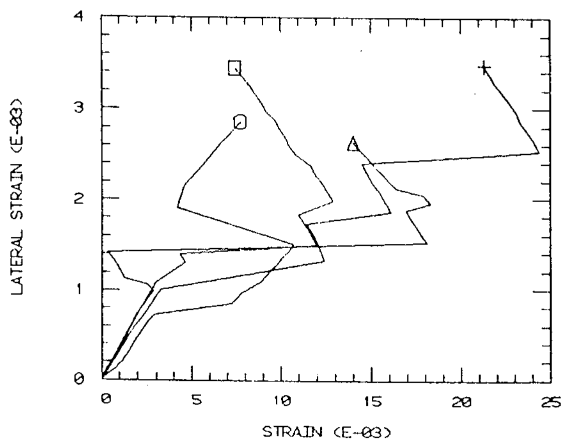
2220-3/AS-4, LONG TENSION 100 DEG DRY



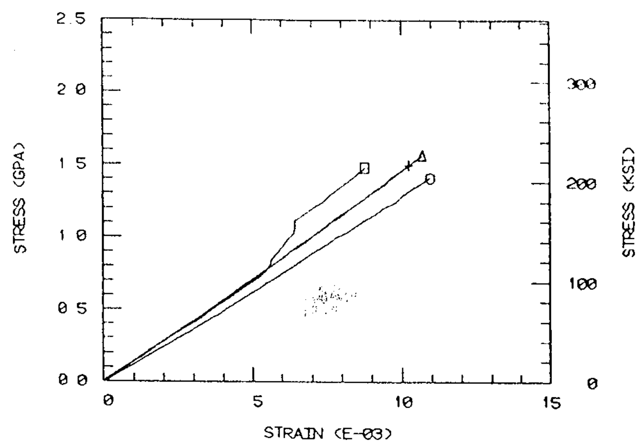
T500/R914, LONG TENS 23 DEG DRY



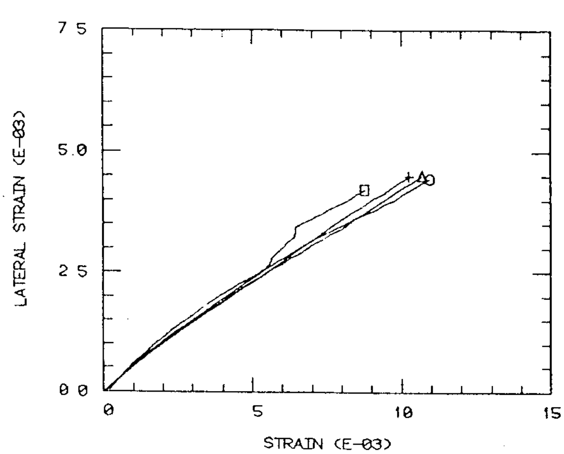
T500/R914, LONG TENS 23 DEG DRY



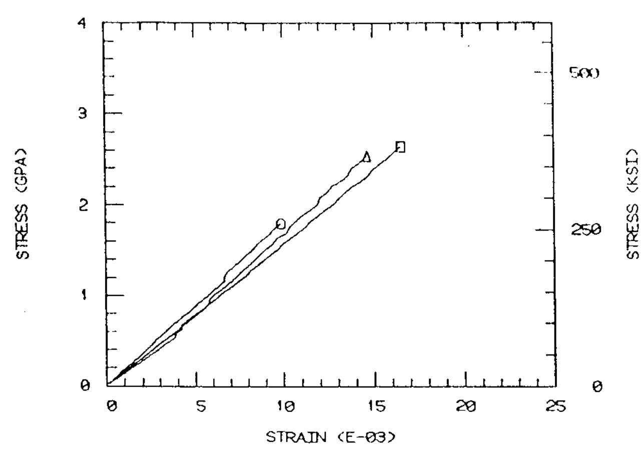
T500/R914, LONG TENSION 100 DEG DRY



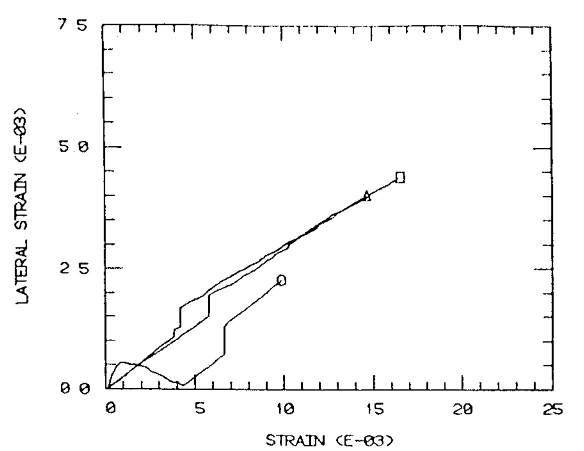
T500/R914, LONG TENSION 100 DEG DRY



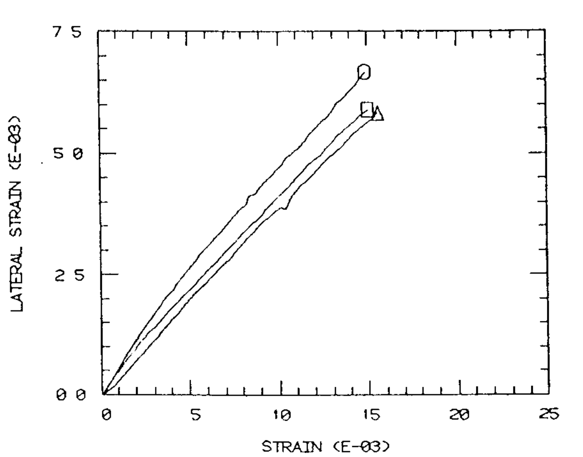
HX1504/IM6, LONG TENSION 23 DEG DRY



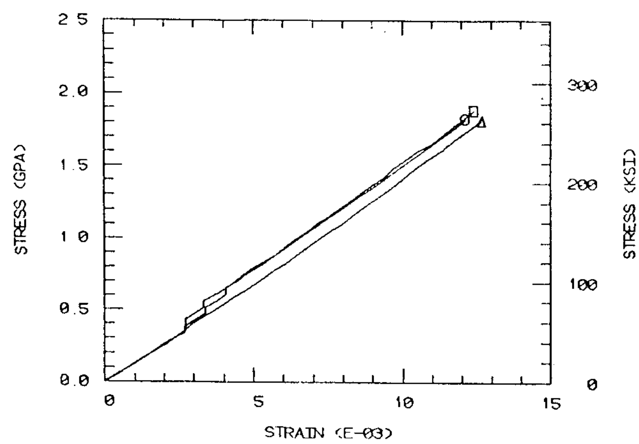
HX1504/IM6, LONG TENSION 23 DEG DRY



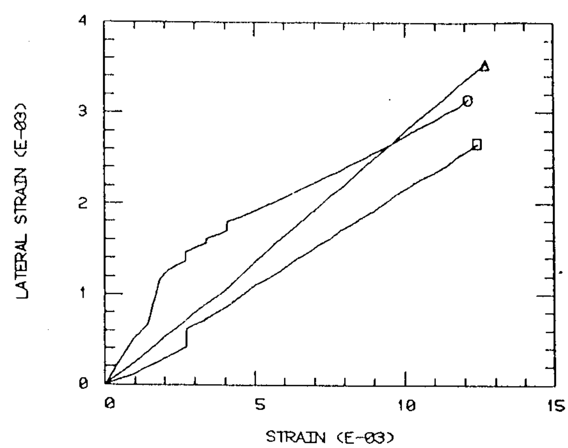
HX1504/IM6, LONG TENSION 100 DEG DRY



T300/4901-A, LONG TENSION 23 DEG DRY



T300/4901-A, LONG TENSION 23 DEG DRY



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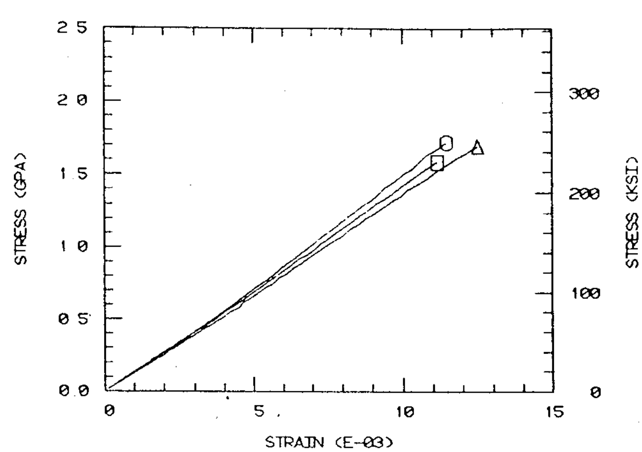

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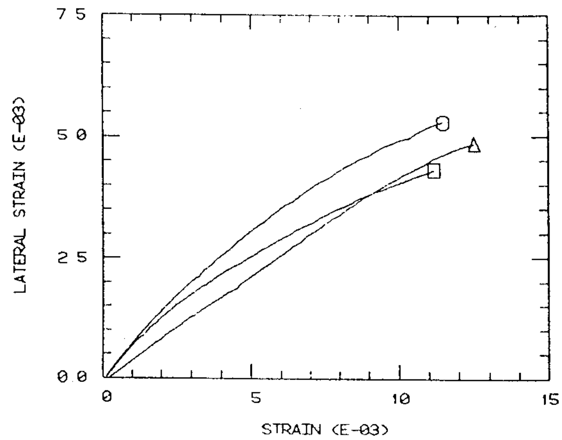
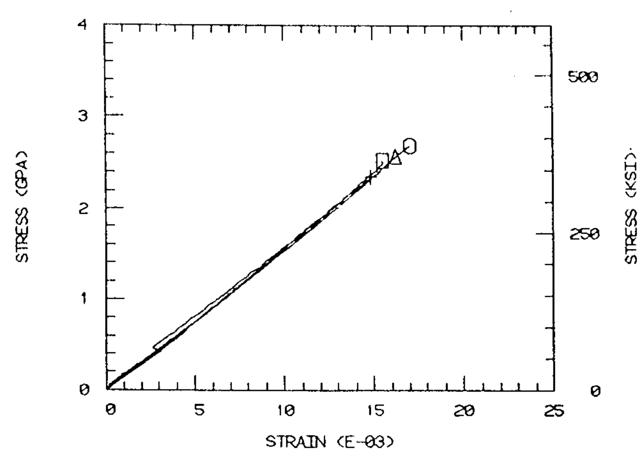
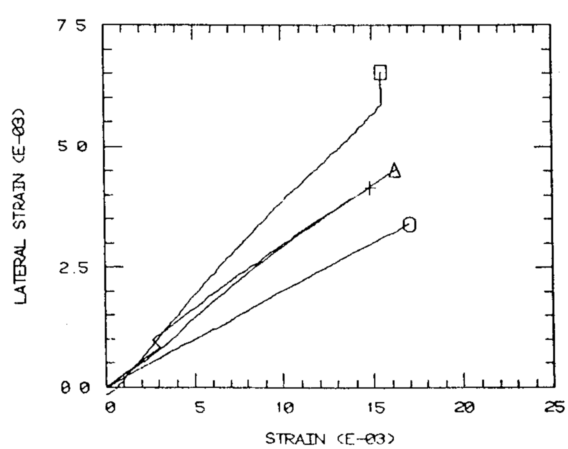


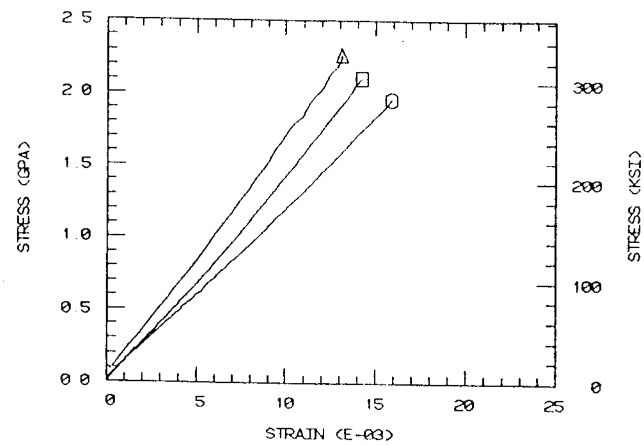
T700/4901A, LONG TENSION 23 DEG DRY



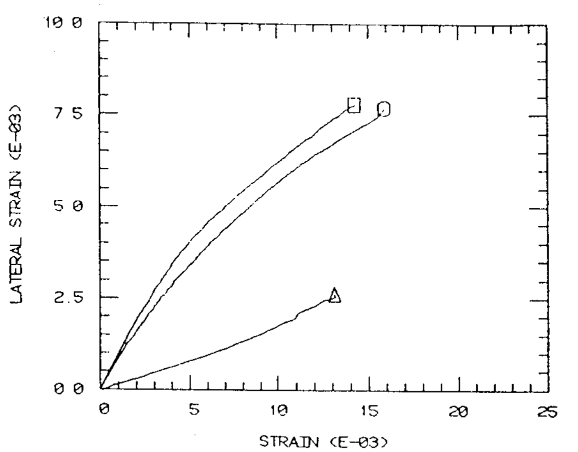
T700/4901A, LONG TENSION 23 DEG DRY



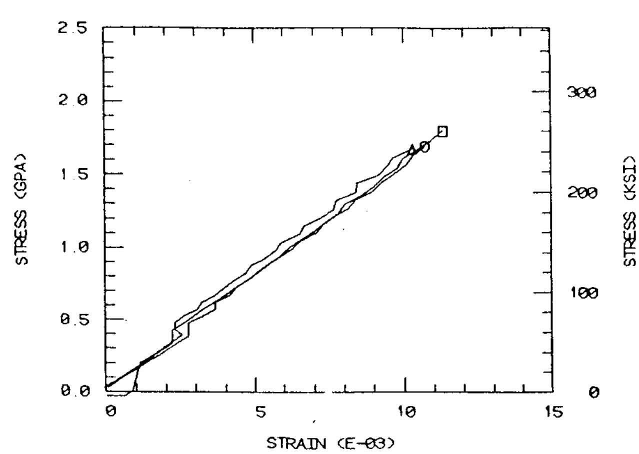
T700/4901A, LONG TENSION 100 DEG DRY



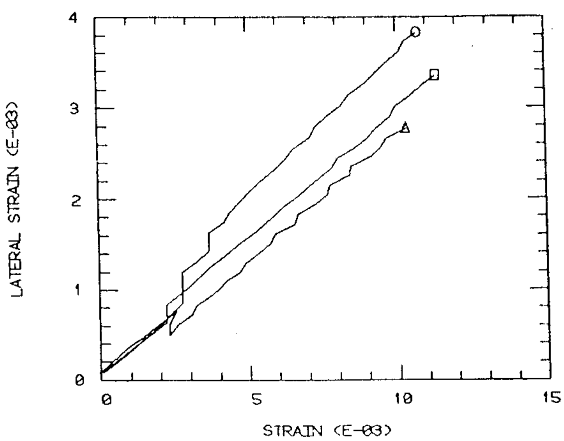
T700/4901A, LONG TENSION 100 DEG DRY



T300/4901B, LONG TENSION 23 DEG DRY



T300/4901B, LONG TENSION 23 DEG DRY



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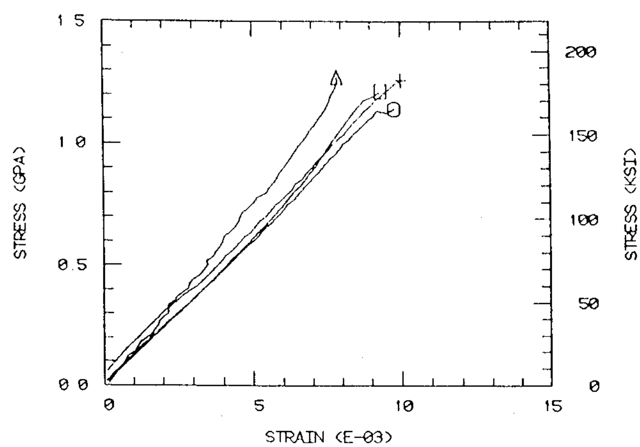
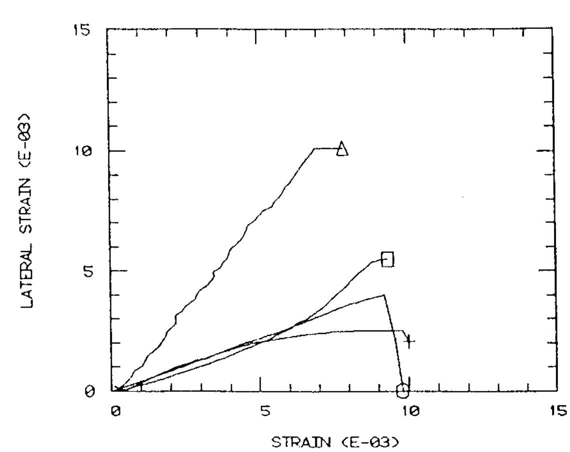


T300/4901B, LONG TENSION 100 DEG DRY



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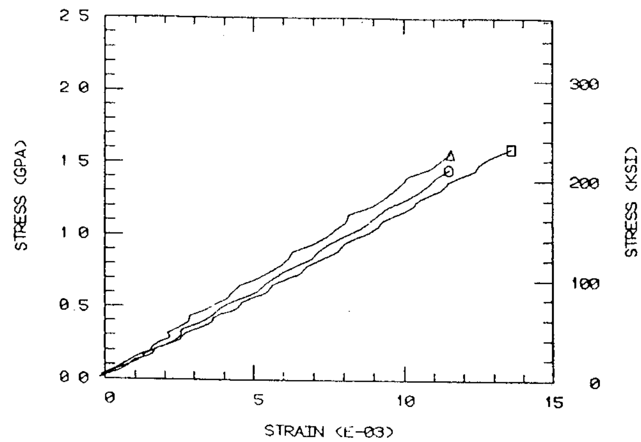

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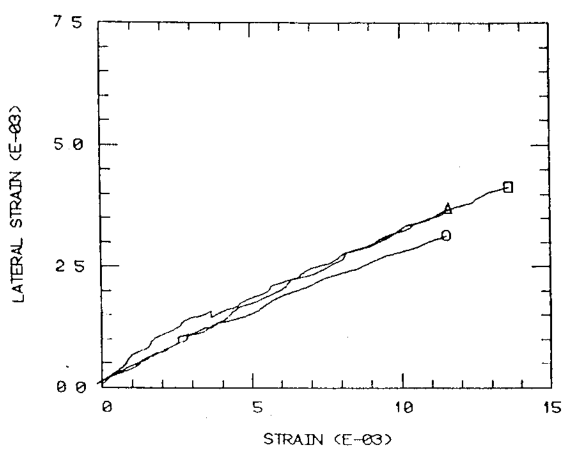
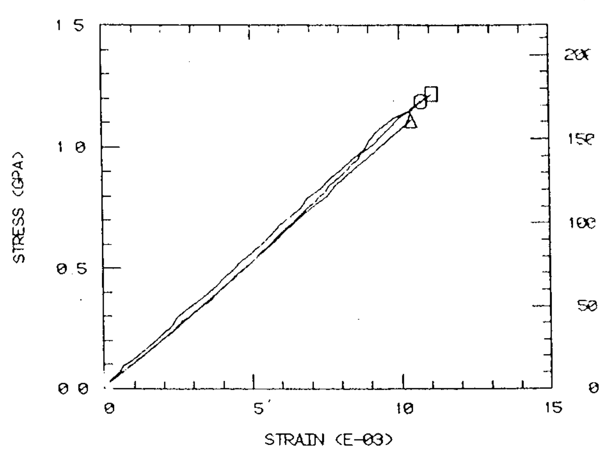
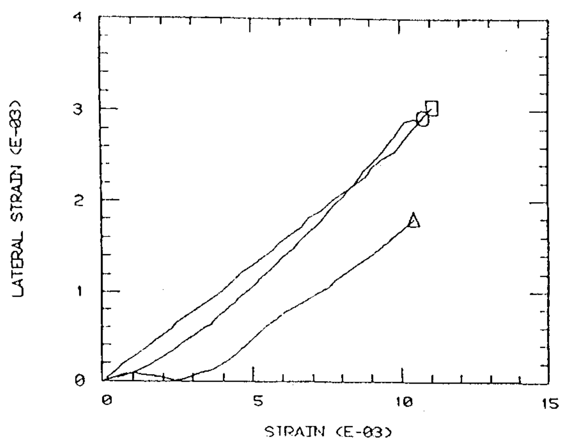


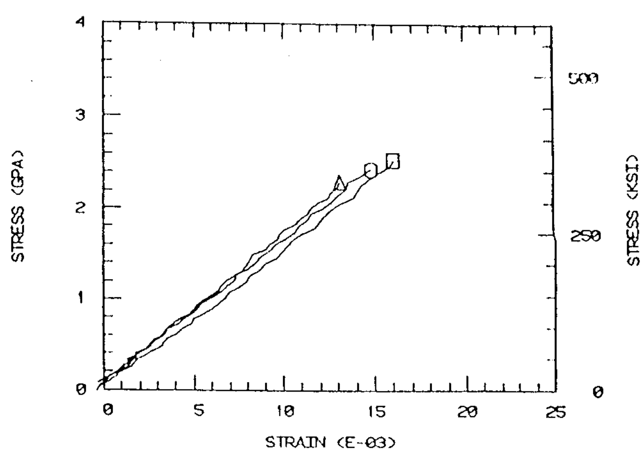
T700/4901B, LONG TENSION 100 DEG DRY



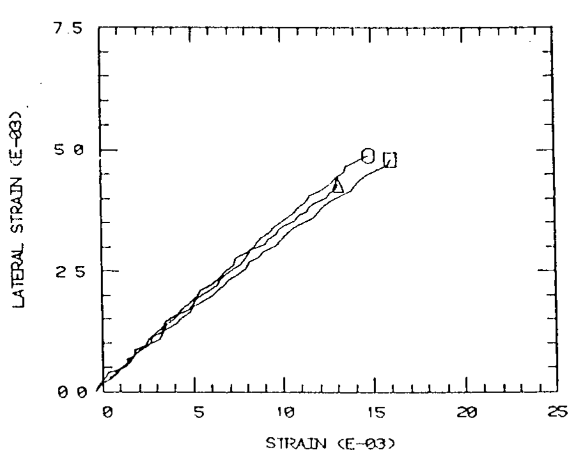
T700/4901B, LONG TENSION 100 DEG DRY



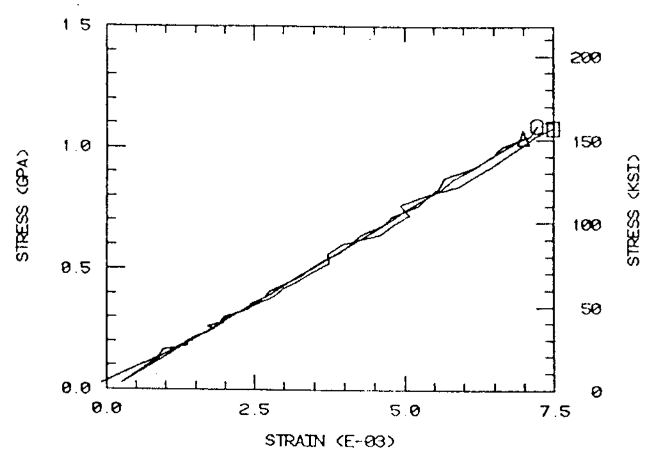
AS4/PEEK LARC, LONG TENSION 23 DEG DRY



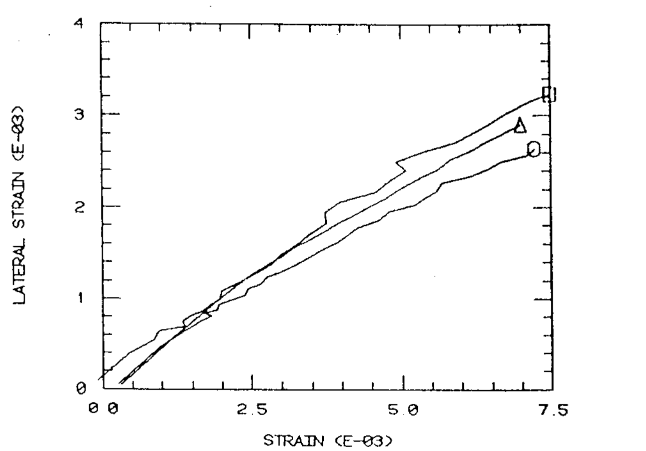
AS4/PEEK LARC, LONG TENSION 23 DEG DRY



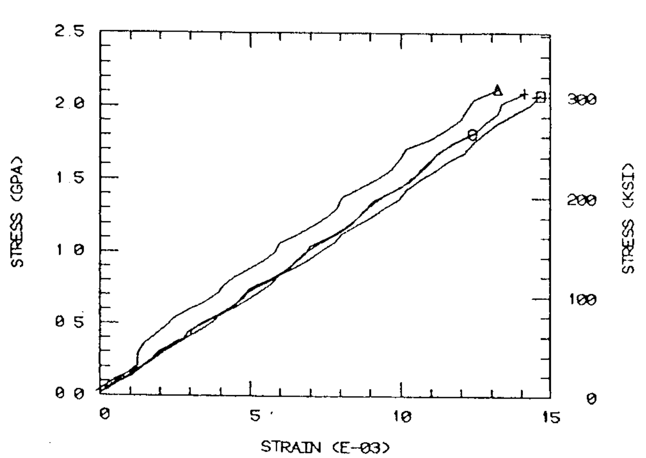
AS4/PEEK LARC, LONG TENSION 100 DEG DRY



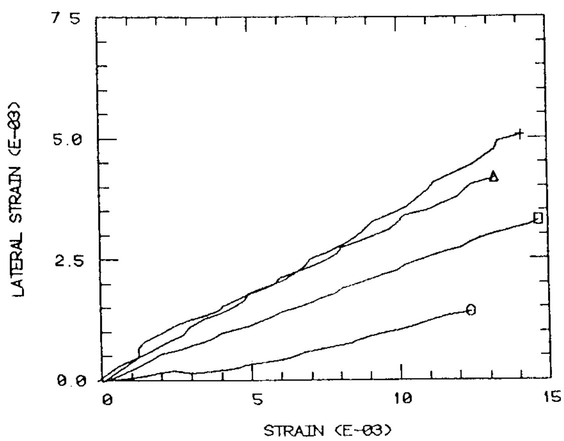
AS4/PEEK LARC, LONG TENSION 100 DEG DRY



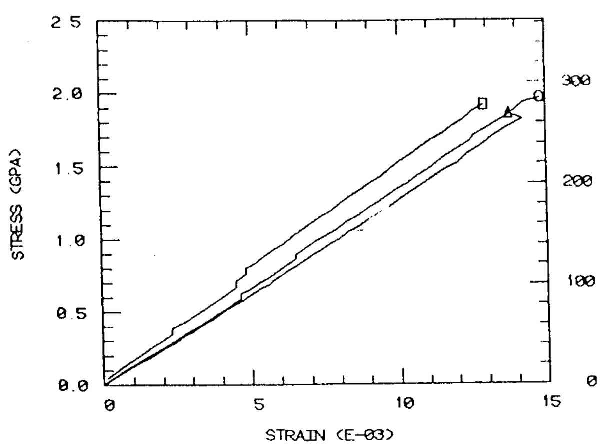
AS4/PEEK ICI, LONG TENSION 23 DEG DRY



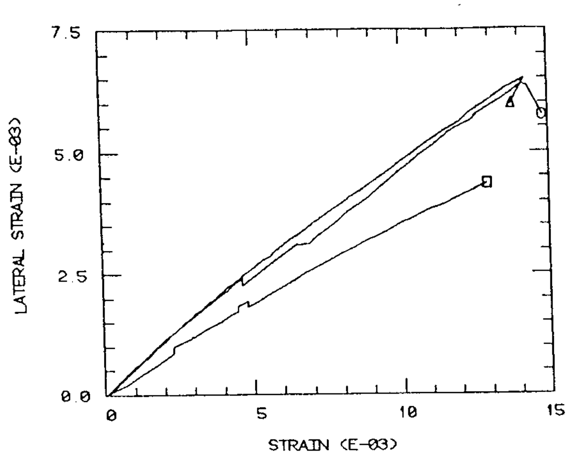
AS4/PEEK ICI, LONG TENSION 23 DEG DRY



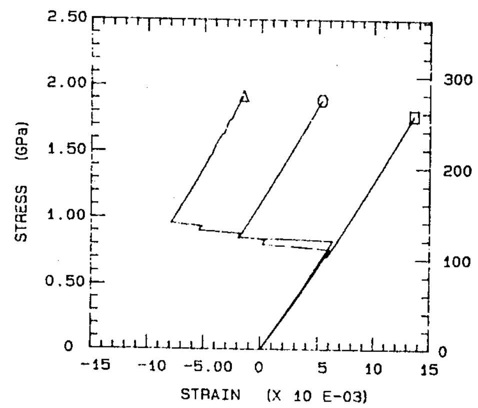
AS4/PEEK ICI, LONG TENSION 100 DEG DRY



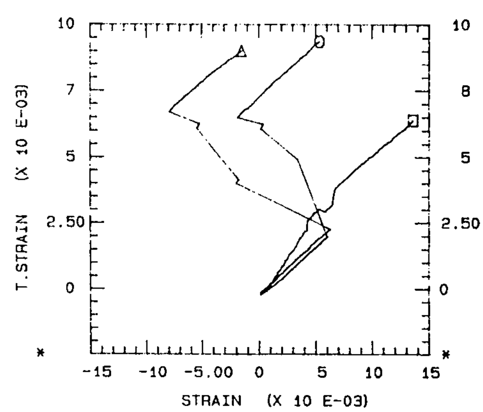
AS4/PEEK ICI, LONG TENSION 100 DEG DRY



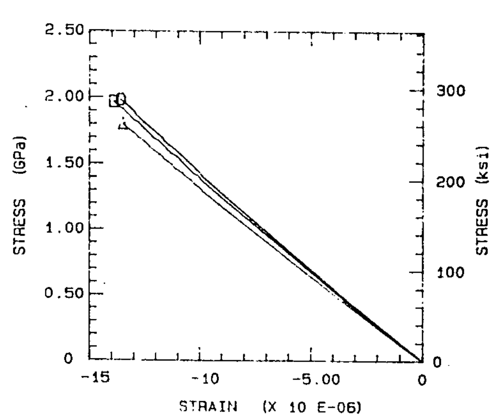
AS4/8551-7 LONG TENSION 23DEG C DRY



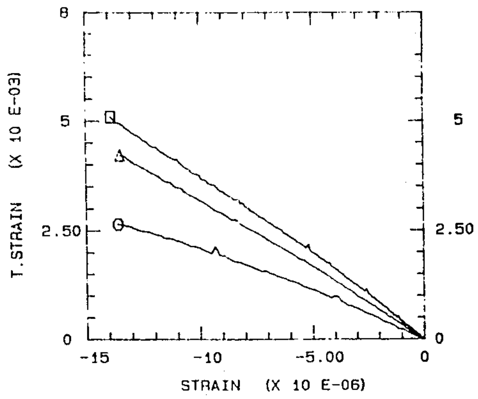
AS4/8551-7 LONG TENSION 23DEG C DRY



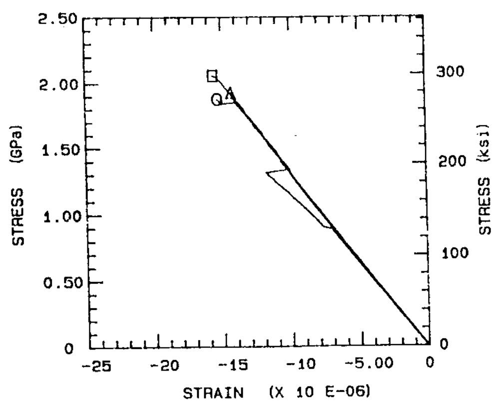
AS4/8551-7 LONG TENSION 100DEGC DRY



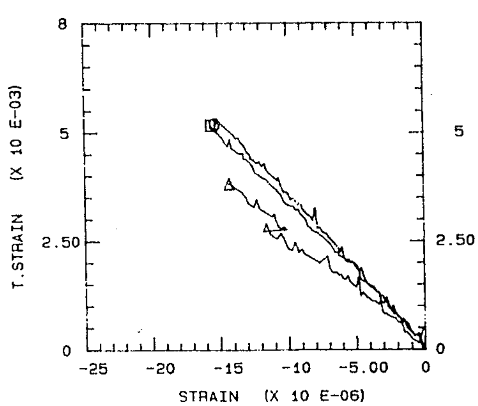
AS4/8551-7 LONG TENSION 100DEGC DRY



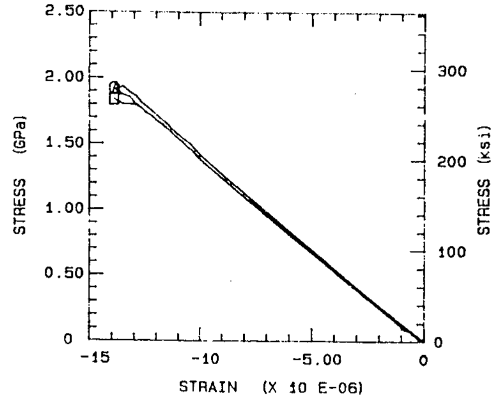
AS4/8551-7 LONG TENSION 23DEG C WET



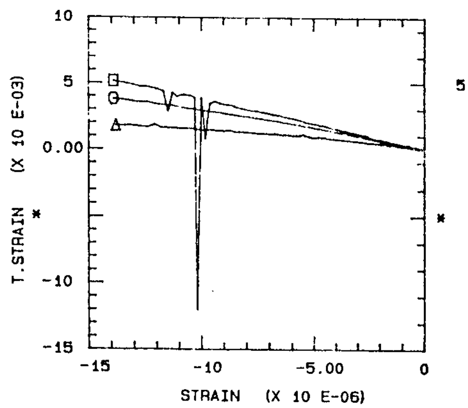
AS4/8551-7 LONG TENSION 23DEG C WET



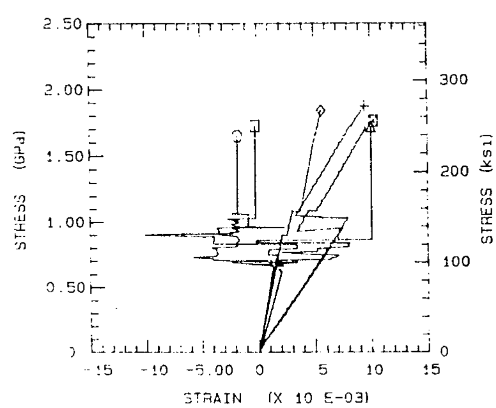
AS4/8551-7 LONG TENSION 100DEGC WET



AS4/8551-7 LONG TENSION 100DEGC WET



AS4/PISO2-TPI TENSION 23 DEG C DRY



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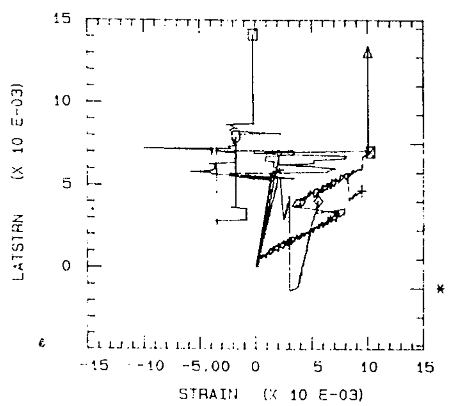
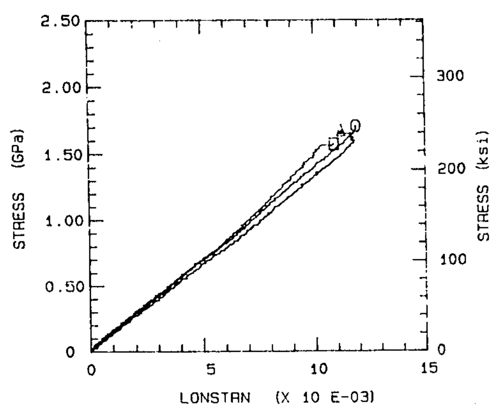
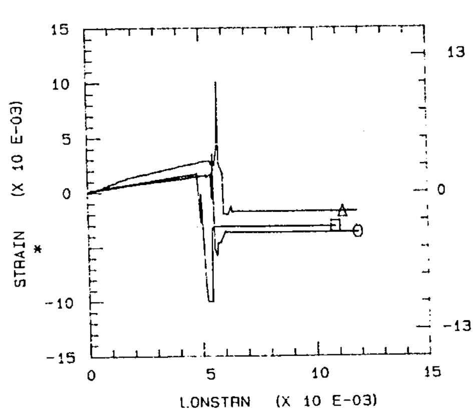
AS4/PIS02-TPI TENSION 23 DEG C DRY



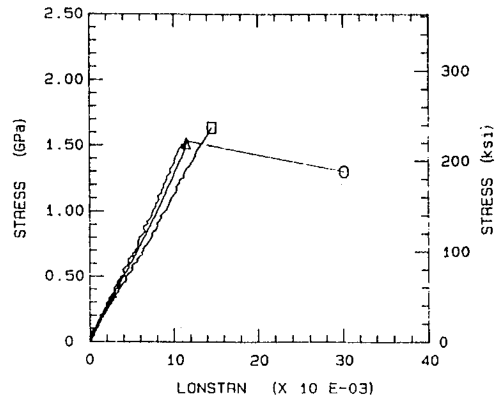
AS4/PIS02-TPI TENSION 100 DEG C DRY



AS4/PIS02-TPI TENSION 100 DEG C DRY



AS4/PISO2-TPI TENSION 100 DEG C WET



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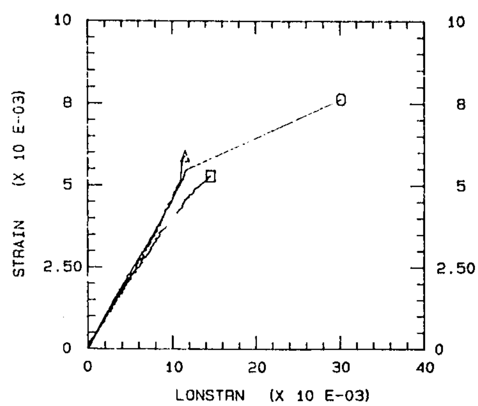
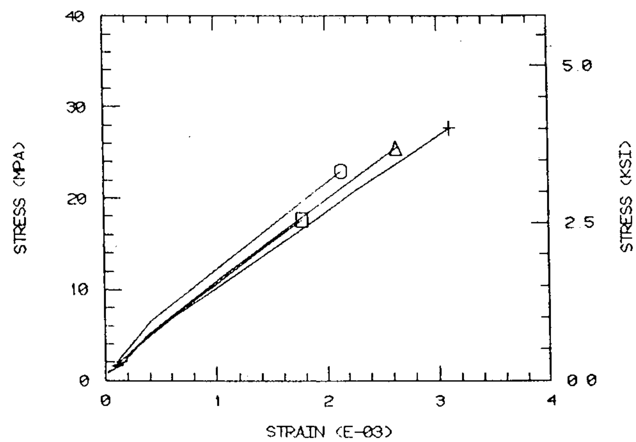


2220-1/AS-4, TRANS TENSION 23 DEG DRY



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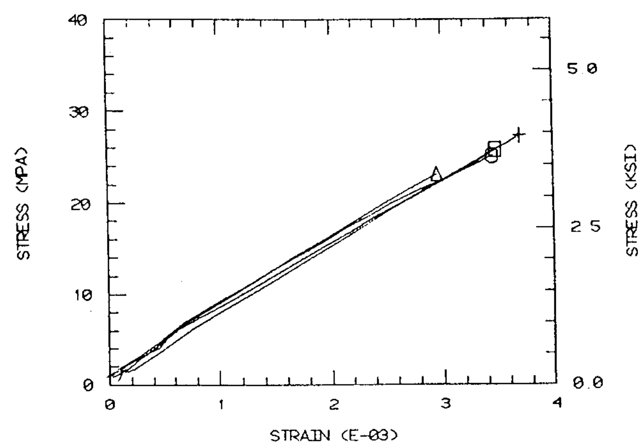

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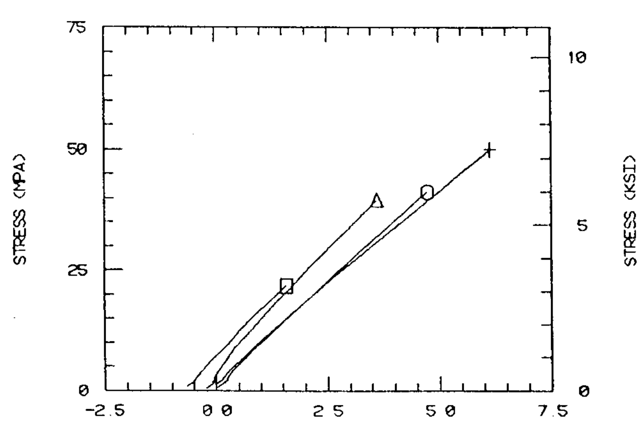

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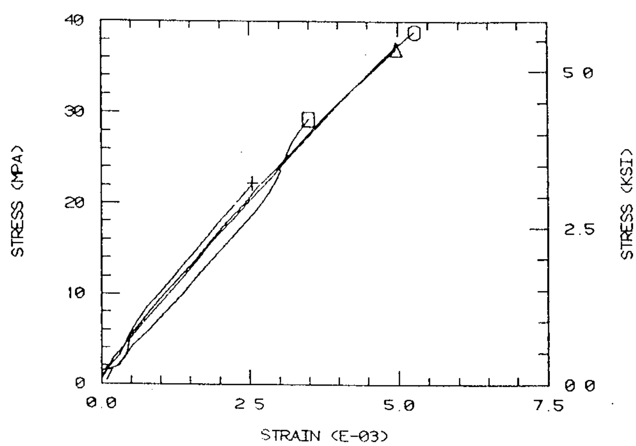

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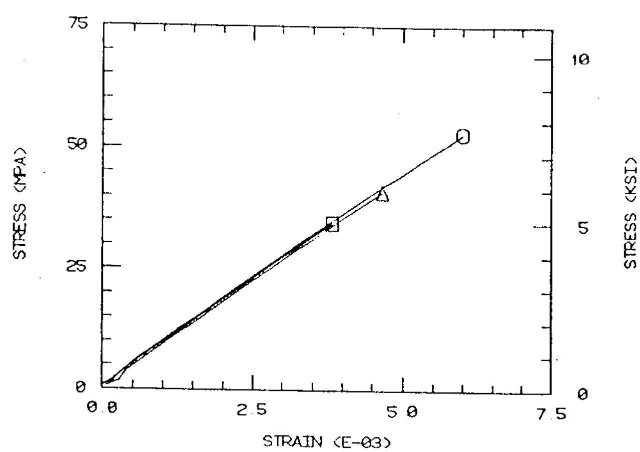

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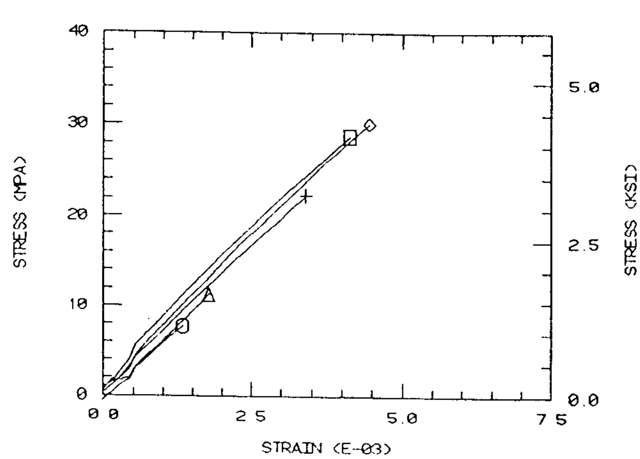
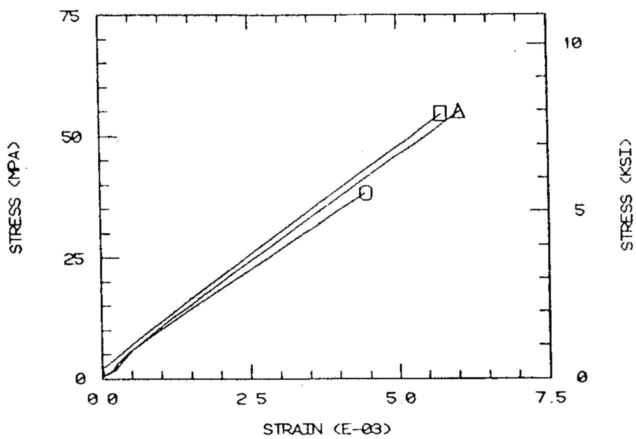


HX1504/IM6, TRANS TENSION 23 DEG DRY



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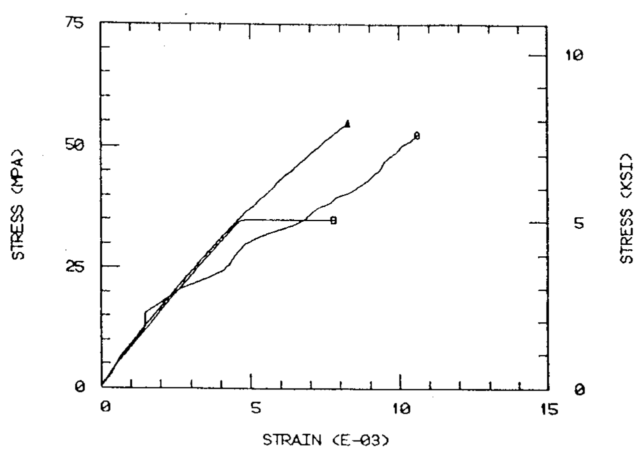
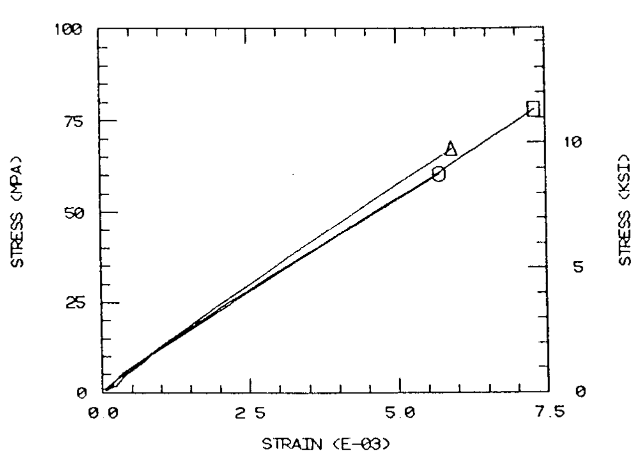
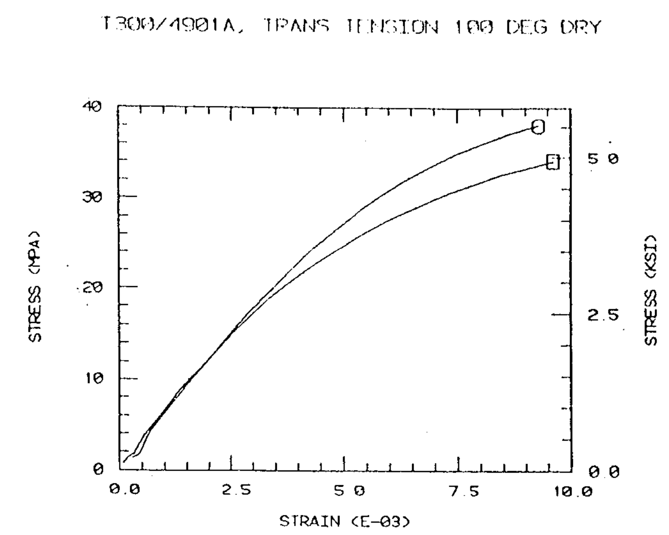
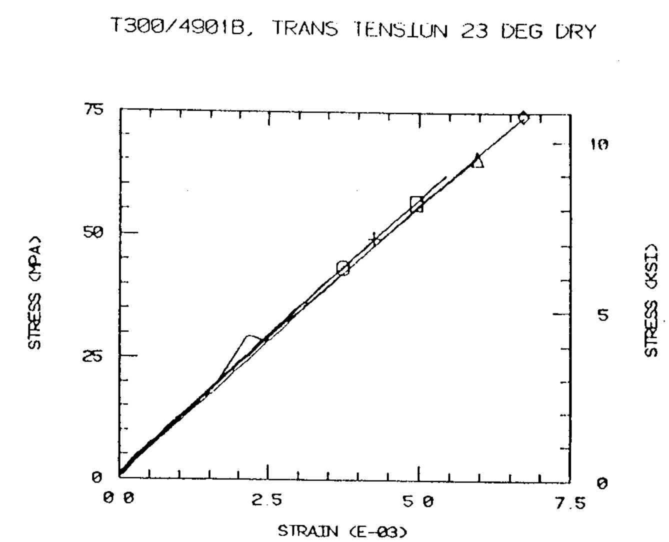
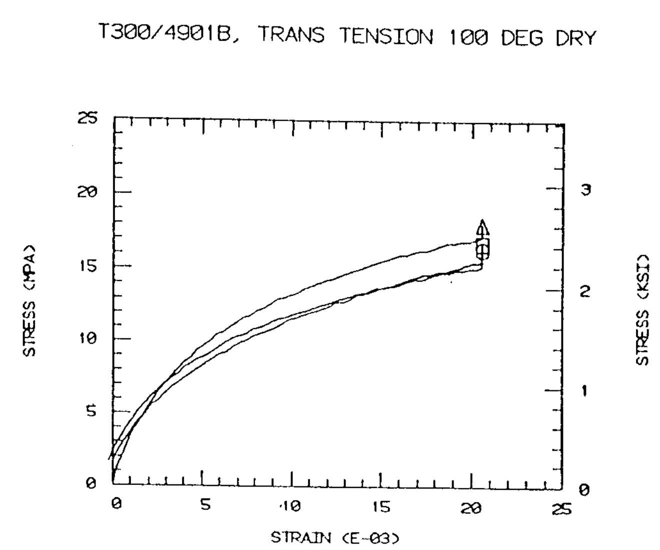


T300/4901A, TRANS TENSION 23 DEG DRY

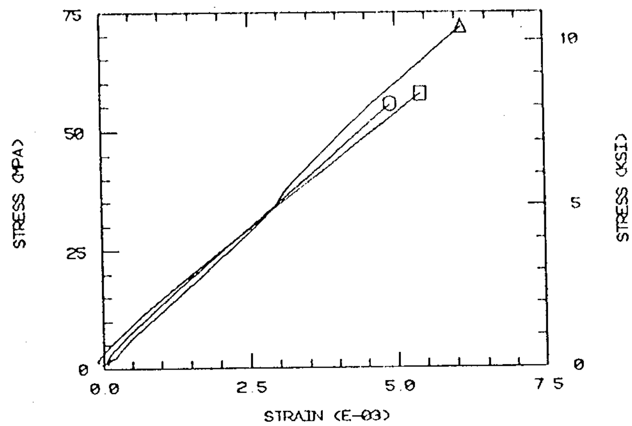



T300/4901A, TRANS TENSION 100 DEG DRY
STRESS (MPA)
STRESS (KSI)
STRAIN (E-03)
0
10
20
30
40
0.0
2.5
5.0
7.5
10.0
0.0
2.5
5.0


T300/4901B, TRANS TENSION 23 DEG DRY
STRESS (MPA)
STRESS (KSI)
STRAIN (E-03)
0
25
50
75
0.0
2.5
5.0
7.5
0
5
10


T300/4901B, TRANS TENSION 100 DEG DRY
STRESS (MPA)
STRESS (KSI)
STRAIN (E-03)
0
5
10
15
20
25
0
5
10
15
20
25
0
1
2
3

T700/4901A, TRANS TENSION 23 DEG DRY



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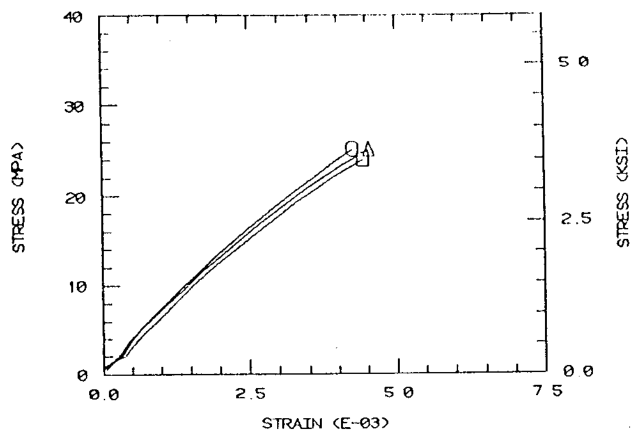

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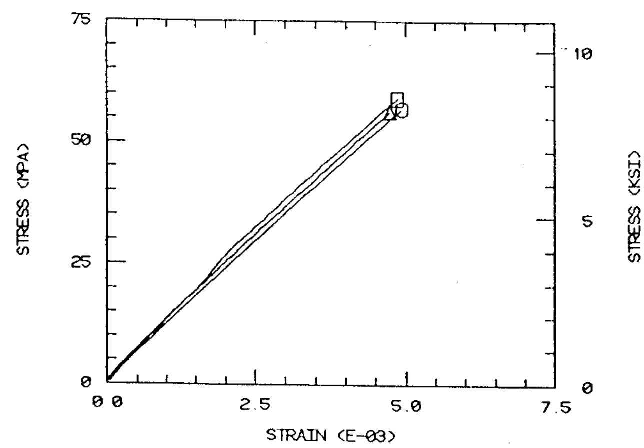

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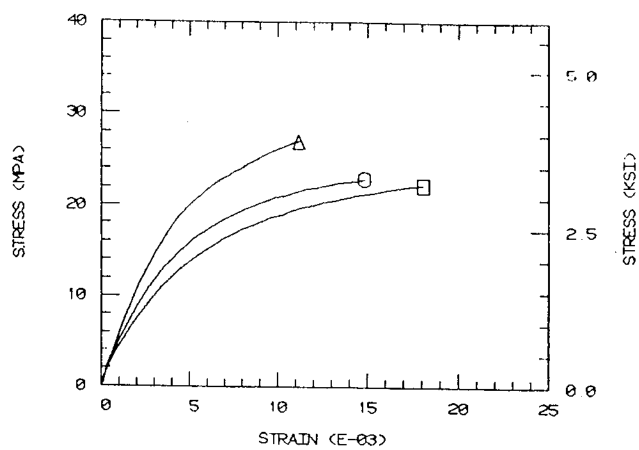
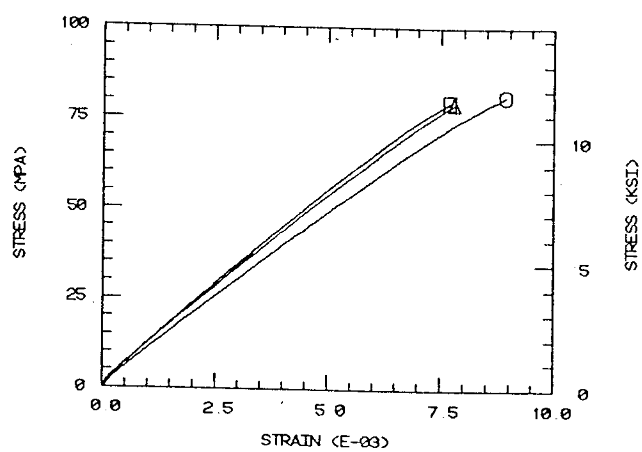


AS4/PEEK LARC, TRANS TENSION 23 DEG DRY



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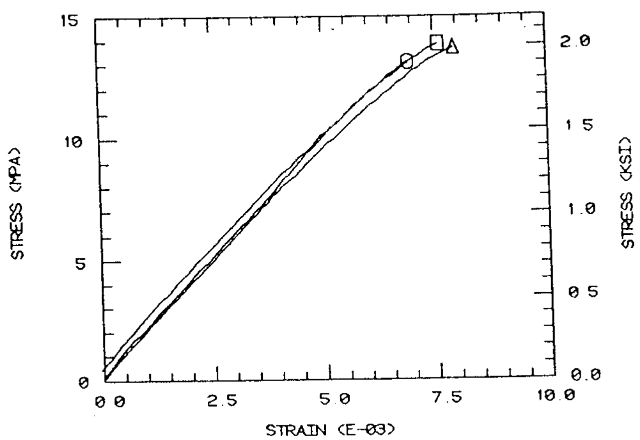

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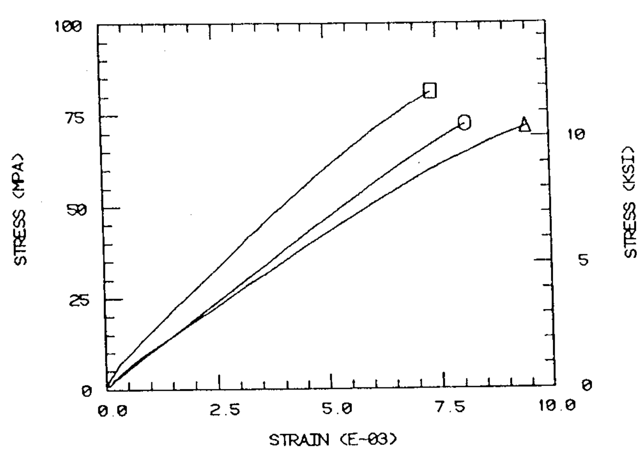

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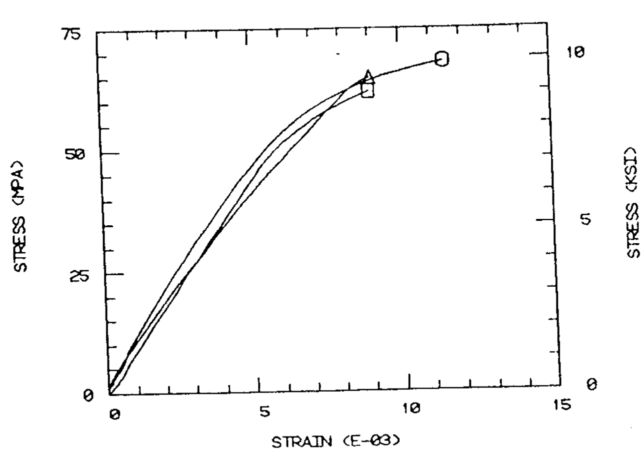
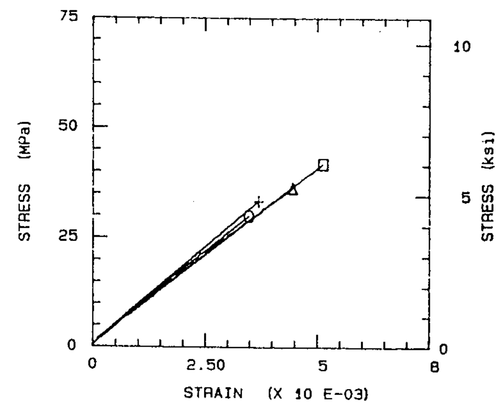


AS4/PISO2-TPI T TENSION 23 DEG DRY



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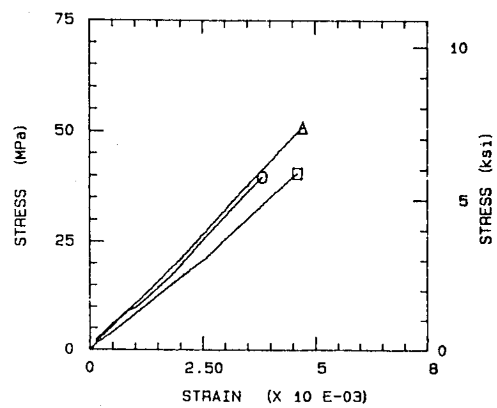
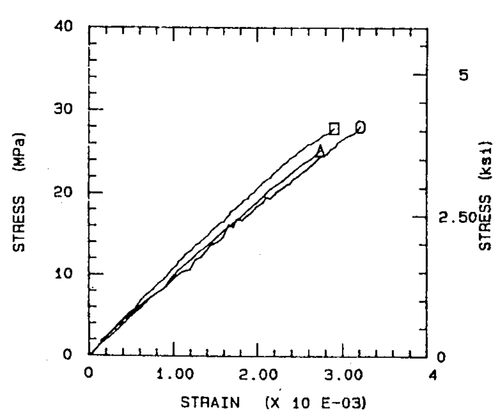
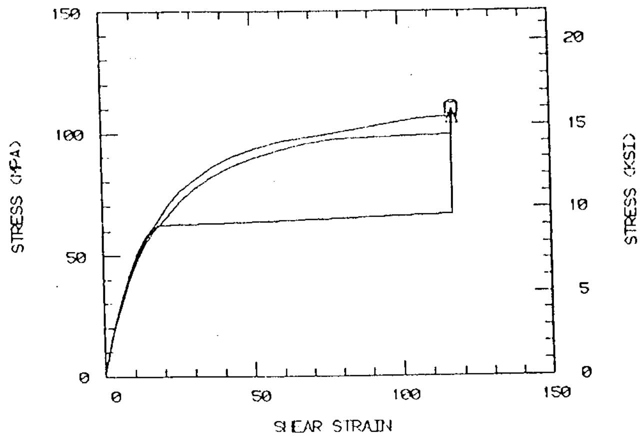


AS4/PISO2-TPI T TENSION 100DEGC WET



2220-1/AS-4, IOSIPESCU SHEAR 23 DEG DRY



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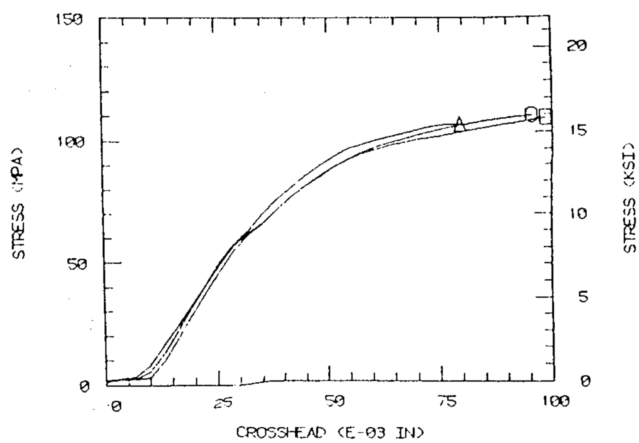

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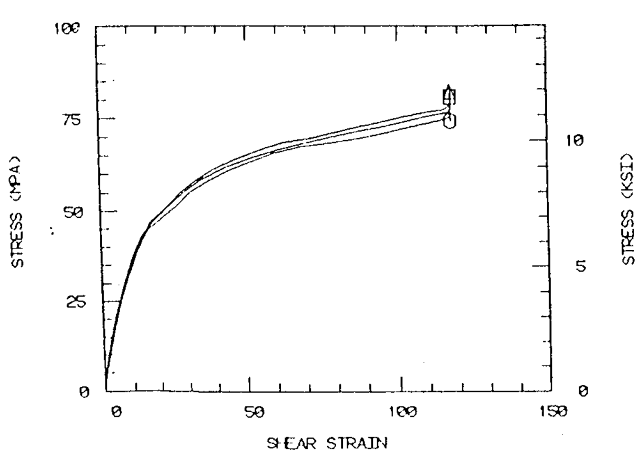

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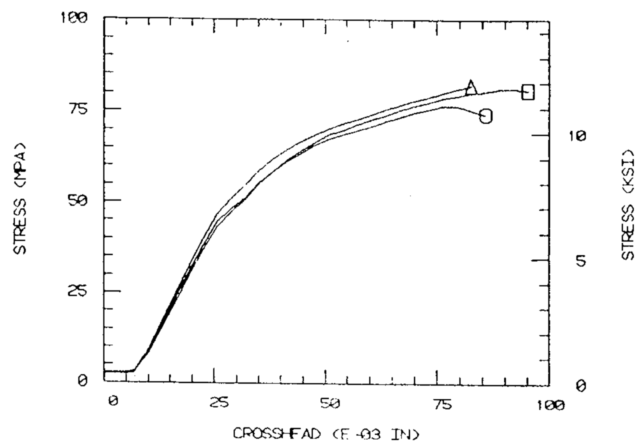

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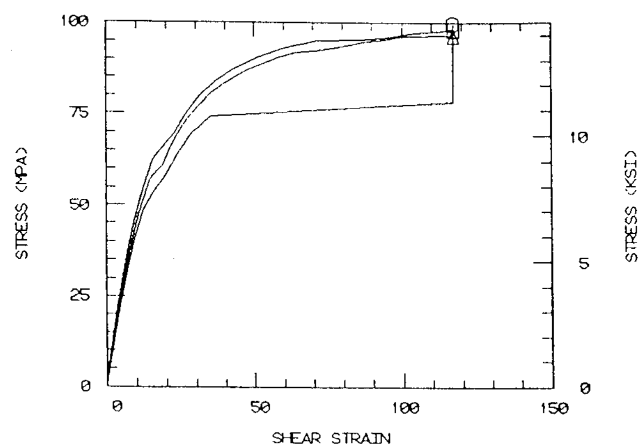

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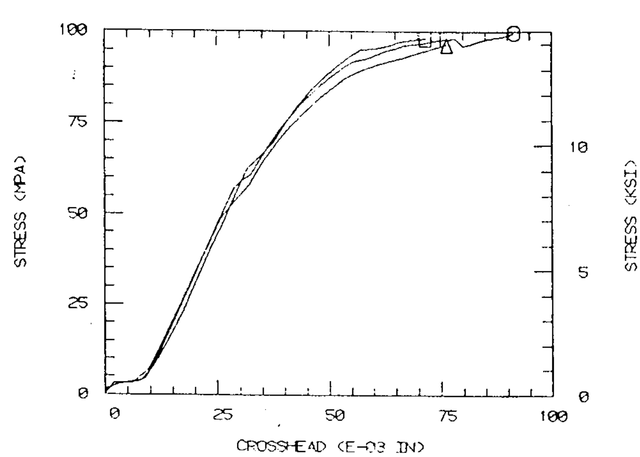

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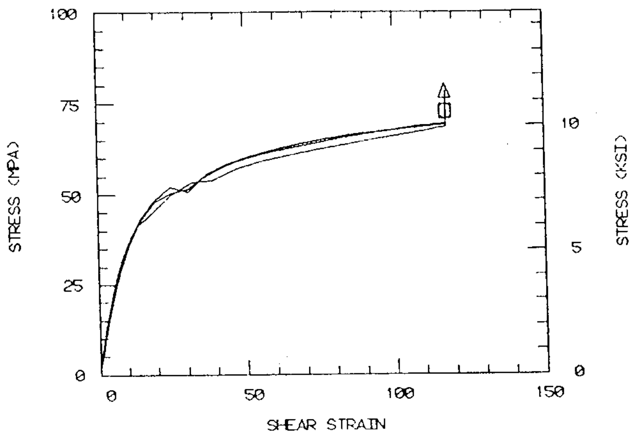

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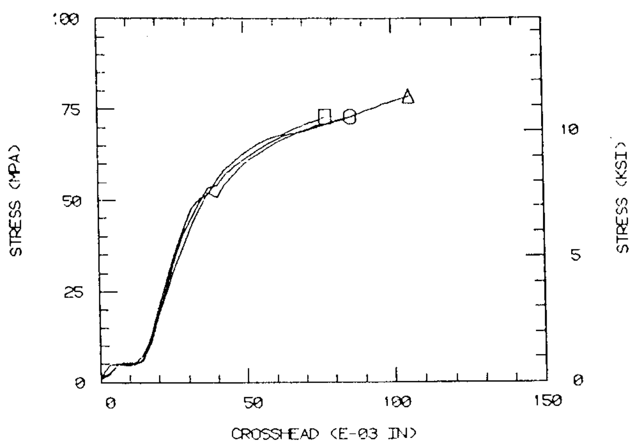
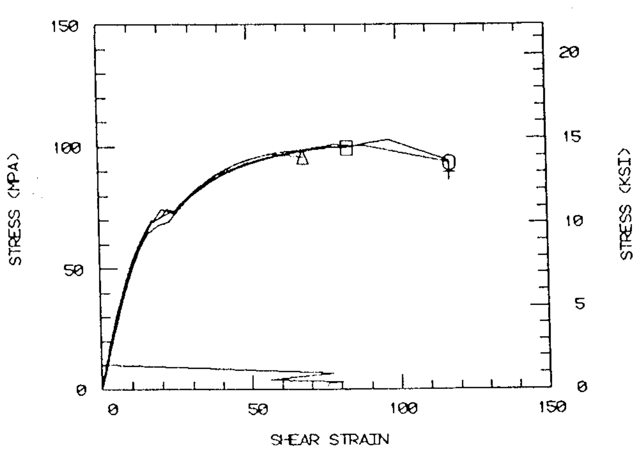


T500/R914, IOSIPESCU 23 DEG DRY



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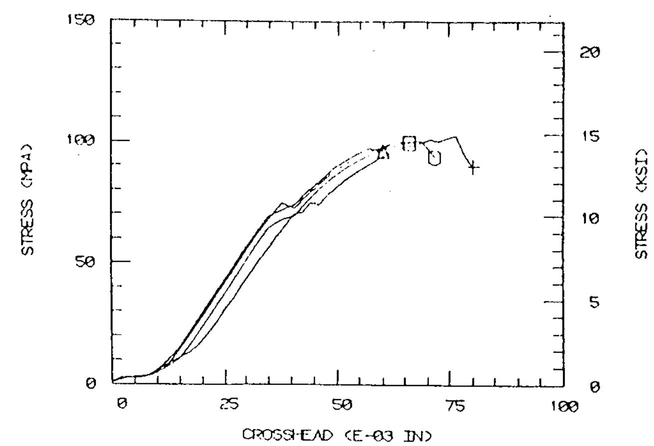

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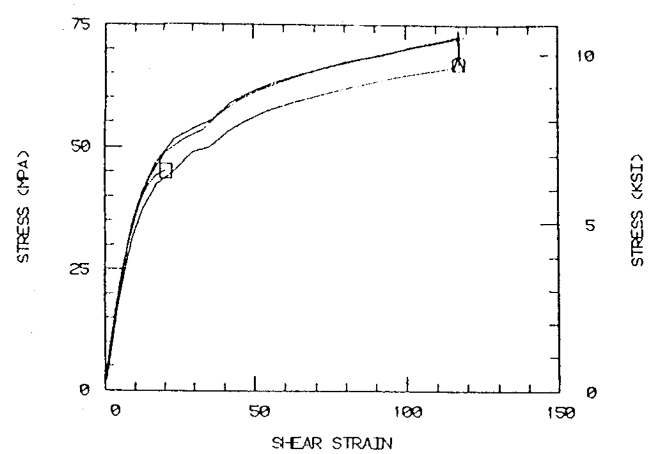

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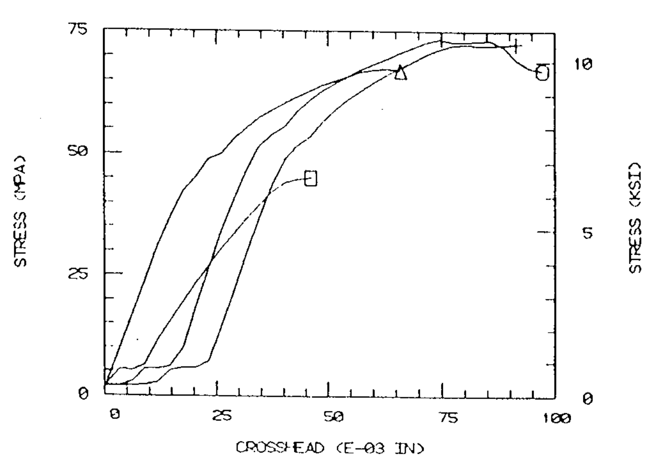

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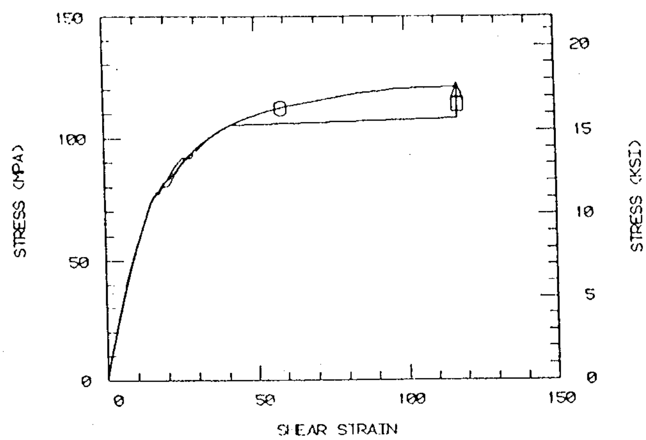

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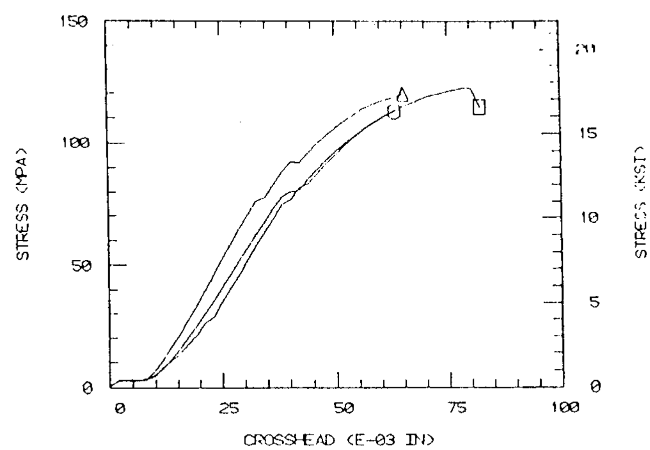

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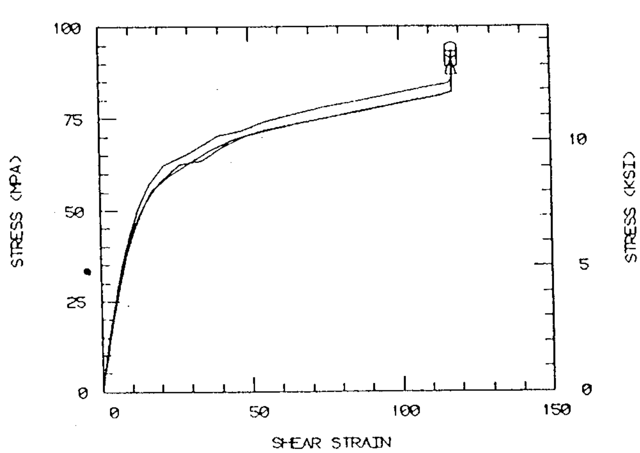

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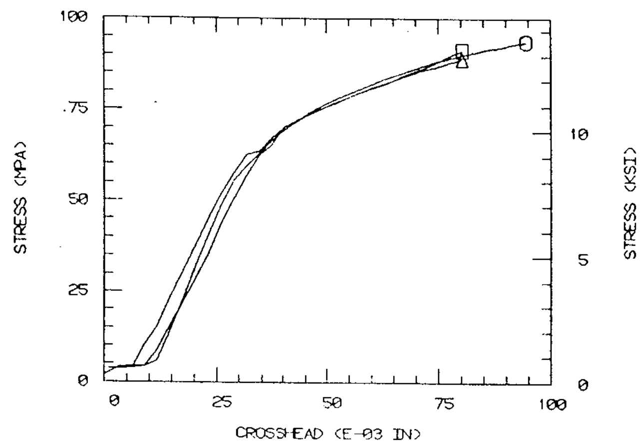

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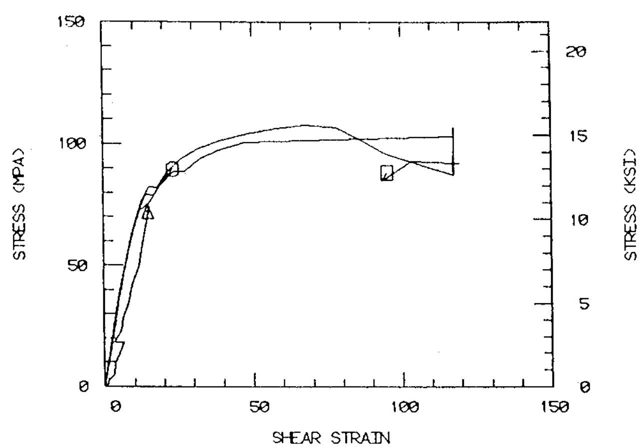

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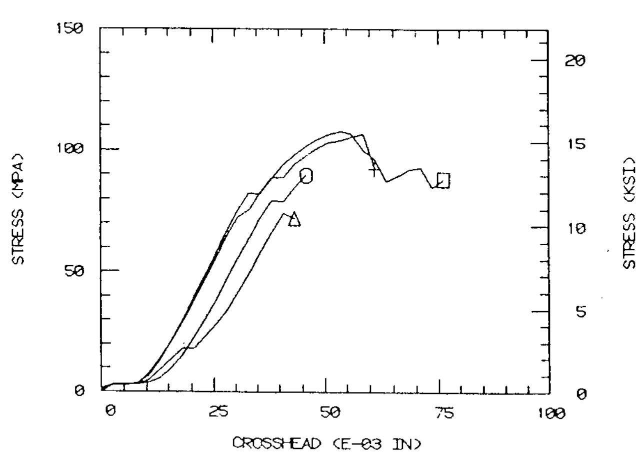

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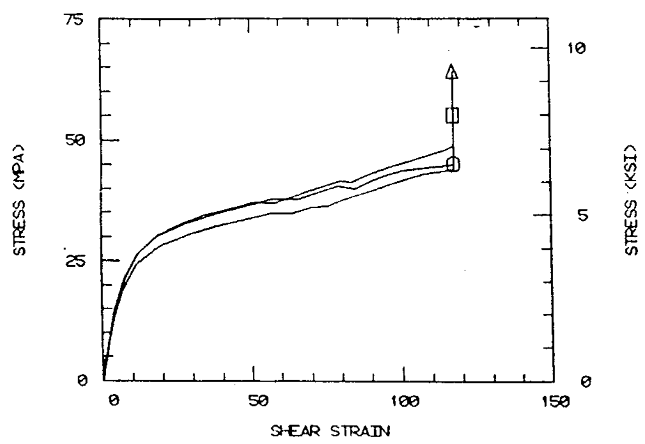

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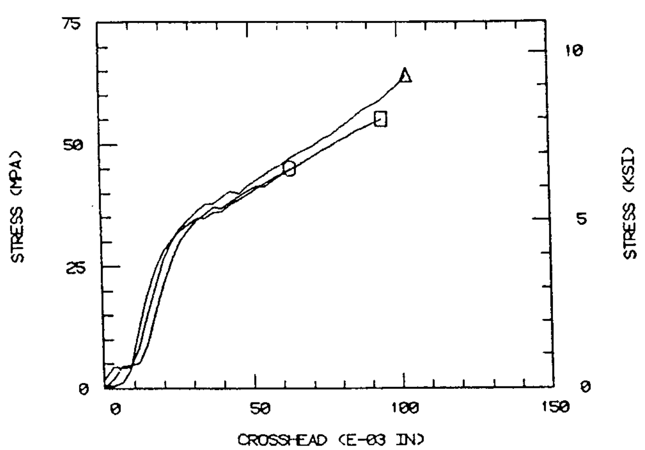

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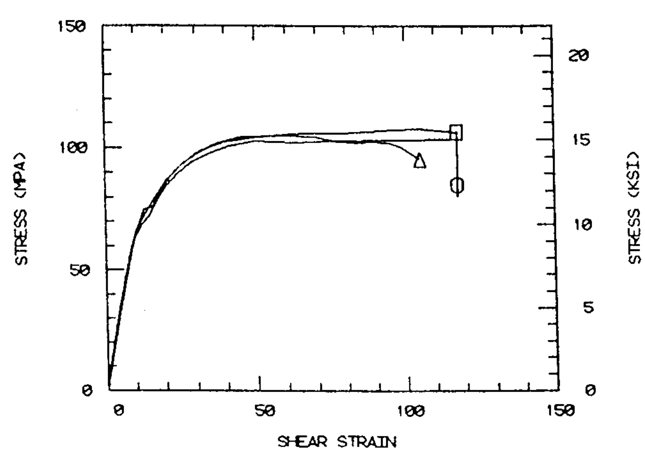

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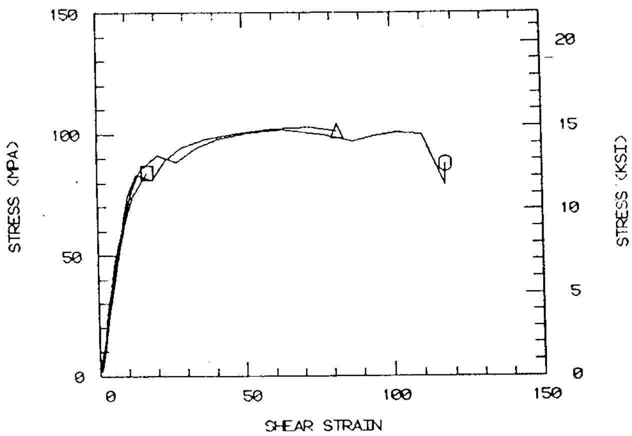

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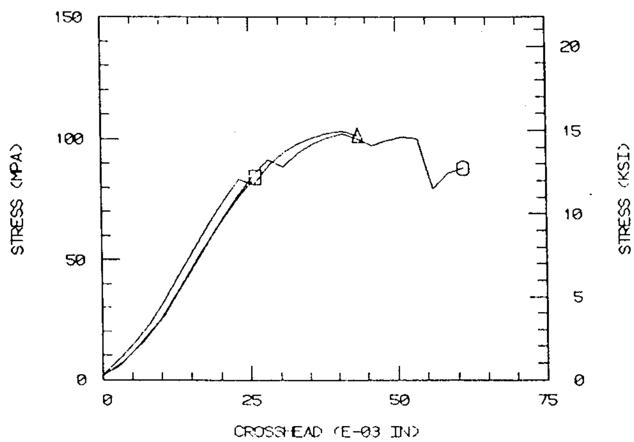

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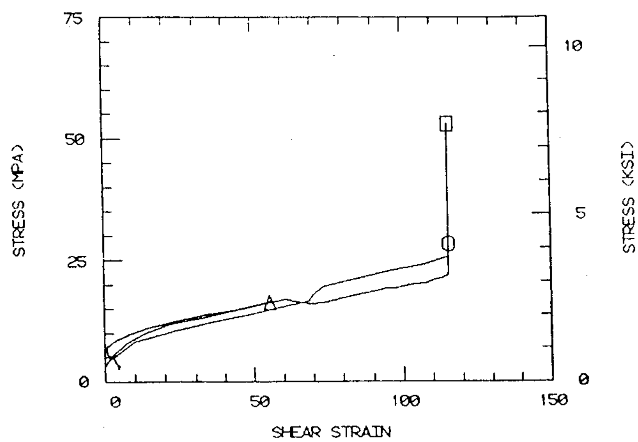

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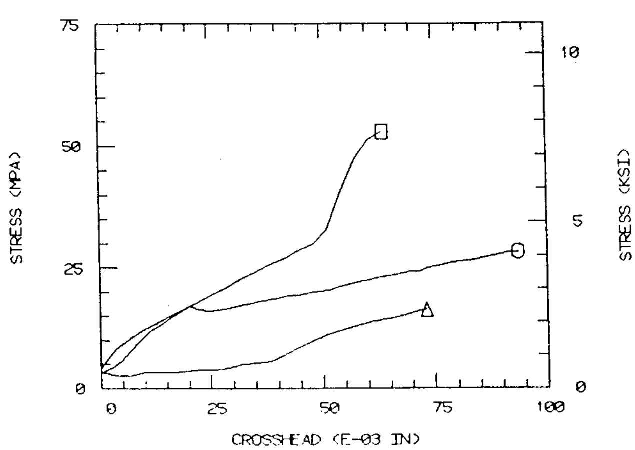

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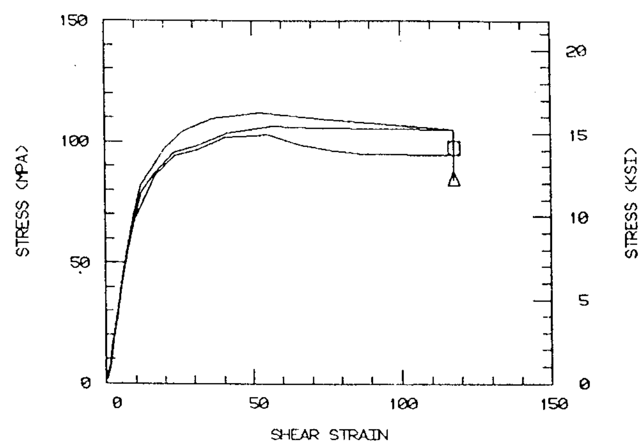

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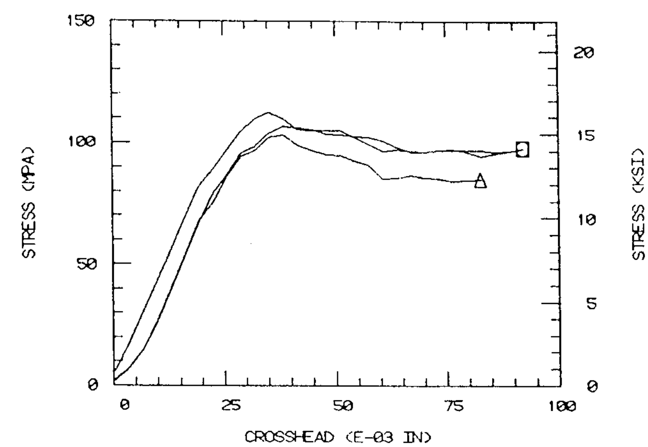

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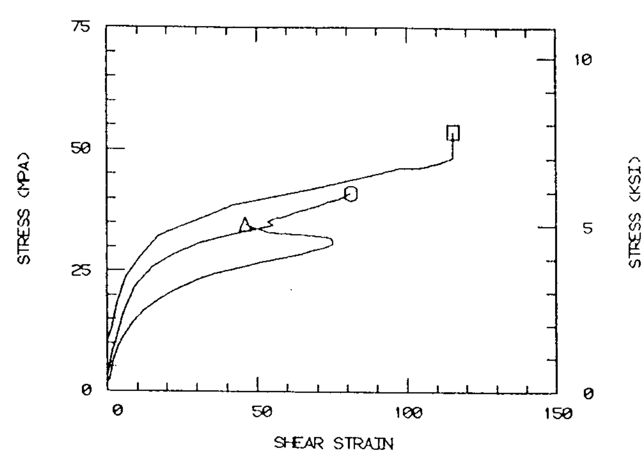

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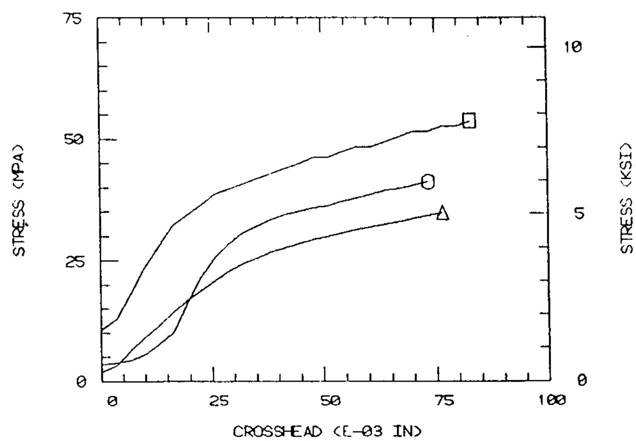
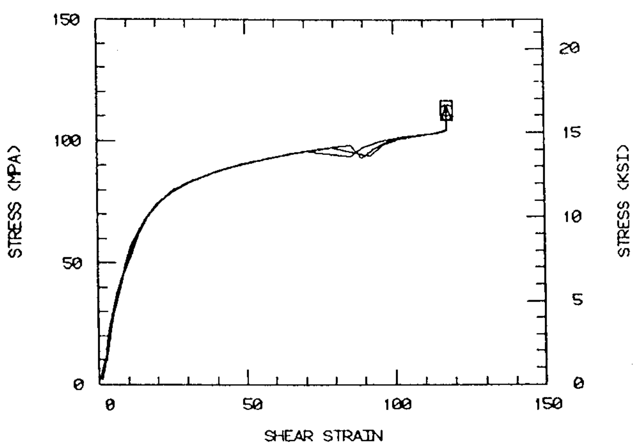


AS4/PEEK LARC, IOSIPESCU 23 DEG DRY



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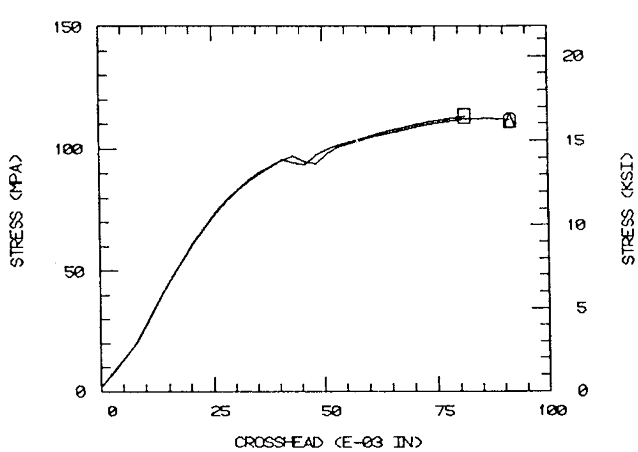
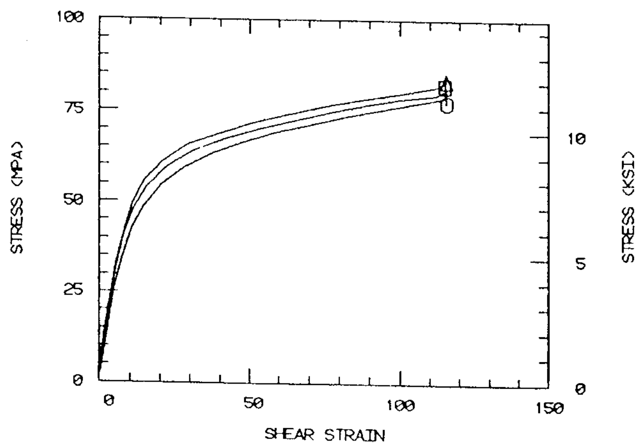
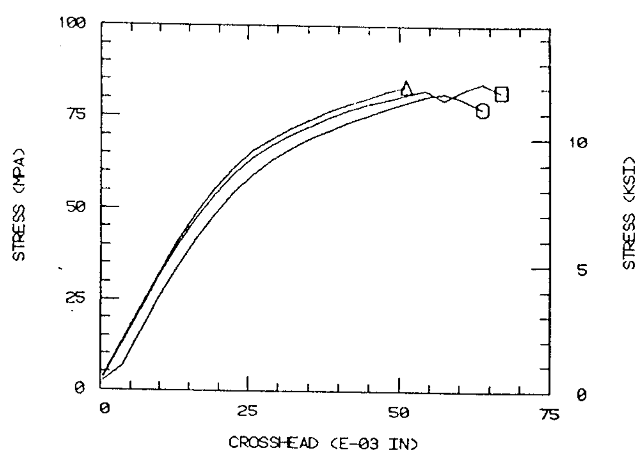


AS4/PEEK LARC, IOSIPESCU 100 DEG DRY



AS4/PEEK LARC, IOSIPESCU 100 DEG DRY



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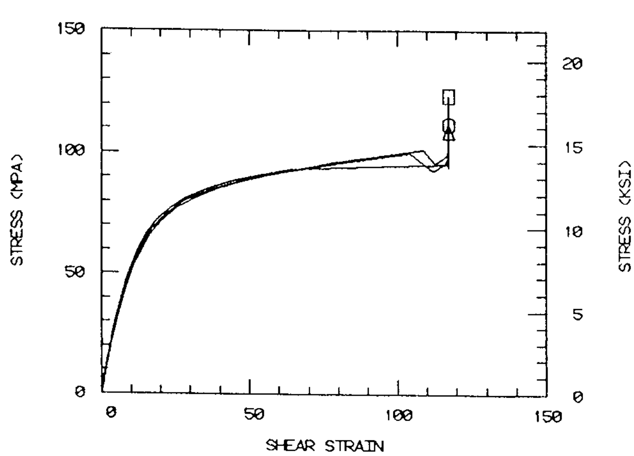

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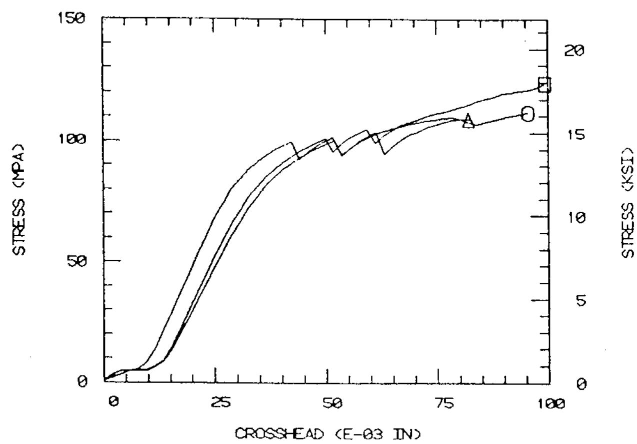
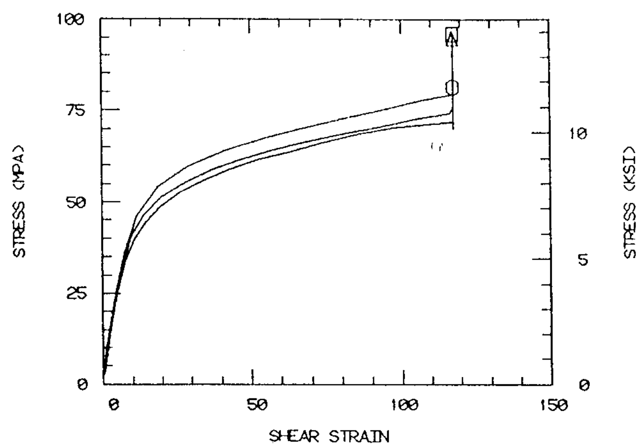


AS4/PEEK ICI, IOSIPESCU SHEAR 100 DEG D



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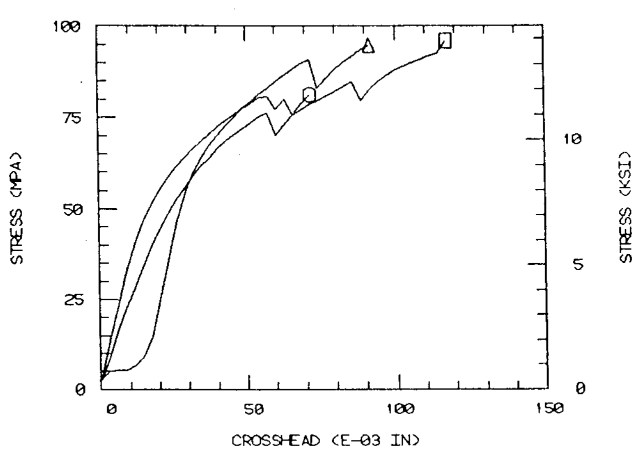
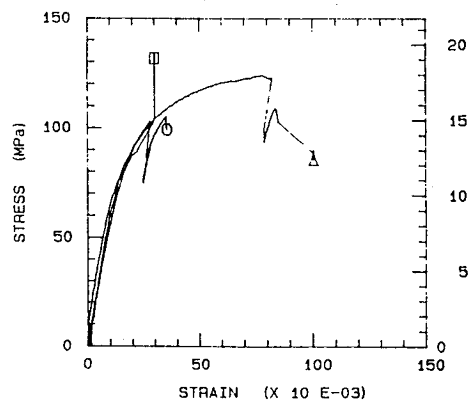
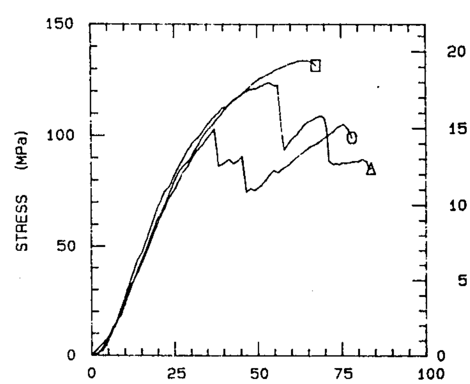


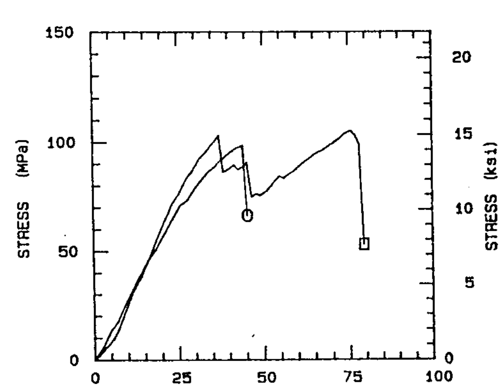
AS4/PISO2-TPI IOS SHEAR 23 DEG DRY



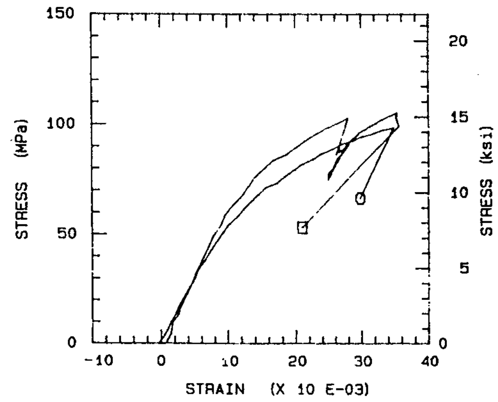
AS4/PISO2-TPI IOS SHEAR 23 DEG DRY



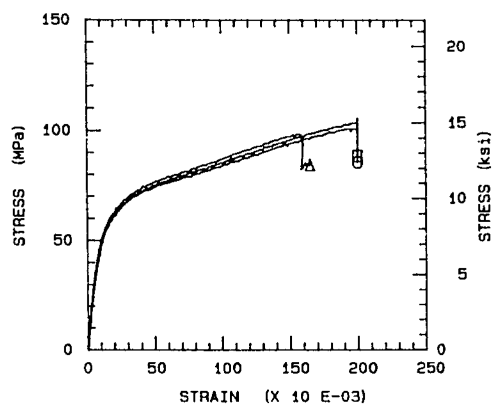
AS4/PISO2-TPI UNLIDR1-2 23 DEG DRY



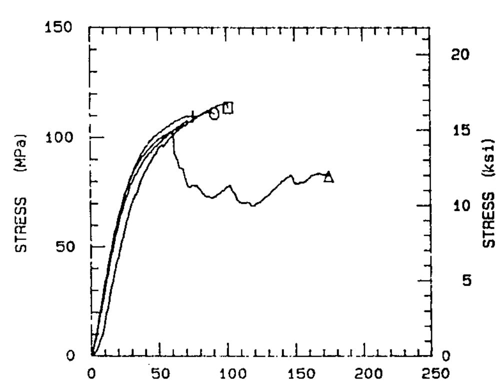
AS4/PISO2-TPI UNLIDR1-2 23 DEG DRY



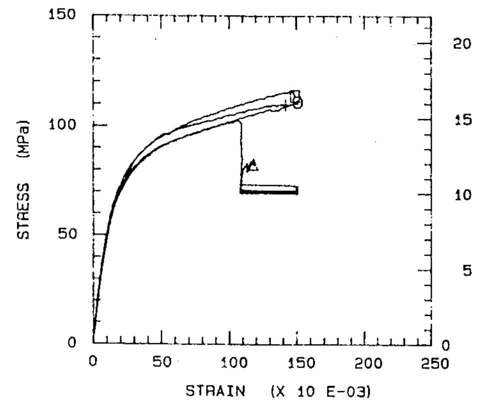
AS4/PISO2-TPI IOS SHEAR 100 DEG WET



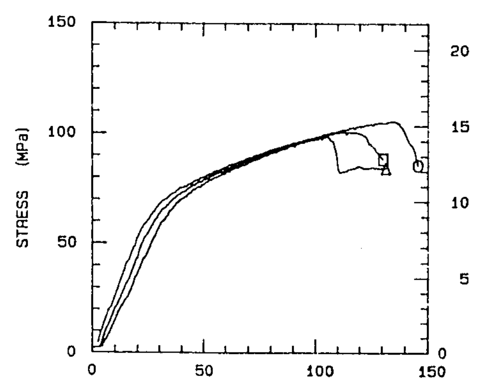
AS4/PISO2-TPI IOS SHEAR 100 DEG DRY



AS4/PISO2-TPI IOS SHEAR 100 DEG DRY

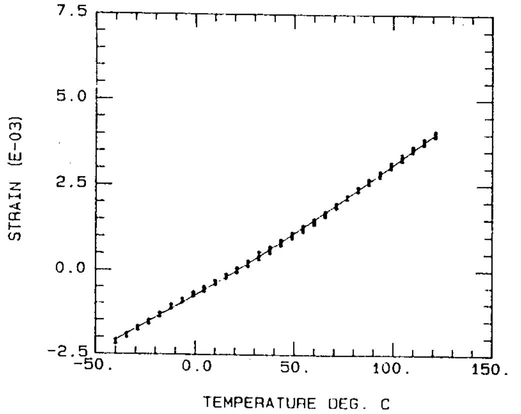


AS4/PISO2-TPI IOS SHEAR 100 DEG WET



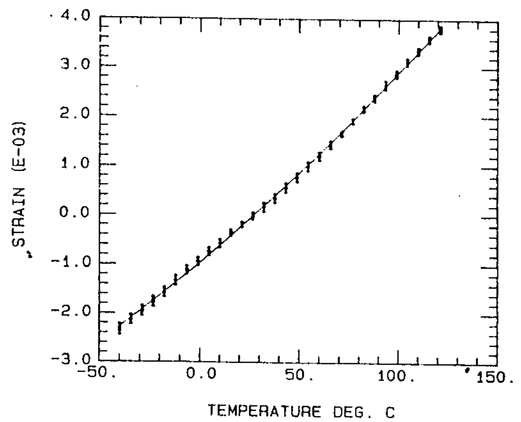
AS4/2220-1 #1 90 DEG

ALPHA = +3.494E-05 /C +7.035E-08 X T /C



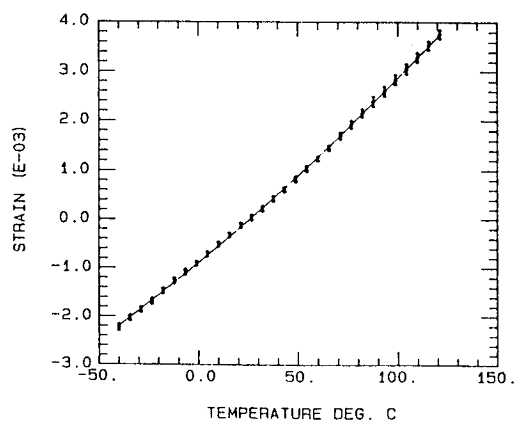
AS4/2220-1 #2 90 DEG

ALPHA = +3.430E-05 /C +8.614E-08 X T /C



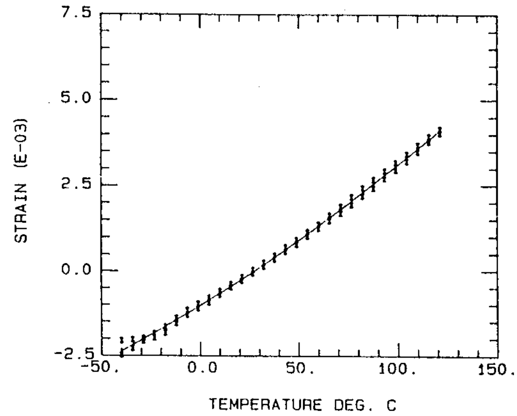
AS4/2220-1 #3 90 DEG

ALPHA = +3.392E-05 /C +7.414E-08 X T /C



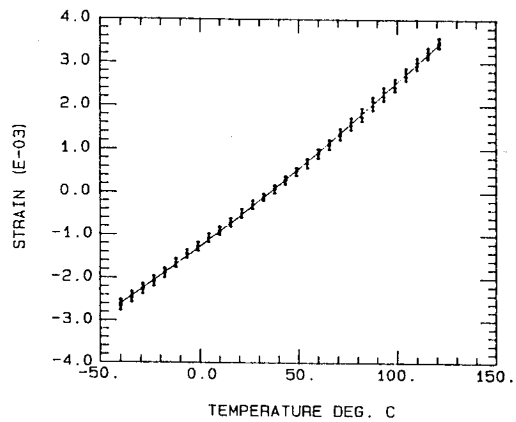
AS4/2220-3 #1 90 DEG

ALPHA = +3.579E-05 /C +1.107E-07 X T /C



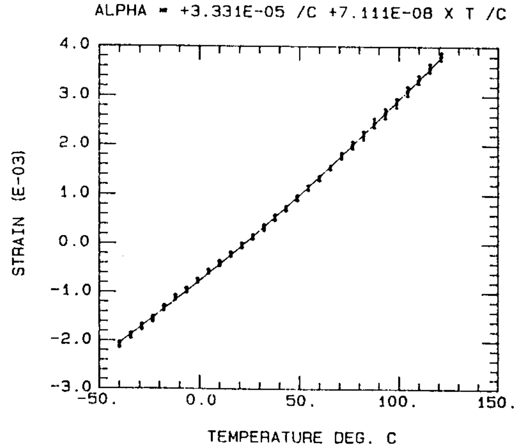
AS4/2220-3 #2 90 DEG

ALPHA = +3.465E-05 /C +6.959E-08 X T /C



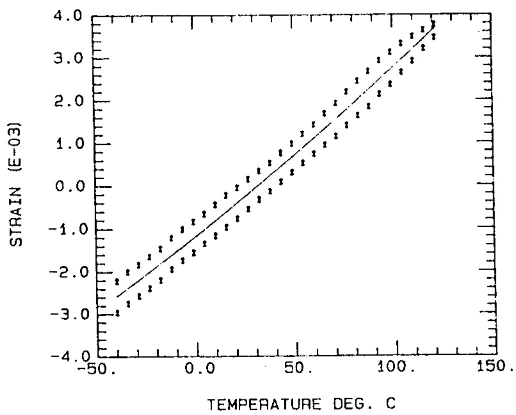
AS4/2220-3 #3 90 DEG

ALPHA = +3.331E-05 /C +7.111E-08 X T /C



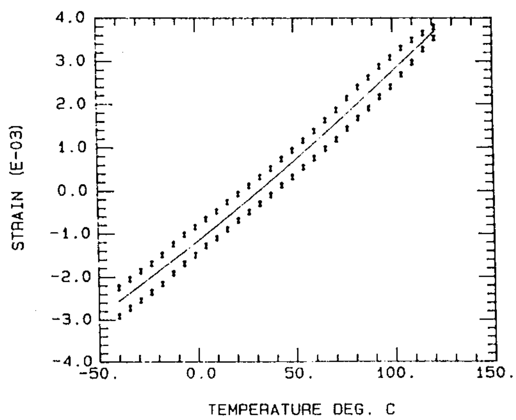
T500/914 #1 90 DEG

ALPHA = +3.613E-05 /C +6.444E-08 X T /C



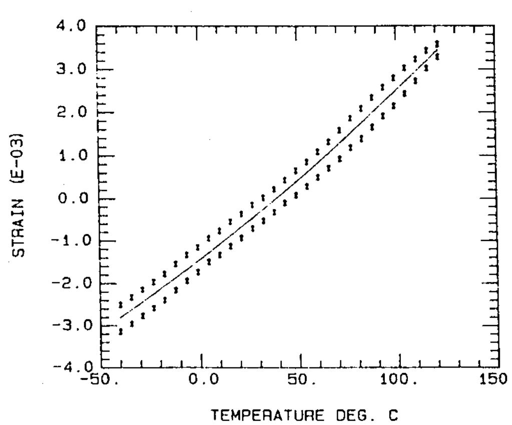
T500/914 #2 90 DEG

ALPHA = +3.595E-05 /C +7.044E-08 X T /C



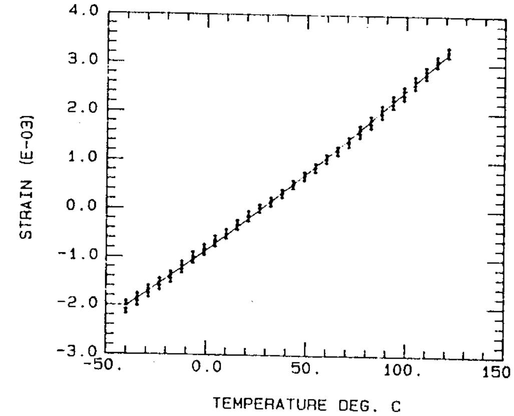
T500/914 #3 90 DEG

ALPHA = +3.566E-05 /C +7.761E-08 X T /C



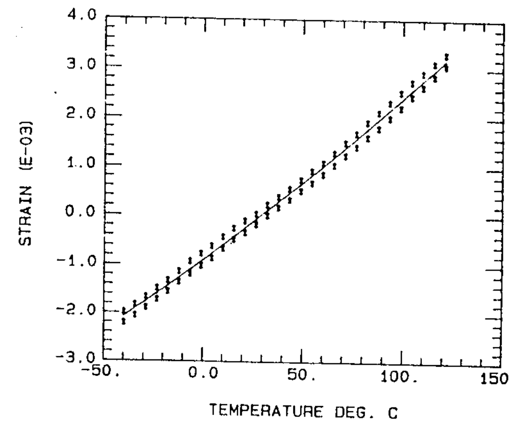
IM6/1504 #1 90 DEG

ALPHA = +3.026E-05 /C +5.532E-08 X T /C



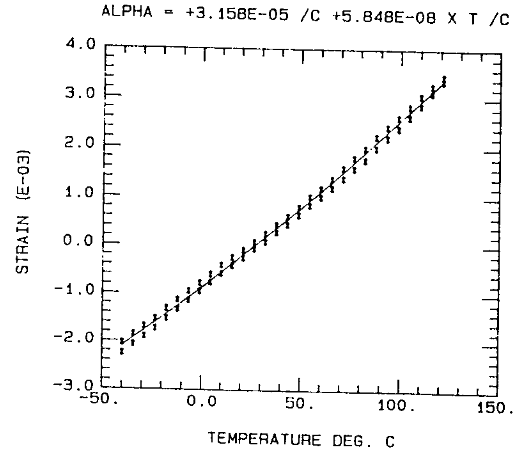
IM6/1504 #2 90 DEG

ALPHA = +3.027E-05 /C +5.658E-08 X T /C



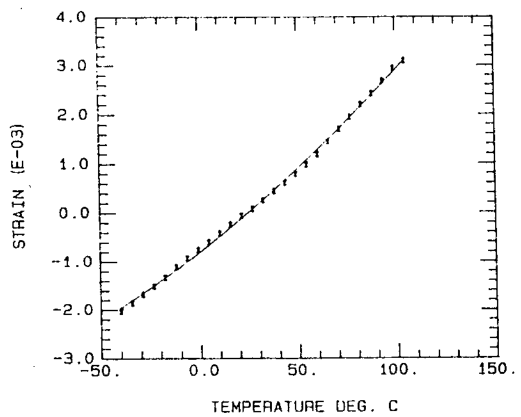
IM6/1504 #3 90 DEG

ALPHA = +3.158E-05 /C +5.848E-08 X T /C



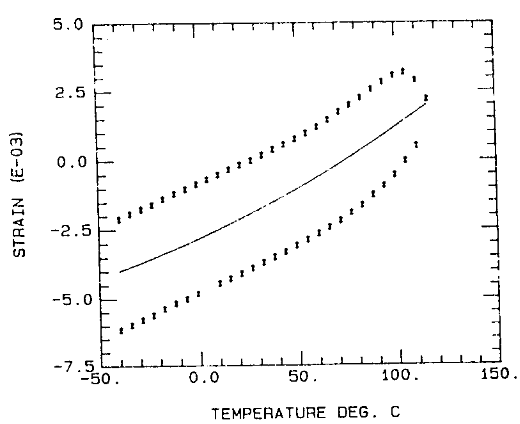
T300/4901-A #1 (MDA) 90 DEG

ALPHA = +3.126E-05 /C +1.166E-07 X T /C



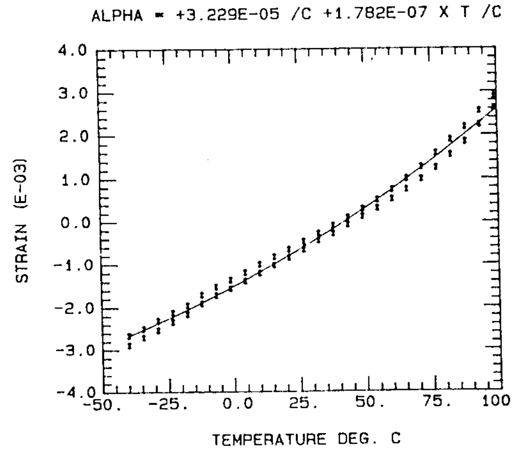
T300/4901-A #2 (MDA) 90 DEG

ALPHA = +3.217E-05 /C +1.628E-07 X T /C



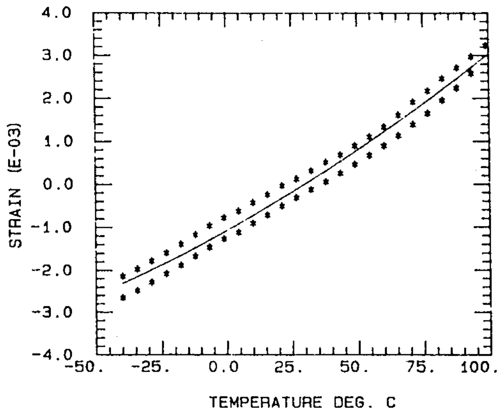
T300/4901-A #3 (MDA) 90 DEG

ALPHA = +3.229E-05 /C +1.782E-07 X T /C



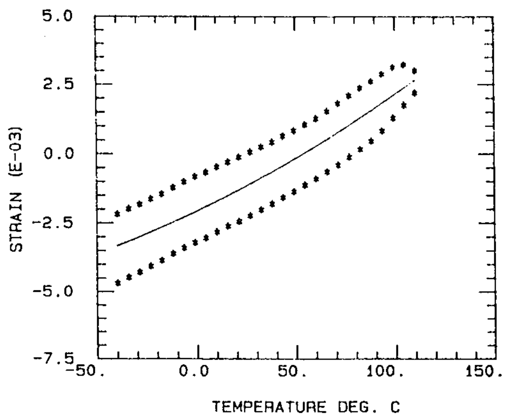
T700/4901A #1 (MDA) 90 DEG

ALPHA = +3.378E-05 /C +1.490E-07 X T /C



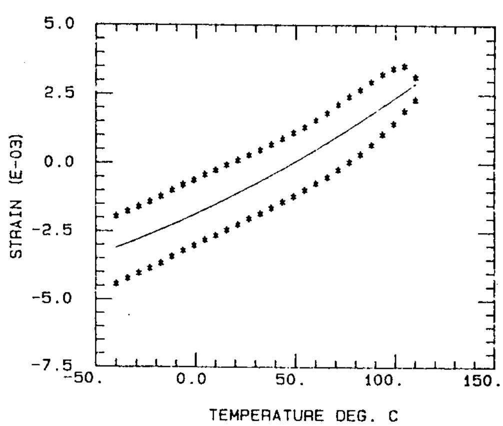
T700/4901A #2 (MDA) 90 DEG

ALPHA = +3.466E-05 /C +1.509E-07 X T /C



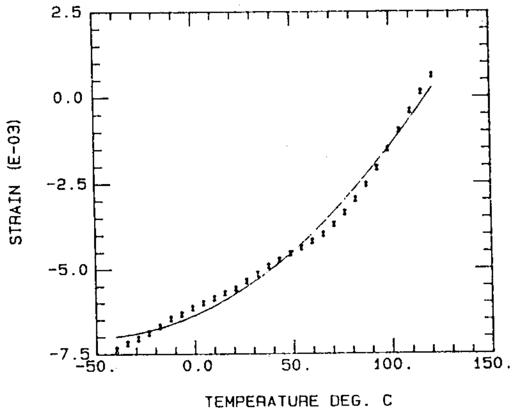
T700/4901A #3 (MDA) 90 DEG

ALPHA = +3.448E-05 /C +1.565E-07 X T /C



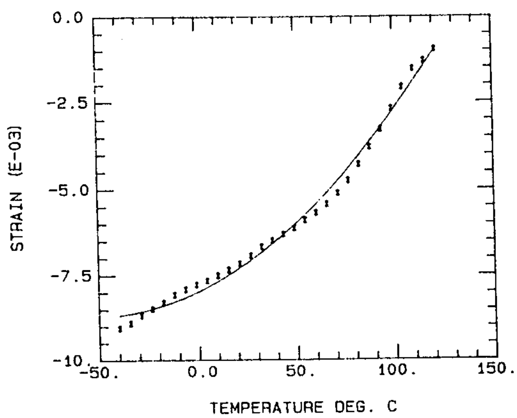
T300/4901-B #1 90 DEG 2ND CYCLE

ALPHA = +2.533E-05 /C +4.859E-07 X T /C



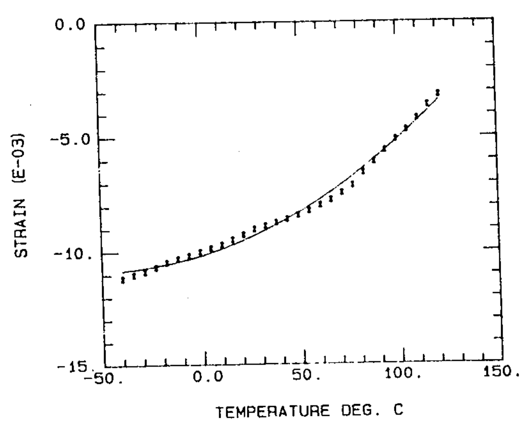
T300/4901-B #2 90 DEG 2ND CYCLE

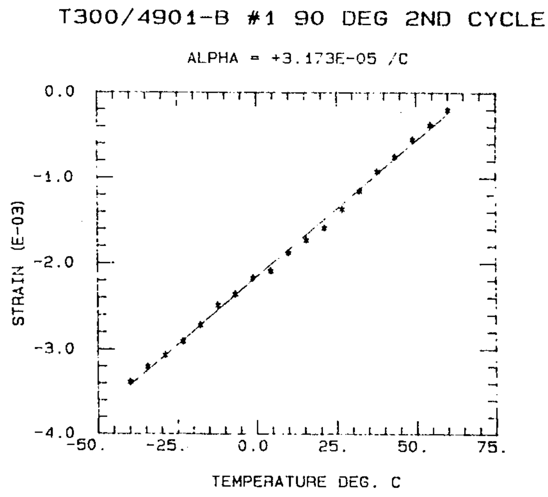
ALPHA = +2.737E-05 /C +5.024E-07 X T /C

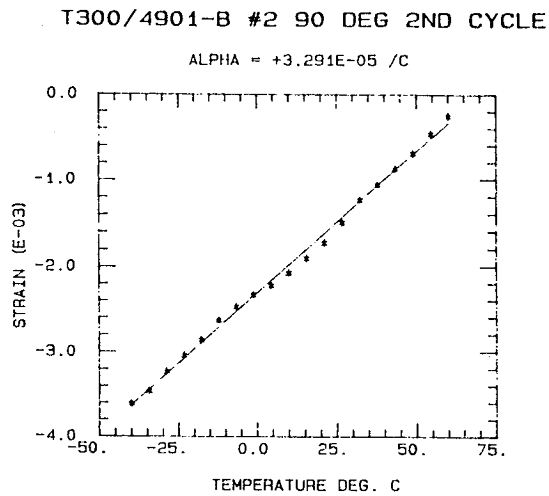


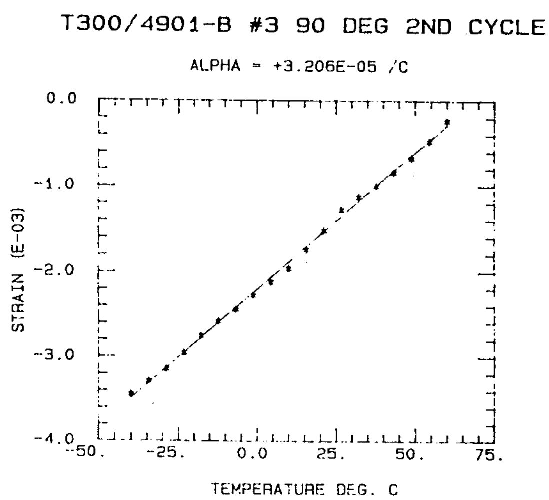
T300/4901-B #3 90 DEG 2ND CYCLE

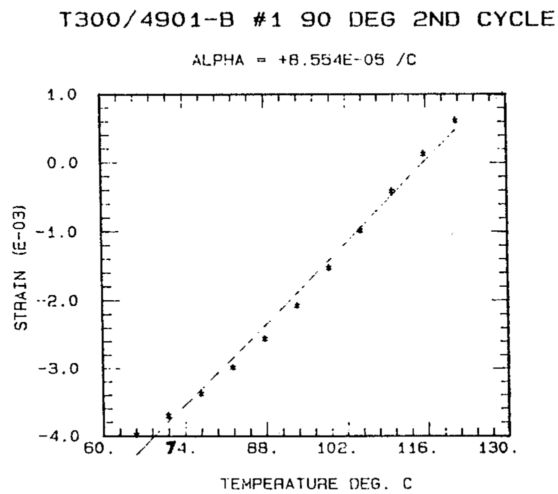
ALPHA = +2.651E-05 /C +4.821E-07 X T /C

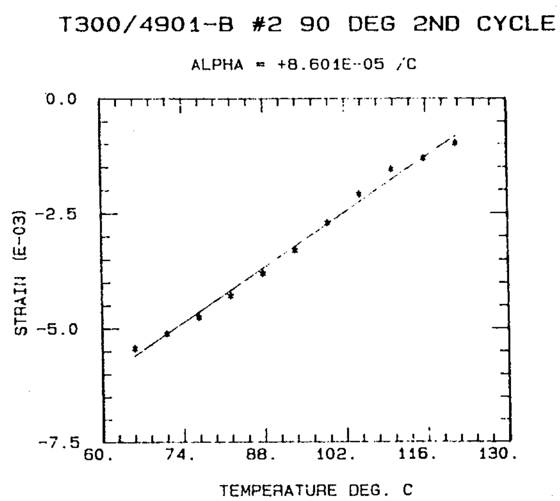


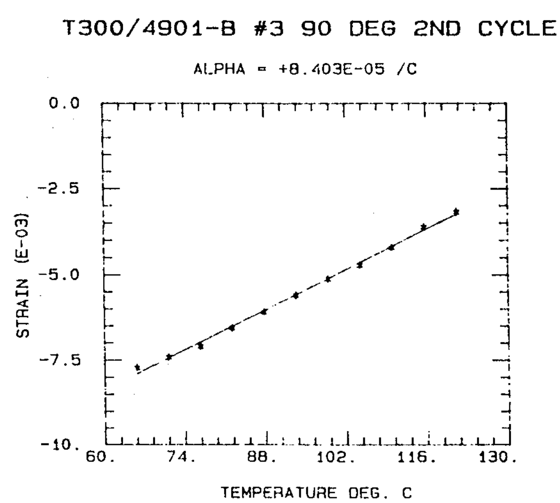

T300/4901-B #1 90 DEG 2ND CYCLE
ALPHA = +3.173E-05 /C
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50.
-25.
0.0
25.
50.
75.
TEMPERATURE DEG. C


T300/4901-B #2 90 DEG 2ND CYCLE
ALPHA = +3.291E-05 /C
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50.
-25.
0.0
25.
50.
75.
TEMPERATURE DEG. C


T300/4901-B #3 90 DEG 2ND CYCLE
ALPHA = +3.206E-05 /C
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50.
-25.
0.0
25.
50.
75.
TEMPERATURE DEG. C

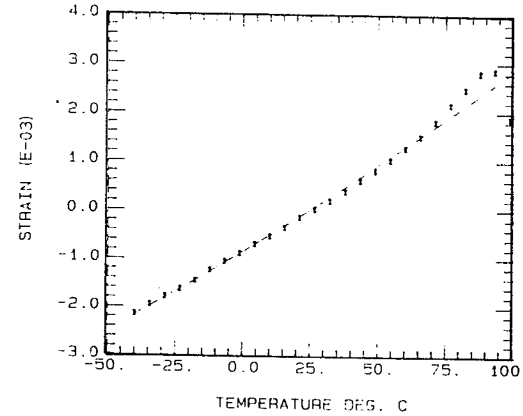

T300/4901-B #1 90 DEG 2ND CYCLE
ALPHA = +8.554E-05 /C
1.0
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
60.
74.
88.
102.
116.
130.
TEMPERATURE DEG. C


T300/4901-B #2 90 DEG 2ND CYCLE
ALPHA = +8.601E-05 /C
0.0
-2.5
-5.0
-7.5
STRAIN (E-03)
60.
74.
88.
102.
116.
130.
TEMPERATURE DEG. C


T300/4901-B #3 90 DEG 2ND CYCLE
ALPHA = +8.403E-05 /C
0.0
-2.5
-5.0
-7.5
-10.
STRAIN (E-03)
60.
74.
88.
102.
116.
130.
TEMPERATURE DEG. C

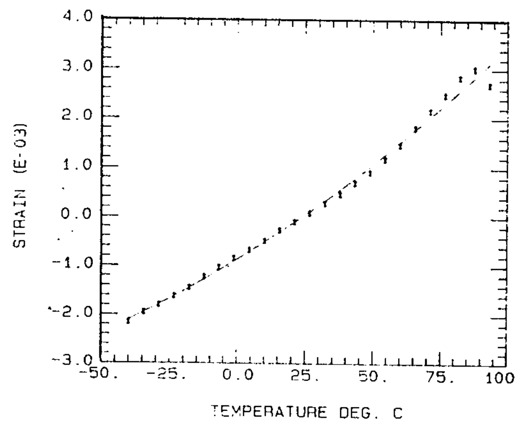
T700/4901-B #4 90 DEG

ALPHA = +3.412E-05 /C +5.594E-08 X T /C



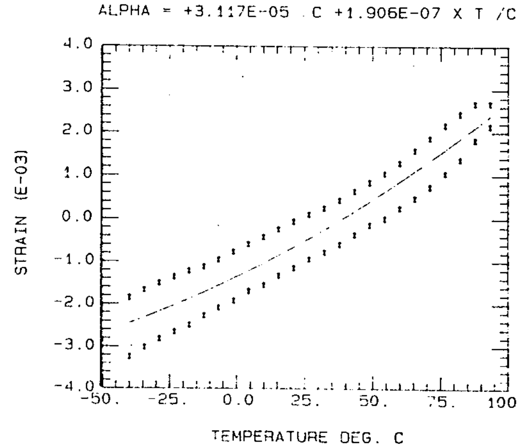
T700/4901-B #6 90 DEG

ALPHA = +3.444E-05 /C +1.787E-07 X T /C



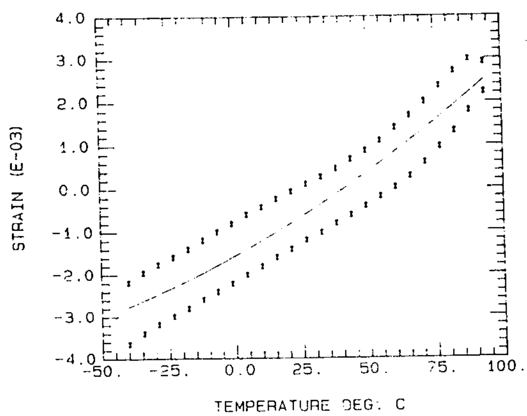
T700/4901-B #7 90 DEG

ALPHA = +3.117E-05 /C +1.906E-07 X T /C



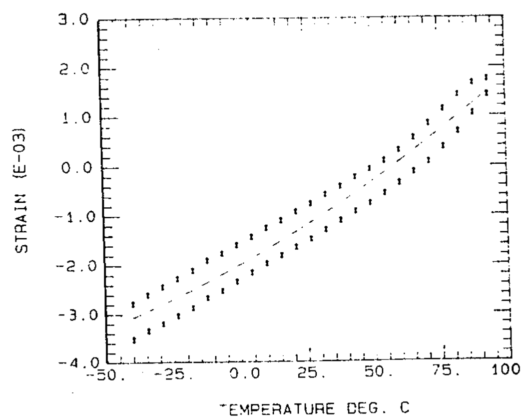
T700/4901-B #8 90 DEG

ALPHA = +3.416E-05 /C +1.974E-07 X T /C



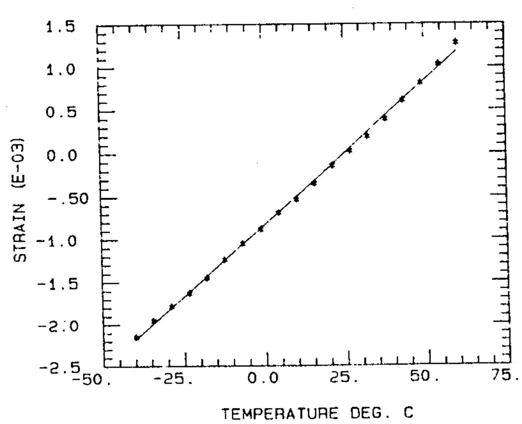
T700/4901-B #9 90 DEG

ALPHA = +3.003E-05 /C +1.552E-07 X T /C



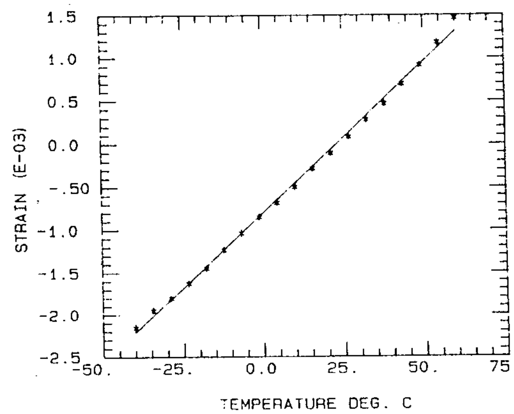
T700/4901-B #4 90 DEG

ALPHA = +3.356E-05 /C



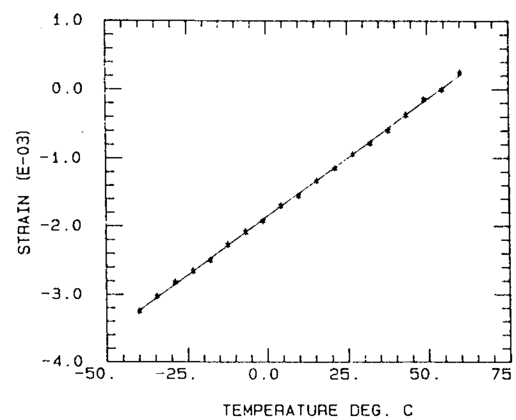
T700/4901-B #6 90 DEG

ALPHA = +3.519E-05 /C



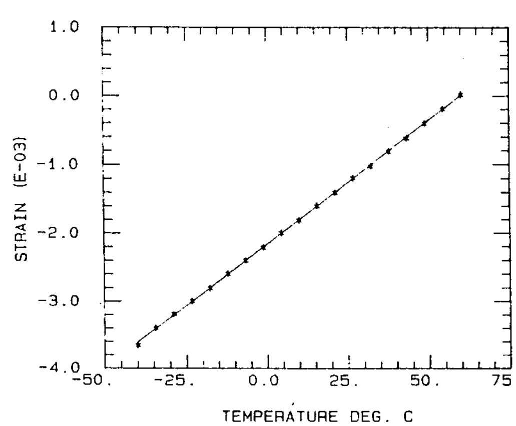
T700/4901-B #7 90 DEG 2ND CYCLE

ALPHA = +3.440E-05 /C



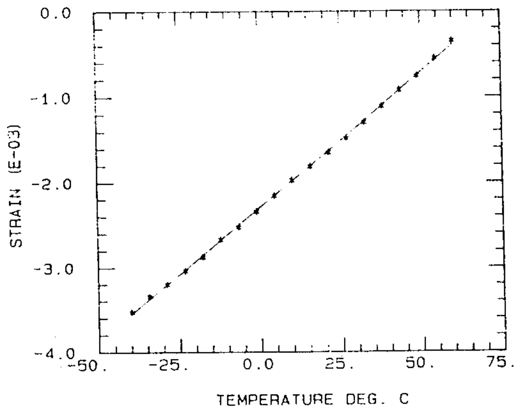
T700/4901-B #8 90 DEG 2ND CYCLE

ALPHA = +3.613E-05 /C



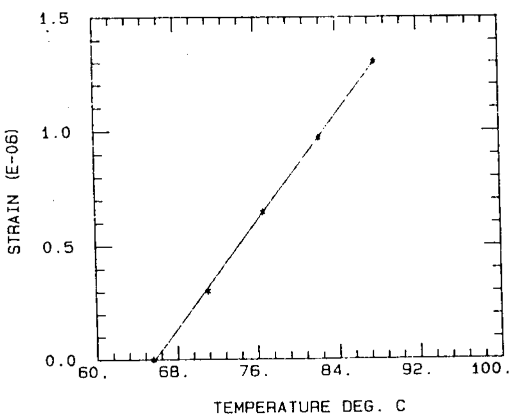
T700/4901-B #9 90 DEG 2ND CYCLE

ALPHA = +3.154E-05 /C



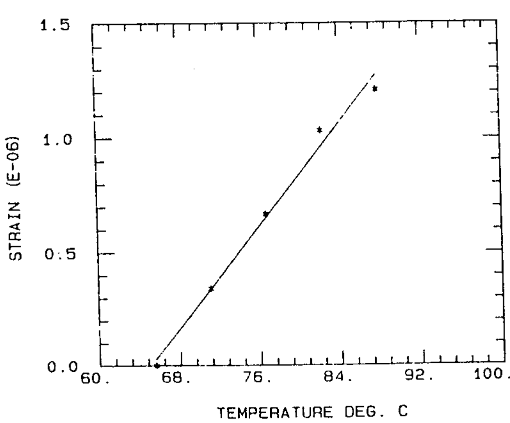
T700/4901-B #4 90 DEG

ALPHA = +5.896E-05 /C



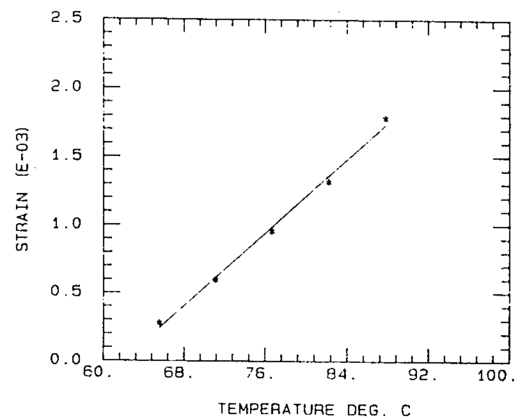
T700/4901-B #6 90 DEG

ALPHA = +5.595E-05 /C



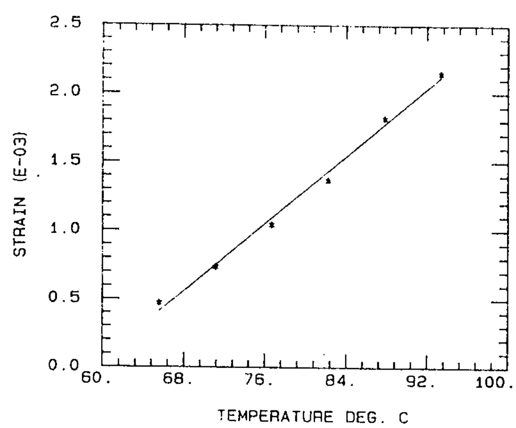
T700/4901-B #8 90 DEG 2ND CYCLE

ALPHA = +6.730E-05 /C



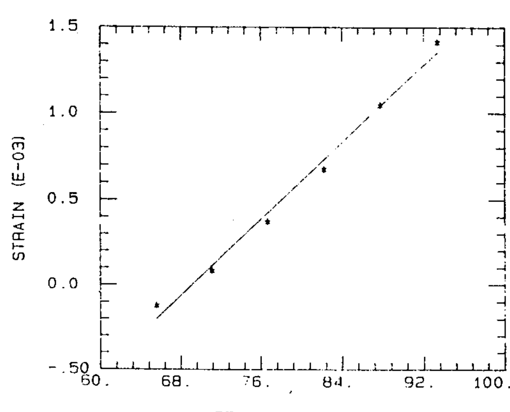
T700/4901-B #7 90 DEG 2ND CYCLE

ALPHA = +6.149E-05 /C



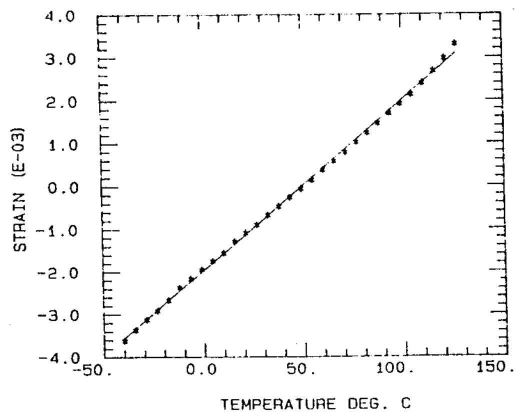
T700/4901-B #9 90 DEG 2ND CYCLE

ALPHA = +5.601E-05 /C



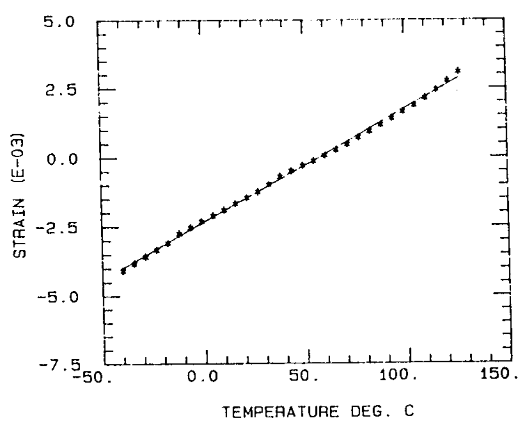
AS4/PEEK (ICI) 90 D #1 REDO 2ND CYCLE

ALPHA = +3.981E-05 /C



AS4/PEEK (ICI) 90 D #2 REDO 2ND CYCLE

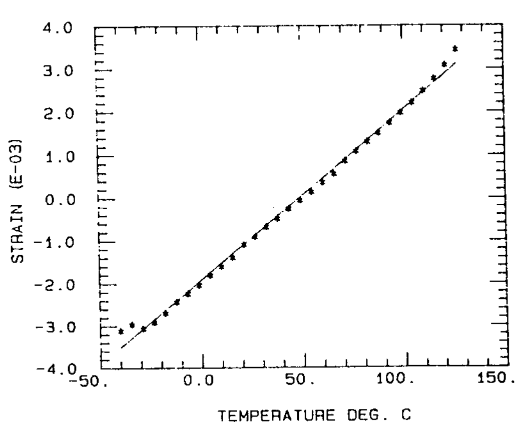
ALPHA = +4.110E-05 /C



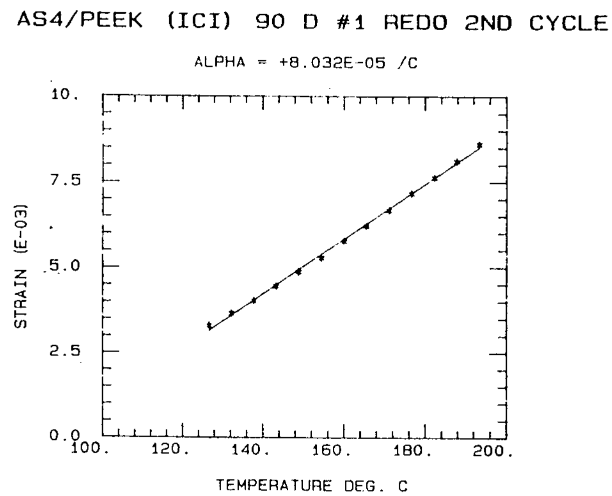
#3

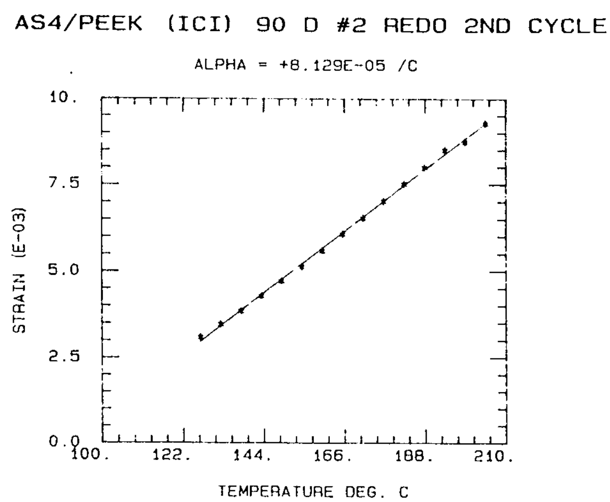
AS4/PEEK (ICI) 90 D REDO 2ND CYCLE

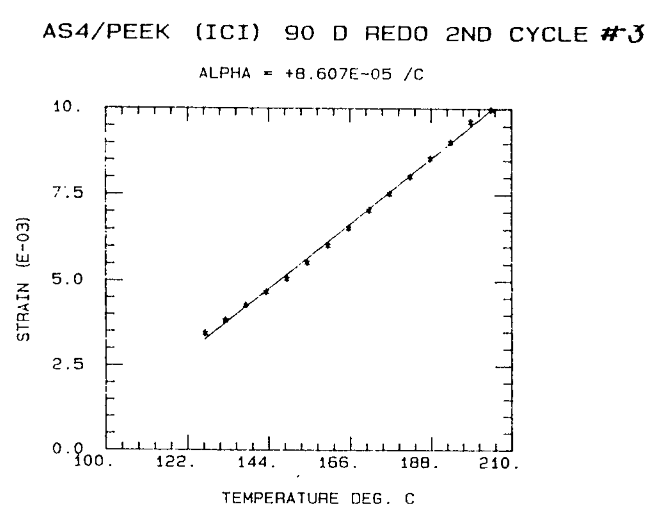
ALPHA = +3.971E-05 /C



C-4

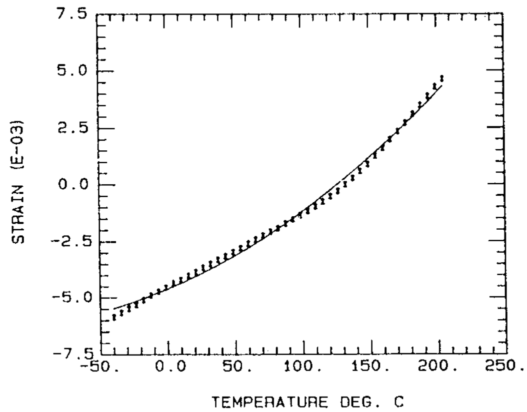

AS4/PEEK (ICI) 90 D #1 REDO 2ND CYCLE
ALPHA = +8.032E-05 /C
STRAIN (E-03)
10.
7.5
5.0
2.5
0.0
100.
120.
140.
160.
180.
200.
TEMPERATURE DEG. C


AS4/PEEK (ICI) 90 D #2 REDO 2ND CYCLE
ALPHA = +8.129E-05 /C
STRAIN (E-03)
10.
7.5
5.0
2.5
0.0
100.
122.
144.
166.
188.
210.
TEMPERATURE DEG. C


AS4/PEEK (ICI) 90 D REDO 2ND CYCLE #3
ALPHA = +8.607E-05 /C
STRAIN (E-03)
10.
7.5
5.0
2.5
0.0
100.
122.
144.
166.
188.
210.
TEMPERATURE DEG. C

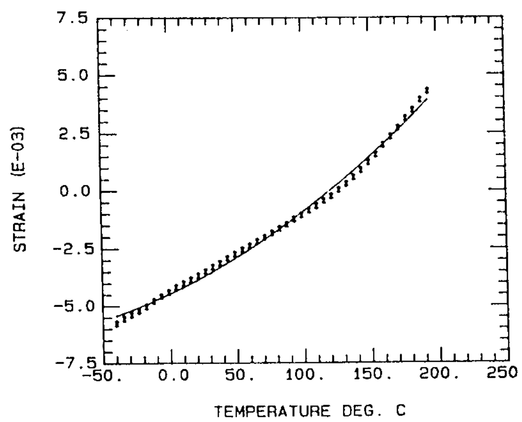
AS4/PEEK (LARC) #1 90 DEG (2ND CYCLE)

ALPHA = +2.504E-05 /C +1.833E-07 X T /C



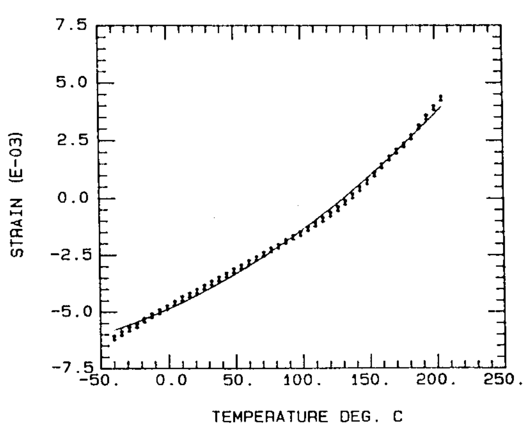
AS4/PEEK (LARC) #2 90 DEG (2ND CYCLE)

ALPHA = +2.735E-05 /C +1.648E-07 X T /C

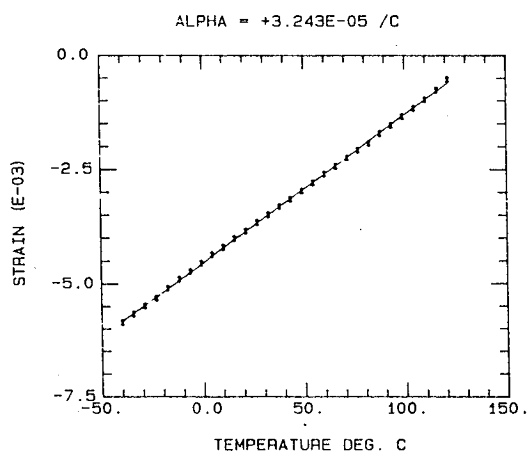


AS4/PEEK (LARC) #3 90 DEG (2ND CYCLE)

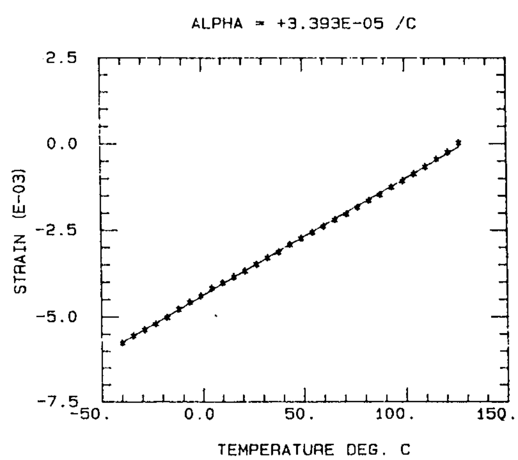
ALPHA = +2.679E-05 /C +1.596E-07 X T /C



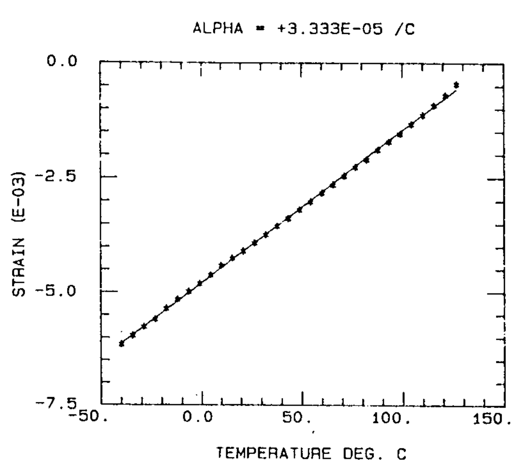
AS4/PEEK (LARC) #1 90 DEG (2ND CYCLE)



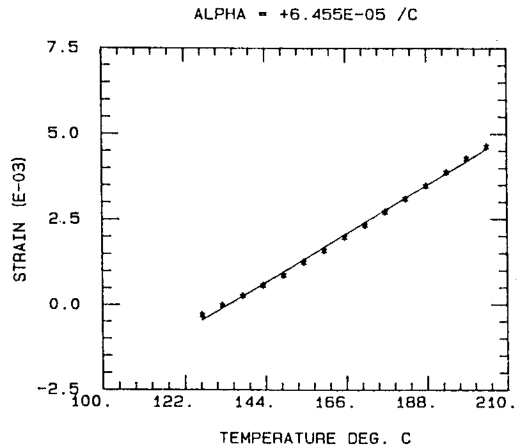
AS4/PEEK (LARC) #2 90 DEG (2ND CYCLE)



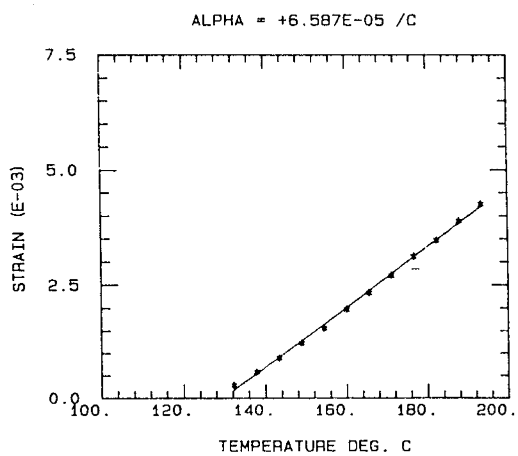
AS4/PEEK (LARC) #3 90 DEG (2ND CYCLE)



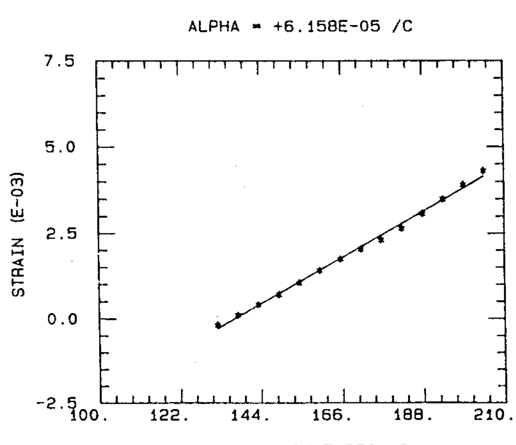
AS4/PEEK (LARC) #1 90 DEG (2ND CYCLE)



AS4/PEEK (LARC) #2 90 DEG (2ND CYCLE)

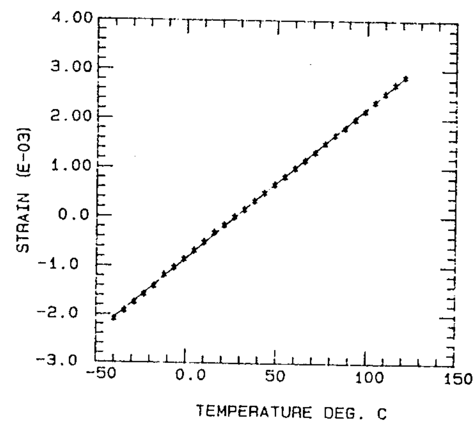


AS4/PEEK (LARC) #3 90 DEG (2ND CYCLE)



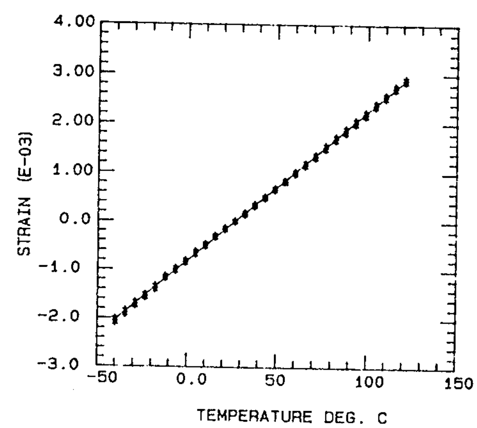
AS4/8551-7 90 DEG DRY #1 2ND CYCLE

ALPHA = +3.048E-05 /C



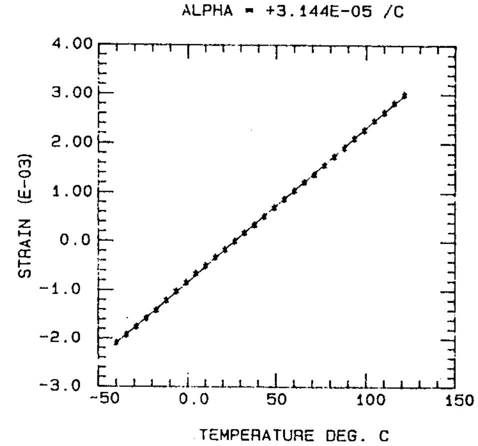
AS4/8551-7 90 DEG DRY #1

ALPHA = +3.052E-05 /C



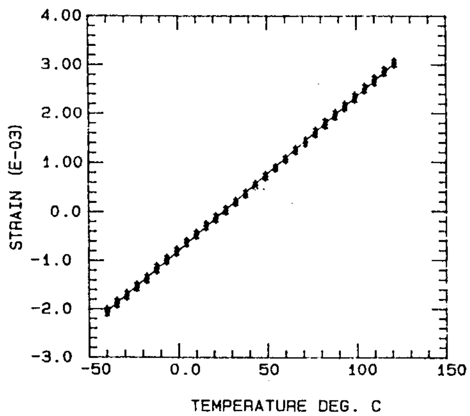
AS4/8551-7 90 DEG DRY #2 2ND CYCLE

ALPHA = +3.144E-05 /C



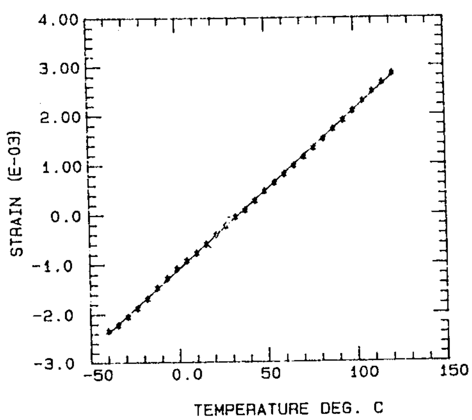
AS4/8551-7 90 DEG DRY #2

ALPHA = +3.146E-05 /C



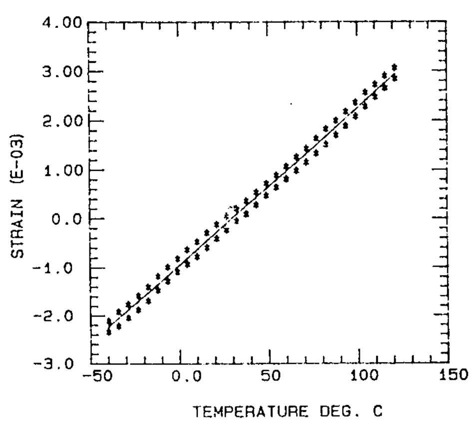
AS4/8551-7 90 DEG DRY #3 2ND CYCLE

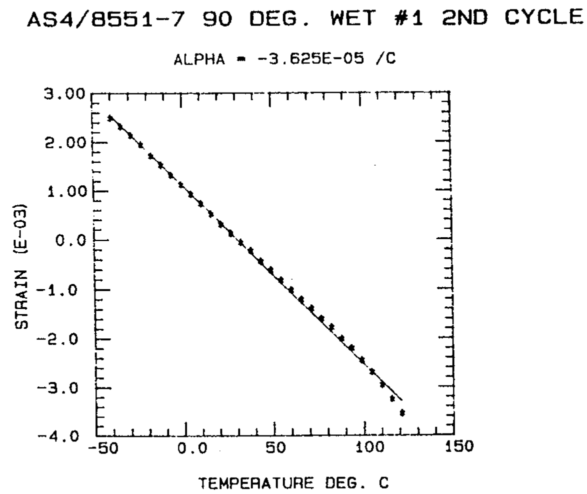
ALPHA = +3.213E-05 /C

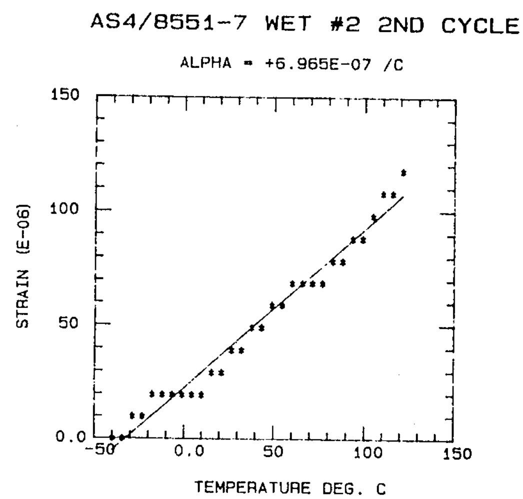


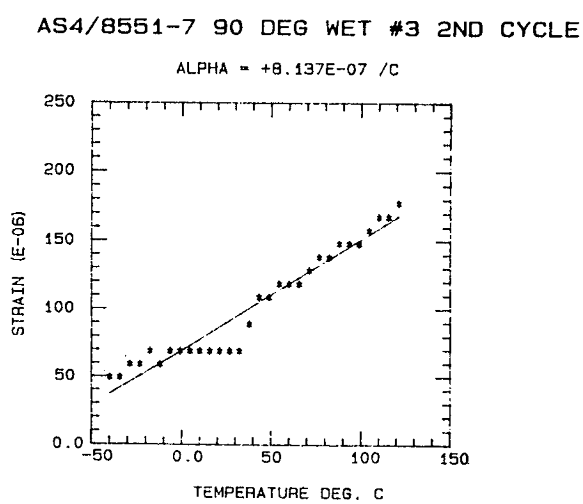
AS4/8551-7 90 DEG DRY #3

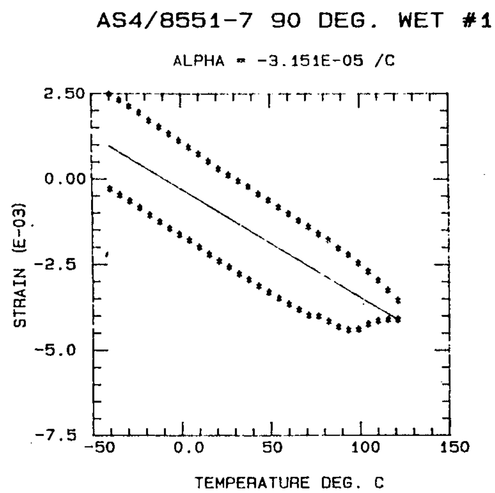
ALPHA = +3.206E-05 /C

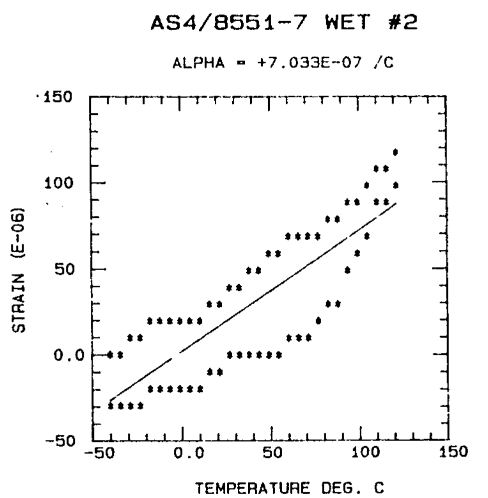


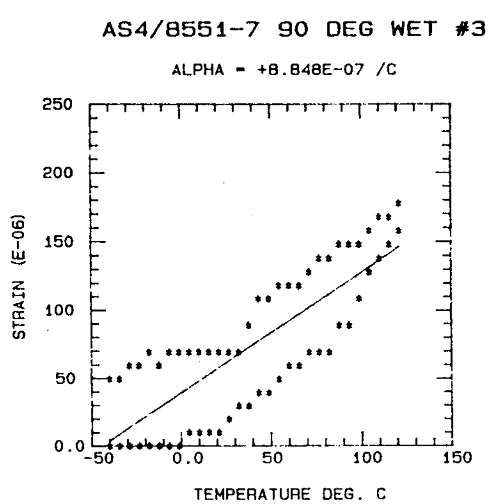

AS4/8551-7 90 DEG. WET #1 2ND CYCLE
ALPHA = -3.625E-05 /C
3.00
2.00
1.00
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50
0.0
50
100
150
TEMPERATURE DEG. C


AS4/8551-7 WET #2 2ND CYCLE
ALPHA = +6.965E-07 /C
150
100
50
0.0
STRAIN (E-06)
-50
0.0
50
100
150
TEMPERATURE DEG. C


AS4/8551-7 90 DEG WET #3 2ND CYCLE
ALPHA = +8.137E-07 /C
250
200
150
100
50
0.0
STRAIN (E-06)
-50
0.0
50
100
150
TEMPERATURE DEG. C

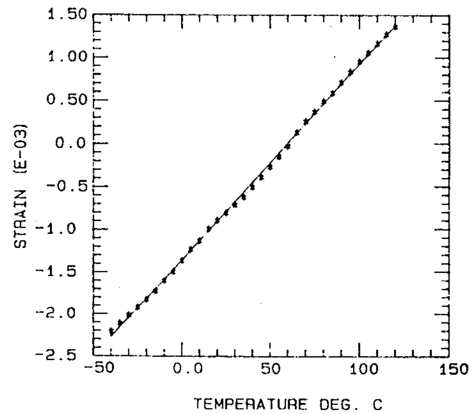

AS4/8551-7 90 DEG. WET #1
ALPHA = -3.151E-05 /C
2.50
0.00
-2.5
-5.0
-7.5
STRAIN (E-03)
-50
0.0
50
100
150
TEMPERATURE DEG. C


AS4/8551-7 WET #2
ALPHA = +7.033E-07 /C
150
100
50
0.0
-50
STRAIN (E-06)
-50
0.0
50
100
150
TEMPERATURE DEG. C


AS4/8551-7 90 DEG WET #3
ALPHA = +8.848E-07 /C
250
200
150
100
50
0.0
STRAIN (E-06)
-50
0.0
50
100
150
TEMPERATURE DEG. C

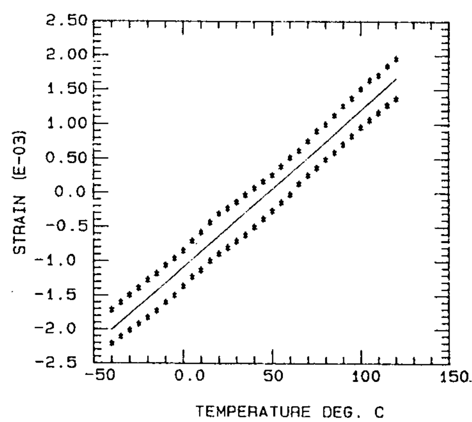
AS4/TPI-DRY, 2nd CYCLE #1

ALPHA = +2.281E-05 /C



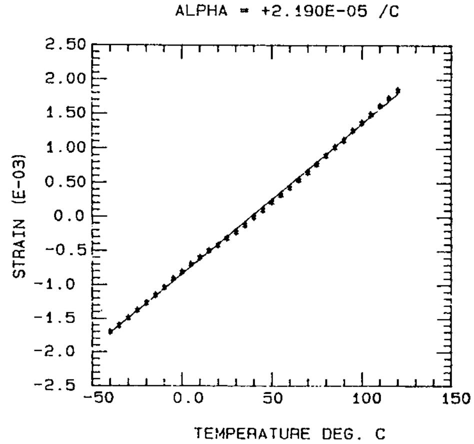
AS4/TPI-DRY #1

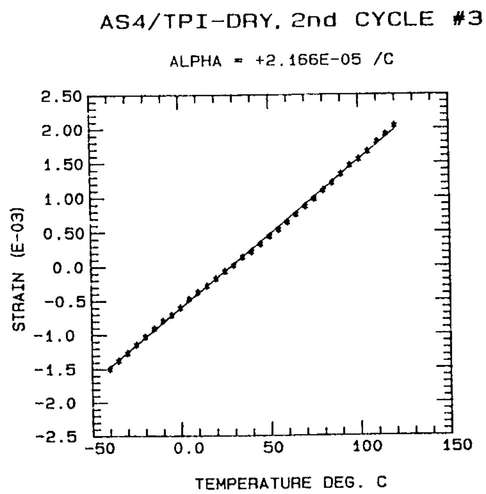
ALPHA = +2.290E-05 /C

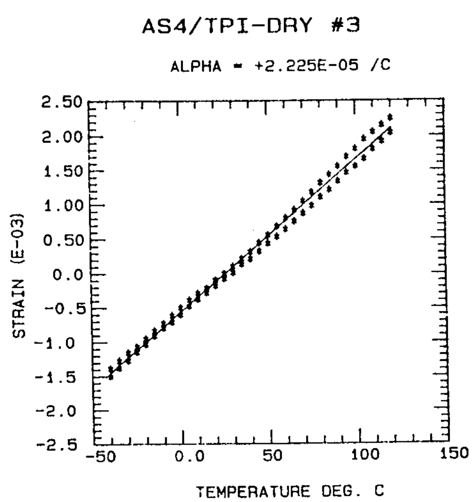


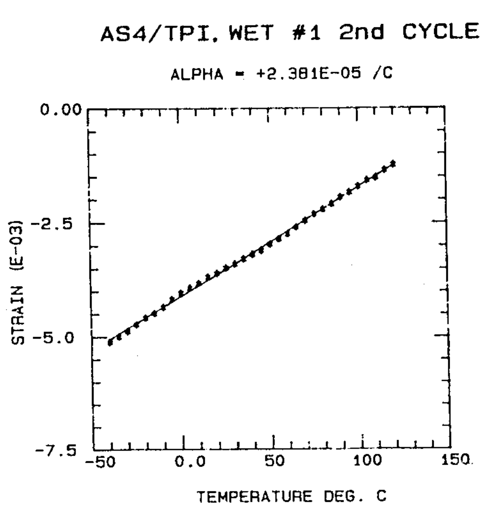
AS4/TPI-DRY, 2nd CYCLE #2

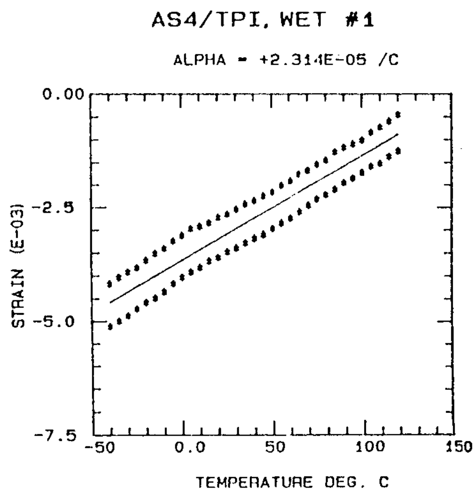
ALPHA = +2.190E-05 /C

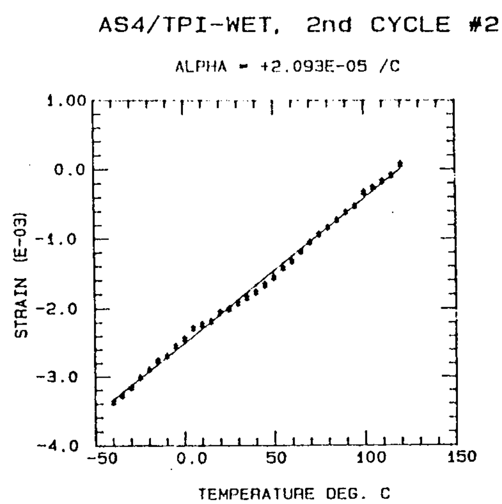


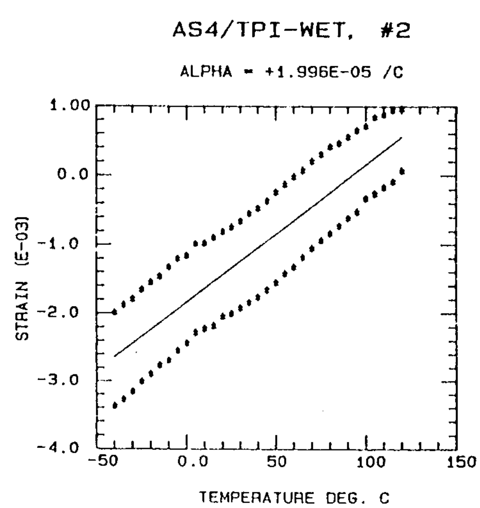

AS4/TPI-DRY, 2nd CYCLE #3
ALPHA = +2.166E-05 /C
STRAIN (E-03)
2.50
2.00
1.50
1.00
0.50
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-50
0.0
50
100
150
TEMPERATURE DEG. C

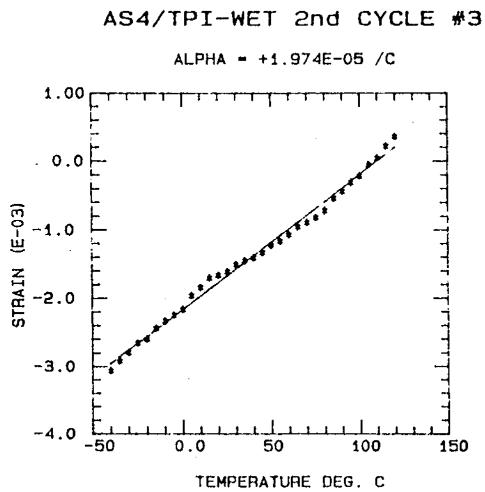

AS4/TPI-DRY #3
ALPHA = +2.225E-05 /C
STRAIN (E-03)
2.50
2.00
1.50
1.00
0.50
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-50
0.0
50
100
150
TEMPERATURE DEG. C


AS4/TPI, WET #1 2nd CYCLE
ALPHA = +2.381E-05 /C
STRAIN (E-03)
0.00
-2.5
-5.0
-7.5
-50
0.0
50
100
150
TEMPERATURE DEG. C

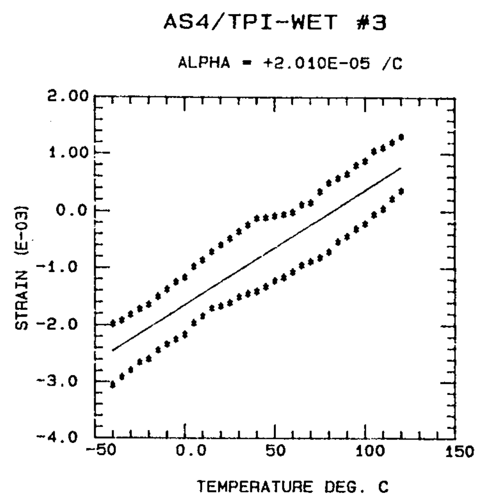

AS4/TPI, WET #1
ALPHA = +2.314E-05 /C
0.00
-2.5
-5.0
-7.5
STRAIN (E-03)
-50
0.0
50
100
150
TEMPERATURE DEG. C


AS4/TPI-WET, 2nd CYCLE #2
ALPHA = +2.093E-05 /C
1.00
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50
0.0
50
100
150
TEMPERATURE DEG. C


AS4/TPI-WET, #2
ALPHA = +1.996E-05 /C
1.00
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50
0.0
50
100
150
TEMPERATURE DEG. C



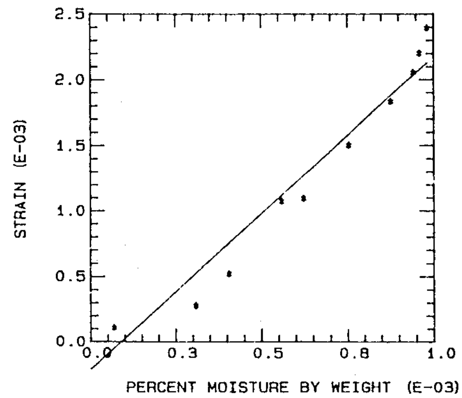
AS4/TPI-WET 2nd CYCLE #3
ALPHA = +1.974E-05 /C
1.00
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50
0.0
50
100
150
TEMPERATURE DEG. C



AS4/TPI-WET #3
ALPHA = +2.010E-05 /C
2.00
1.00
0.0
-1.0
-2.0
-3.0
-4.0
STRAIN (E-03)
-50
0.0
50
100
150
TEMPERATURE DEG. C

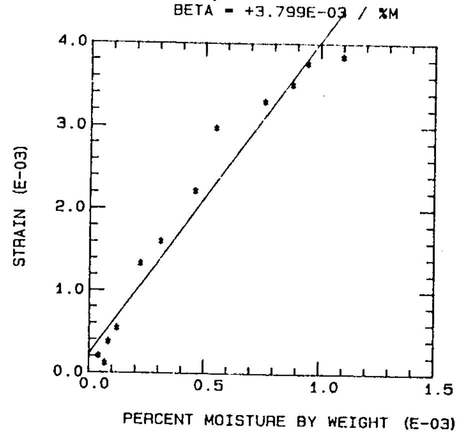
AS4/220-1 90 DEGREE A1

BETA = +2.386E-03 / %M



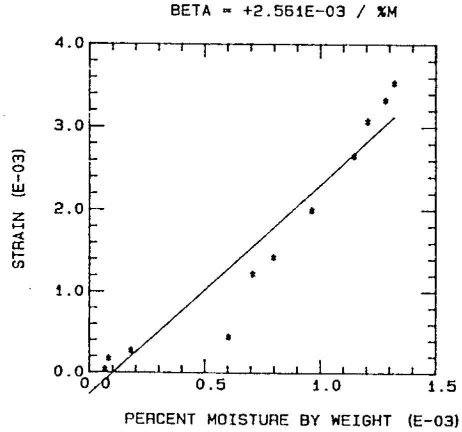
AS4/2220-1 90 DEGREE A2

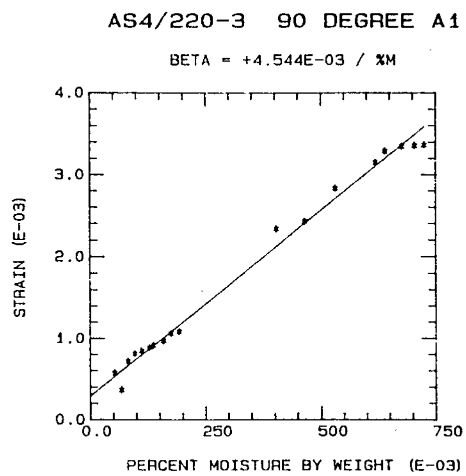
BETA = +3.799E-03 / %M

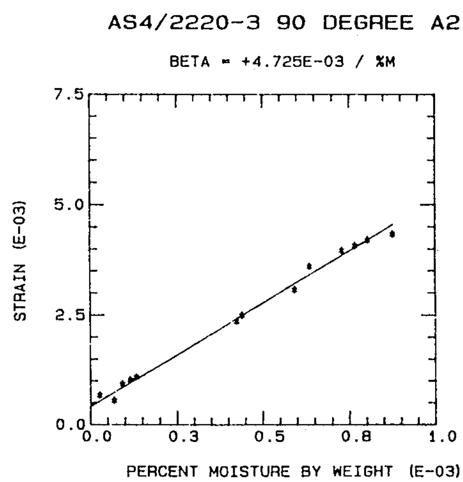


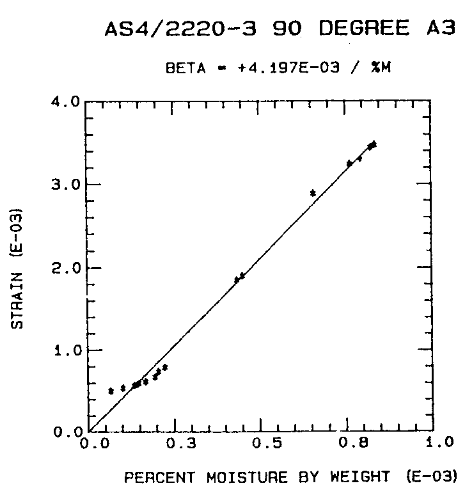
AS4/2220-1 DEGREE 90 A3

BETA = +2.561E-03 / %M



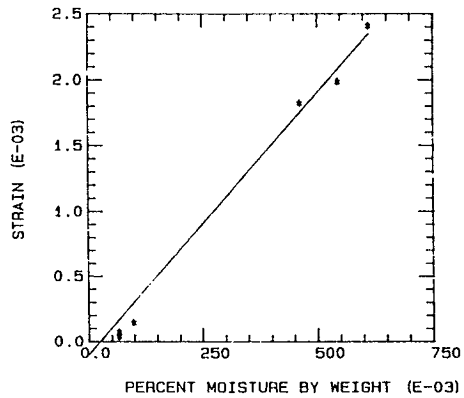

AS4/220-3 90 DEGREE A1
BETA = +4.544E-03 / %M
STRAIN (E-03)
4.0
3.0
2.0
1.0
0.0
0.0
250
500
750
PERCENT MOISTURE BY WEIGHT (E-03)


AS4/2220-3 90 DEGREE A2
BETA = +4.725E-03 / %M
STRAIN (E-03)
7.5
5.0
2.5
0.0
0.0
0.3
0.5
0.8
1.0
PERCENT MOISTURE BY WEIGHT (E-03)


AS4/2220-3 90 DEGREE A3
BETA = +4.197E-03 / %M
STRAIN (E-03)
4.0
3.0
2.0
1.0
0.0
0.0
0.3
0.5
0.8
1.0
PERCENT MOISTURE BY WEIGHT (E-03)

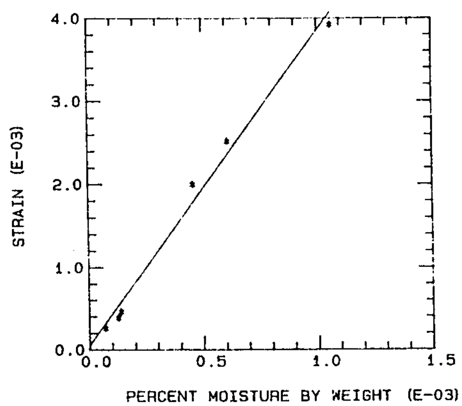
NASA T500 / 914 A1

BETA = +3.998E-03 / %M



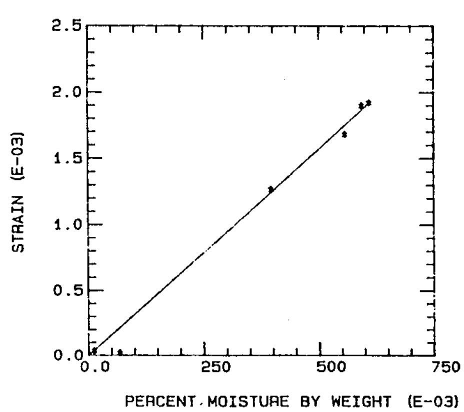
NASA T500 / 914 A2

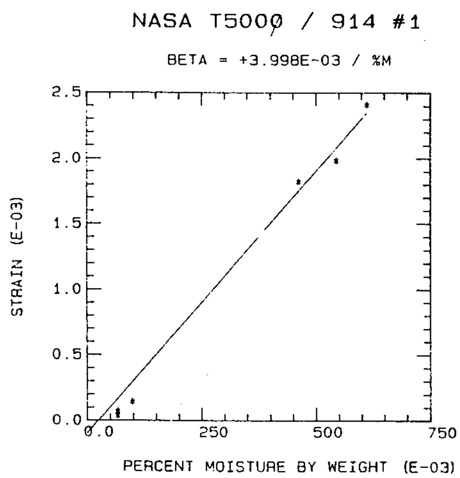
BETA = +3.795E-03 / %M

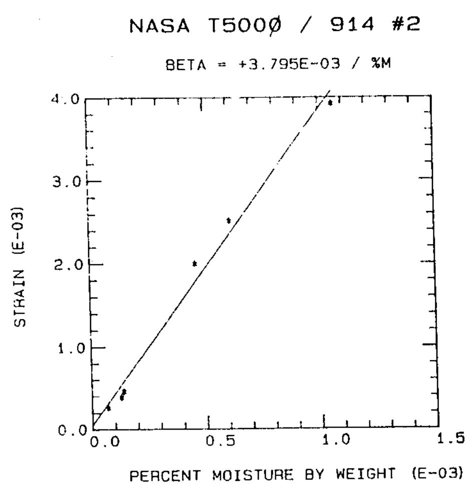


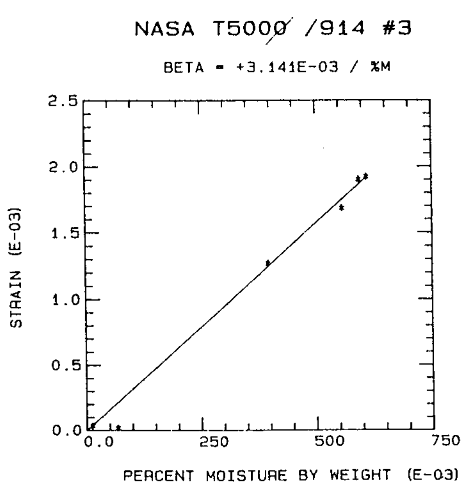
NASA T500 /914 A3

BETA = +3.141E-03 / %M



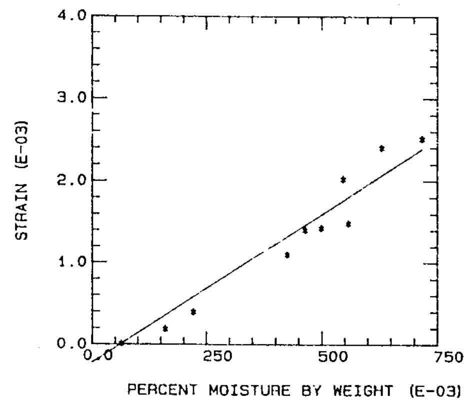

NASA T5000 / 914 #1
BETA = +3.998E-03 / %M
STRAIN (E-03)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
250
500
750
PERCENT MOISTURE BY WEIGHT (E-03)


NASA T5000 / 914 #2
BETA = +3.795E-03 / %M
STRAIN (E-03)
4.0
3.0
2.0
1.0
0.0
0.0
0.5
1.0
1.5
PERCENT MOISTURE BY WEIGHT (E-03)


NASA T5000 /914 #3
BETA = +3.141E-03 / %M
STRAIN (E-03)
2.5
2.0
1.5
1.0
0.5
0.0
0.0
250
500
750
PERCENT MOISTURE BY WEIGHT (E-03)

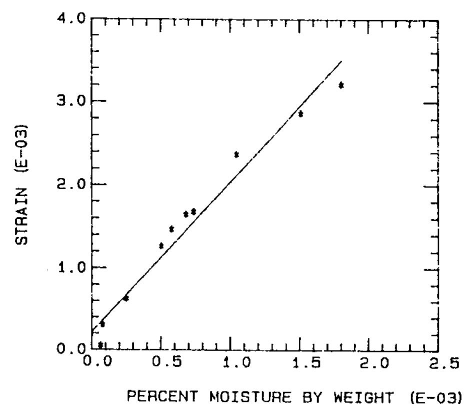
IM6/ 1504 90 DEGREE A1

BETA = +3.635E-03 / %M



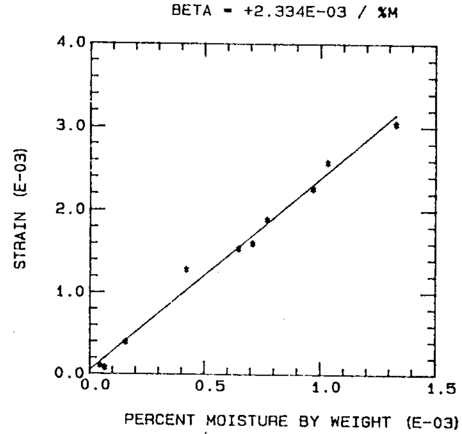
IM6/1504 90 DEGREE A2

BETA = +1.818E-03 / %M



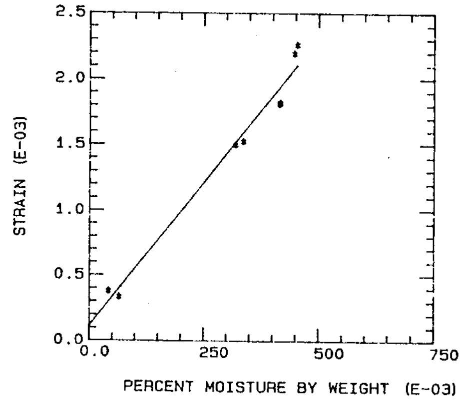
IM6/1504 90 DEGREE A3

BETA = +2.334E-03 / %M



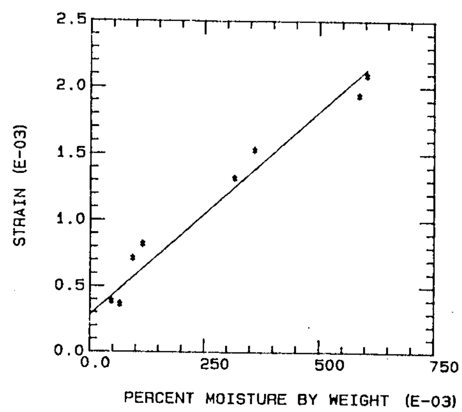
IM6/ 1506 B1

BETA = +4.392E-03 / %M



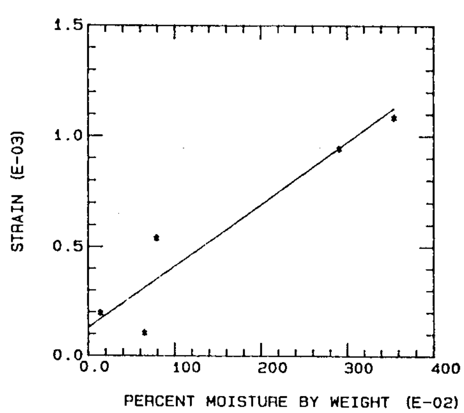
IM6 /1504 B2

BETA = +3.064E-03 / %M



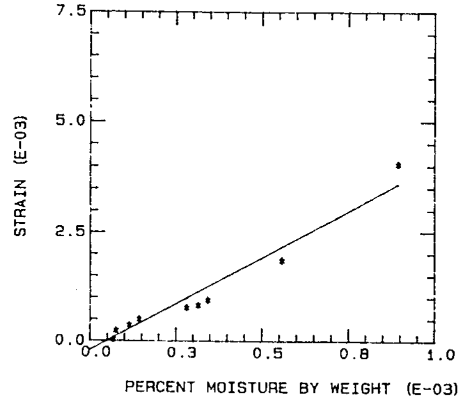
IM6/1504 C1

BETA = +2.808E-03 / %M



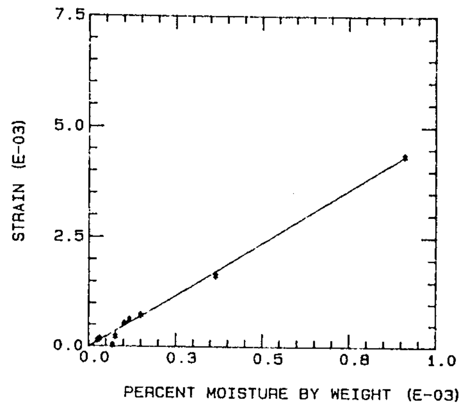
T300 /4901A A1

BETA = +4.246E-03 / %M



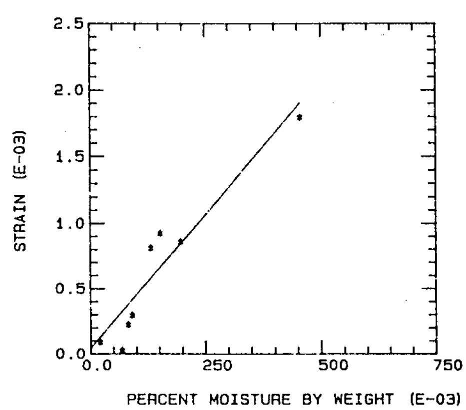
T300 /4901A A2

BETA = +4.769E-03 / %M



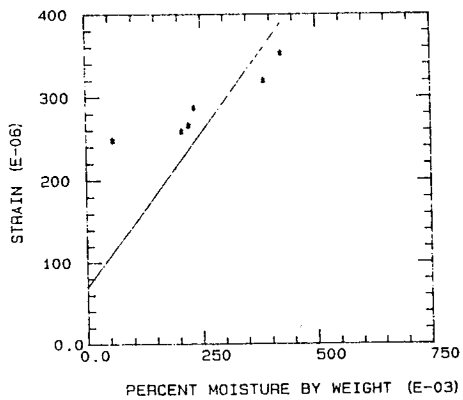
T300/4901A A3

BETA = +4.079E-03 / %M



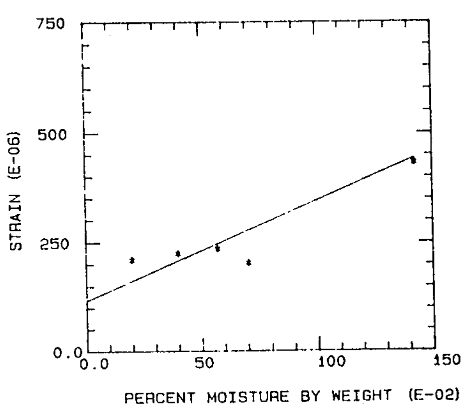
T700/14901-A A1

BETA = +7.533E-04 / %M



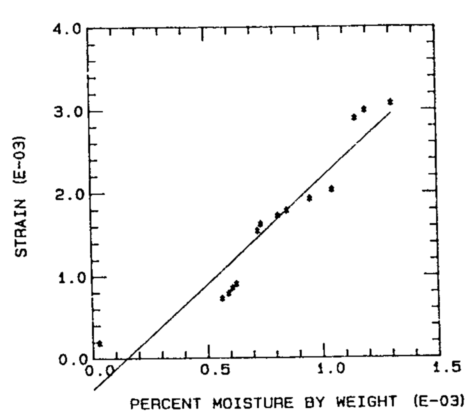
T700/14901-A A2

BETA = +2.282E-03 / %M



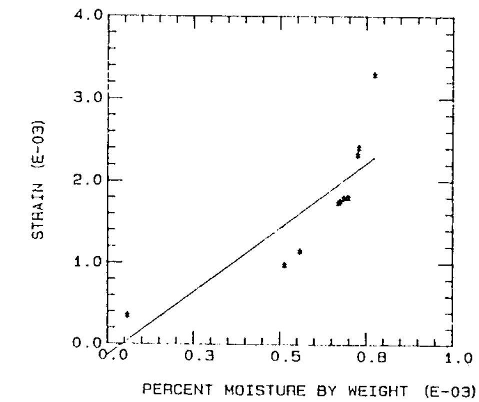
T700/14901-A A3

BETA = +2.549E-03 / %M



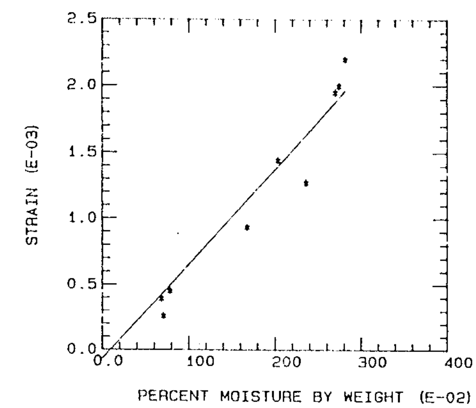
T700 /14901-A B1

BETA = +3.122E-03 / %M



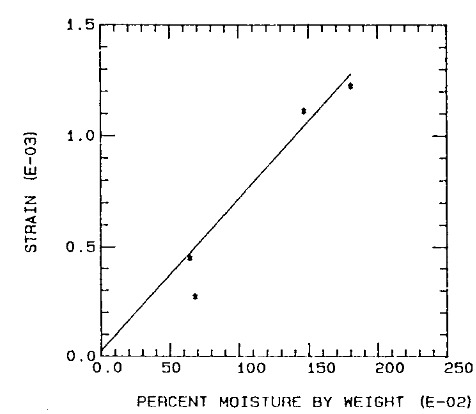
T700/14901-A B2

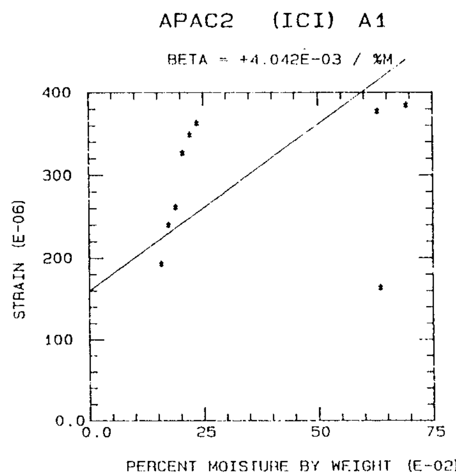
BETA = +7.206E-03 / %M

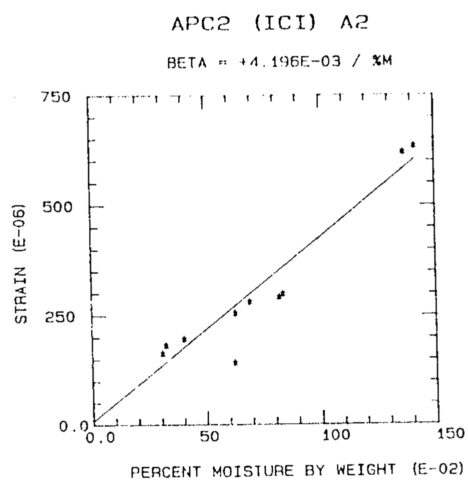


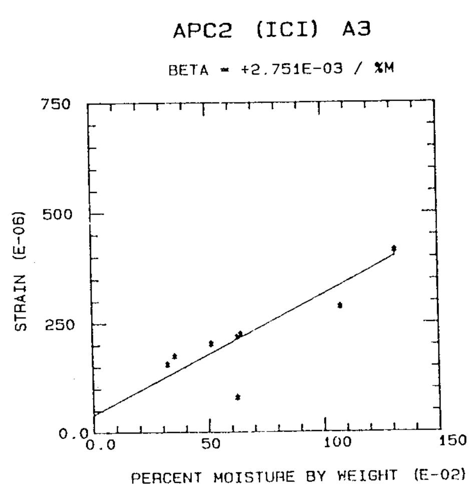
T700/ 14901-A B3

BETA = +6.943E-03 / %M



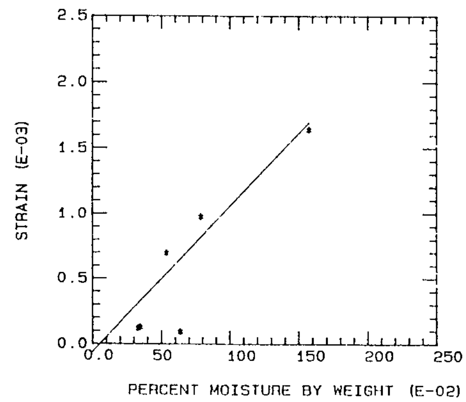

APAC2 (ICI) A1
BETA = +4.042E-03 / %M
STRAIN (E-06)
400
300
200
100
0.0
0.0
25
50
75
PERCENT MOISTURE BY WEIGHT (E-02)


APC2 (ICI) A2
BETA = +4.196E-03 / %M
STRAIN (E-06)
750
500
250
0.0
0.0
50
100
150
PERCENT MOISTURE BY WEIGHT (E-02)


APC2 (ICI) A3
BETA = +2.751E-03 / %M
STRAIN (E-06)
750
500
250
0.0
0.0
50
100
150
PERCENT MOISTURE BY WEIGHT (E-02)

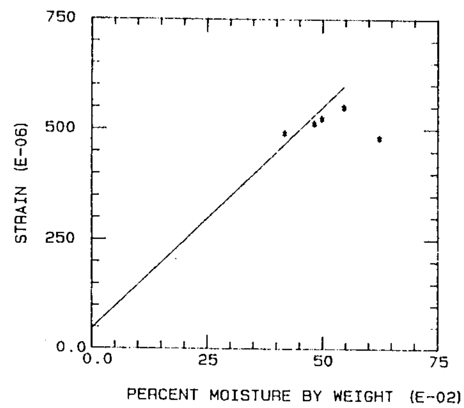
APC2 (ICI) B1

BETA = +1.114E-02 / %M



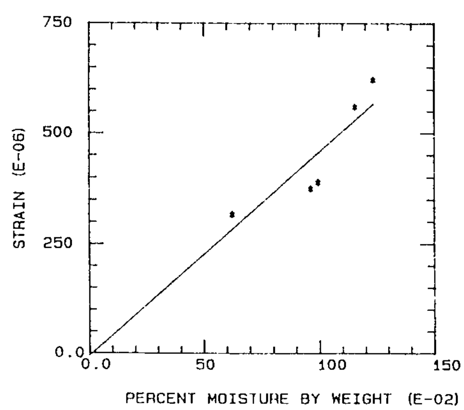
APC2 (ICI) B2

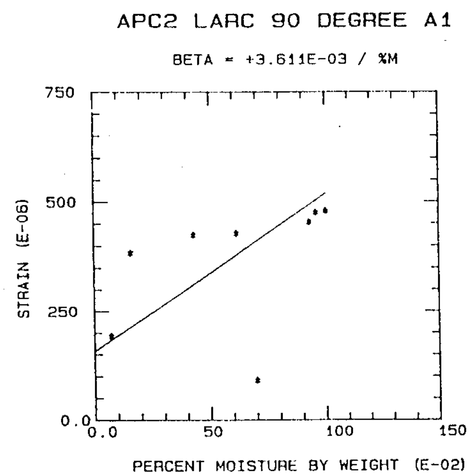
BETA = +1.004E-02 / %M

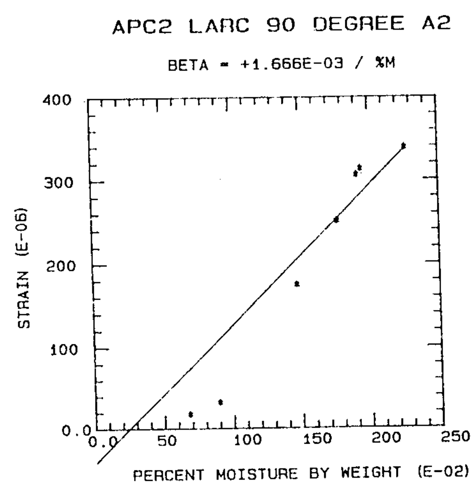


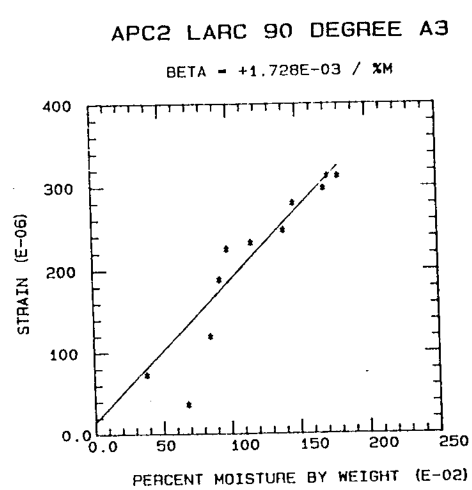
APC2 ICI B3

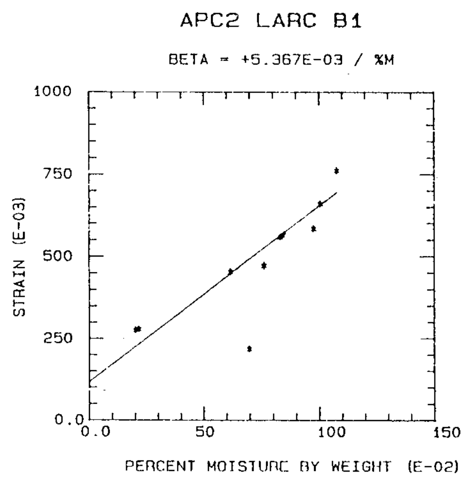
BETA = +4.632E-03 / %M

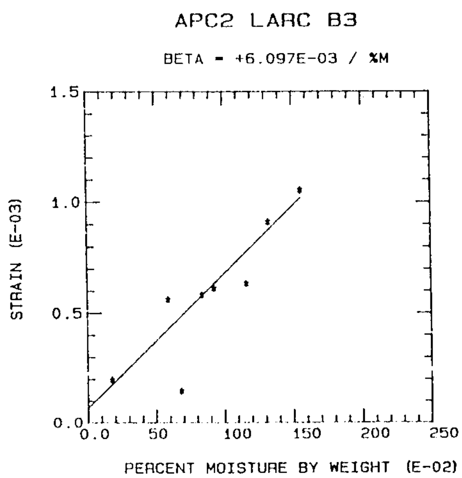



APC2 LARC 90 DEGREE A1
BETA = +3.611E-03 / %M
STRAIN (E-06)
750
500
250
0.0
0.0
50
100
150
PERCENT MOISTURE BY WEIGHT (E-02)


APC2 LARC 90 DEGREE A2
BETA = +1.666E-03 / %M
STRAIN (E-06)
400
300
200
100
0.0
0.0
50
100
150
200
250
PERCENT MOISTURE BY WEIGHT (E-02)

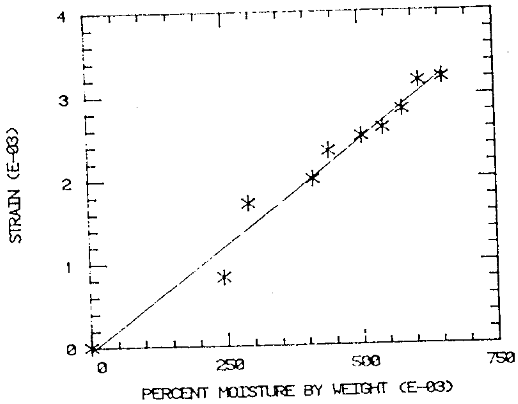

APC2 LARC 90 DEGREE A3
BETA = +1.728E-03 / %M
STRAIN (E-06)
400
300
200
100
0.0
0.0
50
100
150
200
250
PERCENT MOISTURE BY WEIGHT (E-02)


APC2 LARC B1
BETA = +5.367E-03 / %M
1000
750
500
250
0.0
STRAIN (E-03)
0.0
50
100
150
PERCENT MOISTURE BY WEIGHT (E-02)


APC2 LARC B3
BETA = +6.097E-03 / %M
1.5
1.0
0.5
0.0
STRAIN (E-03)
0.0
50
100
150
200
250
PERCENT MOISTURE BY WEIGHT (E-02)

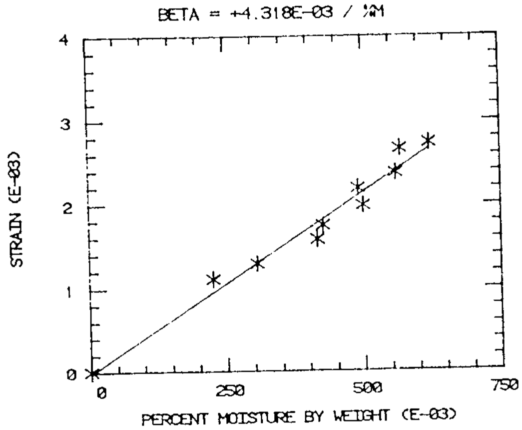
NASA LANGLY YEAR 5 AS4/8551-7 #1

BETA = +5.033E-03 / %M



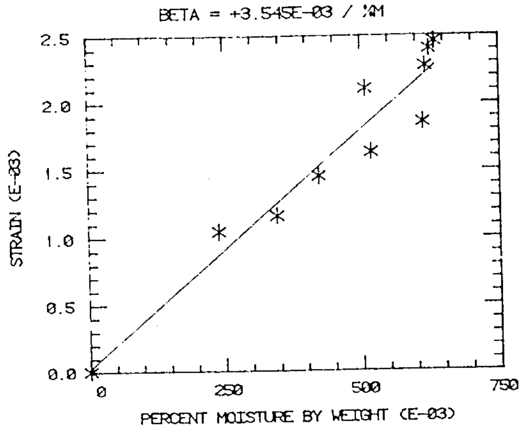
NASA LANGLY YEAR 5 AS4/8551-7 #2

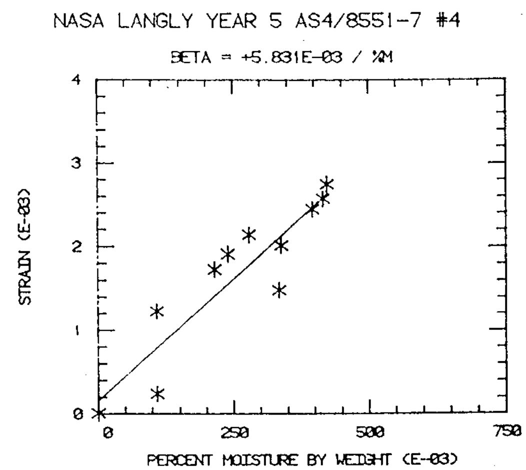
BETA = +4.318E-03 / %M

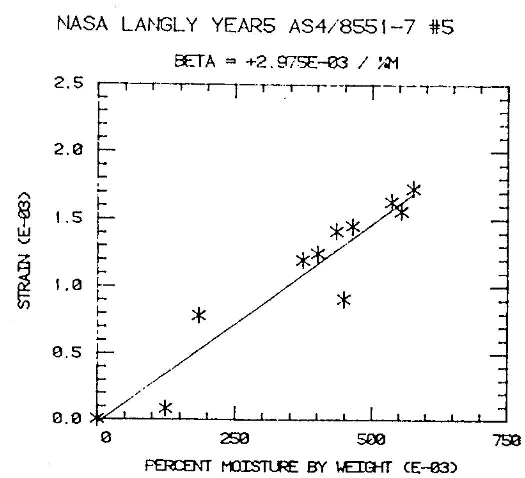


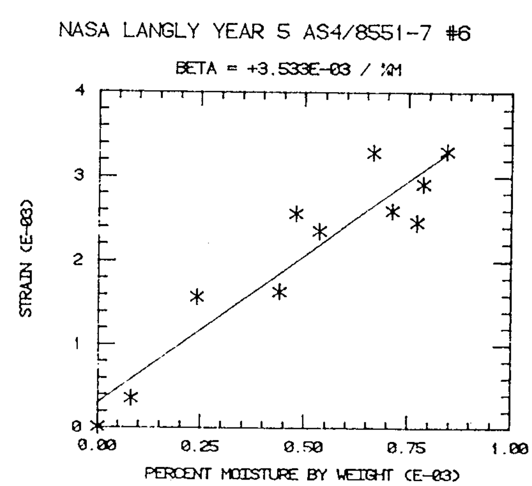
NASA LANGLY YEAR 5 AS4/8551-7 #3

BETA = +3.545E-03 / %M




NASA LANGLY YEAR 5 AS4/8551-7 #4
BETA = +5.831E-03 / %M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT (E-03)
0
1
2
3
4
0
250
500
750


NASA LANGLY YEAR5 AS4/8551-7 #5
BETA = +2.975E-03 / %M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT (E-03)
0.0
0.5
1.0
1.5
2.0
2.5
0
250
500
750


NASA LANGLY YEAR 5 AS4/8551-7 #6
BETA = +3.533E-03 / %M
STRAIN (E-03)
PERCENT MOISTURE BY WEIGHT (E-03)
0
1
2
3
4
0.00
0.25
0.50
0.75
1.00

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National Aeronautics and Space Administration

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16. Abstract
The mechanical and physical properties of three neat matrix materials, i.e., PEEK (polyetheretherketone) thermoplastic, Hexcel F155 rubber-toughened epoxy and Hercules 8551-7 rubber-toughened epoxy, were experimentally determined. Twelve unidirectional carbon fiber composites, incorporating matrix materials characterized in this or earlier studies (with one exception; the $PISO_2$-TPI matrix itself was not characterized), were also tested. These composite systems included AS4/2220-1, AS4/2220-3, T500/R914, IM6/HX1504, T300/4901A (MDA), T700/4901A (MDA), T300/4901B (MPDA), T700/4901B (MPDA), APC2 (AS4/PEEK, ICI), APC2 (AS4/PEEK, Langley Research Center), AS4/8551-7, and AS4/$PISO_2$-TPI.

For the neat matrix materials, the tensile, shear, fracture toughness, coefficient of thermal expansion, and coefficient of moisture expansion properties were measured as a function of both temperature and moisture content.

For the unidirectional composites, axial and transverse tensile, longitudinal shear, coefficient of thermal expansion, and coefficient of moisture expansion properties were determined, at room temperature and 100°C.

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