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TENSILE, COMPRESSIVE, AND SHEAR PROPERTIES OF A 96-kg/m^3 POLYURETHANE FOAM AT LOW TEMPERATURES

National Bureau of Standards
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This document contains the mechanical property data for polyurethane foam (96-kg/m^3) at 295, 111, 76, and 4 K. The engineer or scientist will find the data included in this report valuable when designing with polyurethane foam.

CONTENTS

Tensile, Compressive, and Shear Properties of a 96-kg/m^3 Polyurethane Foam at Low Temperatures

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Polyurethane foam, having a density of 96 kg/m^3, was tested at 295, 111, 76, and 4 K. The material properties reported are Young's modulus, proportional limit, yield strength (at 0.2% offset), tensile, shear, and compressive strengths, and elongation (elastic and plastic). The test apparatus permits tension, compression, and shear testing of materials at any temperature ranging from 295 to 1.8 K. Strain is measured with a concentric, overlapping-cylinder, capacitance extensometer that is highly sensitive and linear in output. The extent of linearity was in excess of 2.5 cm for the cylinder geometry chosen, and the signal noise level was only 10^{-6} cm/cm.

Key words: compressive strength; elongation; foam; insulation; low temperatures; mechanical properties; proportional limit; shear strength; tensile strength; yield strength; Young's modulus.

1. INTRODUCTION

In a continuing effort to increase the available knowledge of the mechanical properties of polyurethane foam (PU), a foam of density 96 kg/m^3 was subjected to the same test program as was previously conducted on less dense materials [1,2]. The data presented will complete a three year effort to characterize the mechanical properties of three densities of PU foam at low temperatures. Previous reports on the mechanical properties of 32 and 64 kg/m^3 density foams may be obtained from the National Technical Information Service (NTIS), Springfield, VA 22161 (request NBSIR 81-1654 and NBSIR 83-1684 respectively).

The apparatus used [1,2] has the capability of operating at various temperatures (295 K to 4 K), in gas or liquid environments and at pressures from subatmospheric to 0.3 MPa absolute. Strain is measured by utilizing concentric overlapping-cylinders and the change in electrical capacitance [3]. This method for strain extensometry is accurate to better than 0.1 percent, linear in excess of 2.5 cm elongation, functions well in low temperature environments, and provides a low-noise output signal ($\leq 10^{-6}$ cm/cm) as long as the device is situated in a stable single-phase fluid [4,5]. The calibration can be accomplished at room temperature, in air, and to conduct a test in any other medium (e.g., liquid nitrogen) the original calibration need only be corrected for the change in dielectric constant [6].

2. MATERIAL CHARACTERIZATION

The material tested in this study is a nominal 96 kg/m^3 PU foam. This amorphous, organic polymer is a thermosetting foam. Our supply of this material was obtained from a commercial producer.

The shear specimens, 1.9 X 2.54 X 0.4 cm, were epoxied to flat plates and each plate was attached to the tensile pull-rod system. An aluminum cylinder slipped over the specimen plates with a resistive heater and thermocouple, built into the cylinder, was used for temperature control during a test.

4. TEST PROCEDURE

Tests were conducted at 295 K (air), 111 K (GN_2), 76 K (LN_2), and 4 K (LH_e). A minimum of three samples were tested at each temperature, and in some cases several more were tested to determine material variability. Minimization of thermal shock to the sample was accomplished by using very slow transfer rates of liquid helium or nitrogen; on the order of 0.2ℓ min^{-1}. A given temperature was held for a minimum of 15 minutes prior to testing, in order to ensure that the specimen was isothermal.

Each specimen was "conditioned" in an environmental chamber for at least four days at 23°C and 50 percent relative humidity. Tension, compression, and shear tests were conducted using a conventional tension/compression test machine at a strain rate of 5×10^{-3} min^{-1}. Preliminary tests were conducted, varying the strain rate from 5×10^{-2} to 5×10^{-4} min^{-1}. The test results indicated there was no measurable effect on the mechanical property values.

Tensile and compressive properties reported include: Young's modulus, proportional limit, yield strength (at 0.2% offset), ultimate strength, and elongation (elastic and plastic).

5. RESULTS

Results are presented in figures 1 through 12 and tables 1 through 6. The bars on these figures indicate the data spread from replicate tests. The scatter is typically higher for compression and shear than for tensile tests because the compressive and shear tests are more sensitive to misalignment during testing (tensile specimens tend to self-align).

All properties were determined in both the longitudinal and transverse orientations. The temperature dependent tensile results for Young's modulus, strength, and strain are shown in figures 1 through 3. Tensile stress versus strain at all test temperatures is shown in figure 4. Temperature dependent compressive results for Young's modulus, strength, proportional limit, yield strength, and strain are shown in figures 5 through 9. Compressive stress versus strain at all test temperatures is shown in figure 10. Figure 11 shows a typical load versus displacement plot that was taken during an actual test. The shear strength versus temperature is plotted in figure 12.

Tables 1 through 3 give the tensile, compressive, and shear results for individual specimens and tables 4 through 6 give the average values for all tests.

Owing to material variability, the stress versus strain graphs were plotted as smooth curves, which do not illustrate the individual cell failure phenomena. Each stress versus strain curve at a given temperature and orientation is the average of three or more specimens tested.

6. DISCUSSION OF RESULTS

Compressive and tensile strength, proportional limit, yield strength, and Young's modulus increase with decreasing temperature. The longitudinally oriented specimens are always higher in strength than those obtained from the transverse orientation.

As shown in figure 3, tensile strain decreases with temperature as the material becomes brittle at temperatures below 111 K. Both tensile and compressive stress versus strain plots (see figures 4 and 10) illustrate the behavior of longitudinal and transverse specimens tested at 295, 111, 76, and 4 K.

Figure 11 is an actual record of load versus displacement for a typical specimen. The load drops that occur at low temperature may be associated with individual or multiple cells collapsing [7,8]. Because the material is less brittle at room temperature this phenomena is not seen.

The shear strength, as shown in figure 12, increases from room temperature to 111 K and then levels off as the test temperature decreases to 4 K. The large range of values of shear strength at a given temperature, as shown in figure 12, could result from misalignment during a test; and except for tests at 76 K the longitudinal and transverse curves are similar.

It is believed that thermal cycling produces cell degradation [9]. Variables such as thermal cycling, moisture content, aging, and others could be studied in the near future.

ACKNOWLEDGMENT

The authors are indebted to Edward A. Pierson for his assistance in the preparation of this manuscript for publication.

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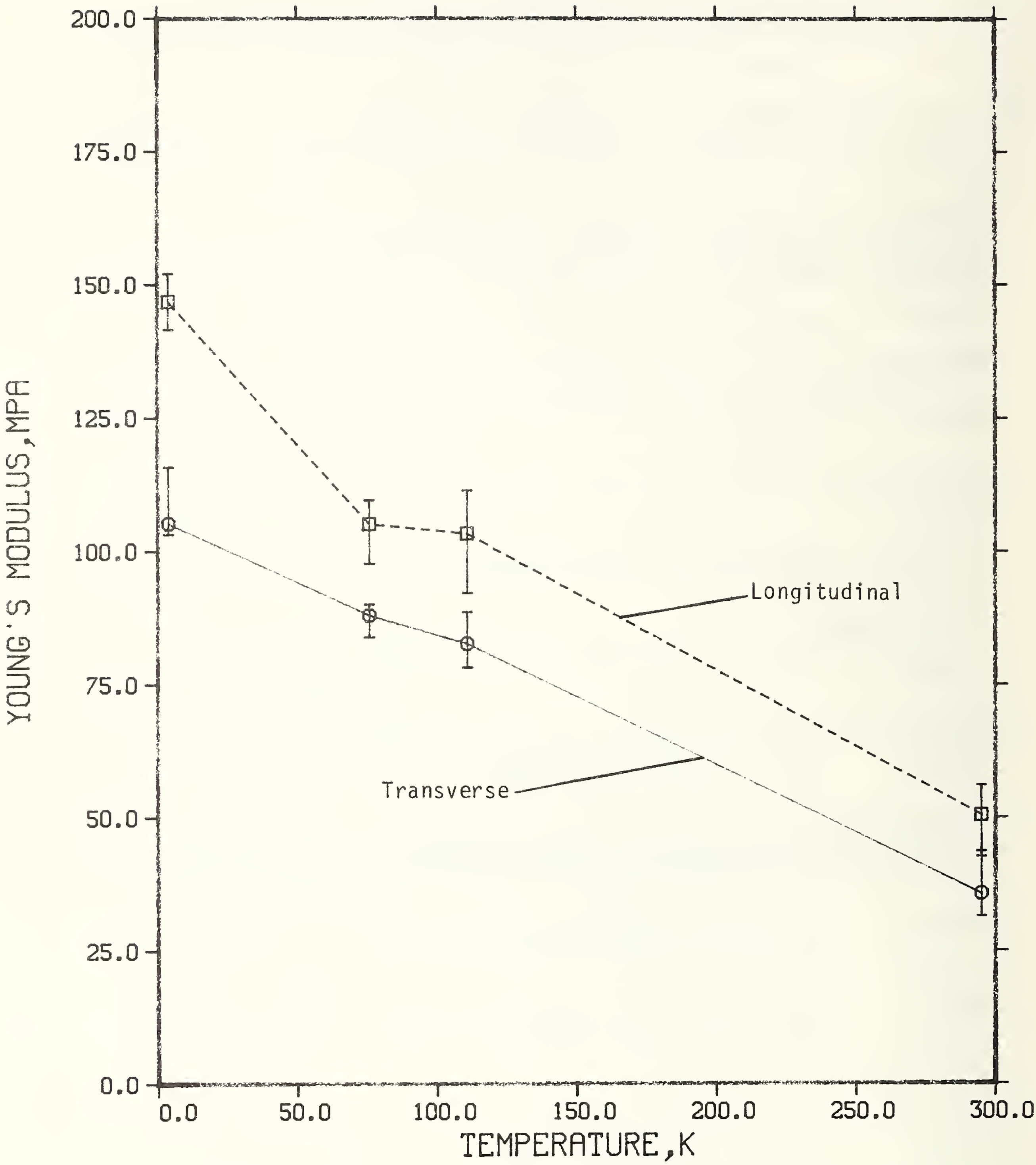

Figure 1. Tensile Young's modulus versus temperature.

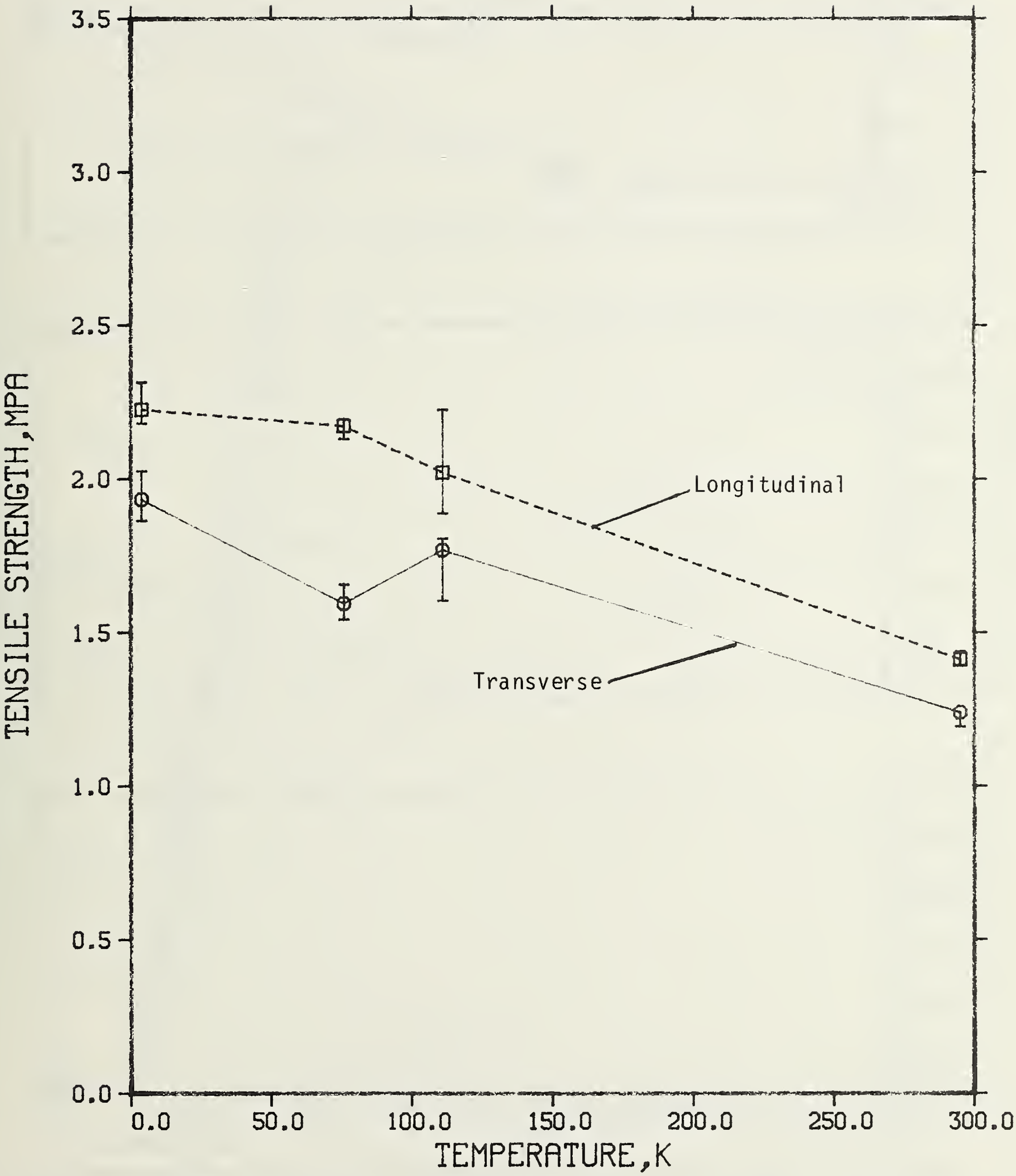

Figure 2. Ultimate tensile strength versus temperature.

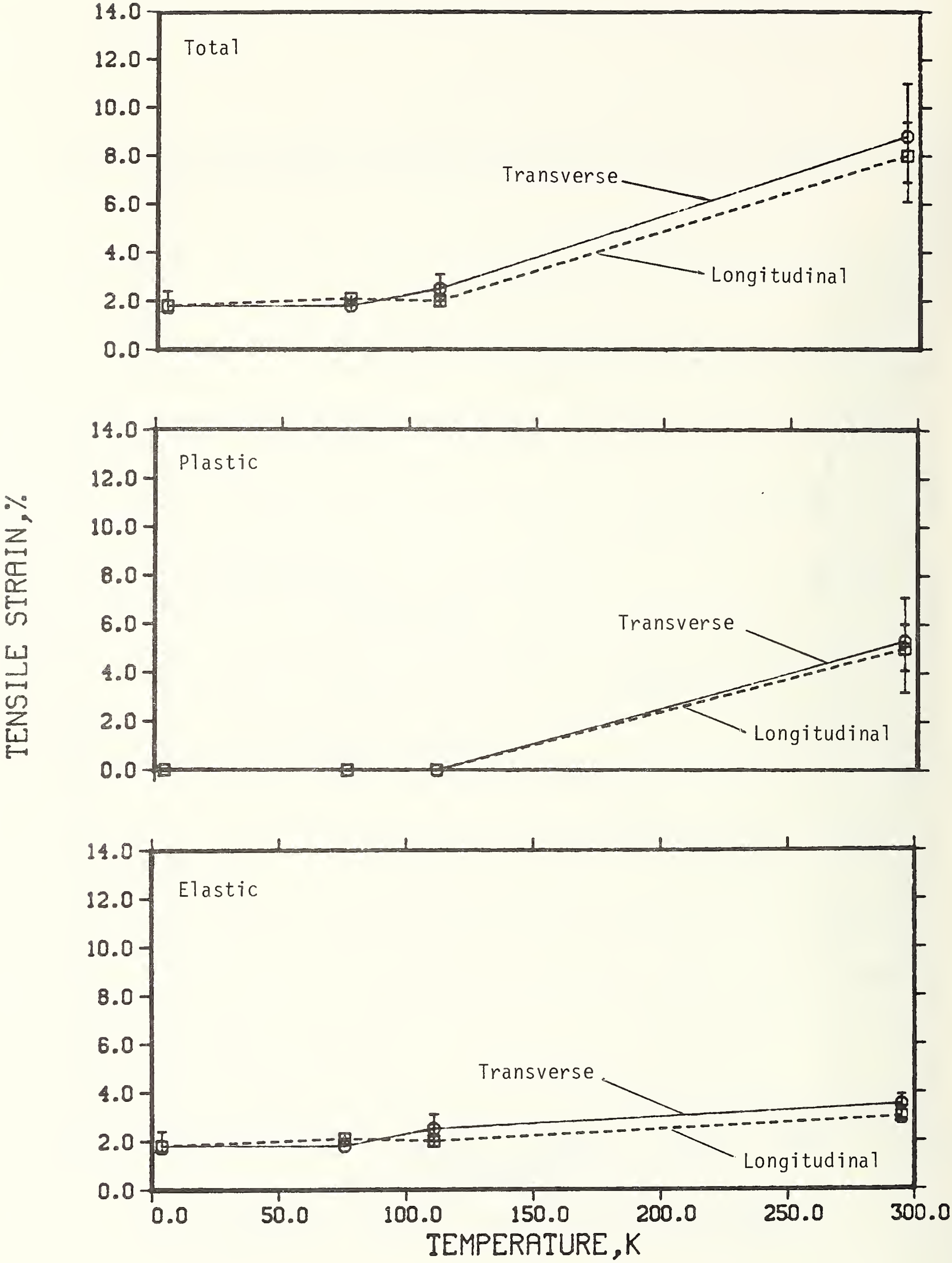

Figure 3. Tensile strain versus temperature.

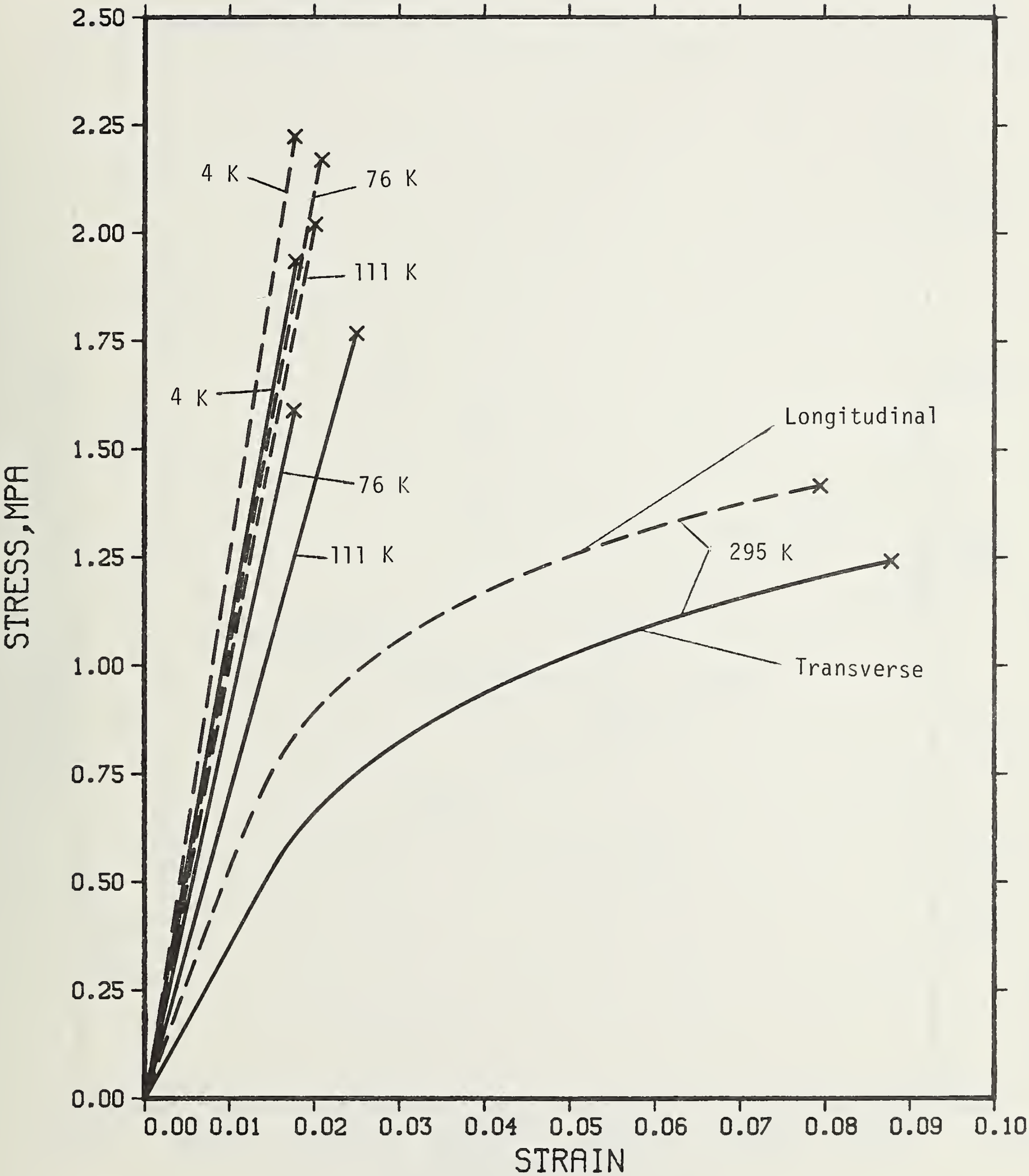

Figure 4. Tensile stress versus strain (longitudinal and transverse).

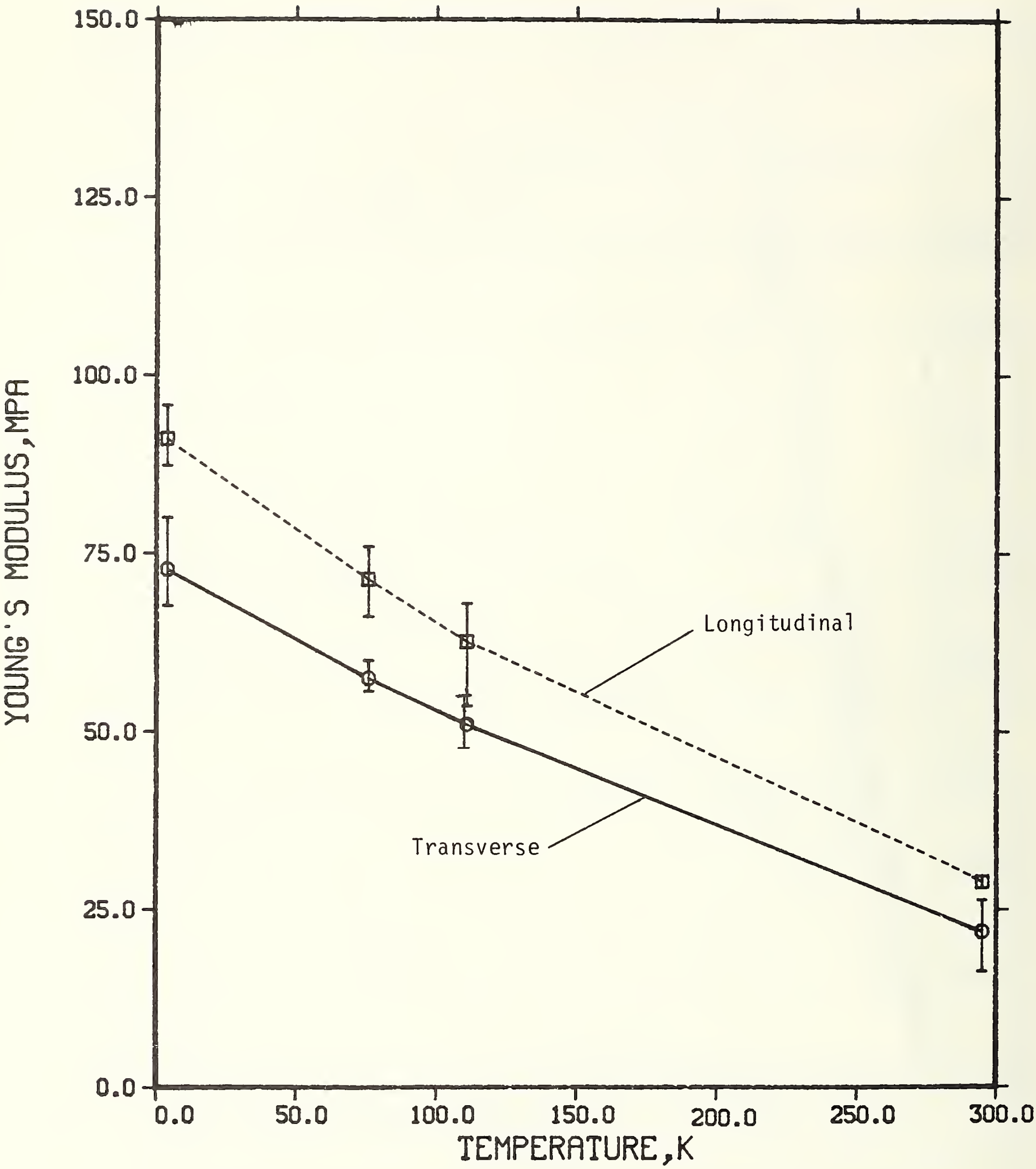

Figure 5. Compressive Young's modulus versus temperature.

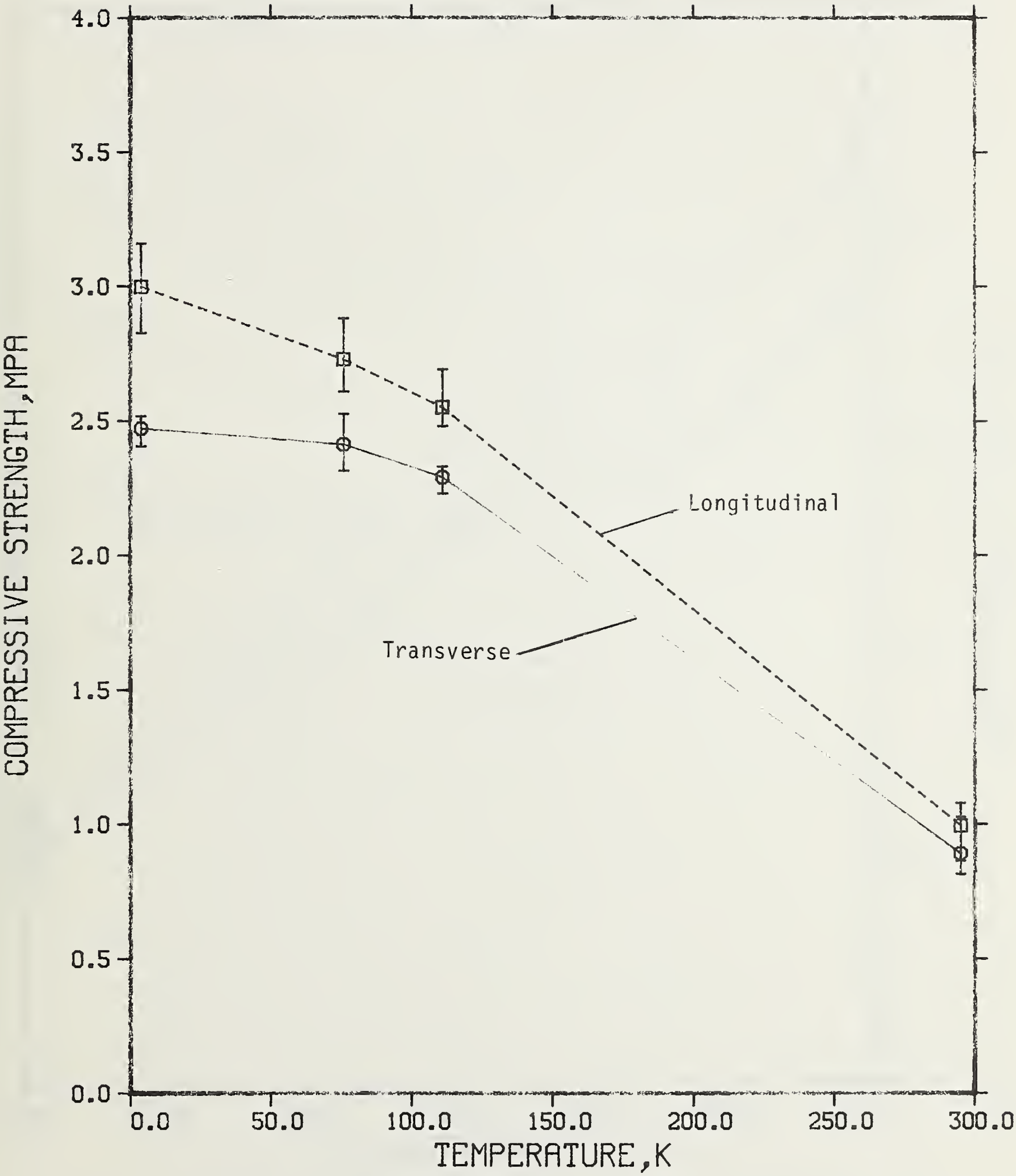

Figure 6. Compressive strength versus temperature.

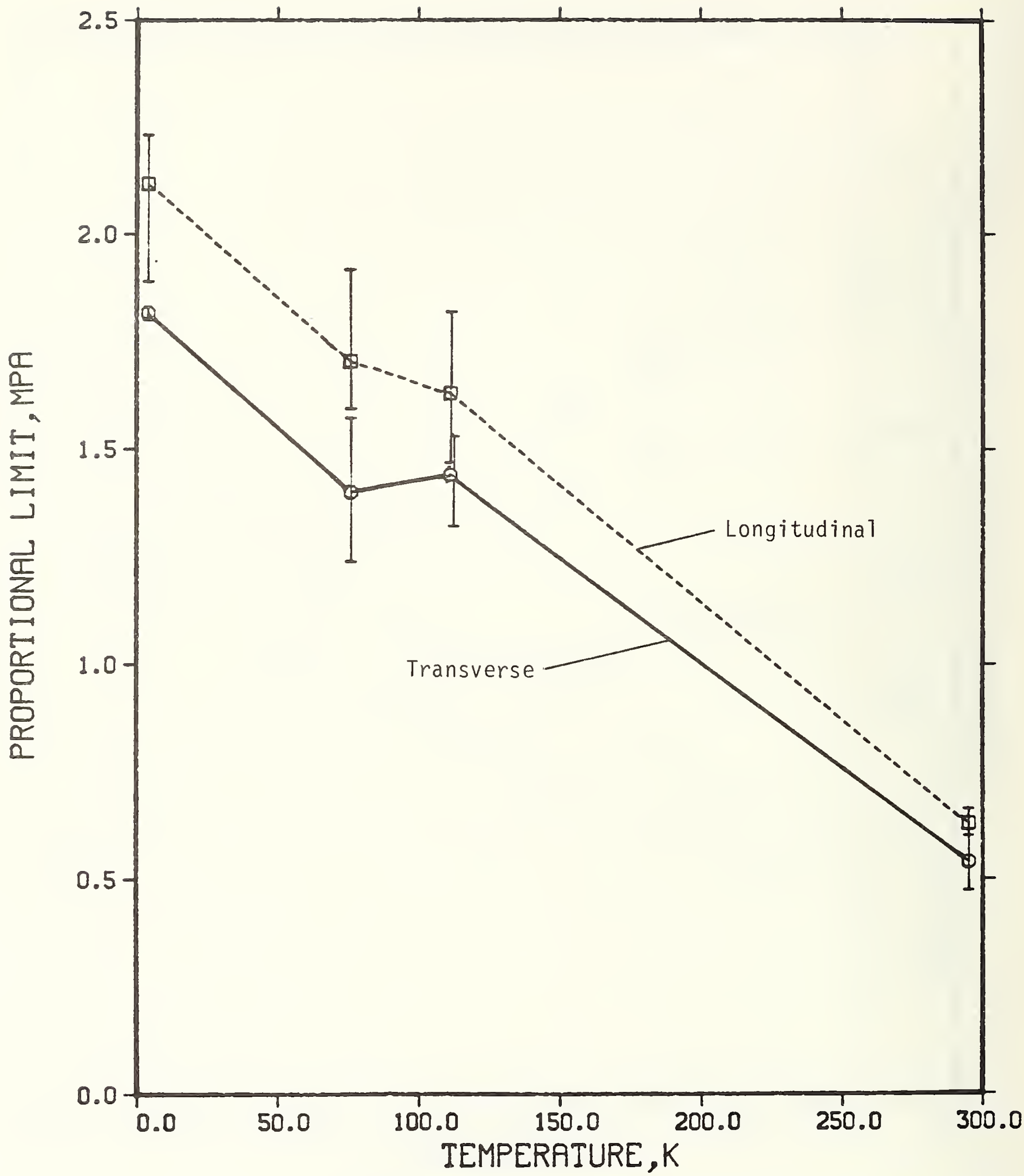

Figure 7. Compressive proportional limit versus temperature.

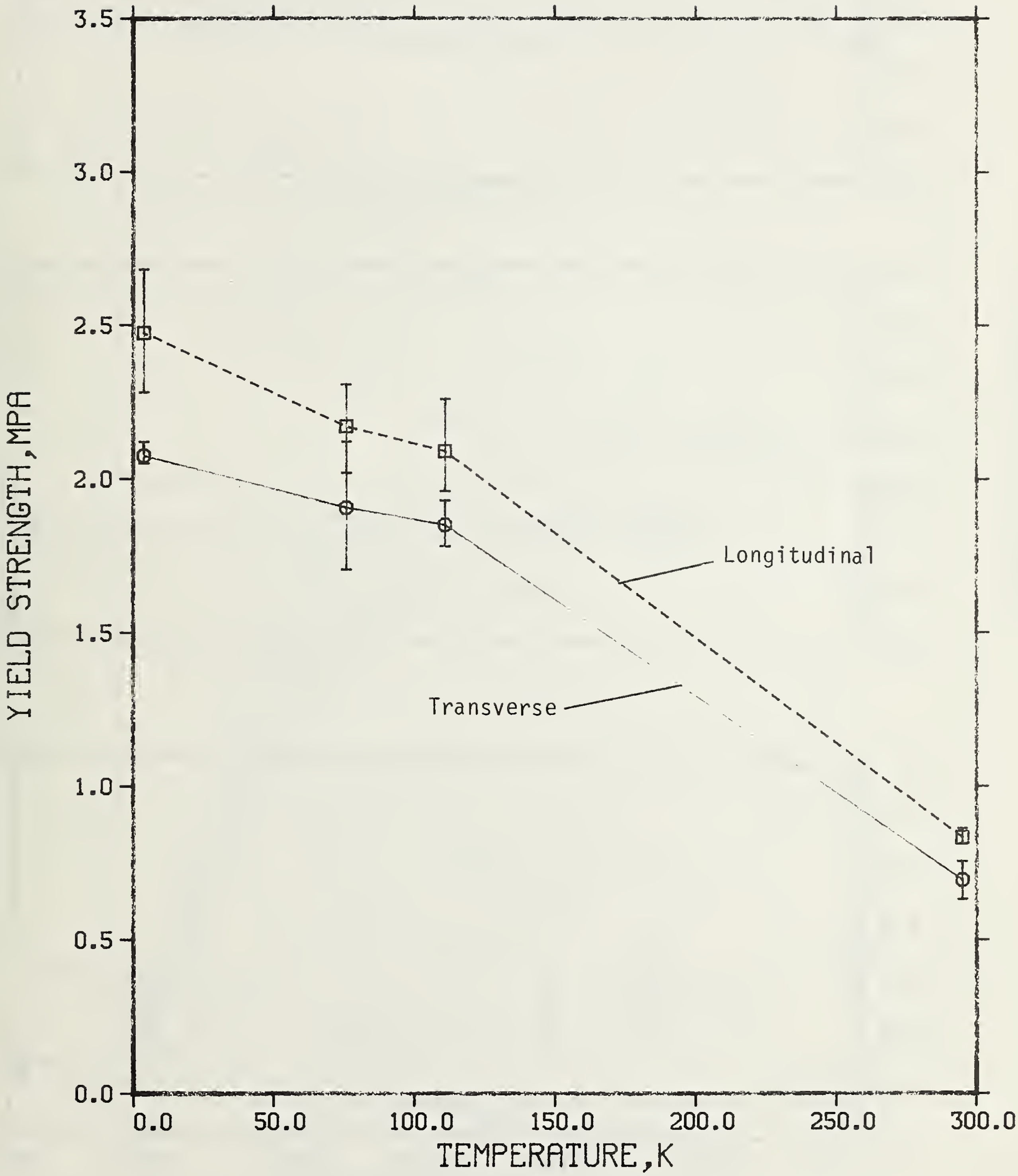

Figure 8. Compressive yield strength versus temperature.

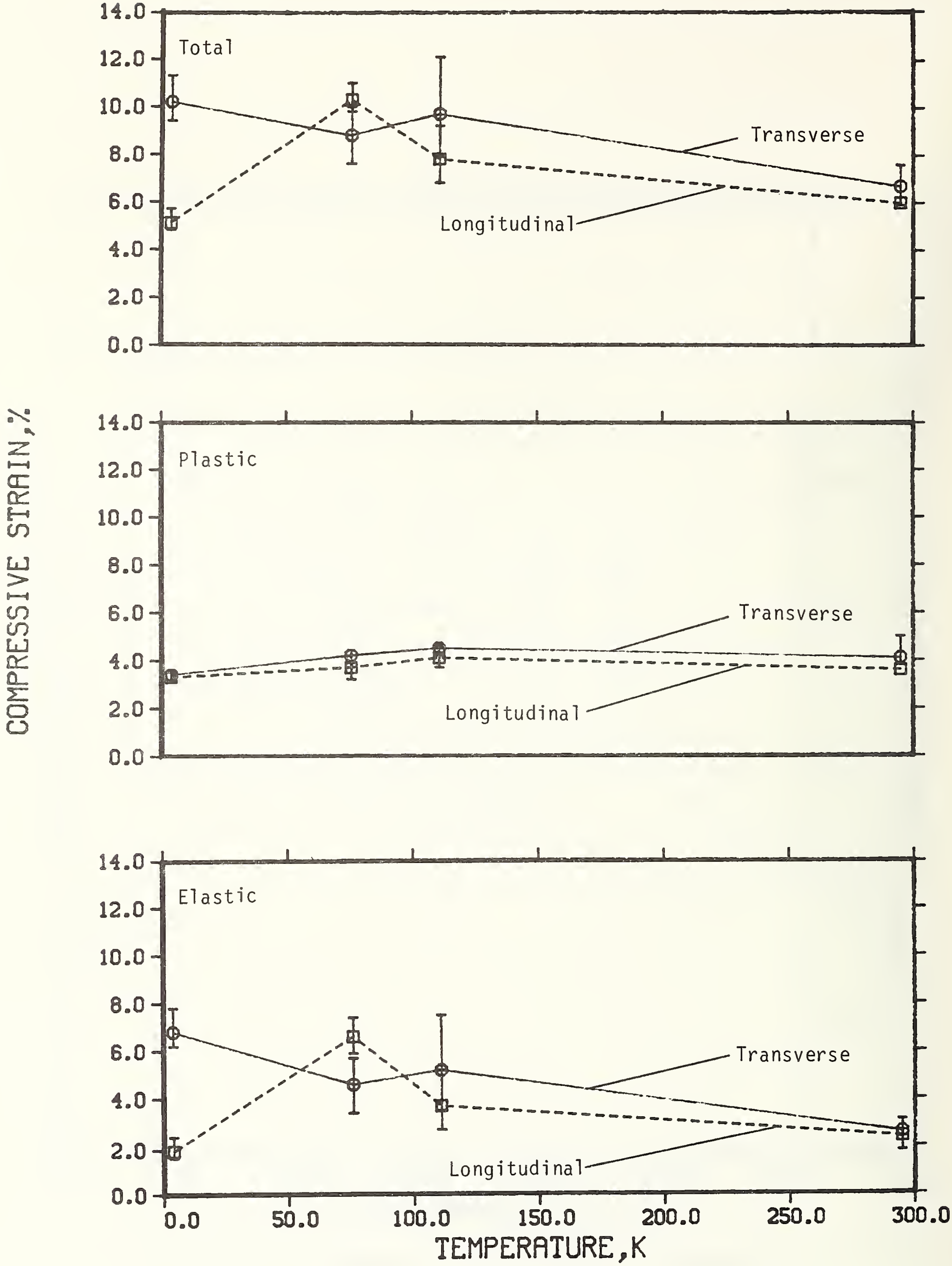

Figure 9. Compressive strain versus temperature.

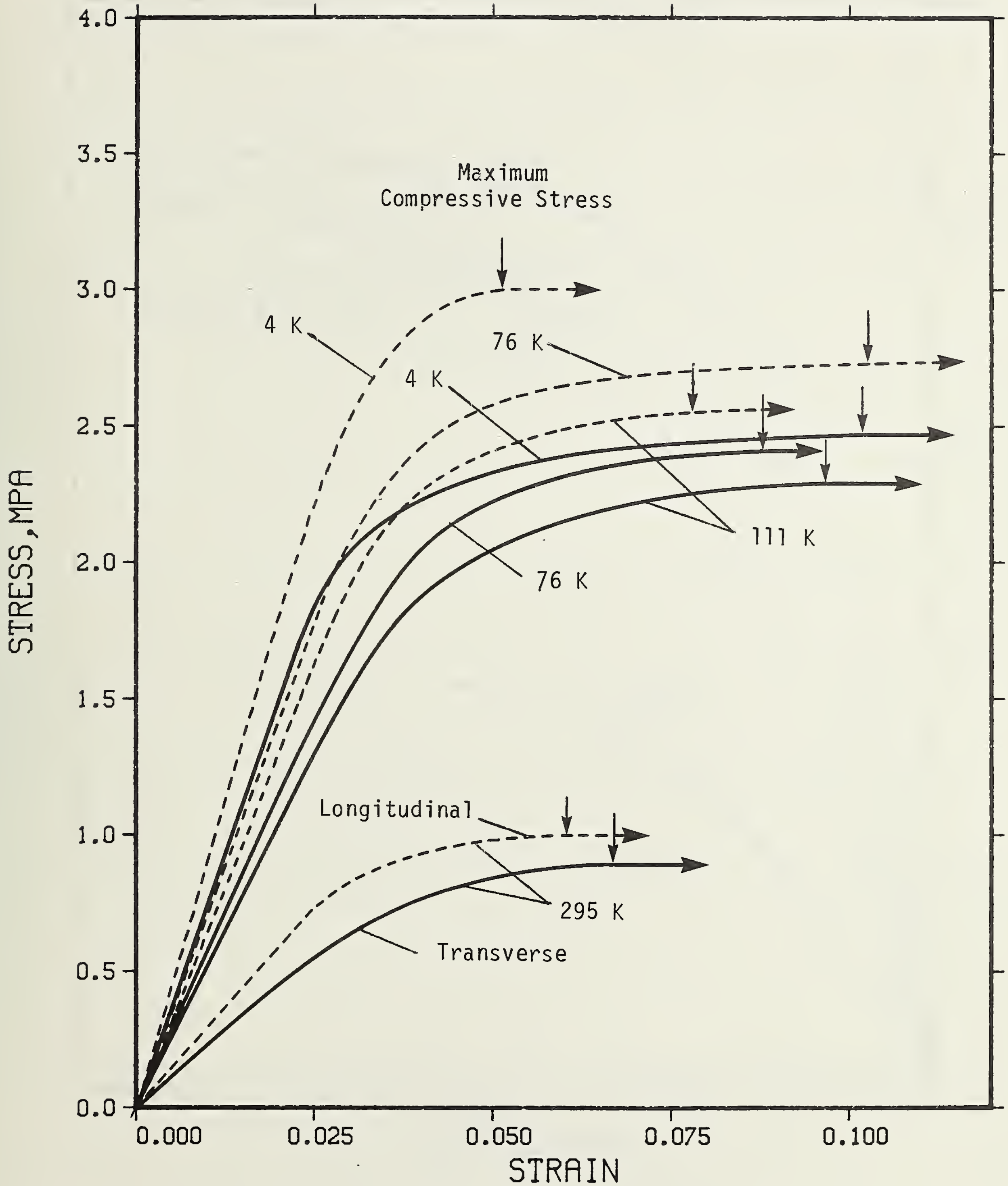

Figure 10. Compressive stress versus strain (longitudinal and transverse).

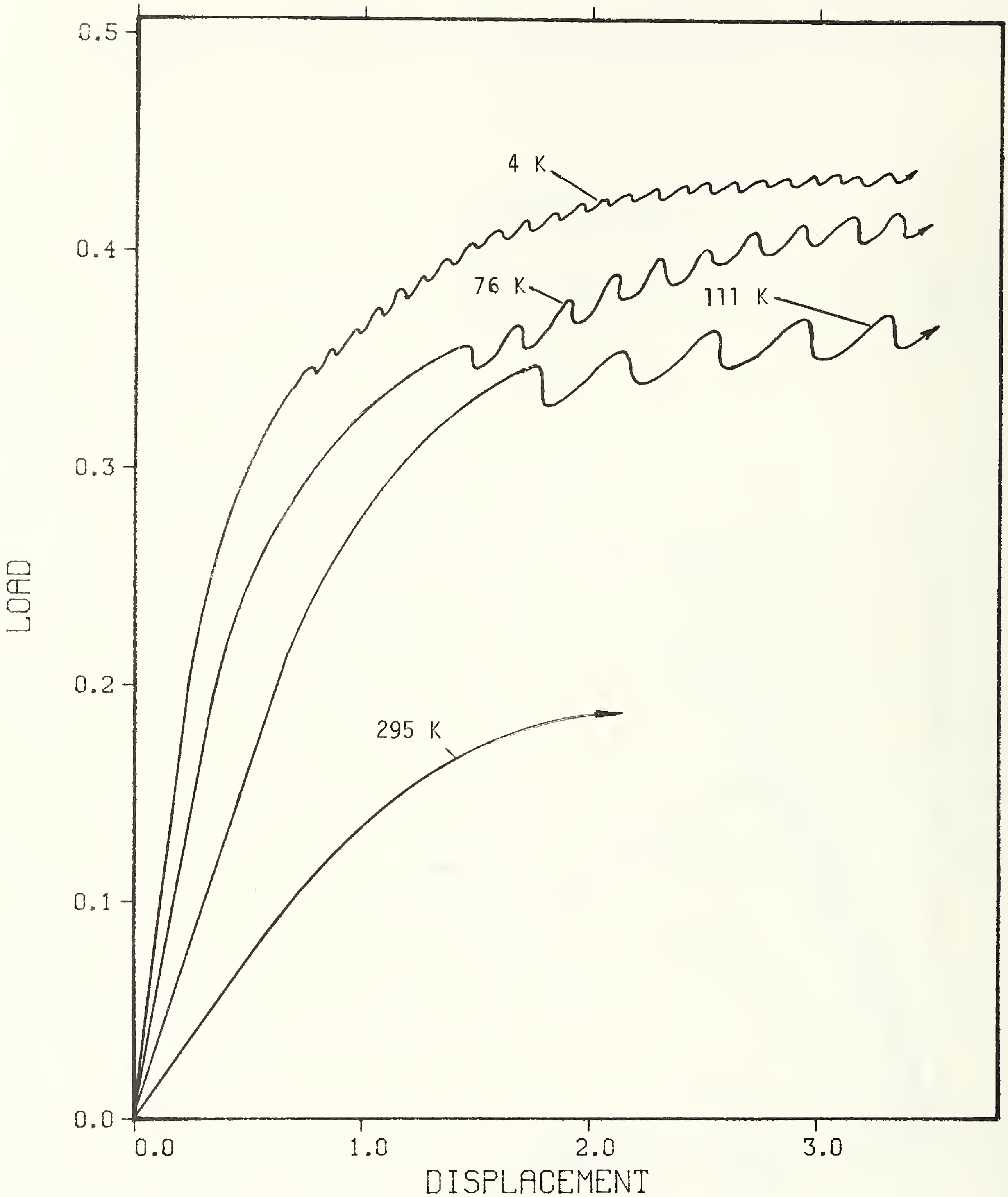

Figure 11. Typical load versus displacement (arbitrary units).

Table 1. Tensile test results for a 96-kg/m^3 polyurethane foam

Specimen number		Test temp., K	Specimen orientation[a]	Young's modulus, MPa	Young's modulus, psi	Proportional limit, MPa	Proportional limit, psi	Yield strength (at 0.2% offset), MPa	Yield strength (at 0.2% offset), psi	Ultimate tensile strength, MPa	Ultimate tensile strength, psi	Tensile strain, % Elastic	Tensile strain, % Plastic	Tensile strain, % Total
1LT	2LRT	295	L	52.68	7639	0.447	64.80	0.784	113.60	1.437	208.35	2.8	4.1	6.9
25LT	26LRT	295	L	42.60	6178	0.638	92.49	0.940	136.35	1.407	204.07	3.4	6.0	9.4
49LT	56LRT	295	L	56.09	8134	0.467	67.73	0.756	109.71	1.391	201.77	2.7	5.0	7.7
				$\bar{x}$ = 50.46	7317	0.517	75.01	0.827	119.89	1.412	204.73	3.0	5.0	8.0
16TT	2TRT	295	T	34.72	5034	0.381	55.21	0.667	96.79	1.239	179.70	3.6	5.0	8.6
19TT	38TRT	295	T	32.02	4643	0.407	59.07	0.580	84.12	1.286	186.41	3.8	6.8	10.6
22TT	62TRT	295	T	31.41	4555	0.439	63.64	0.672	97.42	1.193	172.95	3.9	7.1	1.0
28TT		295	T	34.06	4939	0.429	62.23	0.684	99.21	--	--	3.6	5.2	8.8
37TT		295	T	38.16	5533	0.442	64.02	0.672	97.39	--	--	3.3	4.7	8.0
52TT		295	T	43.64	5173	0.384	55.66	0.651	94.42	--	--	2.9	3.2	6.1
				$\bar{x}$ = 35.67	4979	0.414	59.97	0.654	94.89	1.239	179.70	3.5	5.3	8.8
13LT	14LR	111	L	92.19	13371	--	--	--	--	1.887	273.68	2.2	0	2.2
43LT	32LRT	111	L	106.53	15451	--	--	--	--	1.948	282.48	1.9	0	1.9
61LT	62LRT	111	L	111.49	16170	--	--	--	--	2.224	322.51	1.8	0	1.8
				$\bar{x}$ =103.40	14997					2.020	292.90	2.0	0	2.0
7TT	26TRT	111	T	81.21	11779	--	--	--	--	1.804	261.60	2.4	0	2.4
25TT	56TRT	111	T	78.23	11346	--	--	--	--	1.895	274.81	3.1	0	3.1
49TT	99TRT	111	T	88.66	12859	--	--	--	--	1.602	232.38	2.0	0	2.0
				$\bar{x}$ = 82.70	11995					1.767	256.26	2.5	0	2.5
7LT	8LRT	76	L	108.11	15680	--	--	--	--	2.129	308.76	2.0	0	2.0
31LT	20LRT	76	L	109.65	15903	--	--	--	--	2.194	318.19	2.0	0	2.0
55LT	80LRT	76	L	97.69	14169	--	--	--	--	2.194	318.19	2.2	0	2.2
				$\bar{x}$ =105.15	15251	--	--	--	--	2.172	315.05	2.1	0	2.1
10TT	8TRT	76	T	83.89	12076	--	--	--	--	1.584	229.64	1.9	0	1.9
31TT	32TRT	76	T	90.05	13060	--	--	--	--	1.655	239.91	1.8	0	1.8
43TT	68TRT	76	T	90.05	13060	--	--	--	--	1.541	223.50	1.8	0	1.8
				$\bar{x}$ = 88.00	12762	--	--	--	--	1.593	231.03	1.8	0	1.8
50LRT		4	L			--	--	--	--	2.180	316.22	2.4	0	2.4
67LT	68LRT	4	L	141.57	20532	--	--	--	--	2.314	335.66	1.5	0	1.5
97LT	104LRT	4	L	152.04	22051	--	--	--	--	2.180	316.22	1.5	0	1.5
				$\bar{x}$ =146.81	21292	--	--	--	--	2.225	322.70	1.8	0	1.8
13TT	44TRT	4	T	103.15	14961	--	--	--	--	1.863	270.09	1.9	0	1.9
34TT	50TRT	4	T	115.80	16795	--	--	--	--	2.025	293.67	1.7	0	1.7
46TT	165TRT	4	T	108.02	15667	--	--	--	--	1.190	277.06	1.8	0	1.8
				$\bar{x}$ =105.15	15808	--	--	--	--	1.933	280.27	1.8	0	1.8

[a] L: longitudinal; T: transverse

Table 2. Compressive test results for a 96-kg/m^3 polyurethane foam

Specimen number	Test temp., K	Specimen orientation	Young's modulus, MPa	Young's modulus, psi	Proportional limit, MPa	Proportional limit, psi	Yield strength (at 0.2% offset), MPa	Yield strength (at 0.2% offset), psi	Maximum compressive strength, MPa	Maximum compressive strength, psi	Compressive strain, % Elastic	Compressive strain, % Plastic	Compressive strain, % Total
6LC (A)	295	L	28.85	4183	0.600	87.05	0.827	119.89	0.863	125.11	3.6	2.3	5.9
21LC (B)	295	L	29.70	4307	0.663	96.15	0.811	117.58	1.078	150.25	3.6	2.4	6.0
30LC (C)	295	L	28.18	4086	0.624	90.44	0.862	124.96	1.042	151.11	3.6	2.5	6.1
		$\bar{x}$ =	28.91	4192	0.629	91.21	0.833	120.83	0.994	144.18	3.6	2.4	6.0
3TC (A)	295	T	16.30	2364	0.598	86.77	0.697	101.10	0.827	119.80	5.0	2.6	7.6
6TC (A)	295	T	20.32	2947	0.506	73.30	0.631	91.54	0.813	117.92	4.1	2.7	6.8
12TC (A)	295	T	20.80	3015	0.614	89.02	0.730	105.85	0.850	123.25	4.1	2.6	6.7
15TC (A)	295	T	21.53	3121	0.511	74.14	0.685	99.32	0.870	126.08	4.0	1.8	5.8
18TC (A)	295	T	20.80	3015	0.521	75.55	0.655	94.91	0.835	121.00	3.9	2.7	6.6
21TC (A)	295	T	22.19	3218	0.569	82.56	0.695	100.80	0.869	126.06	3.9	2.3	6.2
24TC (A)	295	T	22.01	3191	0.517	74.98	0.687	99.68	0.869	126.06	4.2	2.7	6.9
39TC (A)	295	T	23.65	3430	0.473	68.51	0.681	98.76	0.947	137.36	3.9	3.1	7.0
45TC (A)	295	T	24.82	3600	0.530	76.83	0.724	105.06	0.991	143.75	3.9	2.9	6.8
51TC (A)	295	T	26.33	3820	0.554	80.34	0.755	109.54	1.026	148.75	3.8	2.5	6.3
		$\bar{x}$ =	21.88	3172	0.539	78.20	0.694	100.63	0.890	129.01	4.1	2.6	6.7
9LC (C)	111	L	67.94	9854	1.472	213.50	1.963	284.64	2.489	360.89	3.7	3.1	6.8
18LC (B)	111	L	53.58	7771	1.612	233.74	2.037	295.38	2.480	359.59	4.6	2.7	7.3
30LC (A)	111	L	66.28	9613	1.819	263.69	2.260	327.67	2.692	390.32	4.0	5.2	9.2
		$\bar{x}$ =	62.60	9079	1.634	236.98	2.087	302.56	2.554	370.27	4.1	3.7	7.8
3TC (D)	111	T	47.77	6929	1.429	207.28	1.821	264.07	2.231	323.50	4.6	7.5	12.1
9TC (D)	111	T	50.80	7368	1.496	216.89	1.883	273.08	2.270	329.27	4.4	3.5	7.9
12TC (B)	111	T	54.87	7958	1.324	192.06	1.783	258.63	2.331	338.01	4.2	4.4	8.6
18TC (C)	111	T	50.59	7337	1.518	220.11	1.928	279.68	2.321	336.65	4.6	5.6	10.2
		$\bar{x}$ =	51.01	7398	1.442	209.09	1.854	268.87	2.288	331.86	4.5	5.2	9.7
6LC (B)	76	L	73.72	10689	1.710	247.96	2.286	331.50	2.880	417.63	3.9	6.2	10.1
12LC (A)	76	L	69.55	10084	1.917	277.99	2.307	334.57	2.741	397.44	3.9	5.9	9.8
18LC (C)	76	L	66.09	9583	1.594	231.13	2.019	292.77	2.608	378.11	3.2	6.8	10.0
2LC (C)	76	L	75.94	11011	1.594	231.13	2.072	300.48	2.683	389.09	3.6	7.4	11.0
		$\bar{x}$ =	71.33	10342	1.704	247.05	2.171	314.80	2.728	395.56	3.7	6.6	10.3
6TC (A)	76	T	55.61	8064	1.238	179.51	1.704	247.16	2.314	335.62	4.1	4.8	8.9
9TC (B)	76	T	56.69	8220	1.390	201.53	1.893	274.47	2.395	347.42	4.3	5.7	10.0
21TC (A)	76	T	59.96	8695	1.573	228.07	2.121	307.59	2.526	366.23	4.2	3.4	7.6
		$\bar{x}$ =	57.42	8326	1.400	203.05	1.906	276.41	2.412	349.69	4.2	4.6	8.8
3LC (A)	4	L	95.74	13883	2.231	323.53	2.681	388.76	3.158	457.91	3.3	1.5	4.8
15LC (B)	4	L	90.14	13070	2.230	323.53	2.460	356.67	3.008	436.22	3.3	2.4	5.7
24LC (C)	4	L	87.27	12654	1.889	263.59	2.281	330.77	2.825	409.59	3.2	1.6	4.8
		$\bar{x}$ =	91.05	13202	2.117	303.49	2.474	358.73	2.997	434.57	3.3	1.8	5.1
6TC (B)	4	T	67.63	9806	1.800	260.92	2.120	307.42	2.405	348.75	3.5	7.8	11.3
21TC (B)	4	T	70.50	10223	1.821	264.04	2.053	297.70	2.517	365.01	3.6	6.5	10.1
24TC (B)	4	T	79.99	11599	1.827	264.90	2.051	297.36	2.490	360.99	3.2	6.2	9.4
		$\bar{x}$ =	72.71	10543	1.816	263.29	2.075	300.83	2.471	358.25	3.4	6.8	10.2

Table 3. Shear strength test results for a 96-kg/m^3 polyurethane foam

Specimen number	Test temperature, K	Specimen orientation		Shear strength, MPa	psi
SL1	295	L		0.902	130.76
SL5	295	L		0.812	117.80
SL10	295	L		0.824	119.53
			$\bar{x}$ =	0.846	122.70
ST2	295	T		0.955	138.52
ST9	295	T		0.864	125.33
ST14	295	T		0.860	124.78
			$\bar{x}$ =	0.893	129.54
SL2	111	L		1.218	176.70
SL6	111	L		1.051	152.38
SL11	111	L		1.073	155.67
			$\bar{x}$ =	1.114	161.58
ST4	111	T		1.102	159.83
ST6	111	T		1.063	154.18
ST10	111	T		1.162	168.55
			$\bar{x}$ =	1.109	160.85
SL3	76	L		0.938	136.10
SL7	76	L		1.073	155.62
SL12	76	L		1.062	154.06
			$\bar{x}$ =	1.025	148.59
ST3	76	T		1.150	166.73
ST11	76	T		1.114	161.59
ST16	76	T		1.090	158.13
			$\bar{x}$ =	1.118	162.15
SL4	4	L		1.069	155.03
SL9	4	L		1.152	167.05
SL15	4	L		0.973	141.05
			$\bar{x}$ =	1.064	154.38
ST1	4	T		0.975	141.48
ST7	4	T		1.014	147.05
ST13	4	T		1.071	155.32
			$\bar{x}$ =	1.020	147.95

Table 4. Summary of tensile test results for a 96-kg/m^3 polyuretane foam (average values)

Material property	Specimen orientation	Temperature 295 K	111 K	76 K	4 K
Young's modulus, MPa (psi)	L	50.46 (7,317)	103.4 (14,997)	105.15 (15,251)	146.81 (21,292)
	T	35.67 (4,979)	82.7 (11,995)	88.00 (12,762)	105.15 (15,808)
Proportional limit, MPa (psi)	L	0.517 (75.01)	--	--	--
	T	0.414 (59.97)	--	--	--
Yield strength (@ 0.2% offset), MPa (psi)	L	0.827 (119.89)	--	--	--
	T	0.654 (94.89)	--	--	--
Ultimate tensile strength, MPa (psi)	L	1.412 (204.73)	2.020 (292.9)	2.172 (315.05)	2.225 (322.7)
	T	1.239 (179.7)	1.767 (256.26)	1.593 (231.03)	1.933 (280.27)
Tensile Strain, %					
Elastic	L	3.0	2.0	2.1	1.8
Plastic		5.0	0.0	0.0	0.0
Total		8.0	2.0	2.0	1.8
Elastic	T	3.5	2.5	1.8	1.8
Plastic		5.3	0.0	0.0	0.0
Total		8.8	2.5	1.8	1.8

Table 5. Summary of compressive test results for a 96-kg/m^3 polyurethane foam (average values)

Material property	Specimen orientation	Temperature 295 K	111 K	76 K	4 K
Young's modulus, MPa (psi)	L	28.91 (4,192)	62.60 (9,079)	71.33 (10,342)	91.05 (13,202)
	T	21.79 (3,159)	51.01 (7,398)	57.42 (8,326)	72.71 (10,543)
Proportional limit, MPa (psi)	L	0.629 (91.21)	1.63 (237.0)	1.704 (247.05)	2.117 (303.49)
	T	0.539 (78.20)	1.44 (209.1)	1.400 (203.05)	1.816 (263.29)
Yield strength (0.2% offset), MPa (psi)	L	0.833 (120.83)	2.09 (302.6)	2.171 (314.80)	2.474 (358.73)
	T	0.694 (100.63)	1.85 (268.9)	1.906 (276.41)	2.075 (300.83)
Maximum compressive strength, MPa (psi)	L	0.994 (144.18)	2.55 (370.3)	2.728 (395.56)	2.997 (434.57)
	T	0.890 (129.01)	2.29 (331.8)	2.412 (349.69)	2.471 (358.25)
Compressive strain, %					
Elastic	L	3.6	4.1	3.7	3.3
Plastic	L	2.4	3.7	6.6	1.8
Total	L	6.0	7.8	10.3	5.1
Elastic	T	4.1	4.5	4.2	3.4
Plastic	T	2.6	5.2	4.6	6.8
Total	T	6.7	9.7	8.8	10.2

Table 6. Summary of shear strength test results for a 96-kg/m^3 polyurethane foam (average values)

Test temperature, K	Specimen orientation	Shear strength, MPa	psi
295	L	0.846	122.70
	T	0.893	129.54
111	L	1.114	161.58
	T	1.109	160.85
76	L	1.025	148.59
	T	1.118	162.15
4	L	1.064	154.38
	T	1.020	147.99

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Polyurethane foam, having a density of 96 kg/m^3, was tested at 295, 111, 76, and 4 K. The material properties reported are Young's modulus, proportional limit, yield strength (at 0.2% offset), tensile, shear, and compressive strengths, and elongation (elastic and plastic). The test apparatus permits tension, compression, and shear testing of materials at any temperature ranging from 295 to 1.8 K. Strain is measured with a concentric, overlapping-cylinder, capacitance extensometer that is highly sensitive and linear in output. The extent of linearity was in excess of 2.5 cm for the cylinder geometry chosen, and the signal noise level was only 10^{-6} cm/cm.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

compressive strength, elongation, foam, insulation, low temperatures, mechanical properties, proportional limit, shear strength, tensile strength, yield strength, Young's modulus

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