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Temperature Effects on High Strain Rate Properties of Graphite/Epoxy Composites

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TEMPERATURE EFFECTS ON HIGH STRAIN RATE PROPERTIES OF GRAPHITE/EPOXY COMPOSITE

ABSTRACT

A unidirectional graphite/epoxy material (AS4/3501-6) was characterized at strain rates ranging from 5×10^{-6} s^{-1} to 5 s^{-1}, at room temperature and at 128°C (263°F). Results are presented in the form of stress-strain curves to failure. The longitudinal properties remain nearly unchanged with strain rate and temperature. The transverse modulus increases with strain rate but decreases with temperature. The transverse strength and transverse ultimate tensile strain have a positive rate sensitivity at low rates which changes to negative at intermediate rates and returns to positive rate sensitivity at the highest rates tested. A temperature-time equivalence principle was applied and master curves were obtained for the transverse mechanical properties. The in-plane shear modulus and in-plane shear strength have a positive rate sensitivity. The ultimate intralaminar shear strain has a positive rate sensitivity at low rates, which changes to negative at high rates. At the elevated temperature of 128°C (263°F) the ultimate shear strain is 25-30% higher than the room-temperature value, but its strain rate dependence is moderate.

FOREWORD

This is an Interim Report on IIT Grant No. 5-54601, "Temperature Effects on High Strain Rate Properties of Graphite/Epoxy Composite", prepared by IIT for NASA-Lewis Research Center, under Grant No. NAG-3-423. The work described in this report was conducted in the period February 1, 1984 to June 30, 1985. Dr. C.C. Chamis was the NASA-Lewis Project Manager. Dr. I.M. Daniel of IIT was the Principal Investigator. Additional contributions to the work reported herein were made by Dr. G. Yaniv and Messrs. S. Cokeing and G.M. Martinez.

Respectfully submitted,
ILLINOIS INSTITUTE OF TECHNOLOGY

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TEMPERATURE EFFECTS ON HIGH STRAIN RATE PROPERTIES OF GRAPHITE/EPOXY COMPOSITE

1. INTRODUCTION

Some applications of composite materials involve dynamically loaded components and structures. For example, composite jet engine blades are exposed to the hazards of foreign object damage (FOD), such as bird impact on rotating blades. Such impact loadings are of short duration and produce stress (strain) wave pulses with strain rates up to a few hundred (m/m) per second. Reliable design of composite components for impact resistance requires characterization of the composite material at high strain rates.

In a recently completed program for the NASA-Lewis Research Center unidirectional and angle-ply composite laminates were characterized at strain-rates ranging from quasi-static to over $500 s^{-1}$.[1-3] Results were obtained for unidirectional, off-axis, and angle-ply laminates of two graphite/epoxy materials and a graphite/S-glass/epoxy hybrid. It was found that, in general, fiber-dominated properties did not increase much with strain rate, contrary to matrix-dominated properties which increased sharply. In most cases ultimate strains did not vary significantly with strain rate.

A need was recognized for determining the influence of environmental parameters, such as moisture and temperature, and defects, such as holes, cracks, or inclusions, on high strain rate properties of composites. The objective of the current investigation is to determine the effects of temperature, moisture content, and defects on the high strain rate properties of graphite/epoxy composite materials. Although it was desirable to continue with the same materials used in the previous study for NASA-Lewis Research Center, it was not possible to do so because the 3M company no longer supplies those prepreg materials.

The first candidate material recommended for this investigation was F-185/T300, having a rubber-modified epoxy resin matrix (F-185, Hexcel Corp.) and Thornel T300 (Union Carbide) fibers. The neat resin as well as the unidirectional F-185/T300 material were characterized mechanically under quasi-static and moderate strain-rate conditions. Results were reported in a previous progress report to NASA-Lewis (February, 1984). It was found that the properties of the resin as well as the matrix dominated properties of the composite are very strongly rate-dependent. even at relatively low strain-rates. However, the F-185/T300 system has a low longitudinal compressive strength and is therefore not suited for some structural applications. For this reason no further study was made of this material.

The material system used in the current work is AS4/3501-6 graphite/epoxy (Hercules, Inc.) a widely used material in the aerospace industry. This report covers one task of the study dealing with effects of strain rate on room and elevated-temperature properties of this material.

2. EXPERIMENTAL PROCEDURE

2.1 Materials and Specimen Fabrication

The material investigated was AS4/3501-6 graphite/epoxy (Hercules, Inc.). The material was characterized by performing the standard physical and mechanical tests to determine the properties of the lamina. The prepreg material was cured according to the following curing cycle (Fig. 2-1):

1. Place the layup in the autoclave.
2. Apply vacuum of at least 85 kPa (25 in. Hg).
3. Raise temperature to $116^{\circ} \pm 6^{\circ}C$ ($240^{\circ} \pm 10^{\circ}F$) at a rate of 1.7-2.0 $^{\circ}C$/min (3-5 $^{\circ}F$/min).
4. Hold vacuum for 60 to 70 min.
5. Apply pressure of 690 ± 35 kPa (100 ± 5 psi) and vent the vacuum bag to atmospheric pressure.
6. Raise temperature to $177^{\circ} \pm 6^{\circ}C$ ($350^{\circ} \pm 10^{\circ}F$) at a rate of 1.7 - 2.8 $^{\circ}C$/min (3-5 $^{\circ}F$/min).
7. Hold pressure for 120 ± 10 min.
8. Shut down autoclave temperature and leave the layup in it.
9. Release pressure after temperature drops below $93^{\circ}C$ ($200^{\circ}F$).
10. Leave plate in the autoclave until it cools down to ambient temperature.
11. Remove plate from autoclave.

Six- , eight- , and sixteen-ply unidirectional plates of dimensions 25.4 cm X 30.5 cm (10in. X 12in.) were fabricated. The plates were tabbed with four 5.08 cm (2 in.) wide strips of 7-ply Scotchply 1002

(3M Company) glass/epoxy bonded to the plates with High-Peel 1105 epoxy (Hysol Corp.). The adhesive was cured at room temperature for seven days. The plates were then machined into coupons for testing. All coupons were 20.3 cm (8 in.) long. The 0-deg. and 10-deg. off-axis specimens were 1.27 cm (0.5 in.) wide and 6-ply thick; the 90-deg. specimens were 2.54 cm (1 in.) wide and 8- and 16-ply thick. All specimens had a gage length of 10.12 cm (4 in.) (Fig. 2-2).

During the first few quasi-static tensile tests of $[0_6]$ specimens at elevated temperature, it was found out that the High Peel epoxy was separated. Thus, an FM300 adhesive film (Cyanamid) was employed instead, with the recommended curing cycle.

Each specimen was instrumented with a two-strain-gage rosette on one side, and every third specimen on both sides to check for bending and misalignment effects. On the 0-deg. and 90-deg. specimens the strain gages were attached along the fiber direction and normal to it, while on the off-axis specimens the gages were attached at ± 45 with respect to fiber direction.

2.2 Testing Procedure

Longitudinal properties, E_{11}, F_{1T}, ε^u_{1T} and ν_{12}, were obtained by testing 6-ply 0-deg. coupons. Transverse properties, E_{22}, F_{2T}, ε^u_{2T} and ν_{21}, were obtained by testing 8-ply and 16-ply 90-deg. coupons. In-plane shear properties, G_{12}, F_{12}, and γ^u_{12}, were obtained by testing 6-ply 10-deg. off-axis coupons.

The tensile tests were carried out in a servohydraulic Instron testing machine at several crosshead speeds which were selected to give strain rates ranging between $10^{-6} s^{-1}$ and $10\ s^{-1}$. The experiments were carried out at both room temperature, $23^\circ C$ ($73^\circ F$) and elevated temperature, 128°C (263°F). The high-temperature tests were conducted in an oven (Associated Environmental Systems) which was controlled to within ±0.6°C (±1°F). (Fig. 2-3). The temperature was monitored by a thermocouple, through a data logger (Digistrip II, Kay Instruments). During the tests, continuous records of load and strains for each specimen were obtained simultaneously by a Norland 3001 digital processing oscilloscope. This data was processed and transferred to a microcomputer and filed on disk for futher analysis. (Fig. 2-4).

The load output was connected directly from the Instron to the digital oscilloscope. The strain signals were conditioned through a Wheatstone bridge (Kaye Instr., Inc.; BC-8SG Strain Gage Conditioner), amplified and then recorded by the digital oscilloscope. For the 0-deg. and 90-deg. specimens, the strain signals from the longitudinal and transverse gages were recorded on separate channels. In some cases the strain gage output at low strain rates was compared with that of an extensometer attached to the specimen in addition to the strain gages.

In the case of the 10-deg. off-axis specimens a technique was used for recording directly the in-plane shear strain on one channel. Referring to Fig. 2-5, where two gages A and B are oriented at angles θ_A and θ_B with respect to the fiber direction, the shear strain γ_{12} referred to the lamina axes is given by

$$\gamma_{12} = \frac{2(\varepsilon_A-\varepsilon_B) - (\varepsilon_1-\varepsilon_2) - (\cos 2\theta_A - \cos 2\theta_B)}{\sin 2\theta_A - \sin 2\theta_B}$$

When $\theta_A = -\theta_B = 45^\circ$ the expression above is simplified to

$$\gamma_{12} = \varepsilon_A - \varepsilon_B = \varepsilon_{45} - \varepsilon_{-45}$$

Thus, the in-plane shear strain above can be recorded on one channel only by mounting the two gages on adjacent arms of a single Wheatstone bridge.

To compensate for any possible bending effects a two-gage rosette, oriented at +45 and -45 with respect to the fiber direction, was mounted on each side of the specimen. A full bridge configuration was used then by connecting the like-oriented gages on opposite arms of the Wheatstone bridge.

The in-plane shear stress was obtained from the applied axial stress along the x-axis as follows:

$$\tau_{12} = \frac{1}{2}\,\sigma_x \sin 2\theta = \frac{1}{2}\,\sigma_x \sin 20^{\circ} = 0.171\sigma_x$$

The output of a strain gage at an elevated temperature is a combination of several effects including a purely thermal output. thermal expansion, and mechanical strain. In the case of the 10-deg. off-axis specimen the temperature-induced effects on the -45 and +45 gages are identical and are subtracted out when the gages are mounted on adjacent arms of the bridge. The algebraic difference of the two strain readings is the in-plane shear strain and independent of thermal effects.

In the case of 0-deg. and 90-deg. specimens temperature compensation of the strain gages was obtained by using similarly oriented dummy gages on an identical but unloaded reference specimen placed inside the environmental chamber. Thus, the longitudinal gages from the test and reference specimens were connected to adjacent arms of a Wheatstone bridge and the transverse gages to the adjacent arms of another bridge. The bridges were balanced (zeroed) at room temperature and checked to see that the balance is maintained at the elevated temperature. When the test and reference specimens reached the desired temperature, the test specimen was loaded and the output was recorded on the Norland oscilloscope as the net induced mechanical strain.

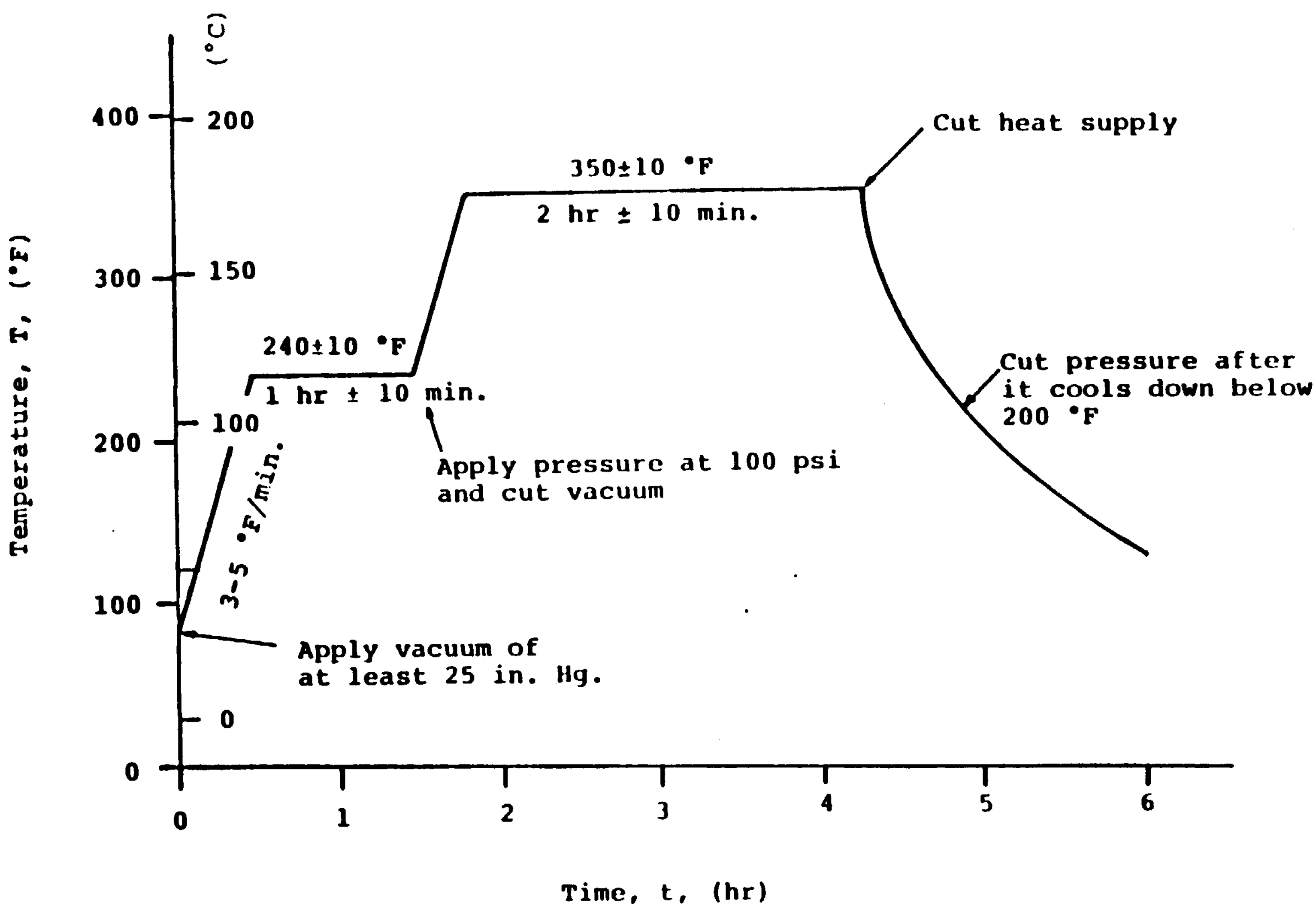
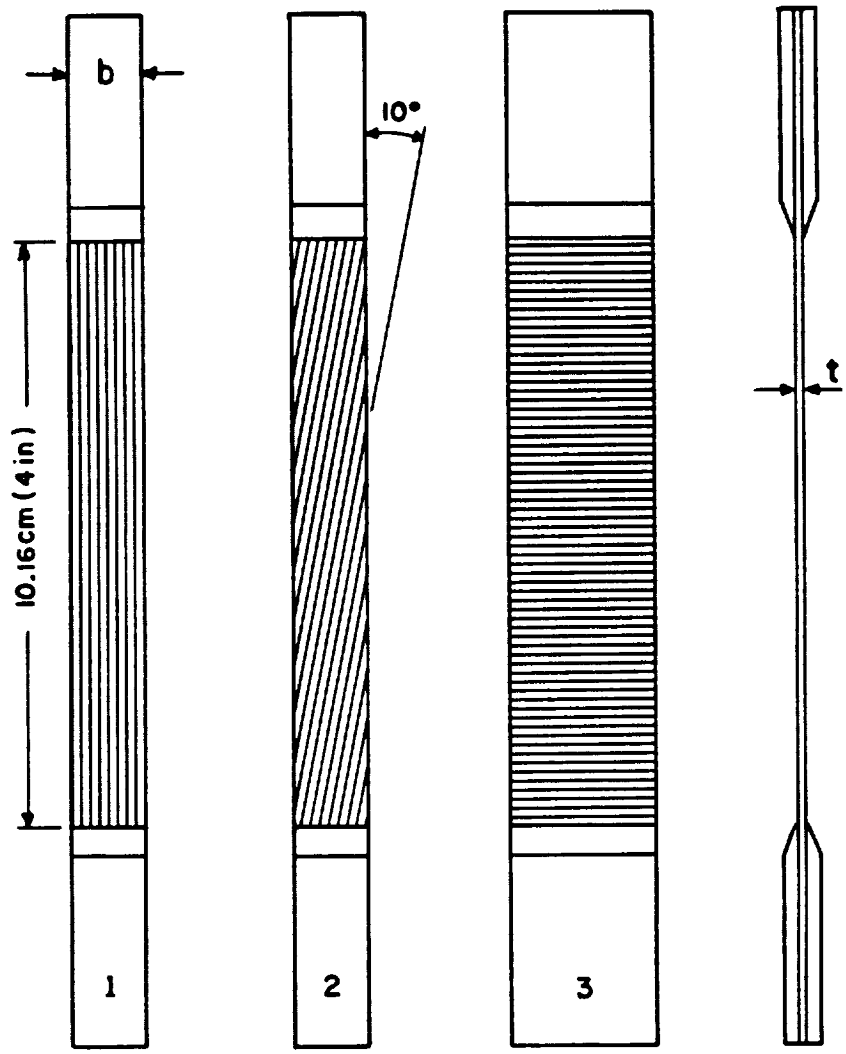


Fig. 2-1. Curing Schedule Used for AS 4/3501-6 Graphite/Epoxy Material



Specimen Type	Layup	Width, b cm (in.)	Thickness, t mm (10^{-3} in.)
1	$[0_6]$	1.27(0.5)	0.76±0.03(30±1)
2	$[10_6]$	1.27(0.5)	0.76±0.03(30±1)
3	$[90_8]$	2.54(1.0)	1.02±0.03(40±1)
4	$[90_{16}]$	2.54(1.0)	2.03±0.05(80±2)

Fig. 2-2. Specimen Geometries for Characterization Tests of Unidirectional Graphite/Epoxy.

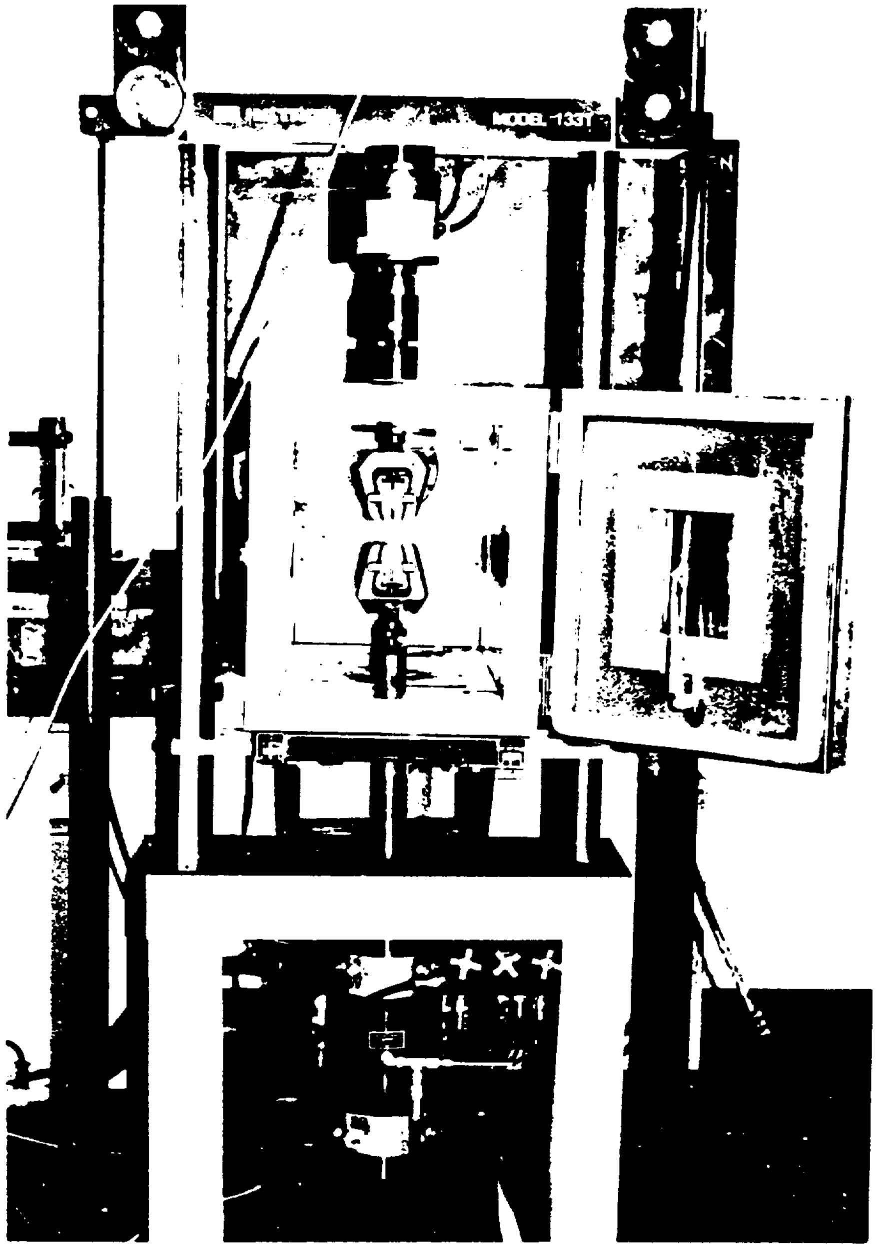


Fig. 2-3. Loading Frame with Environmental Chamber

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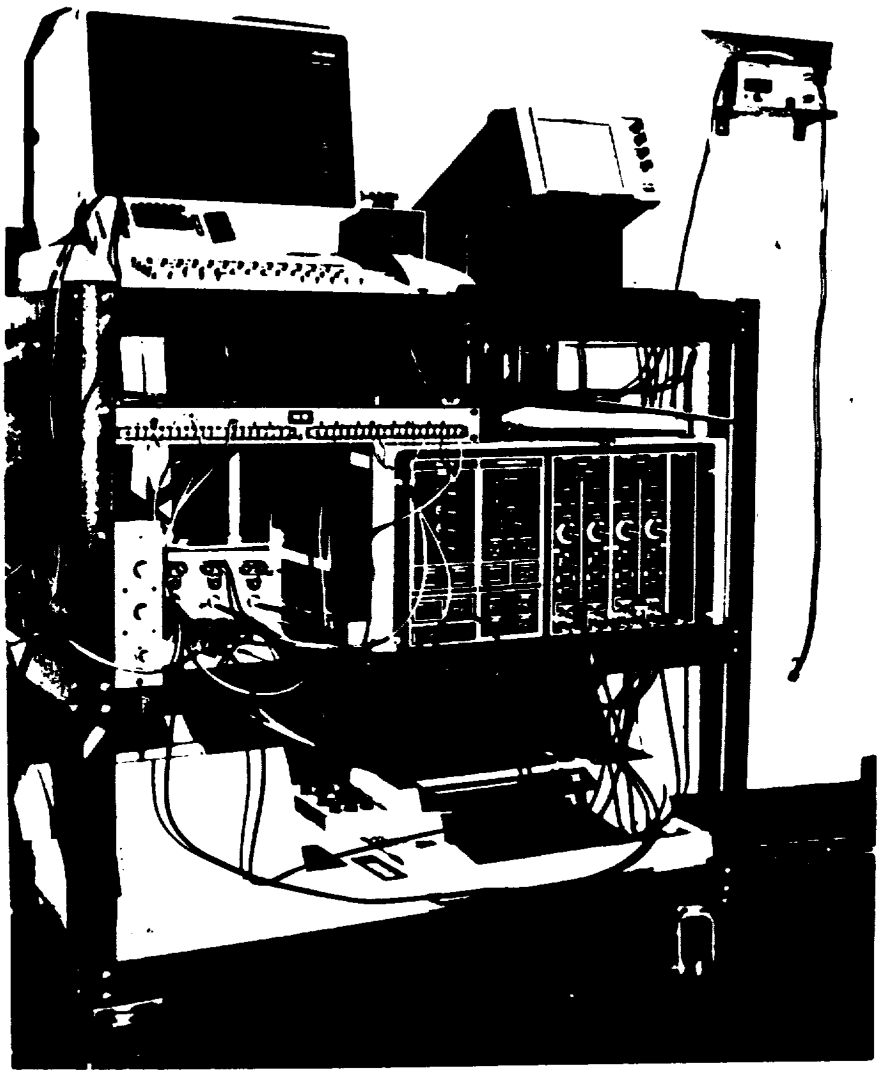

Fig. 2-4. Data Acquisition System Consisting of Microcomputer, Digital Oscilloscope, and Plotter.

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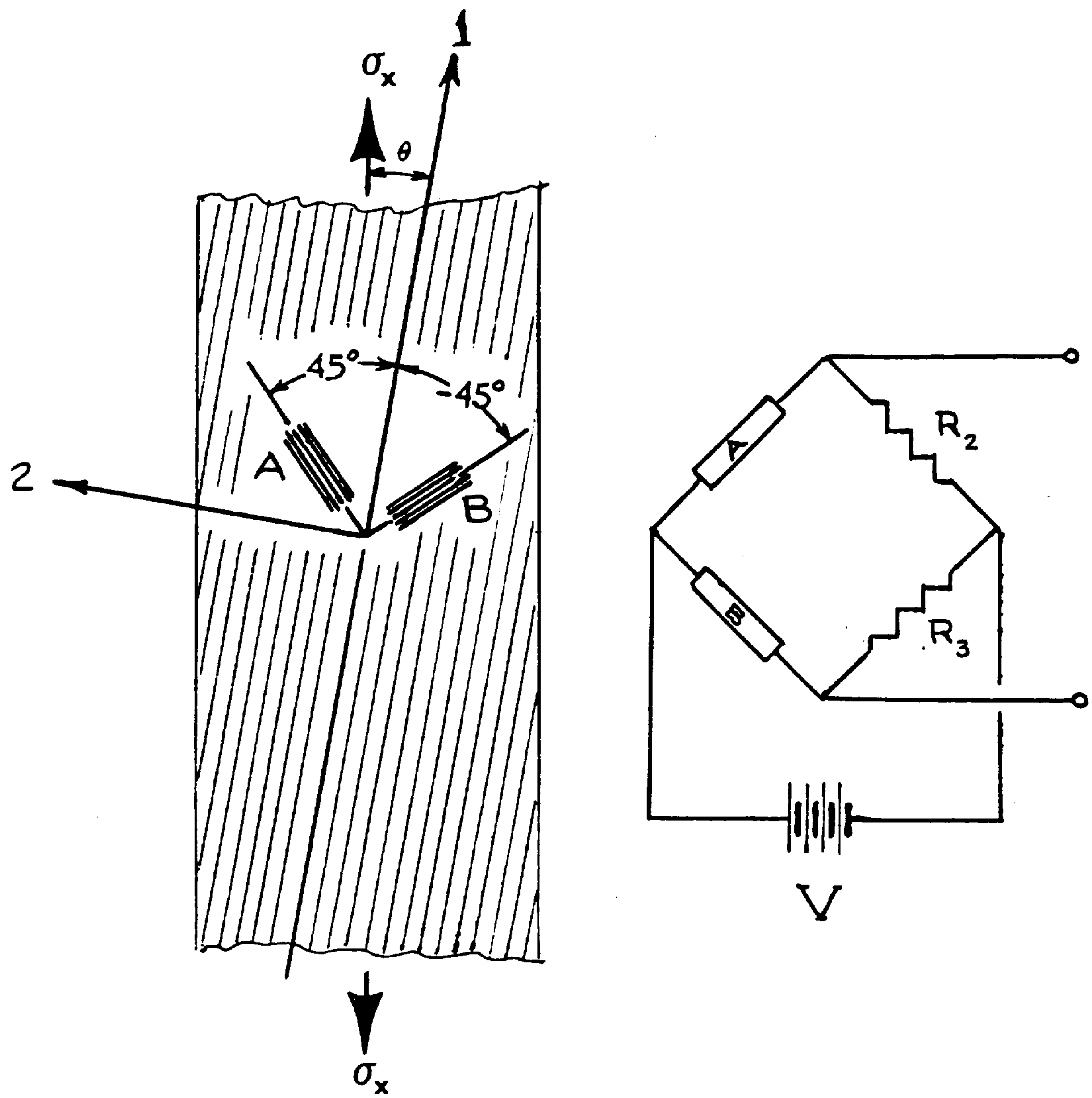


$$\gamma_{12} = \epsilon_A - \epsilon_B$$

Fig. 2-5. Arrangement of Strain Gages on an Off-Axis Composite Specimen for Direct Measurement of In-Plane Shear Strain.

3. RESULTS AND DISCUSSION

3.1 Room Temperature Properties

3.1.1 Longitudinal Tensile Properties

The mechanical properties of AS4/3501-6 are fiber dominated, and are not expected to vary significantly with strain-rate. Thus, it was decided to test $[0_6]$ coupons at two strain-rates, 10^{-4} s^{-1} and 1 s^{-1}.

Typical stress-strain and transverse versus longitudinal strain curves for strain rates of 3.4 X 10^{-4} s^{-1} and 1.03 s^{-1} are shown in Figures 3-1 through 3-4. At both strain rates a characteristic stiffness increase is noted at a strain of approximately 0.006. This well-known behavior has been attributed to nonlinear behavior of the graphite fibers and to some straightening of fiber bundles following longitudinal matrix cracking. Figures 3-5 to 3-8 show the longitudinal properties, namely, modulus E_{11}, tensile strength F_{1T}, ultimate tensile strain ε^u_{1T}, and Poisson's ratio ν_{12} vs. strain rate $\dot{\varepsilon}_{11}$. It can be seen that E_{11} and ν_{12} are unaffected by increasing strain rate while the ultimate properties F_{1T} and ε^u_{1T} tend to decrease slightly with increasing strain rate.

3.1.2 Transverse Tensile Properties

These properties which are matrix-dominated are affected by strain rate in a more pronounced way. Figures 3-9 through 3-13 show typical stress-strain curves for a strain rate range of 6 decades. The wavy shape of the stress-strain curve at the highest rate (Fig. 3-13) reflects the limitation of the testing machine and not the true mechanical behavior. The transverse vs. longitudinal strain curves shown in Figures 3-14 and 3-15 should be considered as qualitative ones because the transverse strain is of the same order of magnitude as the transverse sensitivity factor K_t of the strain gages used. Nevertheless, the tendency of increasing Poisson's ratio with increasing strain rate is clearly observed and conforms with the increase in the transverse modulus and the constant values of E_{11} and γ_{12} as described in section 3.1.1, since the relation $\frac{E_{22}}{E_{11}} = \frac{\nu_{21}}{\nu_{12}}$ holds true for any strain rate, and since E_{11} and ν_{12} are constant with strain rate variations. Thus, the difference in transverse properties at two different strain rates must satisfy the same relation.

$$\frac{\Delta E_{22}}{E_{11}} = \frac{\Delta \nu_{21}}{\nu_{12}}$$

If we examine the relative chage in transverse modulus and the relative change in minor Poisson's ratio between two different strain rates, they both show an increase of the same order of magnitude.

The effect of strain rate on the transverse mechanical properties is shown in Figures 3-16 to 3-19. Both modulus and minor Poisson's ratio show a similar increase with strain rate as described earlier. On the other hand the values of the ultimate transverse tensile strain ε_{2T}^{u} and strength F_{2T} decrease with increasing strain rate, up to approximately $5 \times 10^{-2}\ s^{-1}$, thereafter, they increase with strain rate. This type of change of rate sensitivity from negative to positive and vice versa is known in polymers, and lately has been observed in Mode I fracture toughness of composites.[4]

3.1.3 In-Plane Shear Properties

Typical shear stress vs. shear strain curves at various strain rates are shown in Figs. 3-20 through 3-23. The oscillatory shape of the stress-strain curve at the highest rate (Fig. 3-23) reflects the limitation of the servohydraulic testing machine and not true material behavior. The effects of strain rate on in-plane shear properties, G_{12},

F_{12} and γ_{12}^{u}, are shown in Figs. 3-24, 3-25, and 3-26, respectively.

The variation of the in-plane shear modulus G_{12} with strain rate is very similar to that of the transverse modulus E_{22}, and it shows an increase of approximately 35% from the quasi-static value. The value of the in-plane shear strength, F_{12}, also increases with strain rate, however, the rate of change of F_{12} is higher at low strain rates than at high strain rates. This type of change is more pronounced in the ultimate shear strain behavior which even changes its rate-sensitivity from positive to negative at approximately 5×10^{-2} s^{-1}. Unlike transverse ultimate properties, the in-plane shear strength and strain are highly affected by the nature of the fiber-matrix bonding, which might explain the difference between these modes.

The average quasi-static and high rate mechanical properties at room temperature are summarized in Table 1.

Table 1: PROPERTIES OF AS4/3501-6 UNIDIRECTIONAL GRAPHITE/EPOXY AT ROOM TEMPERATURE

Property	Strain Rate	
	$2 \times 10^{-5}\ s^{-1}$	$2\ s^{-1}$
Longitudinal Modulus, E_{11}, GPa (Msi)	143 (20.8)	147 (21.3)
Longitudinal Tensile Strength, F_{1T}, MPa (ksi)	2405 (349)	2336 (339)
Ultimate Longitudinal Tensile Strain, ε^u_{1T}	0.0155	0.0142
Major Poisson's Ratio, ν_{12}	0.27	0.26
Transverse Modulus, E_{22}, GPa (Msi)	10.0 (1.45)	12 (1.73)
Transverse Tensile Strength, F_{2T}, MPa (ksi)	64 (9.3)	59 (8.6)
Ultimate Transverse Tensile Strain, ε^u_{2T}	0.0064	0.0052
Minor Poisson's Ratio, ν_{21}	0.012	0.014
In-Plane Shear Modulus, G_{12}, GPa (Msi)	7.2 (1.05)	8.9 (1.29)
In-Plane Shear Strength, F_{12}, MPa (ksi)	64 (9.3)	83 (12.1)
Ultimate In-Plane Shear Strain, γ^u_{12}	0.0115	0.0114

3.2 Elevated Temperature Properties

3.2.1 Longitudinal Tensile Properties

Stress-strain and transverse versus longitudinal strain curves obtained at a temperature of 128 $^{\circ}$C (263°F) for strain rates of 3 X 10 s^{-1} and 1 s^{-1} are shown in Figs. 3-27 through 3-30. The material response at the elevated temperature is similar to that at room temperature except for the fact that the characteristic stiffening occurs at a strain of approximately 0.008 for the quasi-static rate and below 0.006 for the high strain rate. Since this phenomenon is associated with longitudinal matrix cracking (and fiber bundle straightening), this change is attributed to effects of the matrix rather than of the fibers. Curves of longitudinal properties versus strain rate are shown in Figs. 3-31 through 3-34. The longitudinal modulus increases by approximately 5% and the ultimate tensile strain decreases by approximately 5% at the high strain rate. The longitudinal tensile strength and major Poisson's ratio remain unchanged over the range of strain rates considered.

It is worth noting that whereas the quasi-static values of the modulus and strength are almost the same as those at room temperature, they both increase with strain rate more than in the room temperature tests. This might imply that the role of the matrix and its interaction with the fibers are more significantly affected by strain rate at elevated temperatures.

3.2.2 Transverse Tensile Properties

Typical stress-strain curves at a temperature of 128°C (263°F) for strain rates ranging from 5 X 10^{-6} s^{-1} to 1.5 s^{-1} are shown in Figs. 3-35 through 3-41. As can be seen from these curves the transverse modulus values are considerably lower than those at room temperature.

The load fluctuations due to the Instron servocontroller appear at lower strain rates than before because of the higher specimen compliance (Figs. 3-40 and 3-41). The variation of transverse properties with strain rate is shown in Figs. 3-42 through 3-44. It can be seen clearly that the average values of the modulus E_{22} at the elevated temperature are considerably lower, by approximately 25%, than the corresponding room temperature values. Like the modulus, transverse strength increases with increasing strain rate over the range considered. The ultimate strain appears to be rate-insensitive. It should be noted that at the highest strain rate applied, the values of modulus and strength may be somewhat uncertain due to the load fluctuations, however, the value of the ultimate strain is unambiguous.

3.2.3 In-Plane Shear Properties

Typical shear stress versus shear strain curves at a temperature of 128 °C (263 °F) for strain rates ranging from 1.6×10^{-5} s^{-1} to 5 s^{-1} are shown in Figs. 3-45 through 3-50. The most significant observation from these stress-strain curves is the high ultimate shear strain at the elevated temperature, ranging between 0.015 and 0.019, compared to a range of 0.010 to 0.013 at room temperature. Figures 3-51 through 3-53 show the effect of shear strain rate, $\dot{\gamma}_{12}$, on the shear modulus G_{12}, shear strength F_{12} and ultimate shear strain γ_{12}^{u}, respectively. Like transverse properties, G_{12} and F_{12} have a positive rate sensitivity which is moderate at low strain rates and then it increases sharply at a strain rate of approximately 5×10^{-2} s^{-1}. The ultimate shear strain increases very moderately with strain rate.

The average quasi-static and high-rate mechanical properties at 128 °C (263 °F) are summarized in Table 2.

Table 2: PROPERTIES OF AS4/3501-6 UNIDIRECTIONAL GRAPHITE/EPOXY AT 128 °C (263 °F)

Property	Strain Rate, s^{-1}	
	$5X10^{-6}$ to $3X10^{-4}$	1 to 5
Longitudinal Modulus, E_{11}, GPa (Msi)	147 (21.4)	161 (23.3)
Longitudinal Tensile Strength, F_{1T}, MPa (ksi)	2391 (347)	2418 (351)
Ultimate Longitudinal Tensile Strain, ε^u_{1T}	0.0147	0.0138
Major Poisson's Ratio, ν_{12}	0.28	0.29
Transverse Modulus, E_{22}, GPa (Msi)	8.3 (1.21)	9.5 (1.38)
Transverse Tensile Strength, F_{2T}, MPa (ksi)	46 (6.7)	65 (9.4)
Ultimate Transverse Tensile Strain, ε^u_{2T}	0.0062	0.0065
Minor Poisson's Ratio, ν_{21}	—	0.015
In-Plane Shear Modulus, G_{12}, GPa (Msi)	7.6 (1.10)	10.6 (1.54)
In-Plane Shear Strength, F_{12}, MPa (ksi)	63 (9.1)	82 (11.9)
Ultimate In-Plane Shear Strain, γ^u_{12}	0.0137	0.0155

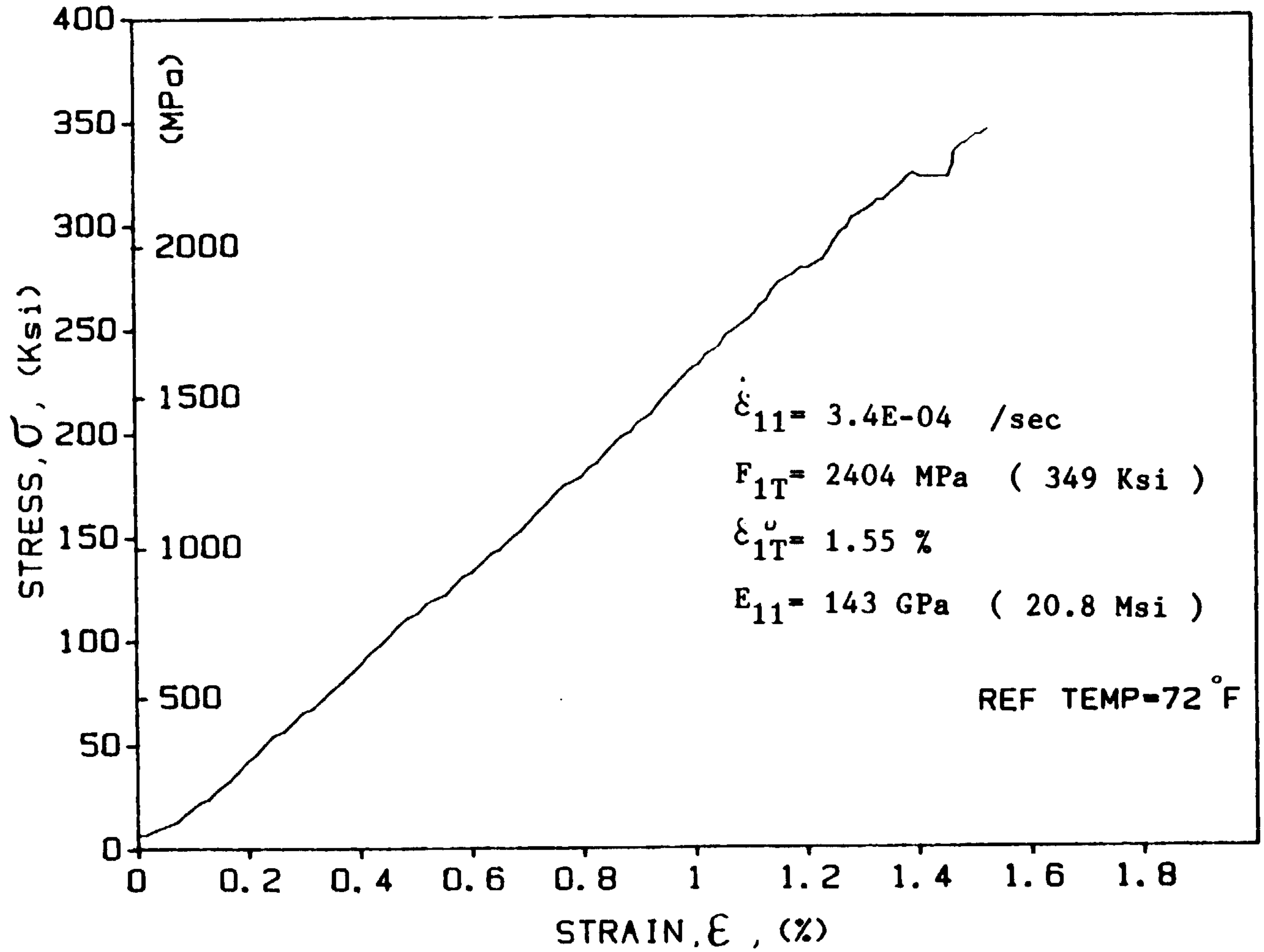


Fig. 3-1. Typical Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{11} = 3.4 \times 10^{-4}$ sec^{-1}, T = 23°C (72°F))

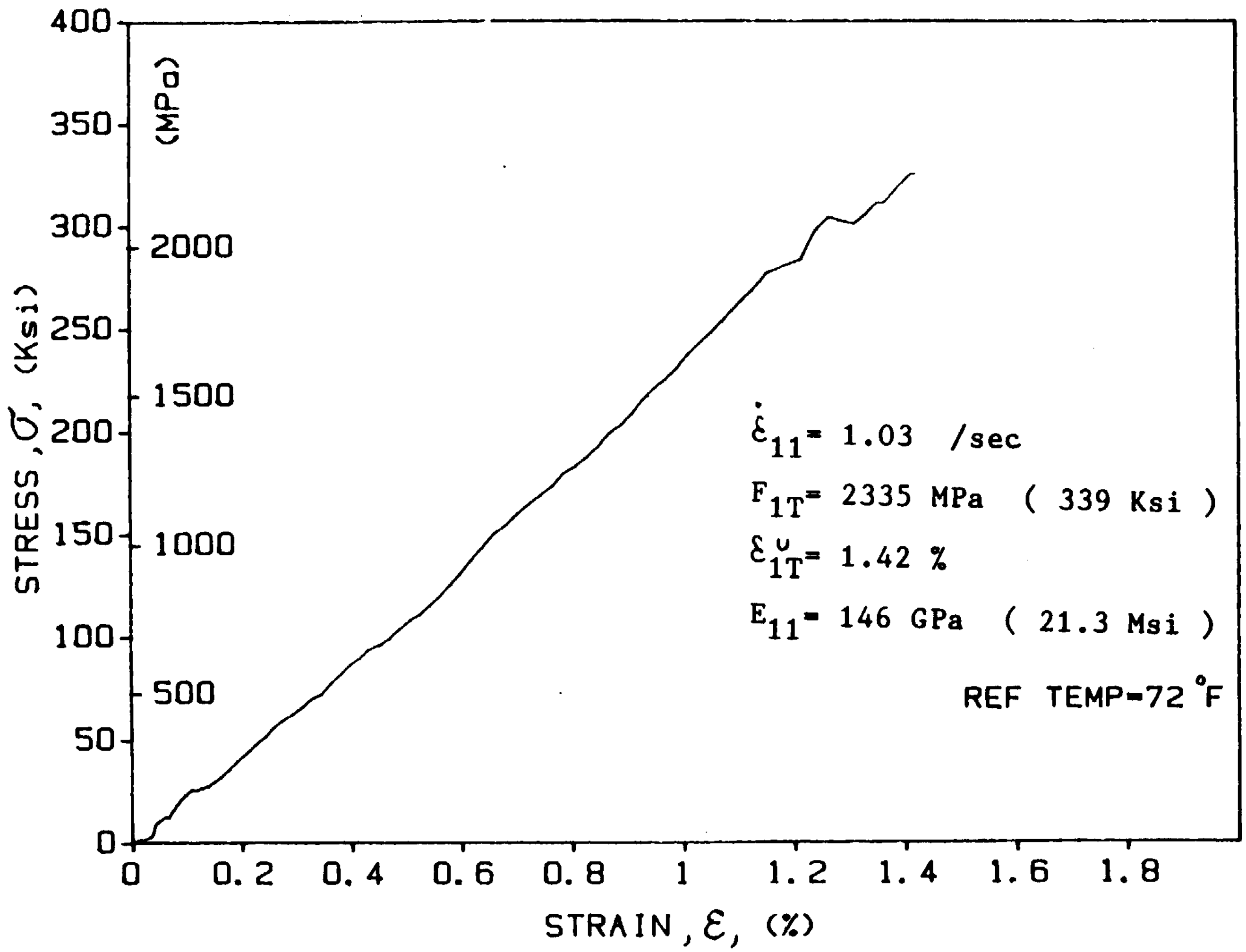


Fig. 3-2 Typical Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{11}$ = 1.03 sec^{-1}, T = 23°C (72°F))

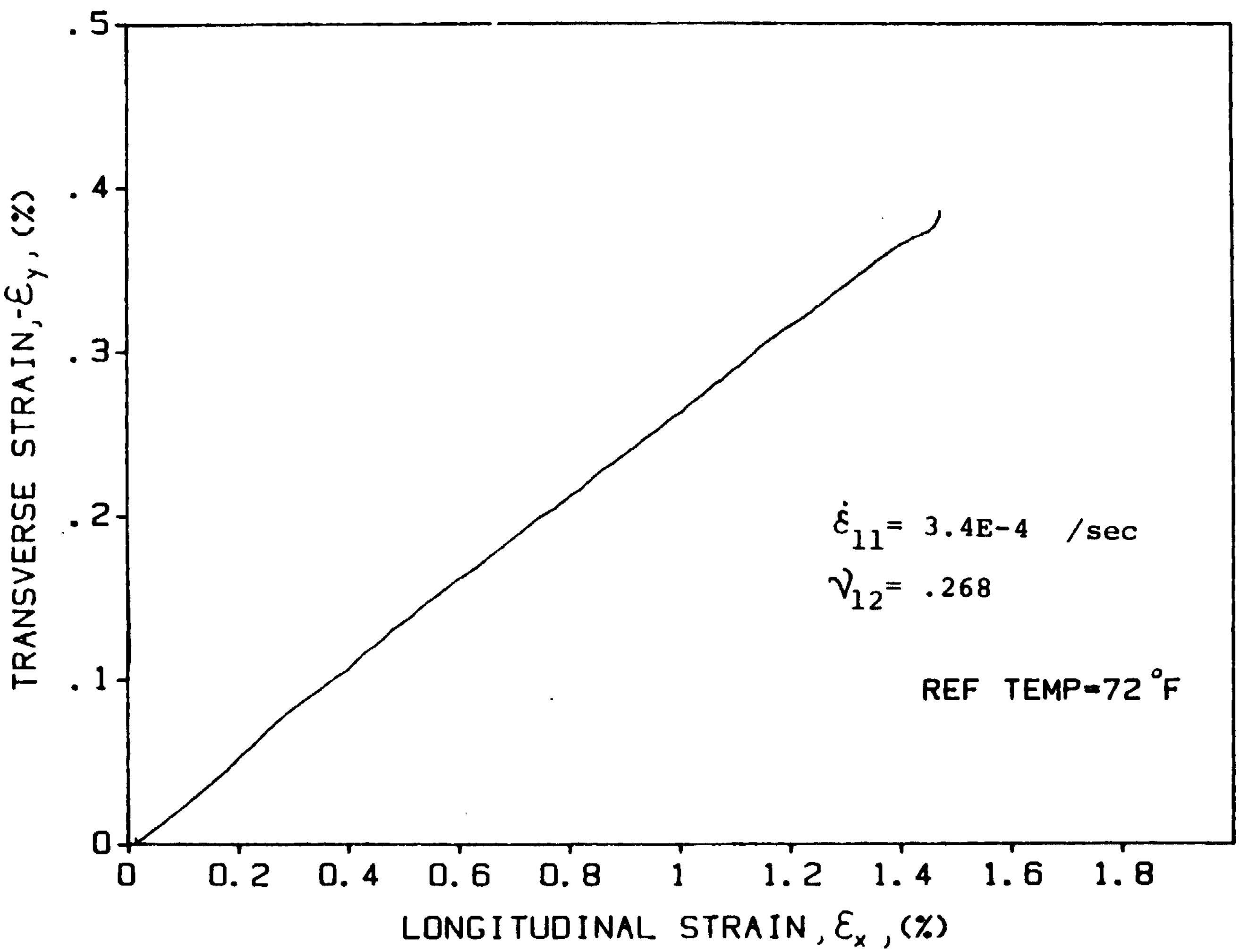


Fig. 3-3. Typical Transverse vs. Longitudinal Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{11} = 3.4 \times 10^{-4}$ sec^{-1}, T = 23°C (72°F))

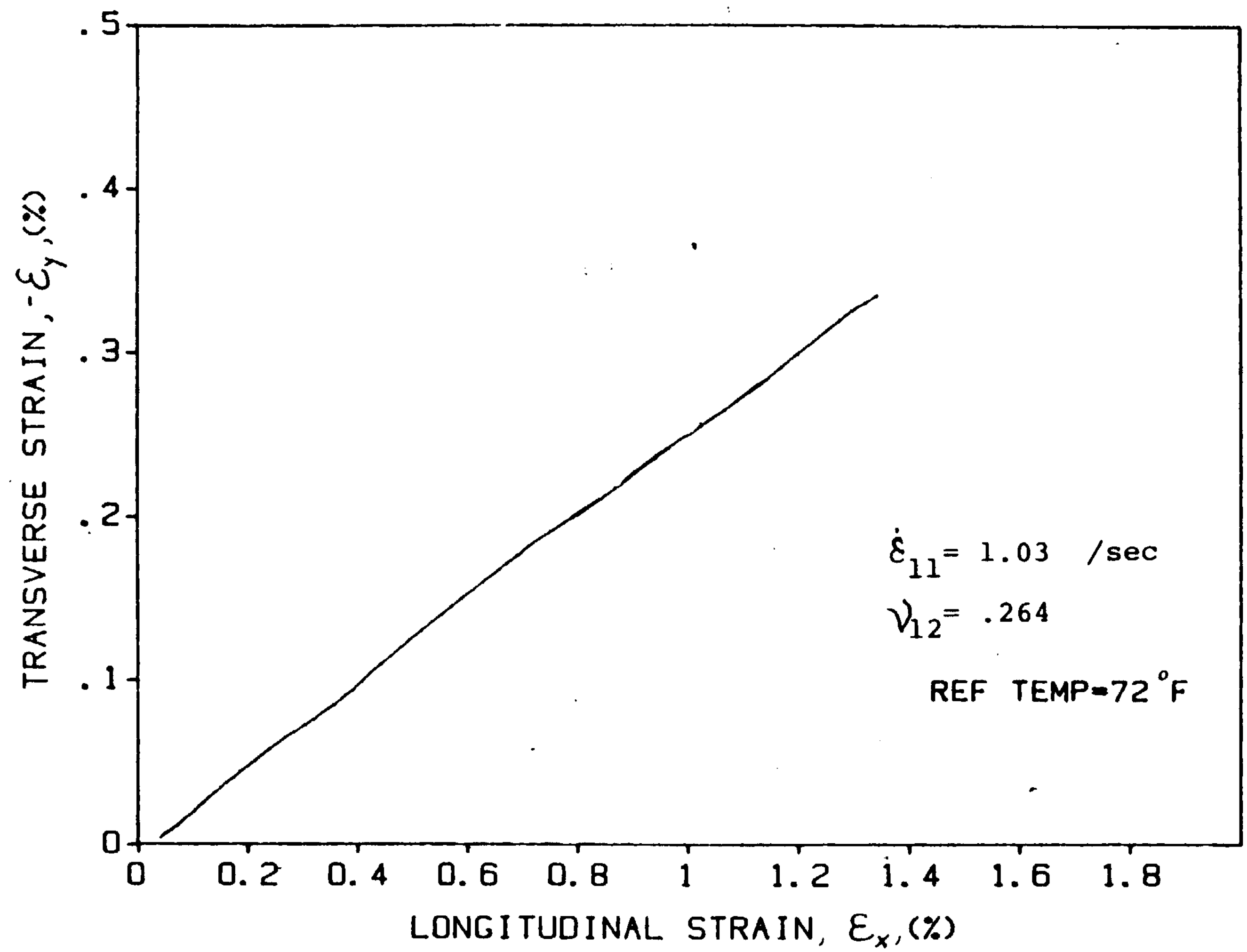


Fig. 3-4. Typical Transverse vs. Longitudinal Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{11}$ = 1.03 sec^{-1}, T = 23°C (72°F))

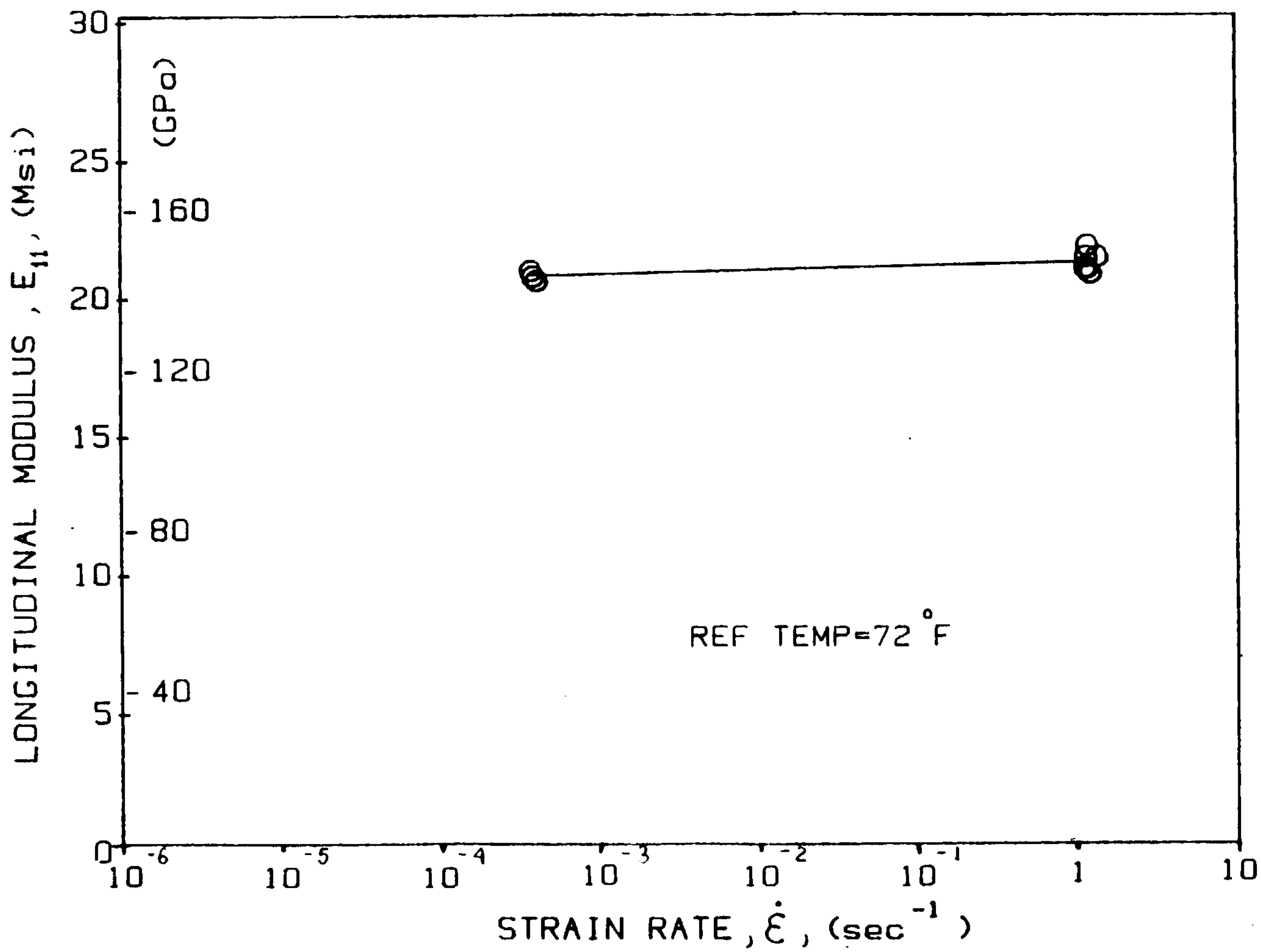


Fig. 3-5. Longitudinal Modulus, E_{11} vs. Strain-Rate, $\dot{\varepsilon}_{11}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

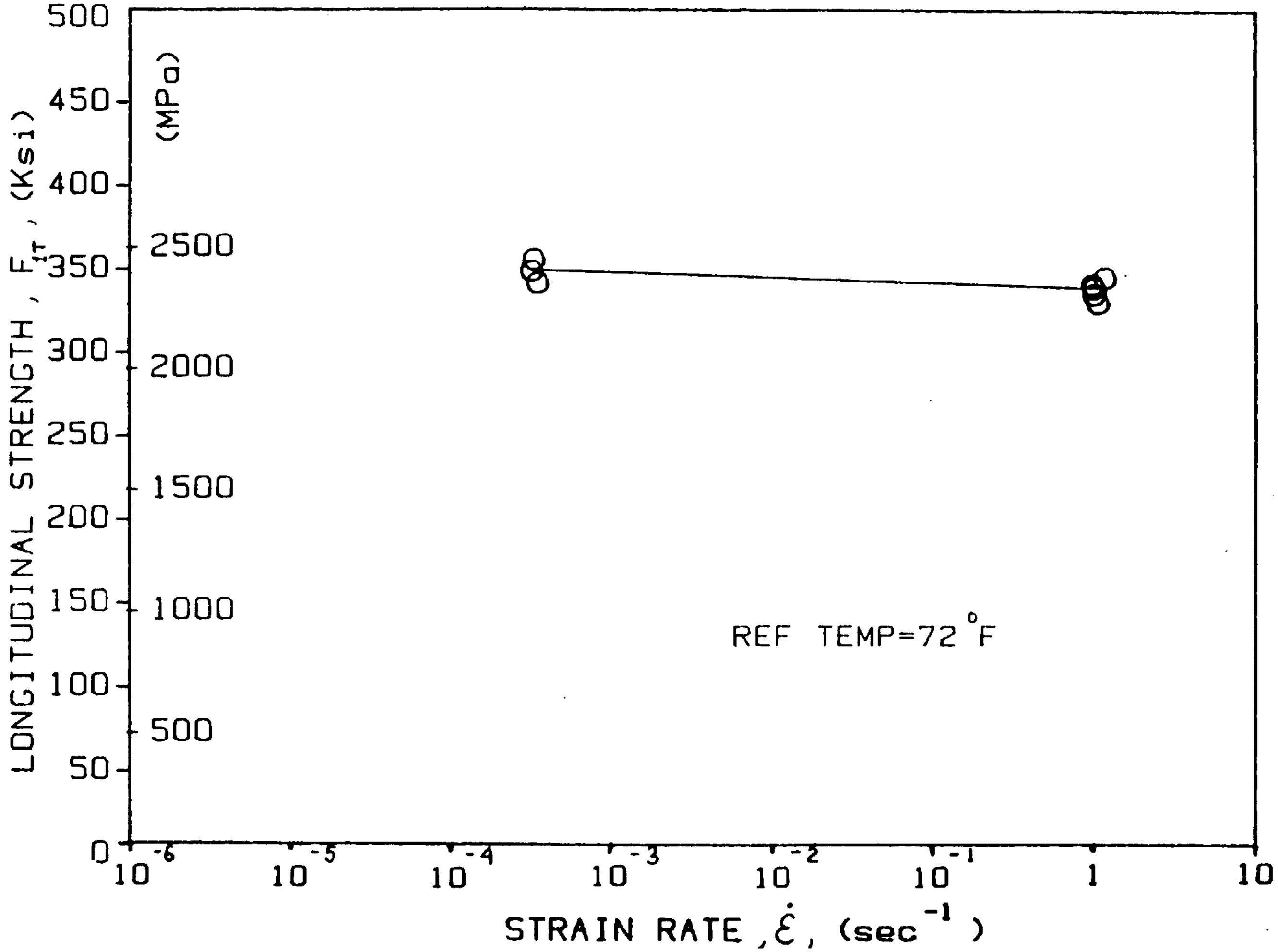


Fig. 3-6. Longitudinal Tensile Strength, F_{1T} vs. Strain-Rate, $\dot{\epsilon}_{11}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

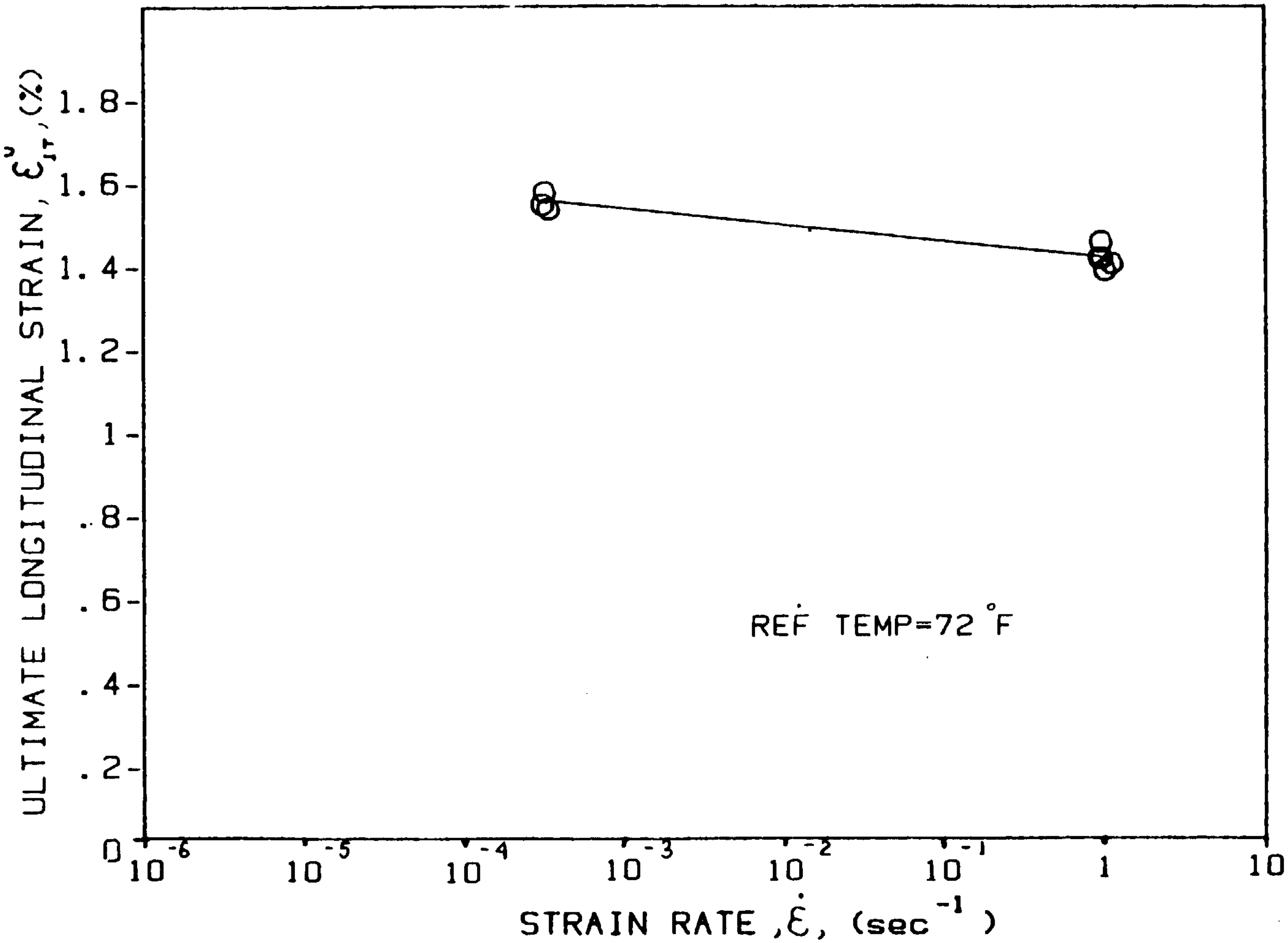


Fig. 3-7. Ultimate Longitudinal Tensile Strain, $\dot{\varepsilon}_{1T}$, vs. Strain Rate, ε^u_{11} for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

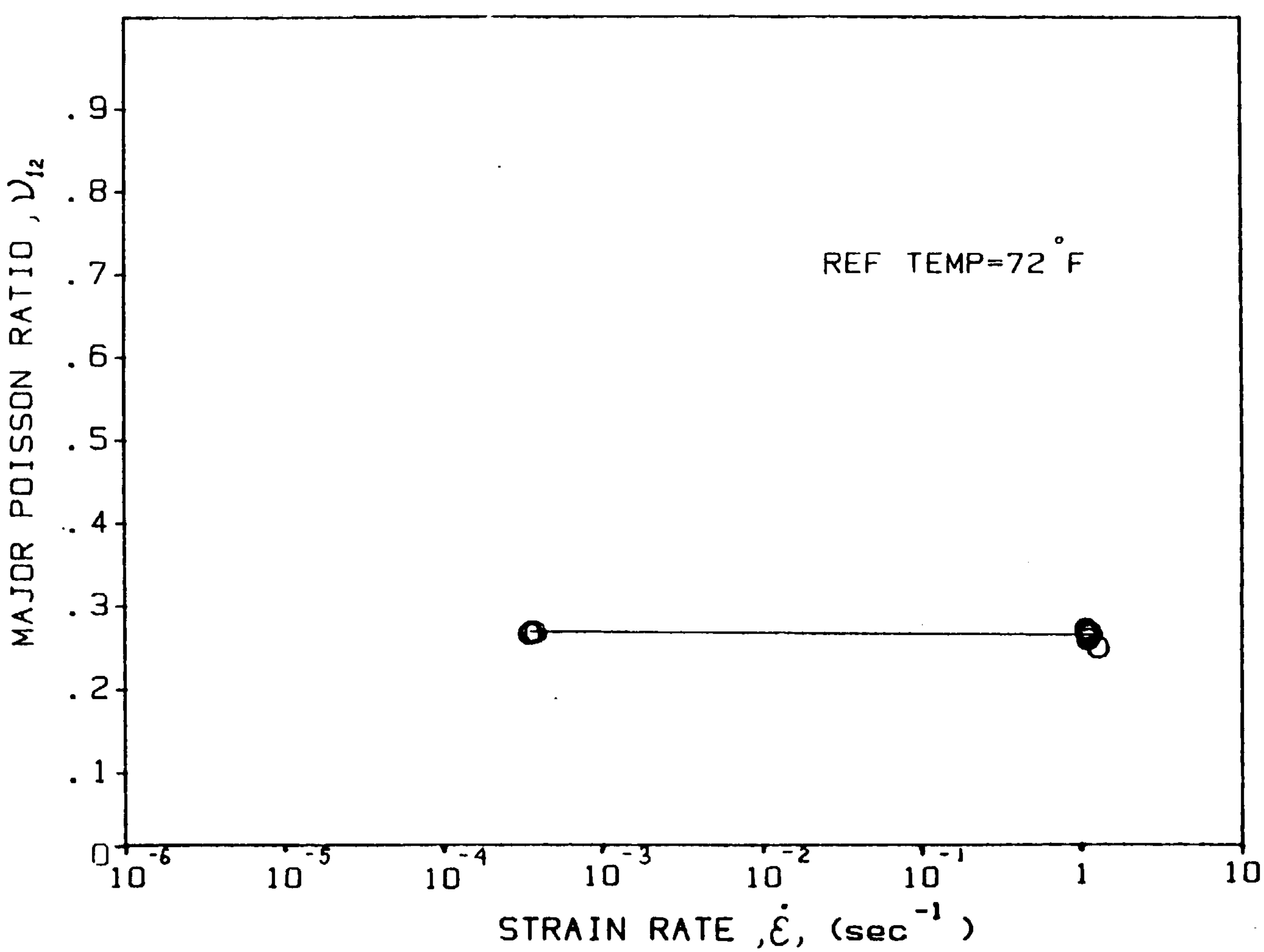


Fig. 3-8. Major Poisson's Ratio, ν_{12}, vs. Strain Rate, $\dot{\varepsilon}_{11}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

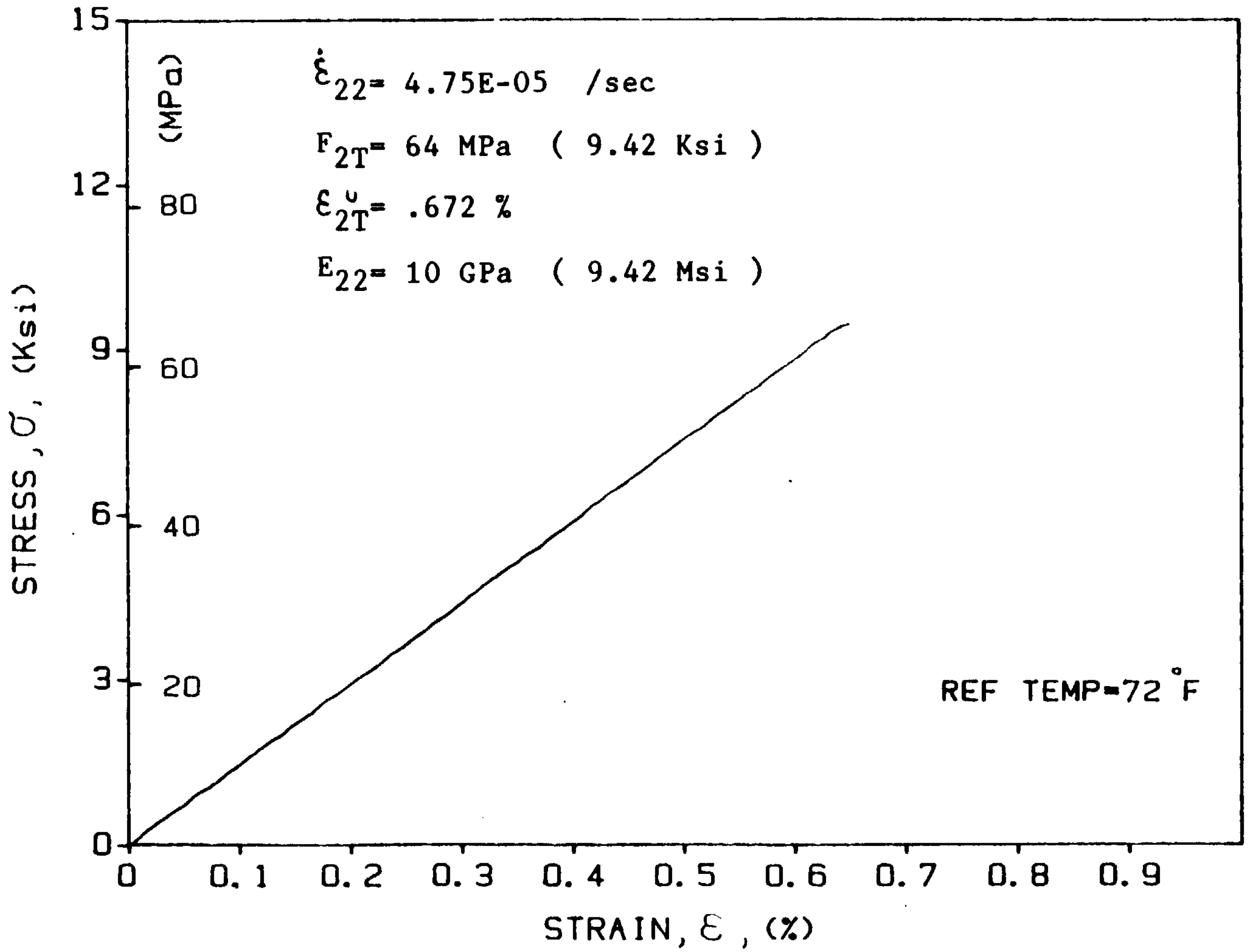


Fig. 3-9. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22}$ = 4.75 x 10^{-5} sec^{-1}, T = 23°C (72°F))

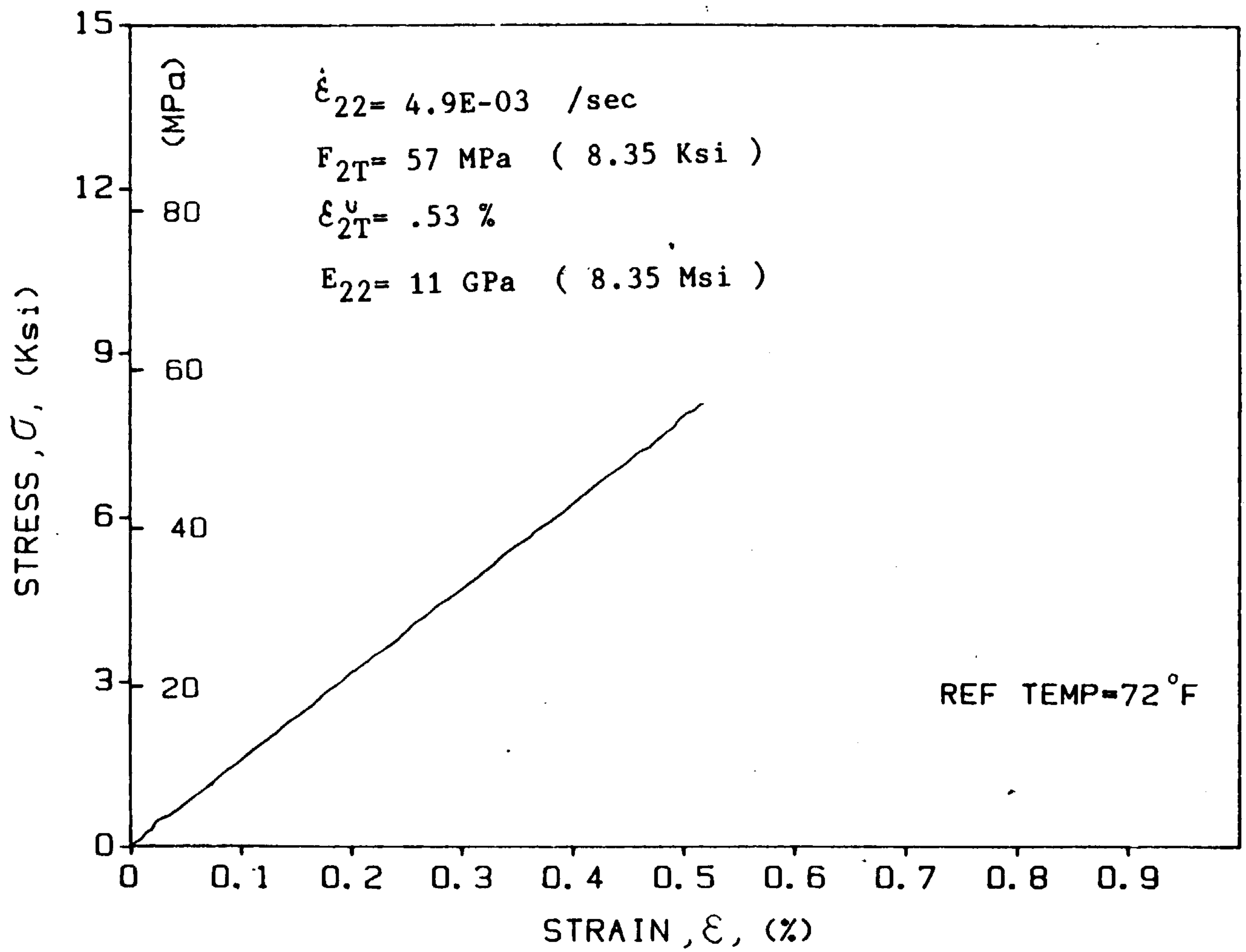


Fig. 3-10. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/ Epoxy ($\dot{\varepsilon}_{22} = 4.9 \times 10^{-3}$ sec^{-1}, T = 23°C (72°F))

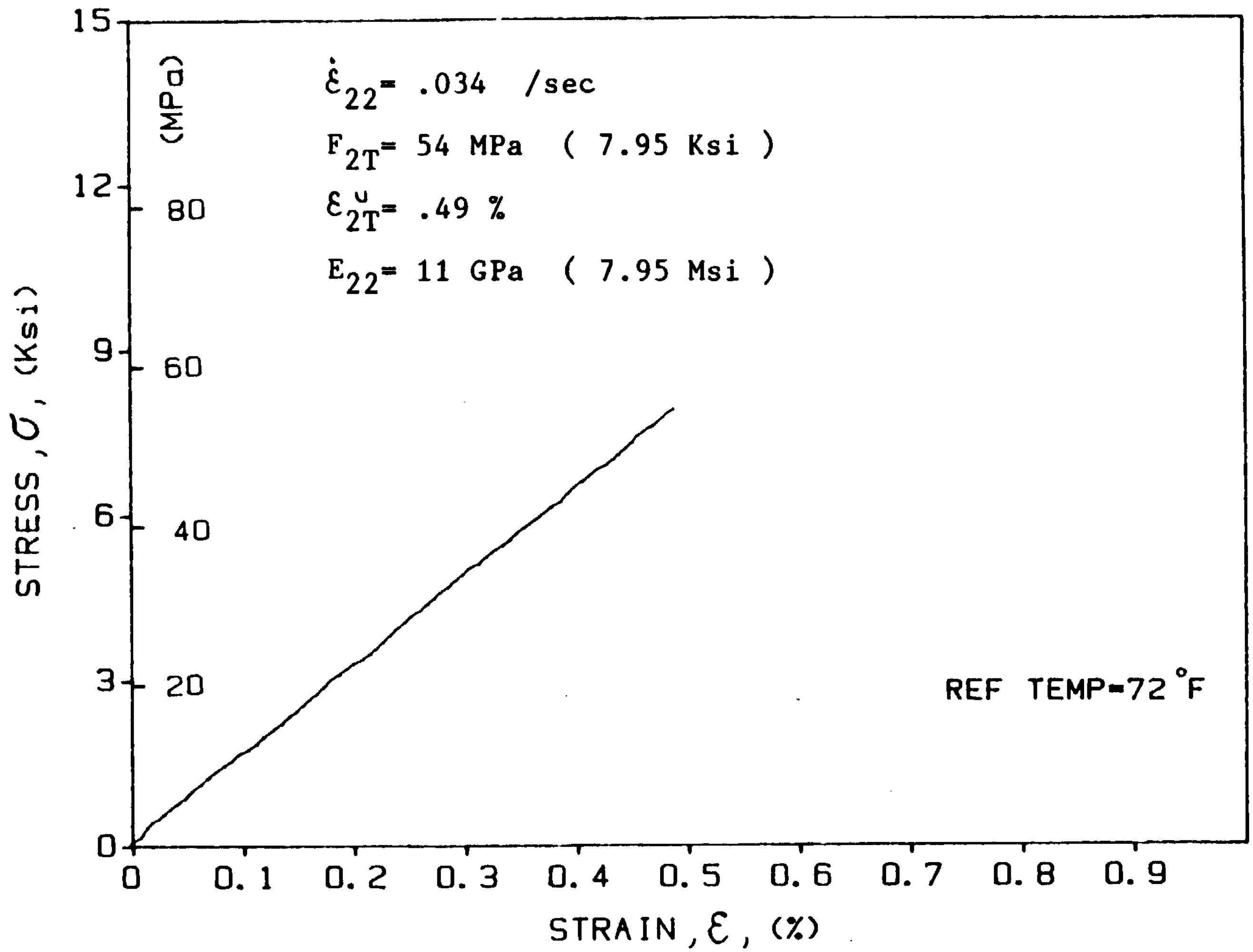


Fig. 3-11L Typical Stress-Strain Curve for [90_8] AS4/3501-6 Graphite/ Epoxy ($\dot{\varepsilon}_{22}$ = 3.4 x 10^{-2} sec^{-1}, T = 23°C (72°F))

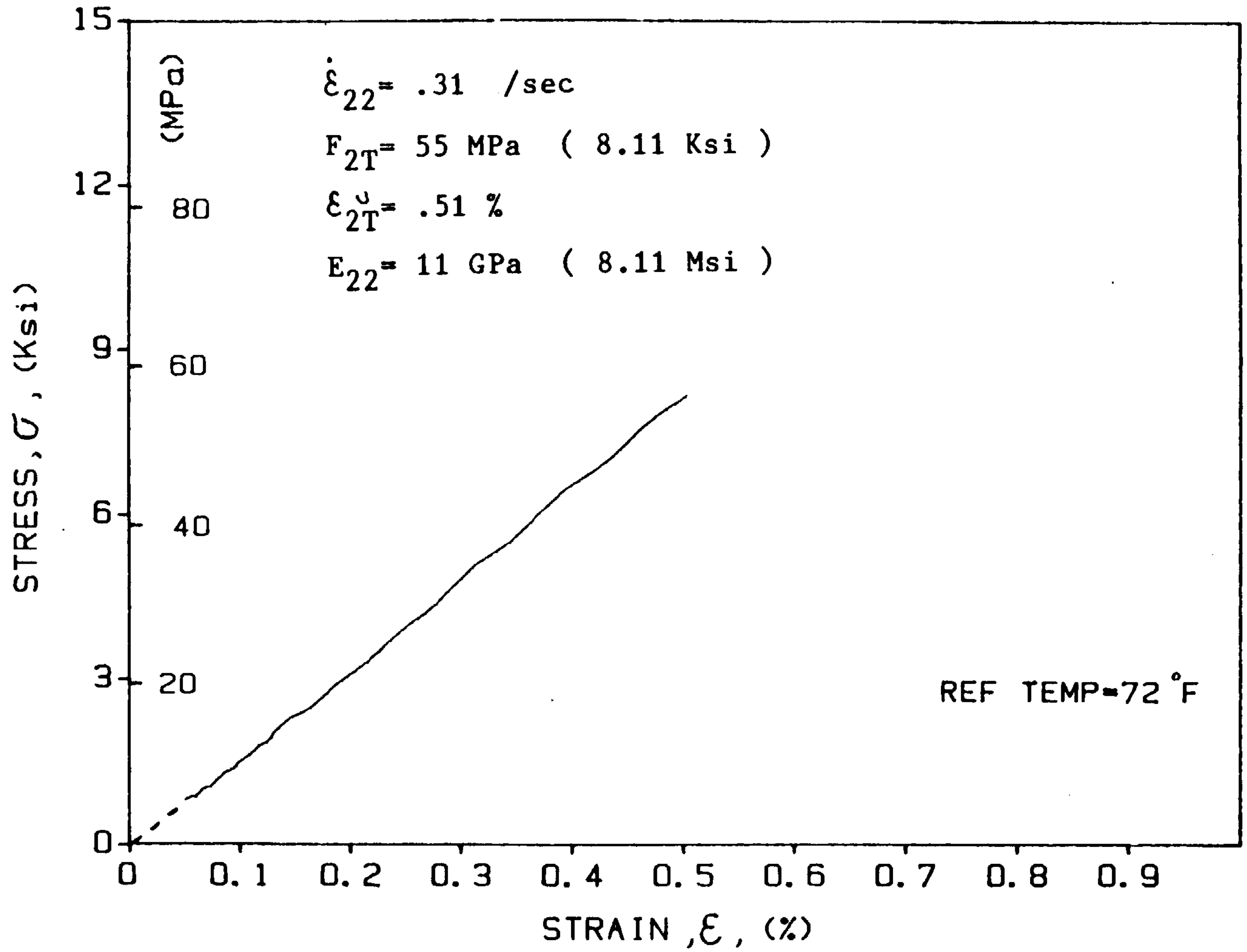


Fig. 3-12. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22}$ = 3.1 x 10^{-1} sec^{-1}, T = 23°C (72°F))

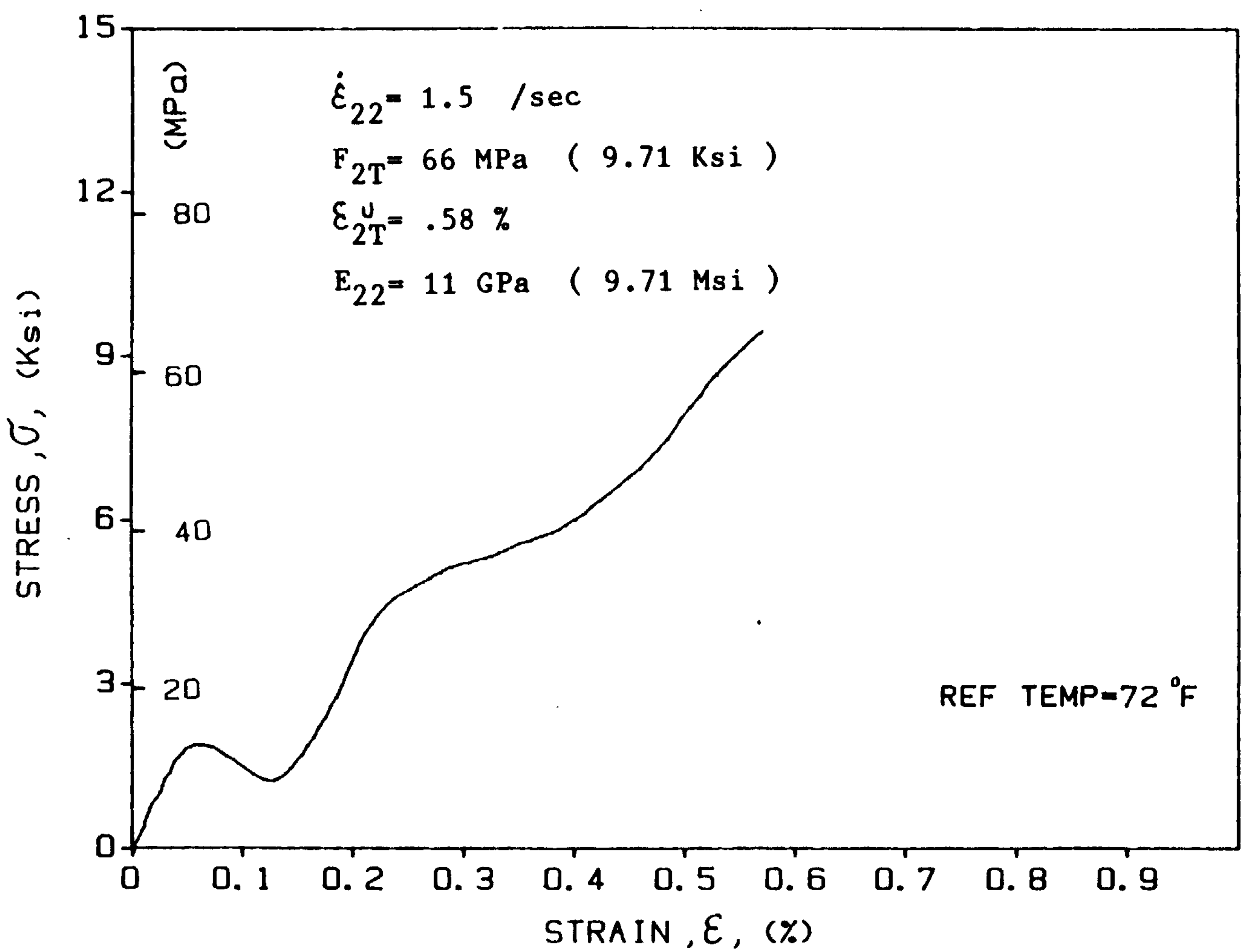


Fig. 3-13. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22}$ = 1.5 sec^{-1}, T = 23°C (72°F))

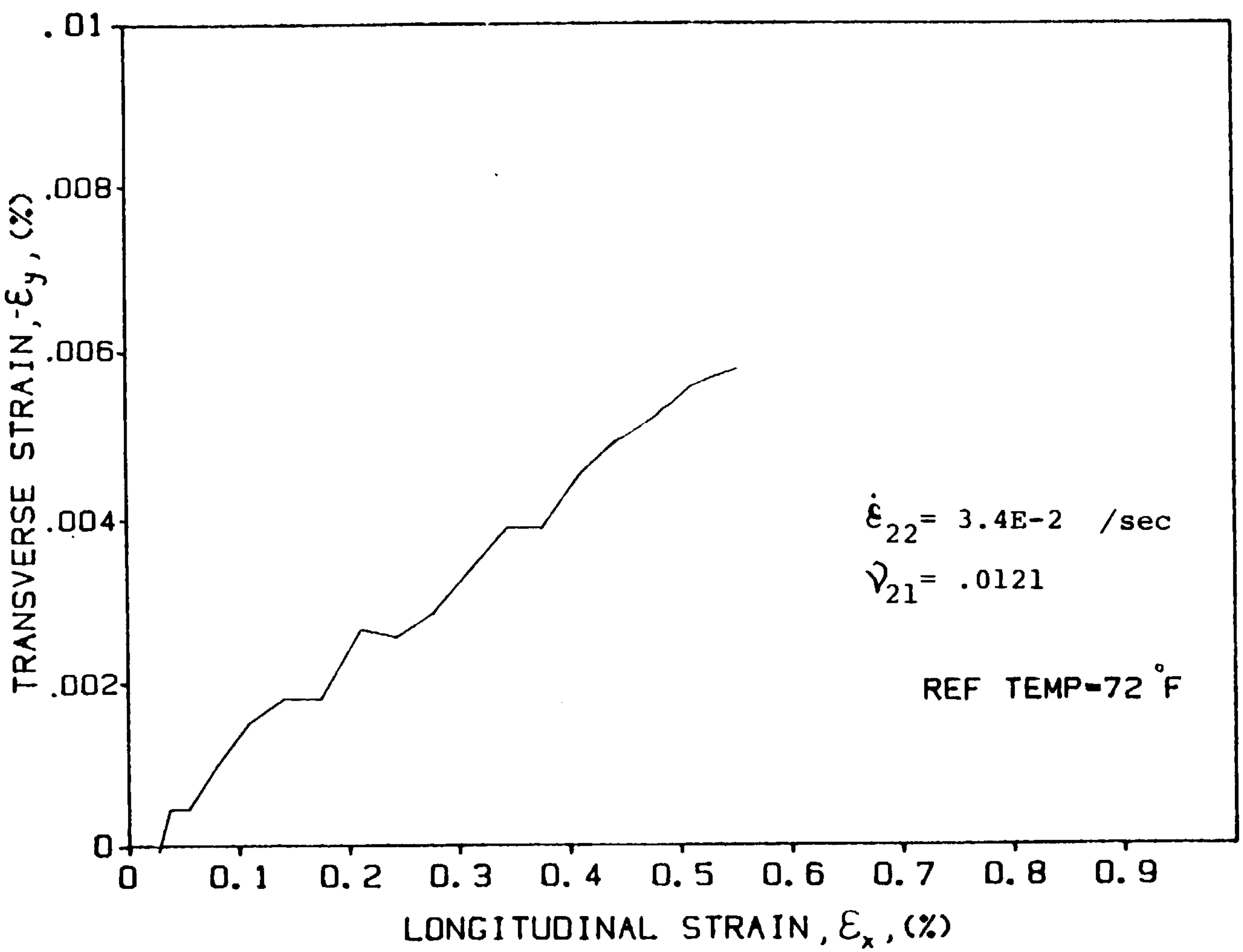


Fig. 3-14· Typical Transverse vs. Longitudinal Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22}$ = 3.4 x 10^{-2} sec^{-1}, T = 23°C (72°F))

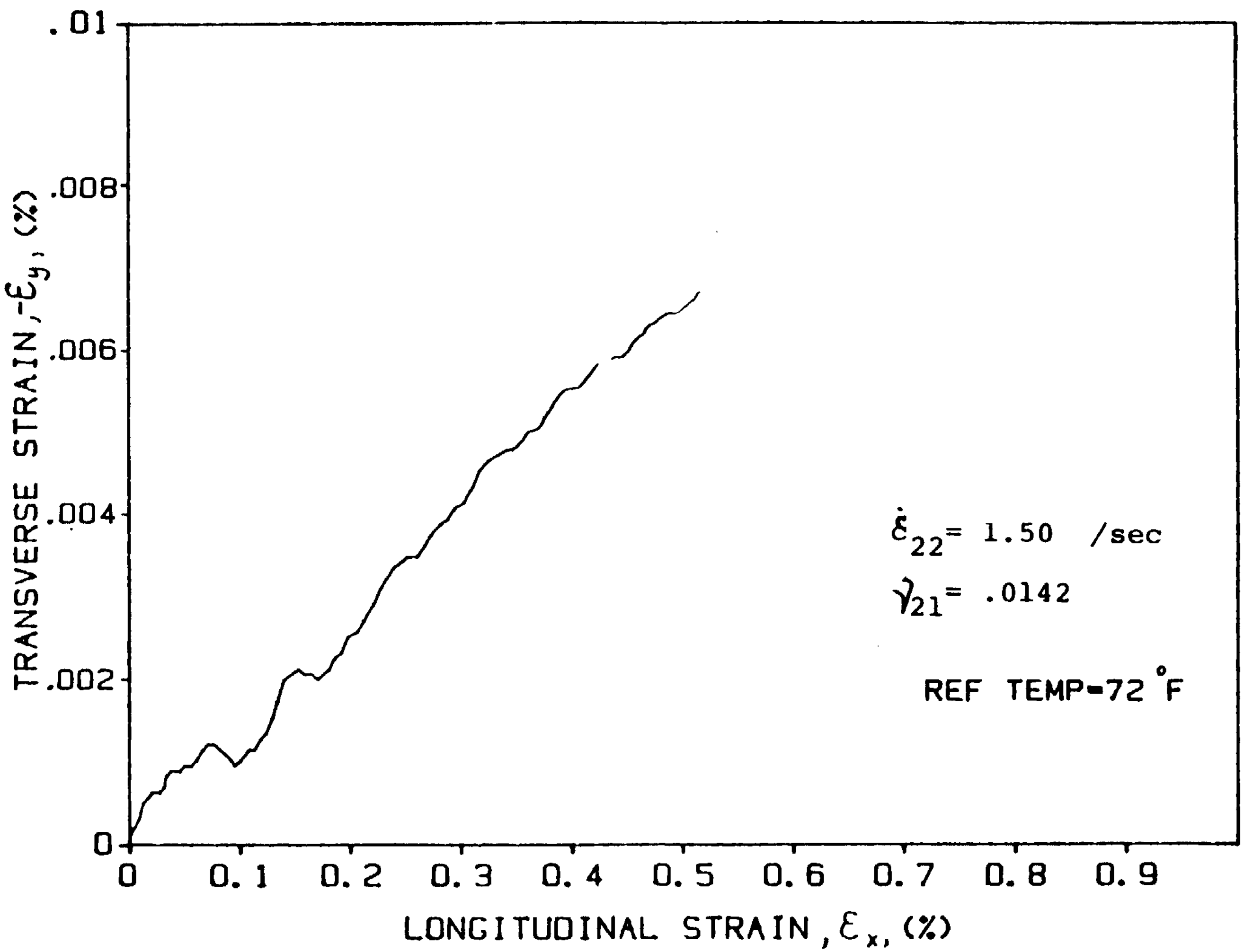


Fig. 3-15. Typical Transverse vs. Longitudinal Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22}$ = 1.5 sec^{-1}, T = 23°C (72°F))

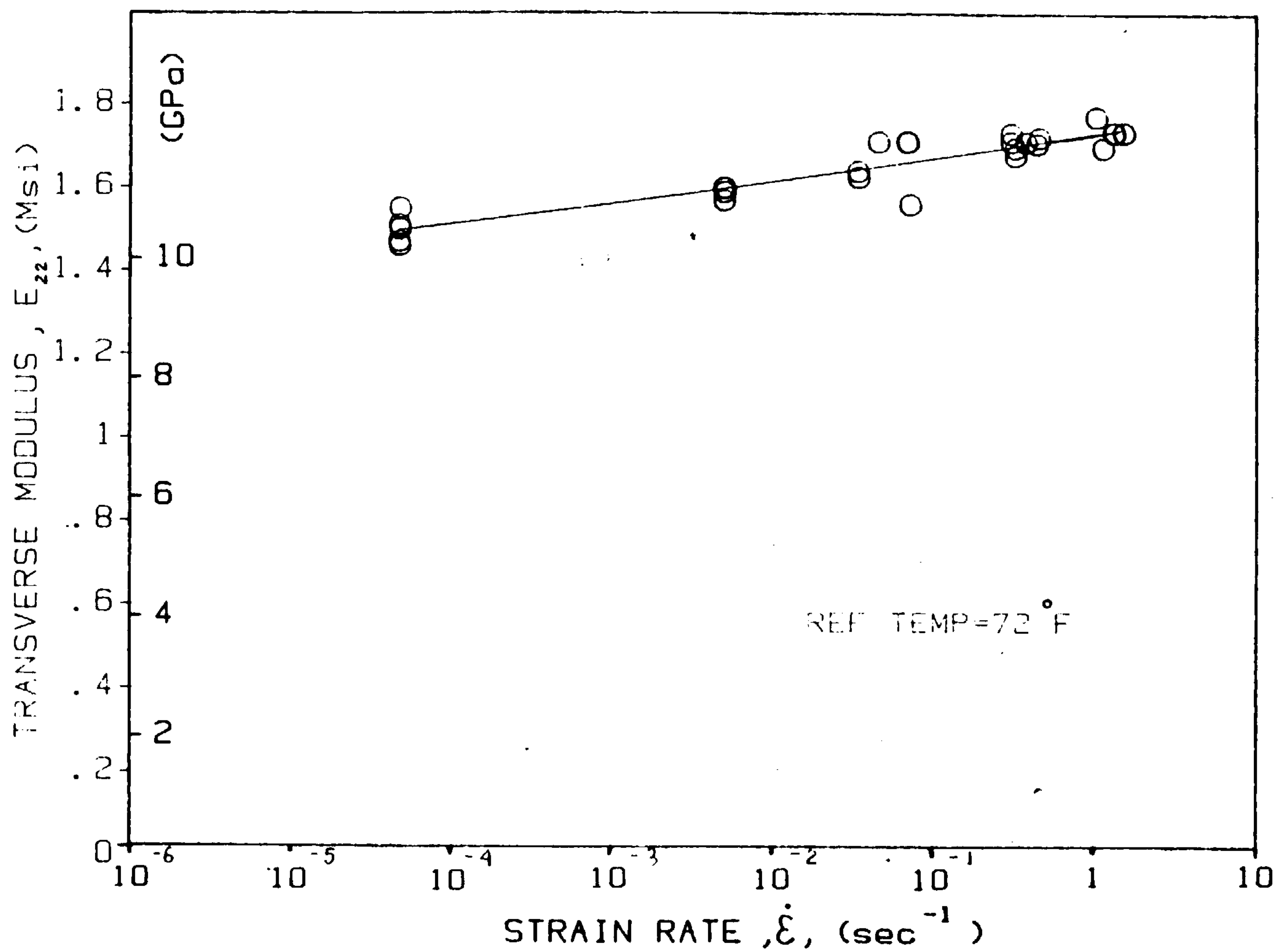


Fig. 3-16. Transverse Modulus, E_{22}, vs. Strain-Rate, $\dot{\varepsilon}_{22}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

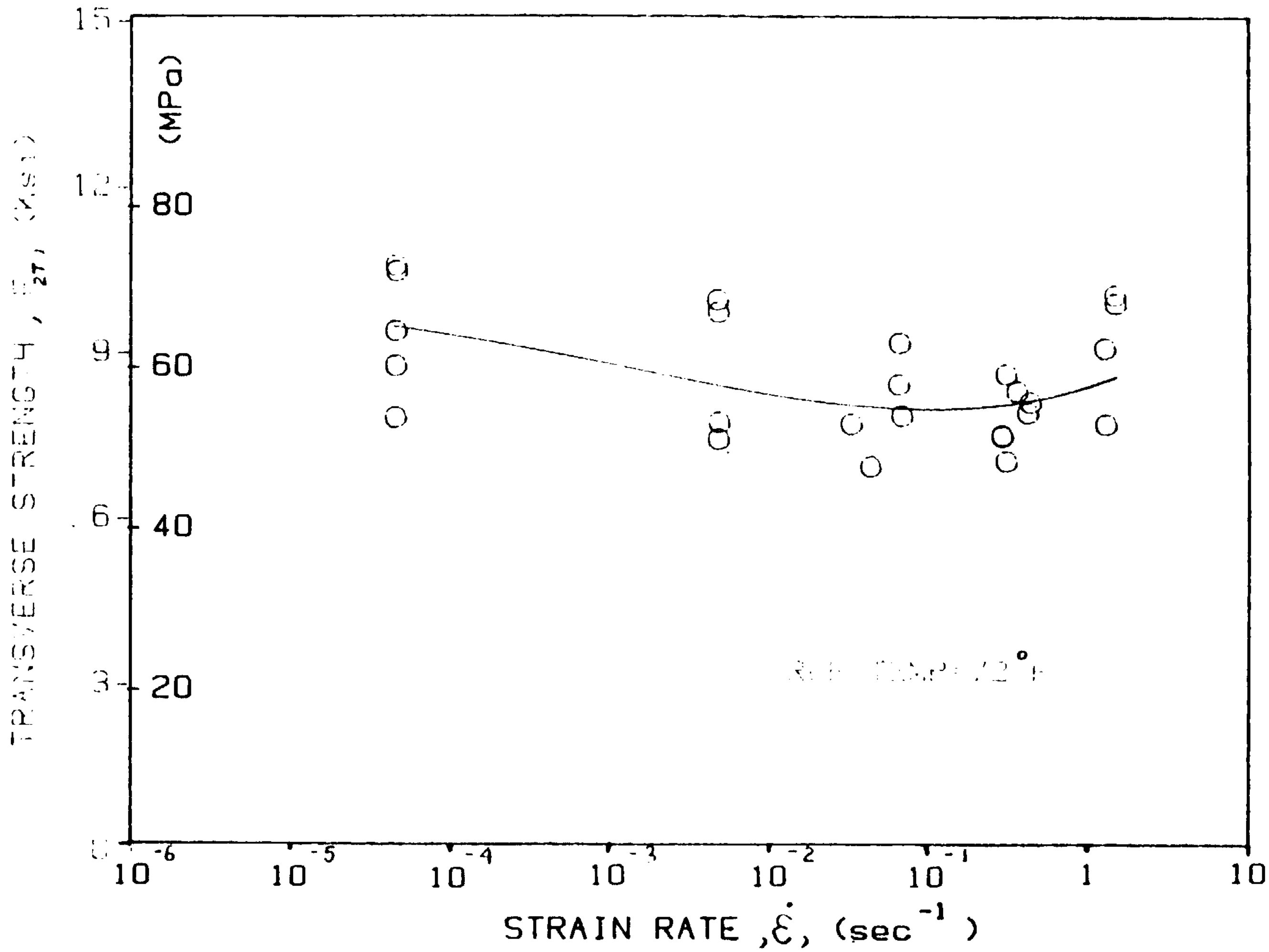


Fig. 3-17. Transverse Tensile Strength, F_{2T}, vs. Strain-Rate, $\dot{\varepsilon}_{22}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

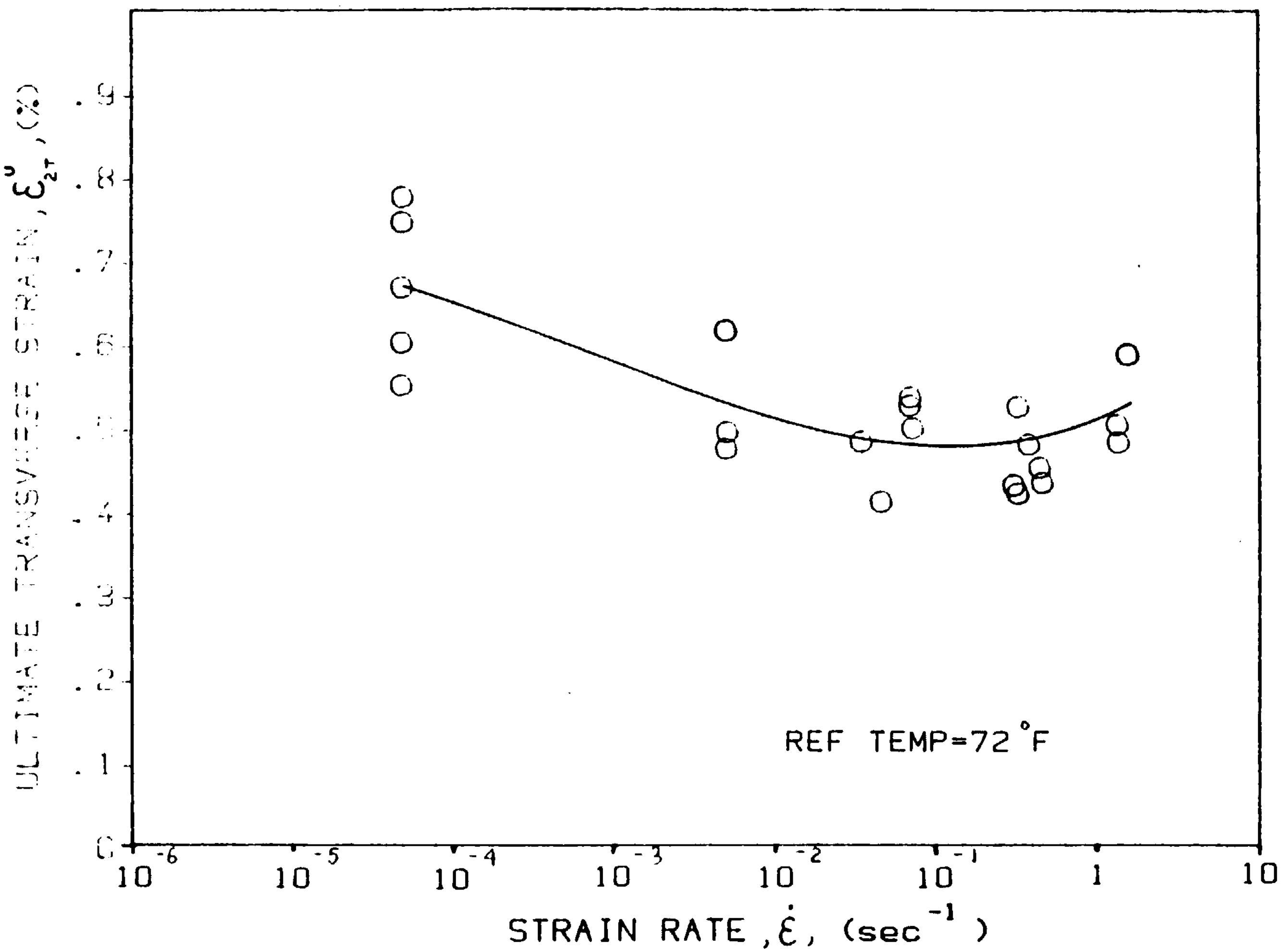


Fig. 3-18. Ultimate Transverse Tensile Strain, ε^{u}_{2T}, vs. Strain-Rate, $\dot{\varepsilon}_{22}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

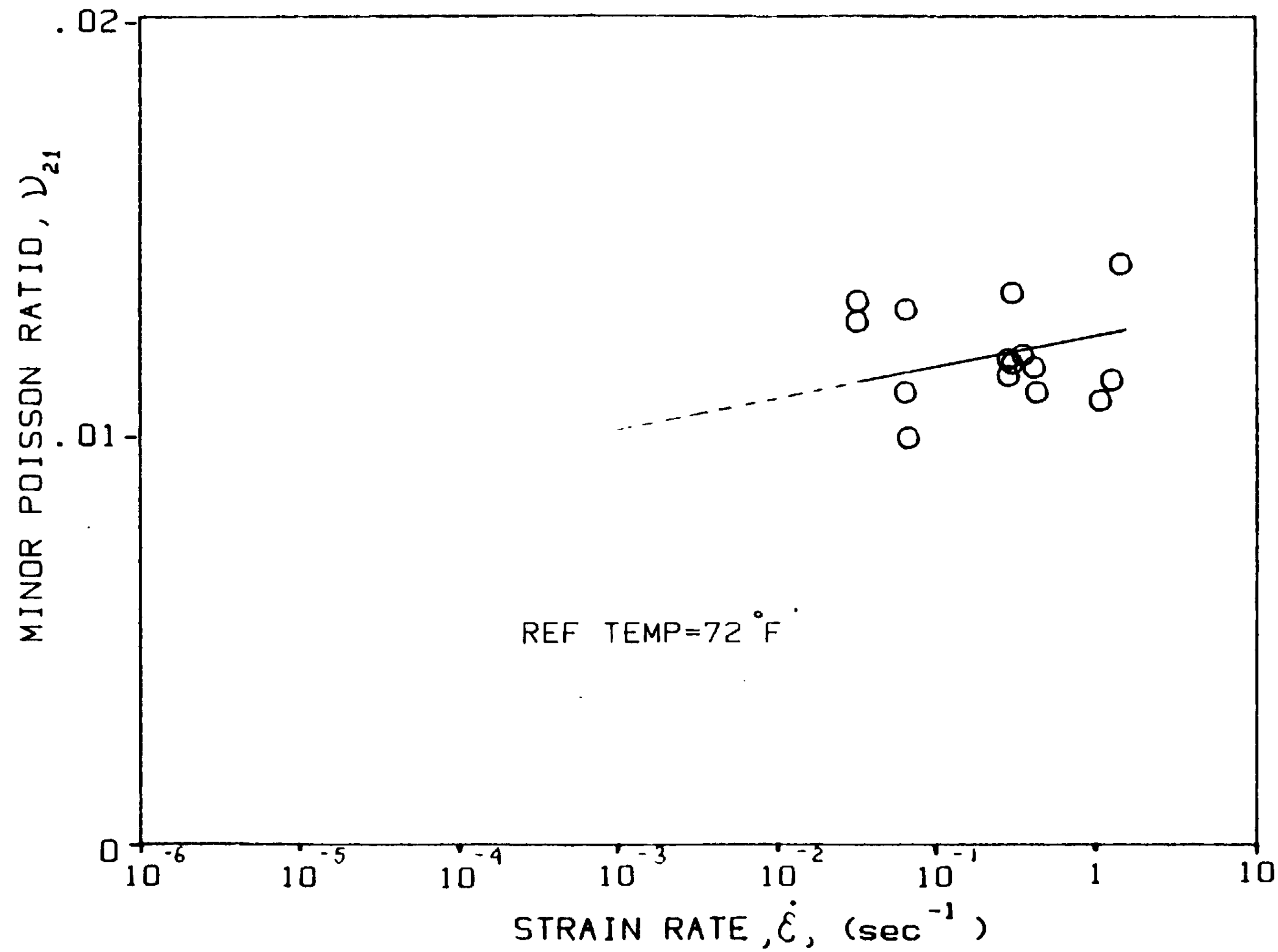


Fig. 3-19. Minor Poisson's Ratio, ν_{21}, vs. Strain-Rate, $\dot{\varepsilon}_{22}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

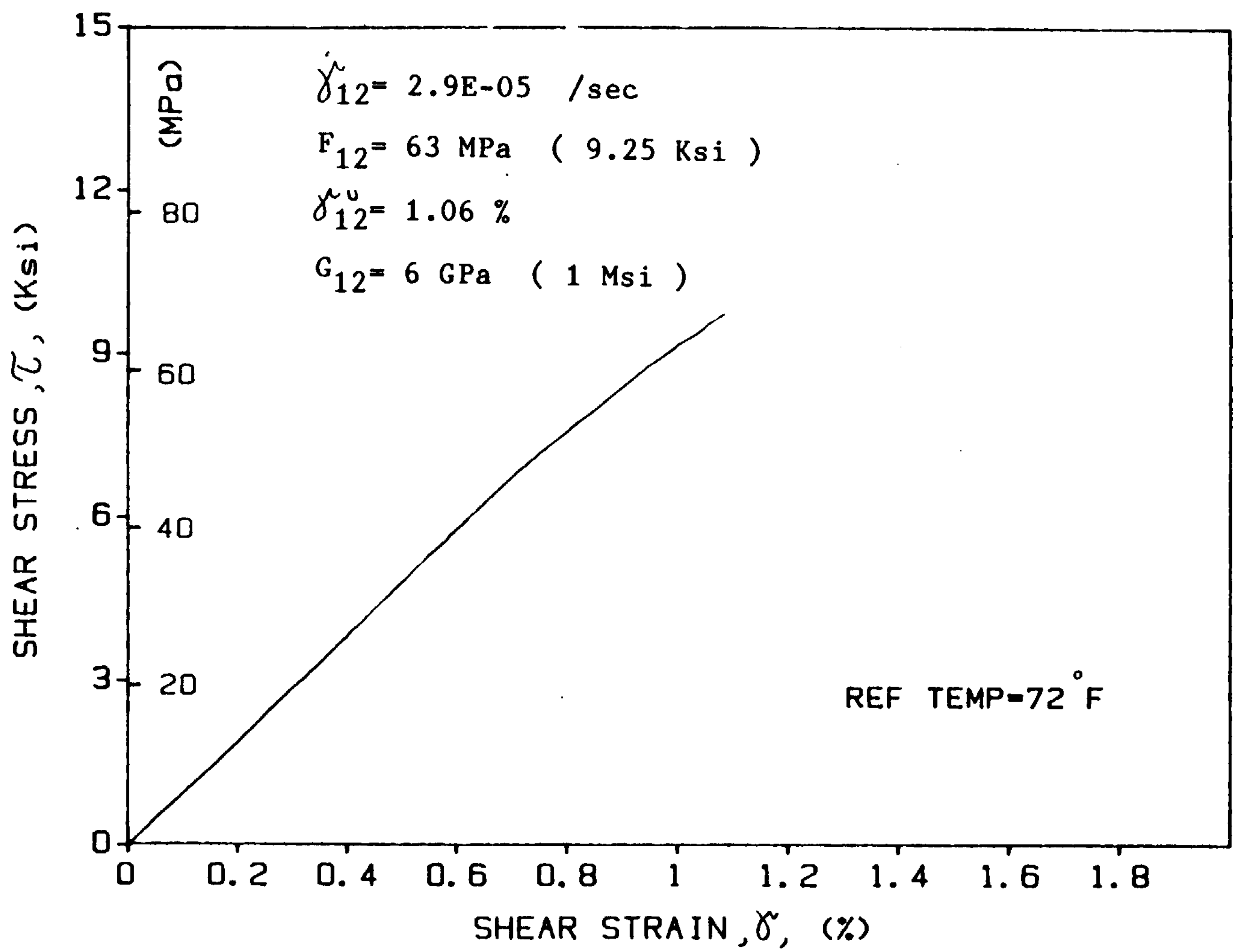


Fig. 3-20. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12}$ = 2.9 x 10^{-5} sec^{-1}, T = 23°C (72°F))

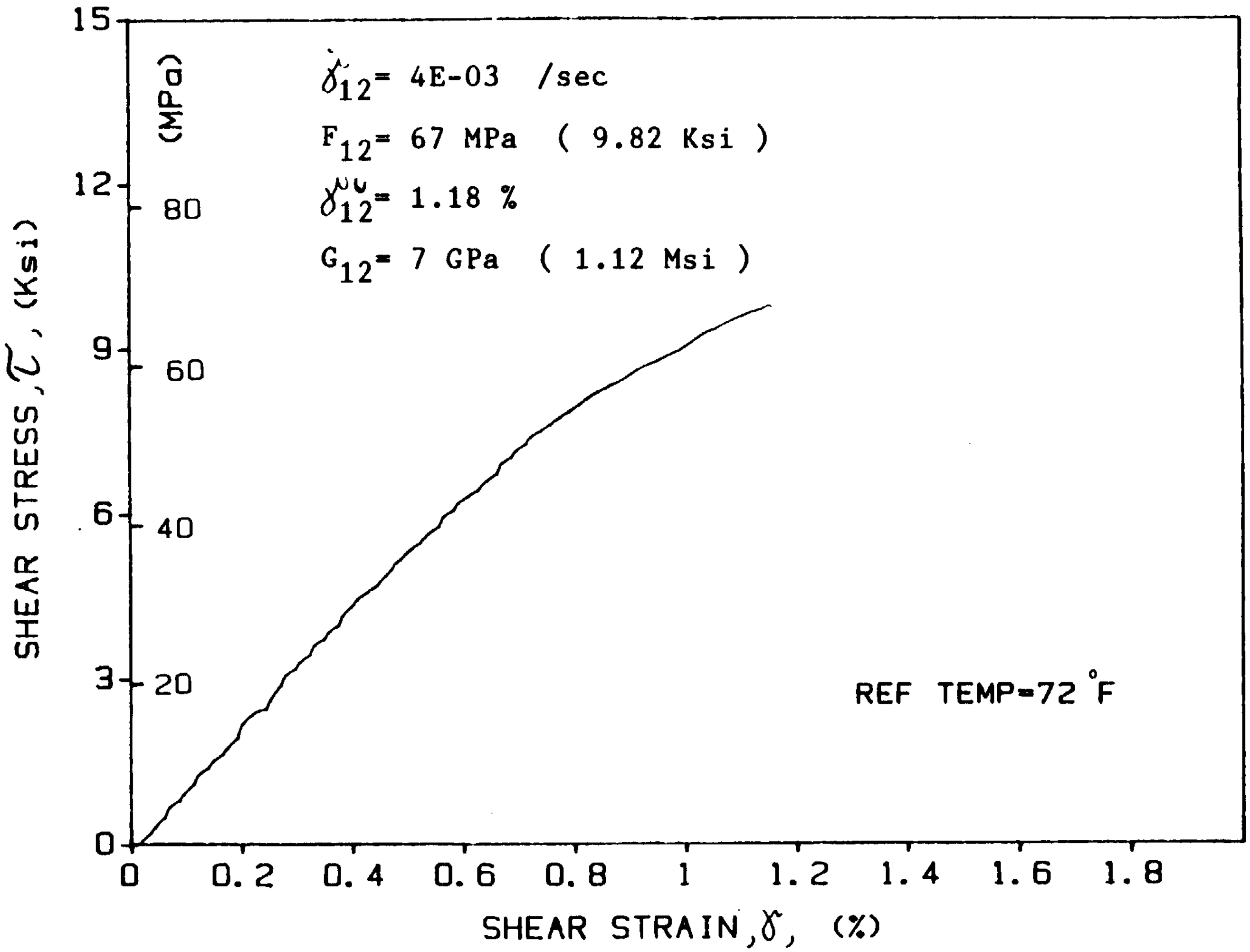


Fig. 3-21. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12} = 4 \times 10^{-3}$ sec^{-1}, T = 23°C (72°F))

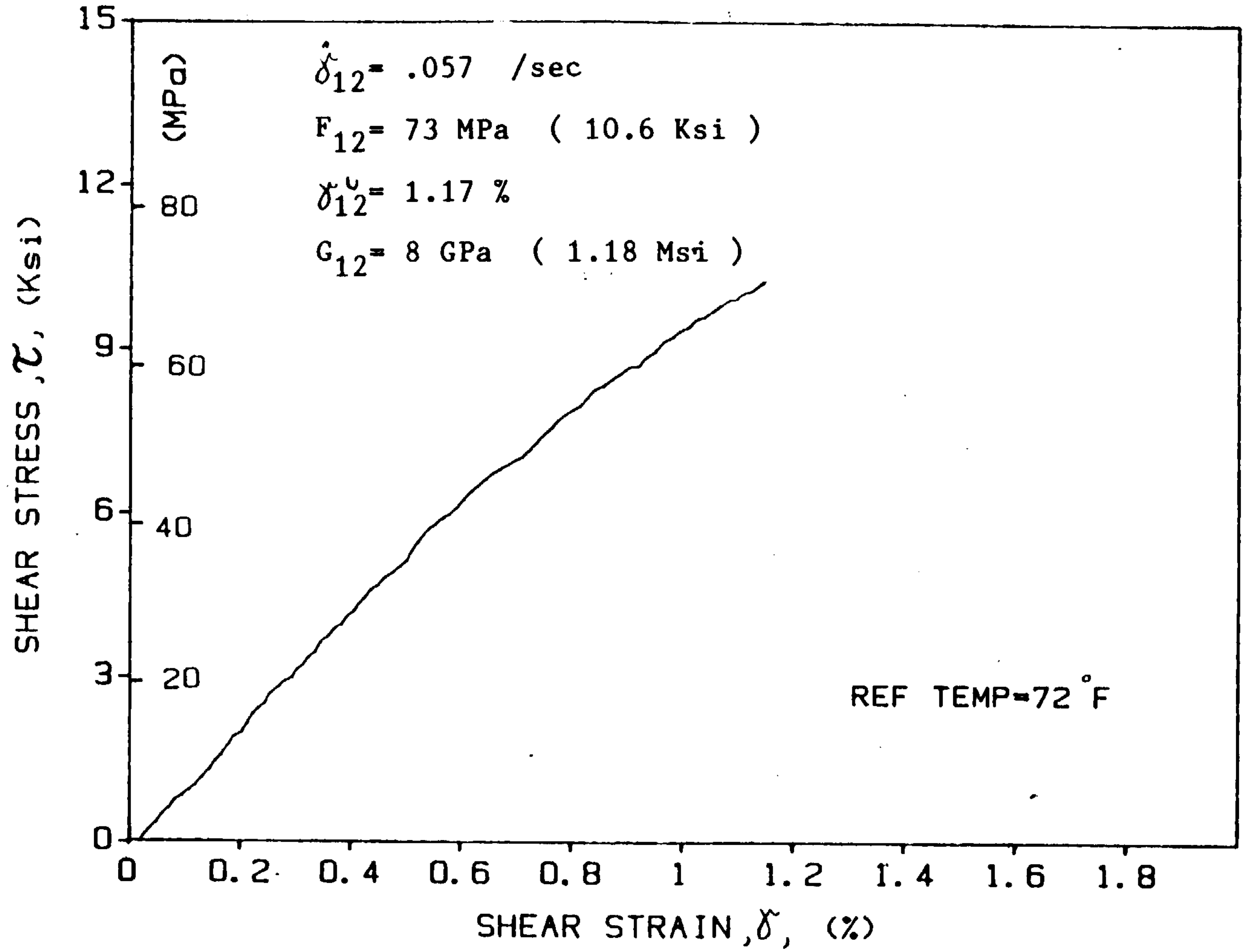


Fig. 3-22. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12} = 5.7 \times 10^{-2}$ sec^{-1}, T = 23°C (72°F))

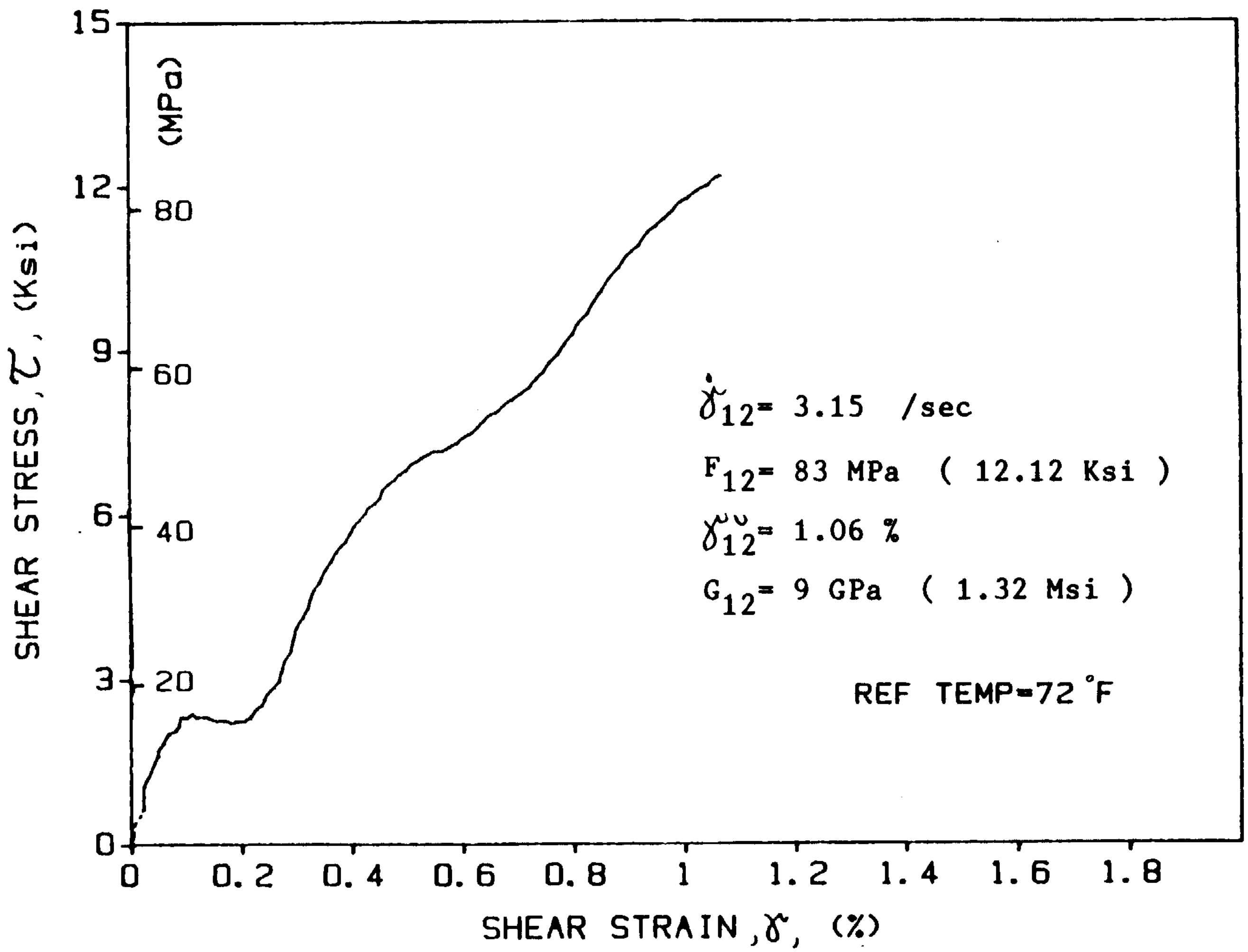


Fig. 3-23. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12}$ = 3.15 sec^{-1}, T = 23°C (72°F))

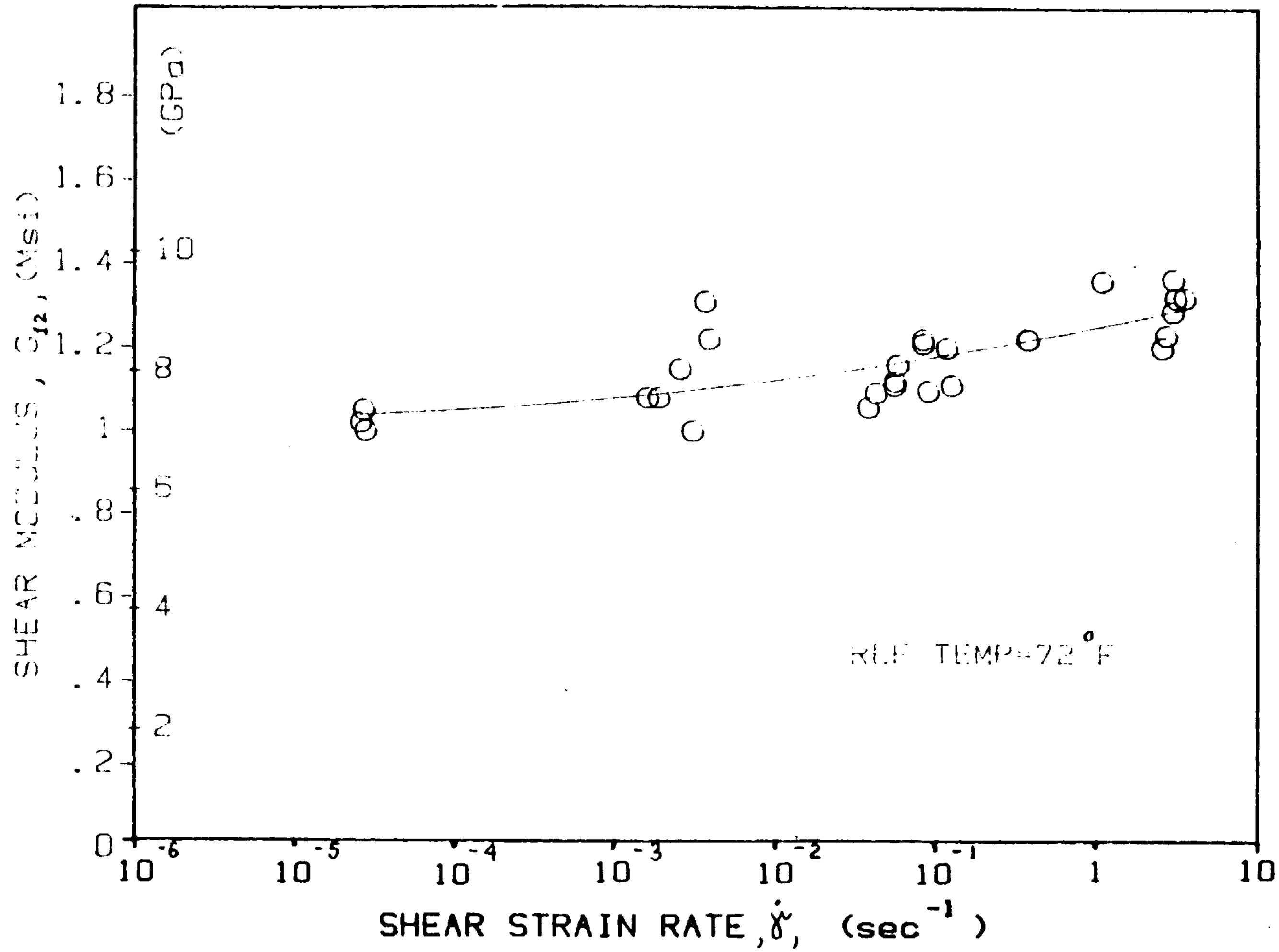


Fig. 3-24. In-Plane Shear Modulus, G_{12}, vs. Shear Strain Rate, $\dot{\gamma}_{12}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

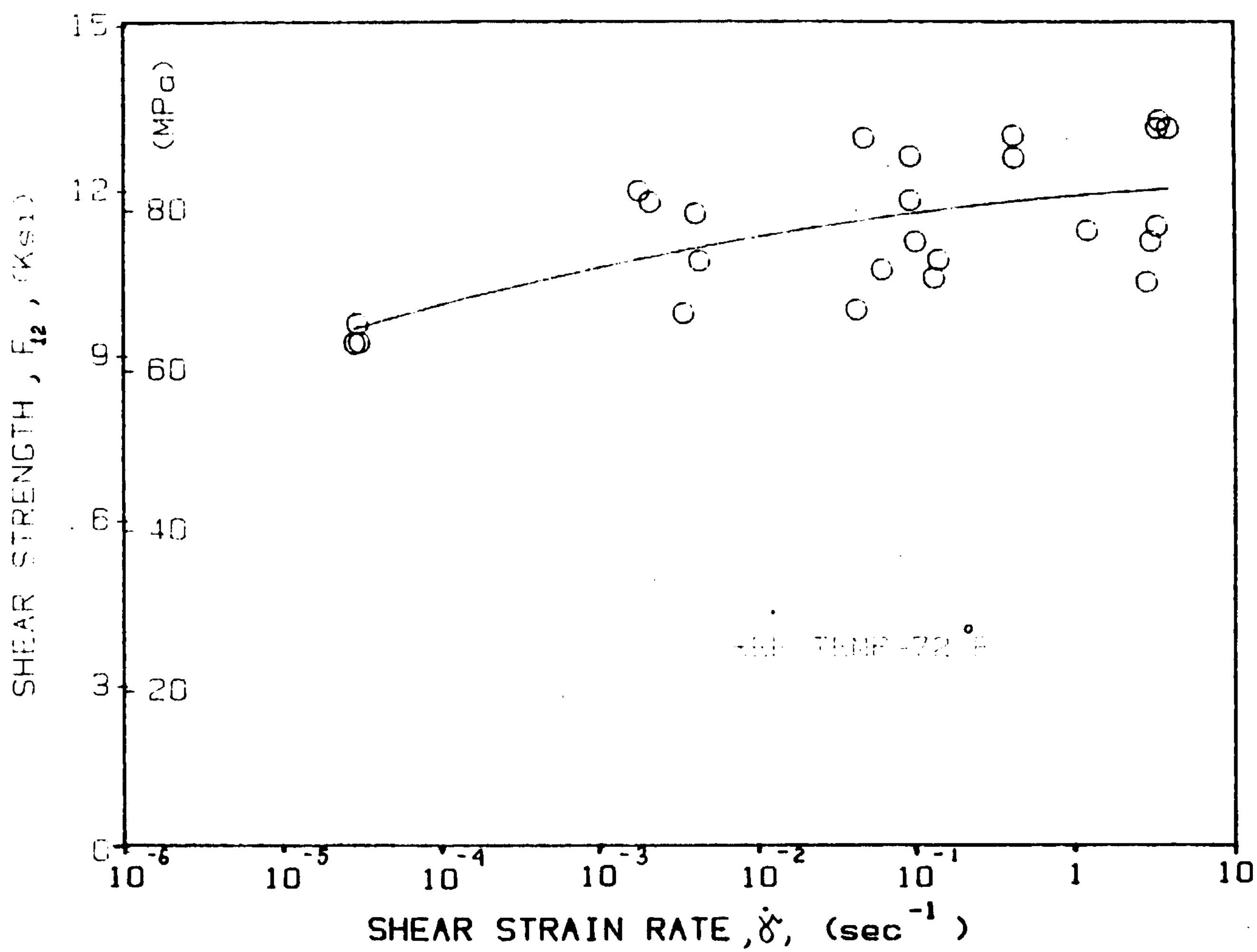


Fig. 3-25. In-Plane Shear Strength, F_{12}, vs. Shear Strain Rate, $\dot{\gamma}_{12}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

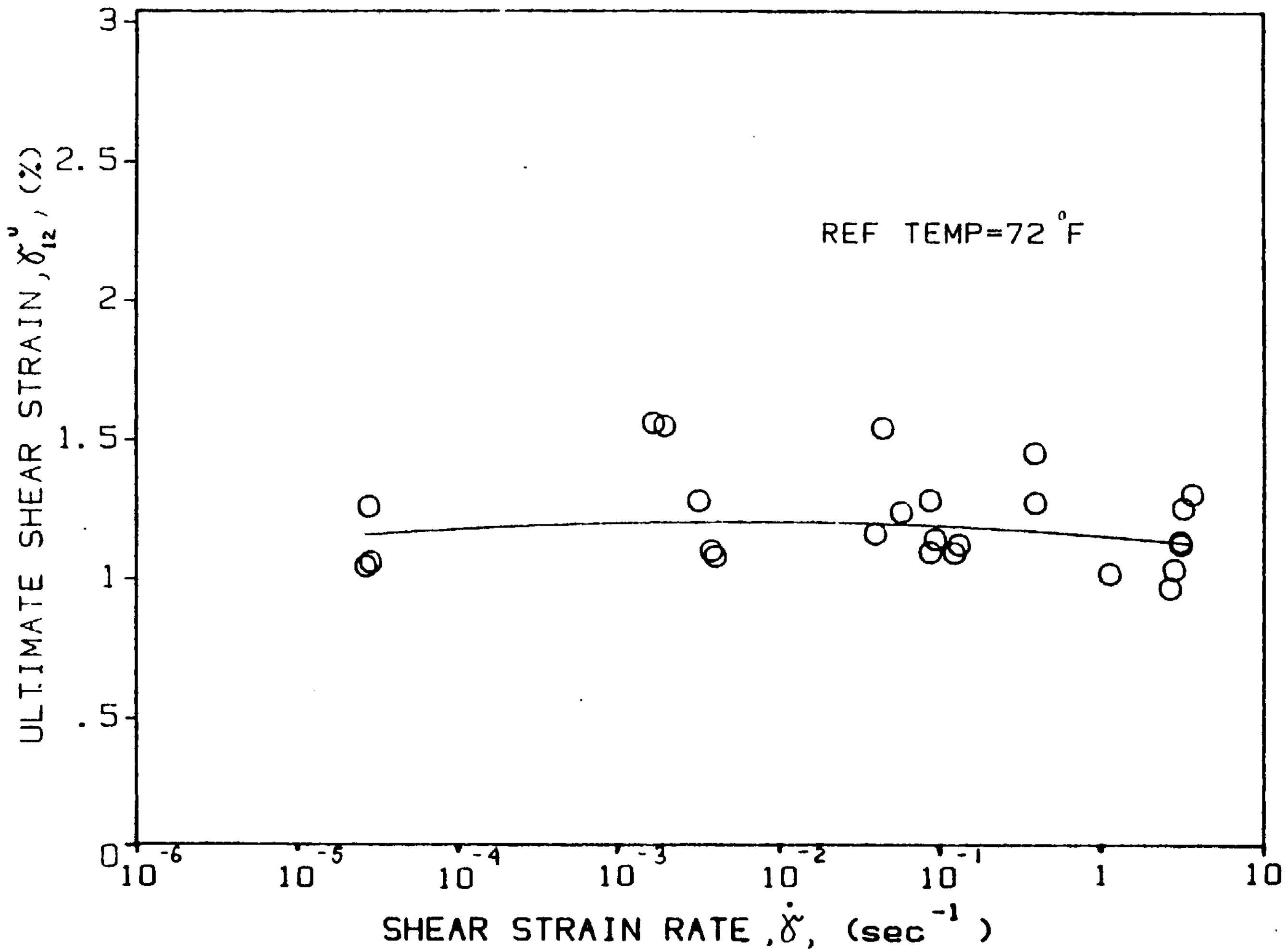


Fig. 3-26. Ultimate Shear Strain, γ_{12}^{u}, vs. Shear Strain Rate, $\dot{\gamma}_{12}$, for AS4/3501-6 Graphite/Epoxy (T = 23°C (72°F))

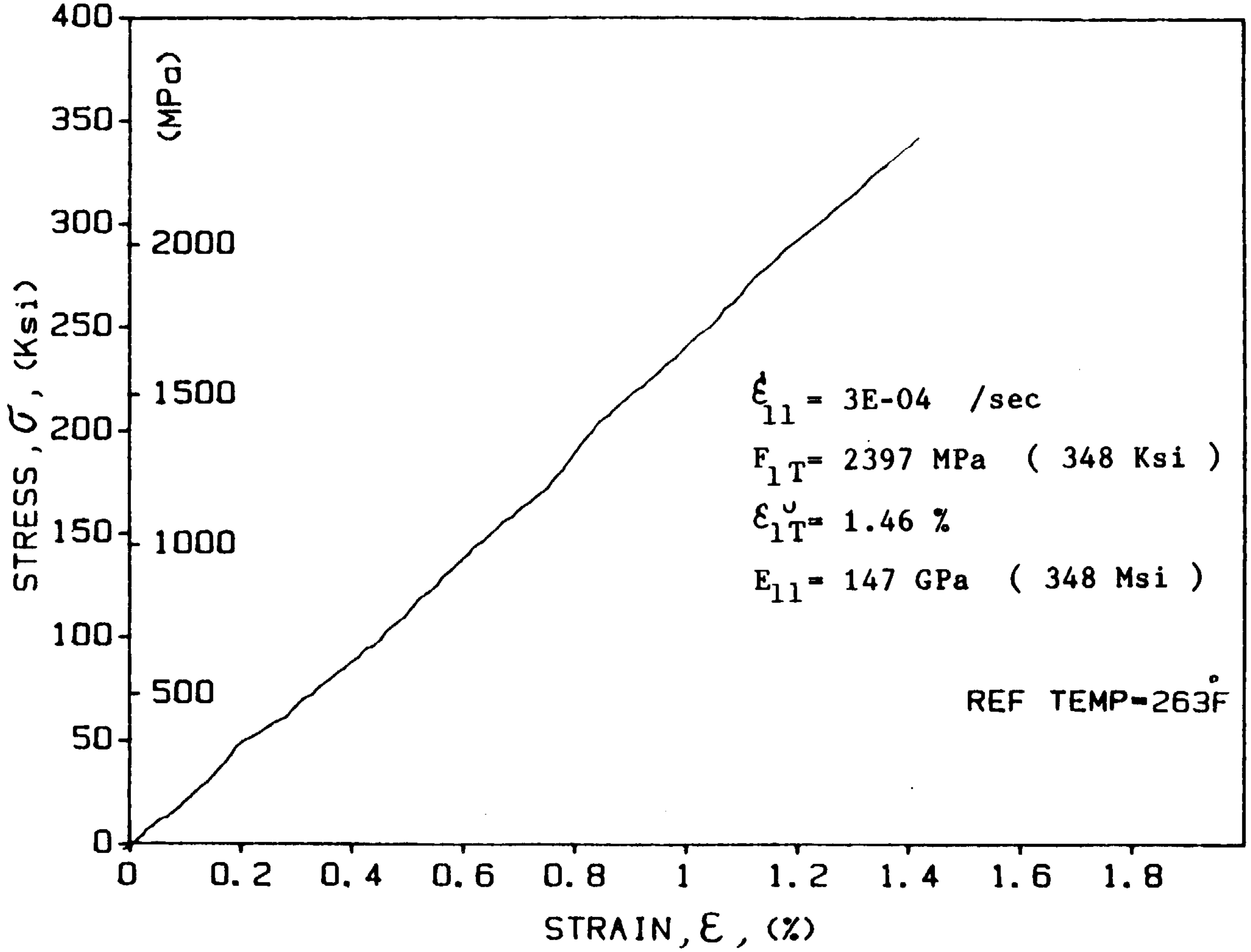


Fig. 3-27. Typical Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{11} = 3 \times 10^{-4}$ sec^{-1}, T = 128°C (263°F))

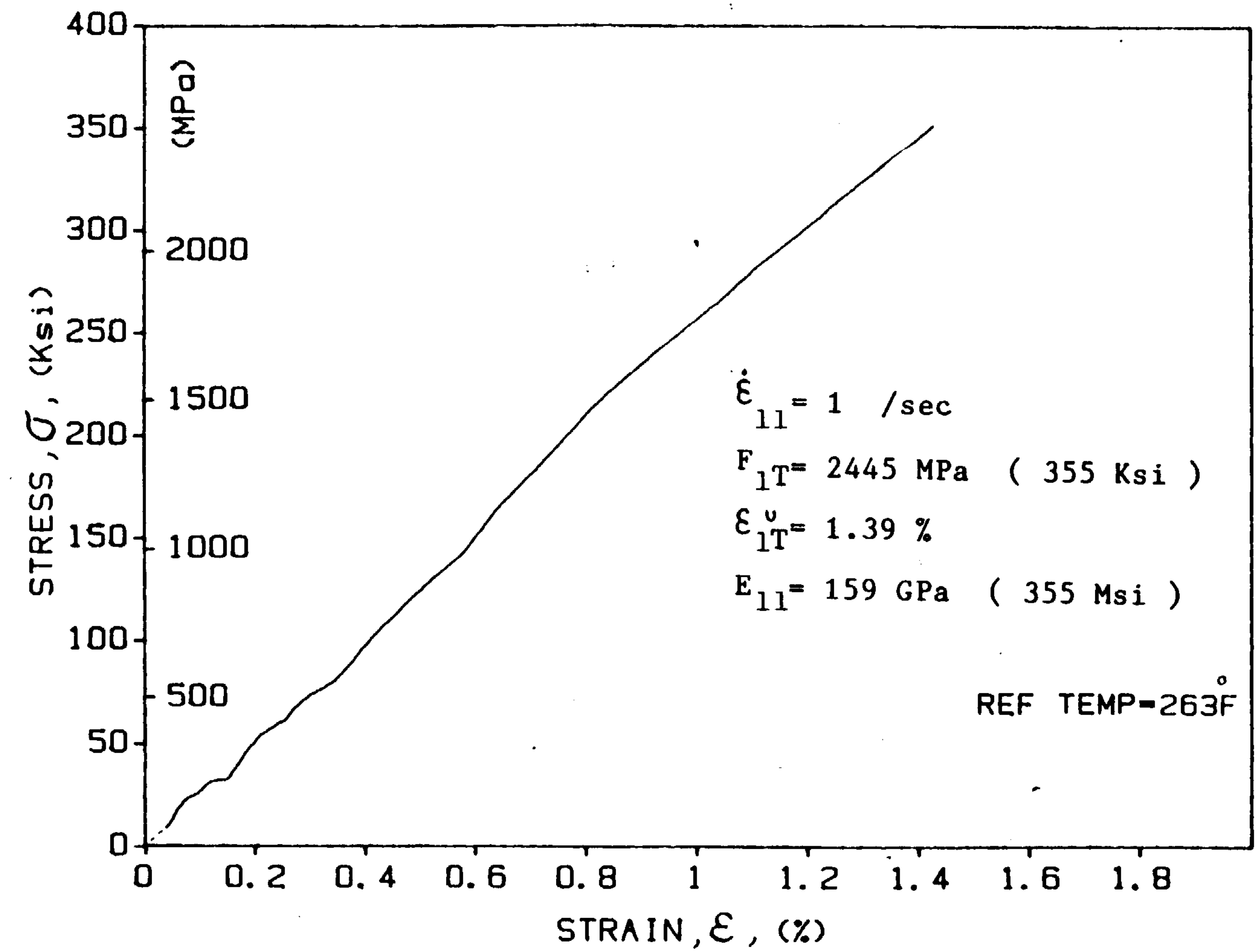


Fig. 3-28. Typical Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/ Epoxy ($\dot{\varepsilon}_{11}$ = 1.0 sec^{-1}, T = 128°C (263°F))

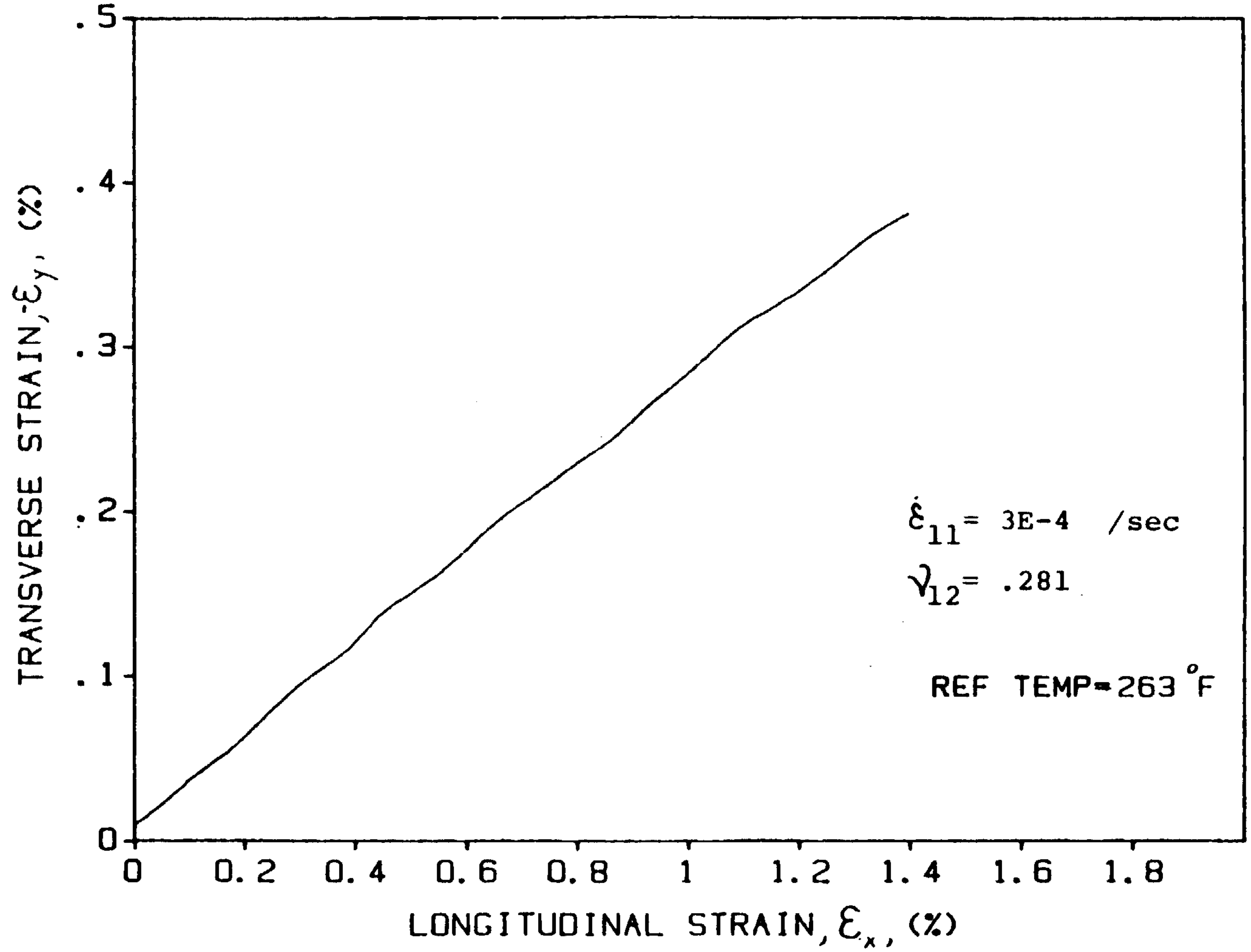


Fig. 3-29. Typical Transverse vs. Longitudinal Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{11} = 3 \times 10^{-4}$ sec^{-1}, T = 128°C (263°F))

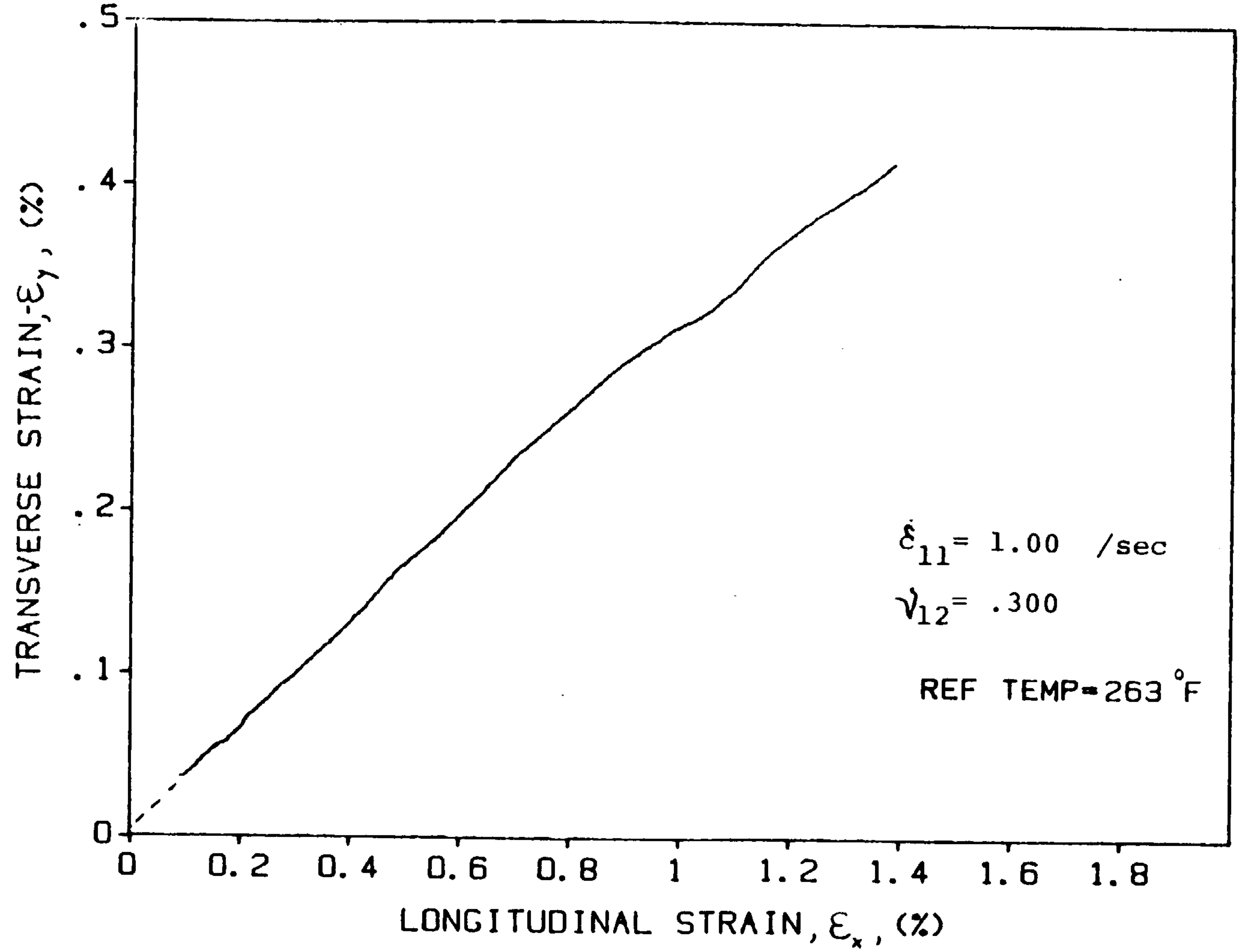


Fig. 3-30. Typical Transverse vs. Longitudinal Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epocy ($\dot{\varepsilon}_{11}$ = 1.0 sec^{-1}, T = 128°C (263°F))

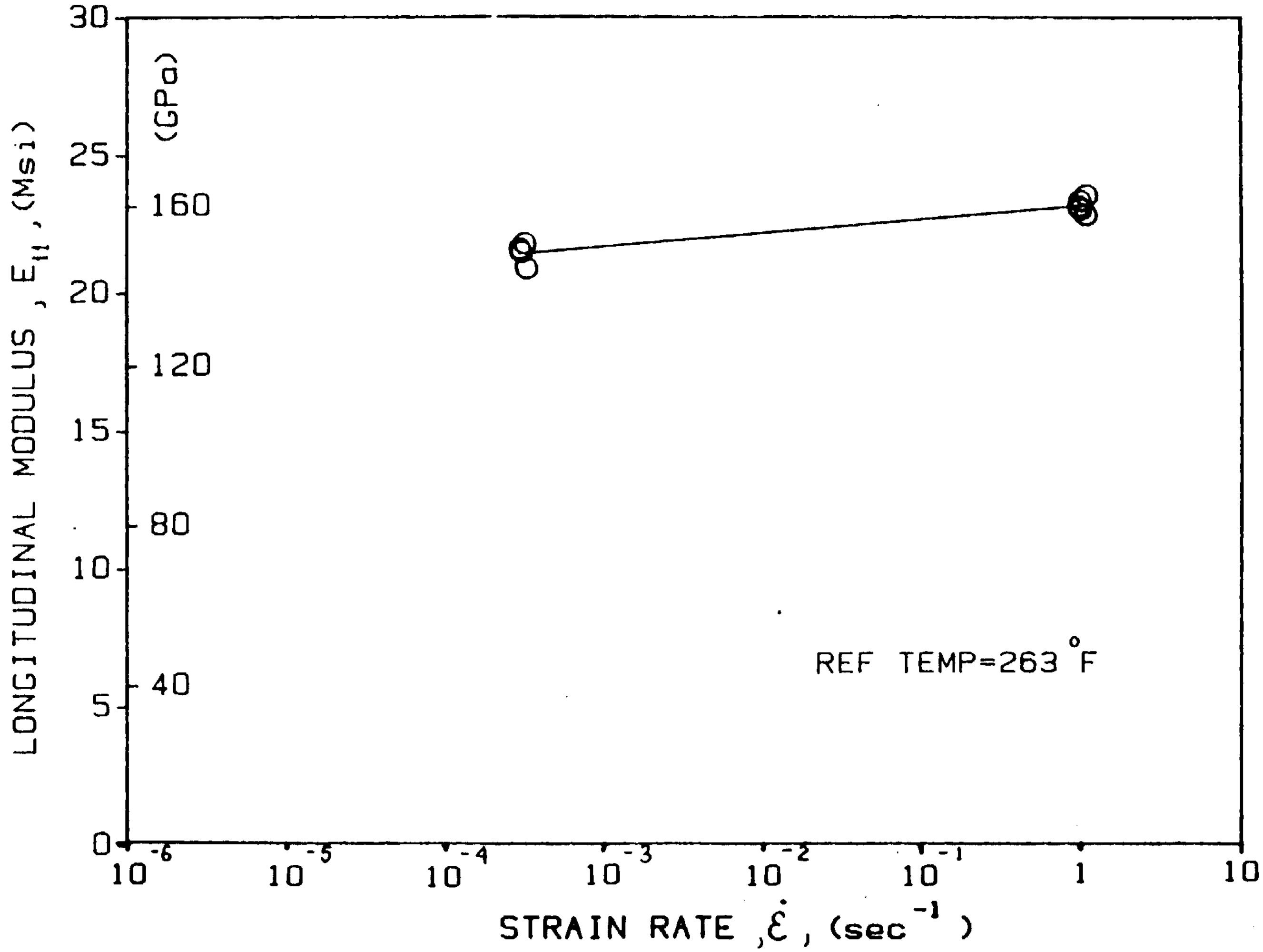


Fig. 3-31. Longitudinal Modulus, E_{11}, vs. Strain-Rate, $\dot{\varepsilon}_{11}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

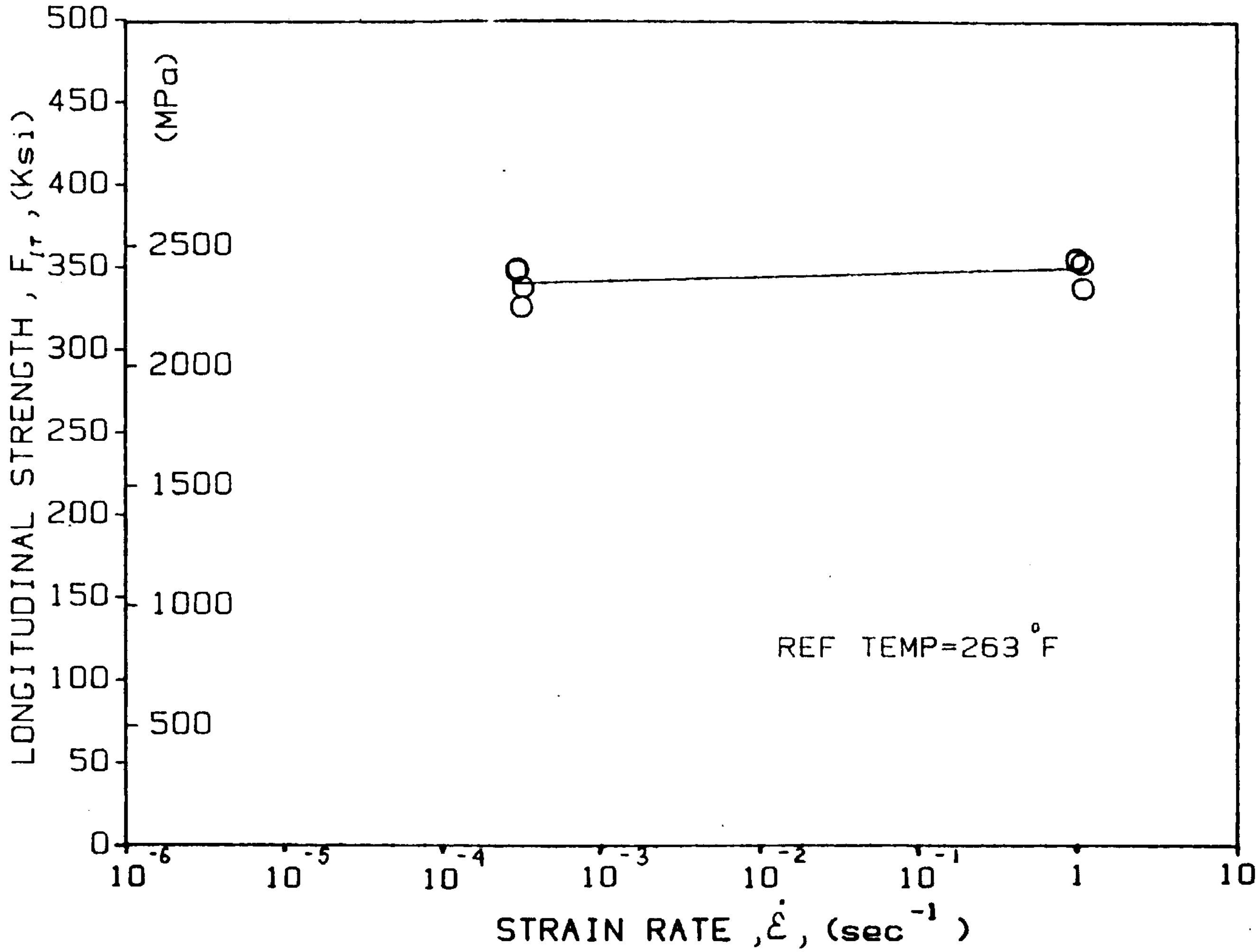


Fig. 3-32. Longitudinal Tensile Strength, F_{1T}, vs. Strain-Rate, $\dot{\varepsilon}_{11}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

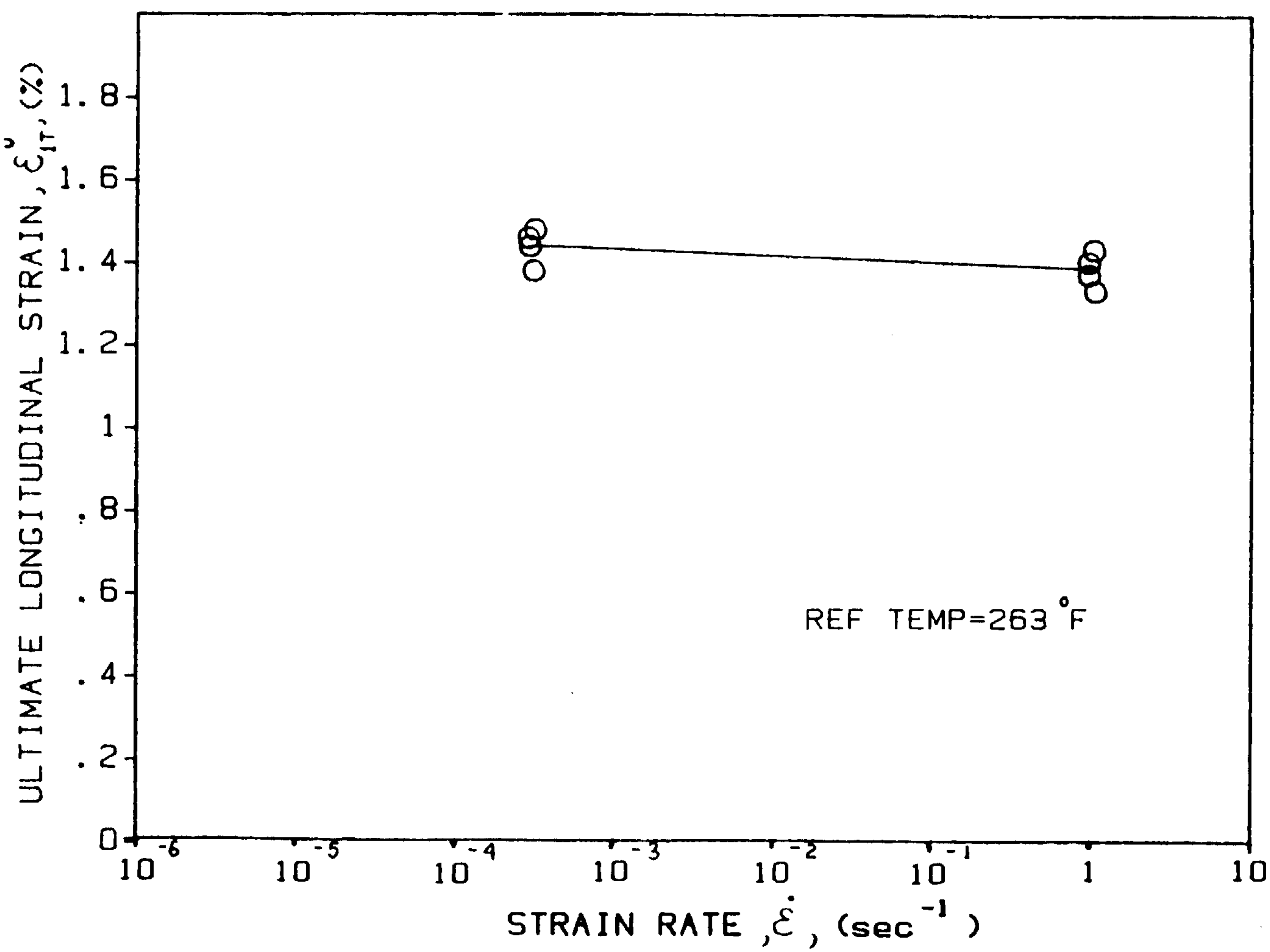


Fig. 3-33. Ultimate Longitudinal Tensile Strain vs. Strain-Rate, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

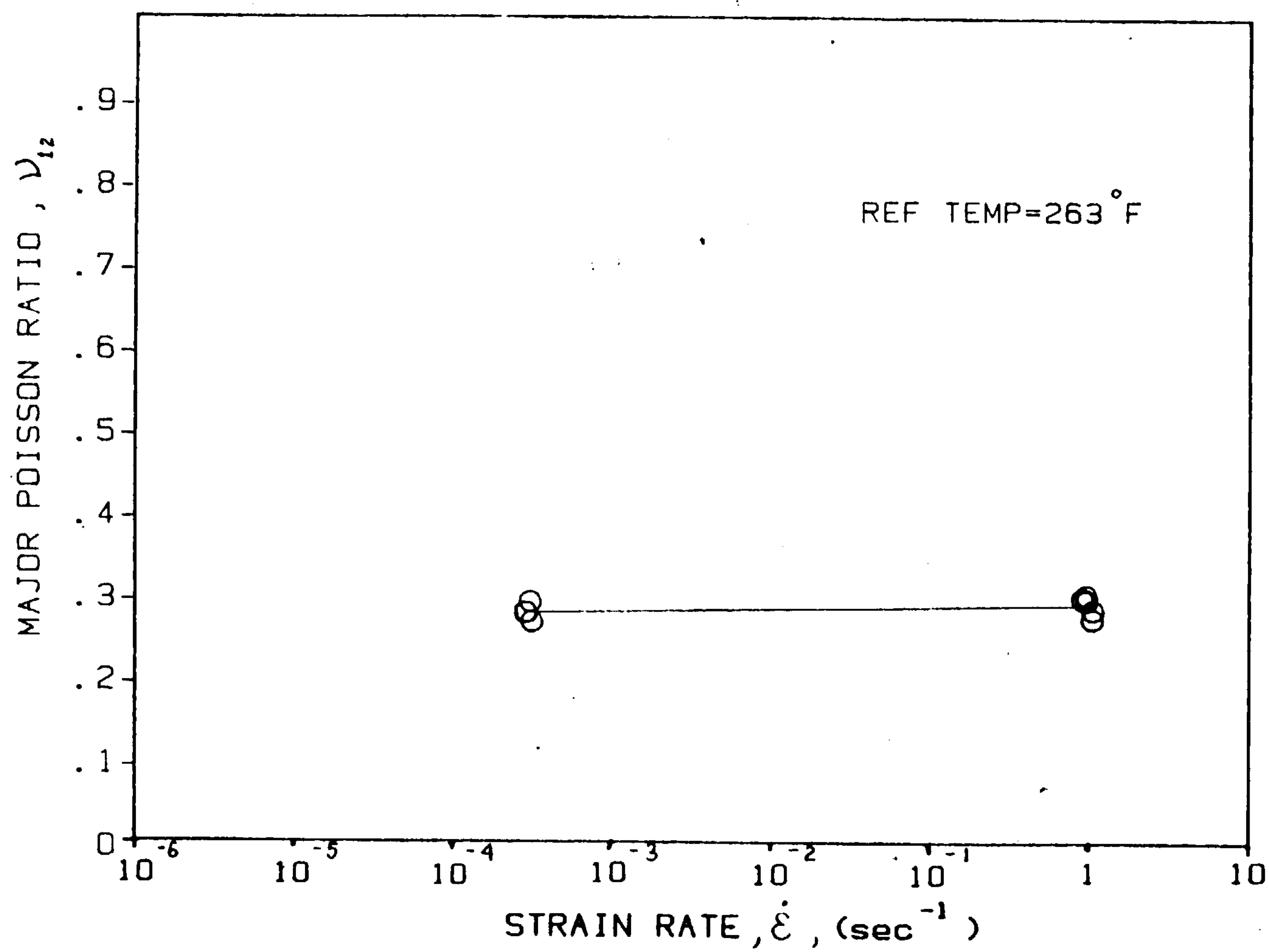


Fig. 3-34. Major Poisson's Ratio, ν_{12}, vs. Strain-Rate, $\dot{\varepsilon}_{11}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

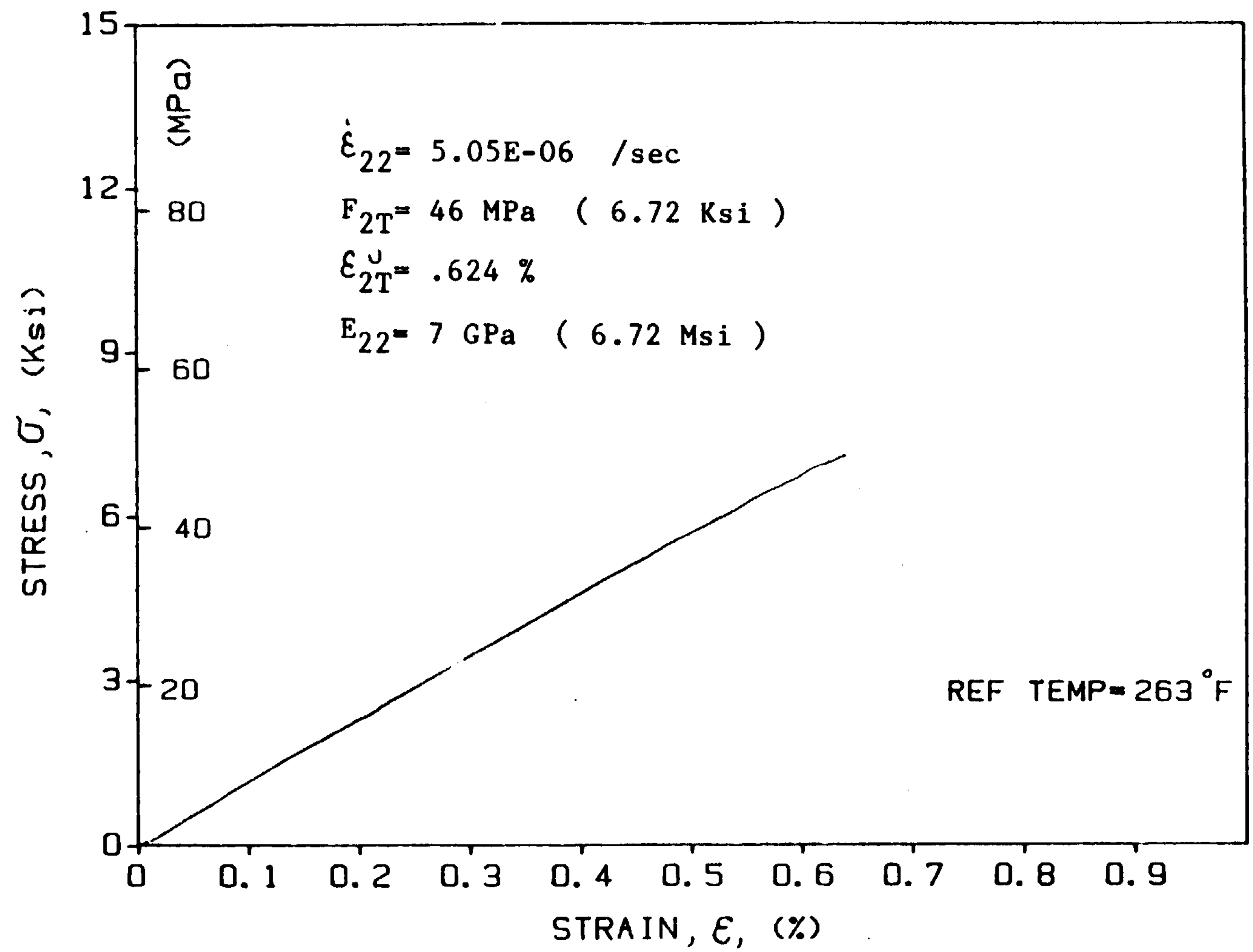


Fig. 3-35. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22}$ = 5.05 x 10^{-6} sec^{-1}, T = 128°C (263°F))

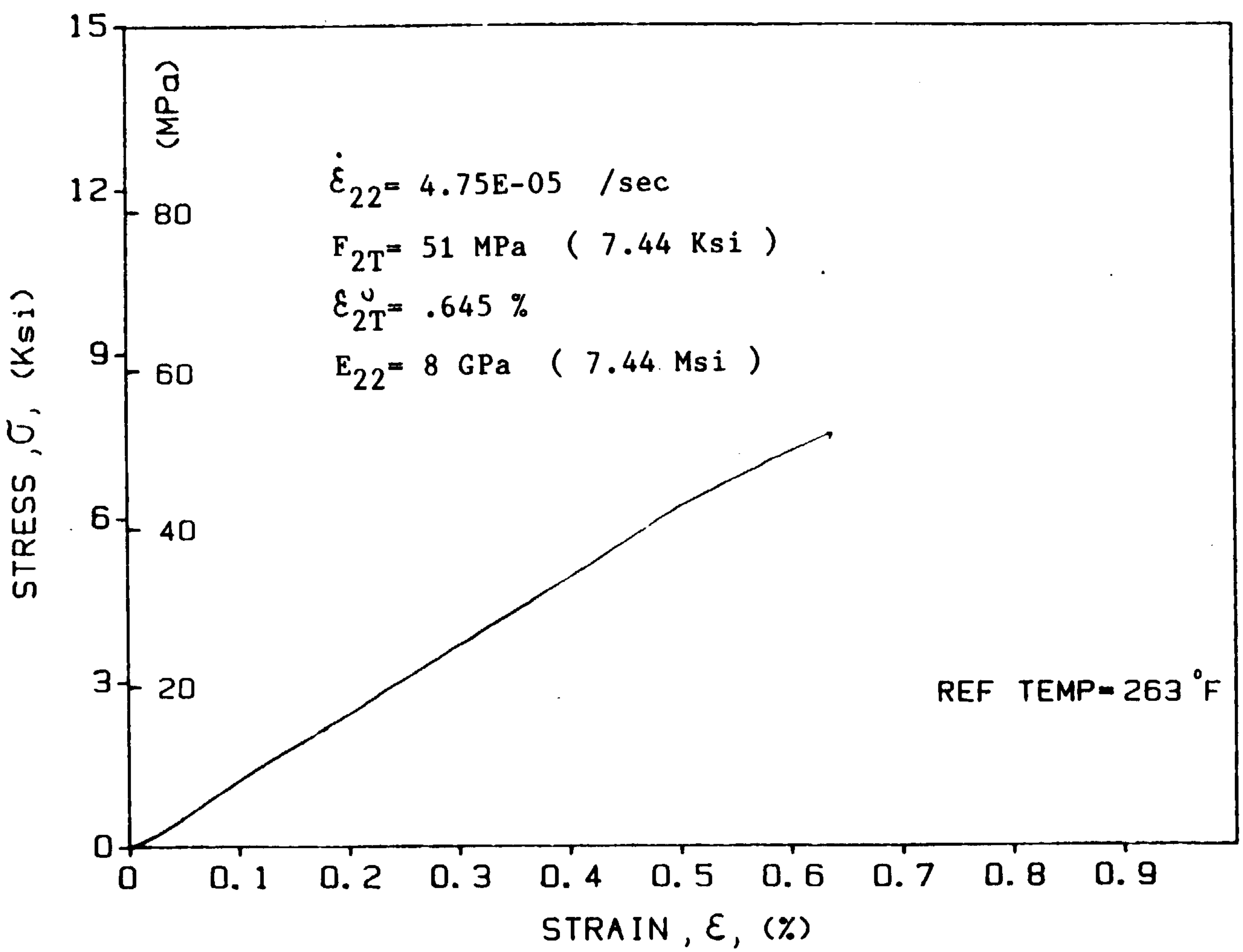


Fig. 3-36. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/ Epoxy ($\dot{\varepsilon}_{22}$ = 4.75 x 10^{-5} sec^{-1}, T = 128°C (263°F))

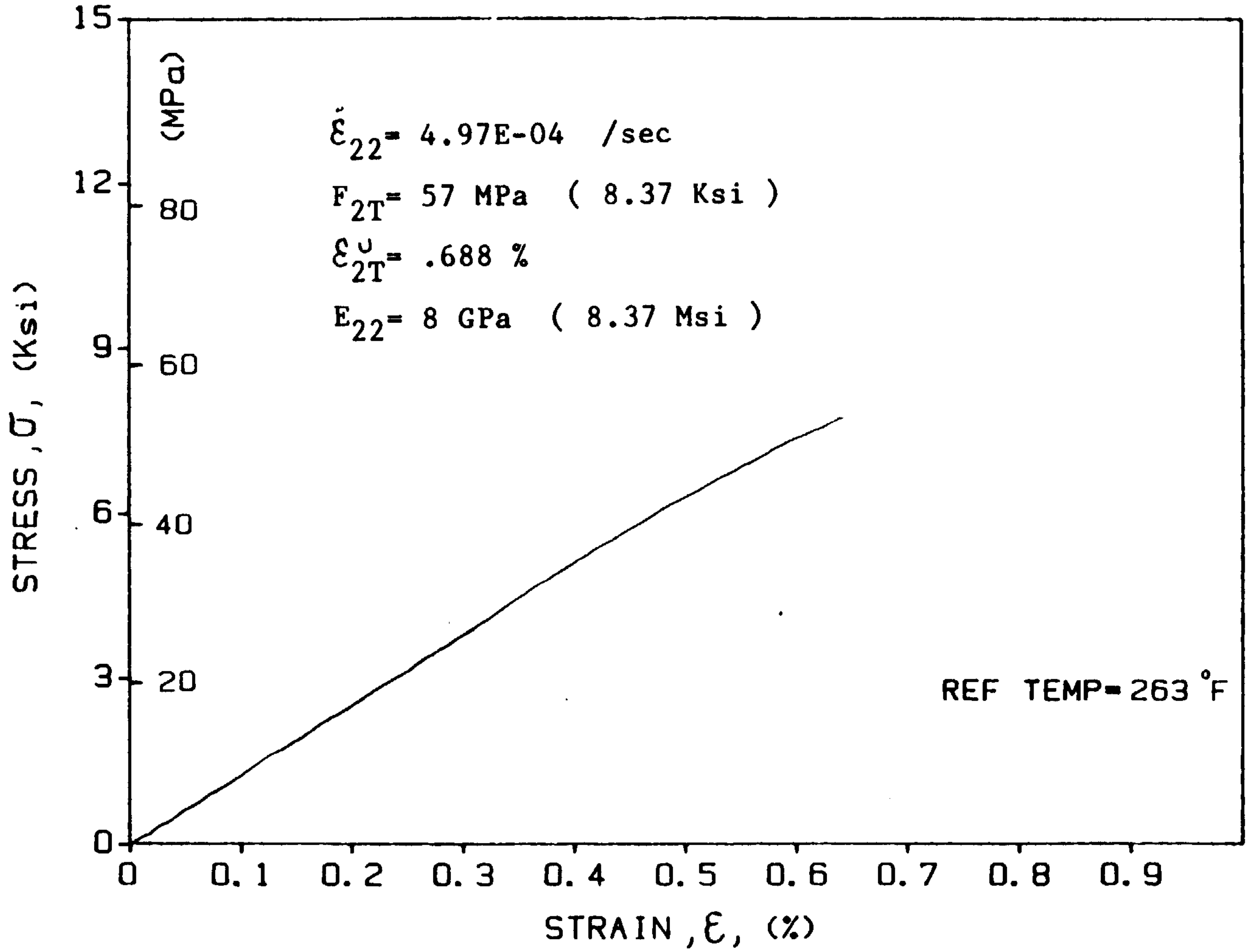


Fig. 3-37. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22}$ = 4.97 x 10^{-4} sec^{-1}, T = 128°C (263°F))

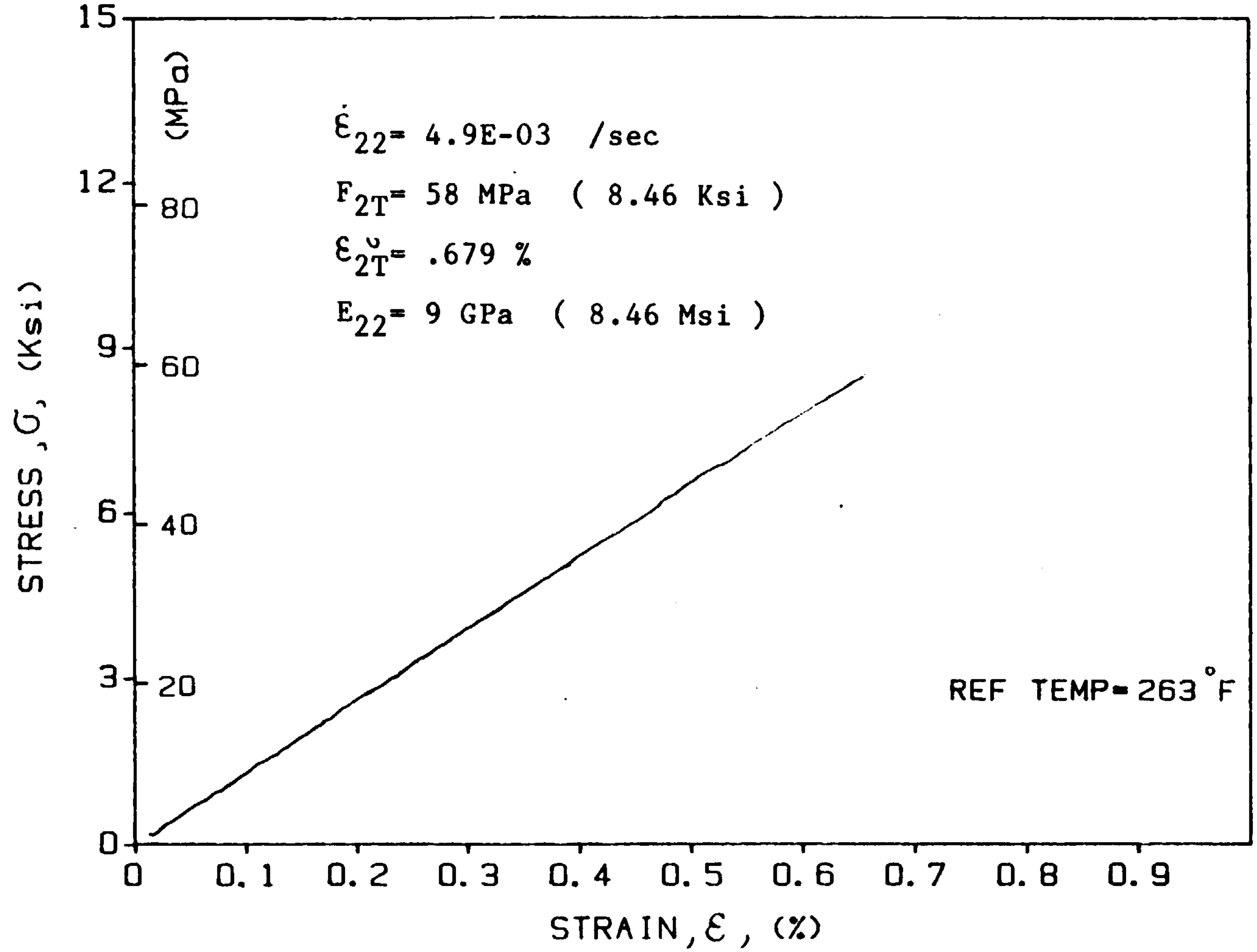


Fig. 3-38. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/ Epoxy ($\dot{\varepsilon}_{22}$ = 4.9 x 10^{-3} sec^{-1}, T = 128°C (263°F))

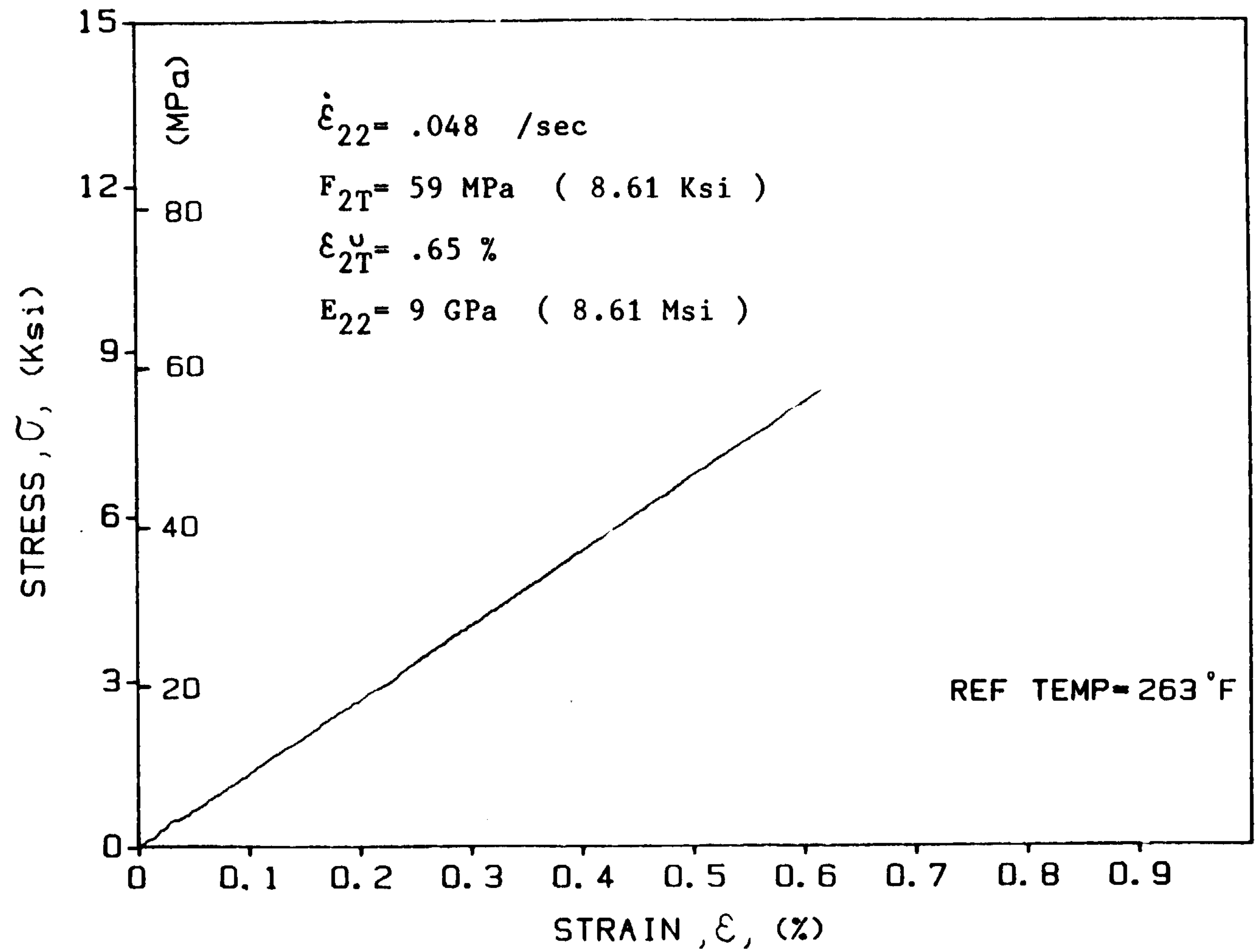


Fig. 3-39. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy ($\dot{\varepsilon}_{22} = 4.8 \times 10^{-2}\ sec^{-1}$, T = 128°C (263°F))

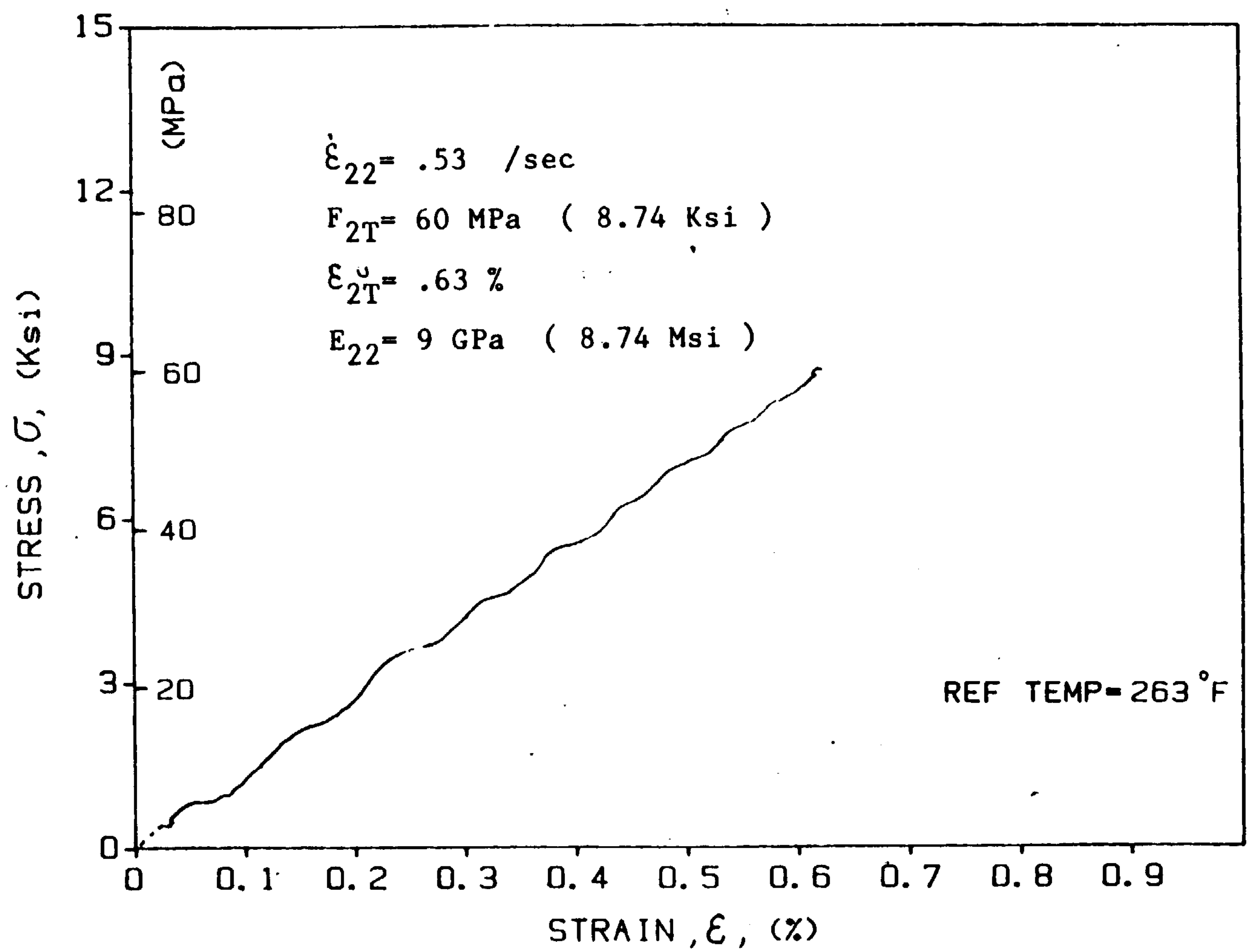


Fig. 3-40. Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/ Epoxy ($\dot{\varepsilon}_{22}$ = 5.3 x 10^{-1} sec^{-1}, T = 128°C (263°F))

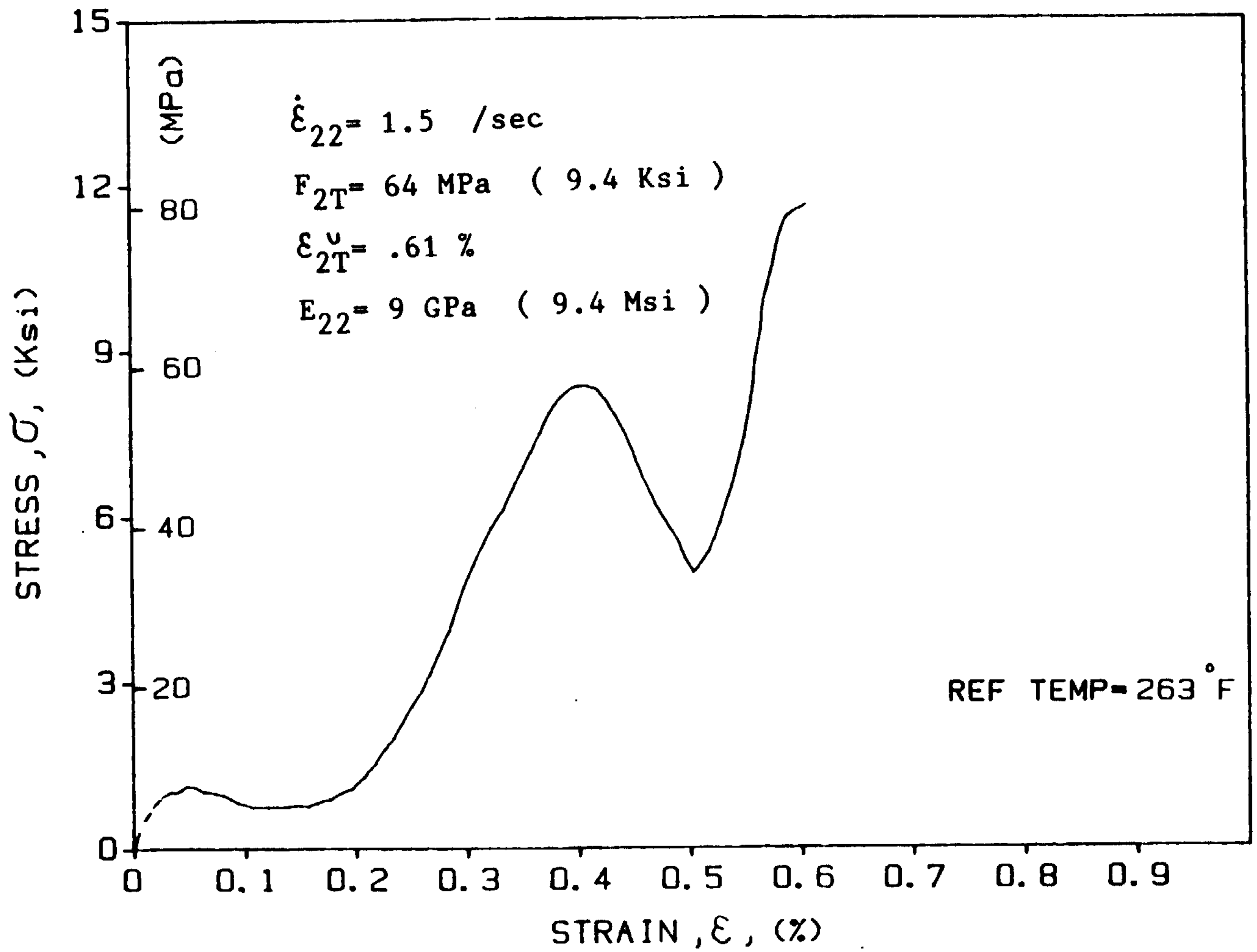


Fig. 3-41L Typical Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/ Epoxy ($\dot{\varepsilon}_{22}$ = 1.5 sec^{-1}, T = 128°C (263°F))

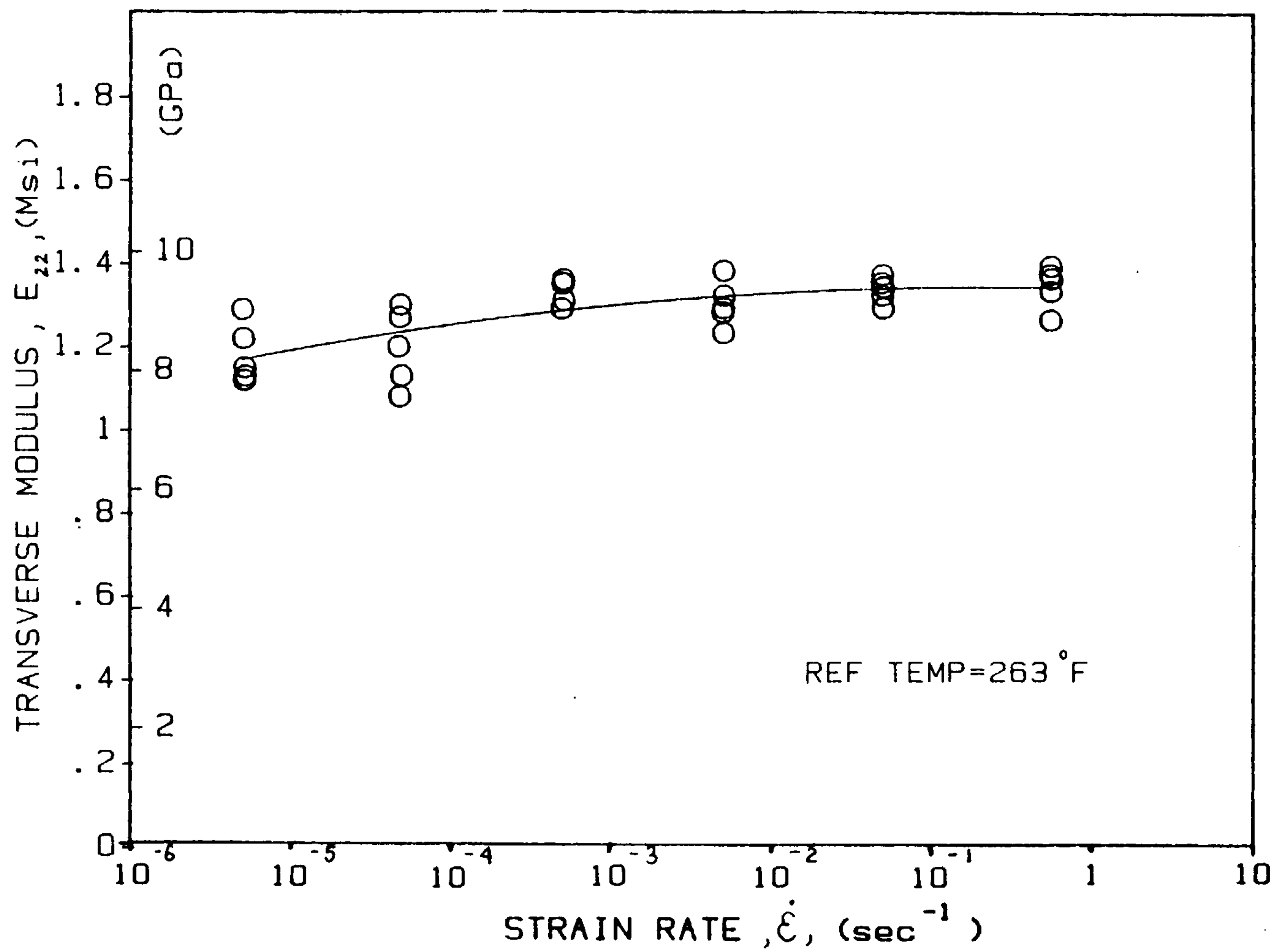


Fig. 3-42. Transverse Modulus, E_{22}, vs. Strain-Rate, $\dot{\varepsilon}_{22}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

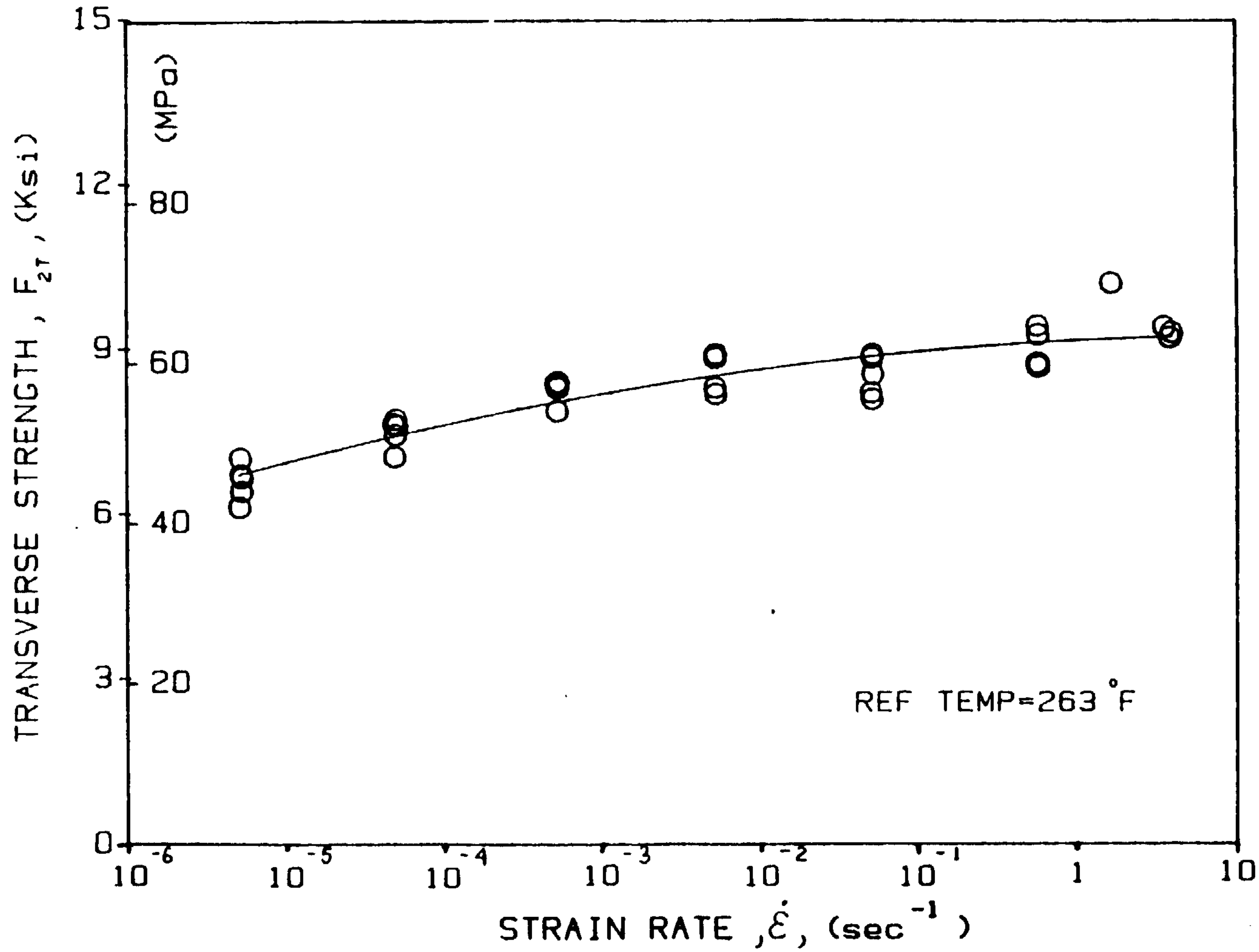


Fig. 3-43. Transverse Tensile Strength, F_{2T}, vs. Strain-Rate, $\dot{\epsilon}_{22}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

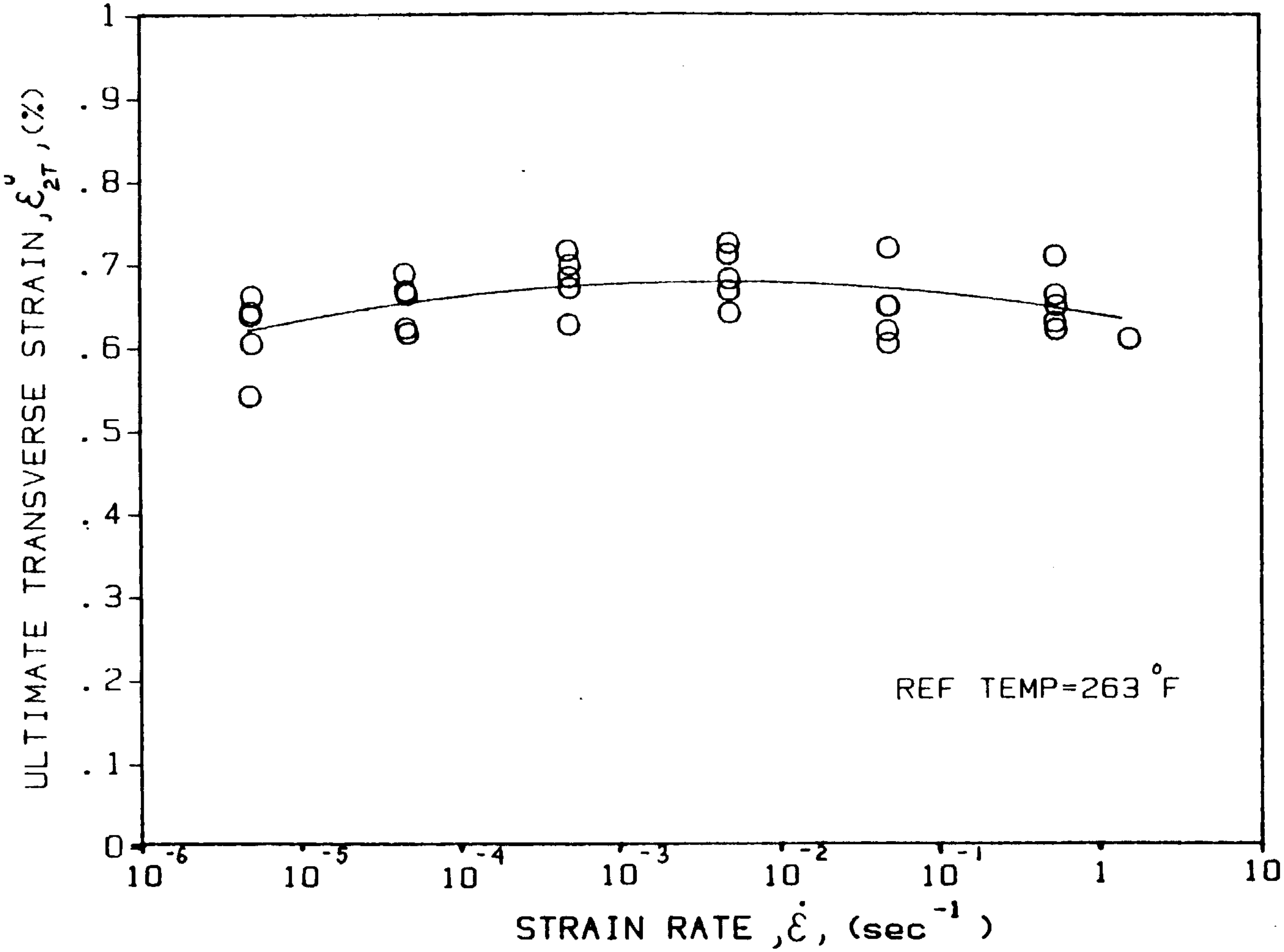


Fig. 3-44. Ultimate Transverse Tensile Strain, ε^u_{2T}, vs. Strain-Rate, $\dot{\varepsilon}_{22}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

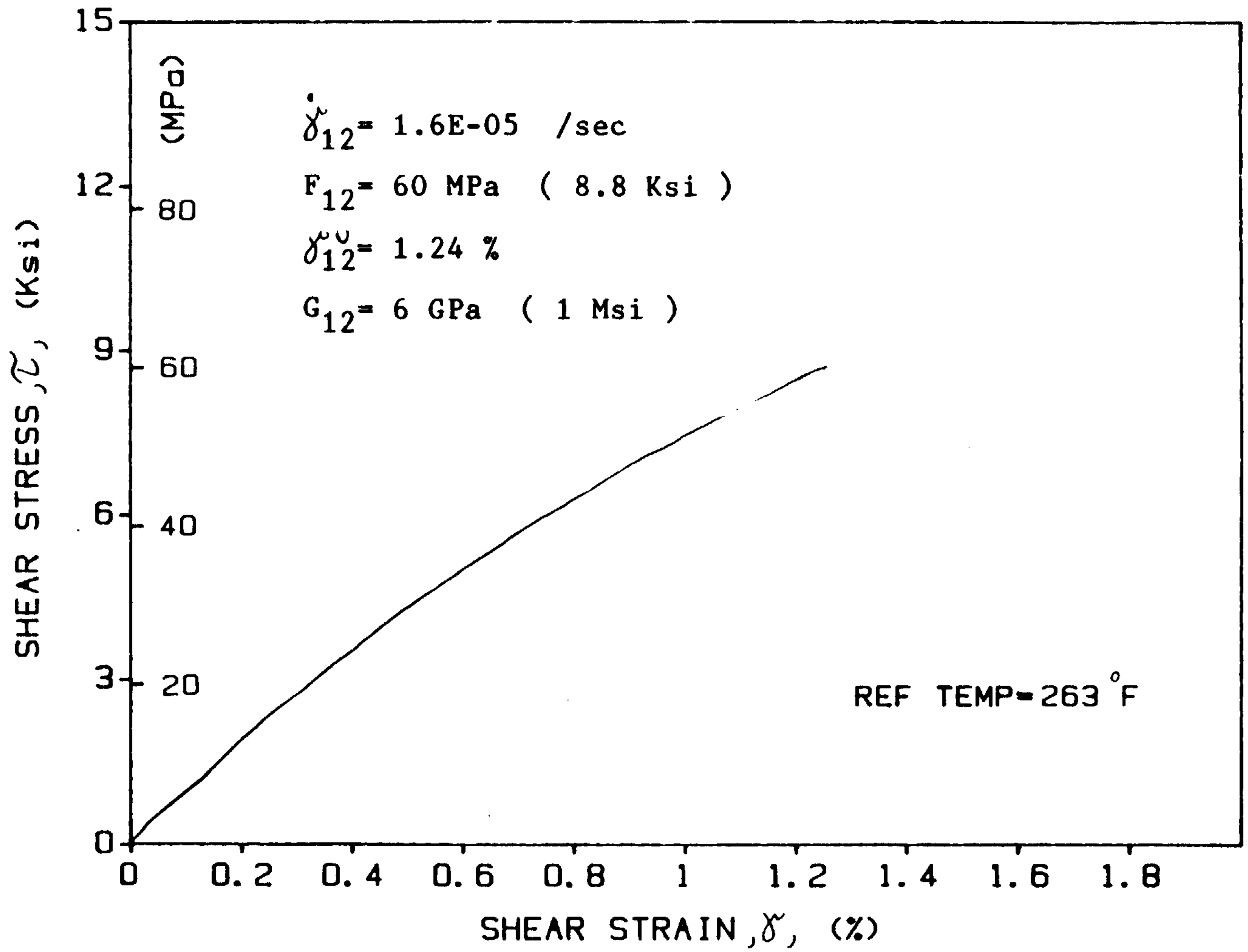


Fig. 3-45. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12} = 1.6 \times 10^{-5}$ sec^{-1}, T = 128°C (263°F))

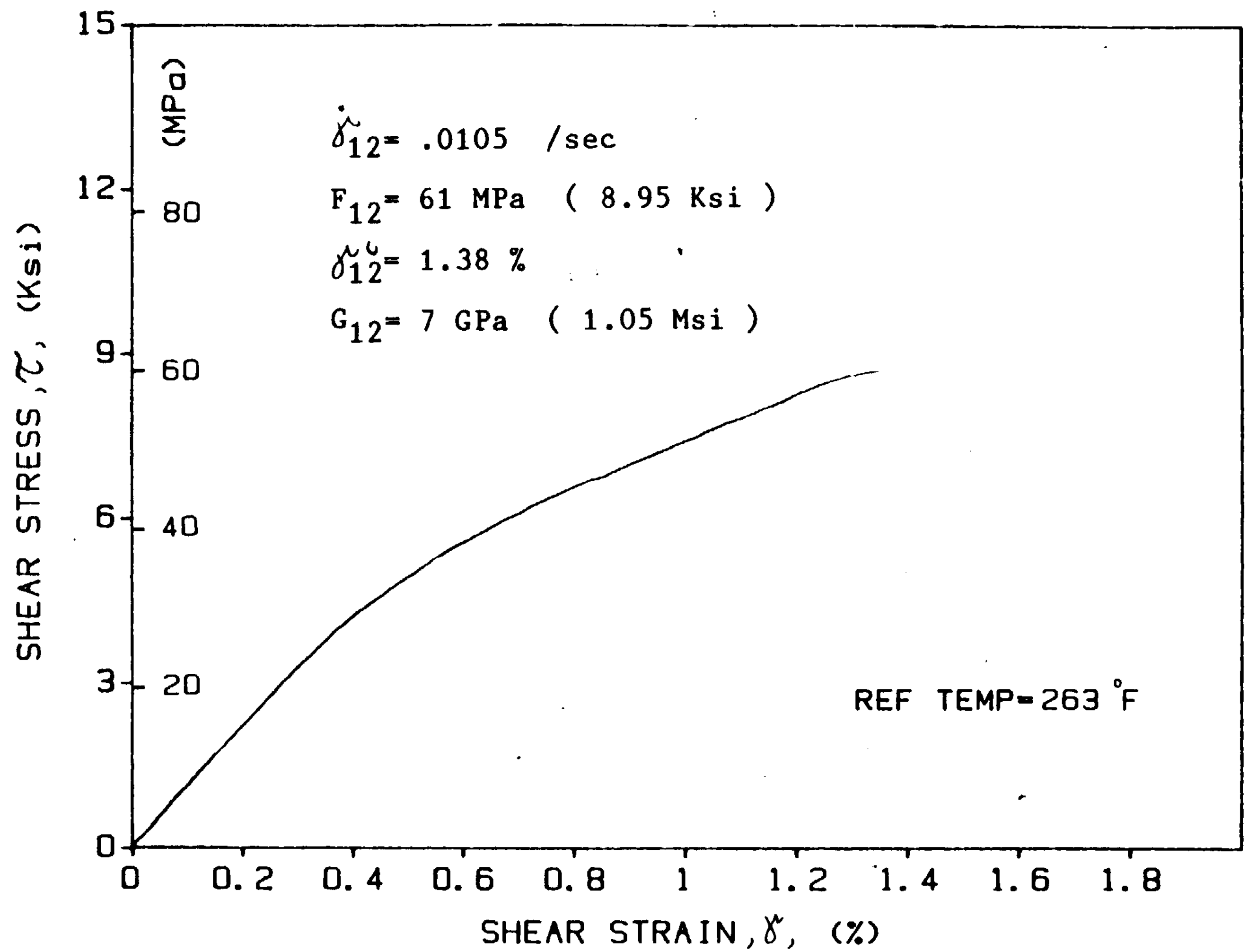


Fig. 3-46. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12}$ = 10.5 x 10^{-3} sec^{-1}, T = 128°C (263°F))

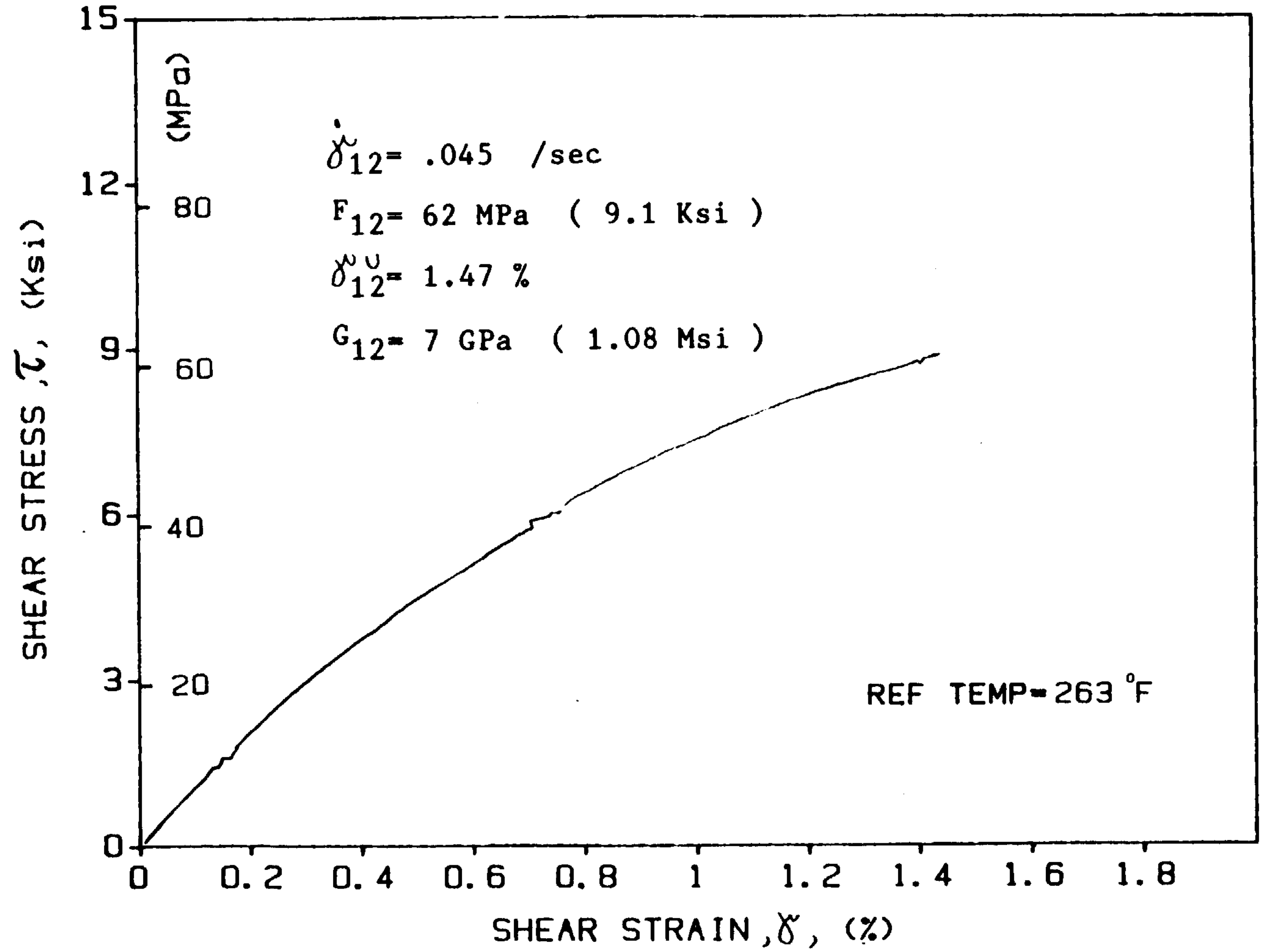


Fig. 3-47. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12} = 4.5 \times 10^{-2}\ sec^{-1}$, T = 128°C (263°F))

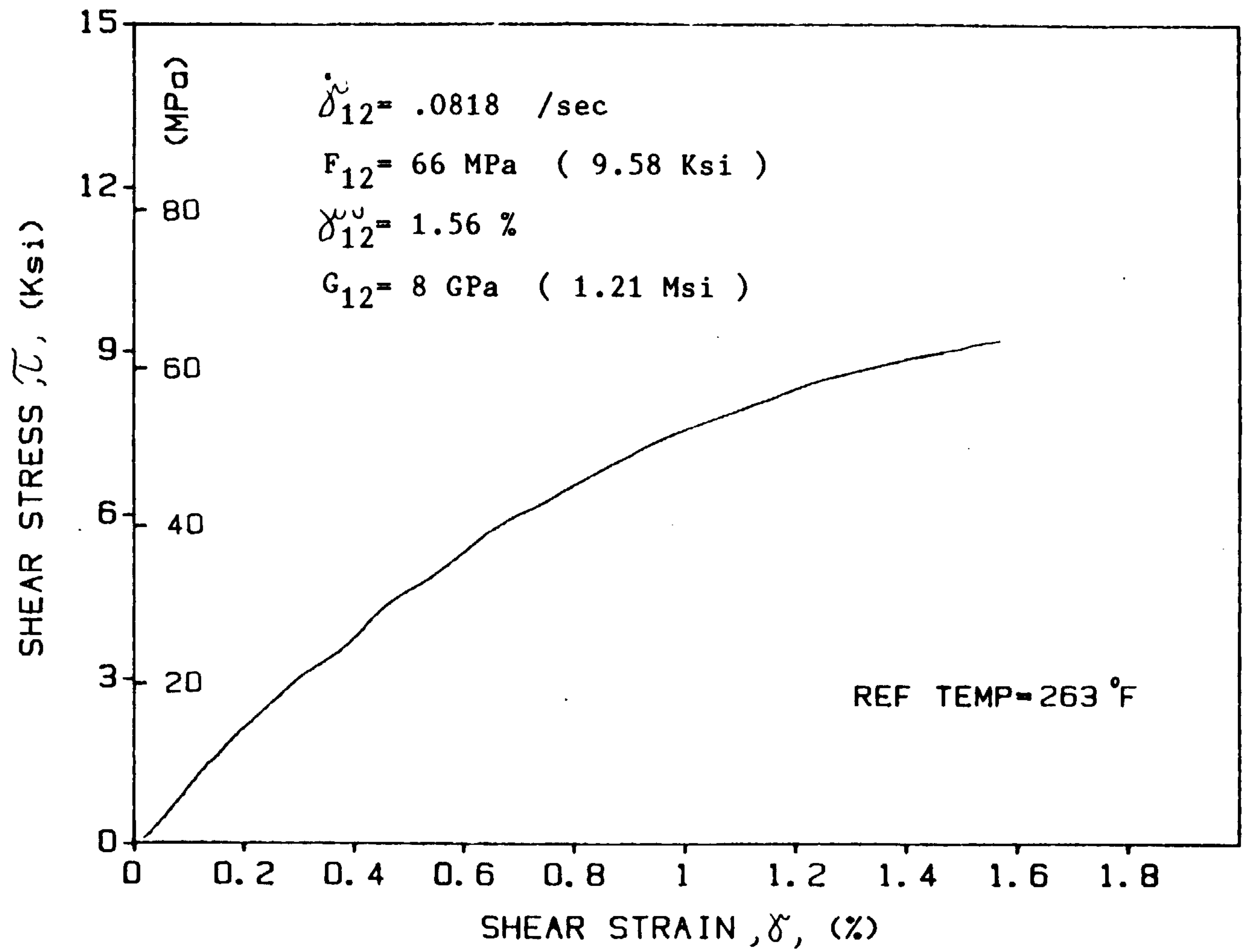


Fig. 3-48. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12}$ = 8.18 x 10^{-2} sec^{-1}, T = 128°C (263°F))

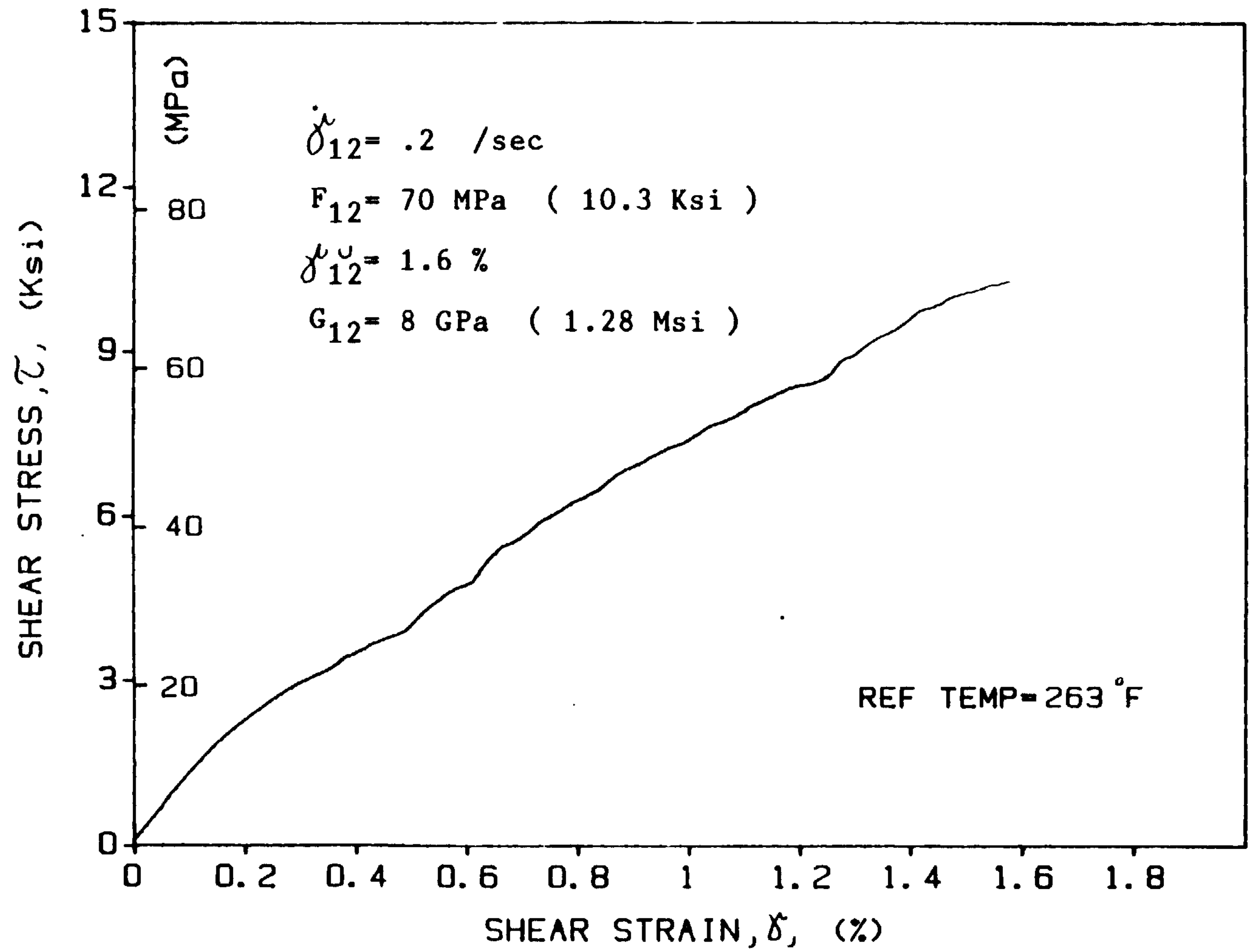


Fig. 3-49. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12}$ = 2.0 x 10^{-1} sec^{-1}, T = 128°C (263°F))

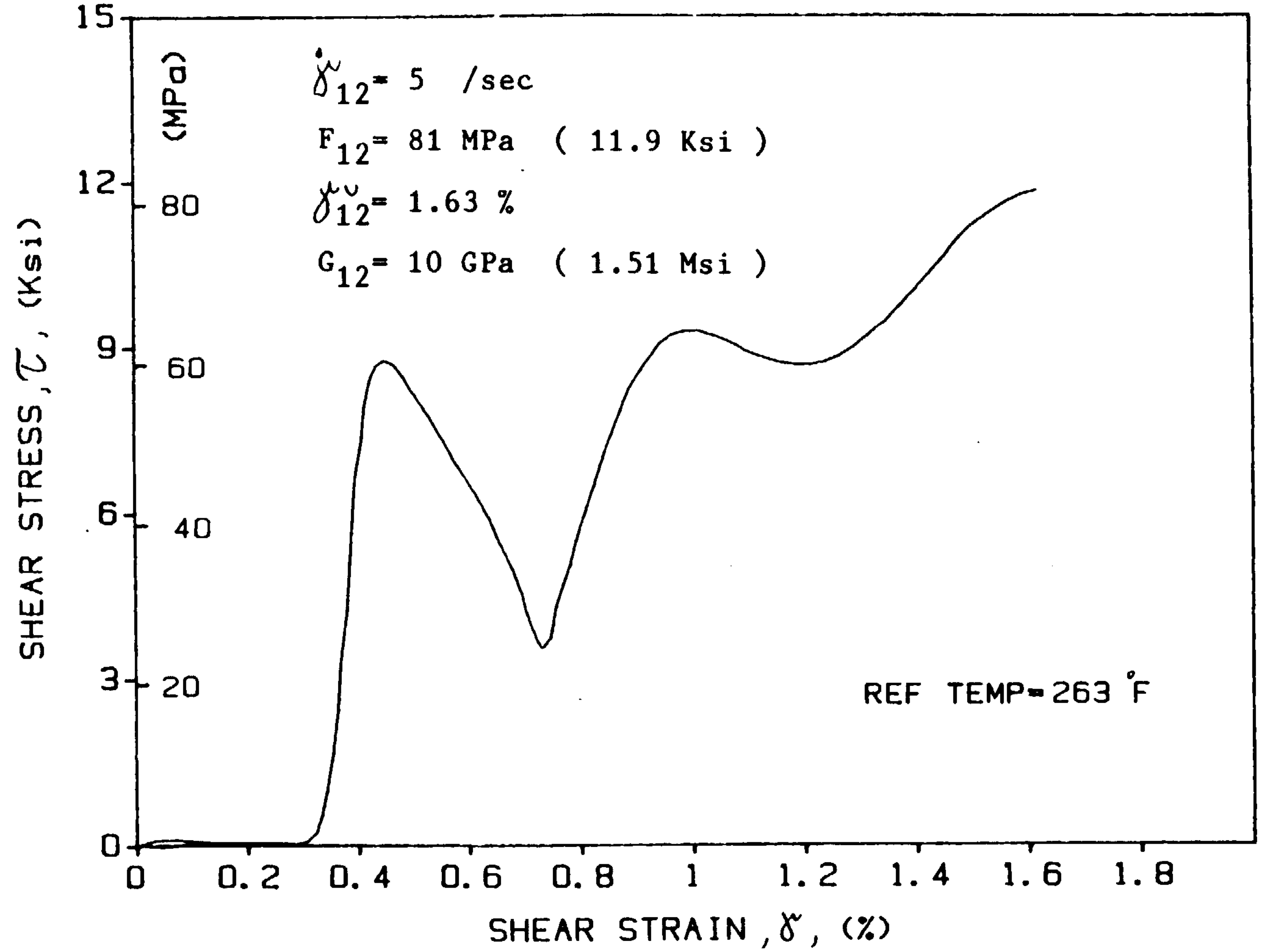


Fig. 3-50. Typical Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy ($\dot{\gamma}_{12}$ = 5.0 sec^{-1}, T = 128°C (263°F))

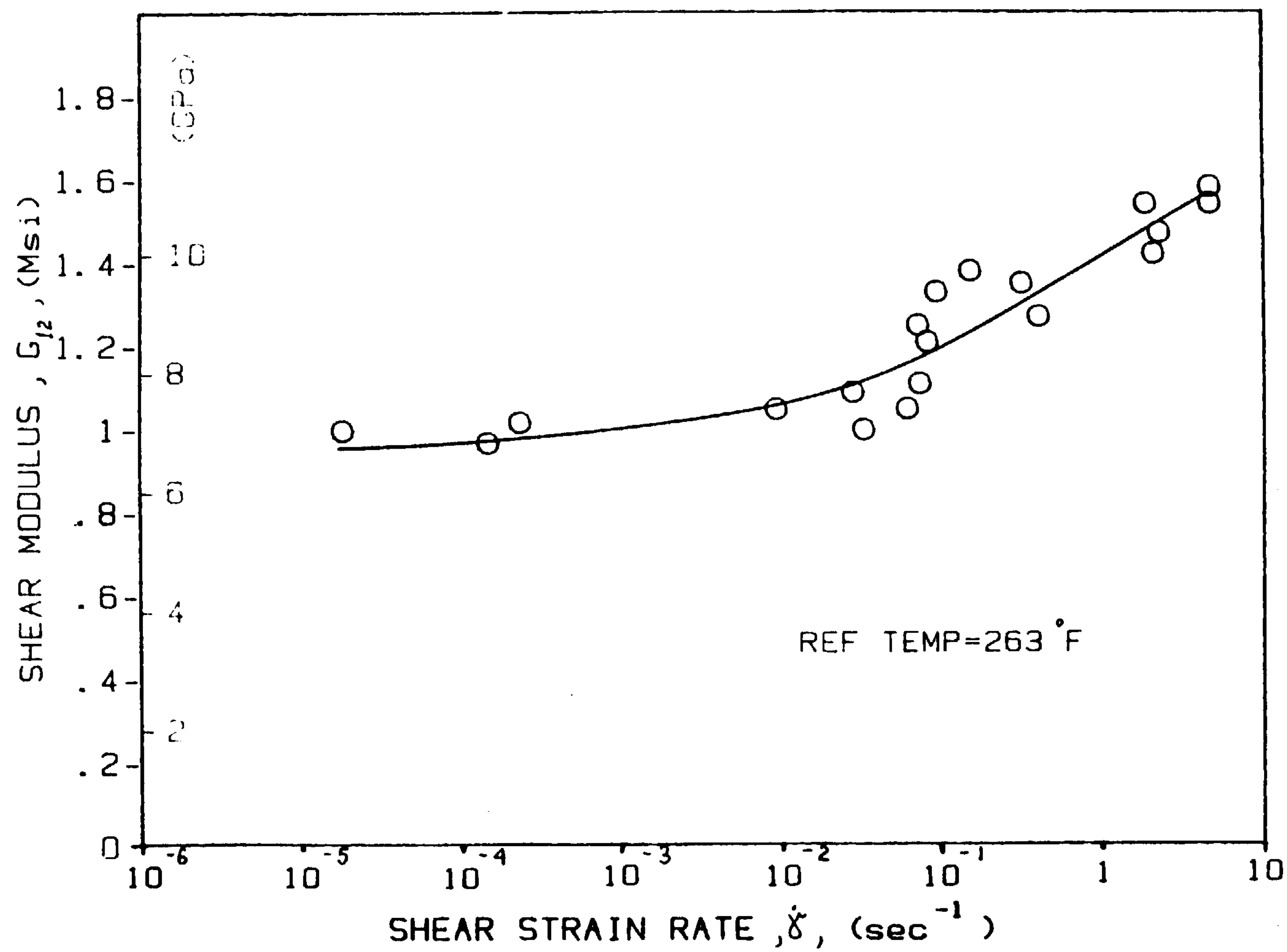


Fig. 3-51. In-Plane Shear Modulus, G_{12}, vs. Shear-Strain Rate, $\dot{\gamma}_{12}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

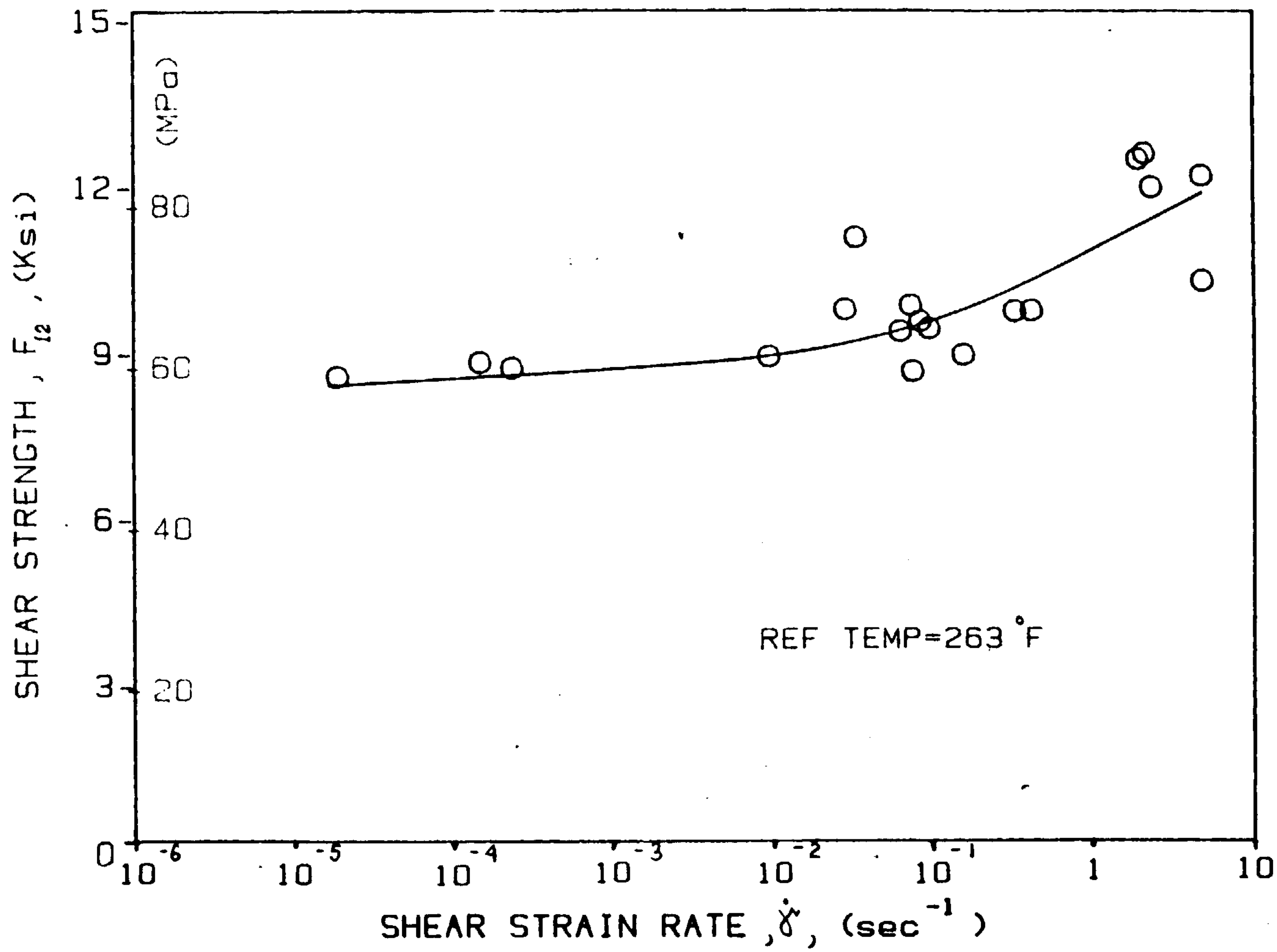


Fig. 3-52. In-Plane Shear Strength, F_{12}, vs. Shear Strain Rate, $\dot{\gamma}_{12}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

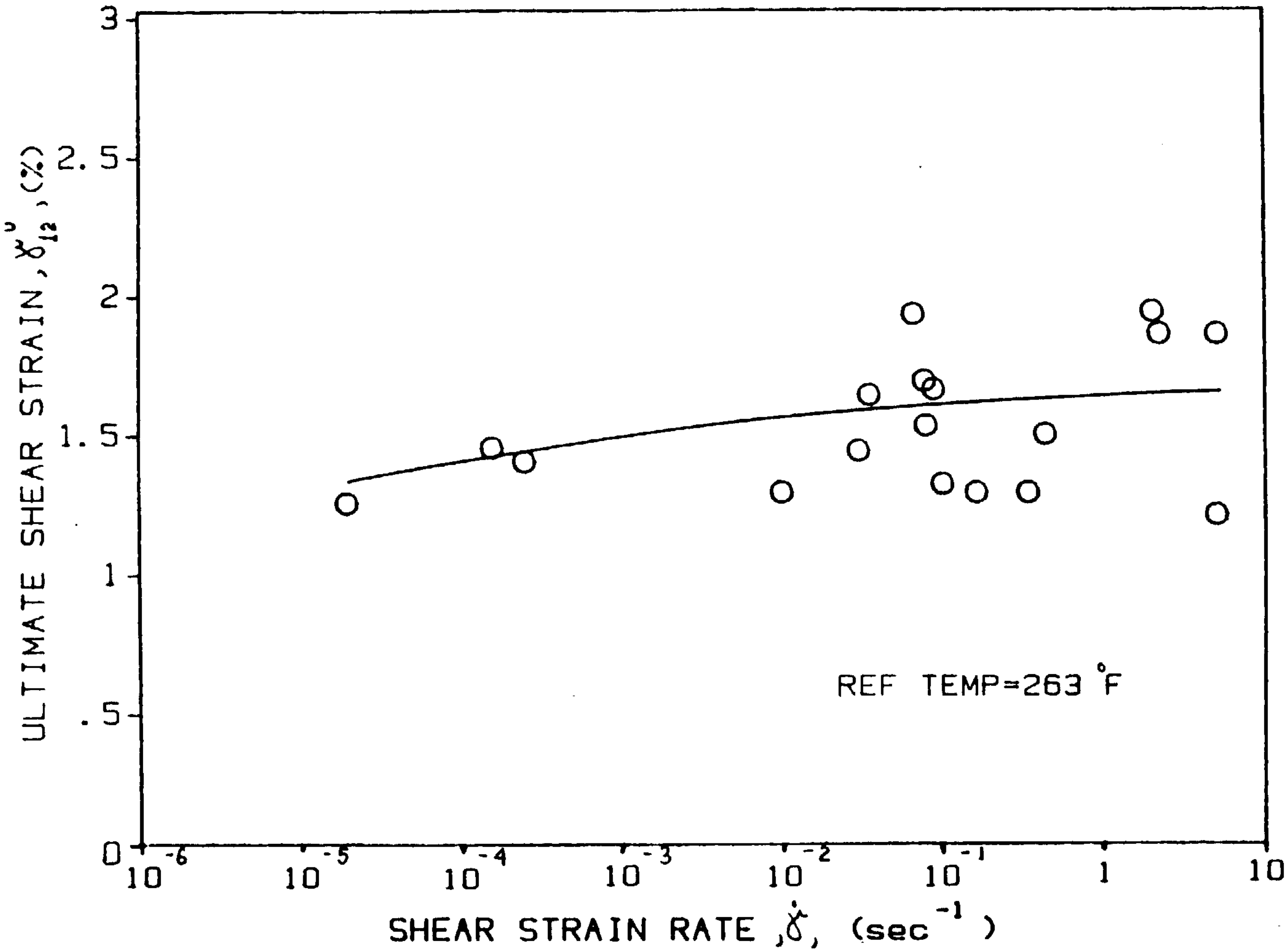


Fig. 3-53. Ultimate Shear Strain, γ_{12}^{u}, vs. Shear Strain Rate, $\dot{\gamma}_{12}$, for AS4/3501-6 Graphite/Epoxy (T = 128°C (263°F))

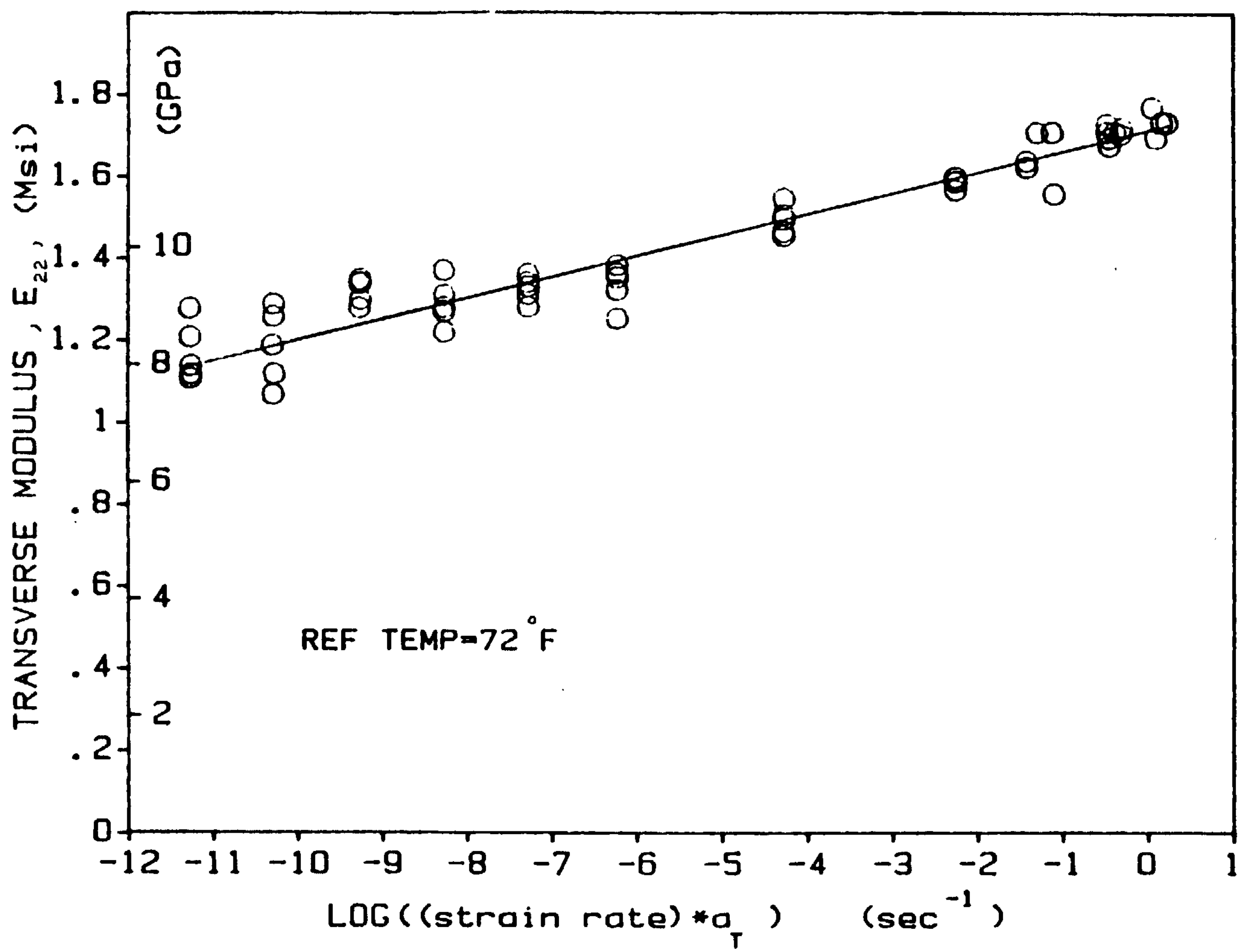


Fig. 3-54. Qualitative Master-Curve of the Transverse Modulus, E_{22}, vs. Shifted Strain Rate, $\dot{\varepsilon}_{22}\ a_T$, for AS4/3501-6 Graphite/Epoxy (Reference Temperature = 23°C (72°F))

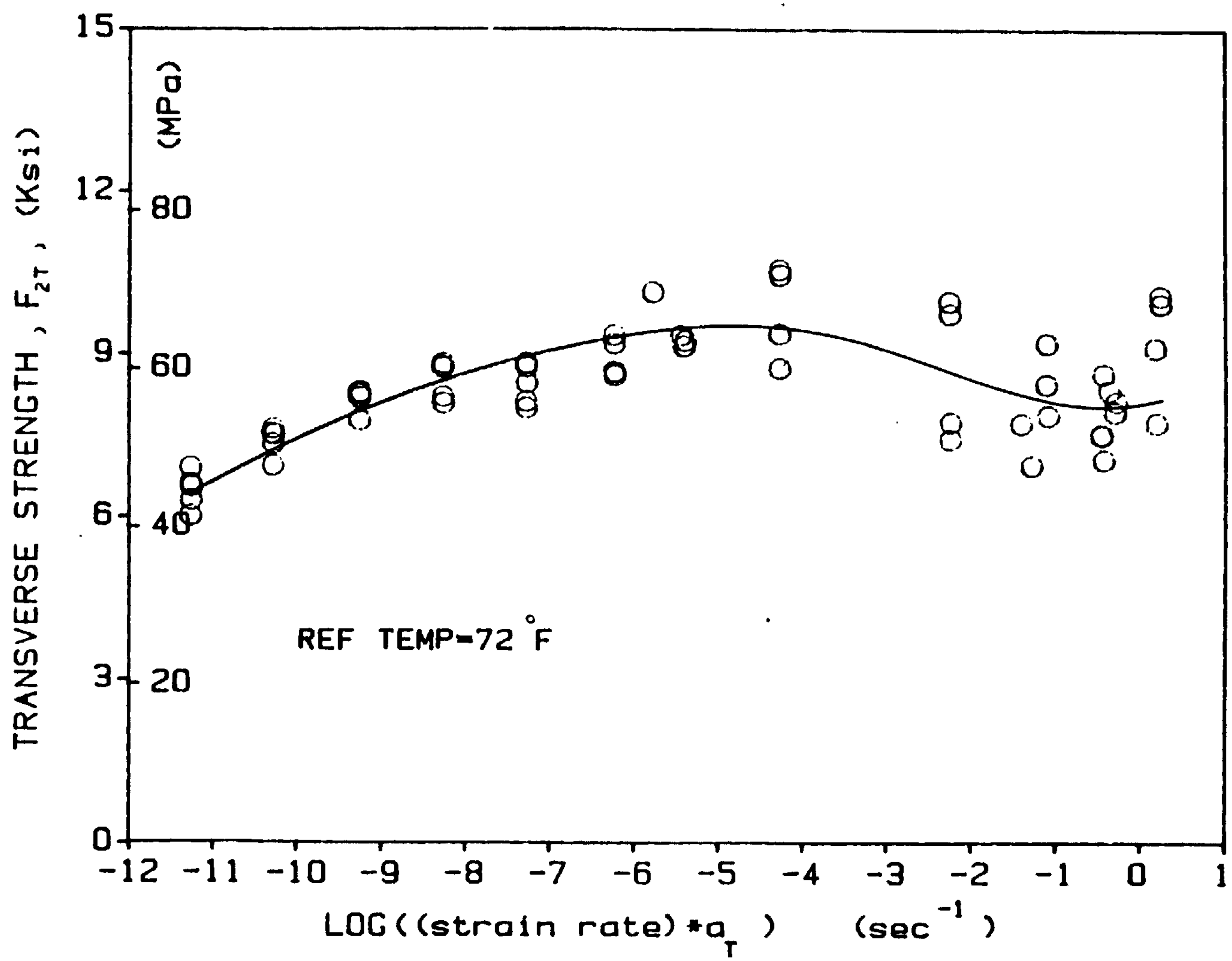


Fig. 3-55. Qualitative Master-Curve of the Transverse Tensile Strength, F_{2T}, vs. Shifted Strain Rate, $\dot{\varepsilon}_{22}\ a_T$, for AS4/3501-6 Graphite/ Epoxy (Reference Temperature = 23°C (72°F))

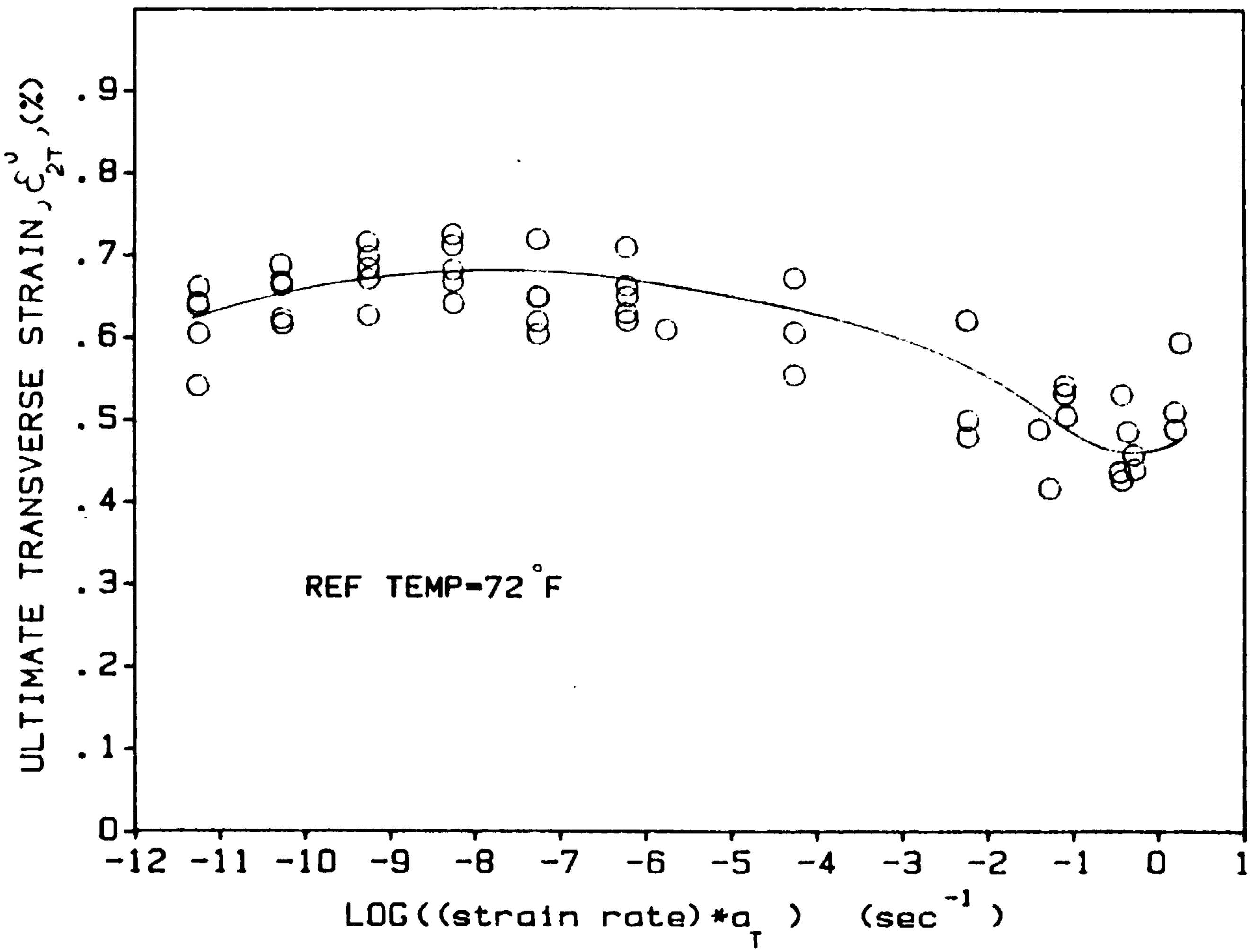


Fig. 3-56. Ultimate Transverse Tensile Strain vs. Shifted Strain Rate for AS4/3501-6 Graphite/Epoxy (Reference Temperature = 23°C (72°F))

4. SUMMARY AND CONCLUSIONS

The effect of loading rate on the mechanical properties of AS4/3501-6 Graphite/Epoxy material was studied at room temperature and at $128^{\circ}C$ ($263^{\circ}F$). The unidirectional material was tested over a strain rate range of six decades, from $5 \times 10^{-6}\ s^{-1}$ to $5\ s^{-1}$.

The longitudinal mechanical properties obtained by testing $[0_6]$ coupons are almost rate and temperature-insensitive, except for the modulus stiffening phenomenon at low strain rates and high temperature which occurs at a strain of 0.8% rather than 0.6% in all other cases. This difference reflects the influence of matrix properties since this stiffening is attributable to some longitudinal matrix cracking that allows some fiber bundles to straighten.

The transverse mechanical properties, obtained by tensile testing of $[90_8]$ and $[90_{16}]$ coupons, are temperature and rate-sensitive as could have been expected for matrix dominated properties. The transverse modulus increases with strain rate but decreases with increasing temperature. The temperature dependence can be explained by an equivalent shift in time, or strain rate, through a shift factor a_T. Invoking such a time-temperature equivalence principle, a master curve is obtained of transverse modulus versus strain rate referred to room temperature (Fig. 3-54). Thus, a linear relationship between transverse modulus and logarithm of strain rate was obtained over a range of more than twelve decades of strain rate. It would be possible to extend the results to higher strain rates by conducting tests at temperatures below room temperature. The transverse strength F_{2T}, and the transverse ultimate tensile strain, ε_{2T}^{u}, have a positive rate sensitivity at low rates which changes to negative at intermediate rates and returns to positive rate sensitivity at the highest rates tested, as can be seen from the shifted master-curves in Figures 3-55 and 3-56. This type of change in rate sensitivity is known for polymers, and lately has been observed in composite materials.[4]

The in-plane shear properties determined by tensile testing of $[10_6]$ off-axis coupons, are also highly affected by strain rate and temperature variations, especially at the high temperature and high rates. The shear modulus G_{12} and shear strength F_{12} have a positive rate sensitivity, like the corresponding transverse properties, however no apparent time-shift technique was possible due to insufficient experimental data. The ultimate shear strain γ_{12}^{u} has a positive rate sensitivity at low rates, which changes to negative at high rate at room temperature. At the elevated temperature of 128°C (263°F) the ultimate shear strain increases by 25-30% over the room temperature value, but its strain rate dependence is very moderate.

REFERENCES

1. I.M. Daniel, "High Strain Rate Properties of Unidirectional Composites," NASA CR-167969, 1982.

2. I.M. Daniel, "High Strain Rate Properties of Off-Axis Composite Laminates," NASA CR-167970, 1982.

3. I.M. Daniel, "High Strain Rate Properties of Angle-Ply Composite Laminates," NASA CR-167971, 1982.

4. G. Yaniv and I.M. Daniel, "Height-Tapered Double Cantilever Beam Specimen for Study of Rate Effects on Fracture Toughness of Composites," submitted for presentation at ASTM Conference on Composite Materials, April 1986, Charleston, SC.

APPENDIX

ADDITIONAL EXPERIMENTAL RESULTS

Typical stress-strain and transverse vs. longitudinal strain curves were shown in the main part of this report. However, the final results presented showing the variation of the various material properties with strain rate were based on the average from a large number of tests.

Results of all these tests are shown here in the Appendix. Figures A-1 through A-235 shows stress-strain, transverse vs. longitudinal strain, and axial strain vs. time curves for all specimens tested. Properties for individual specimens, including initial and ultimate properties, are tabulated in Tables A-1 through A-16.

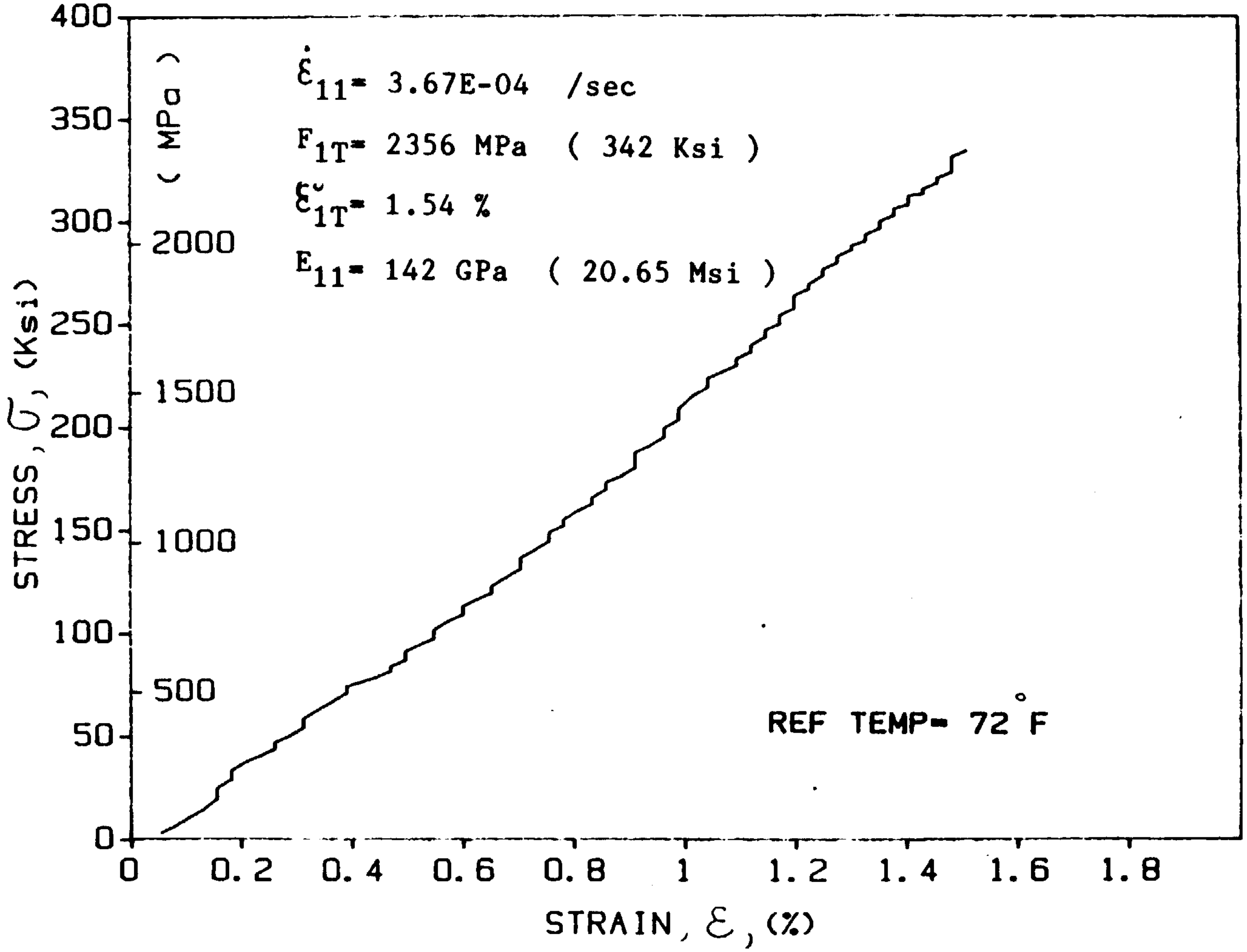


Fig. A-1. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L3 (T = 23°C (72°F))

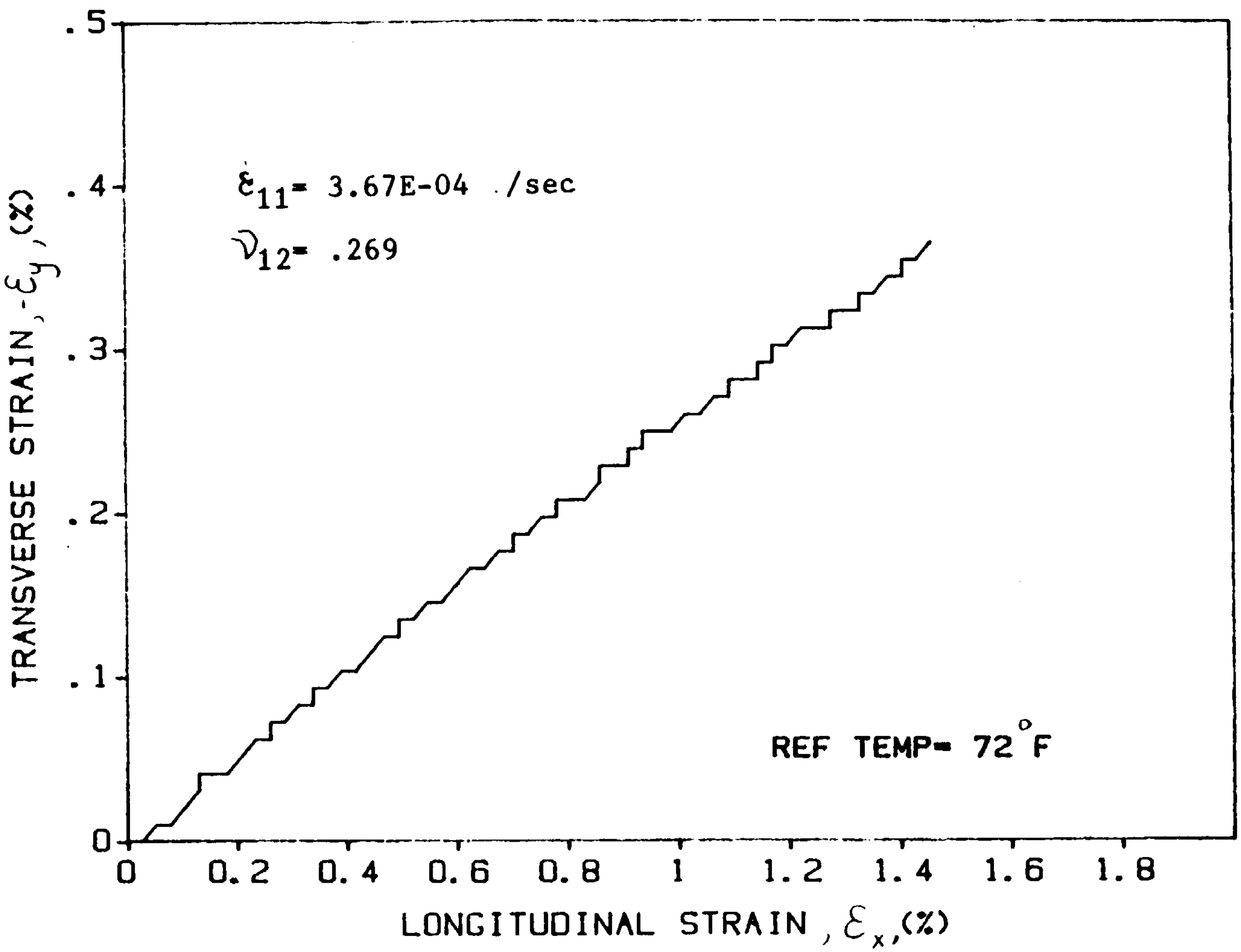


Fig. A-2. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 0/-4L3 (T = 23°C (72°F))

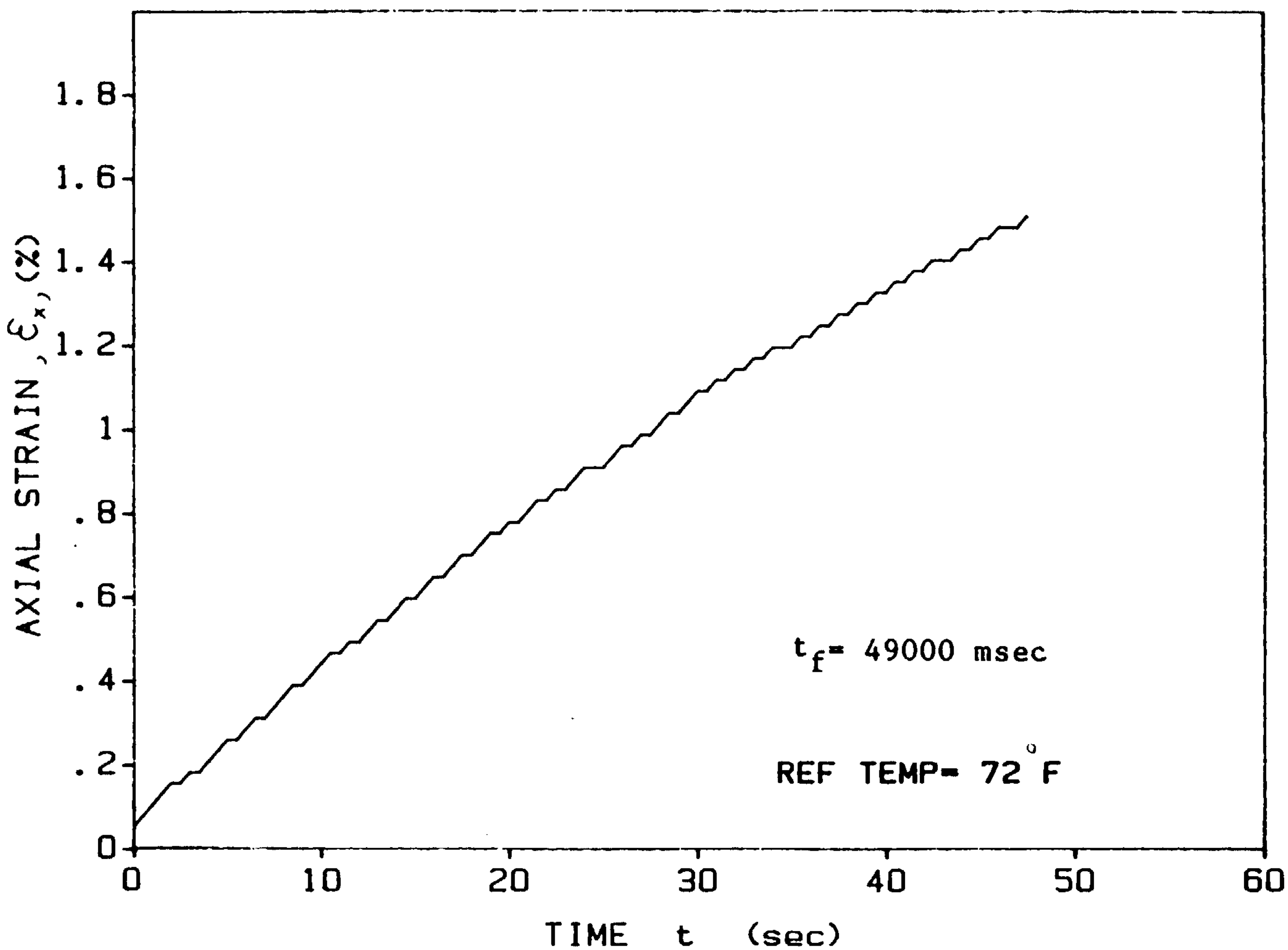


Fig. A-3. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L3 (T = 23°C (72°F))

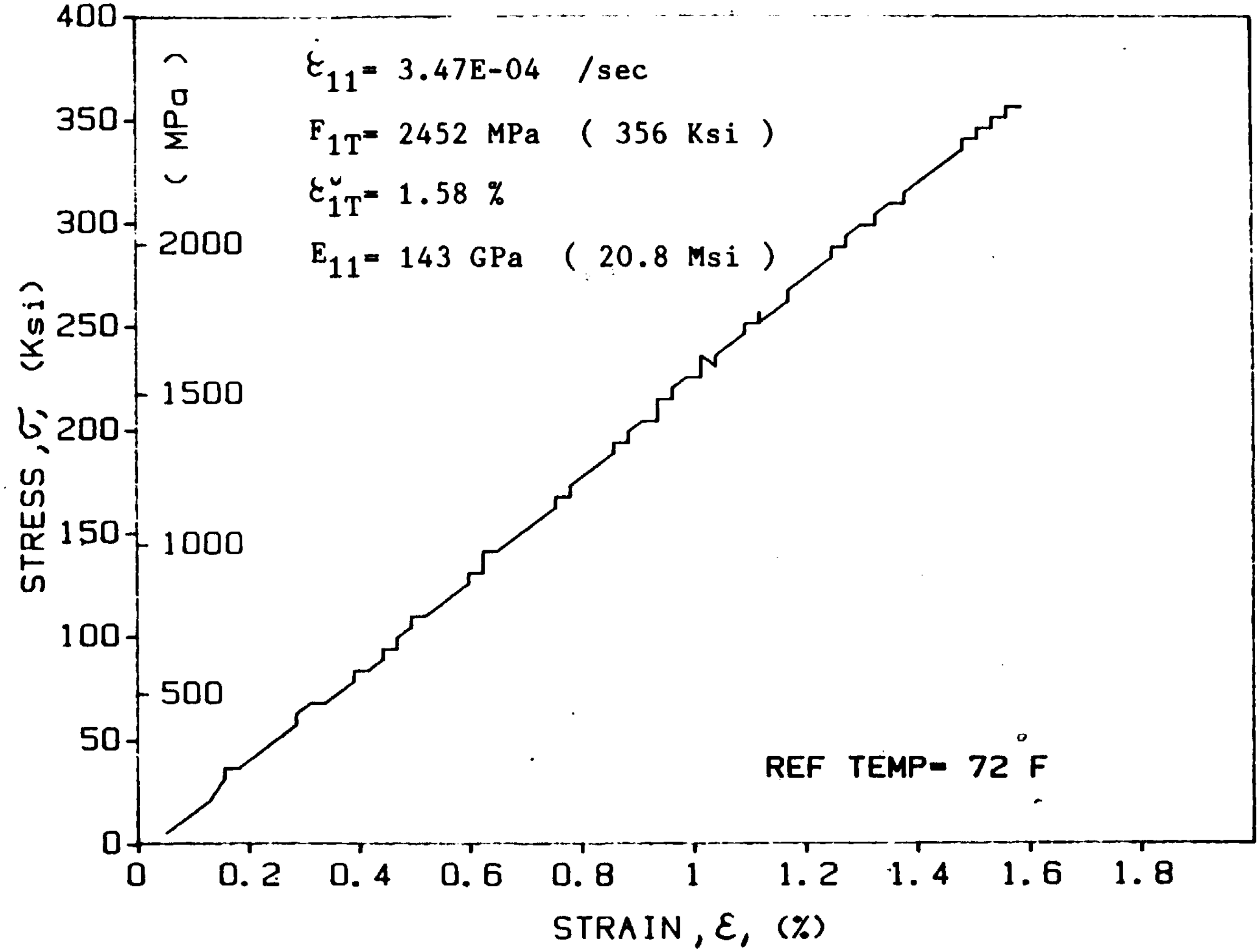


Fig. A-4. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L4 (T = 23°C (72°F))

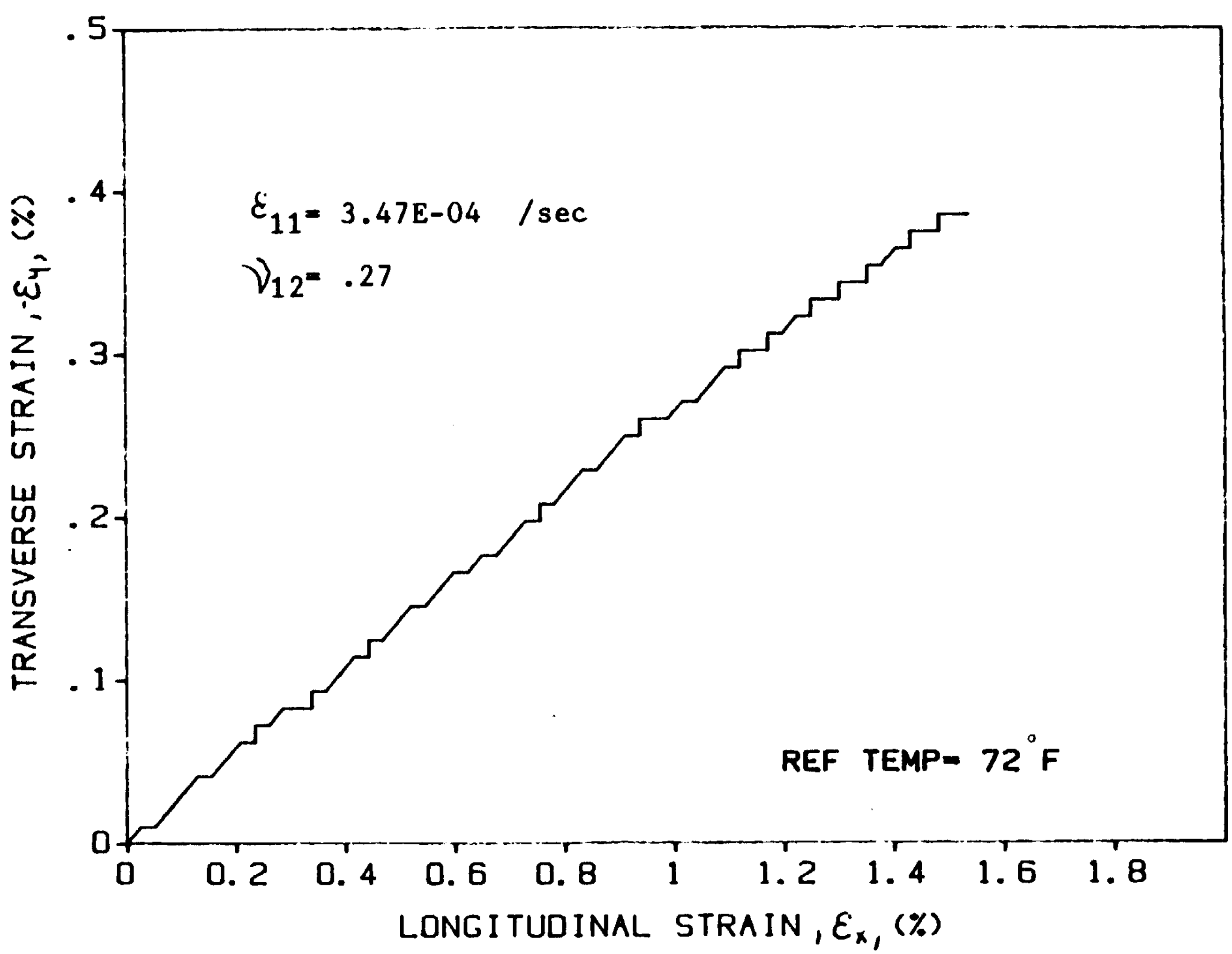


Fig. A-5. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L4 (T = 23°C (72°F))

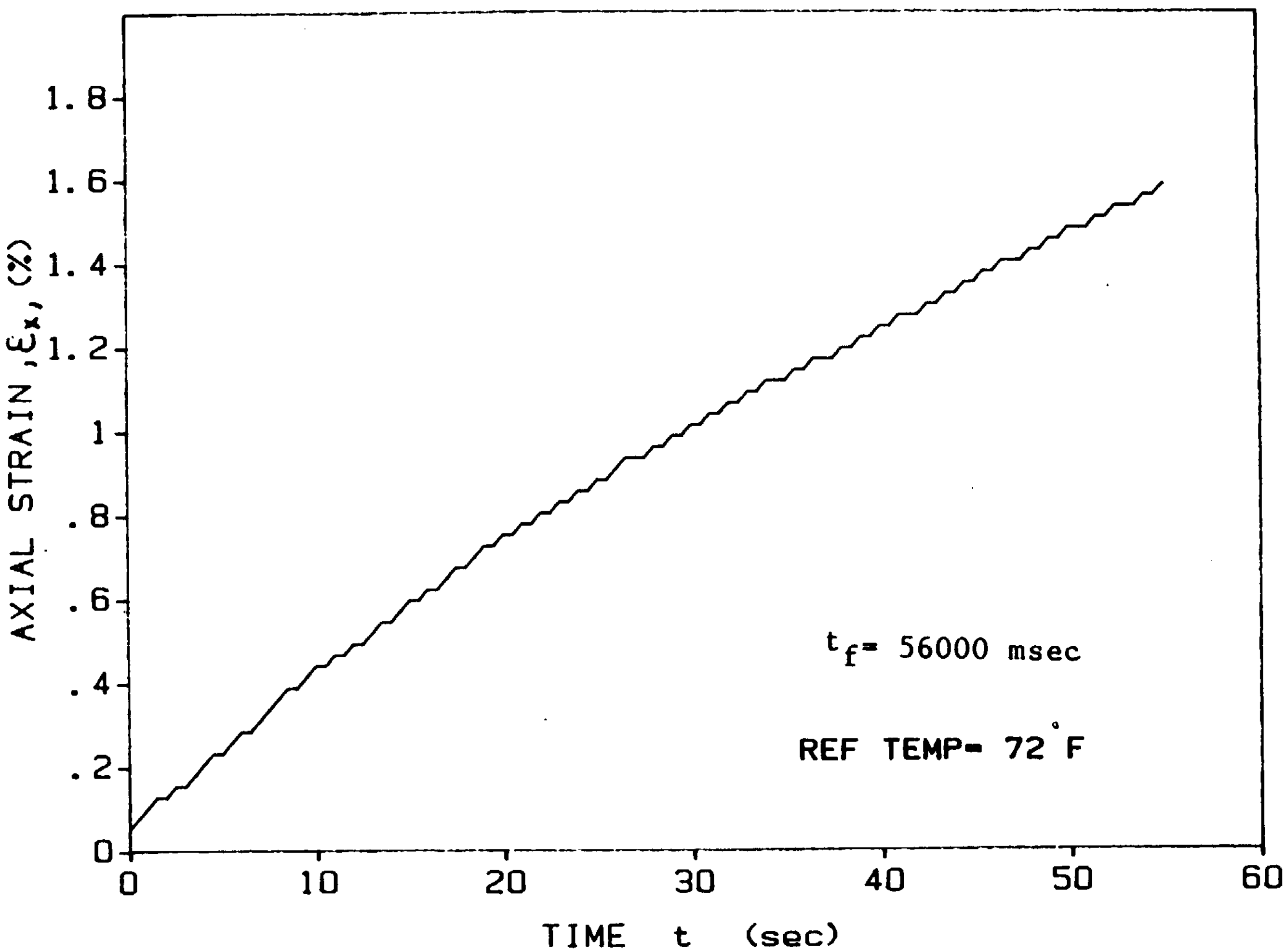


Fig. A-6. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L4 (T = 23°C (72°F))

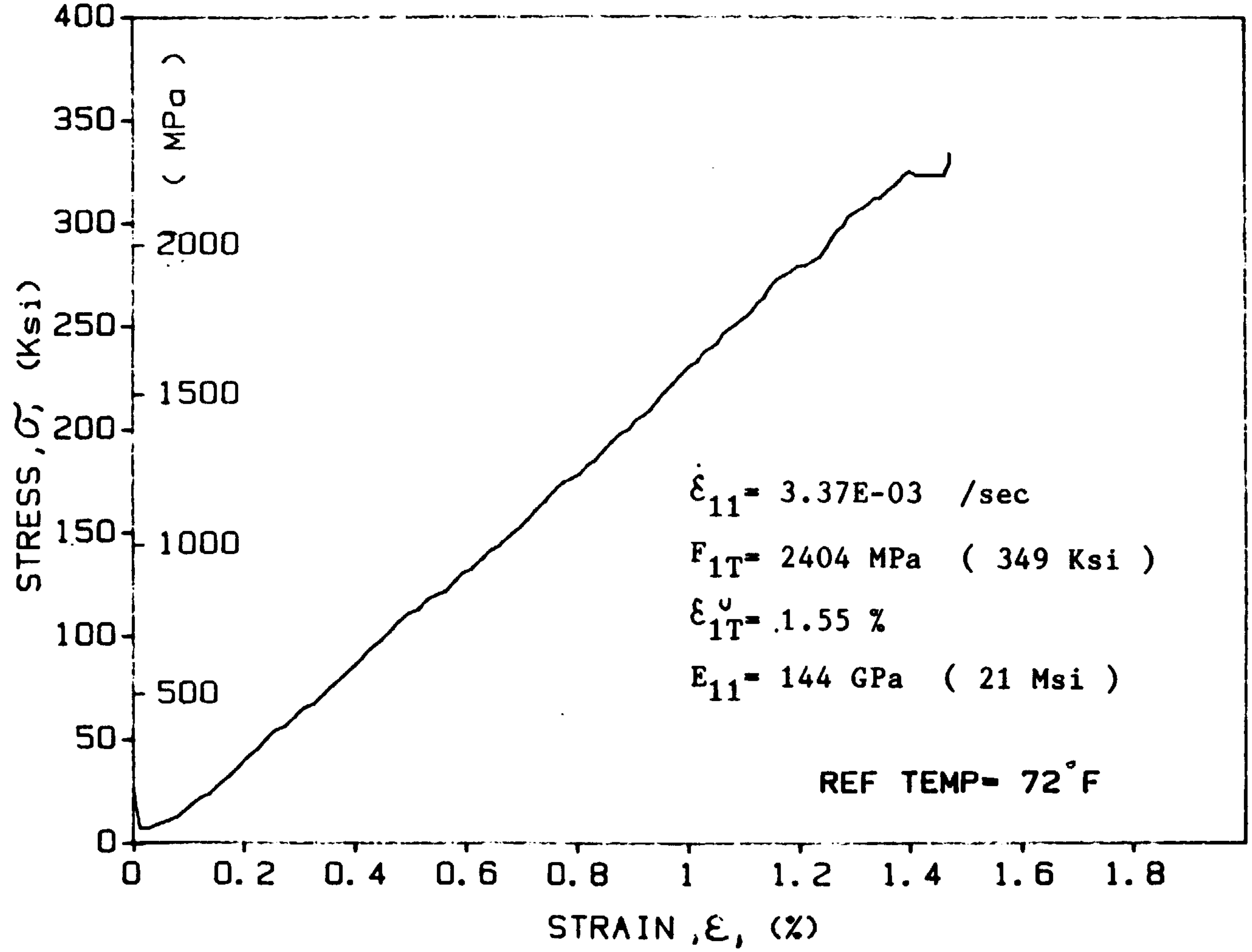


Fig. A-7. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L5 (T = 23°C (72°F))

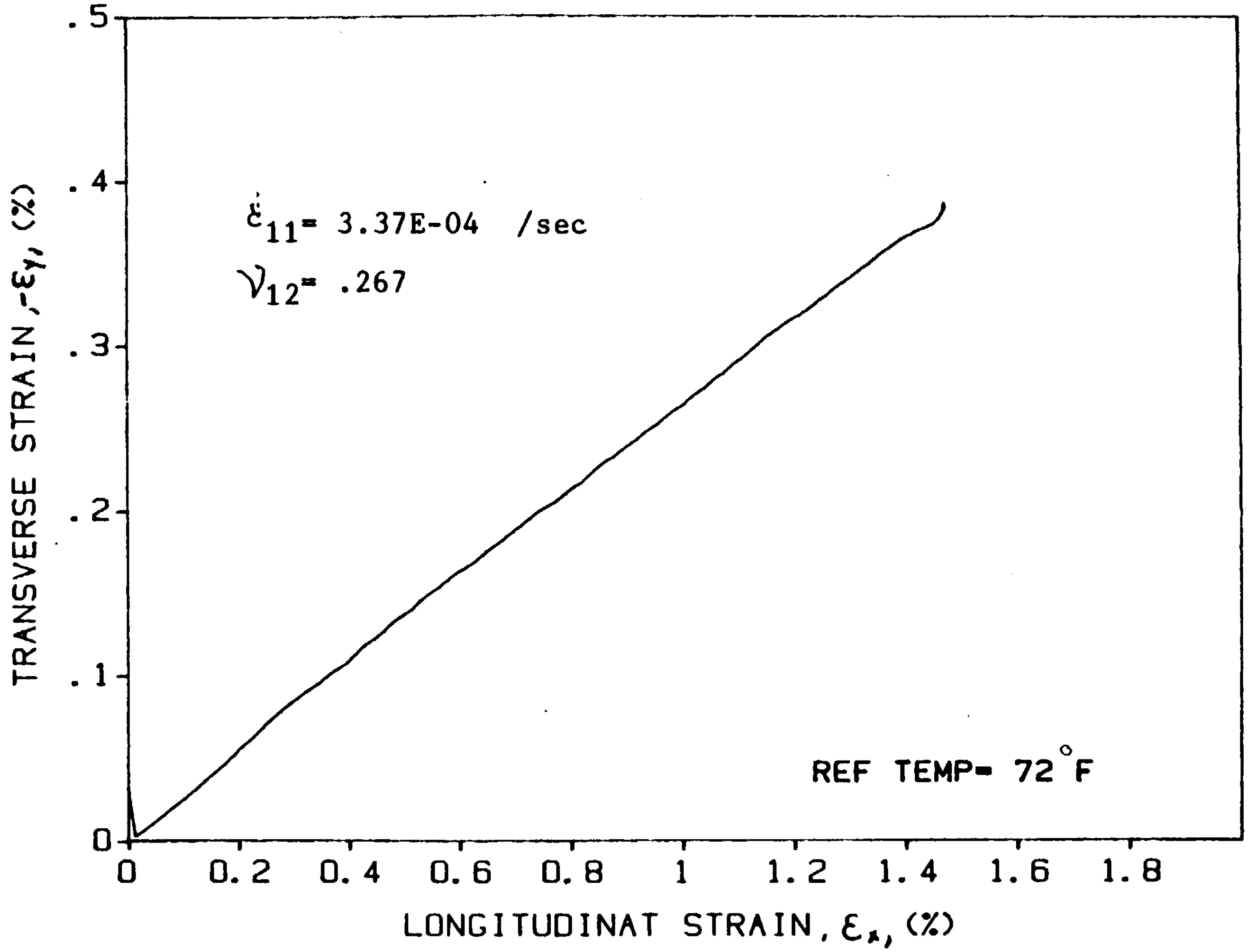


Fig. A-8. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L5 (T = 23°C (72°F))

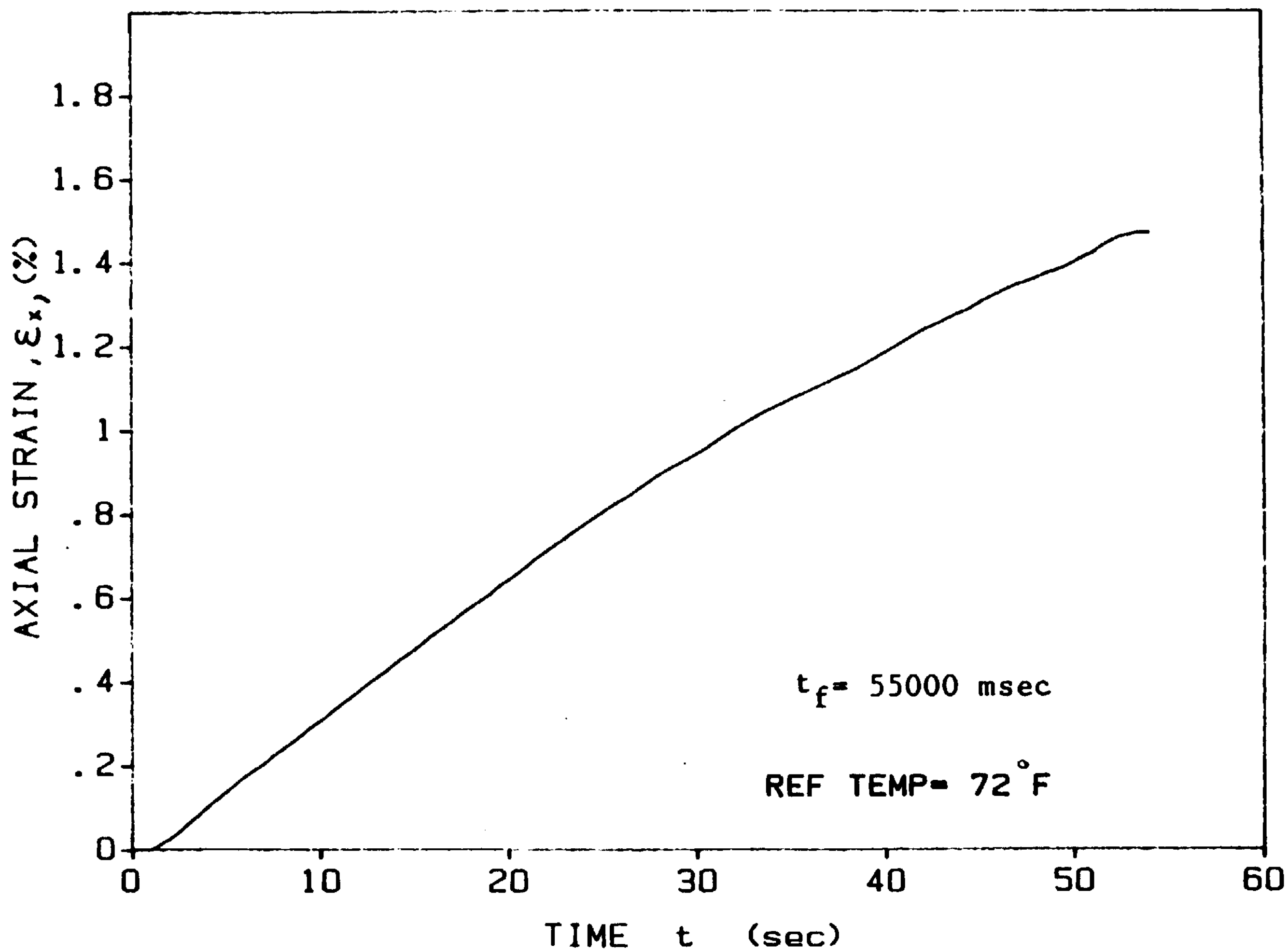


Fig. A-9. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4L5 (T = 23°C (72°F))

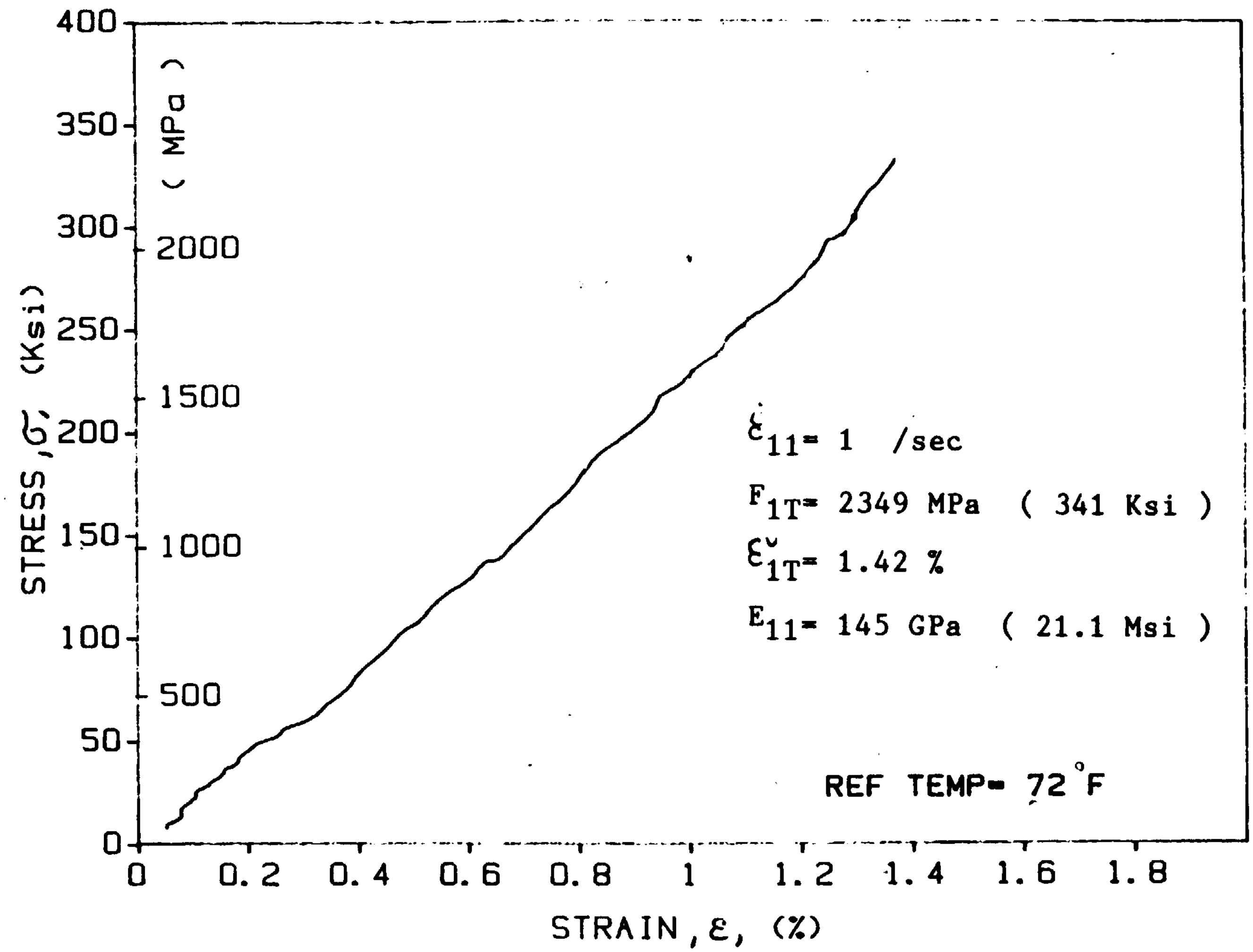


Fig. A-10. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L1 (T = 23°C (72°F))

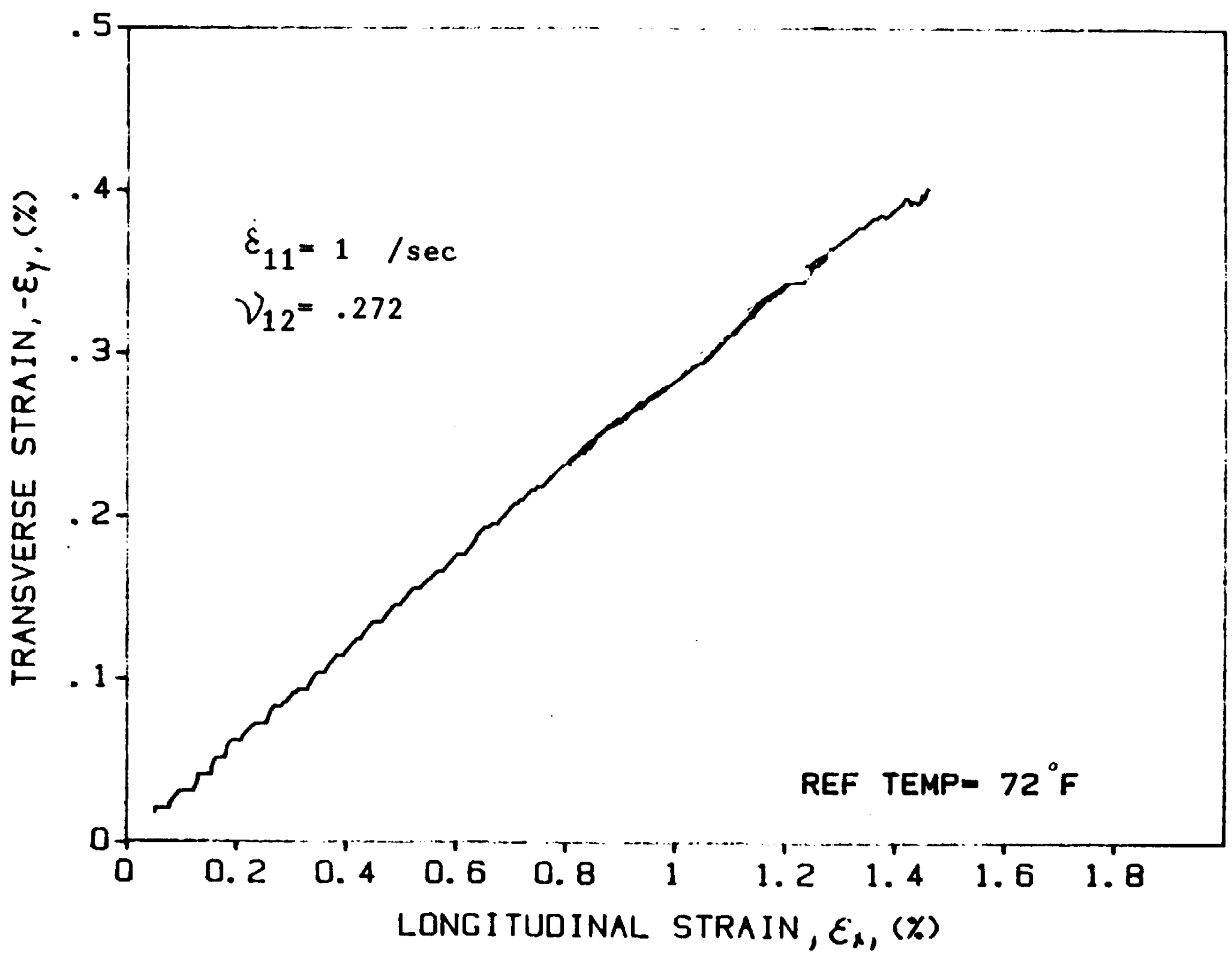


Fig. A-11. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 0/0L1 (T = 23°C (72°F))

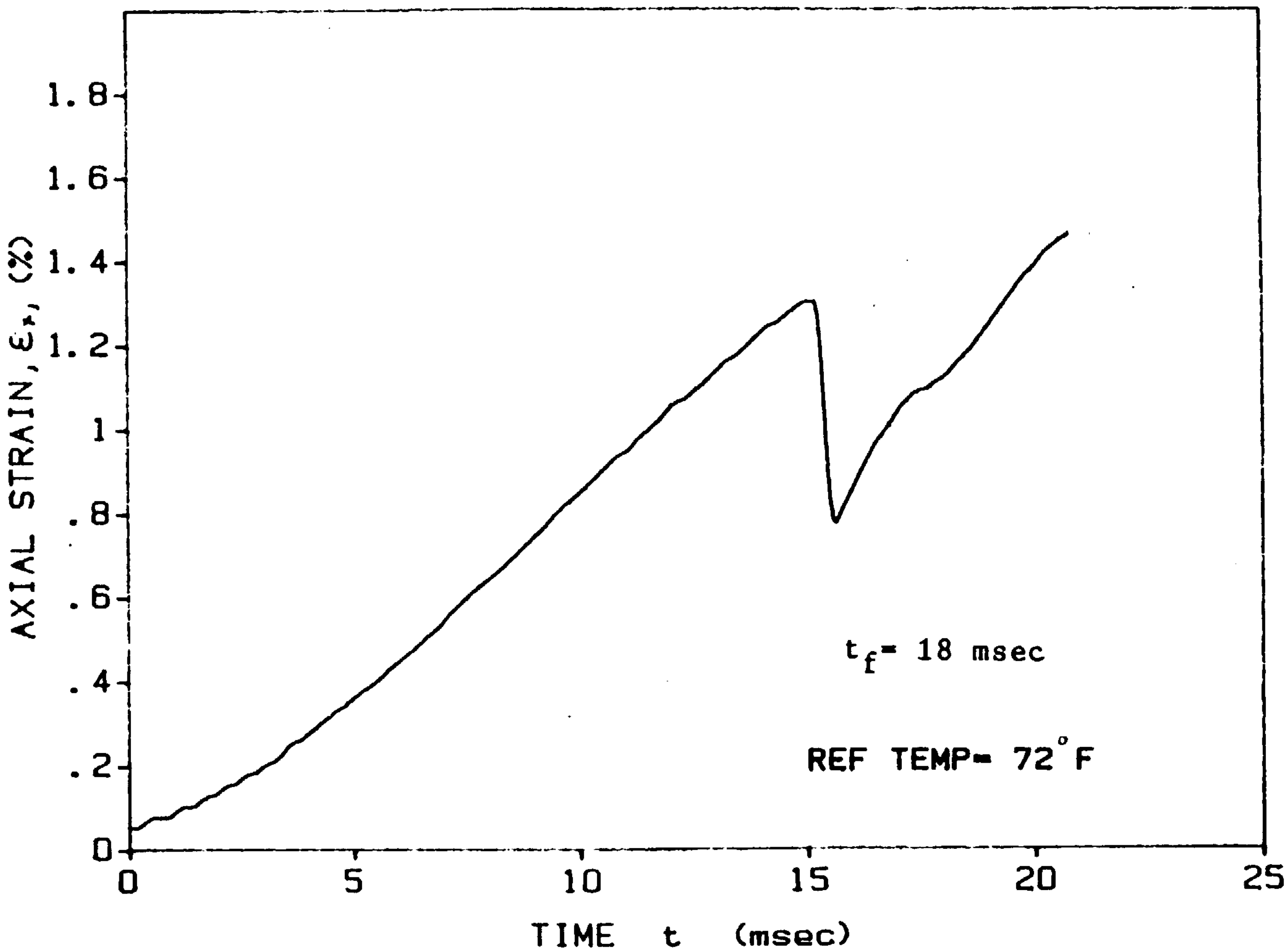


Fig. A-12. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L1 (T = 23°C (72°F))

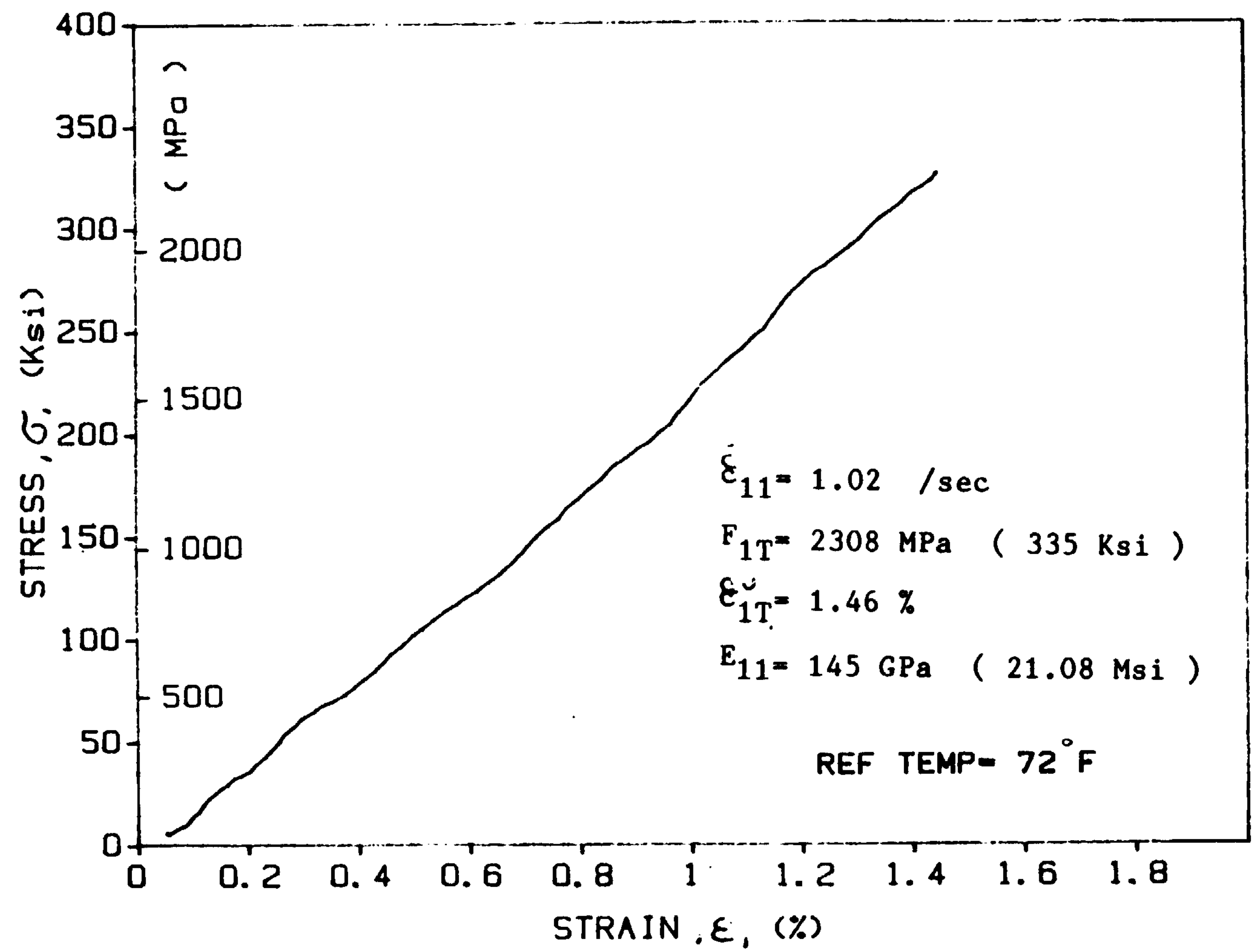


Fig. A-13. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L2 (T = 23°C (72°F))

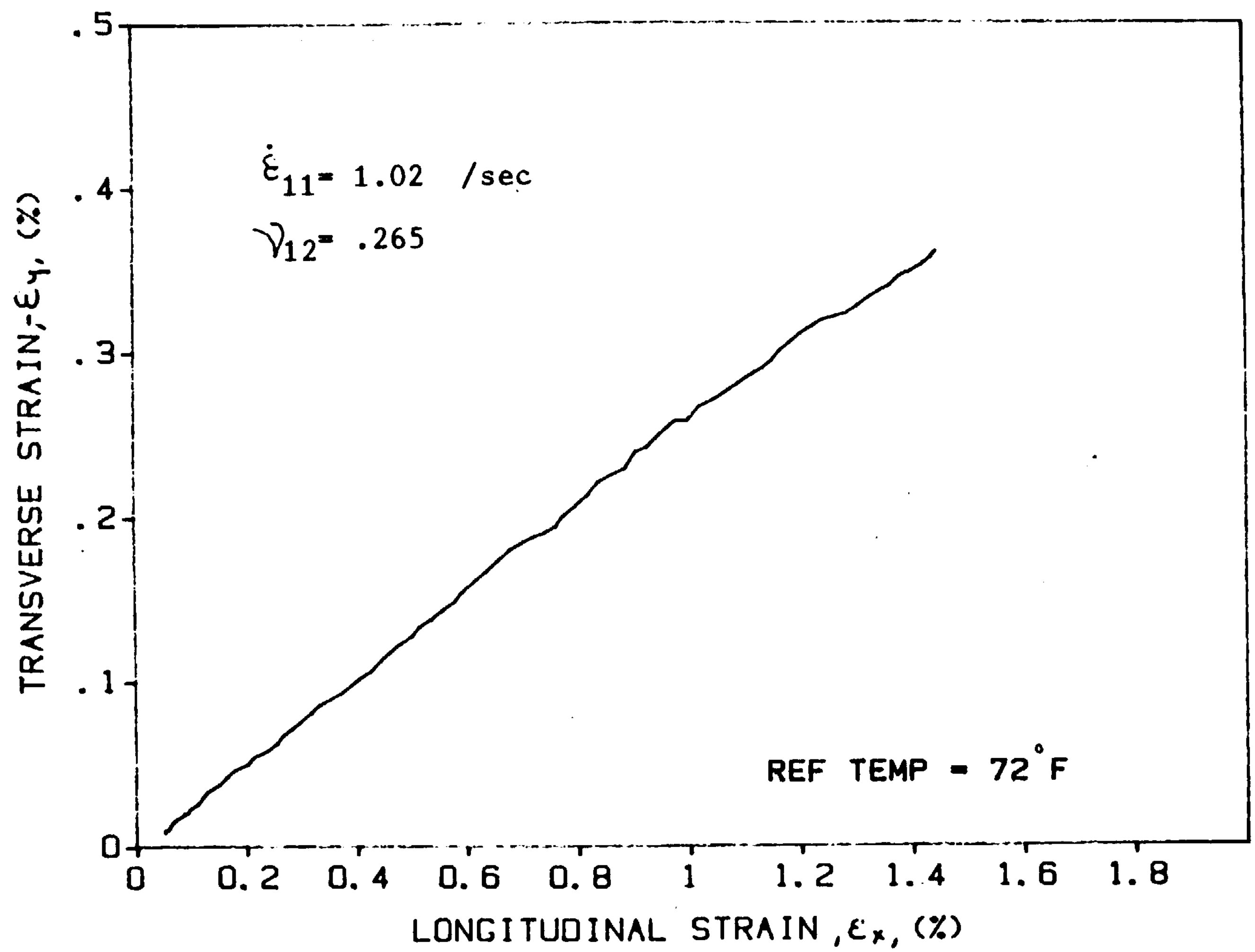


Fig. A-14. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L2 (T = 23°C (72°F))

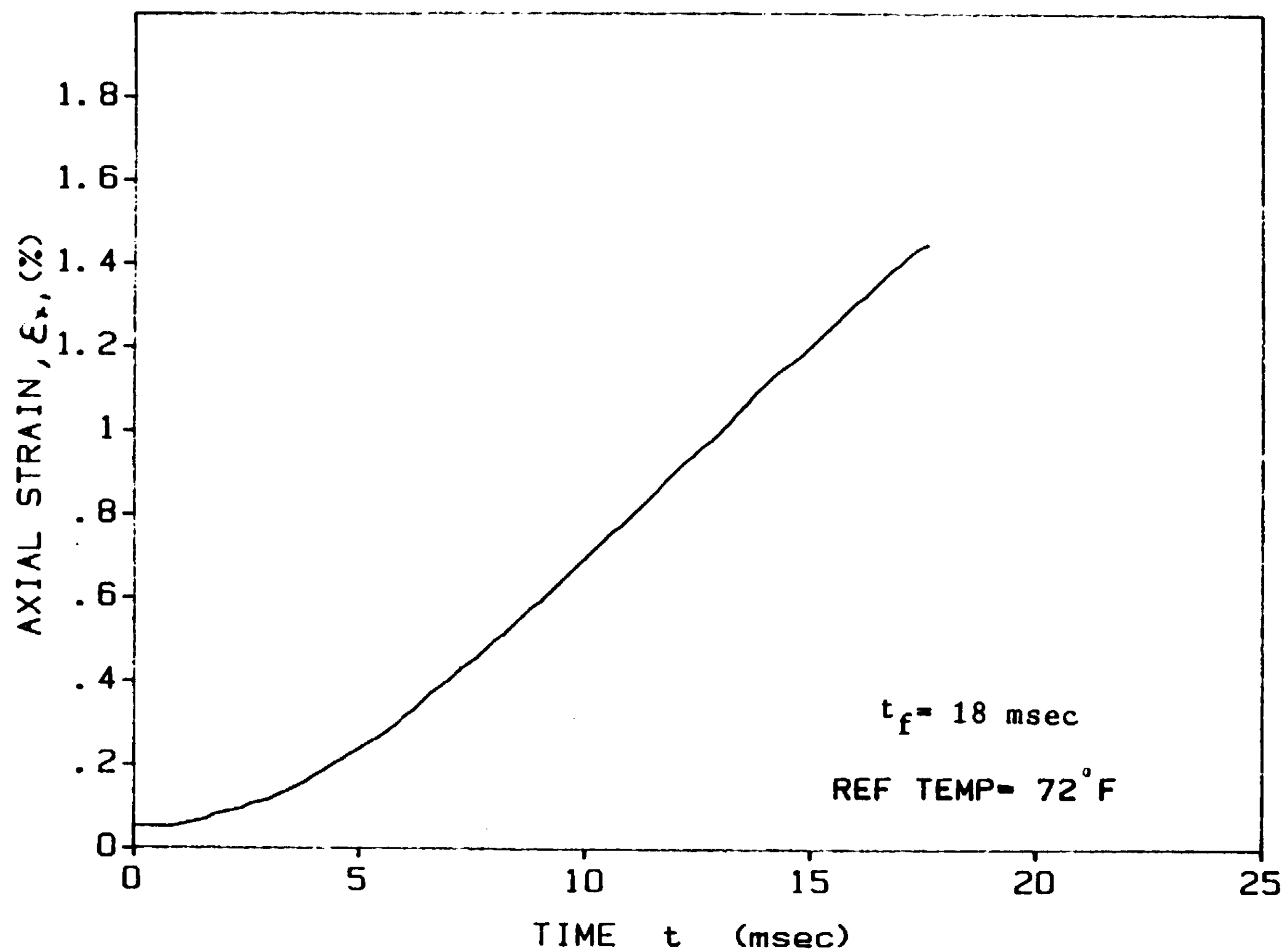


Fig. A-15. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L2 (T = 23°C (72°F))

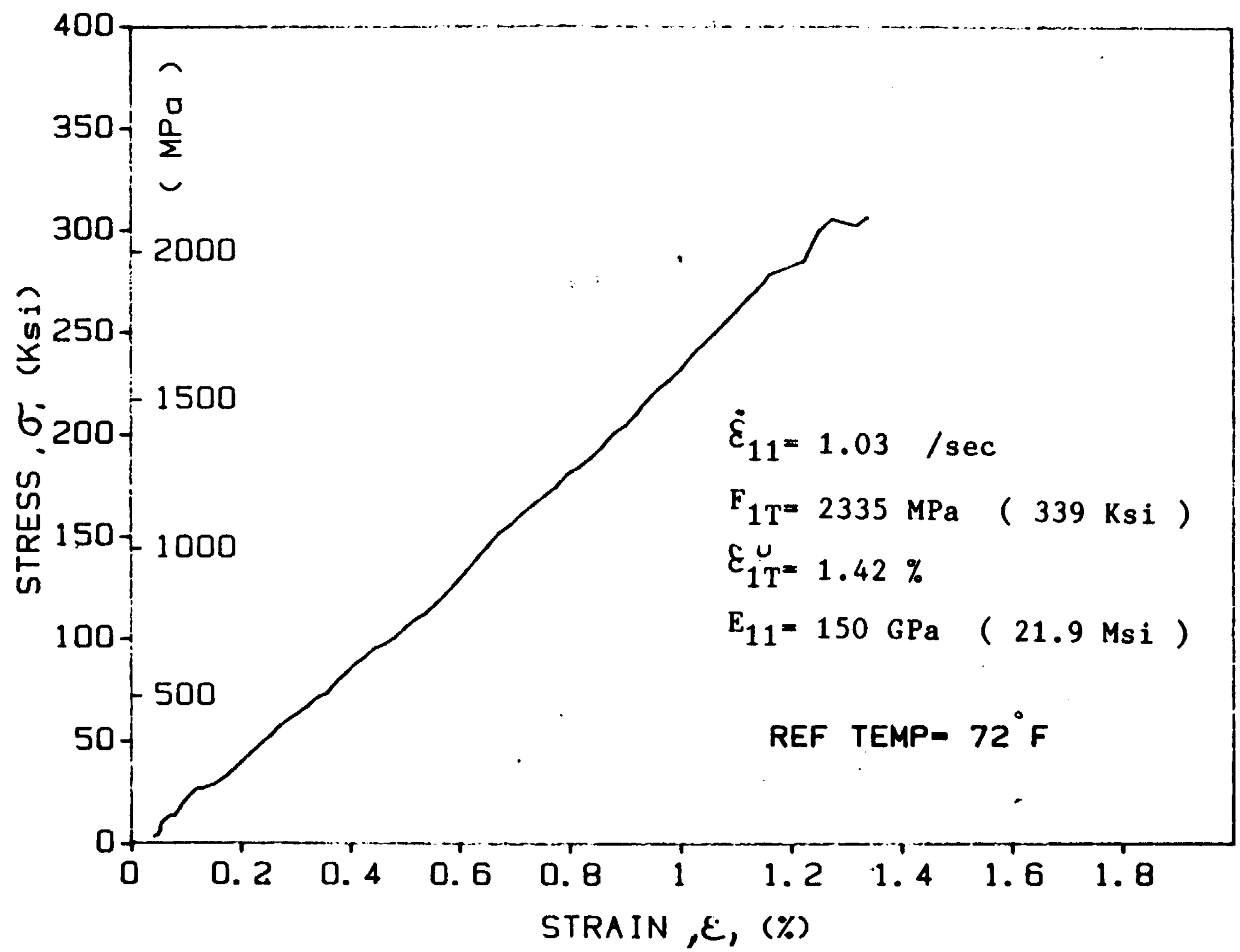


Fig. A-16. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L3.1 (T = 23°C (72°F))

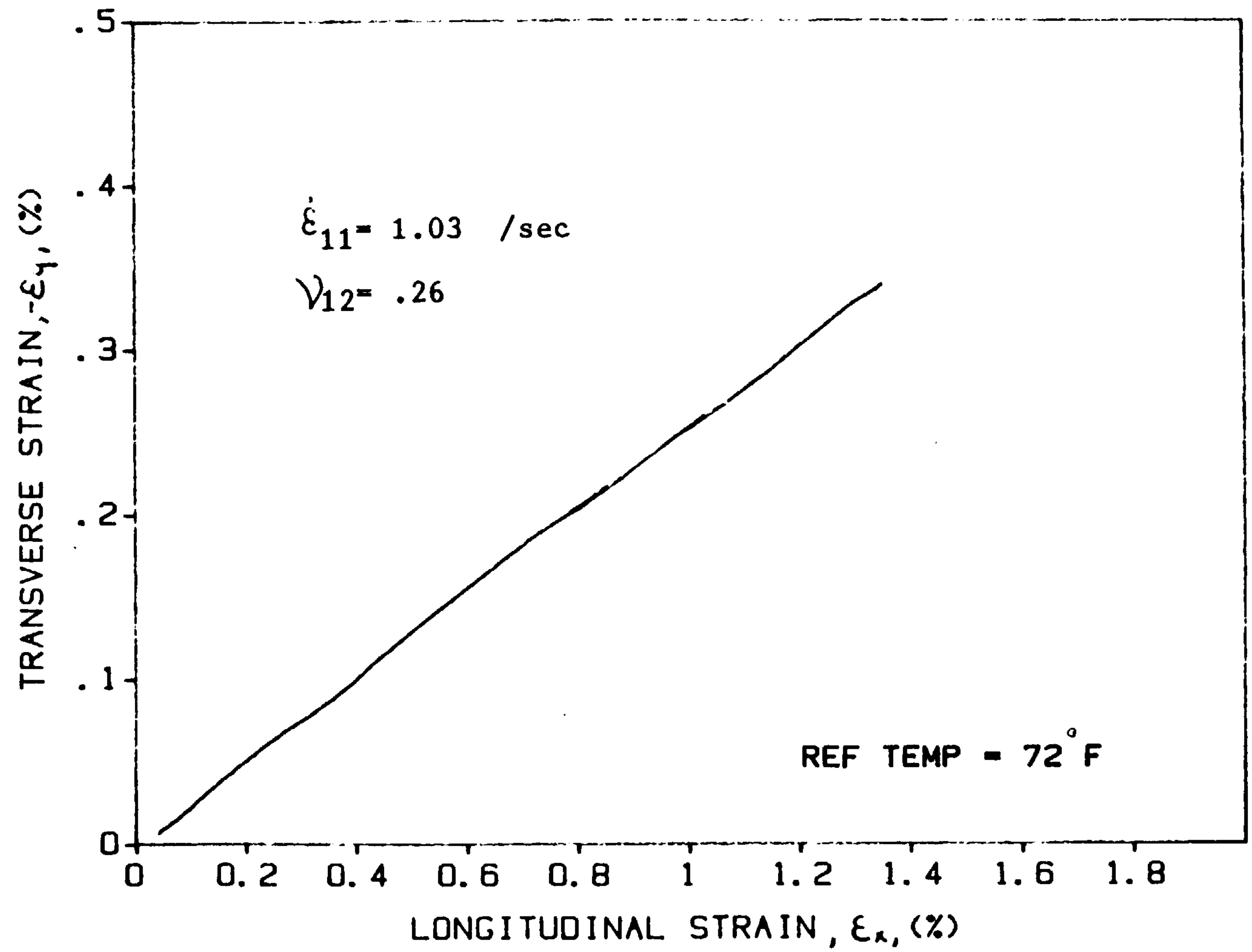


Fig. A-17. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L3.1 (T = 23°C (72°F))

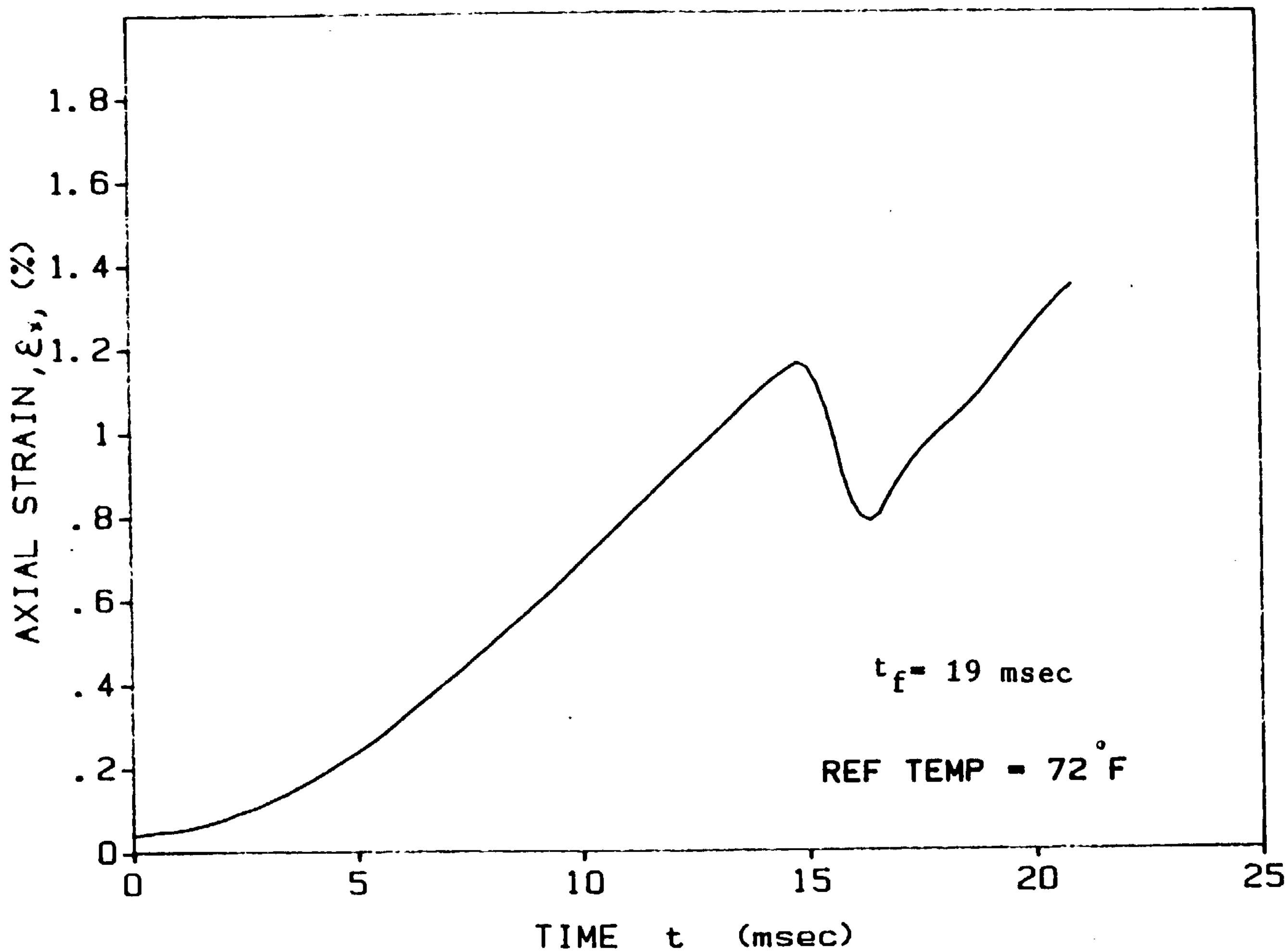


Fig. A-18. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L3.1 (T = 23°C (72°F))

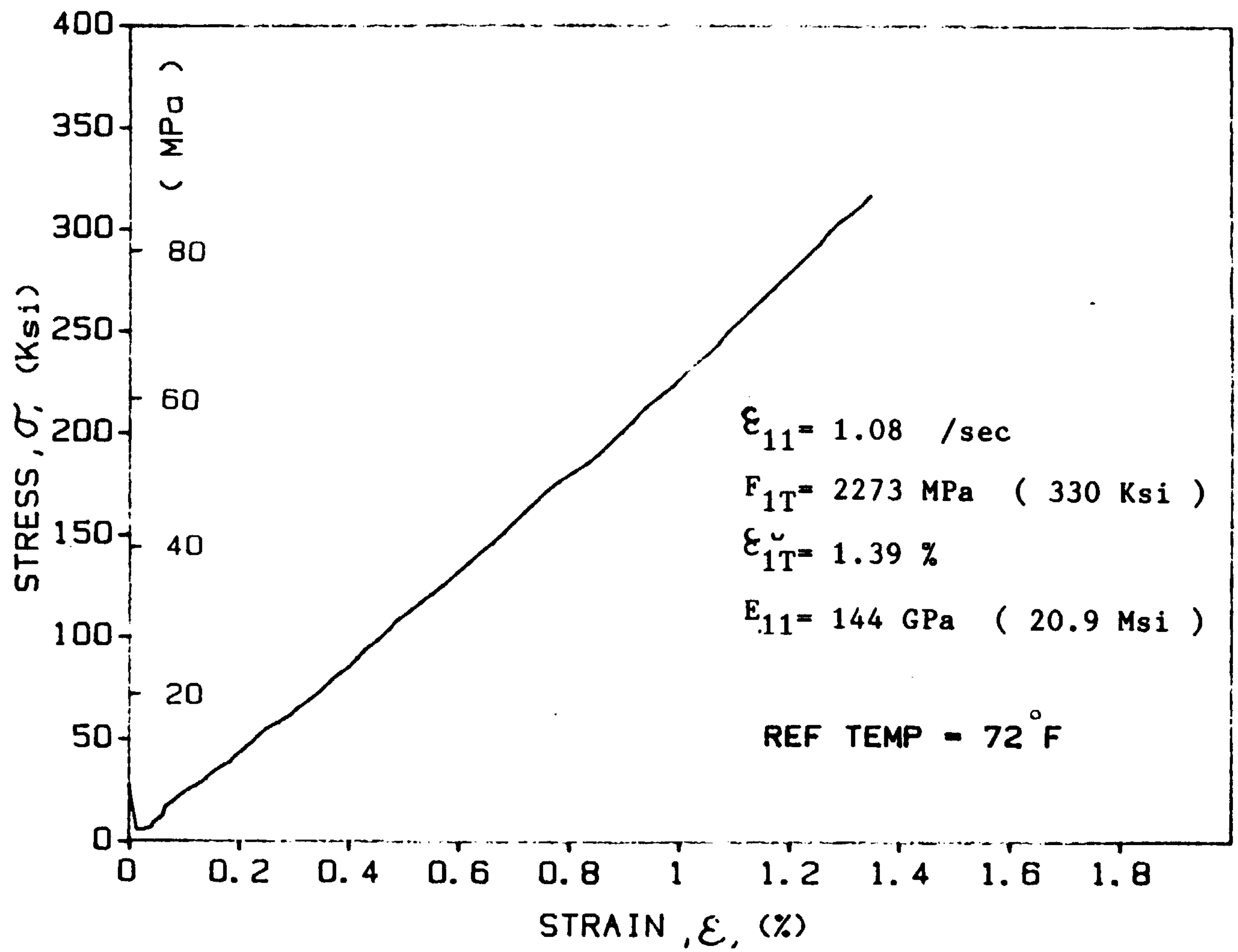


Fig. A-19. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L4 (T = 23°C (72°F))

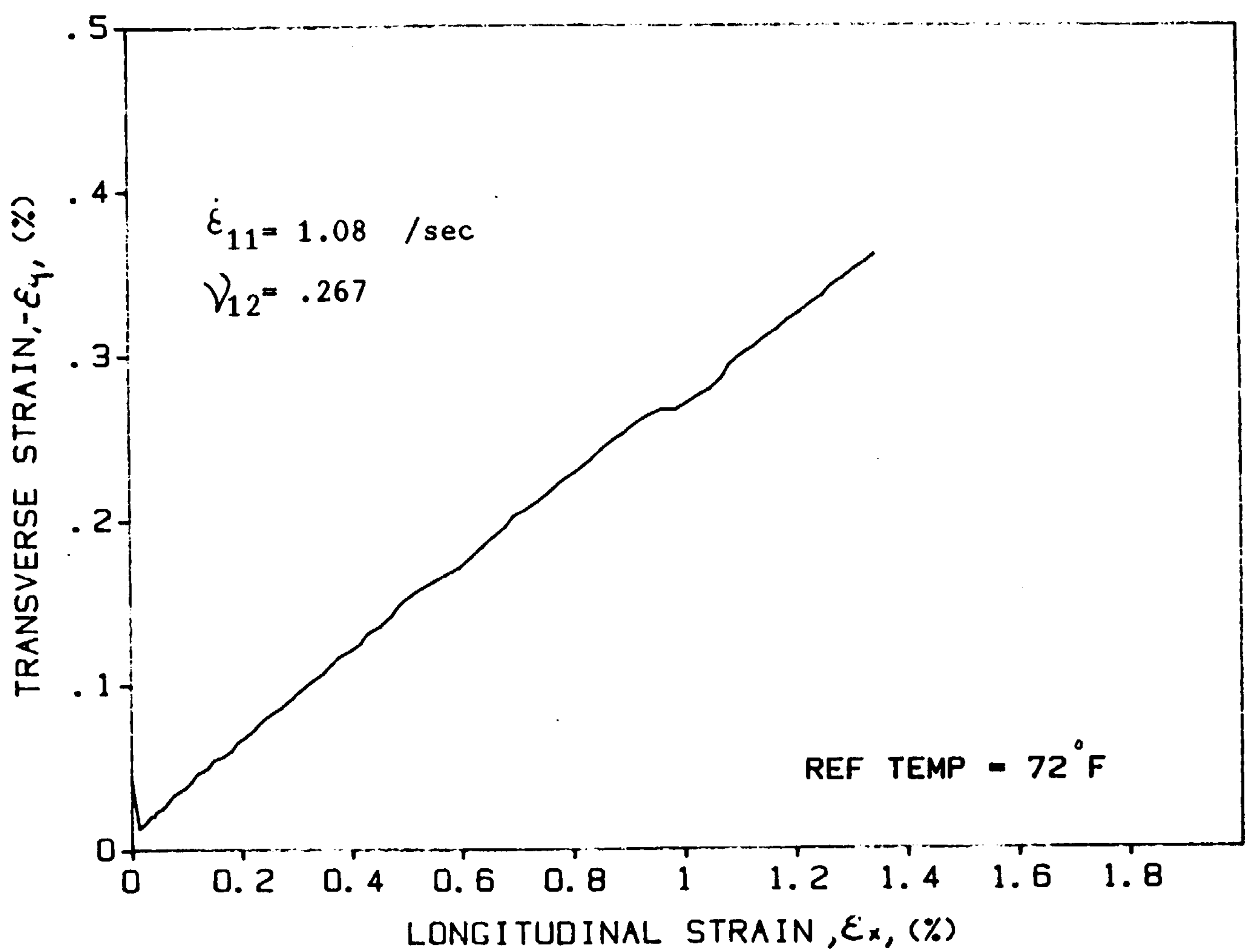


Fig. A-20. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L4 (T = 23°C (72°F))

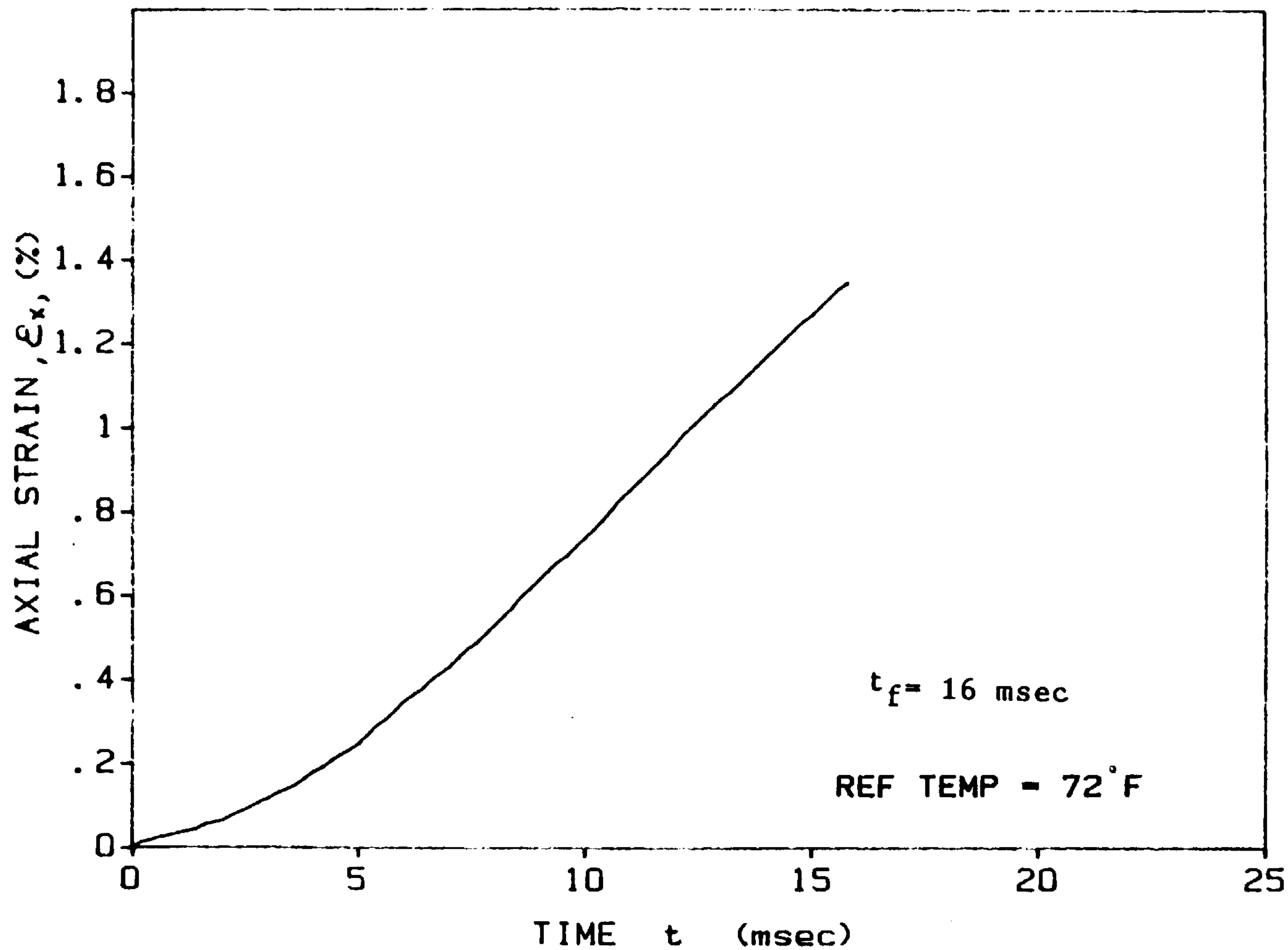


Fig. A-21. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L4 (T = 23°C (72°F))

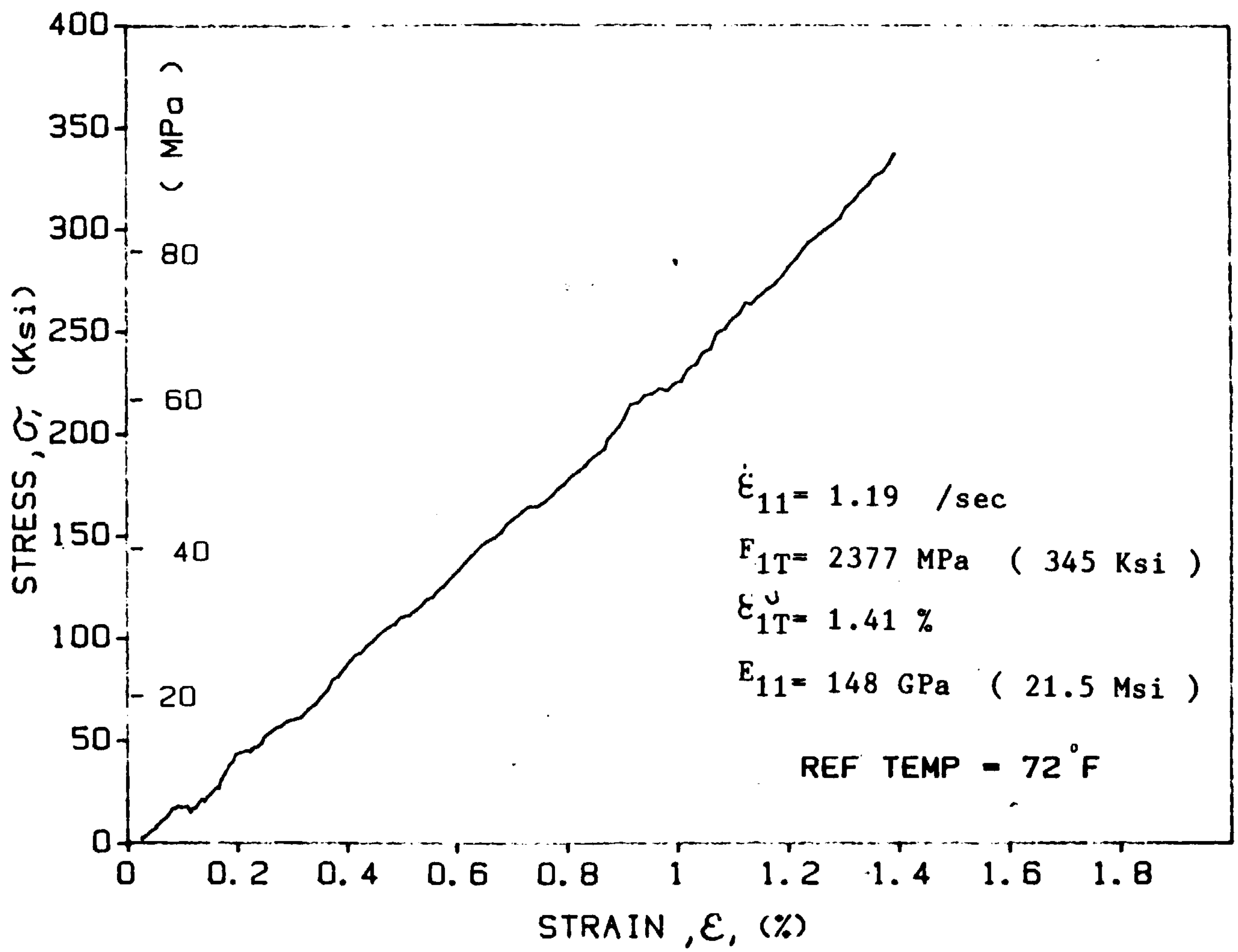


Fig. A-22. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L5 (T = 23°C (72°F))

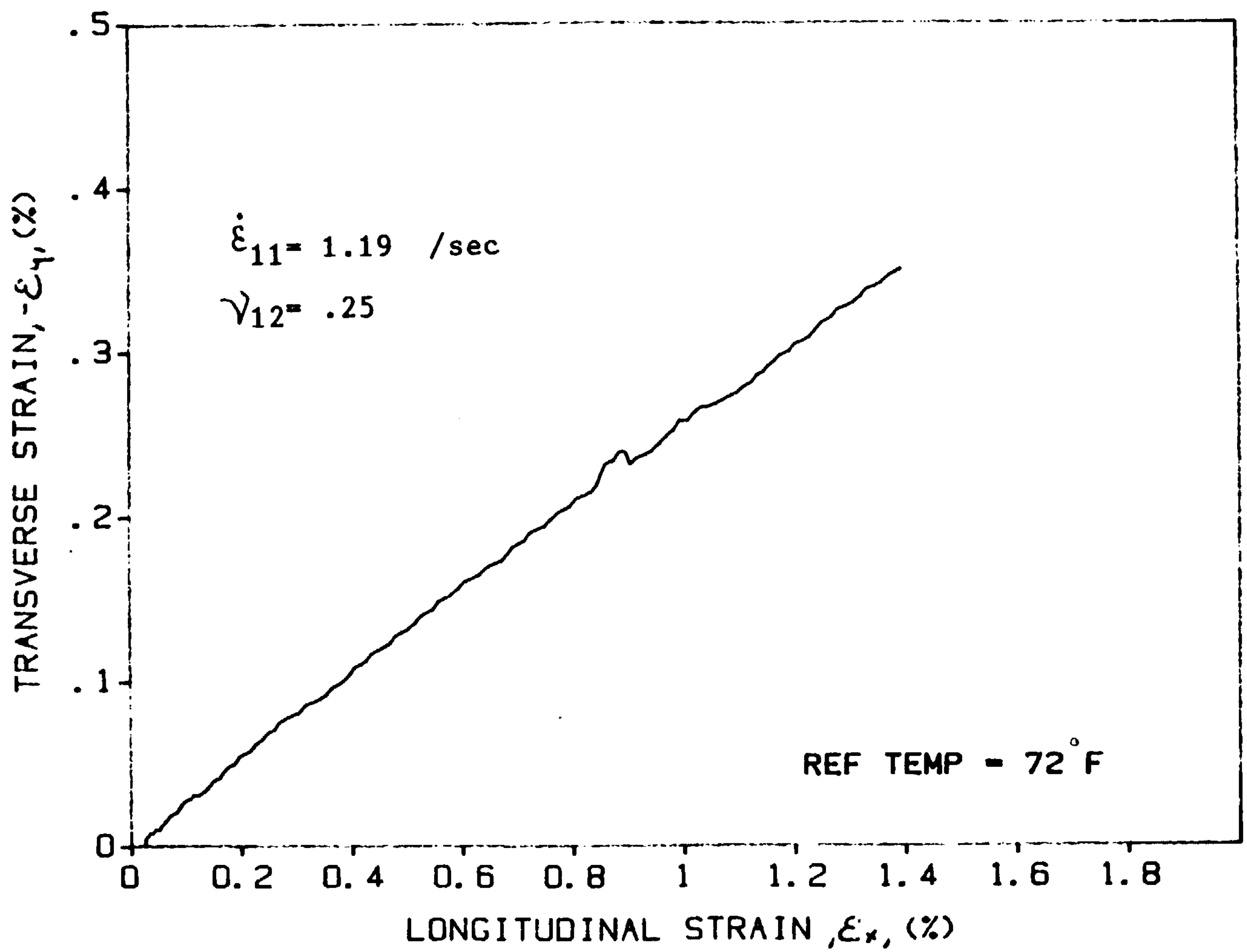


Fig. A-23. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 0/0L5 (T = 23°C (72°F))

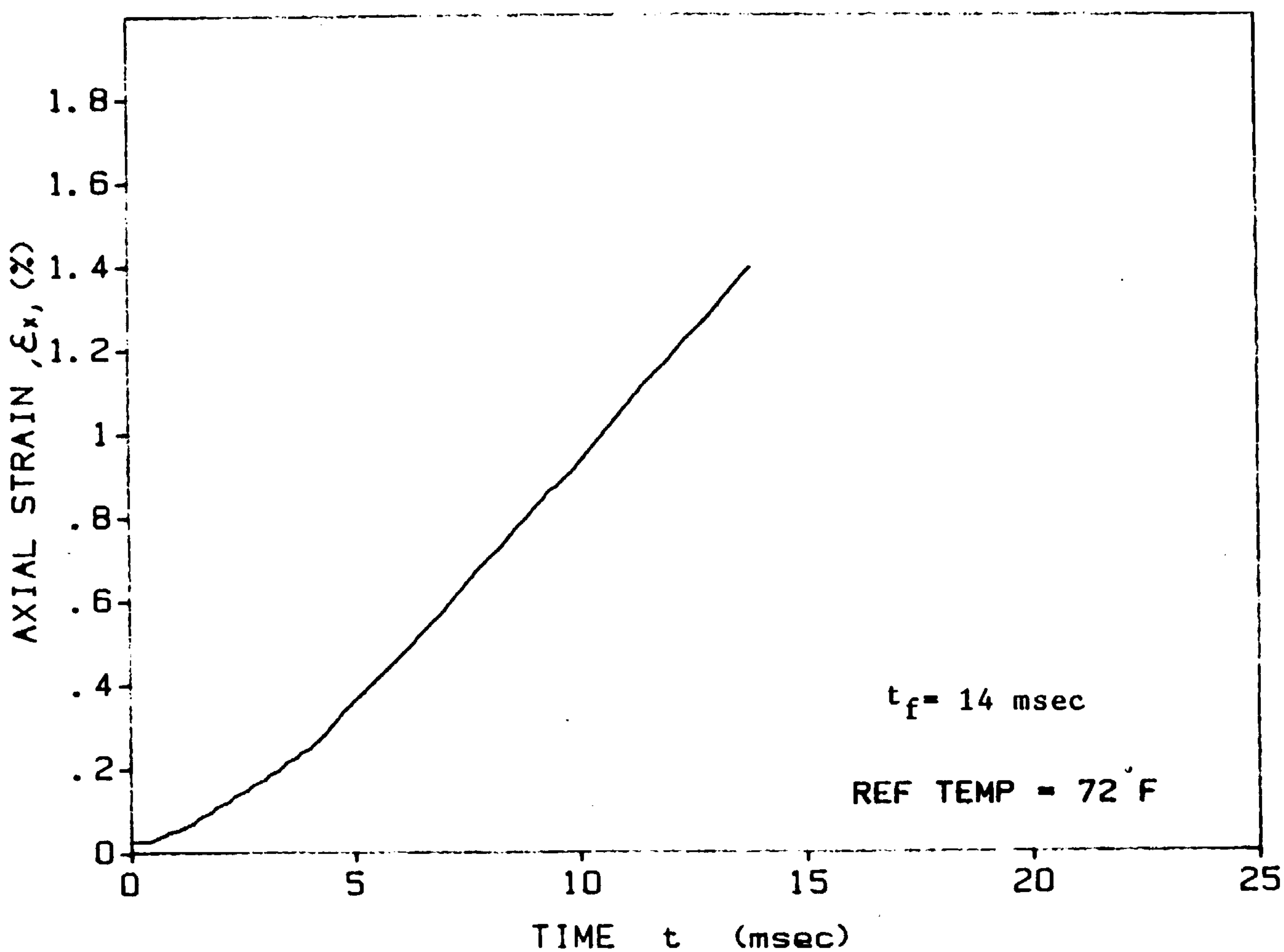


Fig. A-24. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0L5 (T = 23°C (72°F))

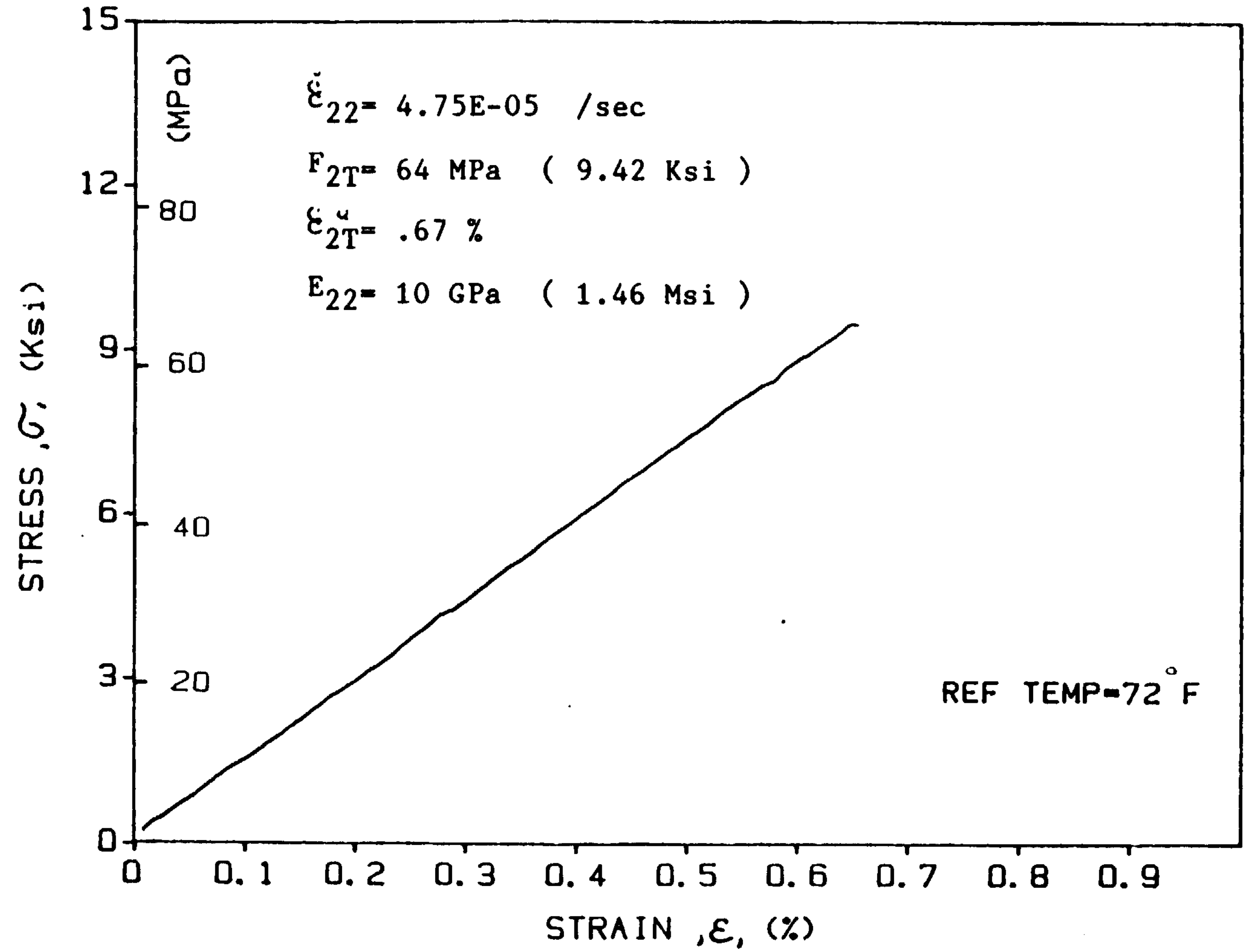


Fig. A-25. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5L1 (T = 23°C (72°F))

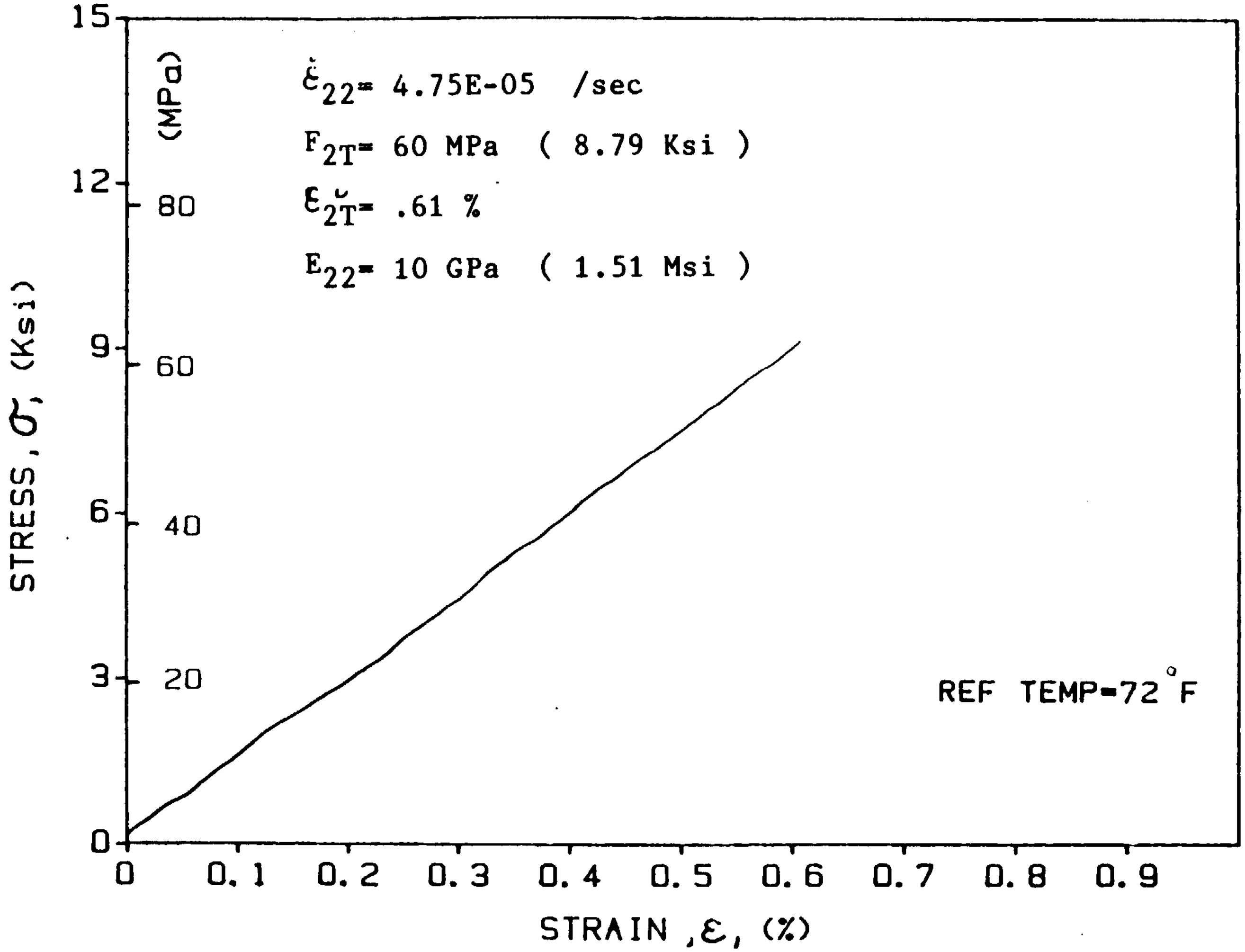


Fig. A-26. Stress- Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5L2 (T = 23°C (72°F))

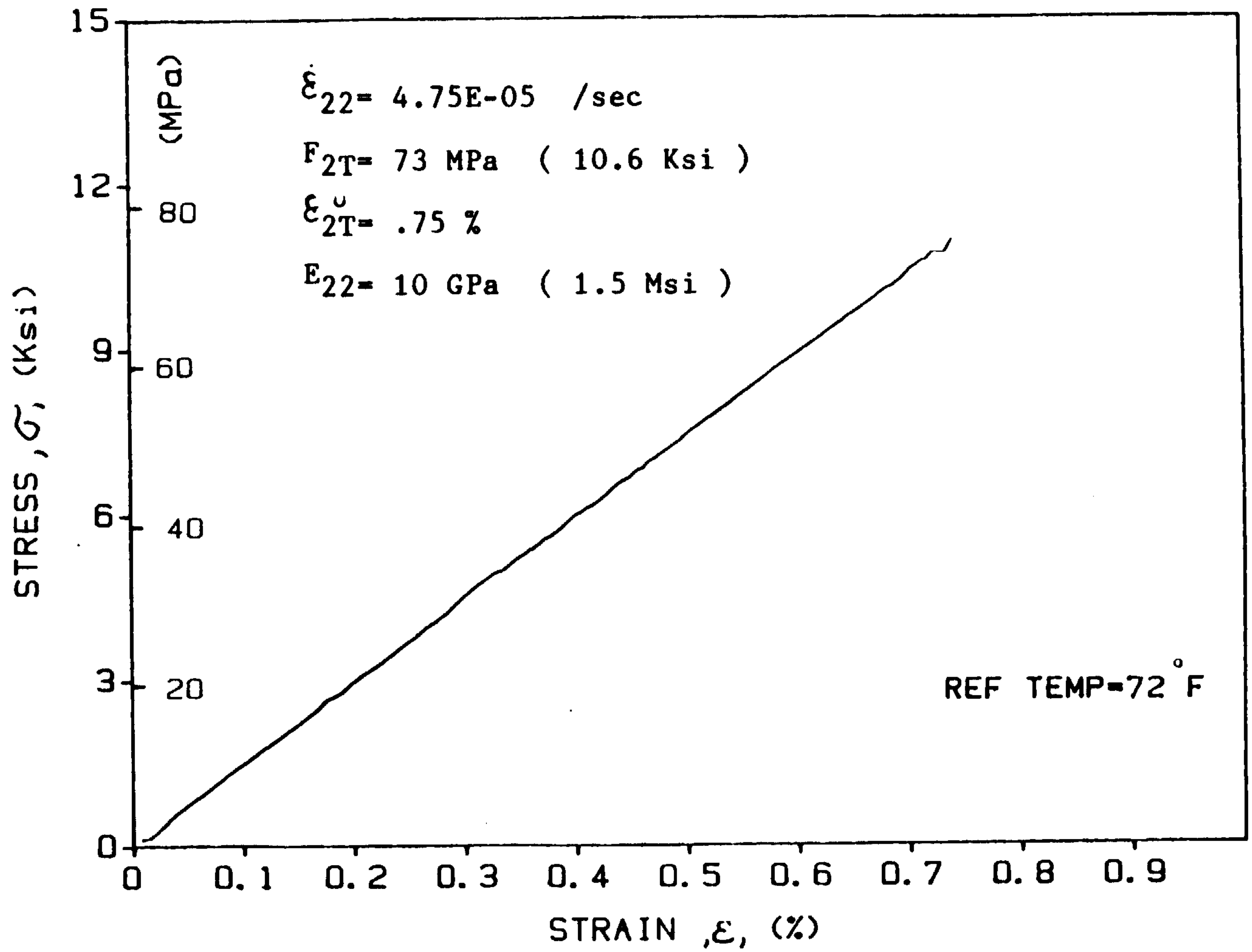


Fig. A-27. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5L3 (T = 23°C (72°F))

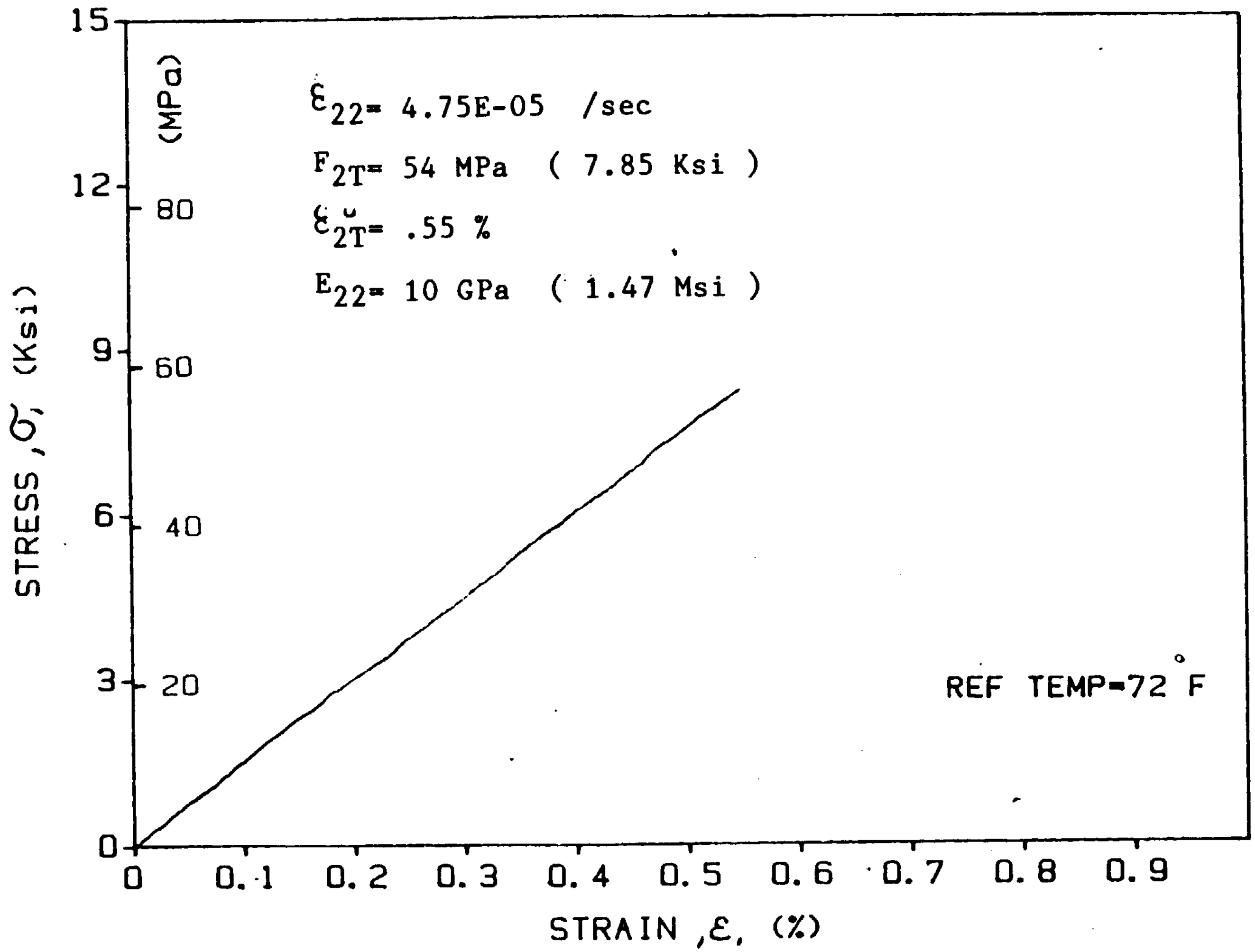


Fig. A-28. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5L4 (T = 23°C (72°F))

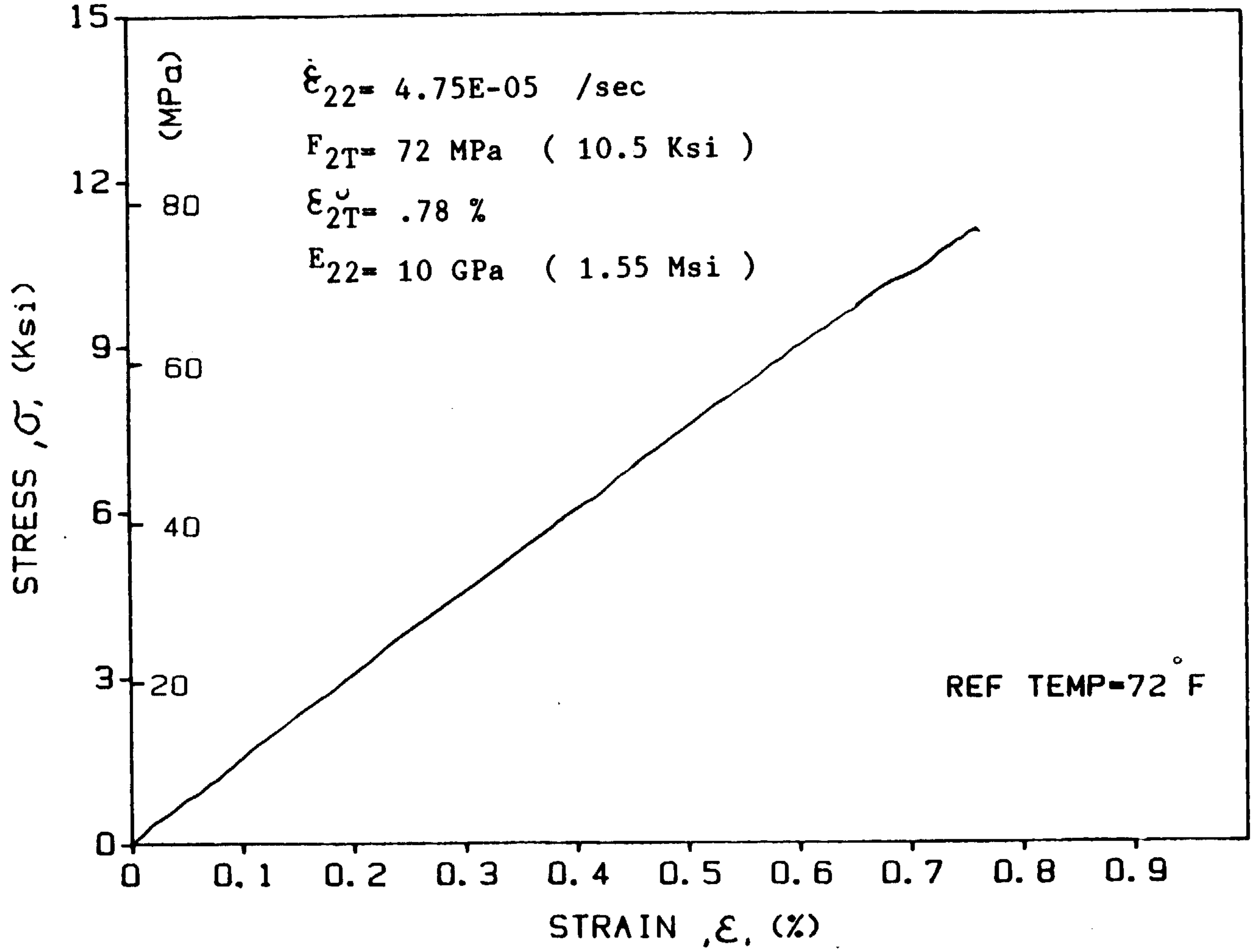


Fig. A-29. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5L5 (T = 23°C (72°F))

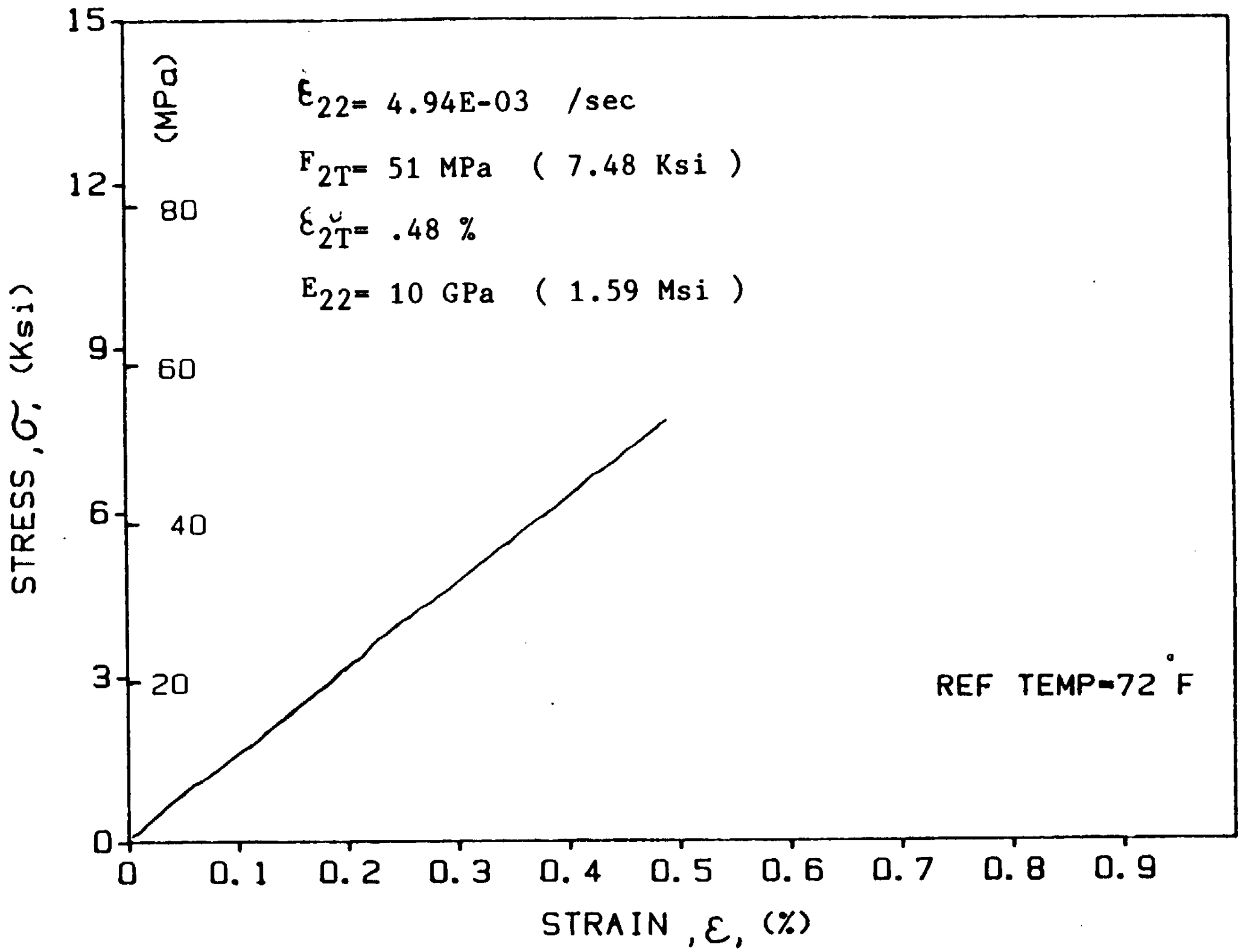


Fig. A-30. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3L1 (T = 23°C (72°F))

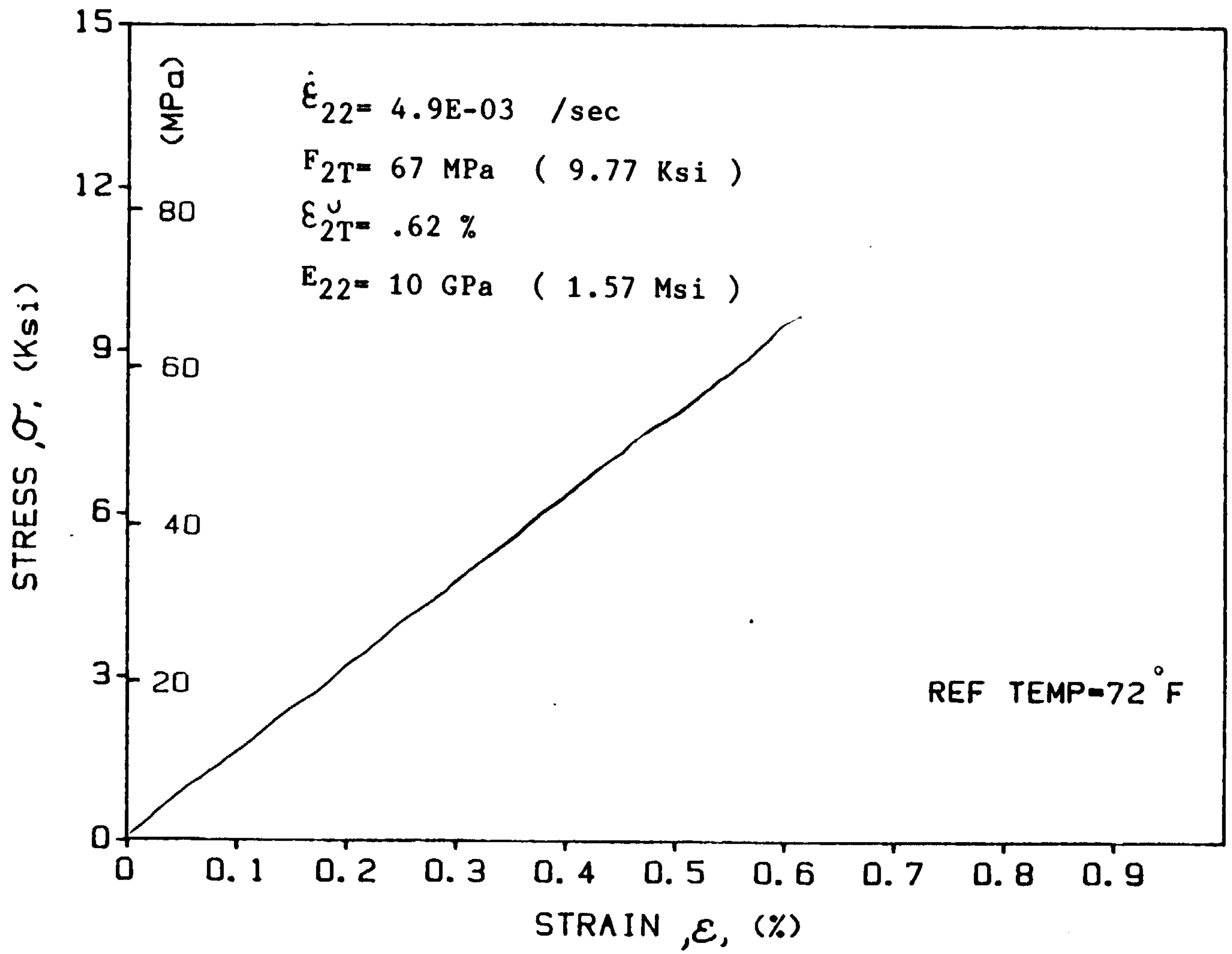


Fig. A-31. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3L2 (T = 23°C (72°F))

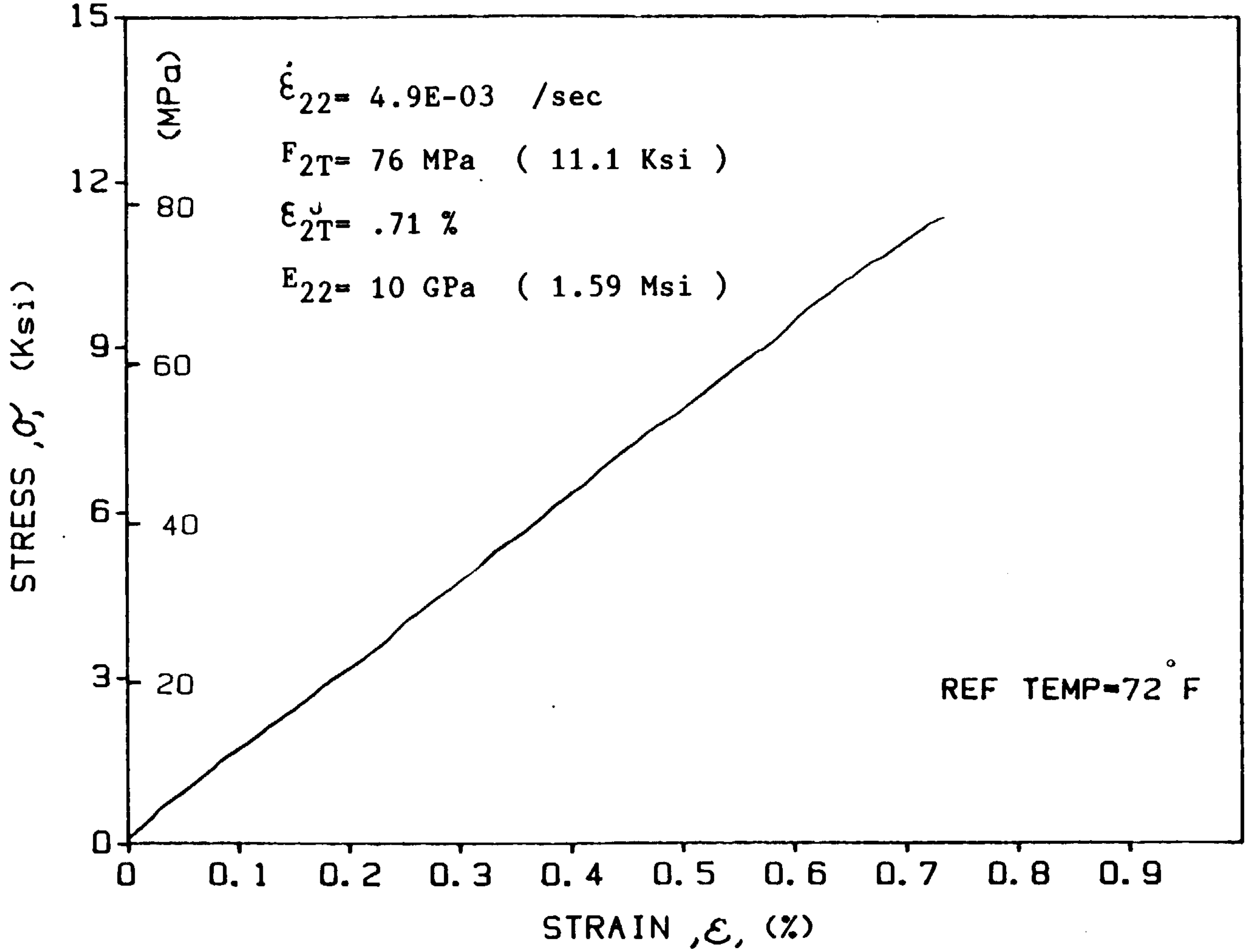


Fig. A-32. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3L3 (T = 23°C (72°F))

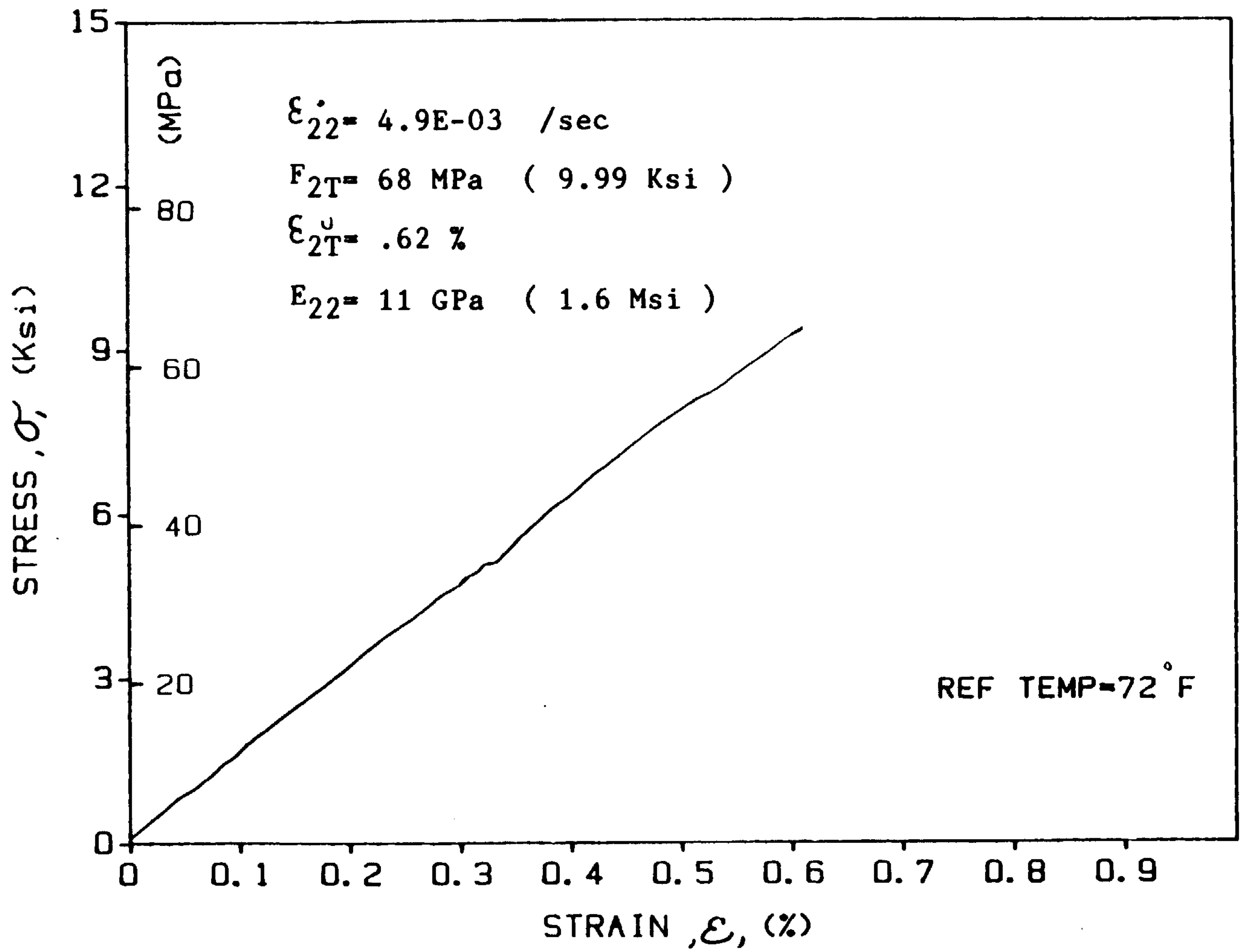


Fig. A-33. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3L4 (T = 23°C (72°F))

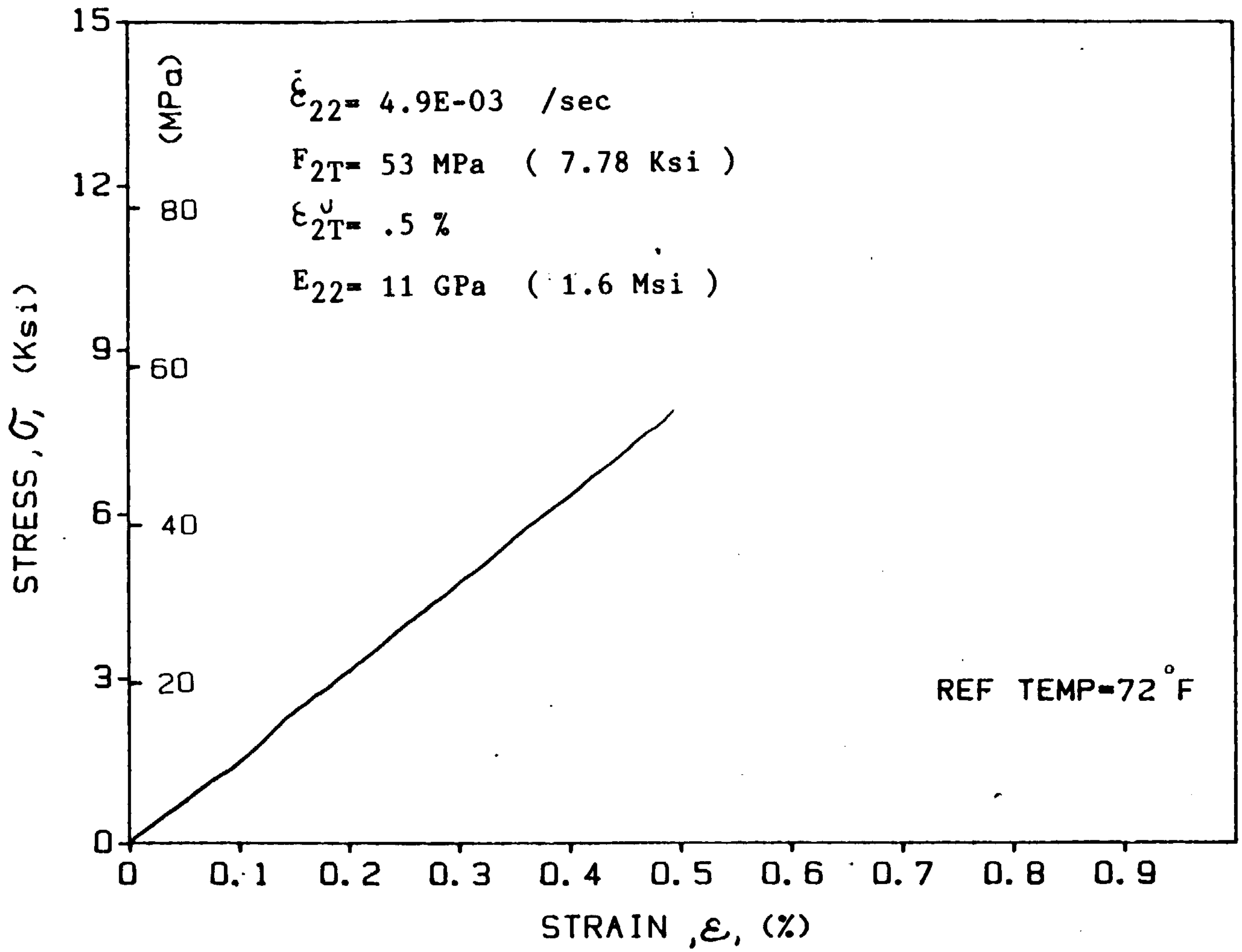


Fig. A-34. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3L5 (T = 23°C (72°F))

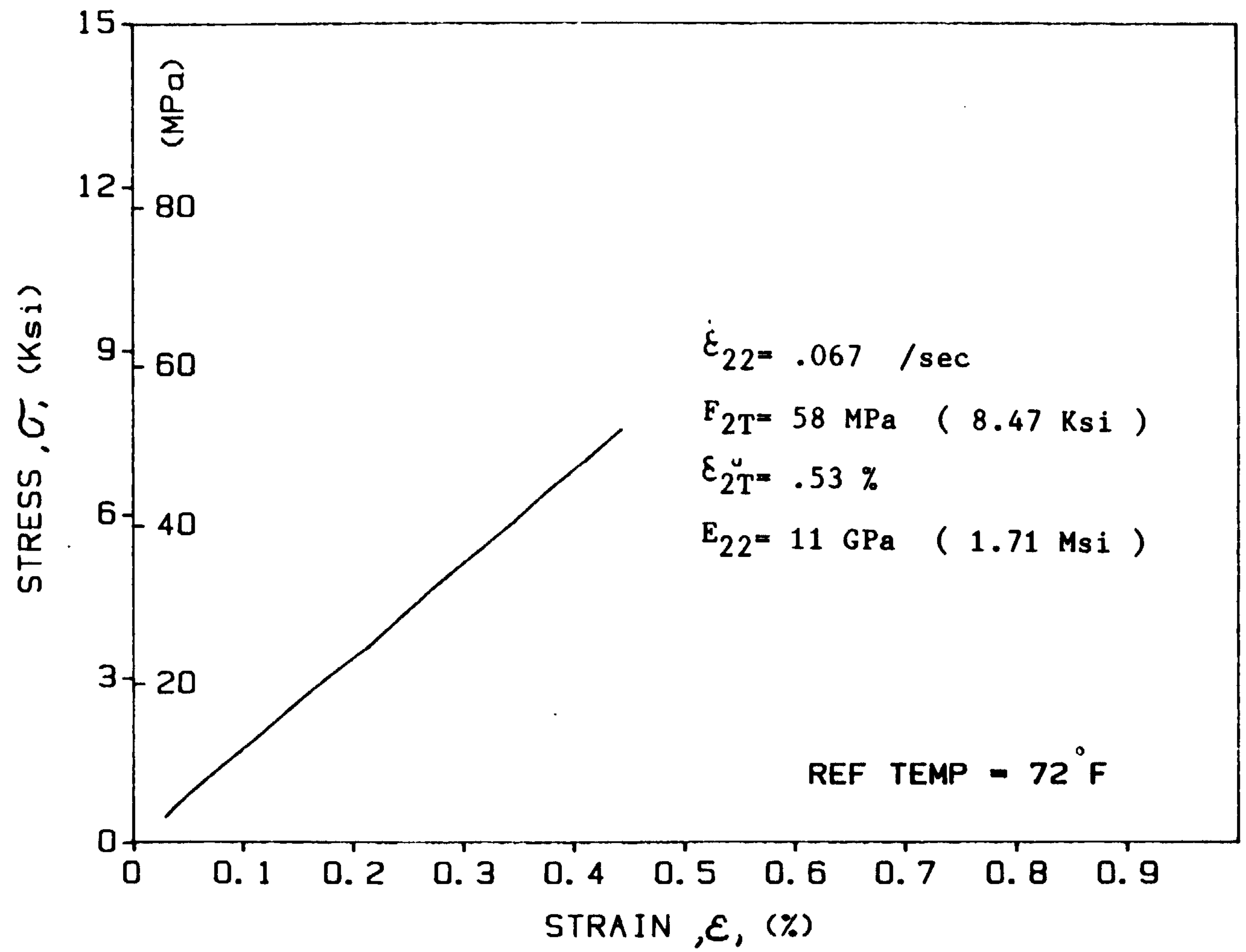


Fig. A-35. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L1 (T = 23°C (72°F))

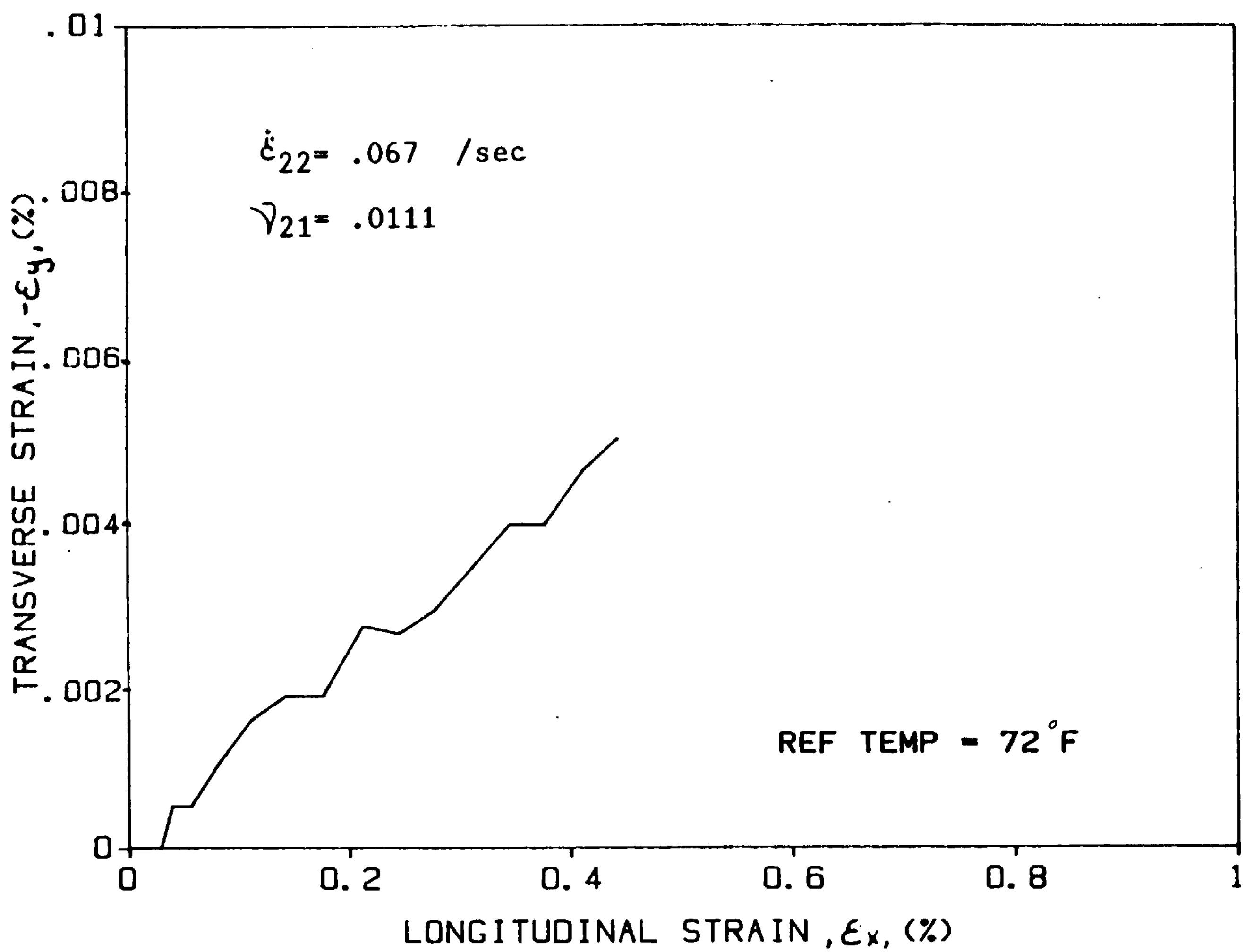


Fig. A-36. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/-2L1 (T = 23°C (72°F))

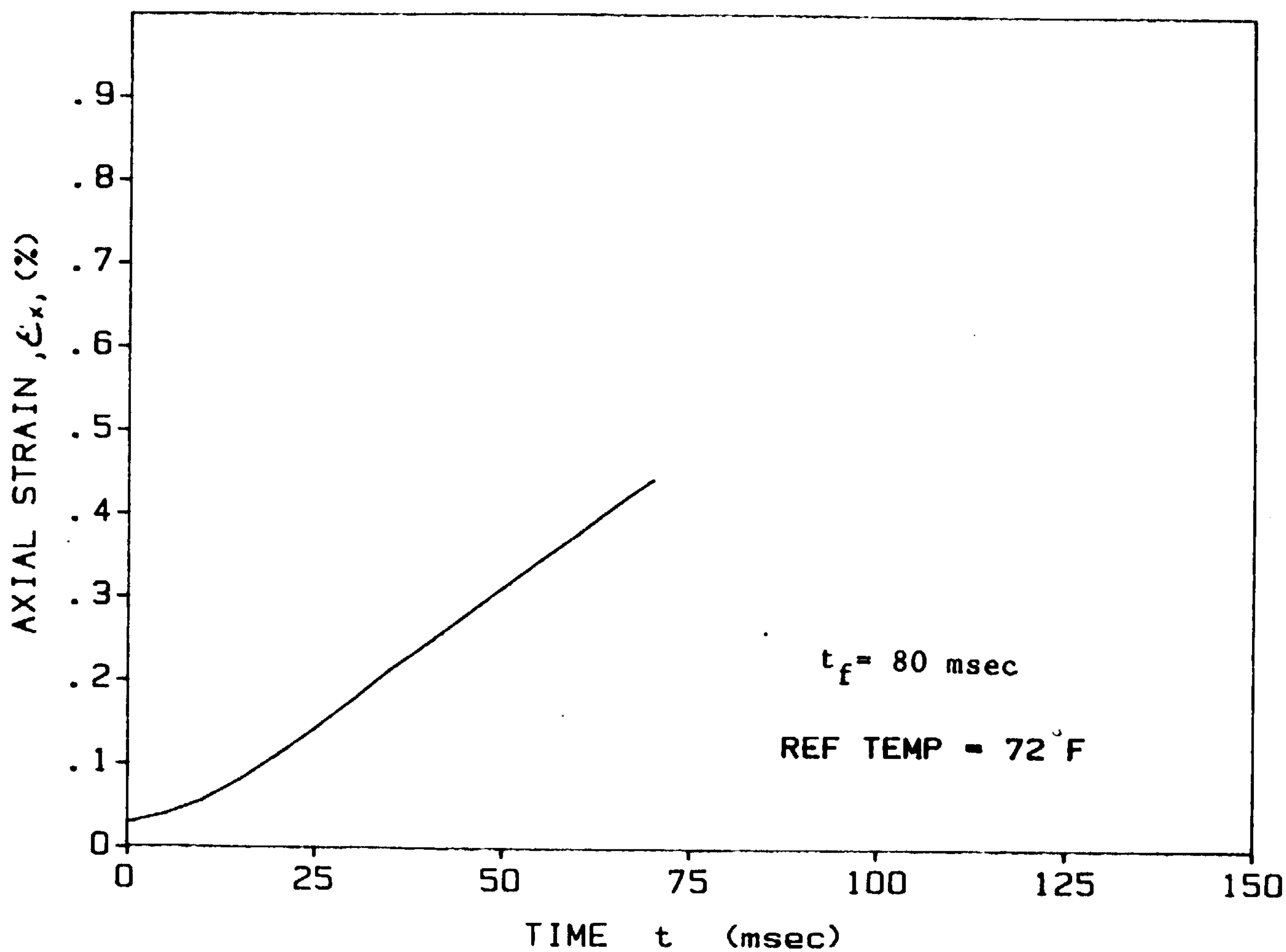


Fig. A-37. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L1 (T = 23°C (72°F))

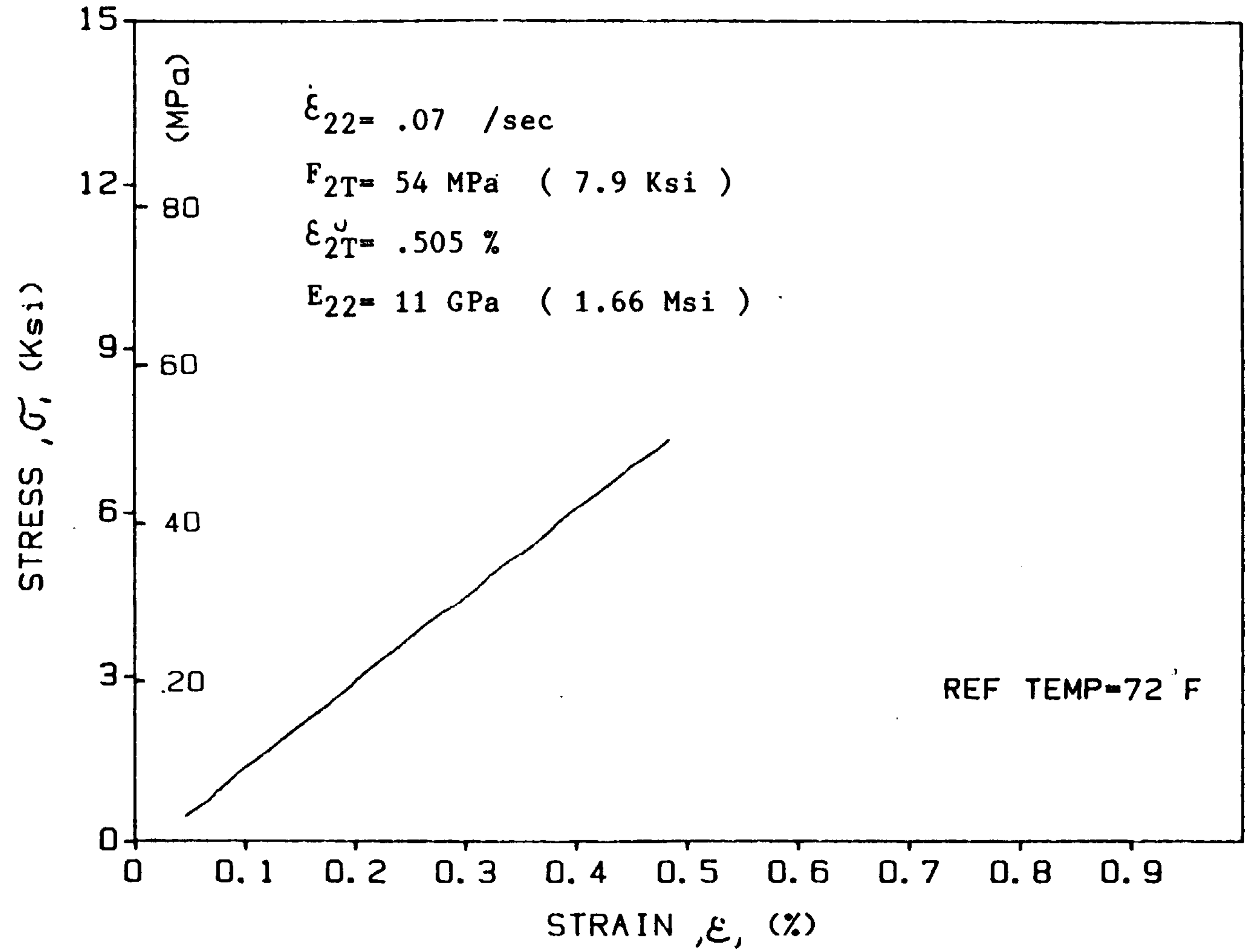


Fig. A-38. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L2 (T = 23°C (72°F))

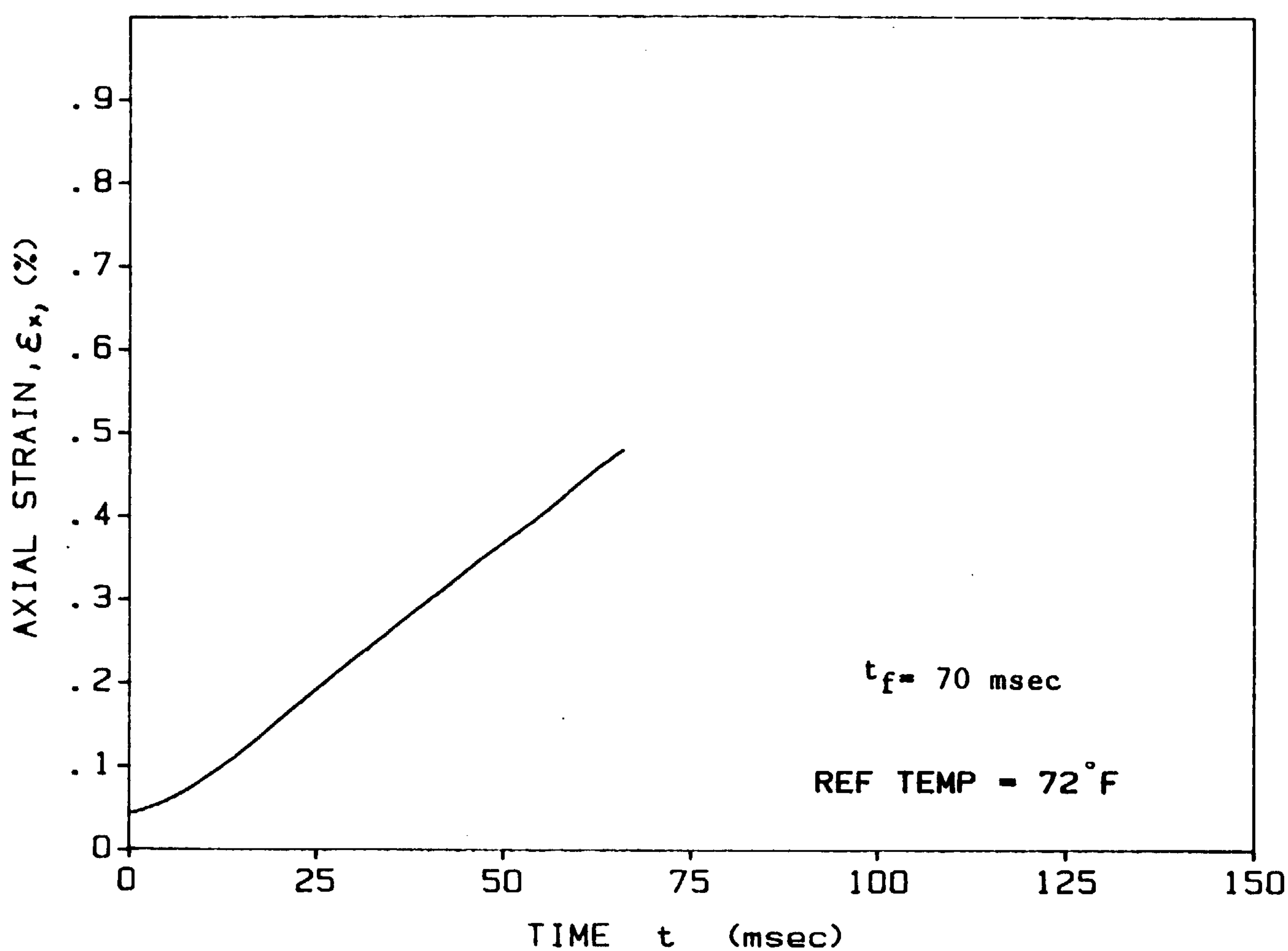


Fig. A-39. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L2 (T = 23°C (72°F))

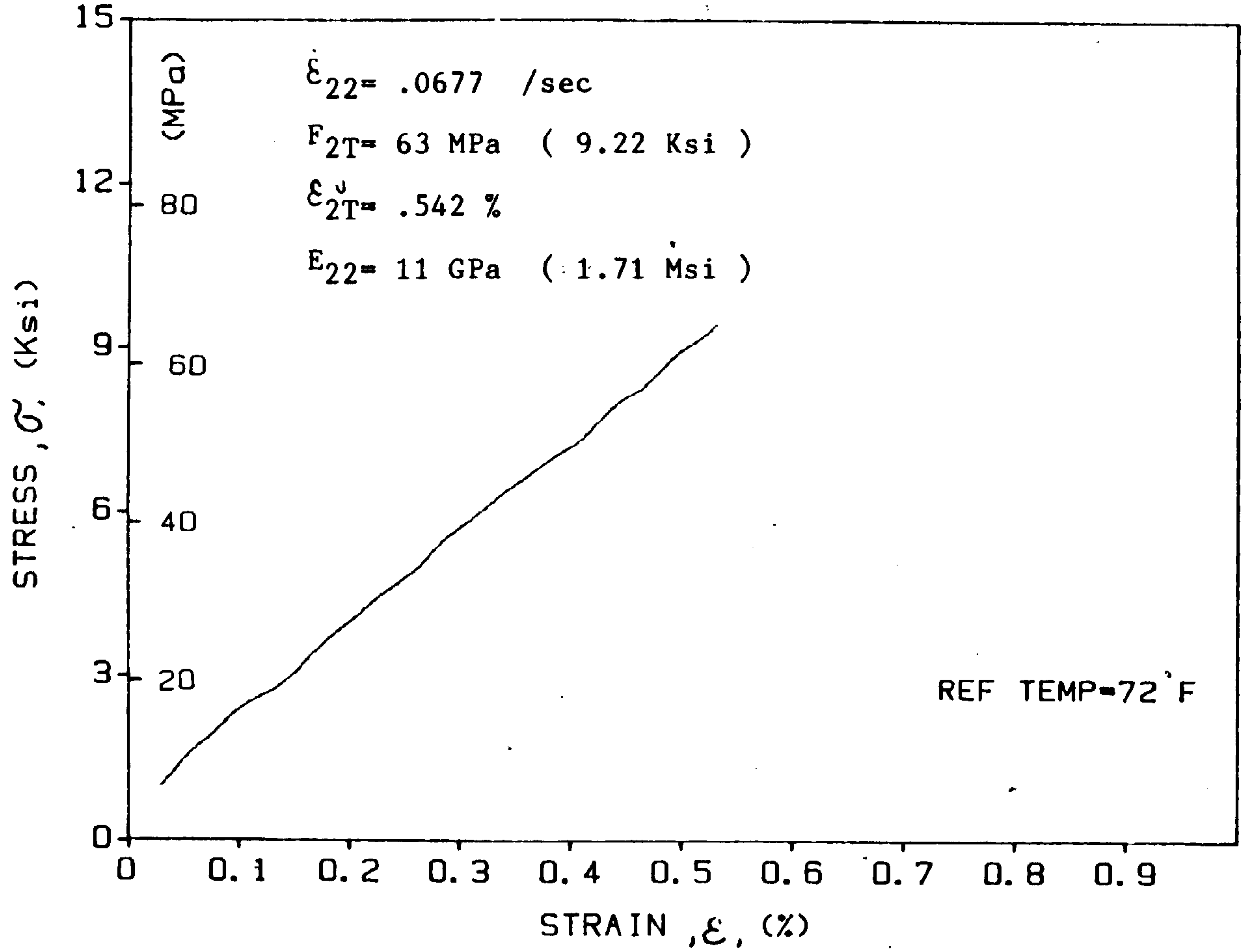


Fig. A-40. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L3 (T = 23°C (72°F))

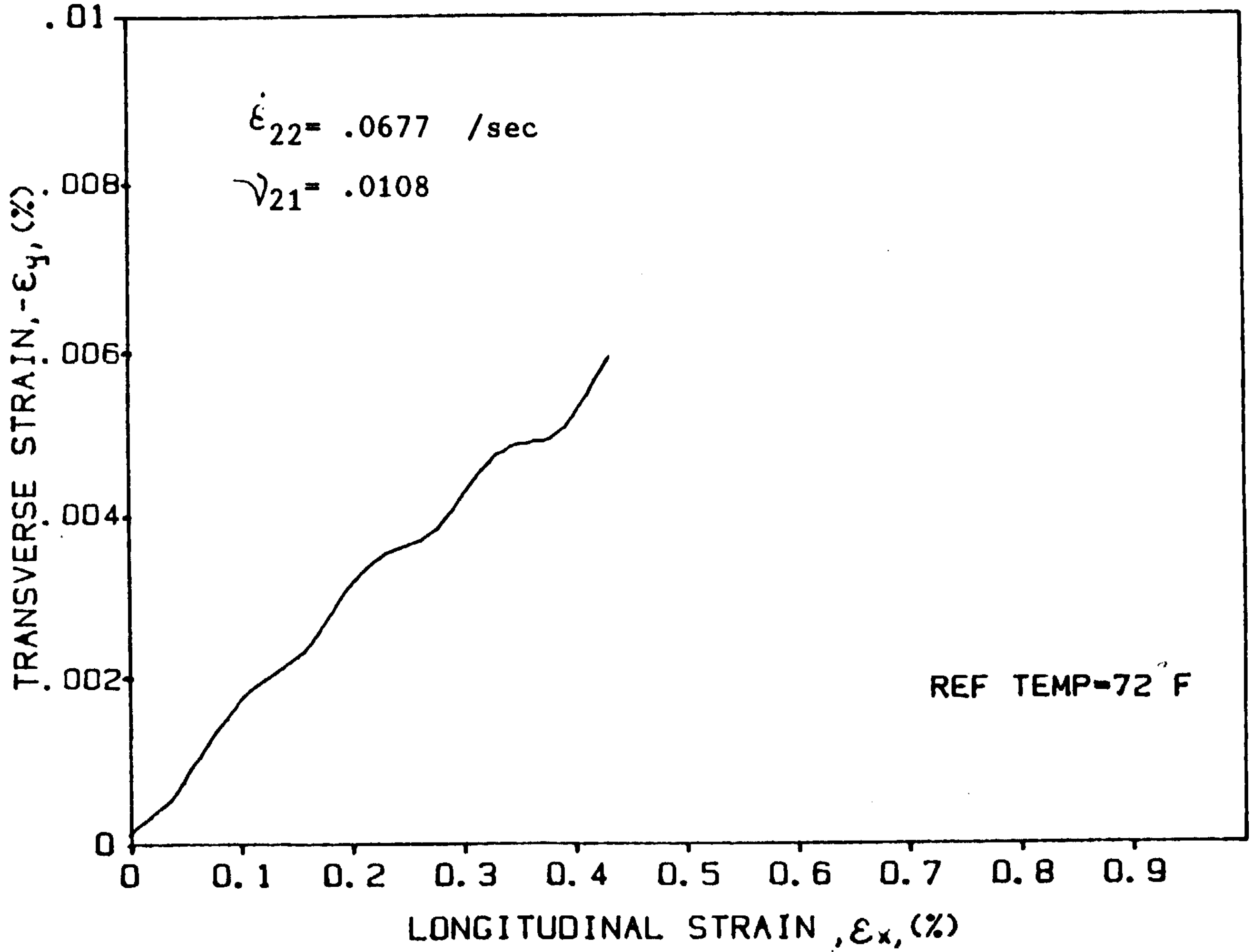


Fig. A-41. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/-2L3 (T = 23°C (72°F))

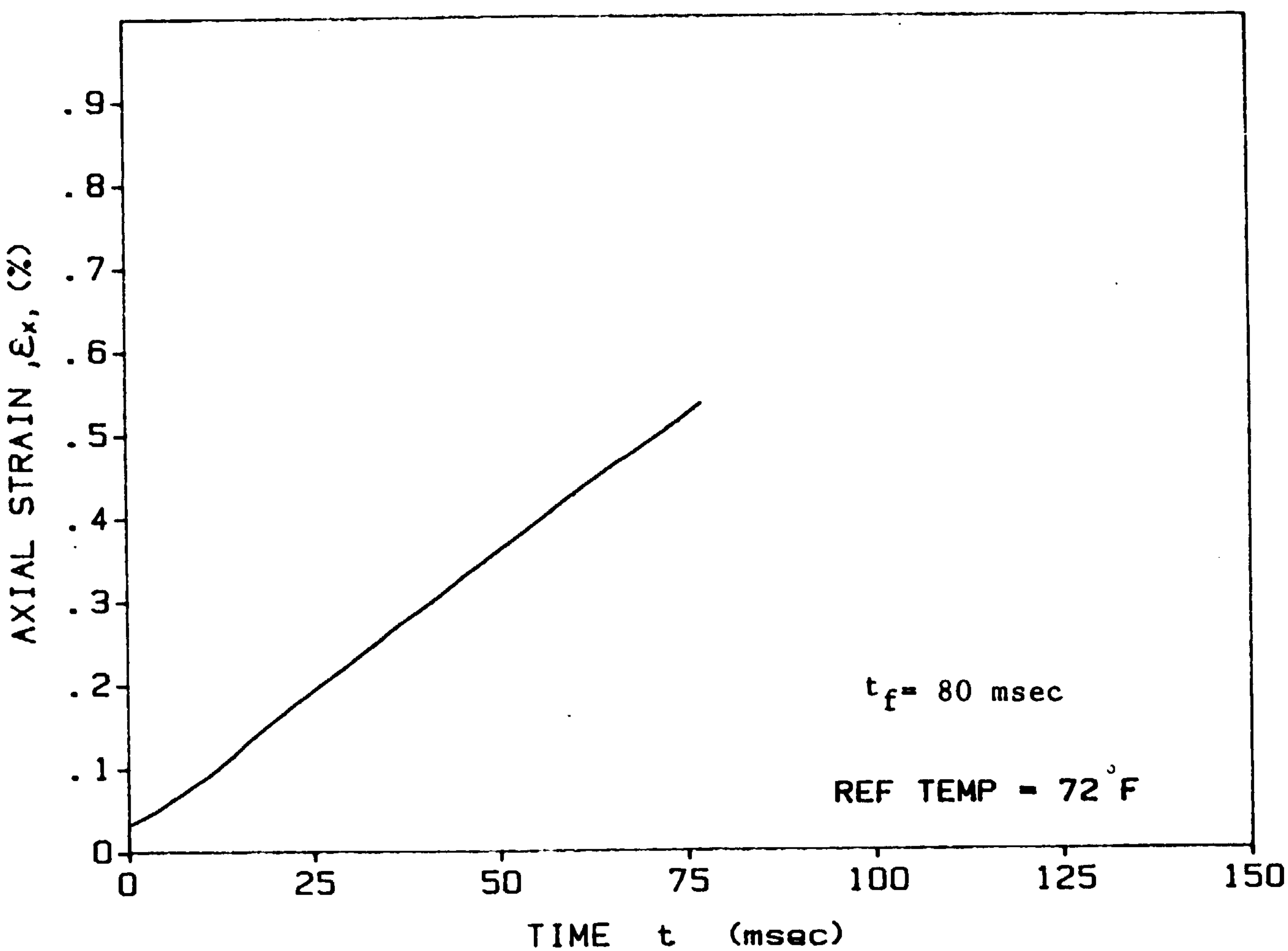


Fig. A-42. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L3 (T = 23°C (72°F))

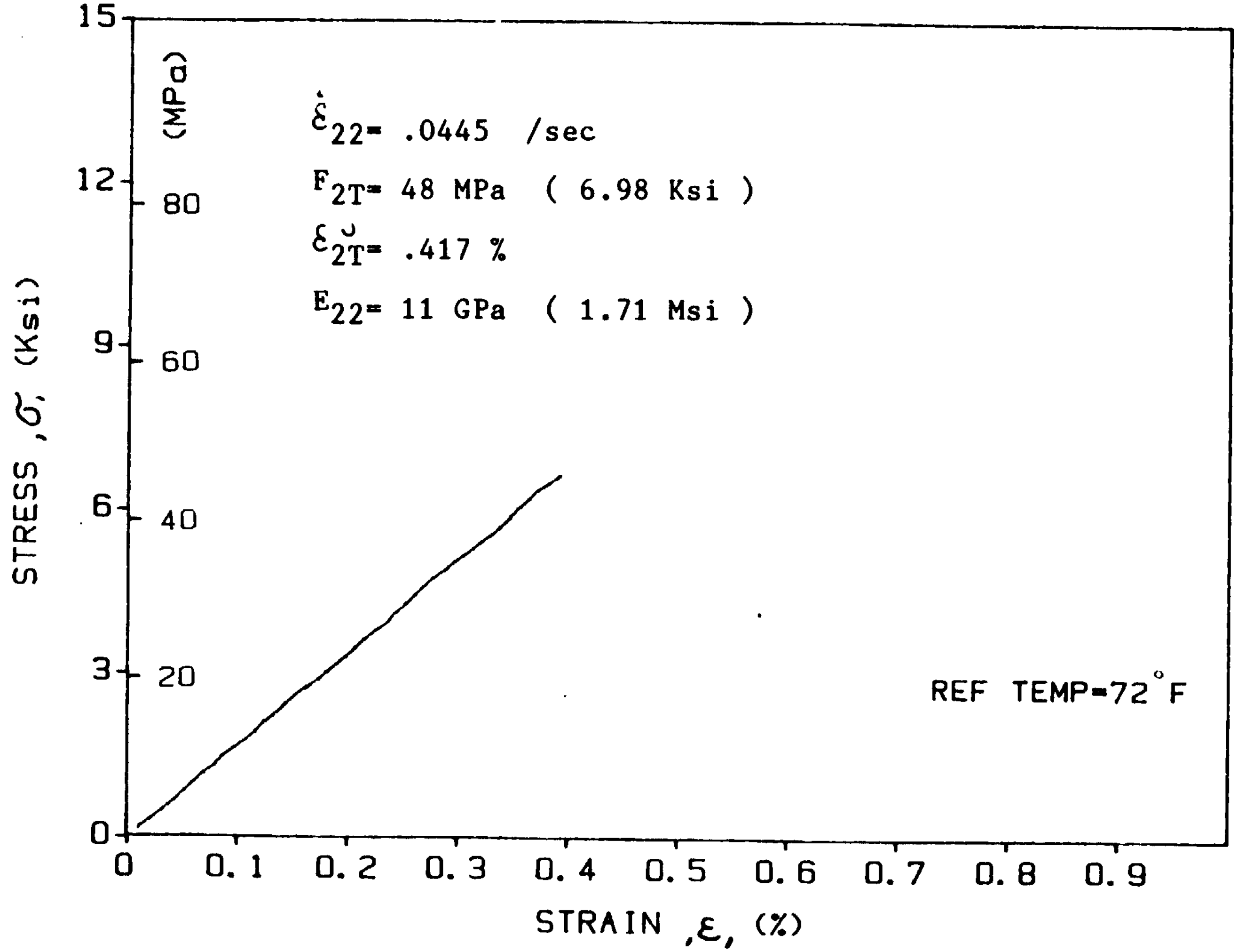


Fig. A-43. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L4 (T = 23°C (72°F))

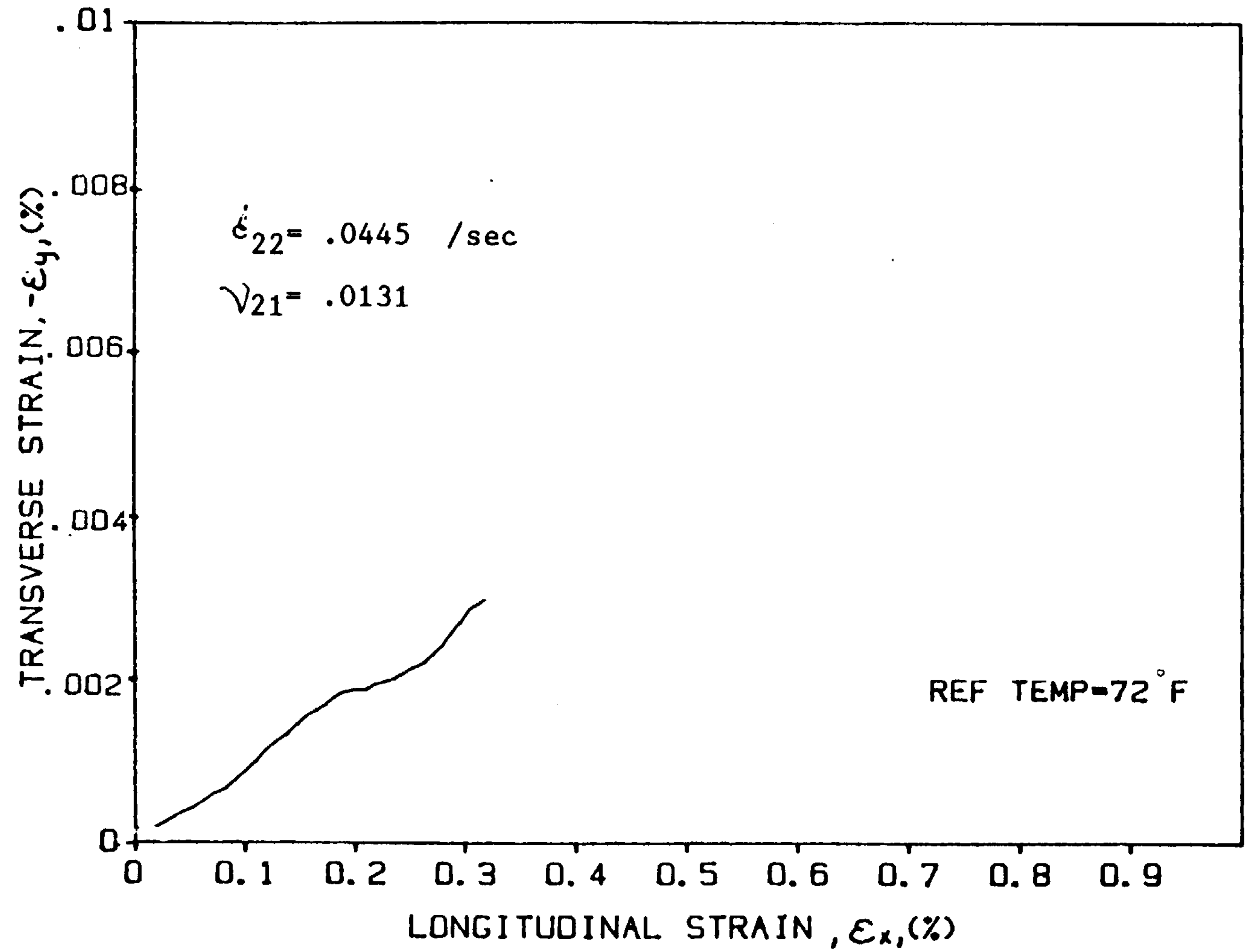


Fig. A-44. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L4 (T = 23°C (72°F))

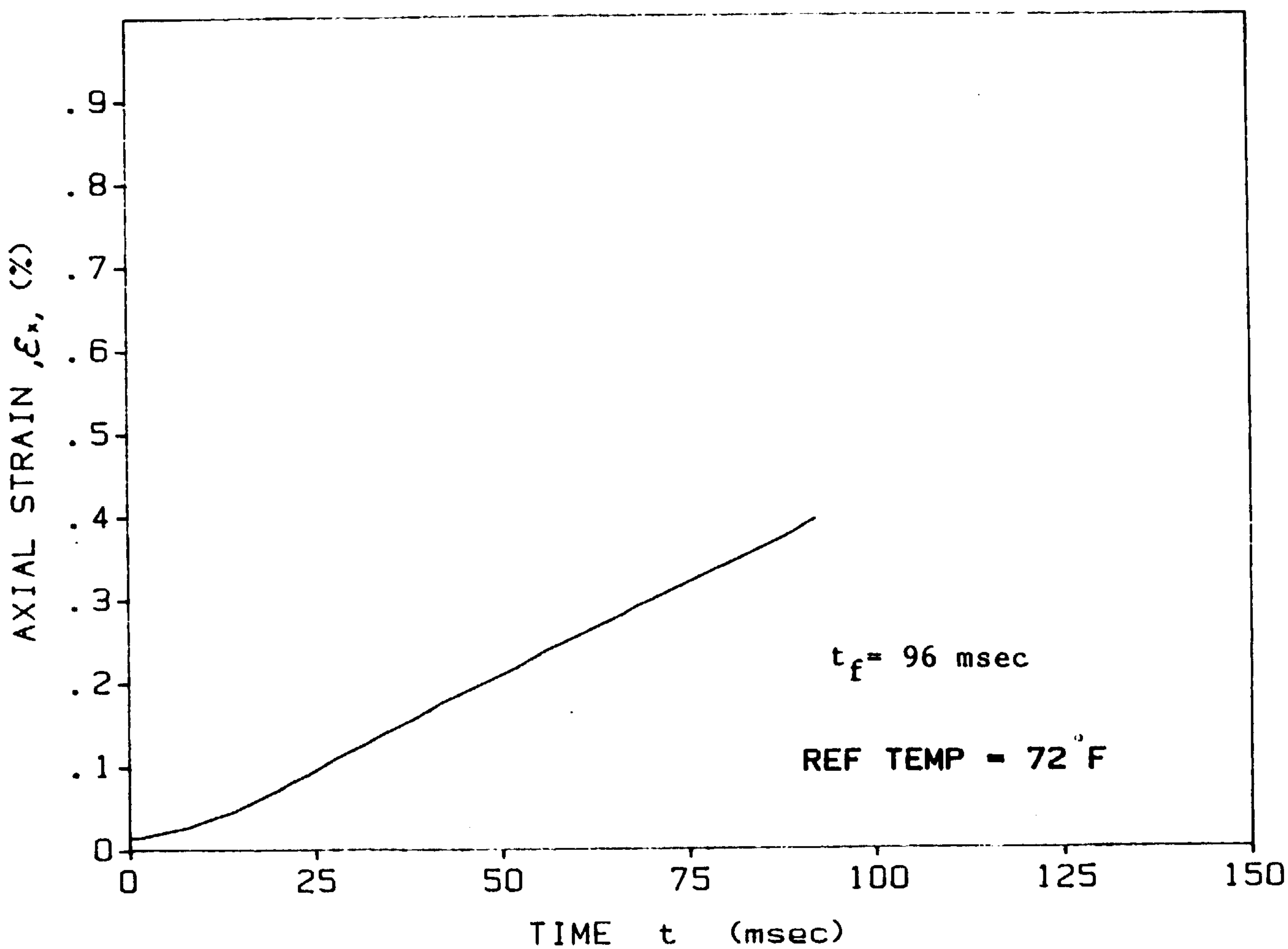


Fig. A-45. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L4 (T = 23°C (72°F))

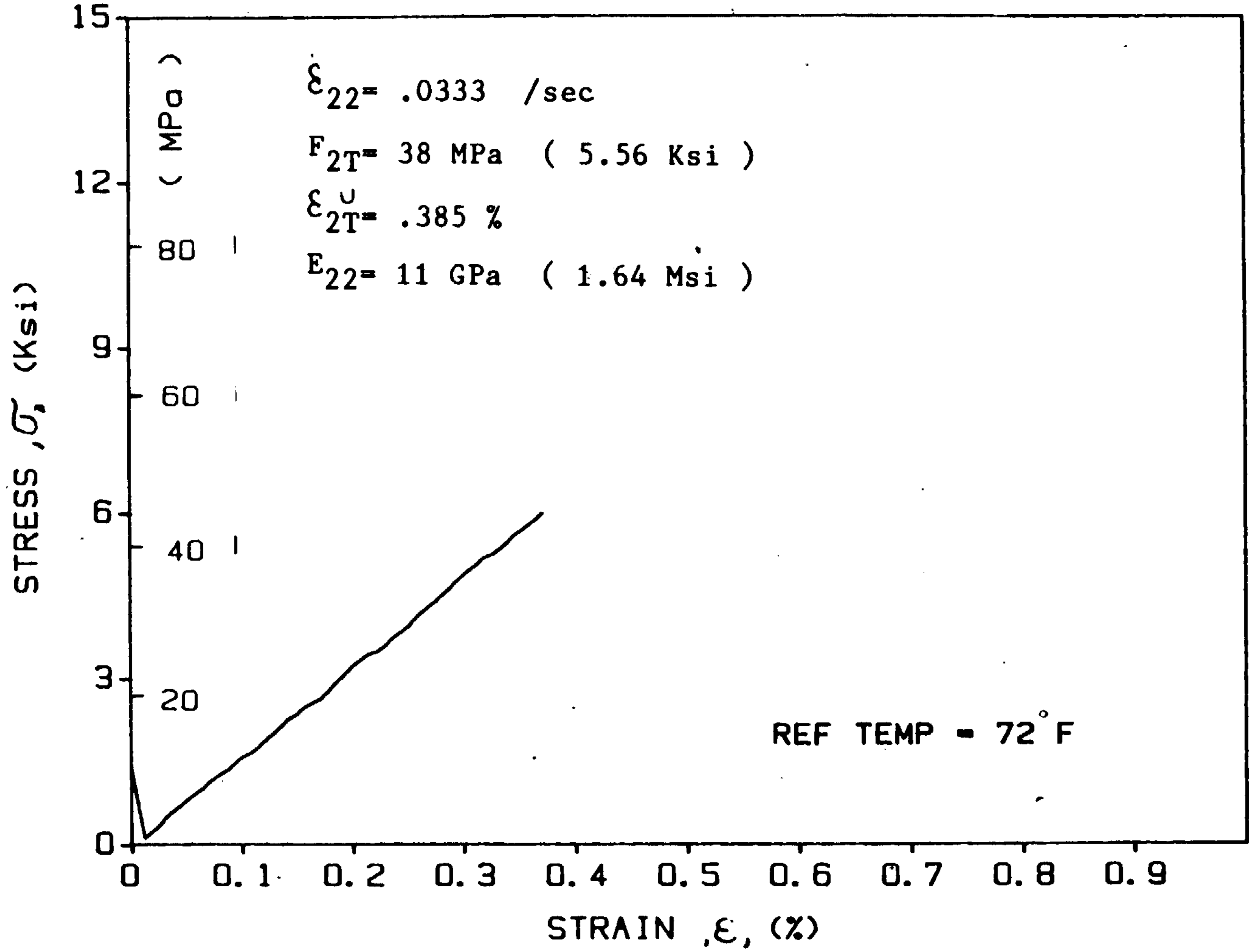


Fig. A-46. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L5 (T = 23°C (72°F))

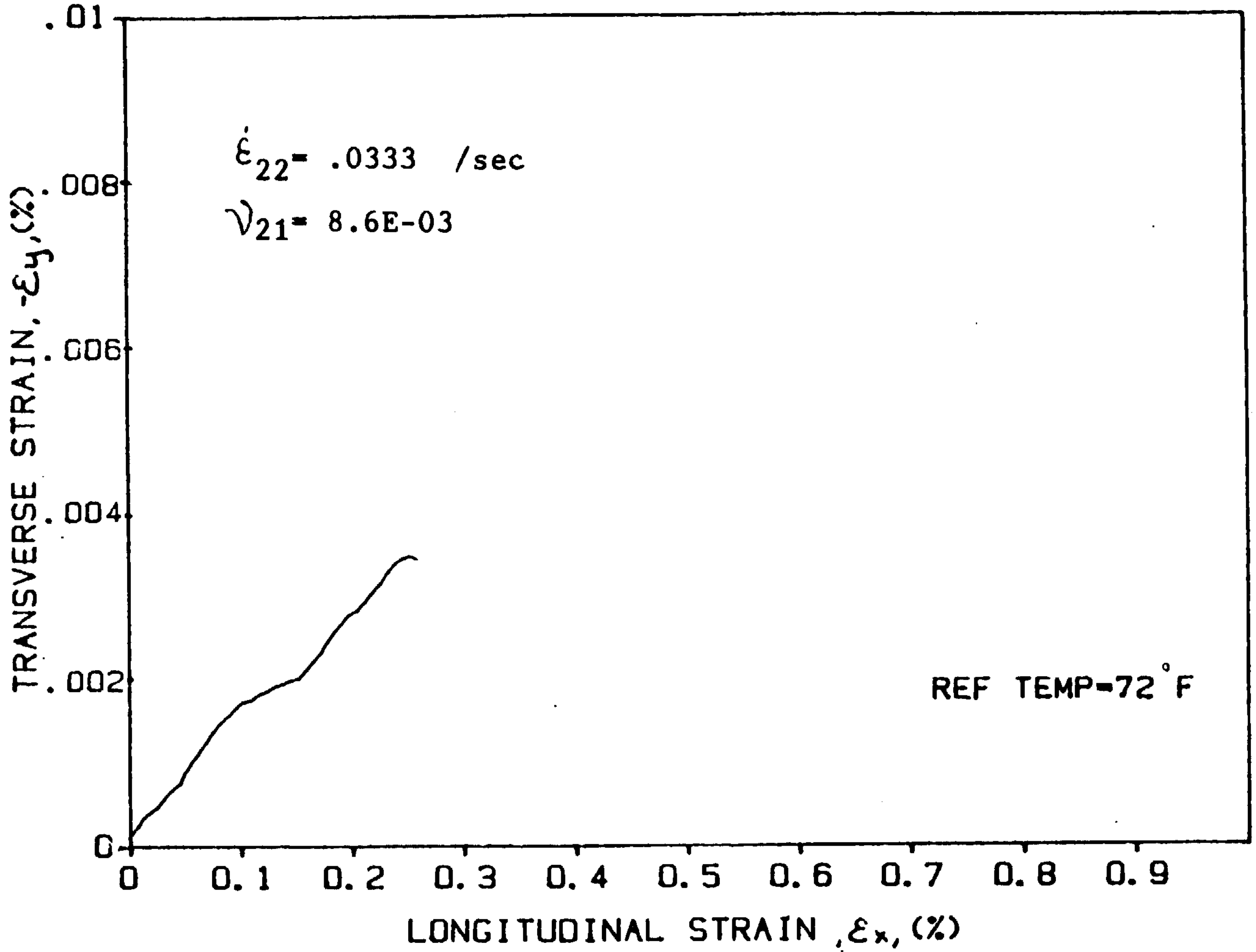


Fig. A-47. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/-2L5 (T = 23°C (72°F))

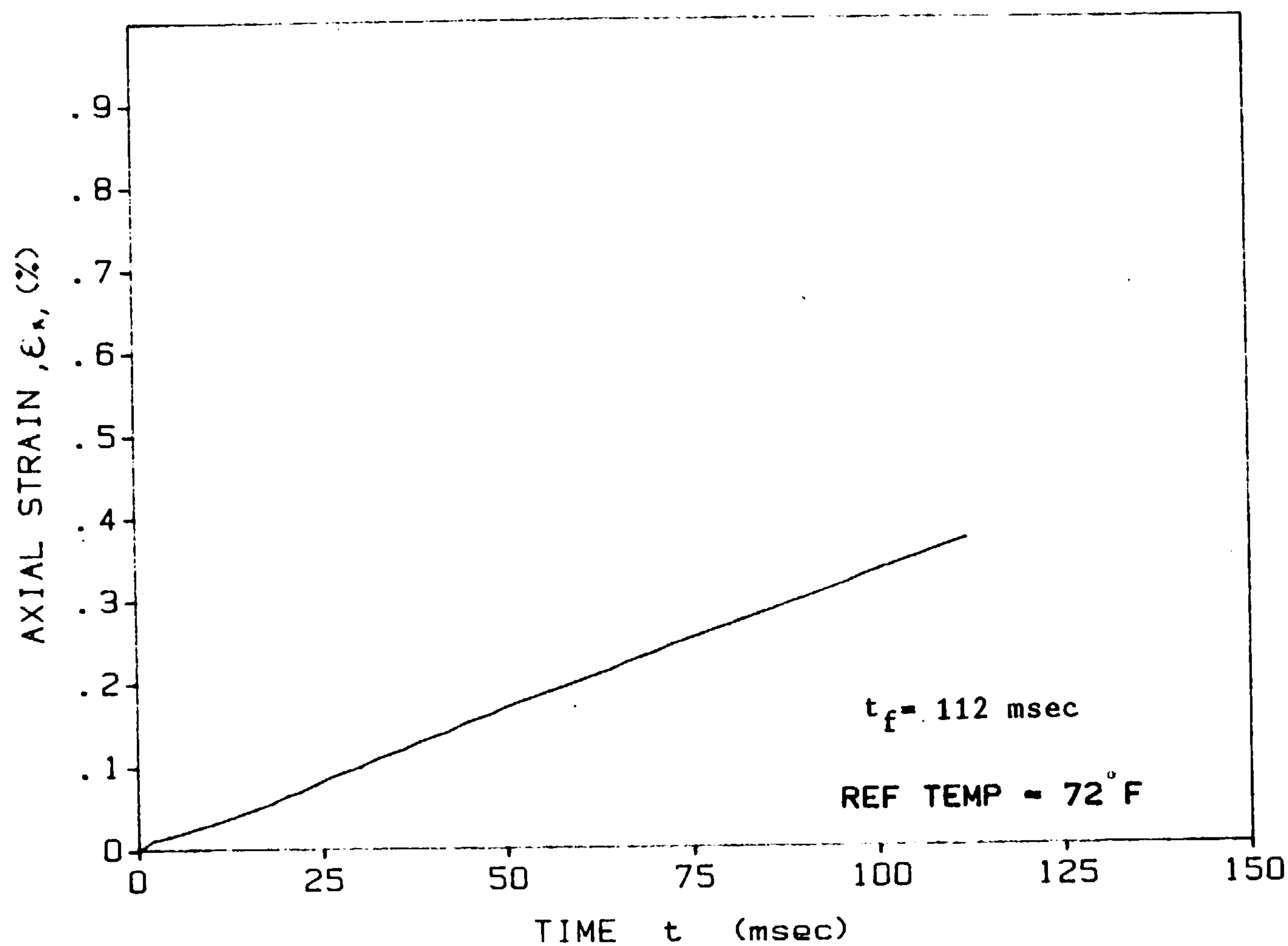


Fig. A-48. Axial Strain vs. Time for [90_8] AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L5 (T = 23°C (72°F))

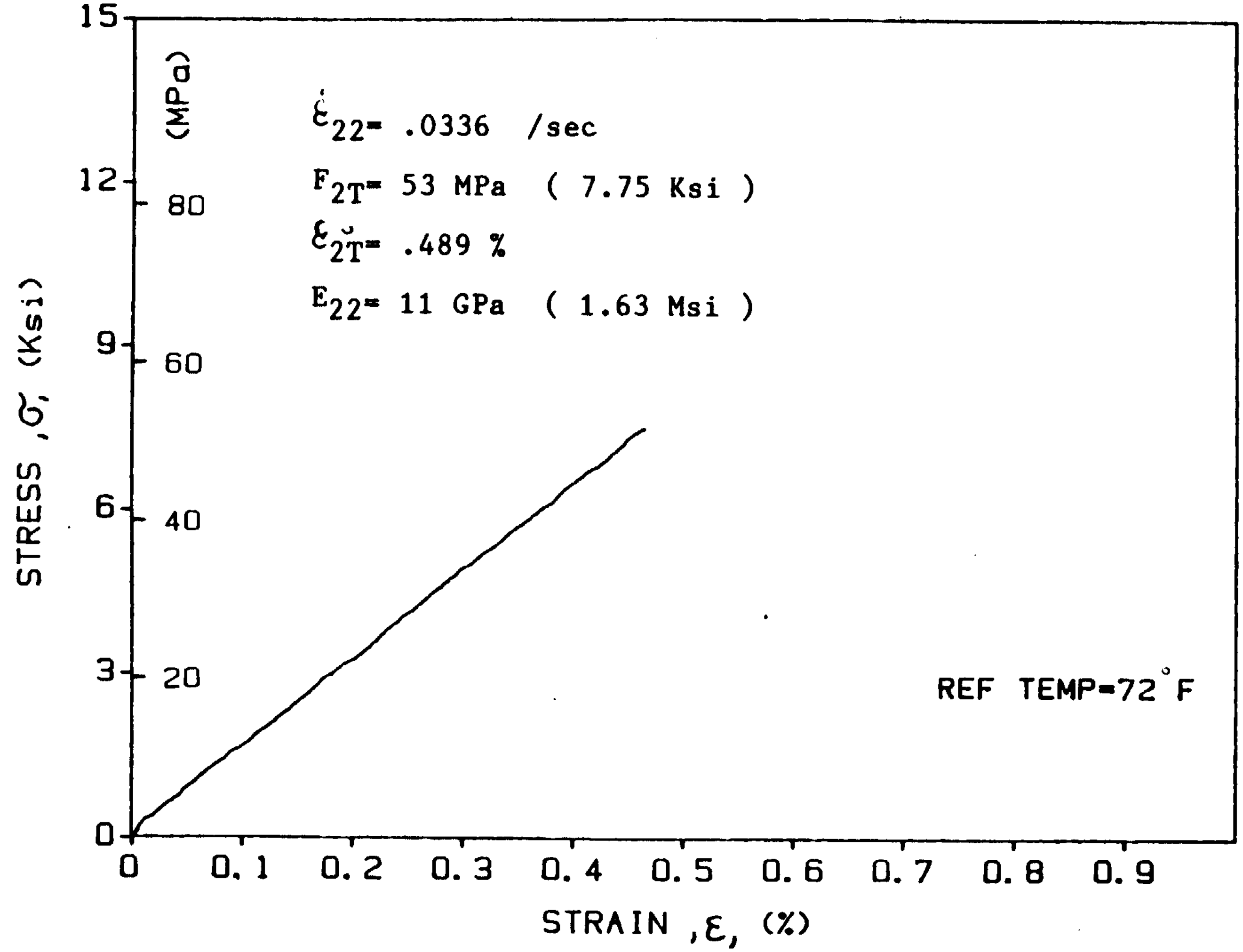


Fig. A-49. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L6 (T = 23°C (72°F))

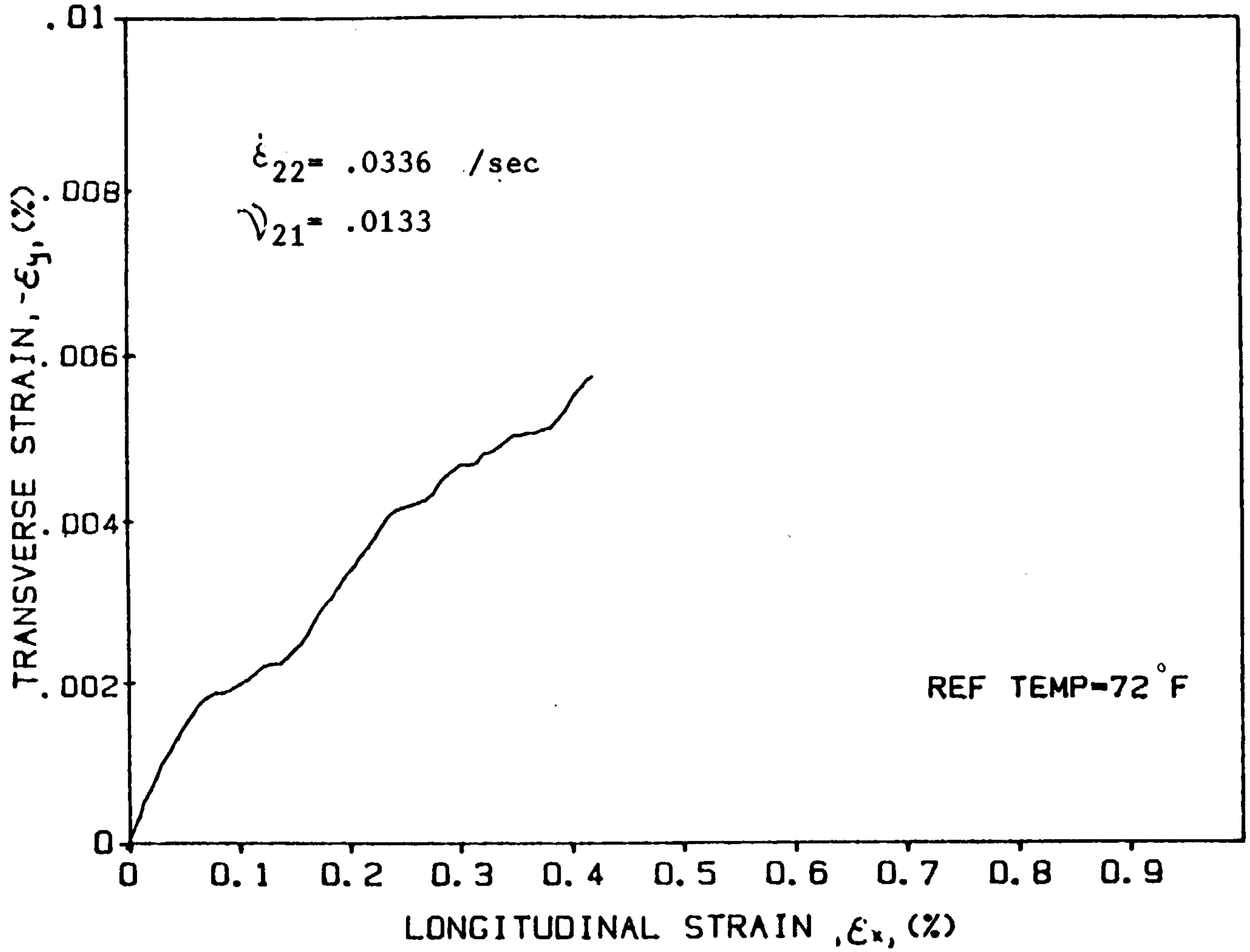


Fig. A-50. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/-2L6 (T =23°C (72°F))

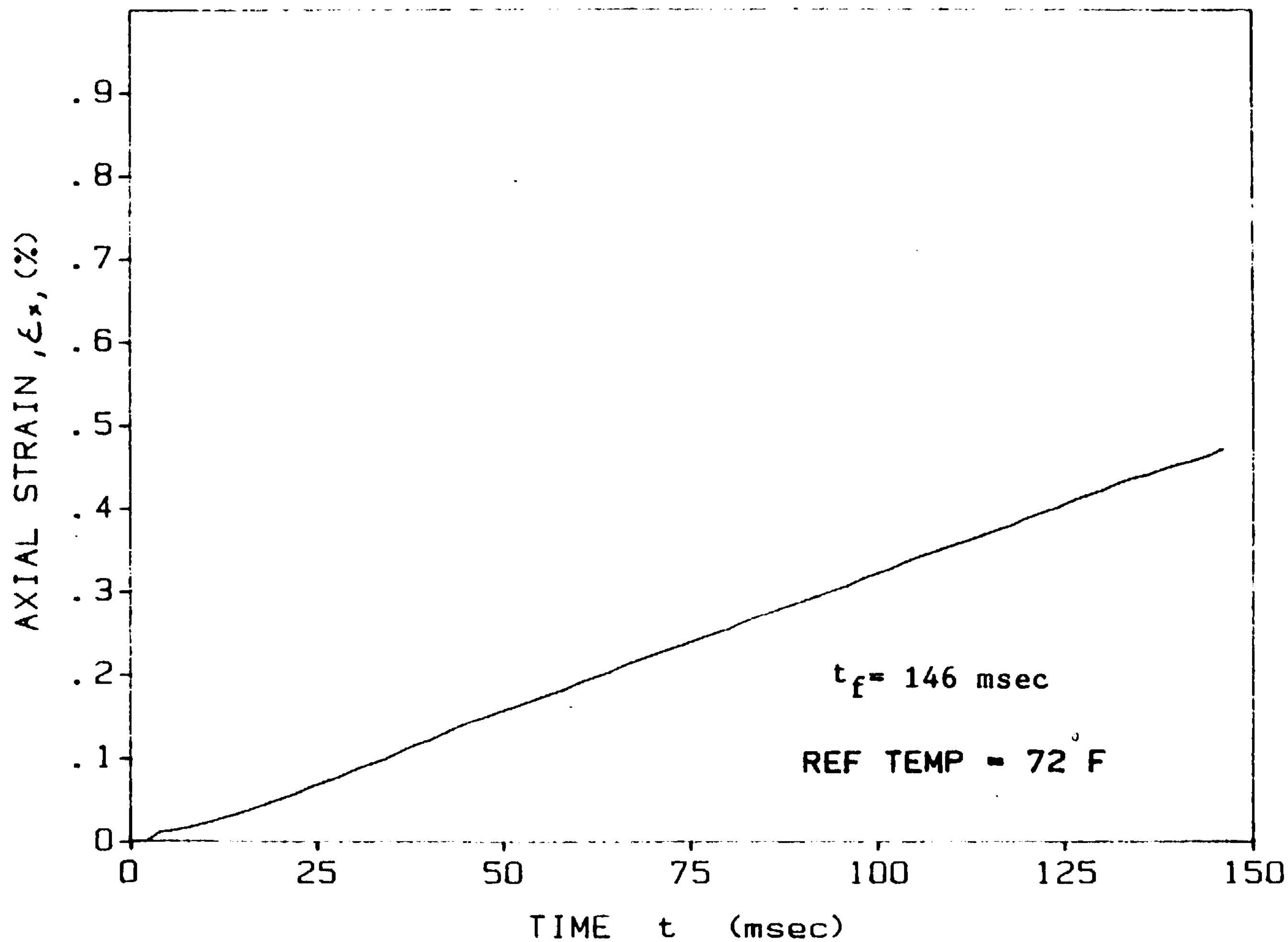


Fig. A-51. Axial Strain vs. Time for [90_8] AS4/3501-6 Graphite/Epoxy, Spec. 90/-2L6 (T = 23°C (72°F))

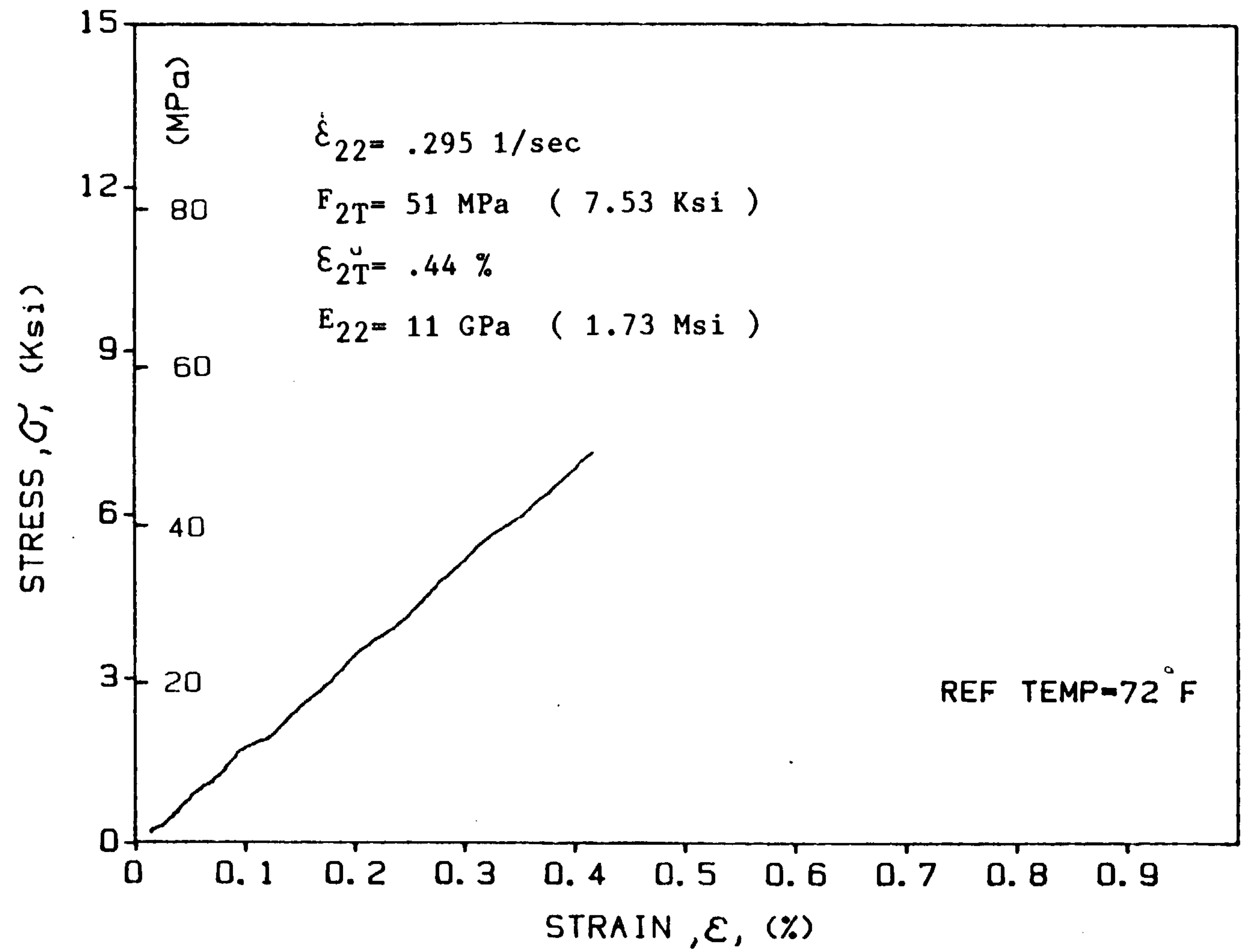


Fig. A-52. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L1 (T = 23°C (72°F))

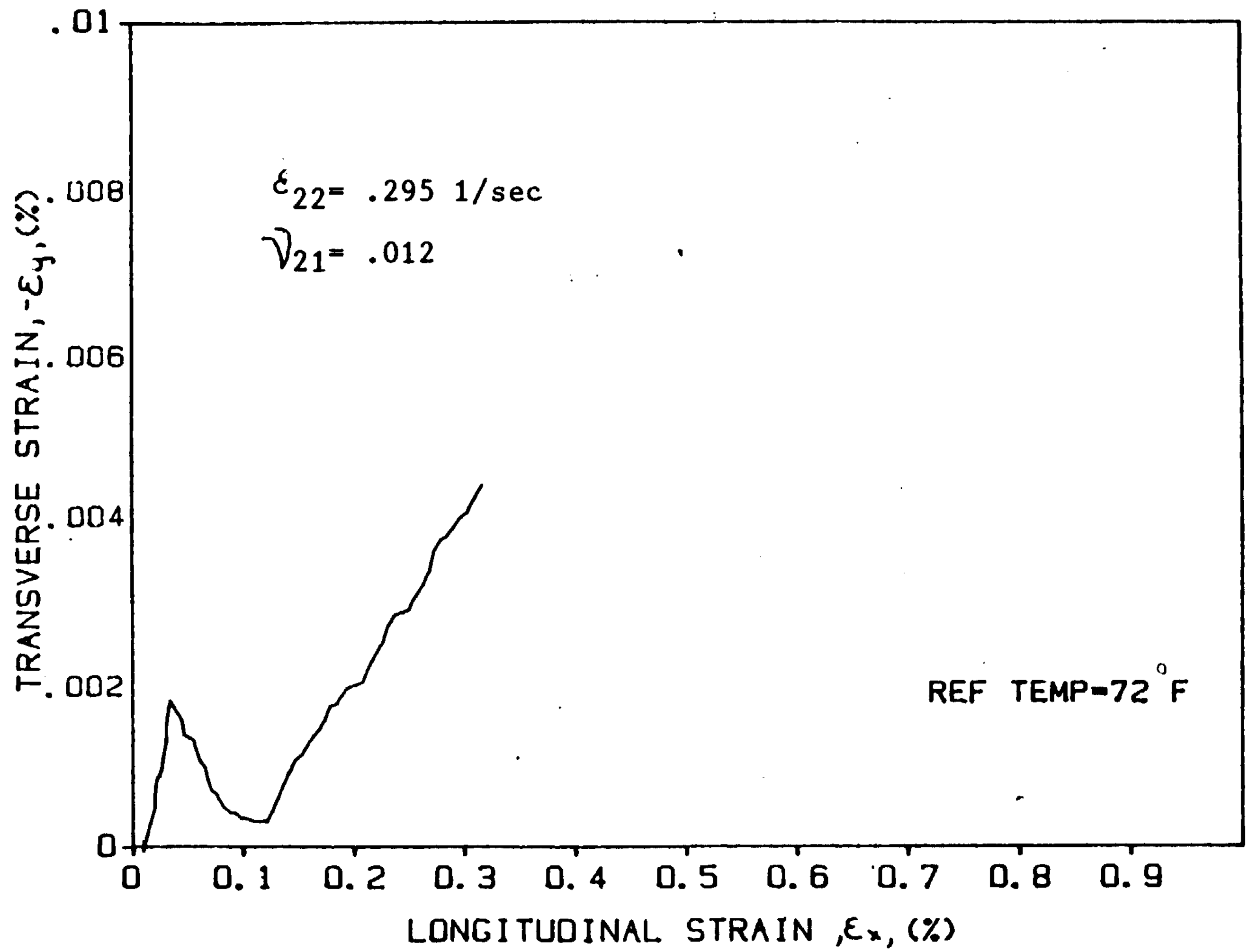


Fig. A-53. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L1 (T = 23°C (72°F))

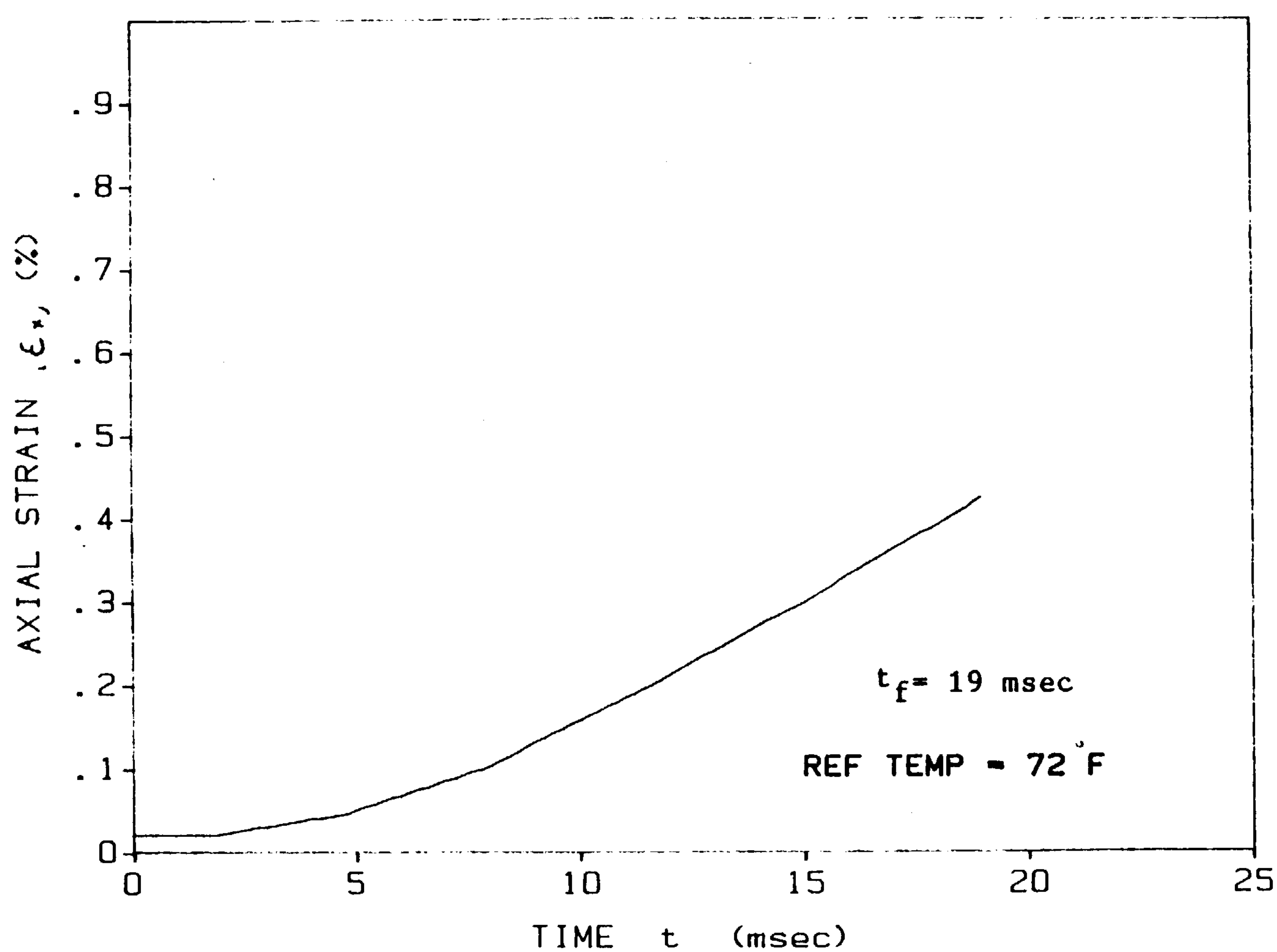


Fig. A-54. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L1 (T = 23°C (72°F))

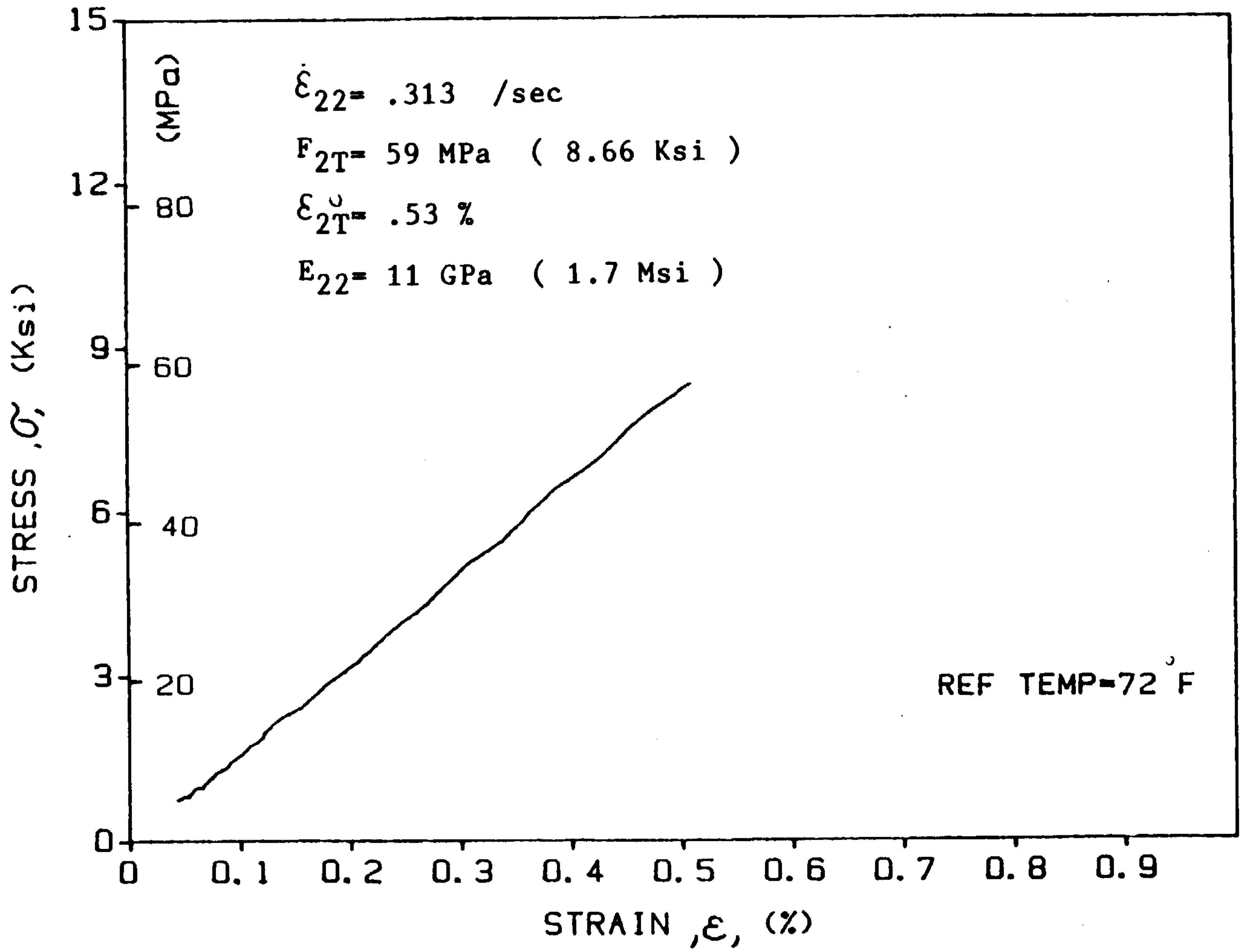


Fig. A-55. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L2 (T = 23°C (73°F))

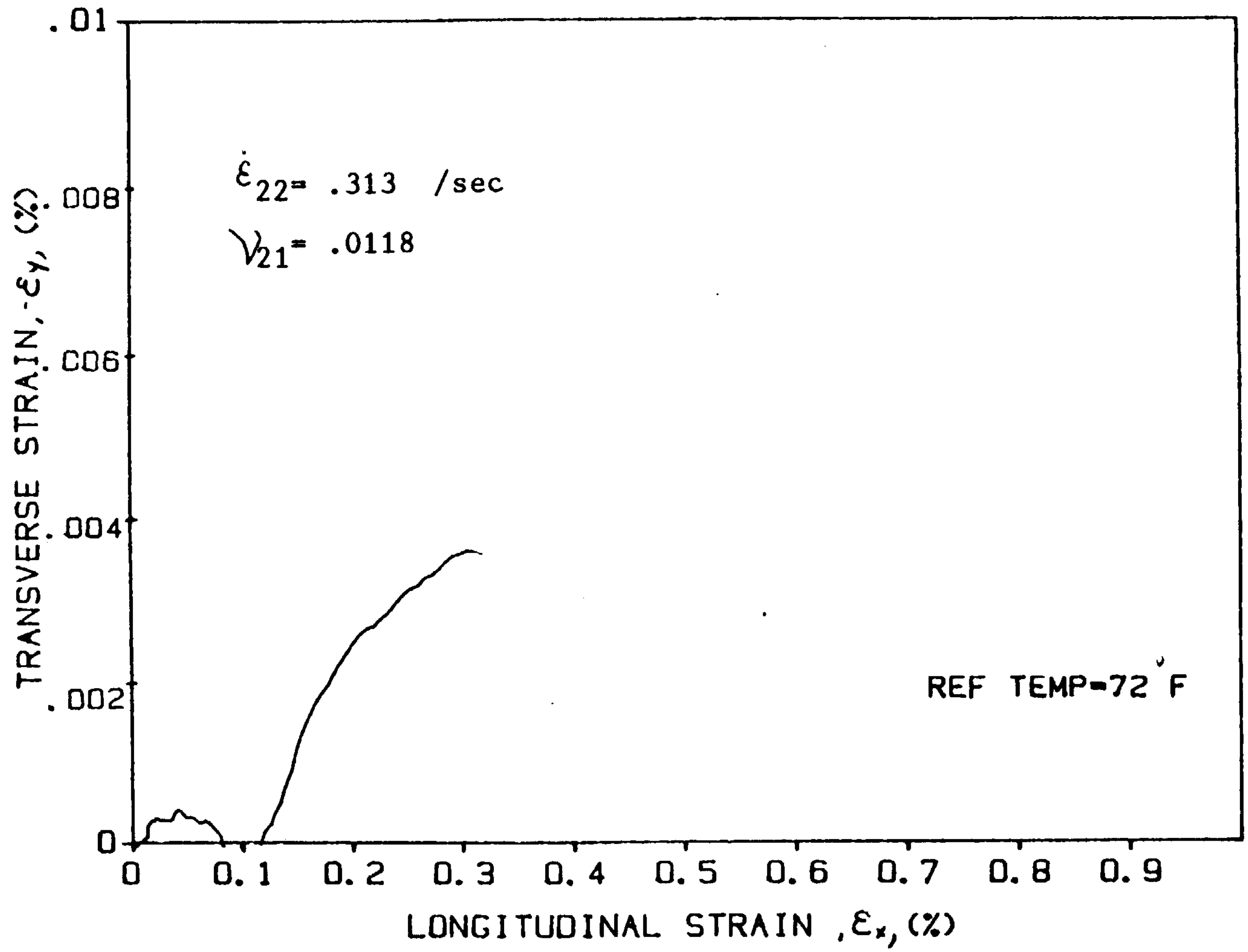


Fig. A-56. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L2 (T = 23°C (72°F))

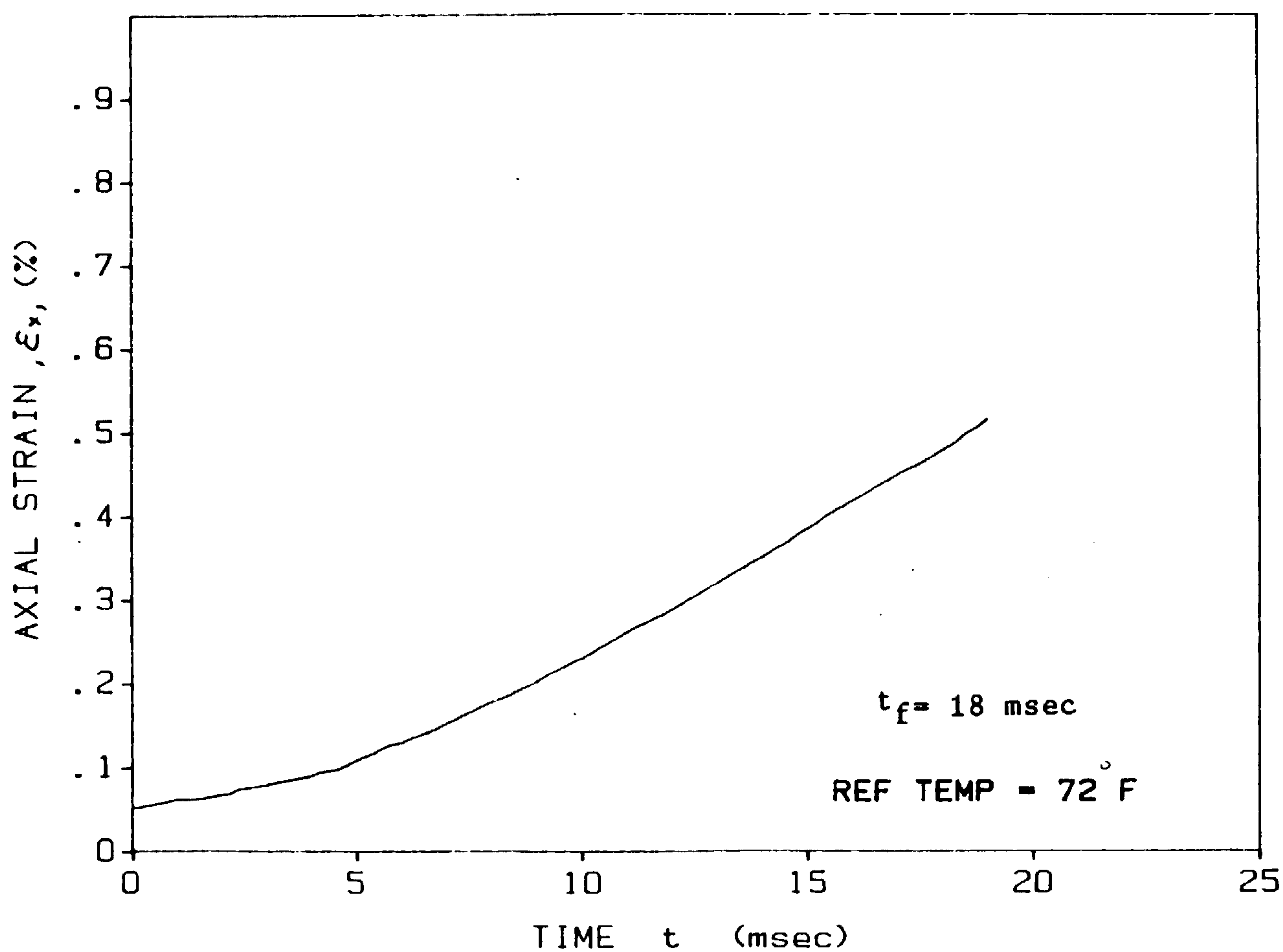


Fig. A-57. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L2 (T = 23°C (72°F))

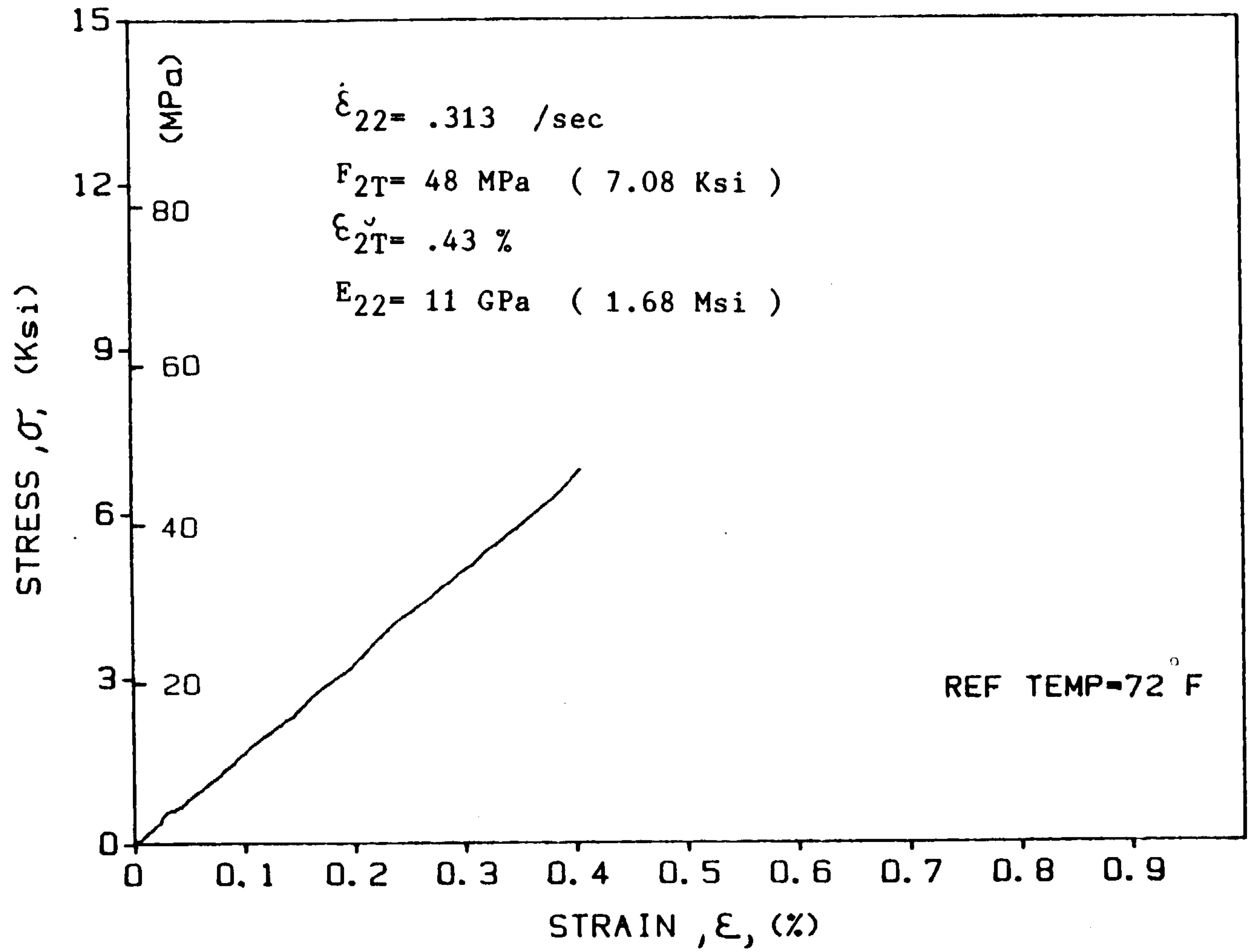


Fig. A-58. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L3 (T = 23°C (72°F))

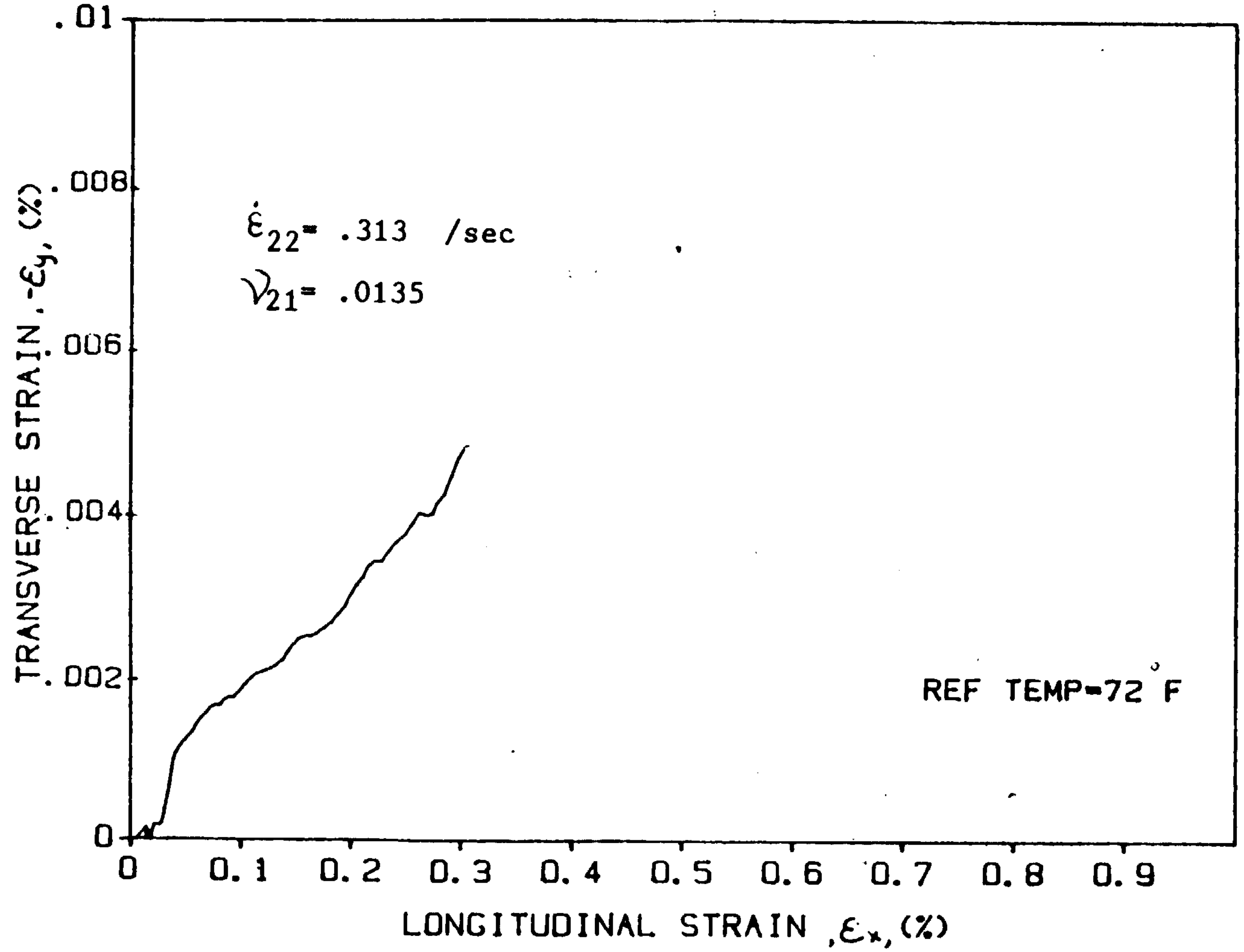


Fig. A-59. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/-1L3 (T = 23°C (72°F))

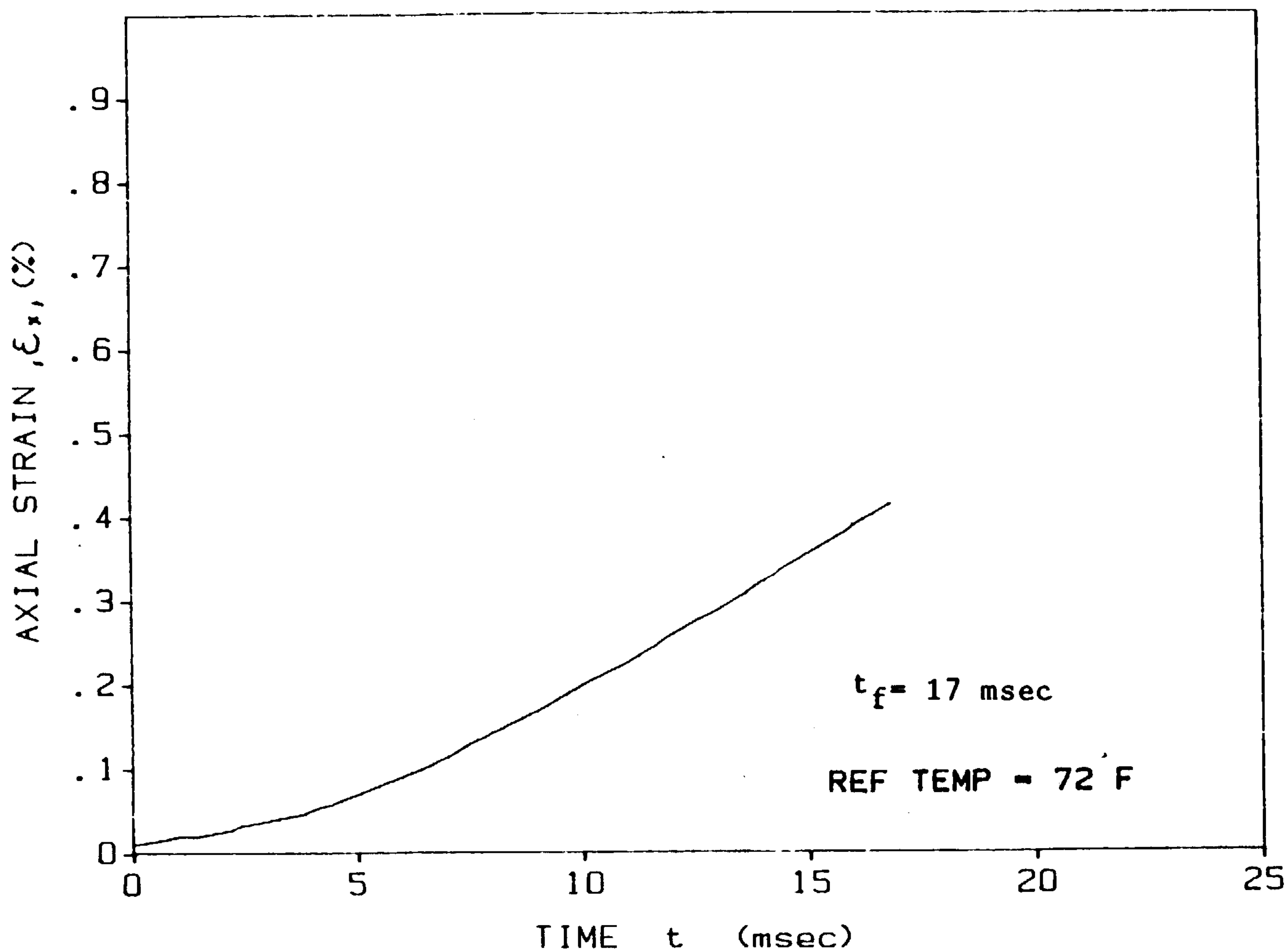


Fig. A-60. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L3 (T = 23°C (72°F))

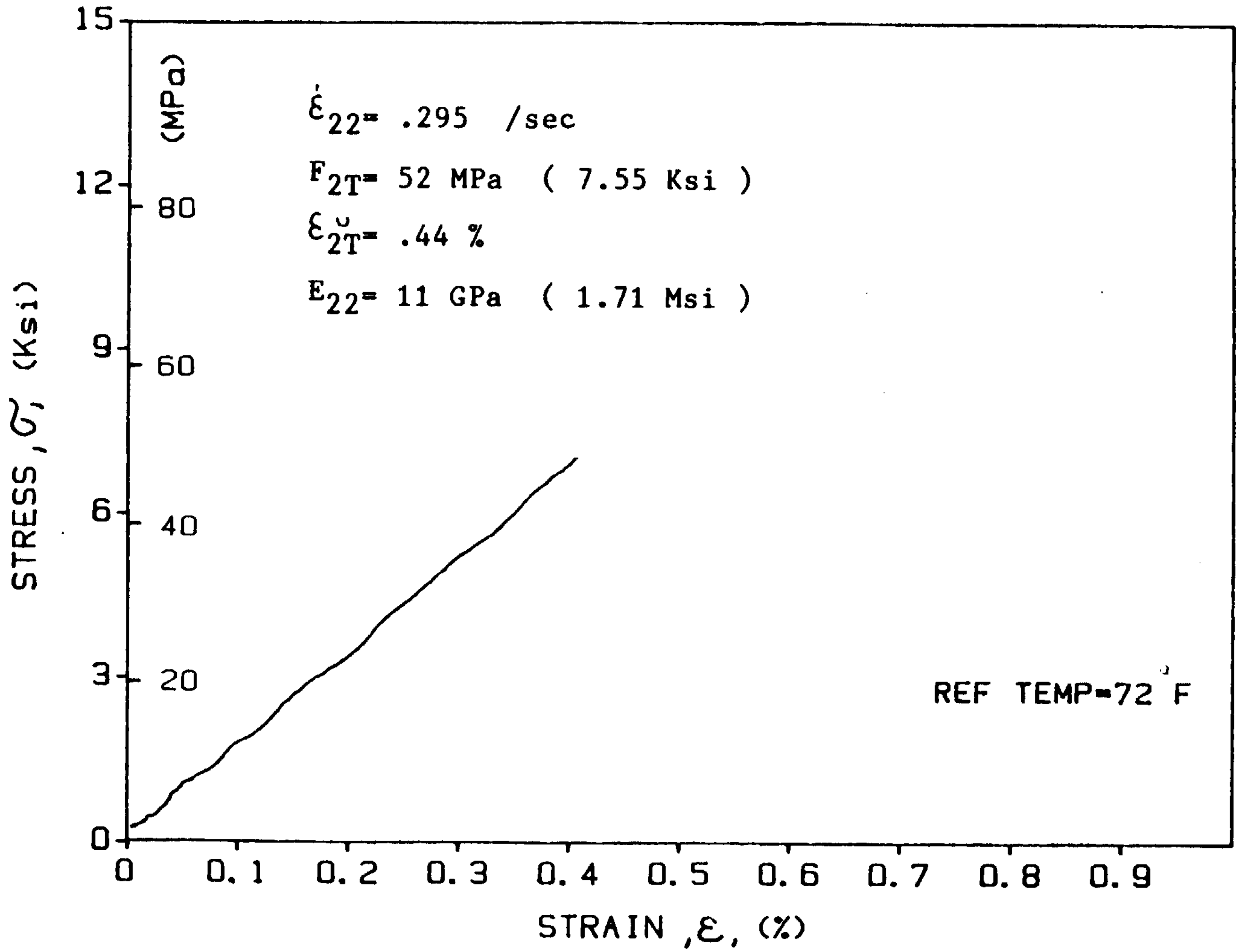


Fig. A-61. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L4 (T = 23°C (72°F))

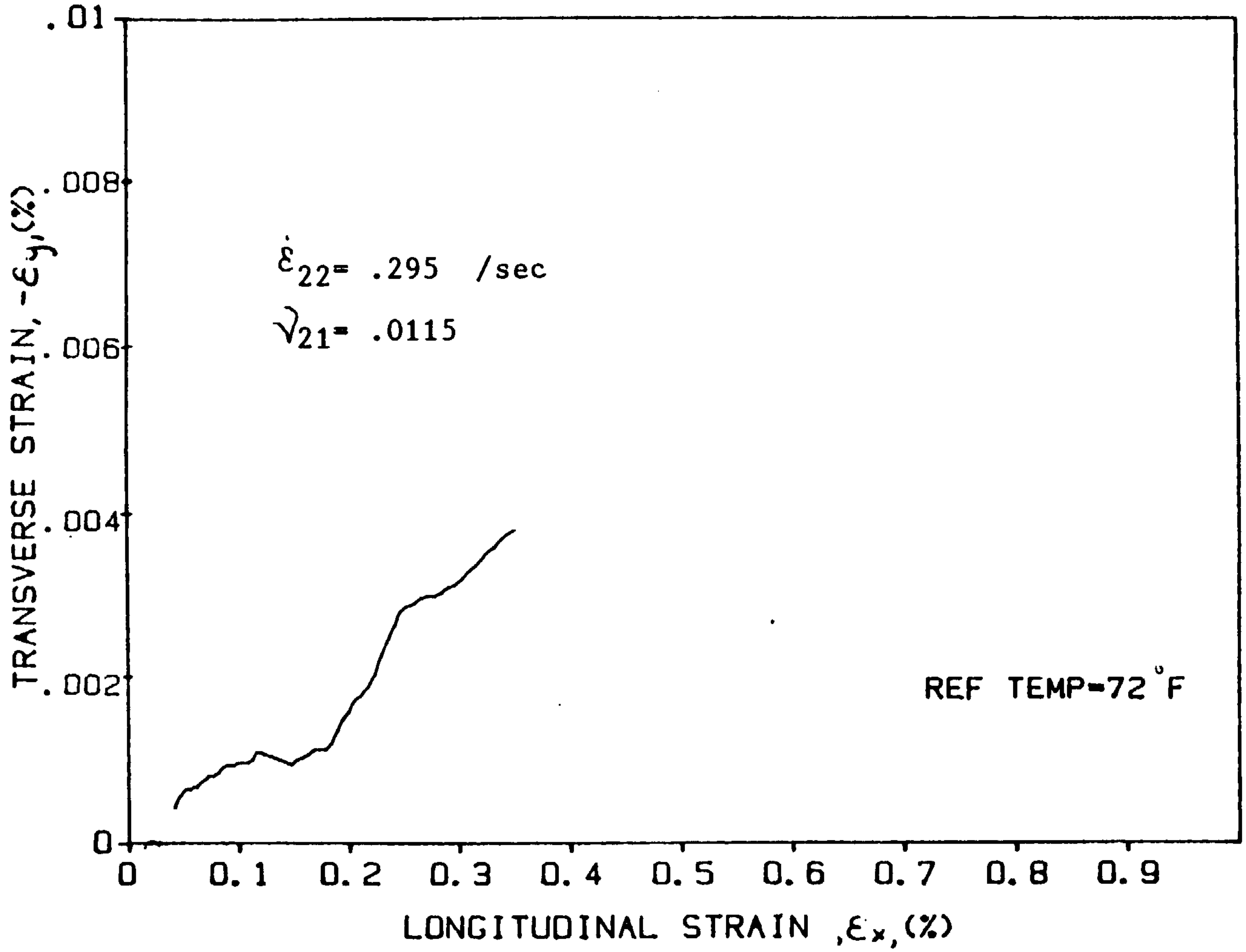


Fig. A-62. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L4 (T = 23°C (72°F))

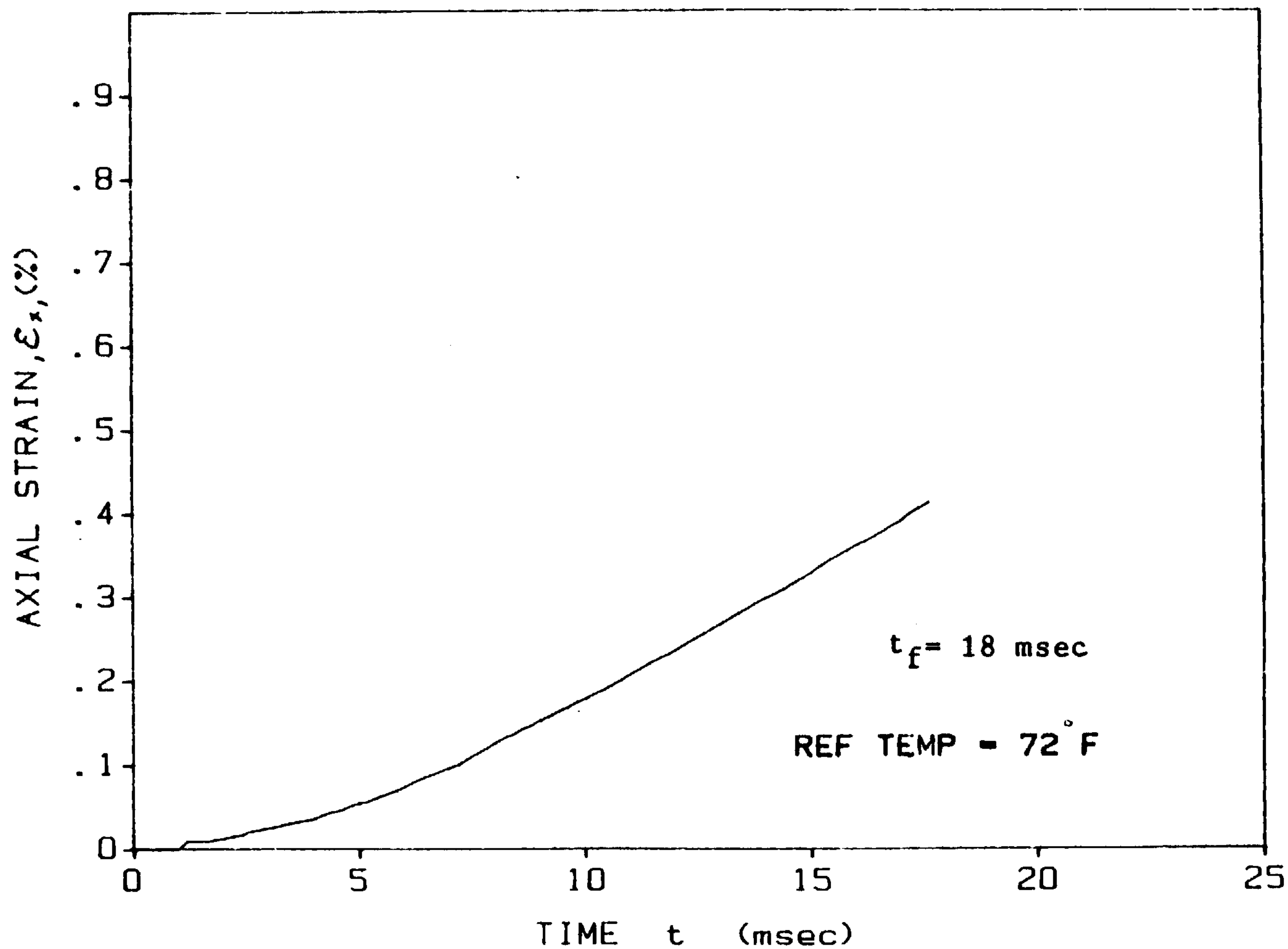


Fig. A-63. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L4 (T = 23°C (72°F))

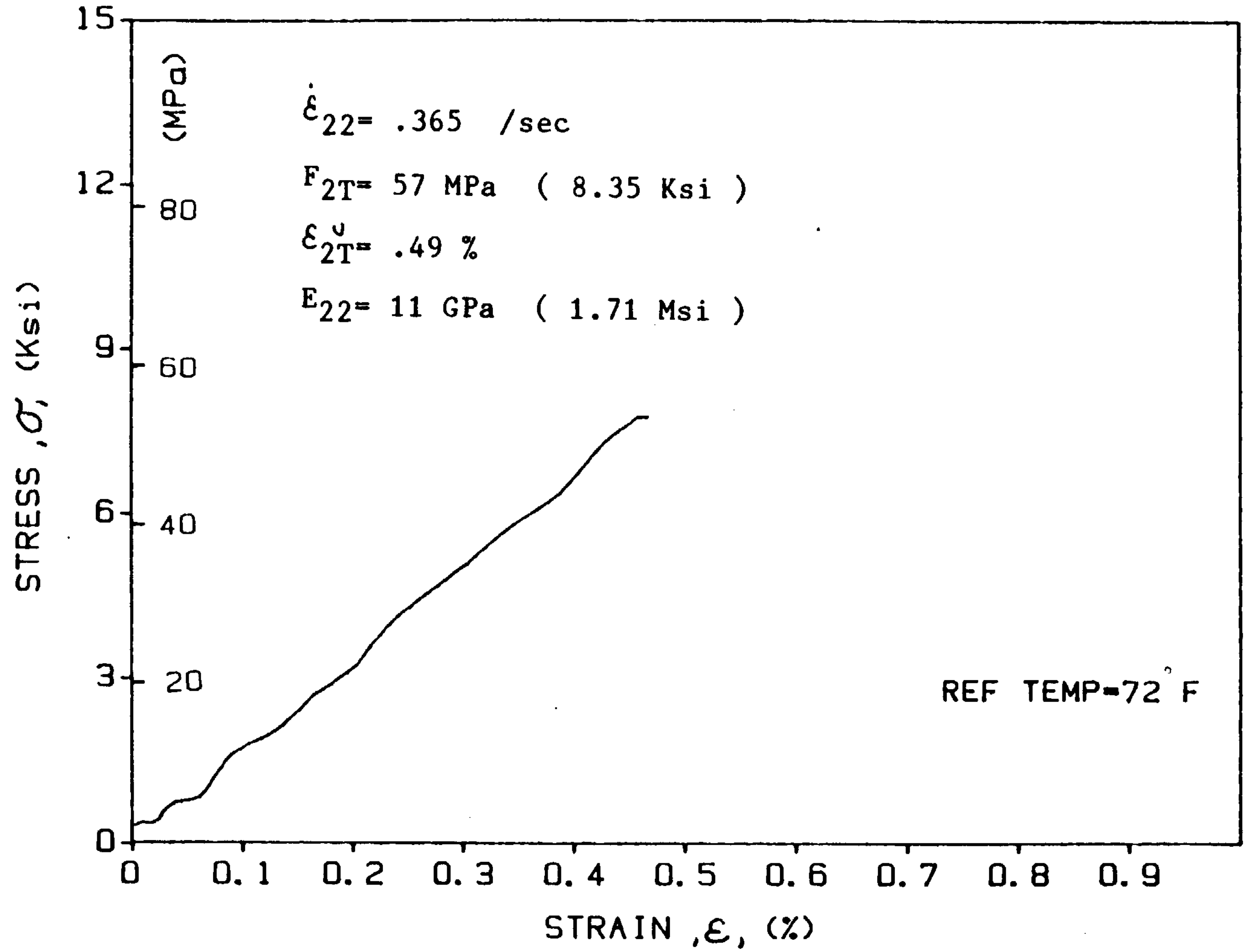


Fig. A-64. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L5 (T = 23°C (72°F))

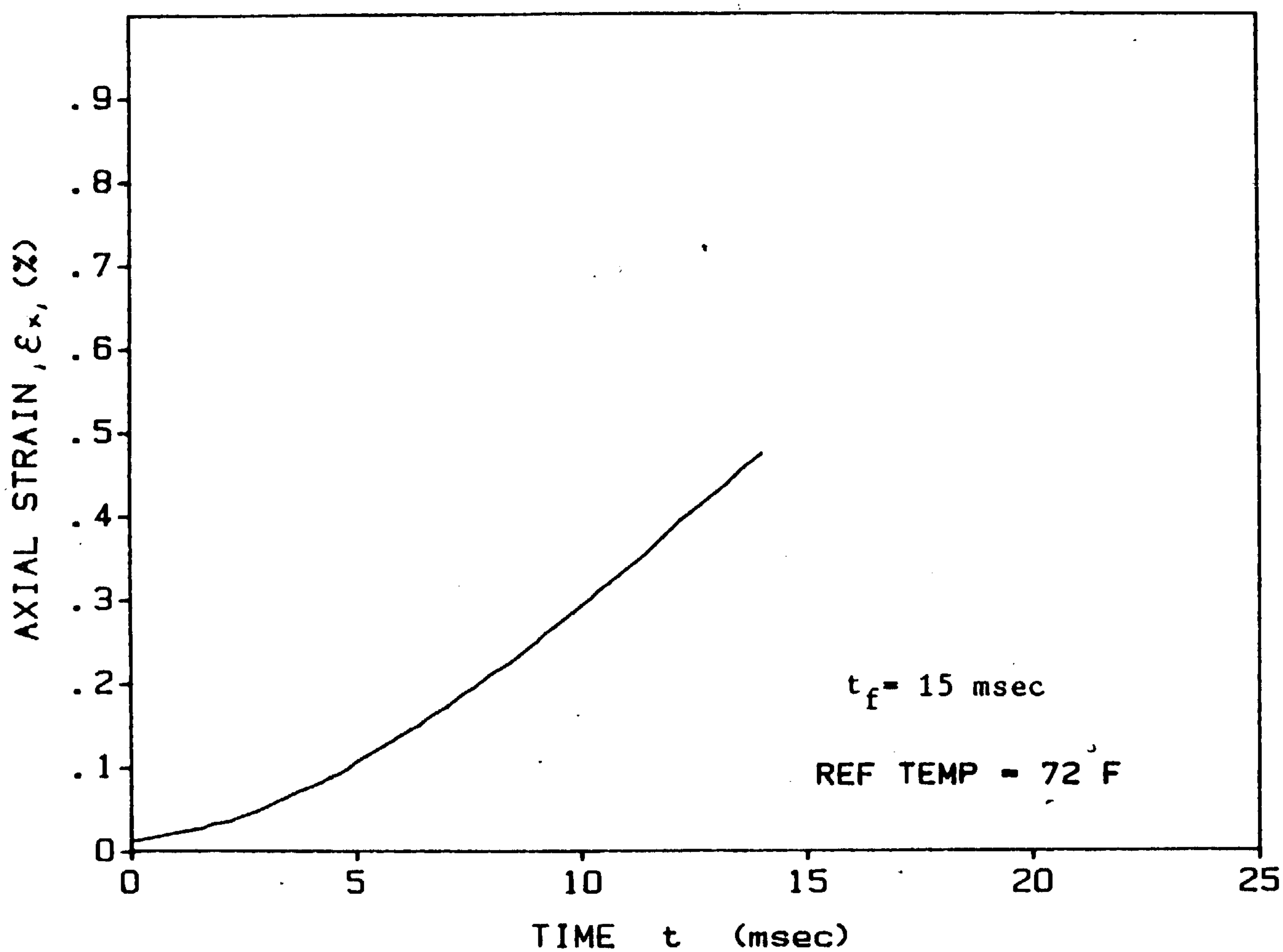


Fig. A-65. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L5 (T = 23°C (72°F))

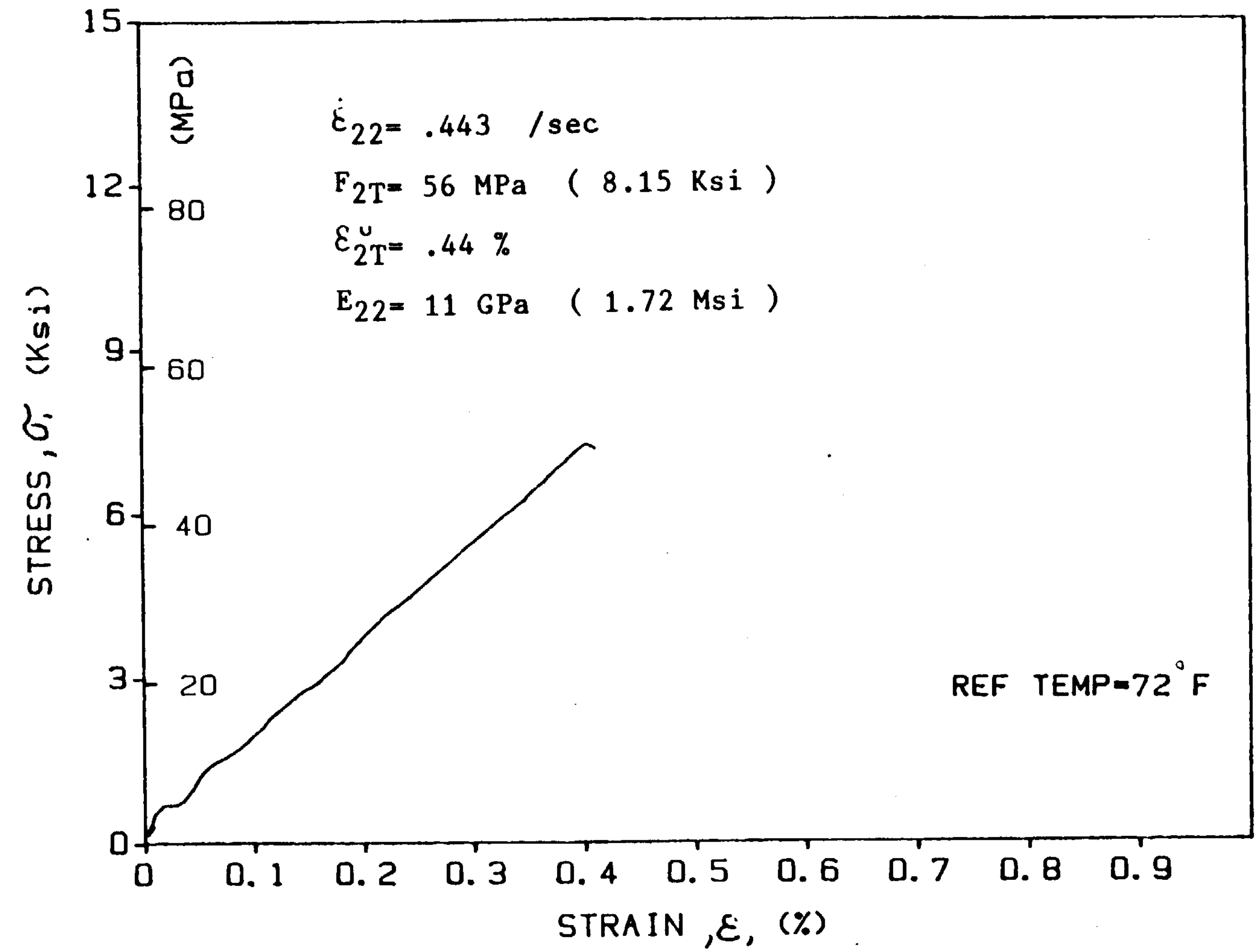


Fig. A-66. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L6 (T = 23°C (72°F))

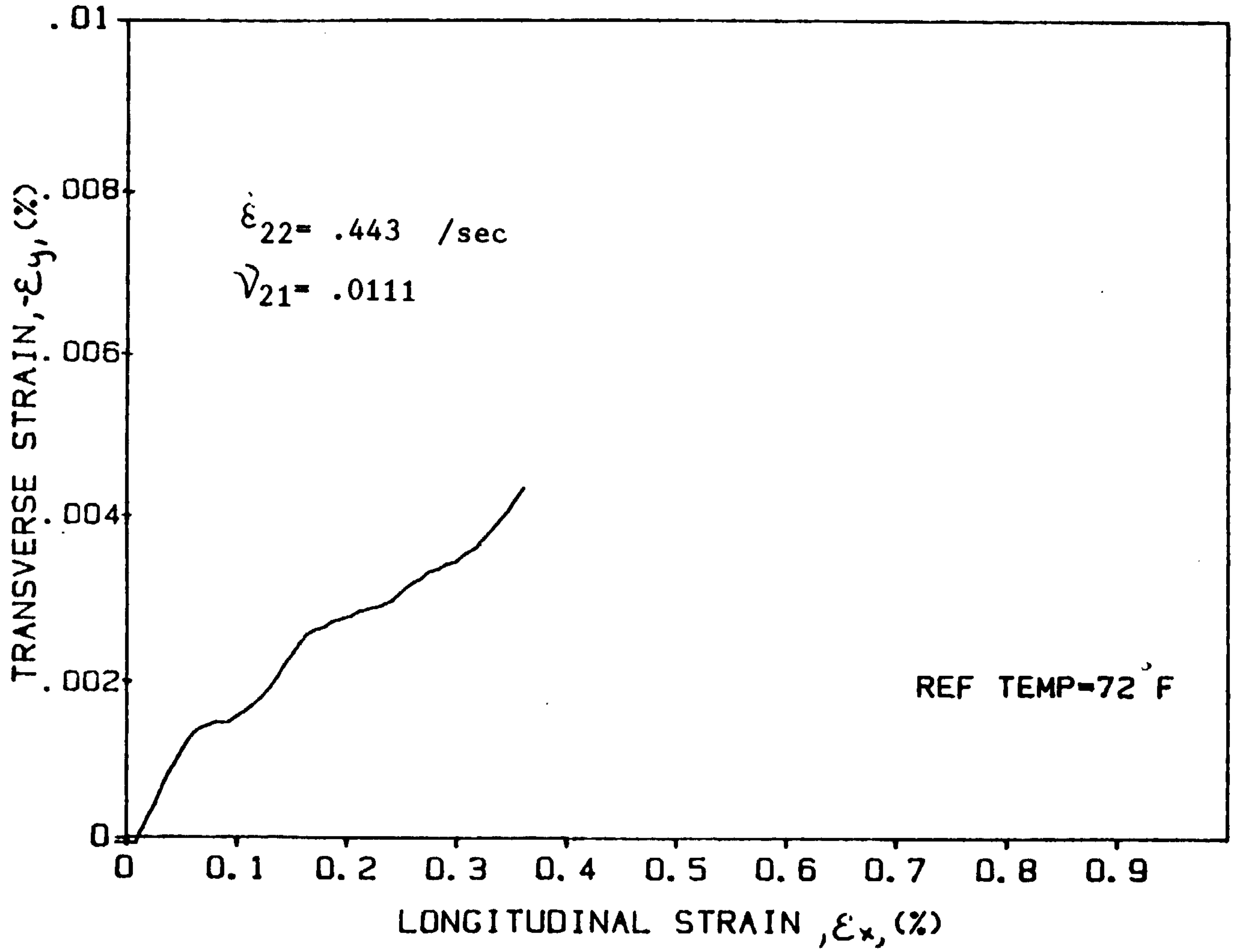


Fig. A-67. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L6 (T = 23°C (72°F))

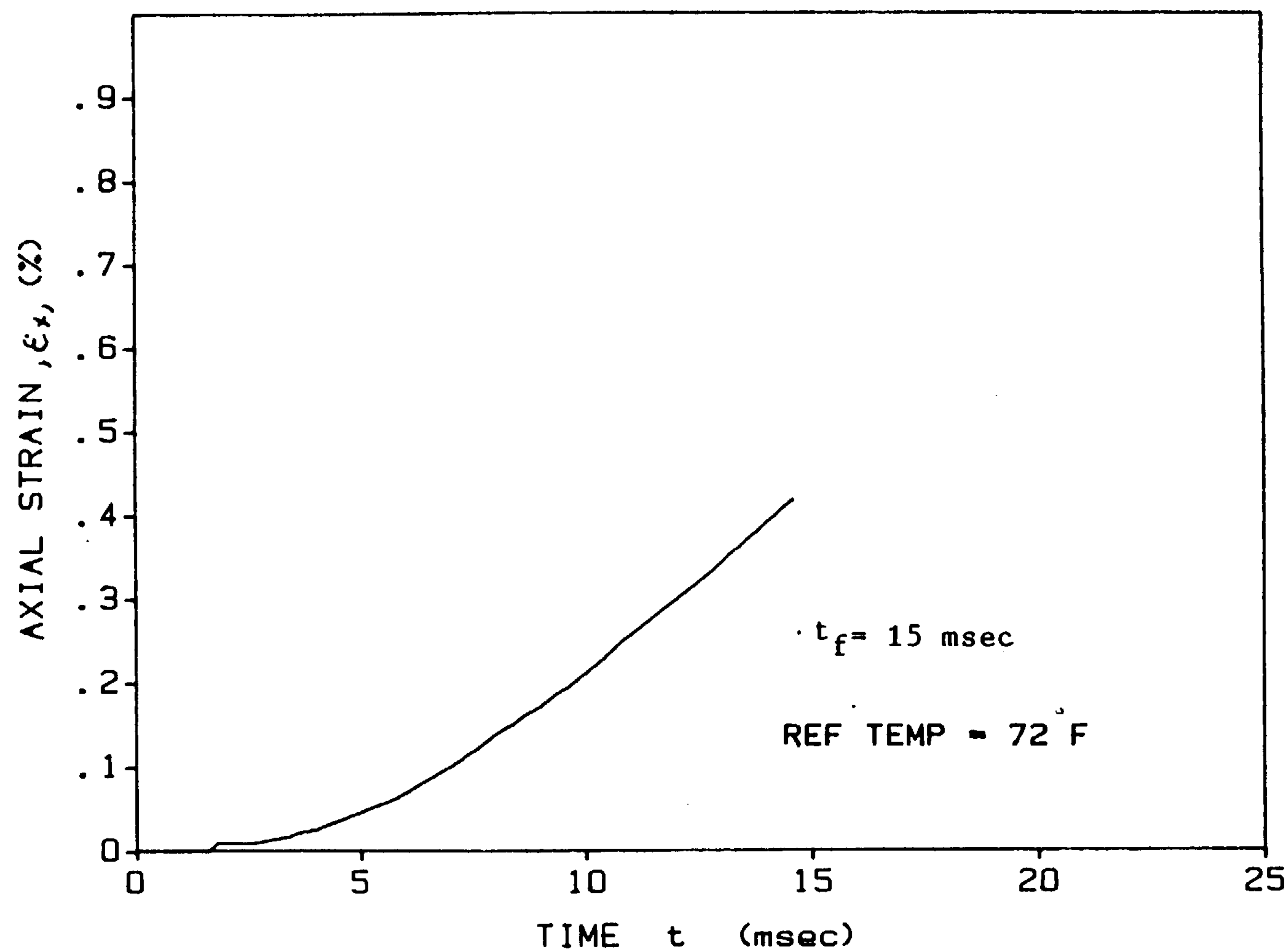


Fig. A-68. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L6 (T = 23°C (72°F))

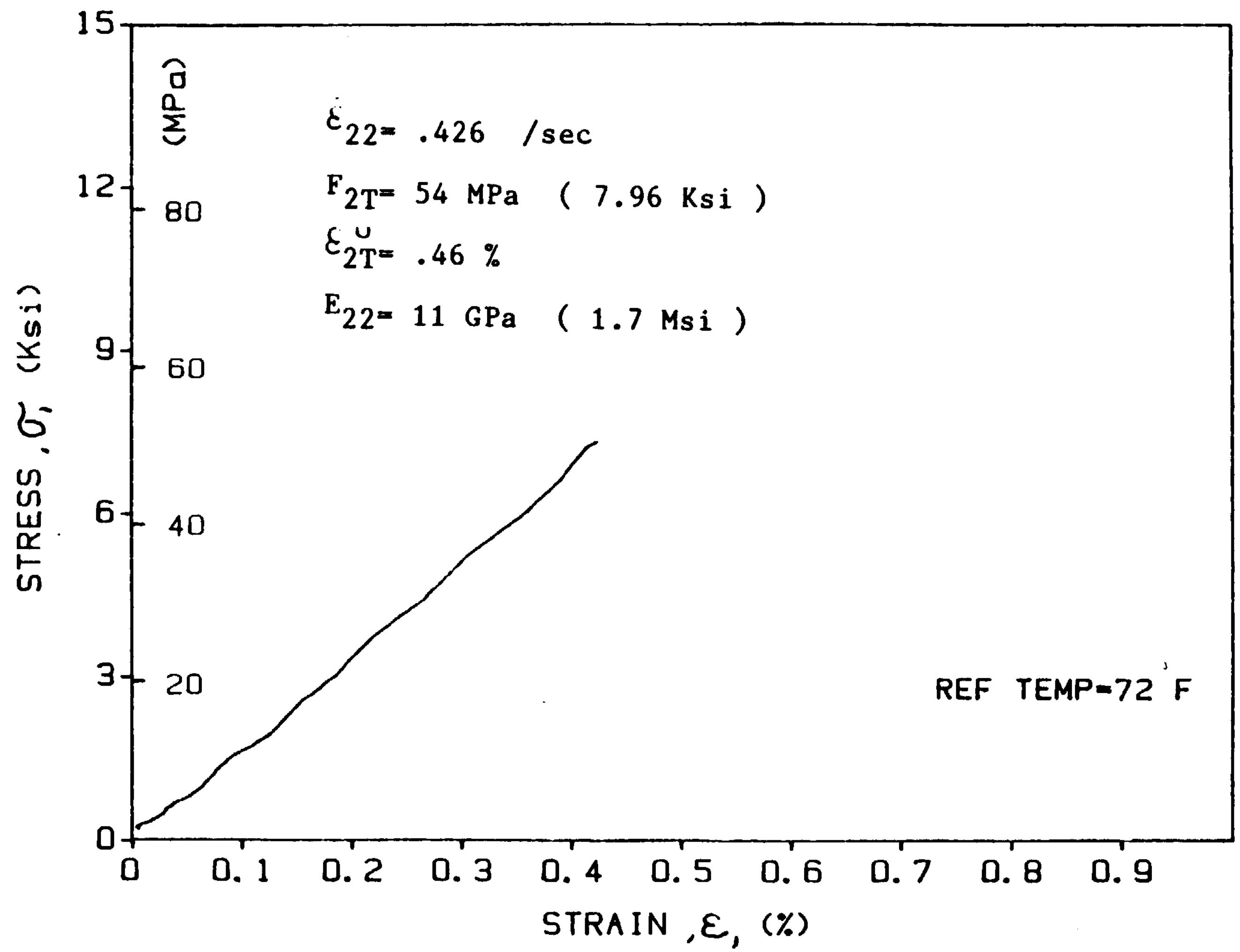


Fig. A-69. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L7 (T = 23°C (72°F))

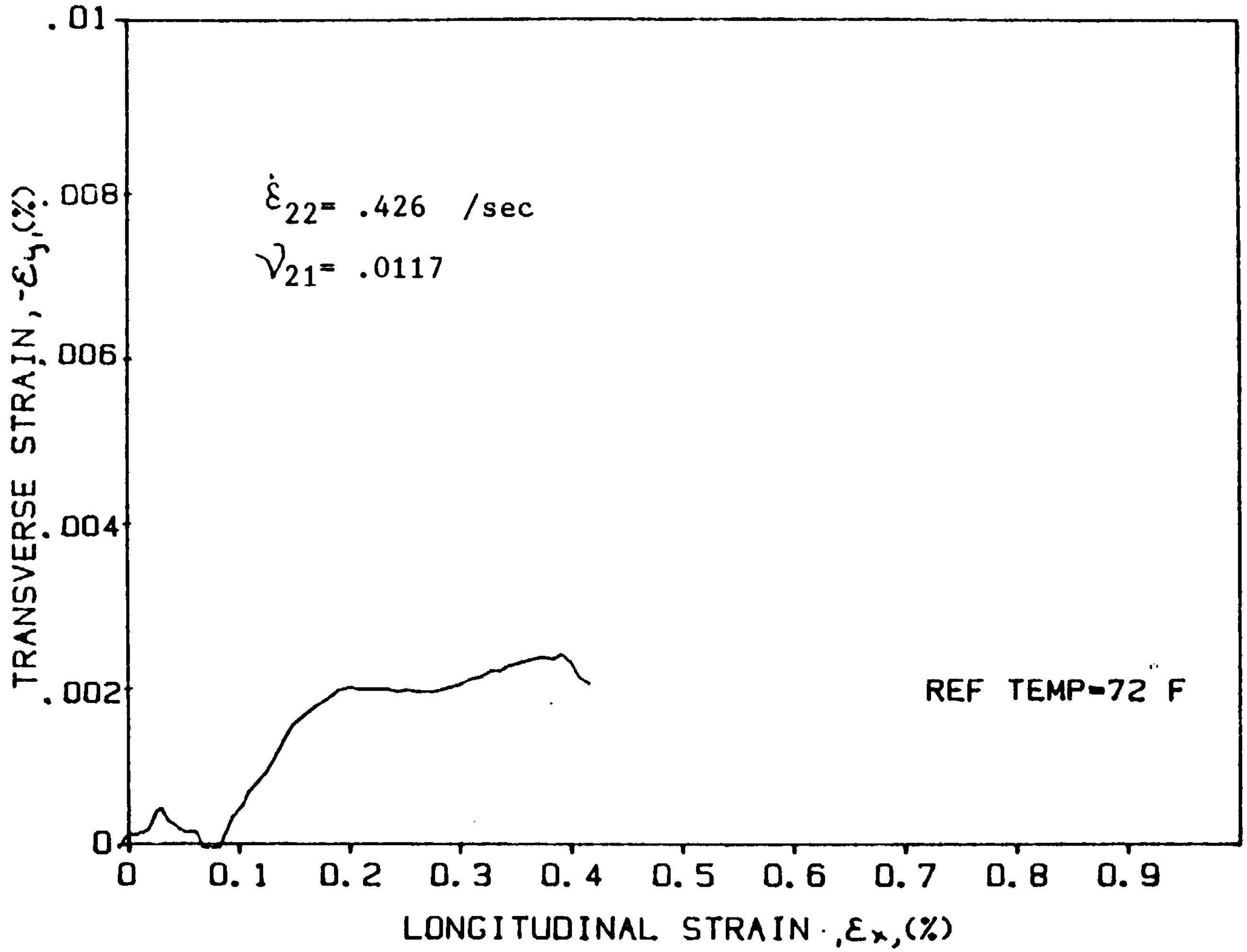


Fig. A-70. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L7 (T = 23°C (72°F))

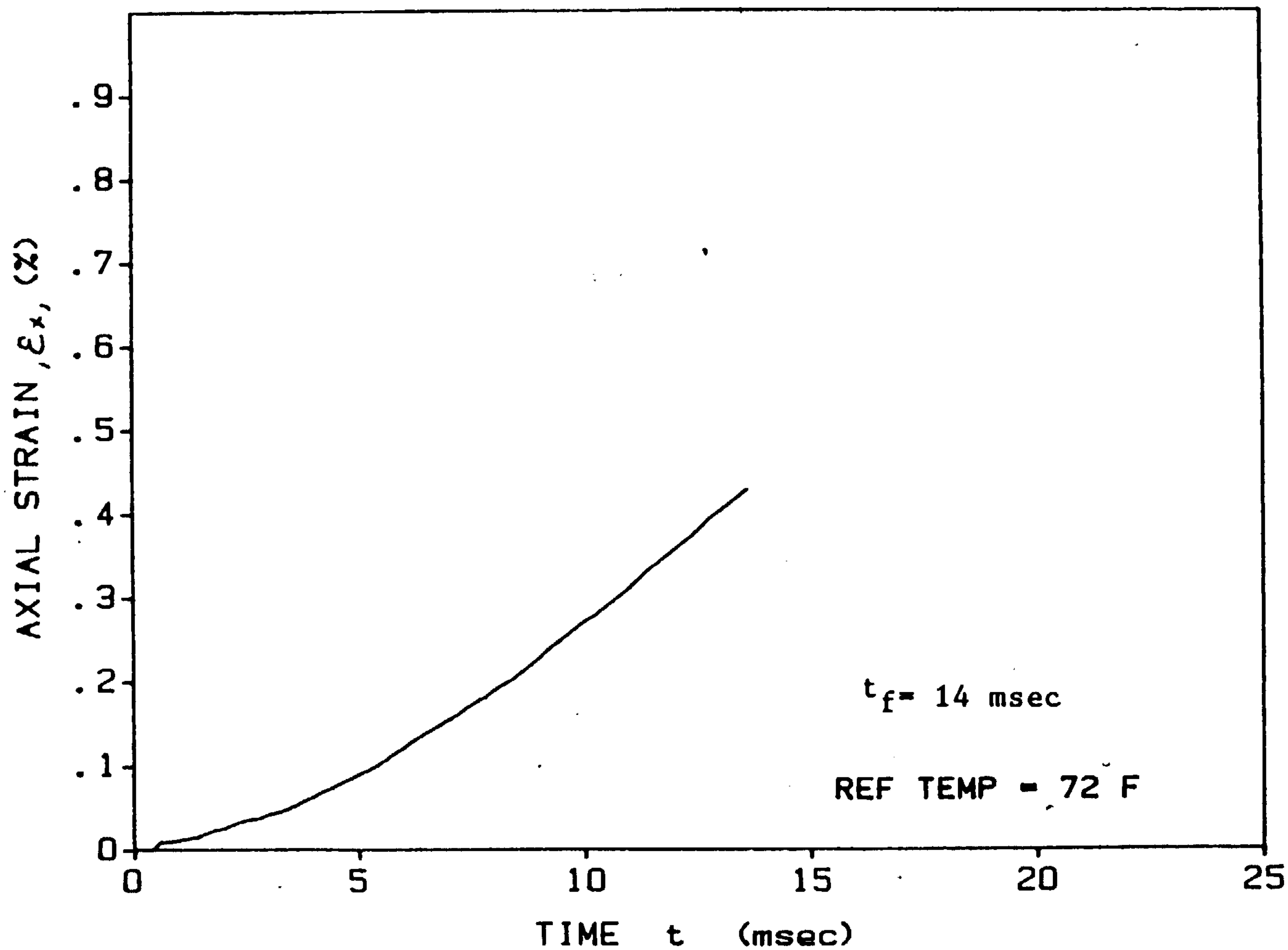


Fig. A-71. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1L7 (T = 23°C (72°F))

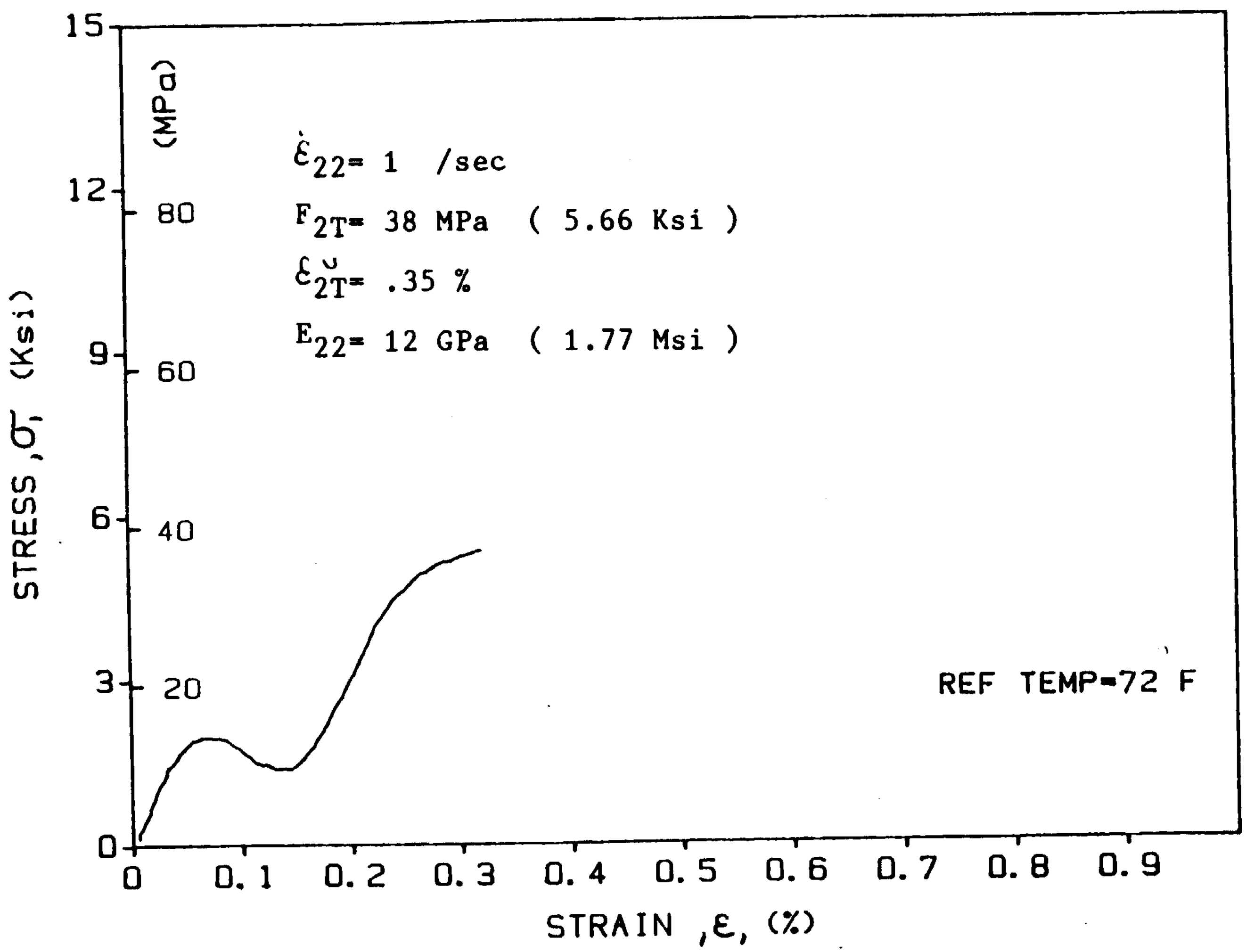


Fig. A-72. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L1 (T = 23°C (72°F))

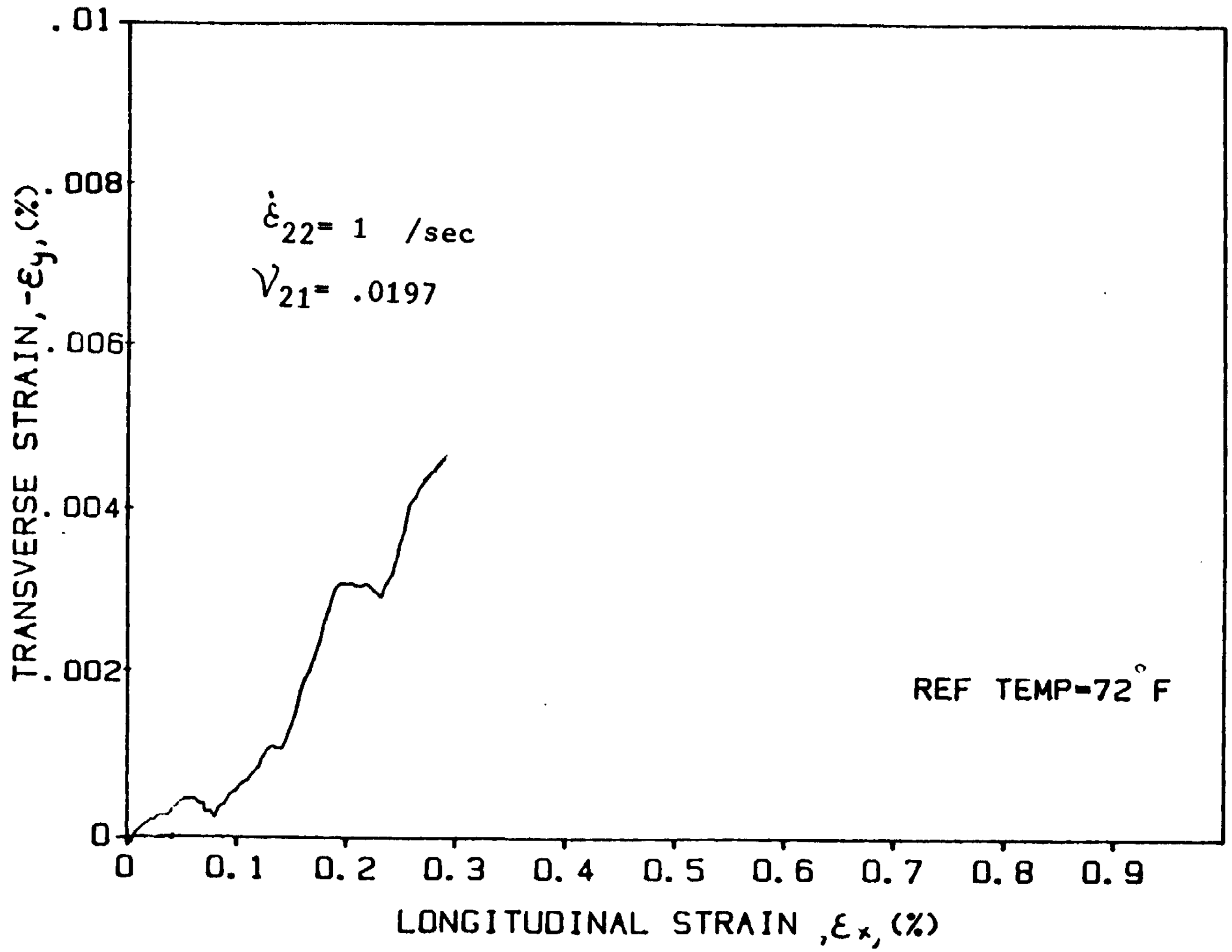


Fig. A-73. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L1 (T = 23°C (72°F))

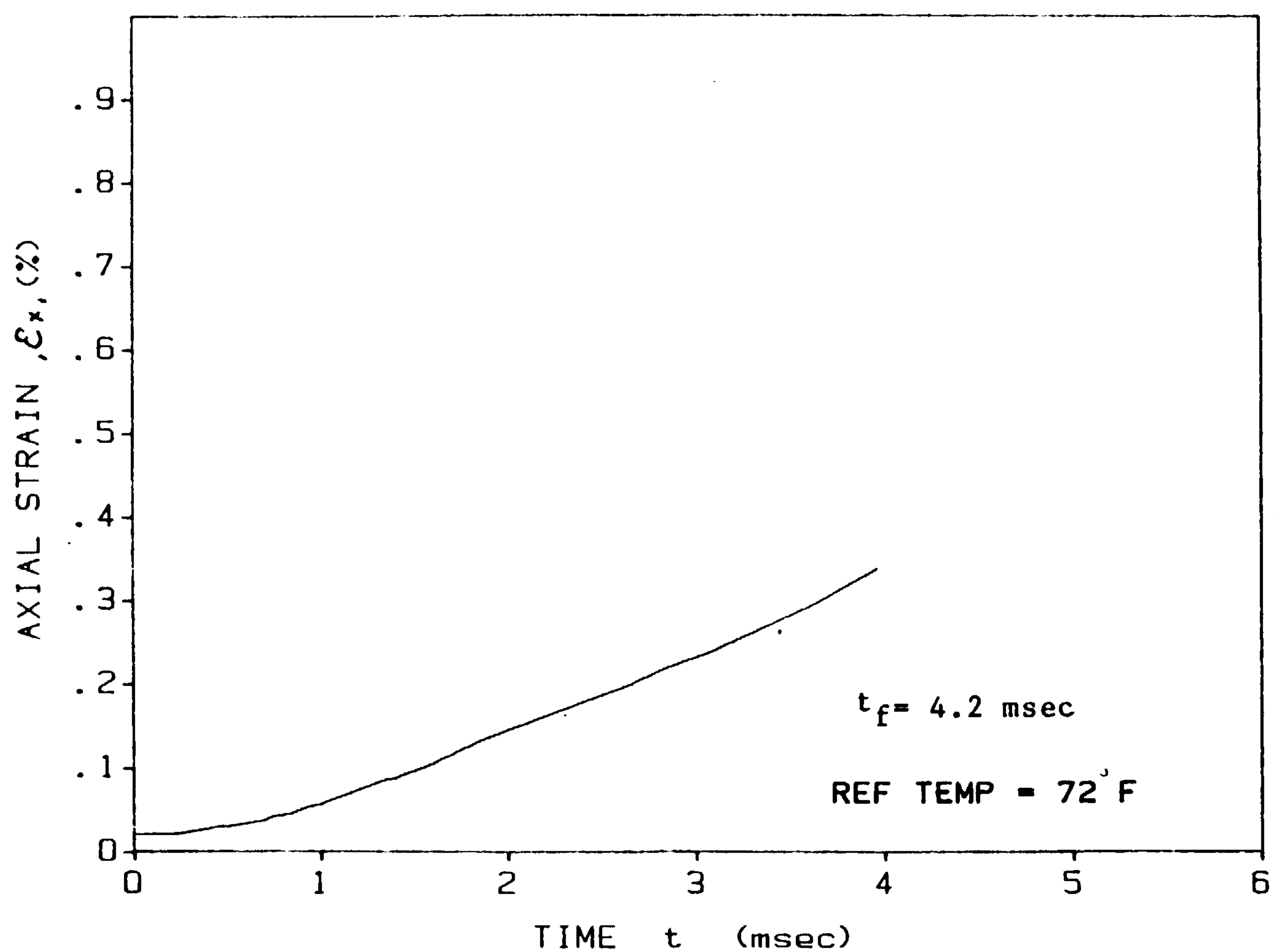


Fig. A-74. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L1 (T = 23°C (72°F))

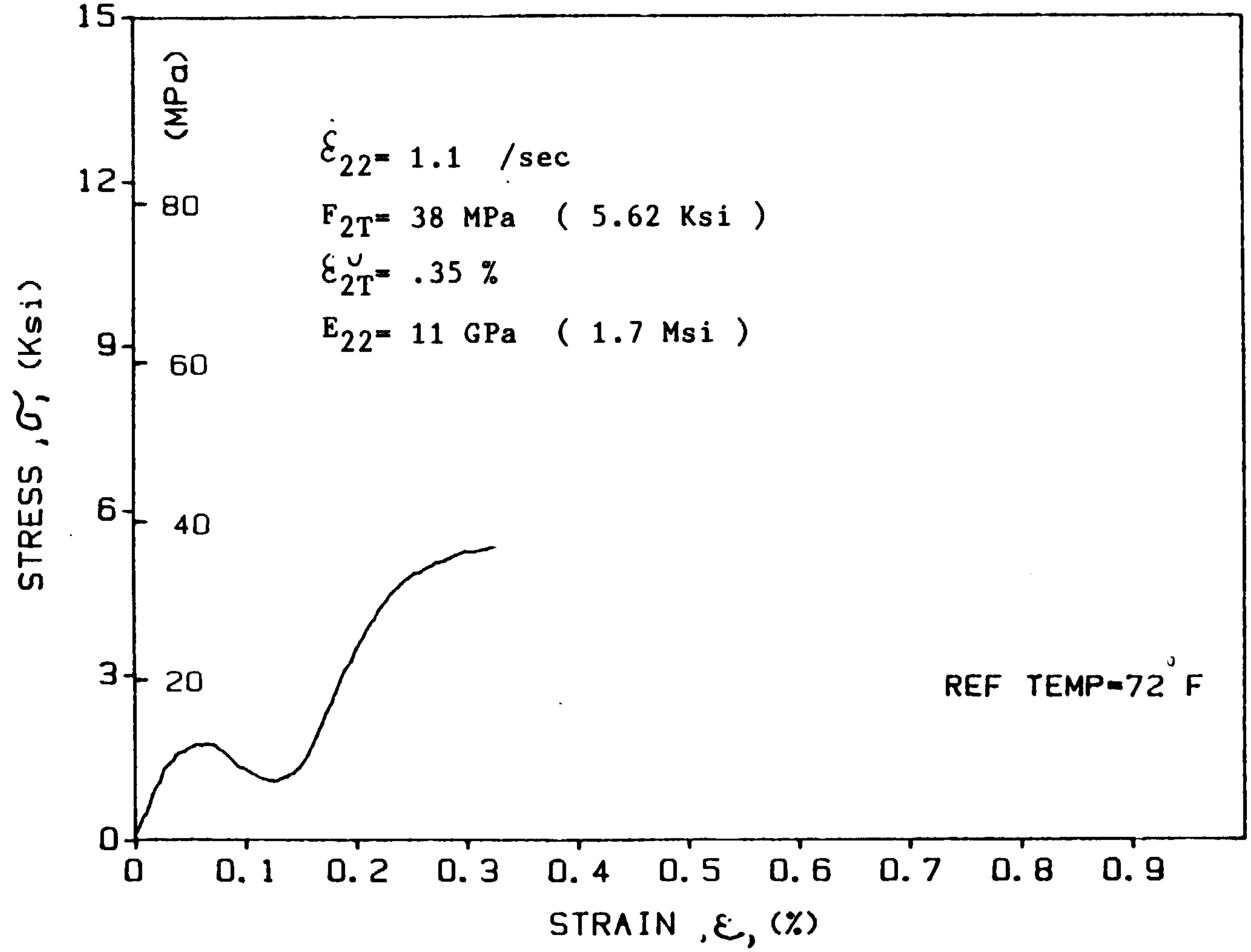


Fig. A-75. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L2 (T = 23°C (72°F))

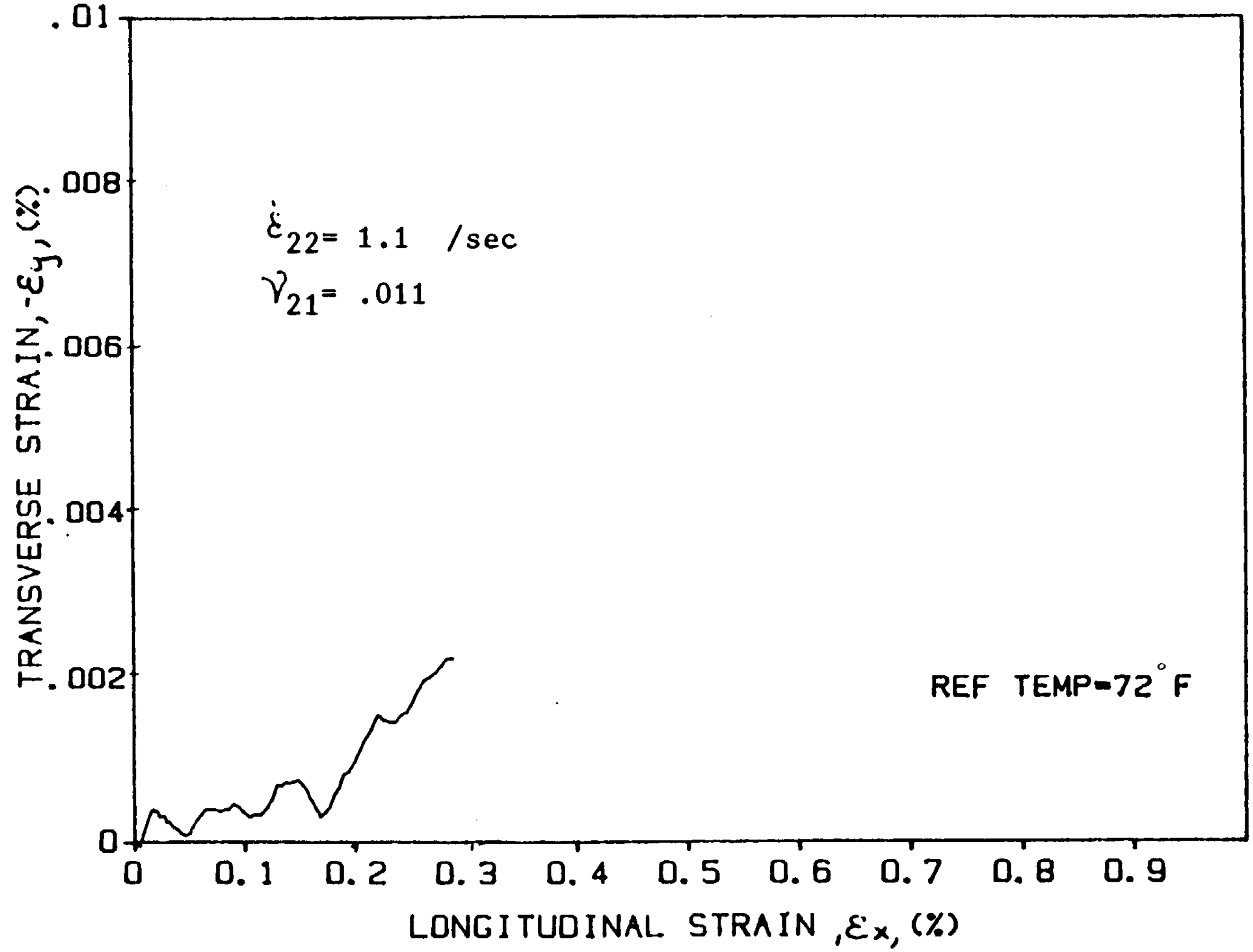


Fig. A-76. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/0L2 (T = 23°C (72°F))

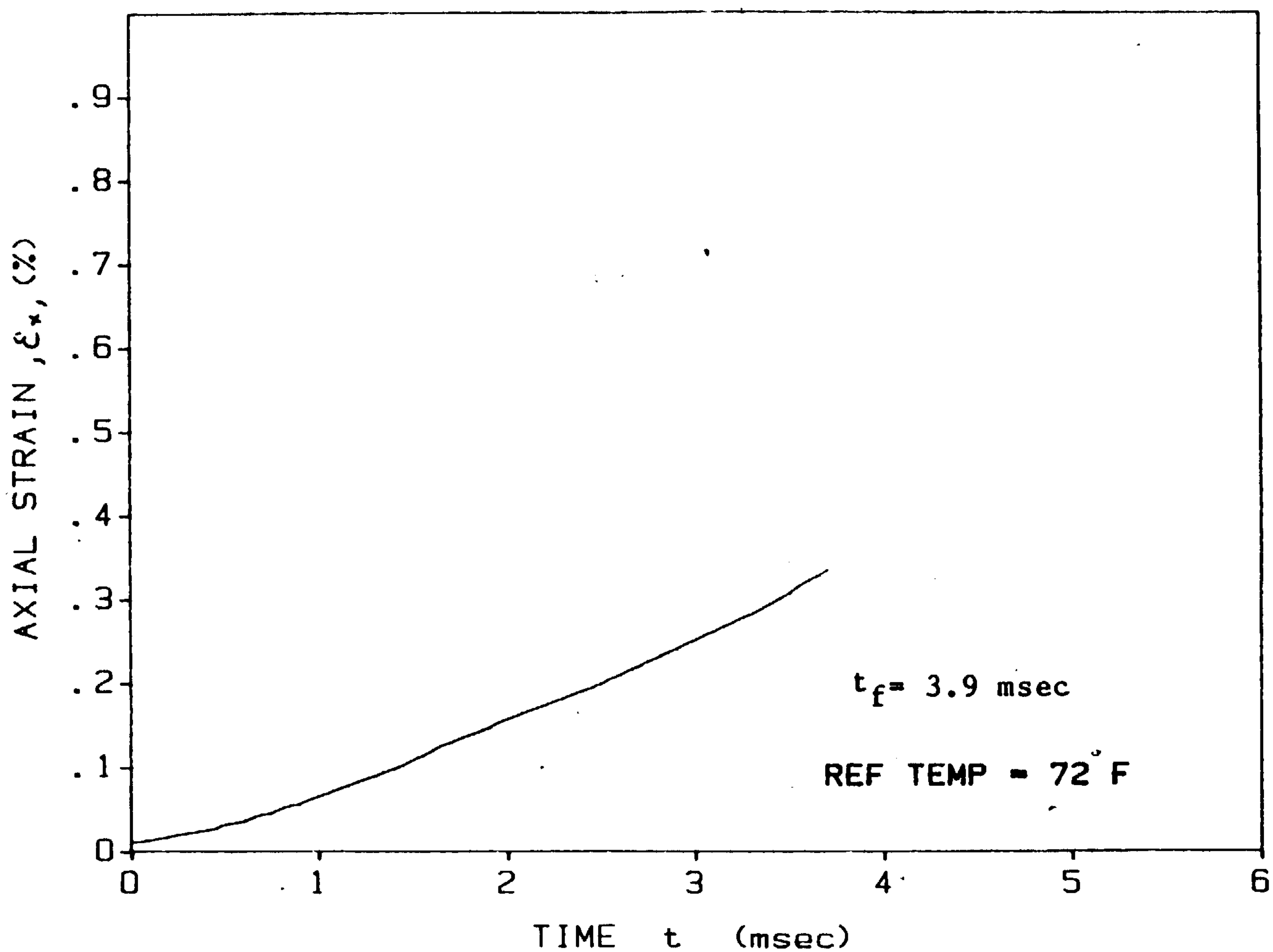


Fig. A-77. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L2 (T = 23°C (72°F))

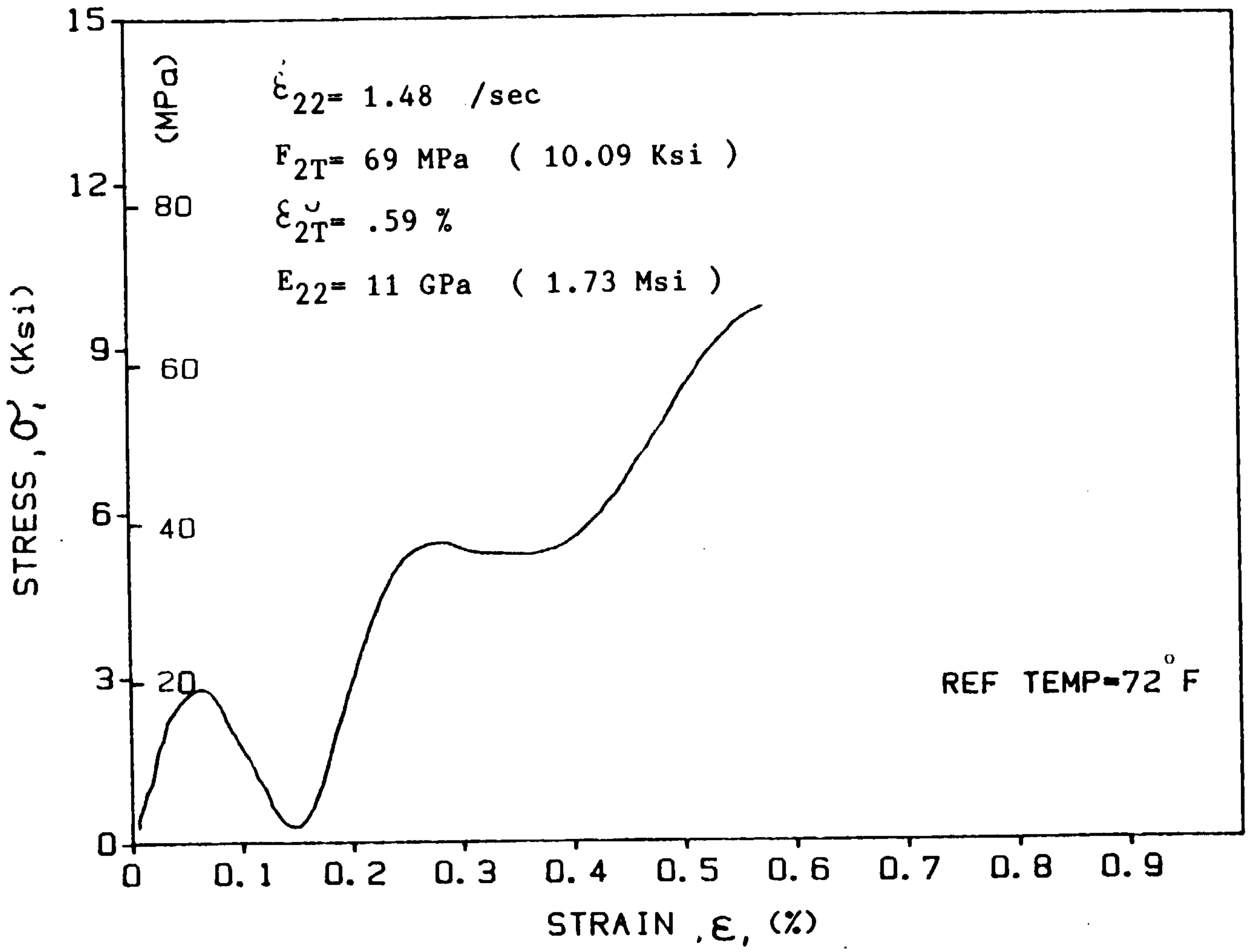


Fig. A-78. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L3 (T = 23°C (72°F))

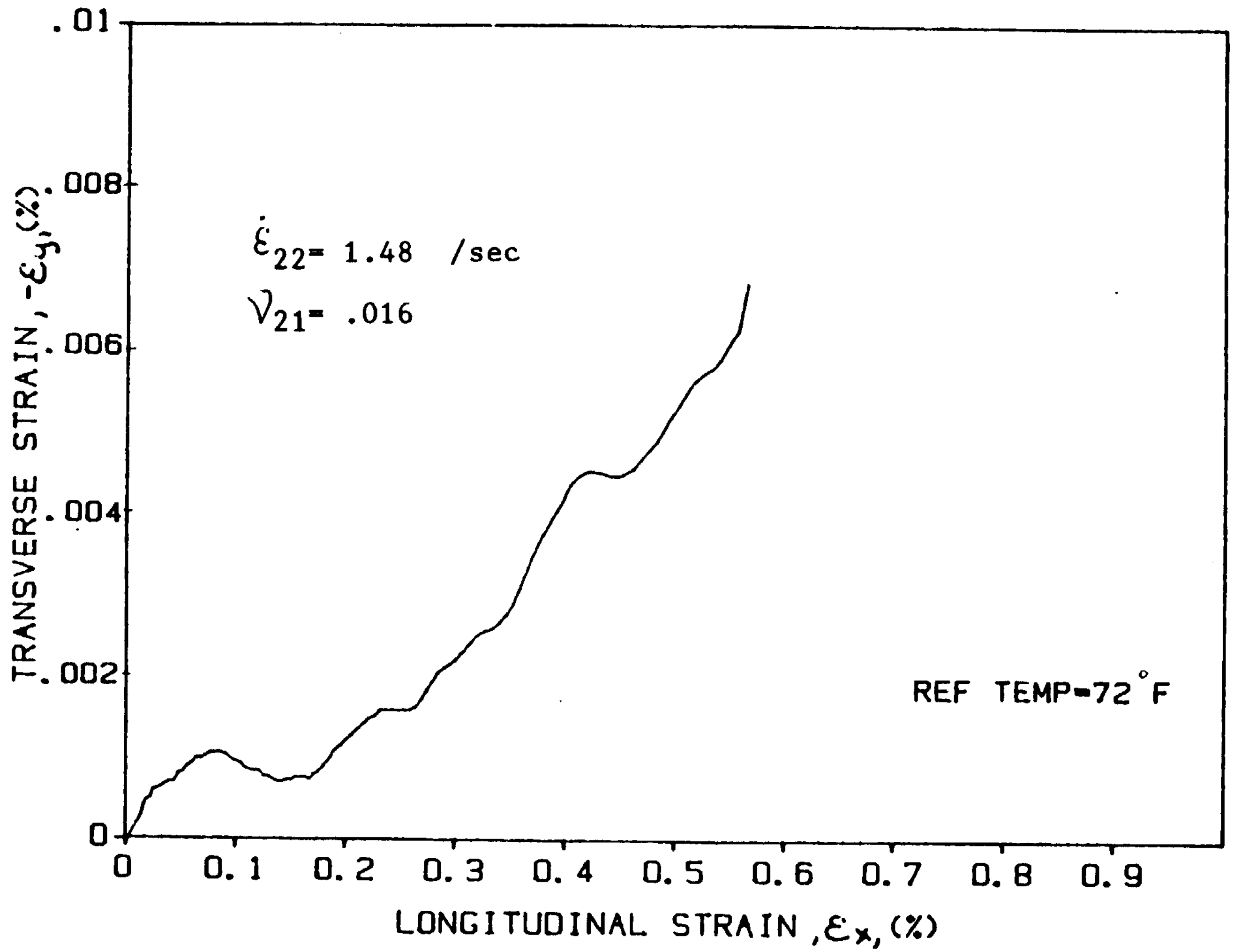


Fig. A-79. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/0L3 (T = 23°C (72°F))

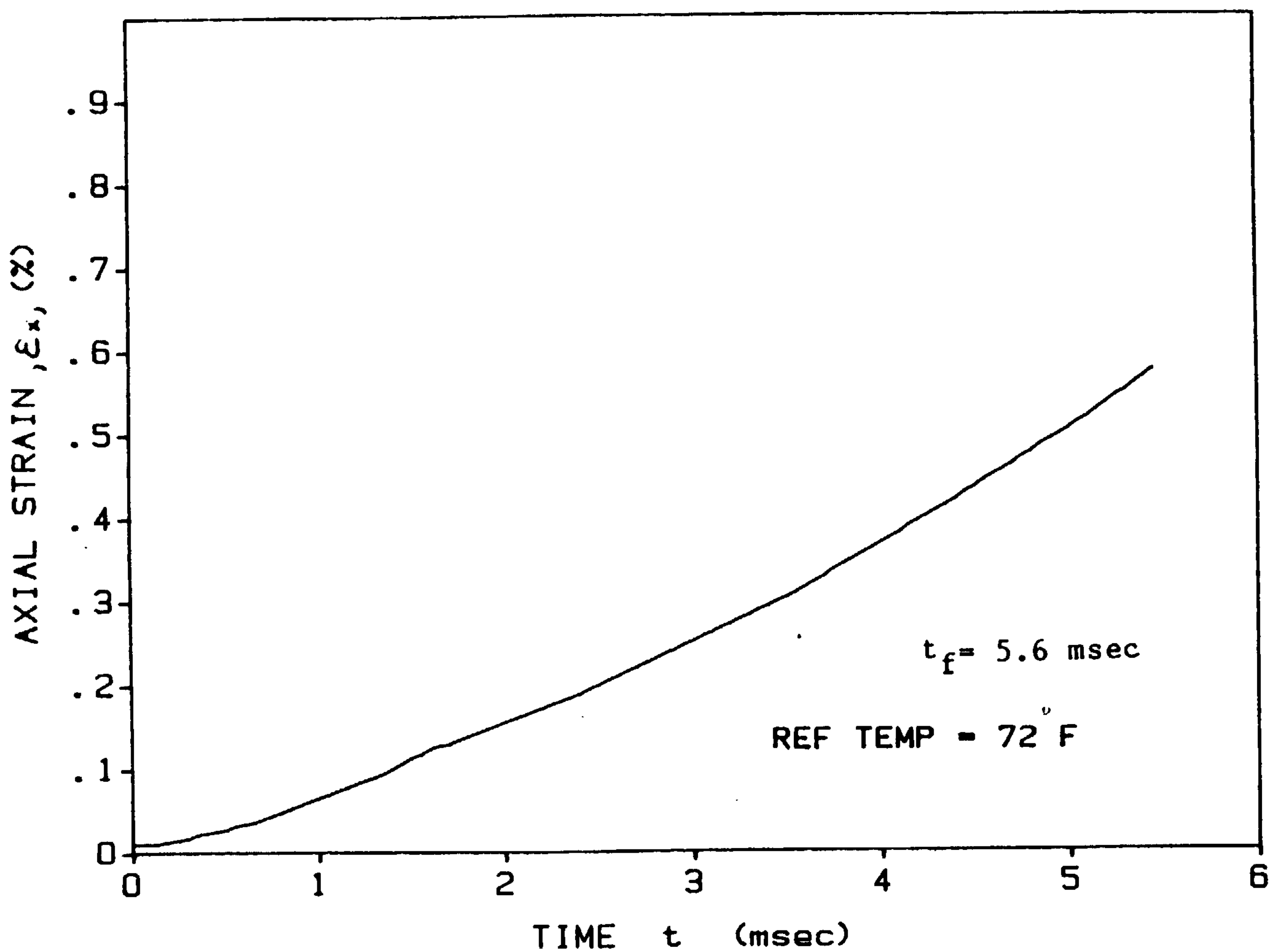


Fig. A-80. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L3 (T = 23°C (72°F))

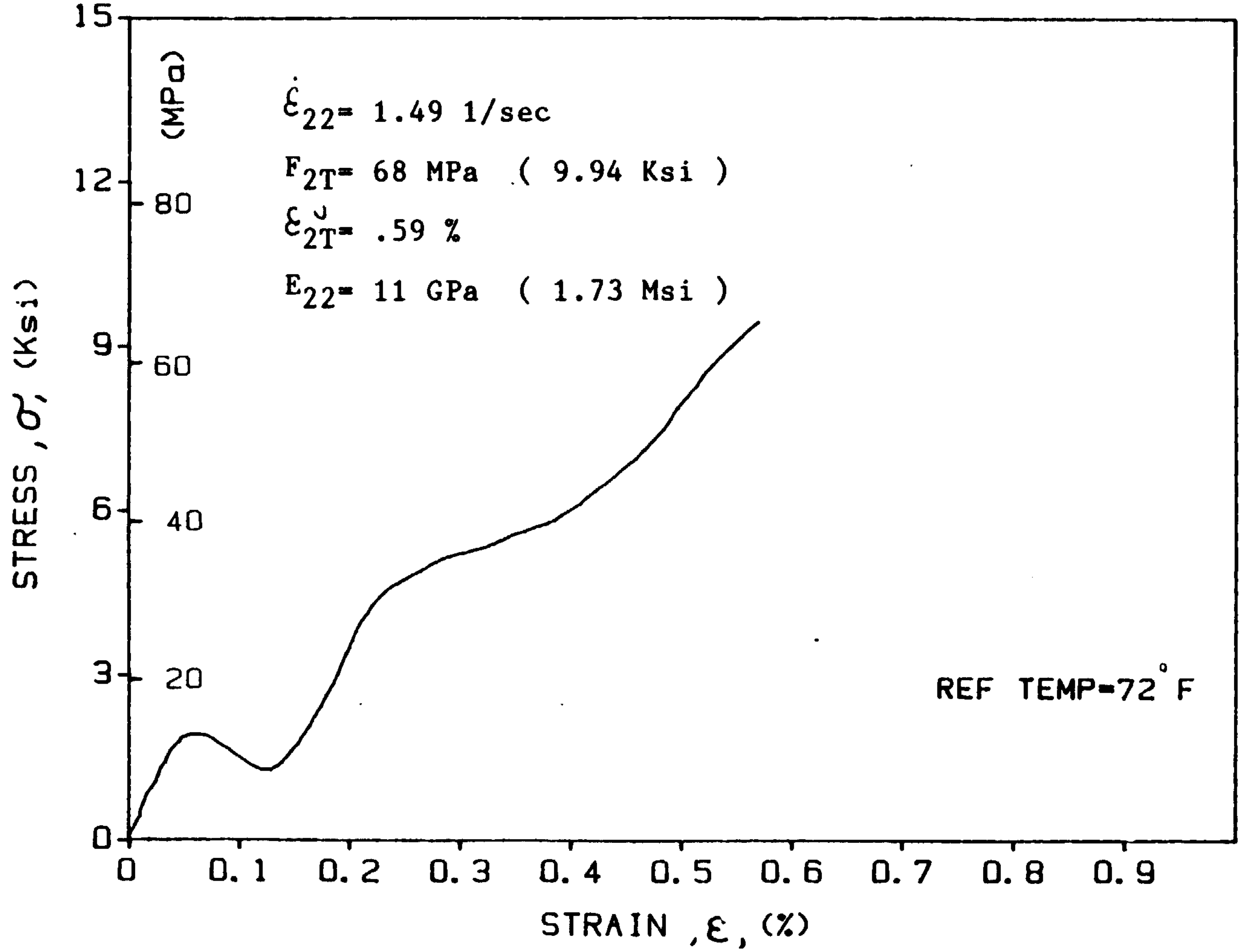


Fig. A-81. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L4 (T = 23°C (72°F))

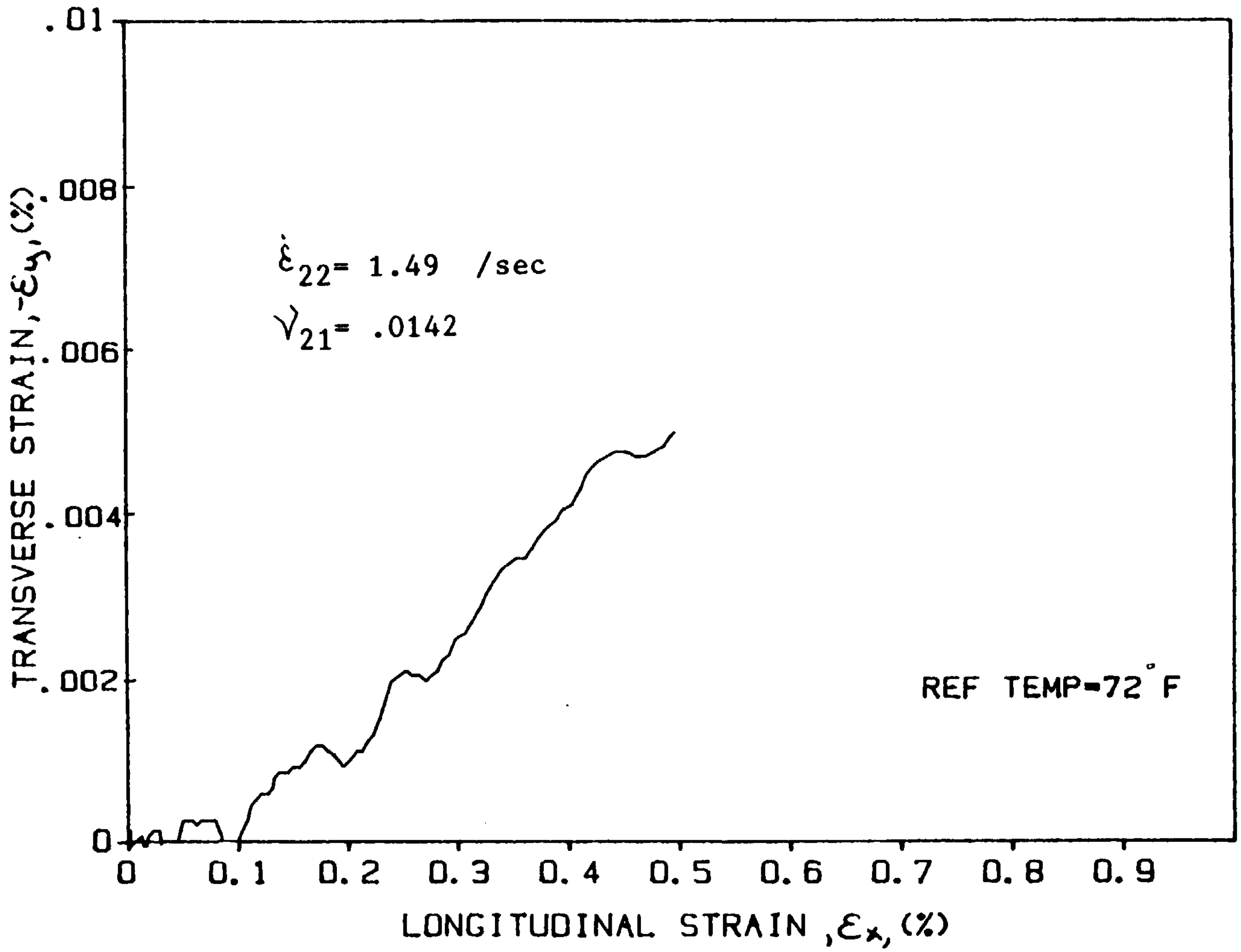


Fig. A-82. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L4 (T = 23°C (72°F))

C-3

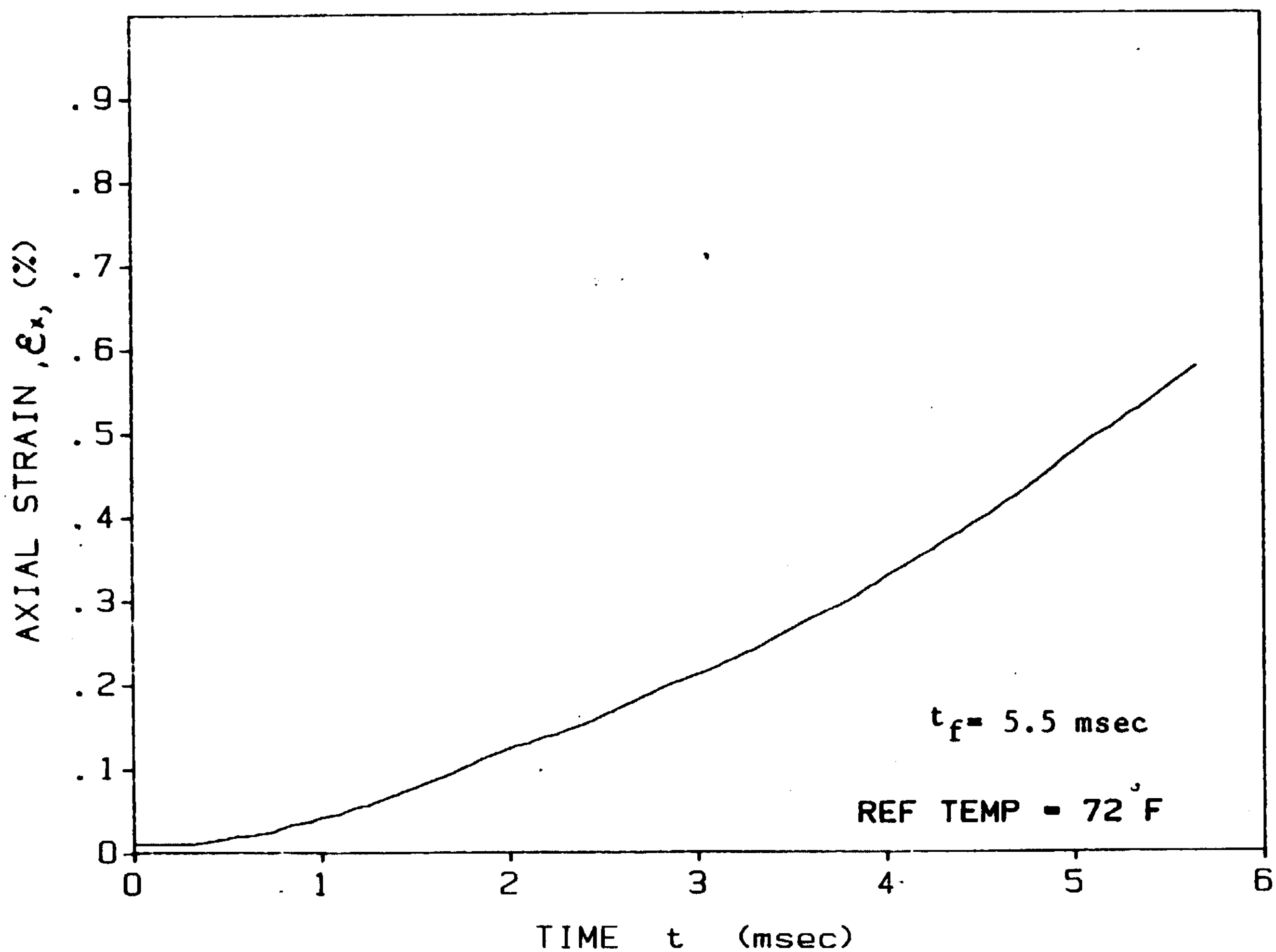


Fig. A-83. Axial Strain vs. Time for [90_8] AS4/3501-6 Graphite/Epoxy, Spec. 90/0L4 (T = 23°C (72°F))

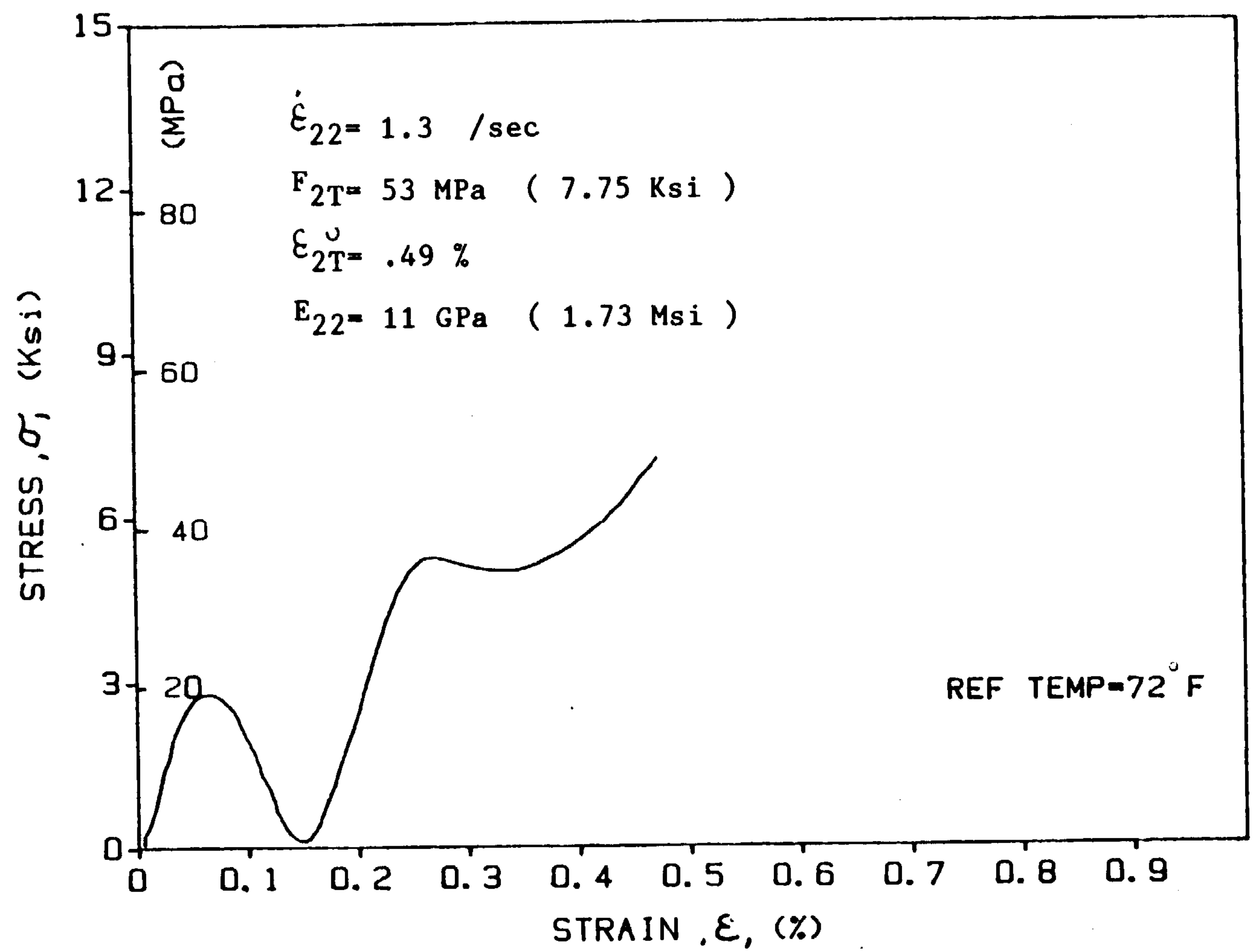


Fig. A-84. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L5 (T = 23°C (72°F))

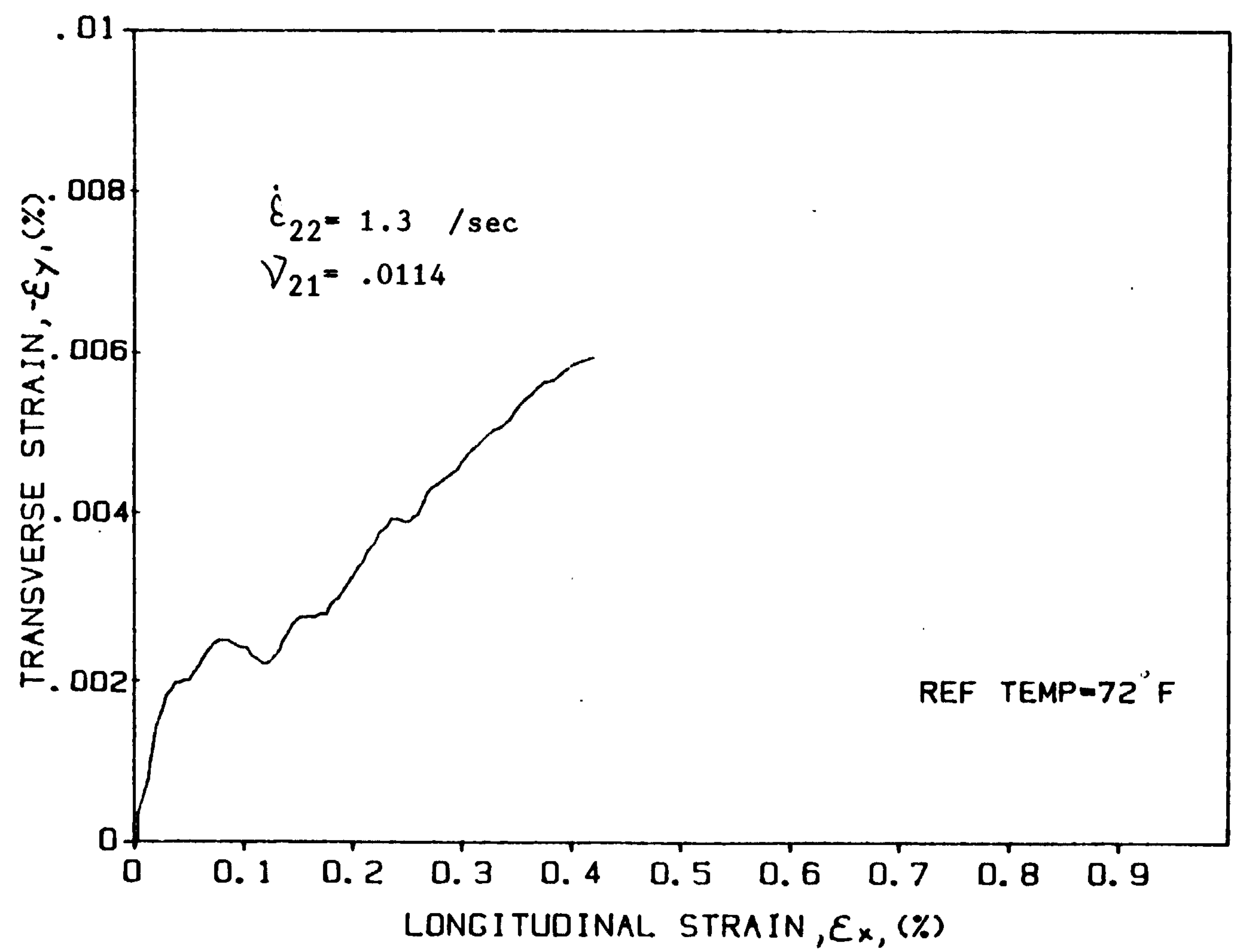


Fig. A-85. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L5 (T = 23°C (72°F))

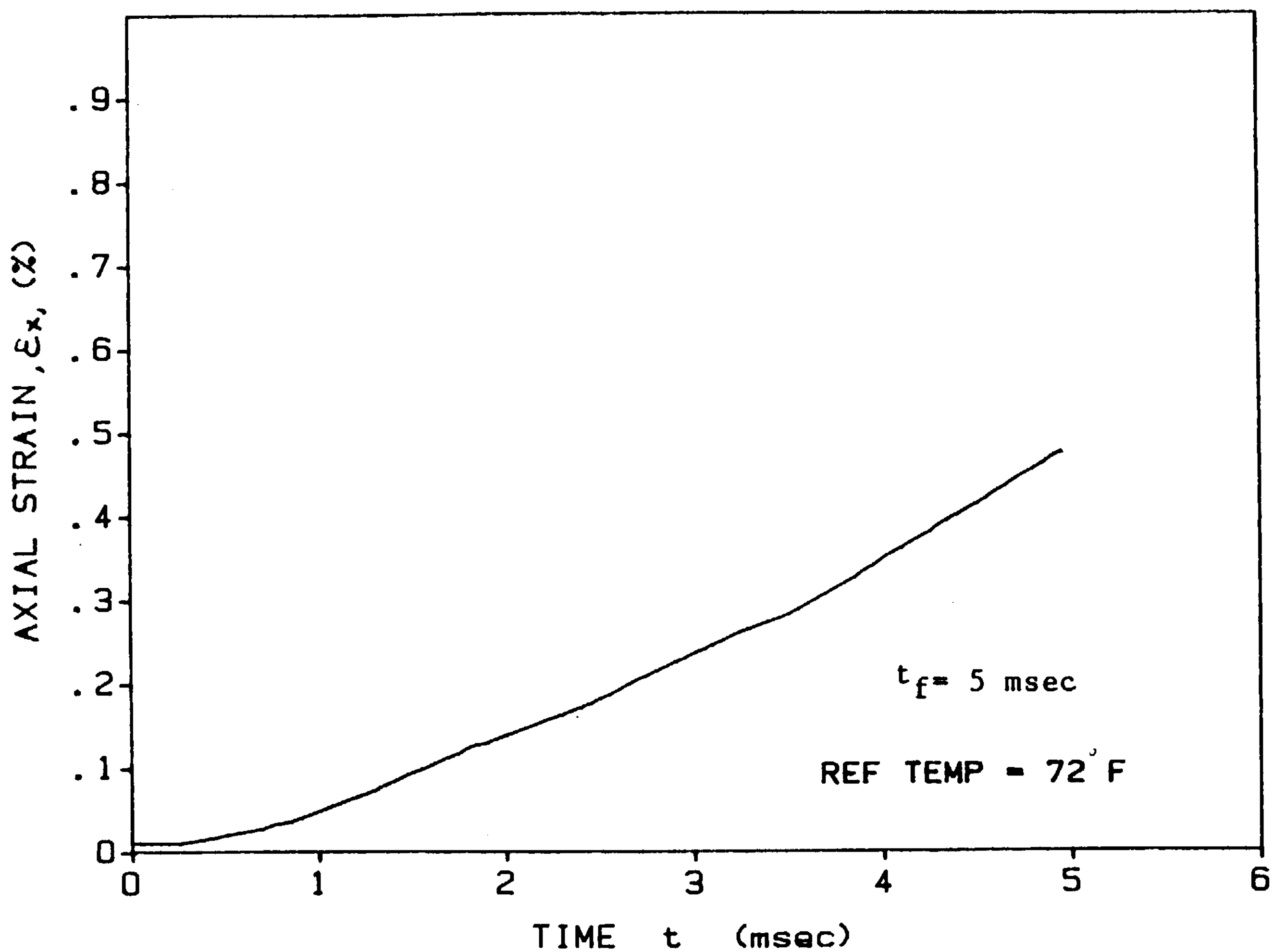


Fig. A-86. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L5 (T = 23°C (72°F))

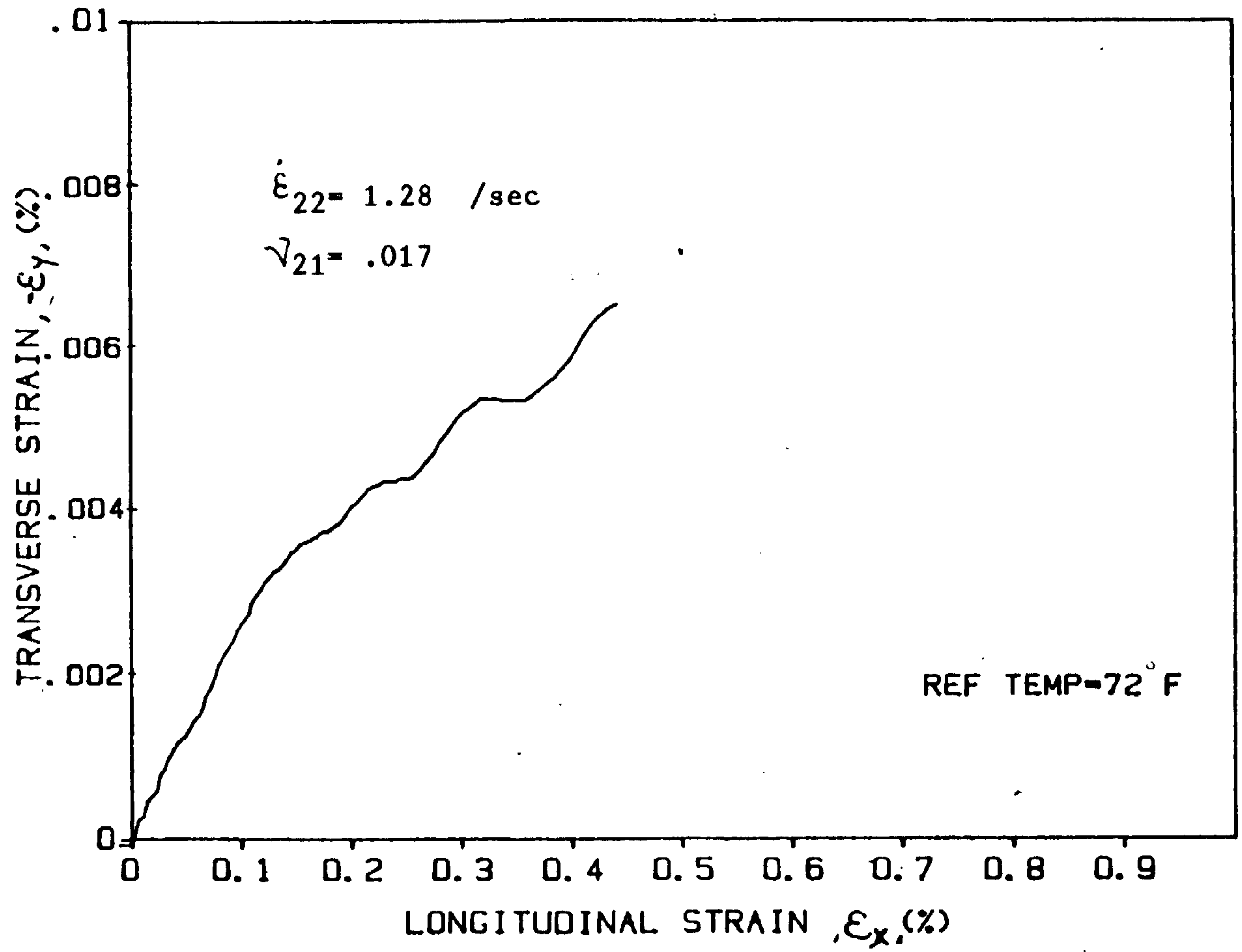


Fig. A-87. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/ Epoxy, Spec. 90/0L6 (T = 23°C (72°F))

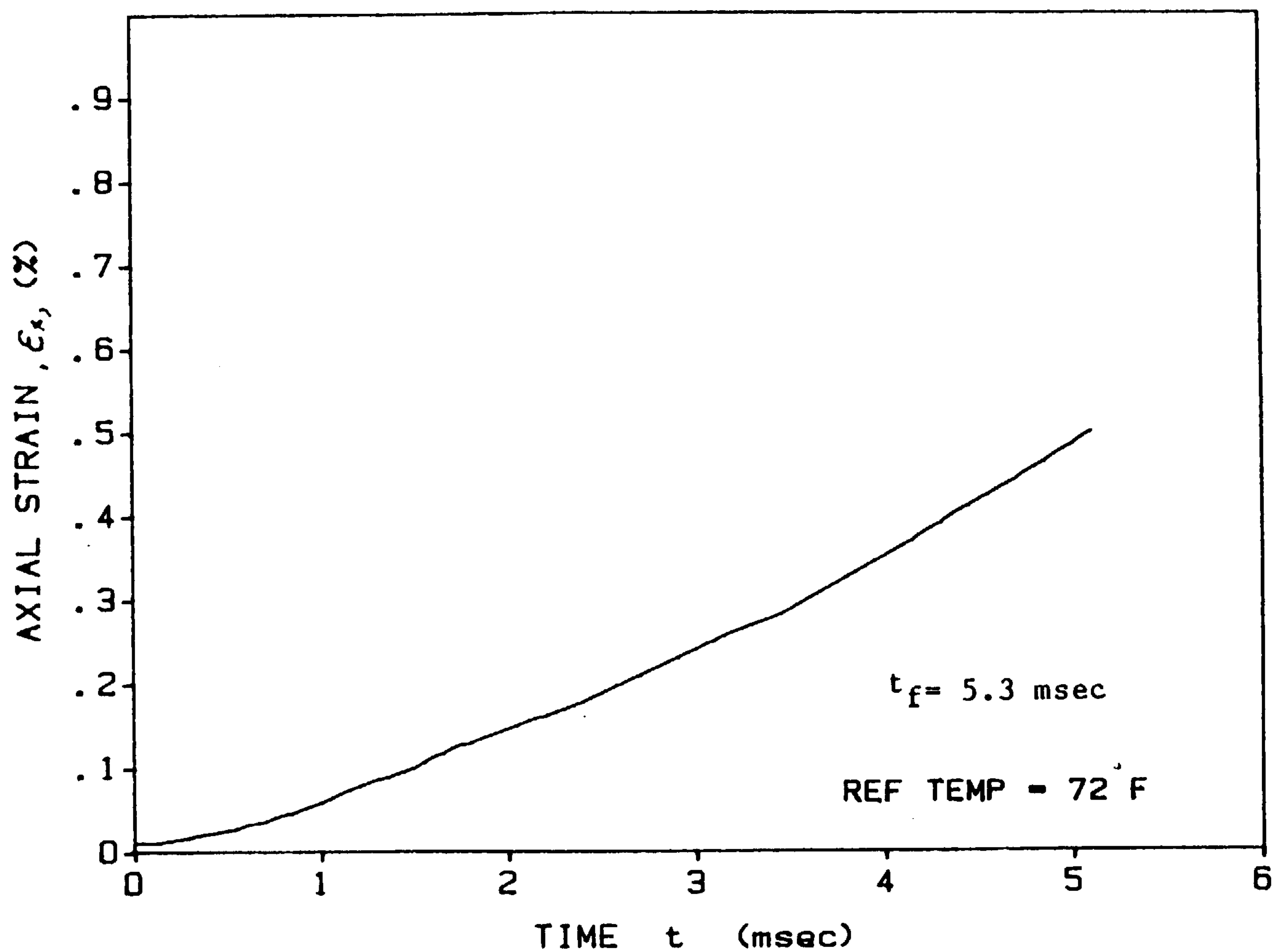


Fig. A-88. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0L6 (T = 23°C (72°F))

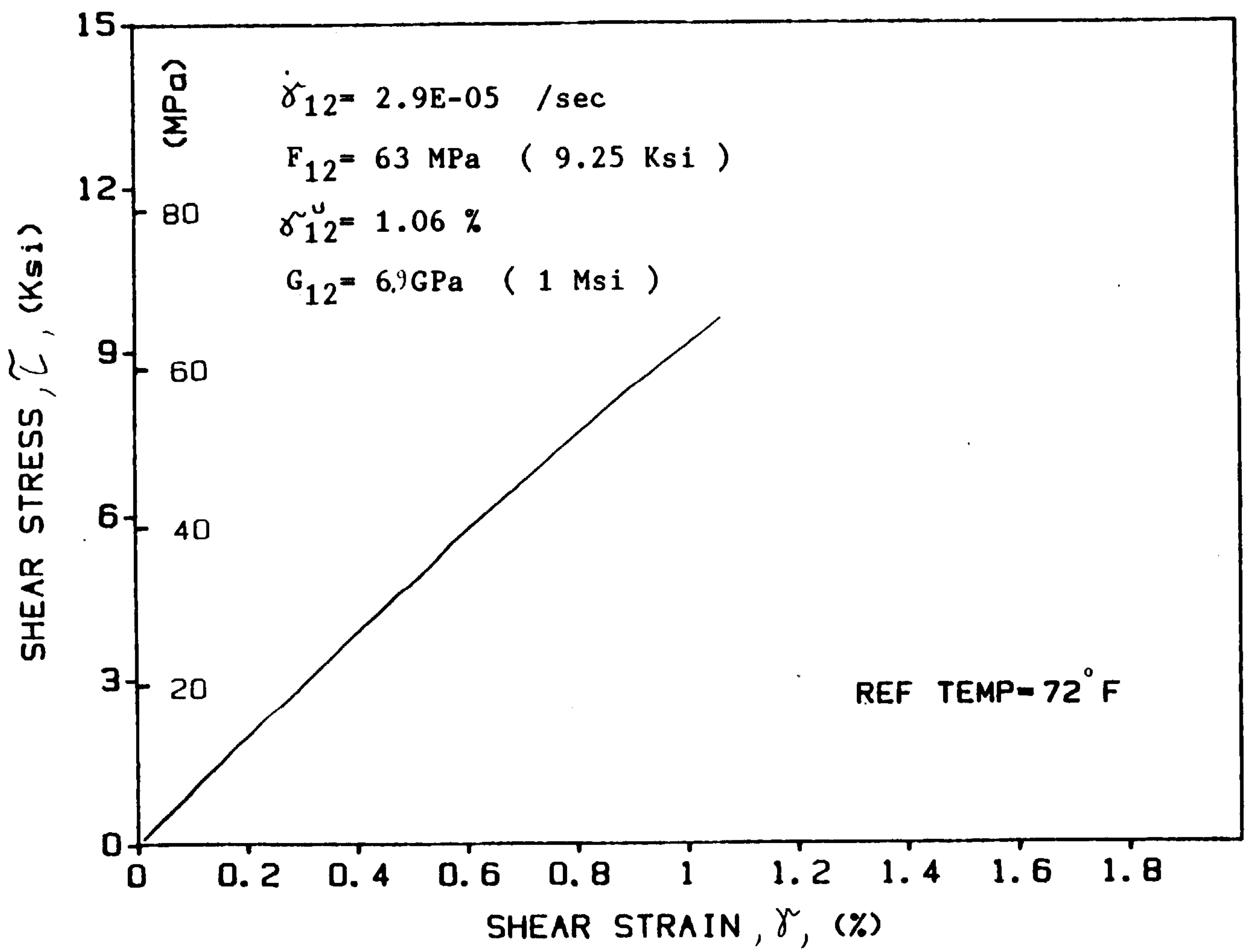


Fig. A-89. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-5L1 (T = 23°C (72°F))

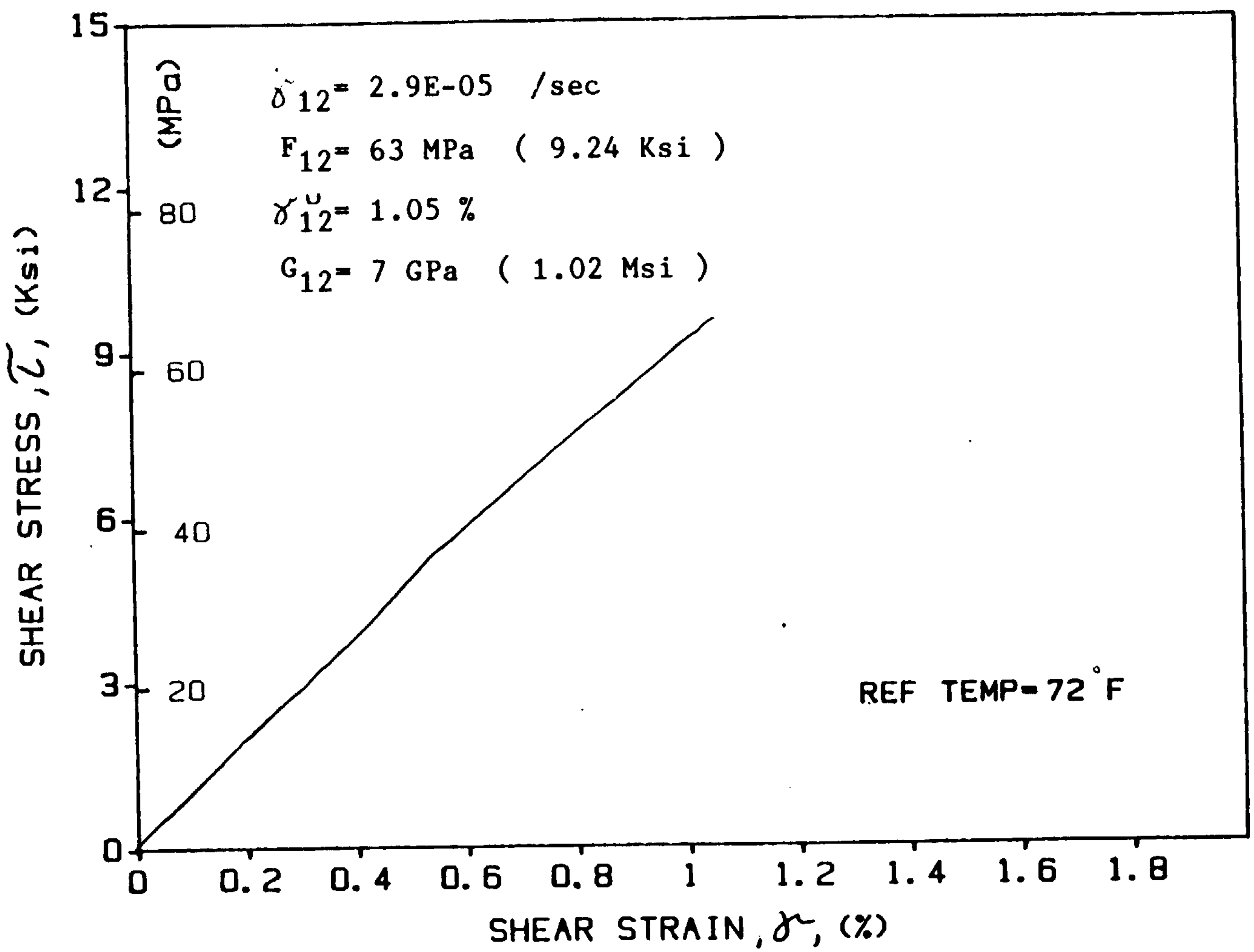


Fig. A-90. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-5L2 (T = 23°C (72°F))

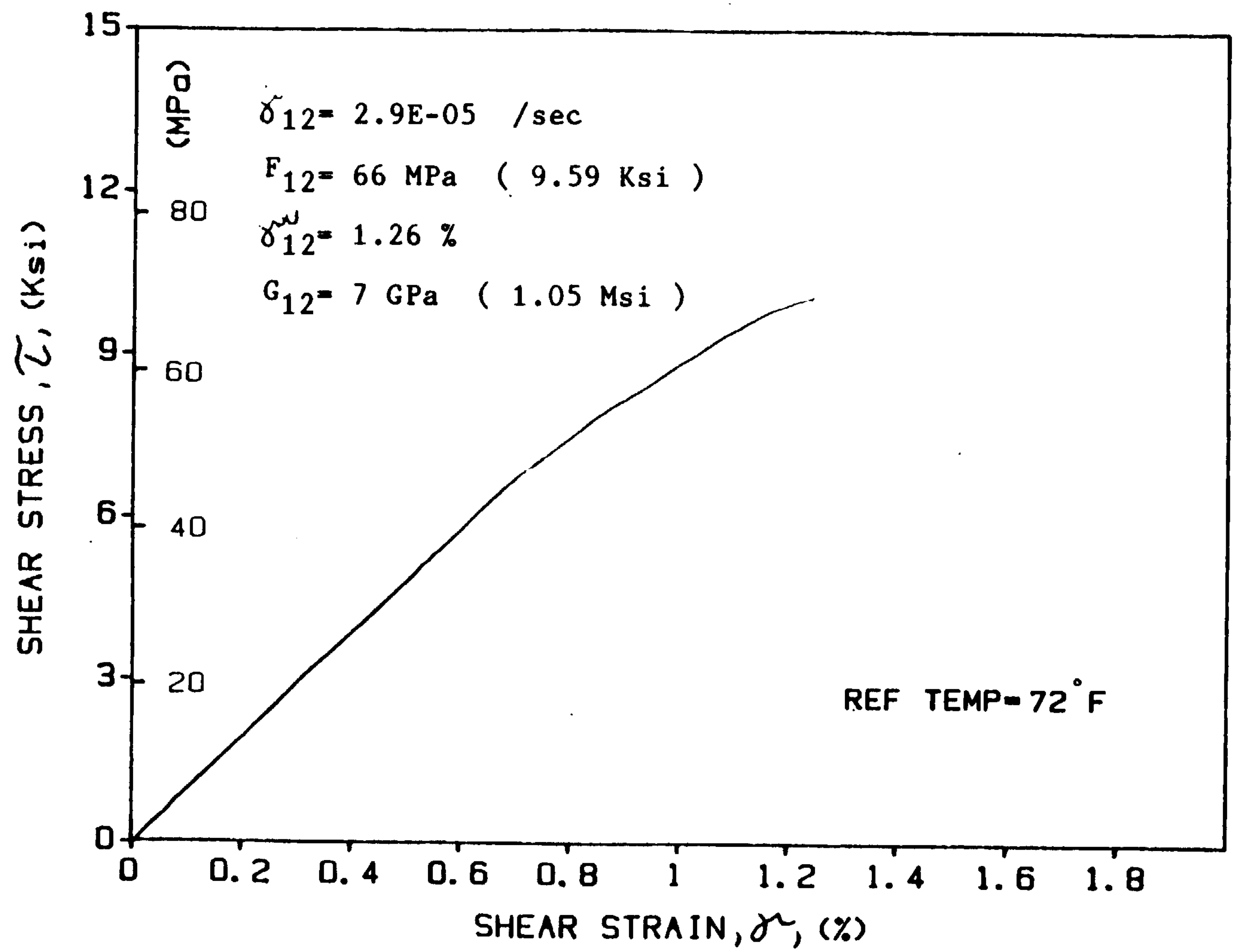


Fig. A-91. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-5L3 (T = 23°C (72°F))

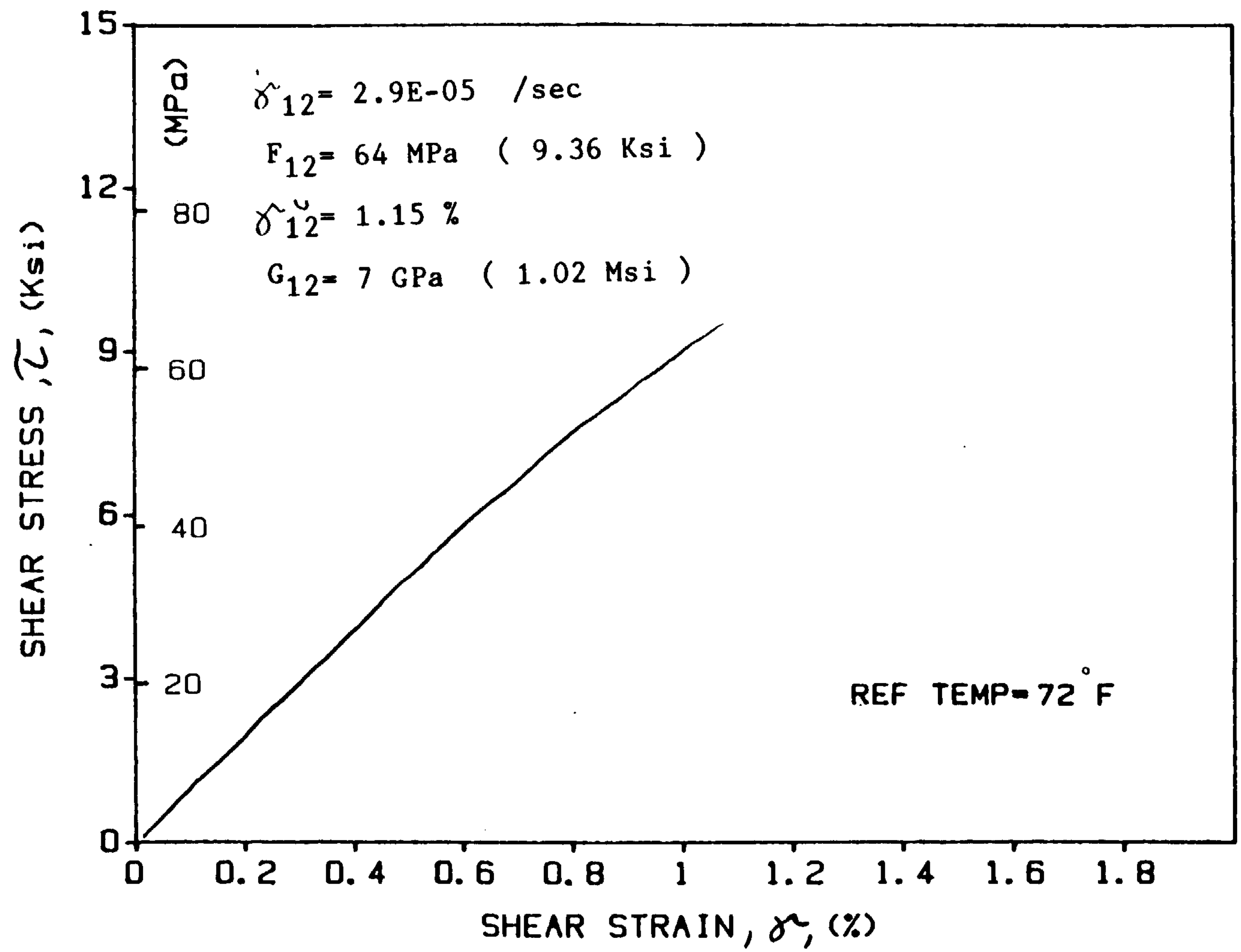


Fig. A-92. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-5L4 (T = 23°C (72°F))

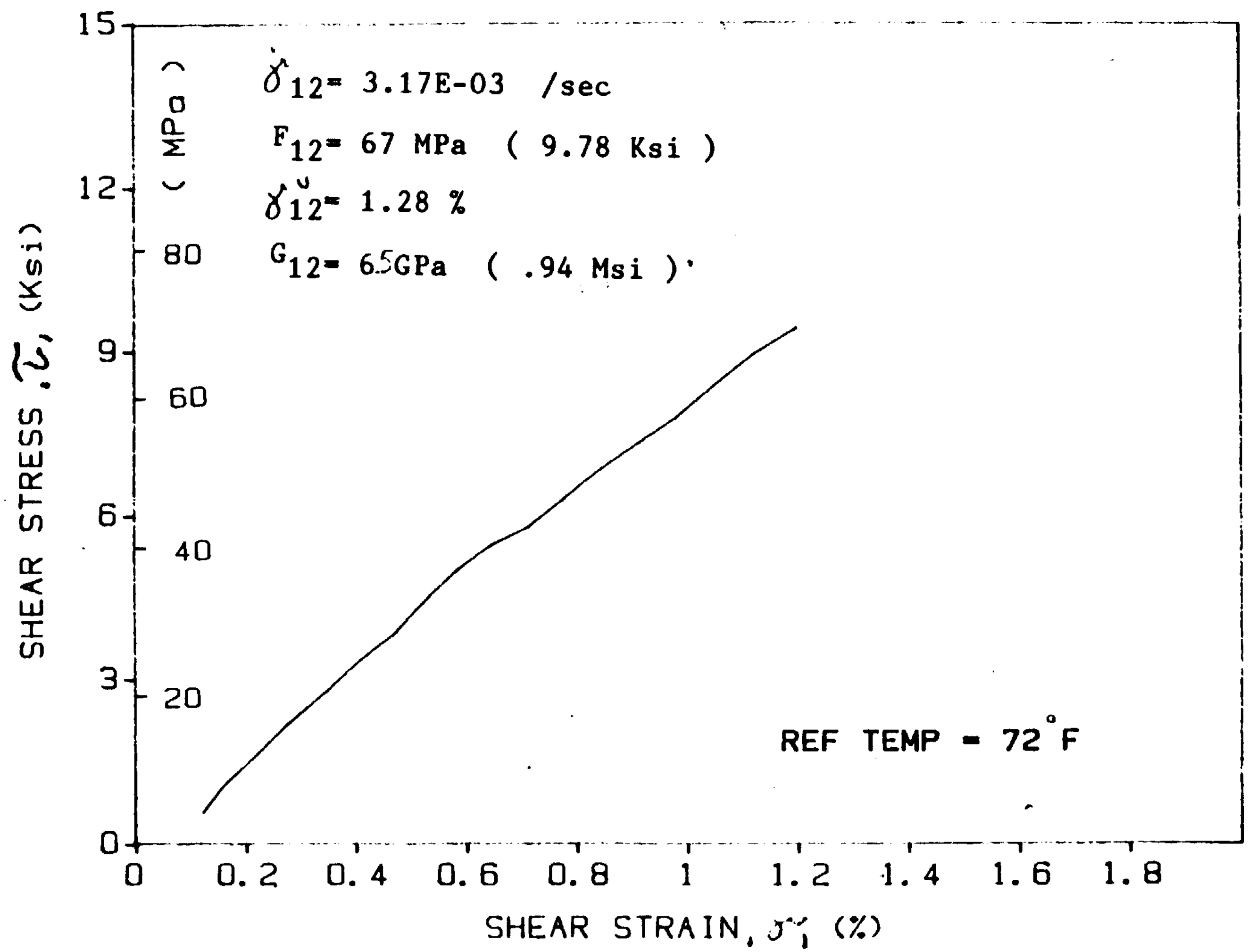


Fig. A-93. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/03L1 (T = 23°C (72°F))

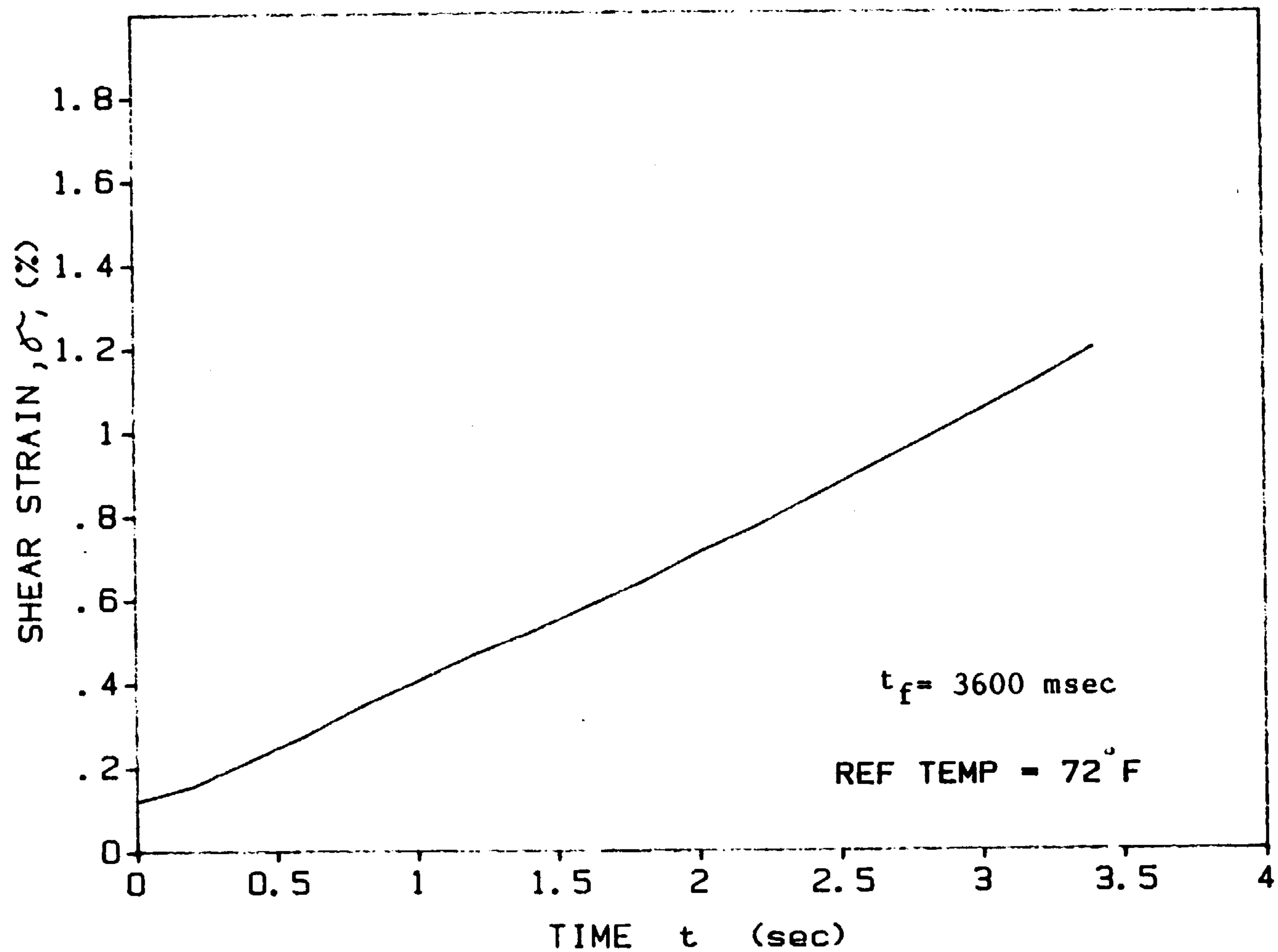
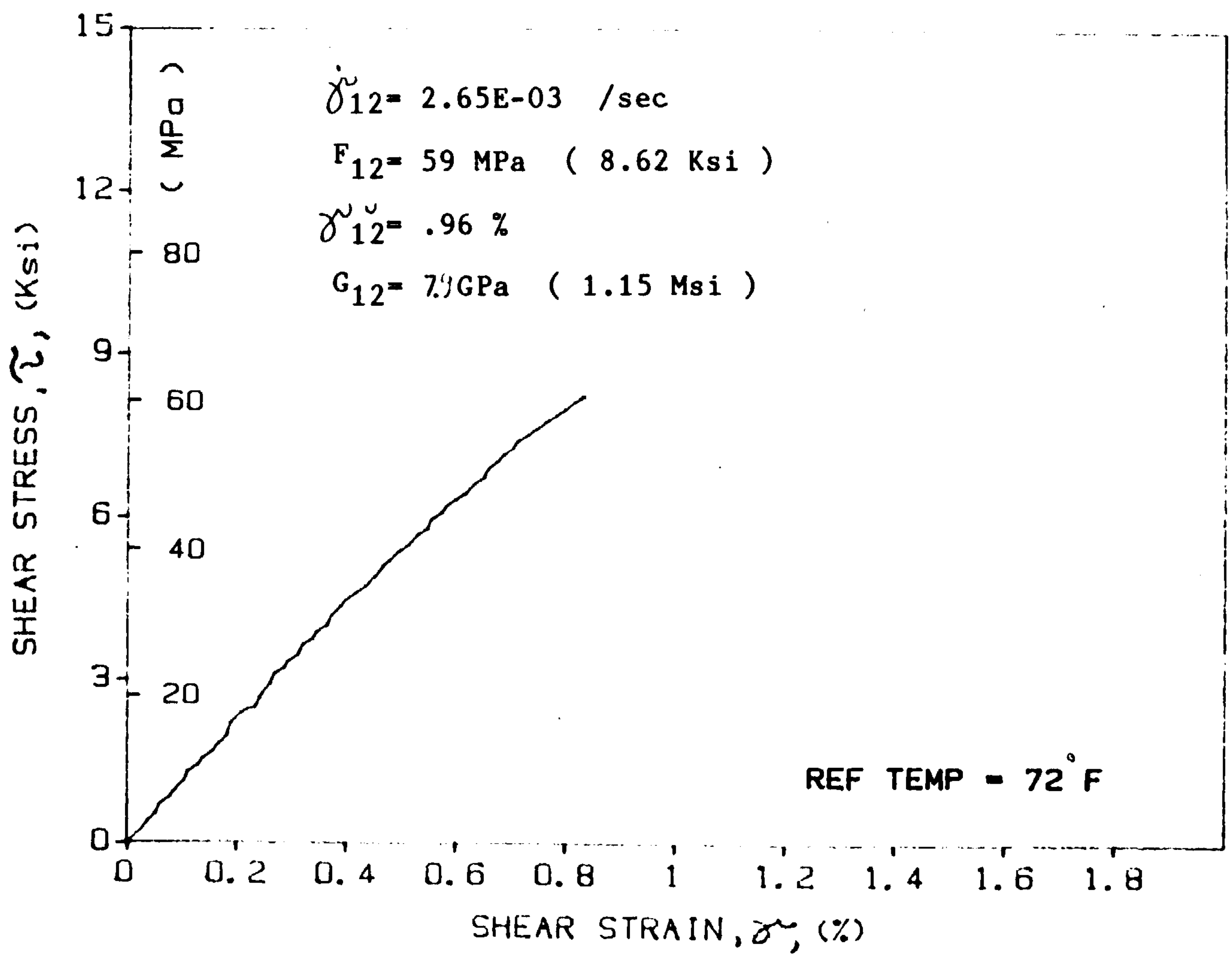


Fig. A-94. Shear Strain vs. Time for [10_6] AS4/3501-6 Graphite/Epoxy, Spec. 10/-3L1 (T = 23°C (72°F))



Fog/ A-95. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-3L2 (T = 23°C (72°F))

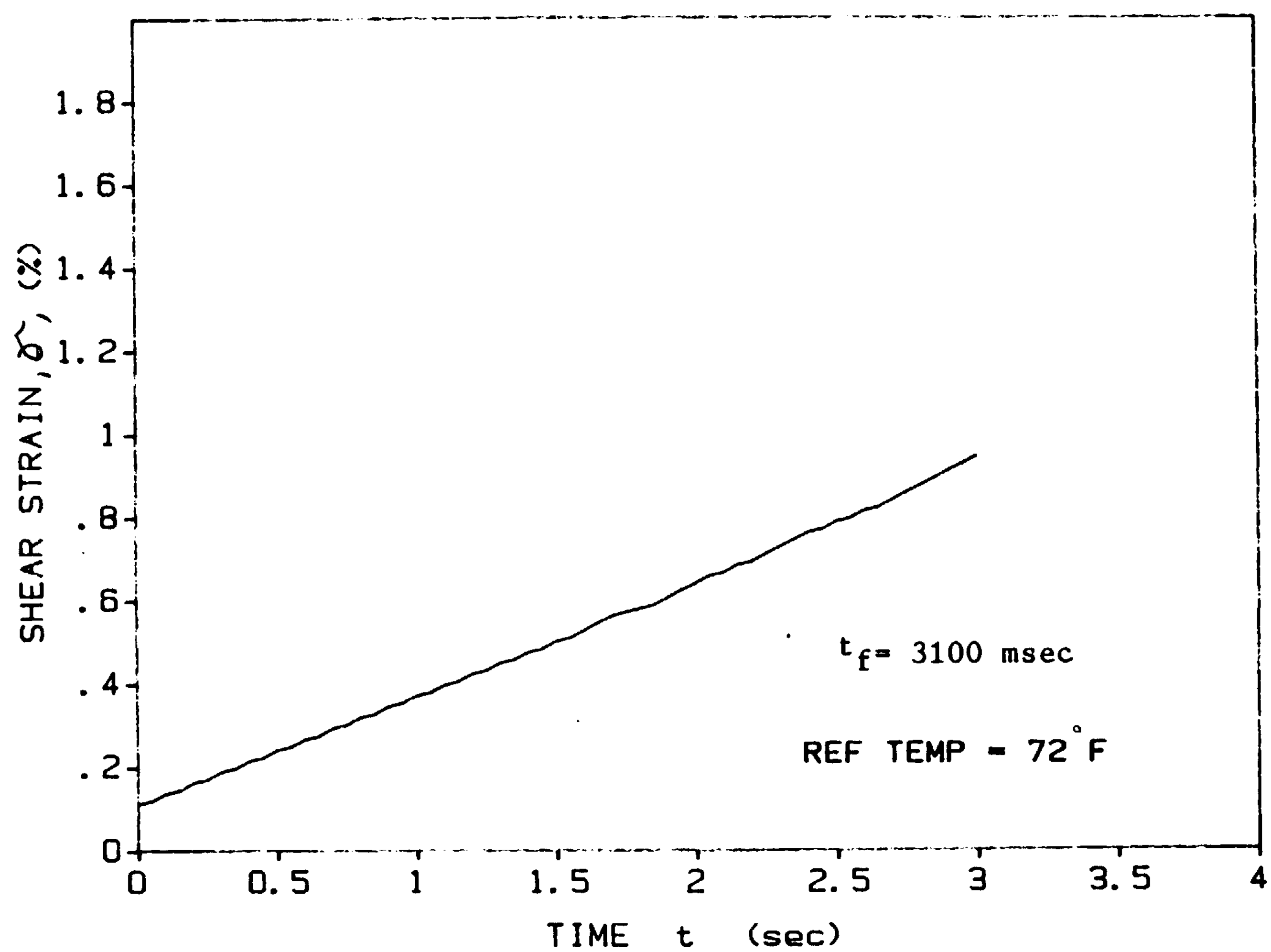


Fig. A-96. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-3L2 (T = 23°C (72°F))

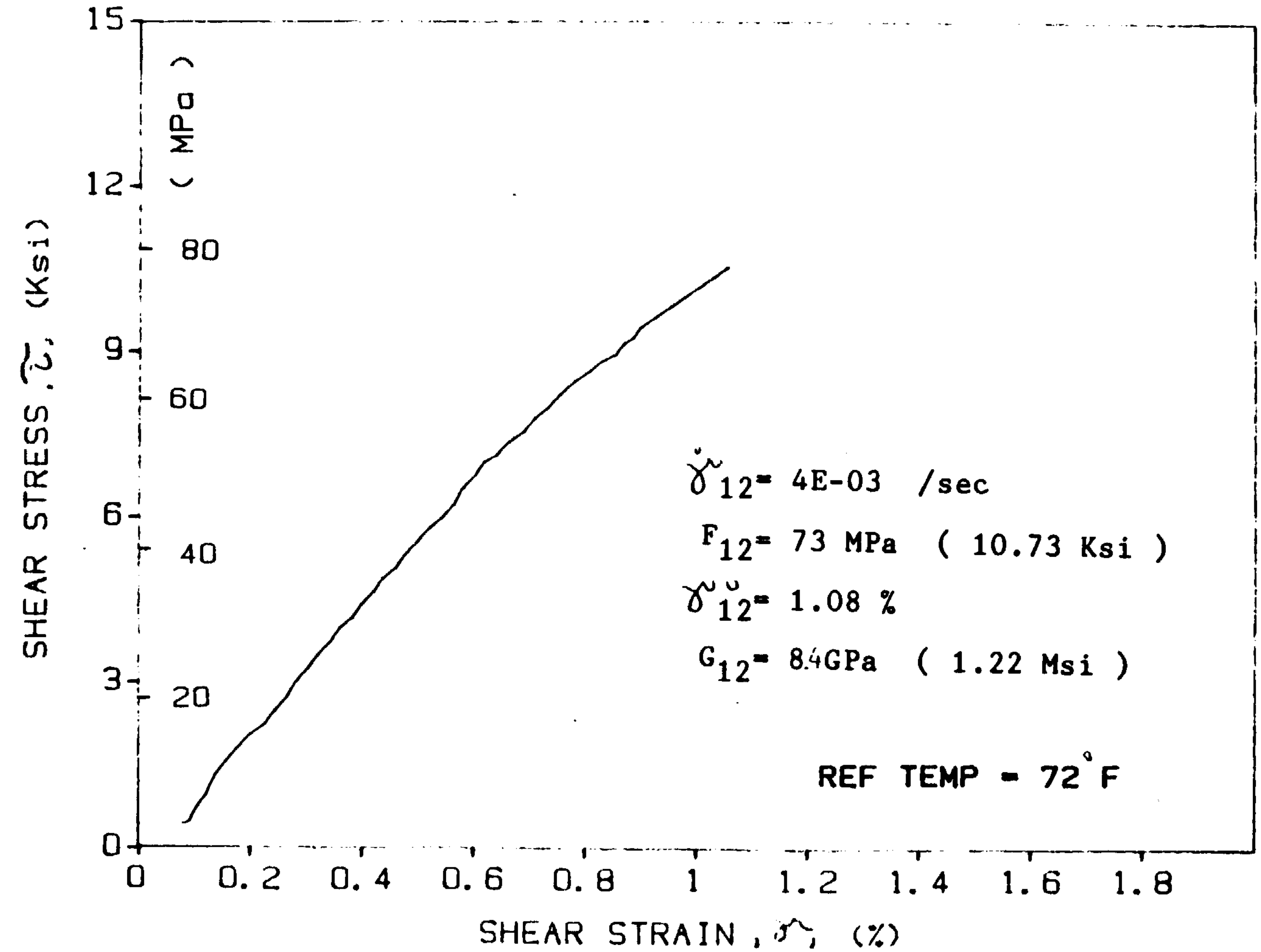


Fig. A-97. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-3L3 (T = 23°C (72°F))

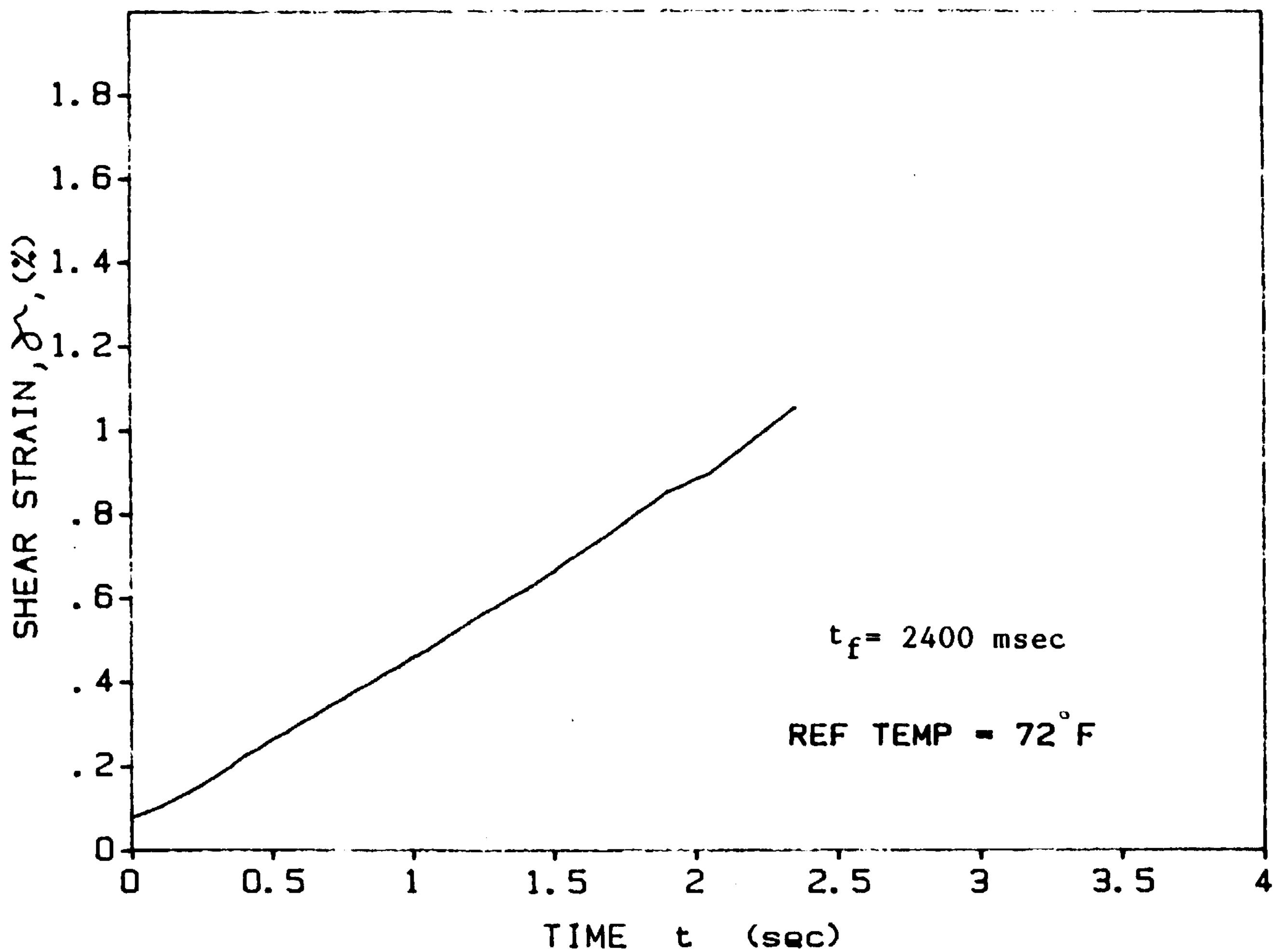


Fig. A-98. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-3L3 (T = 23°C (72°F))

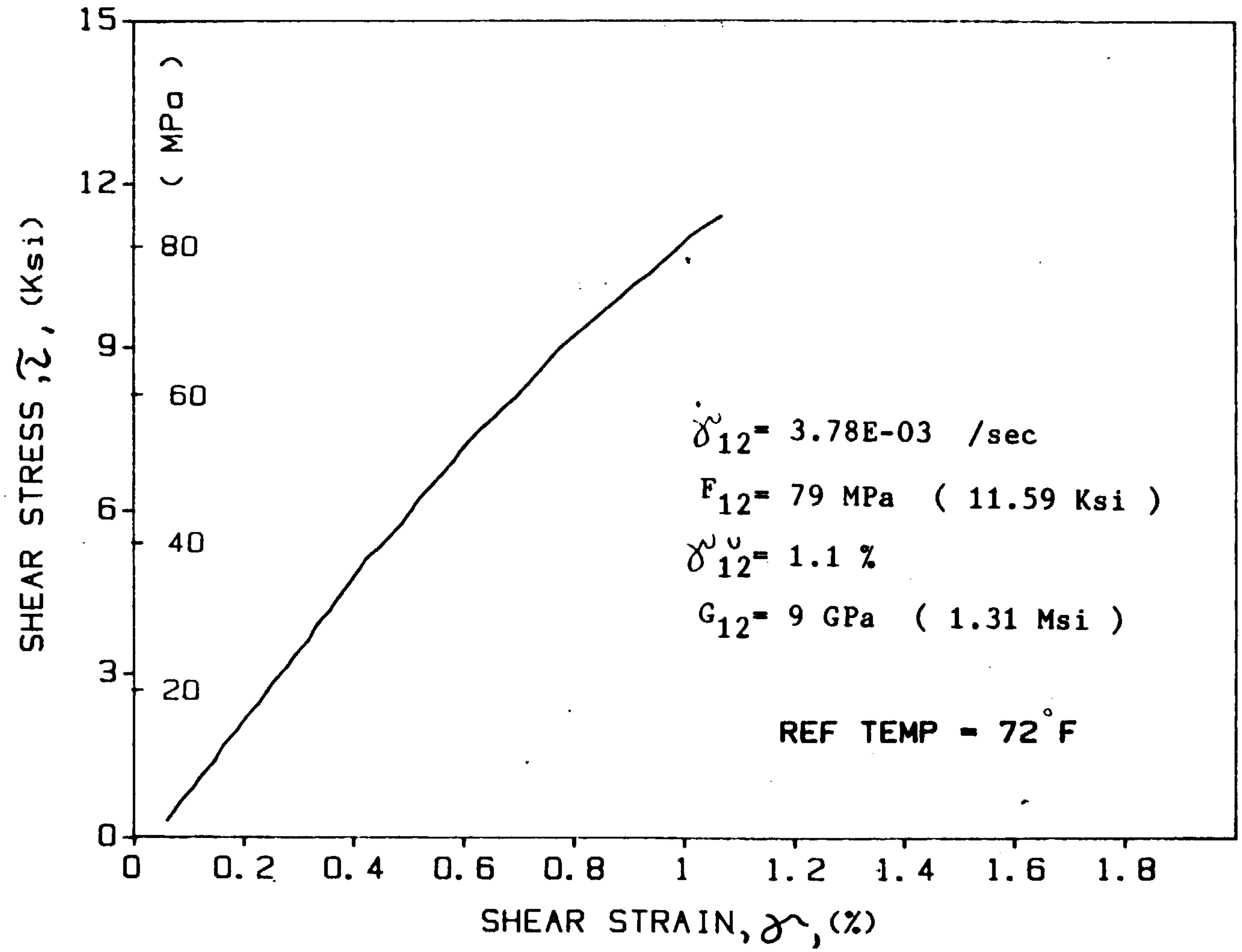


Fig. A-99. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-3L4 (T = 23°C (72°F)).

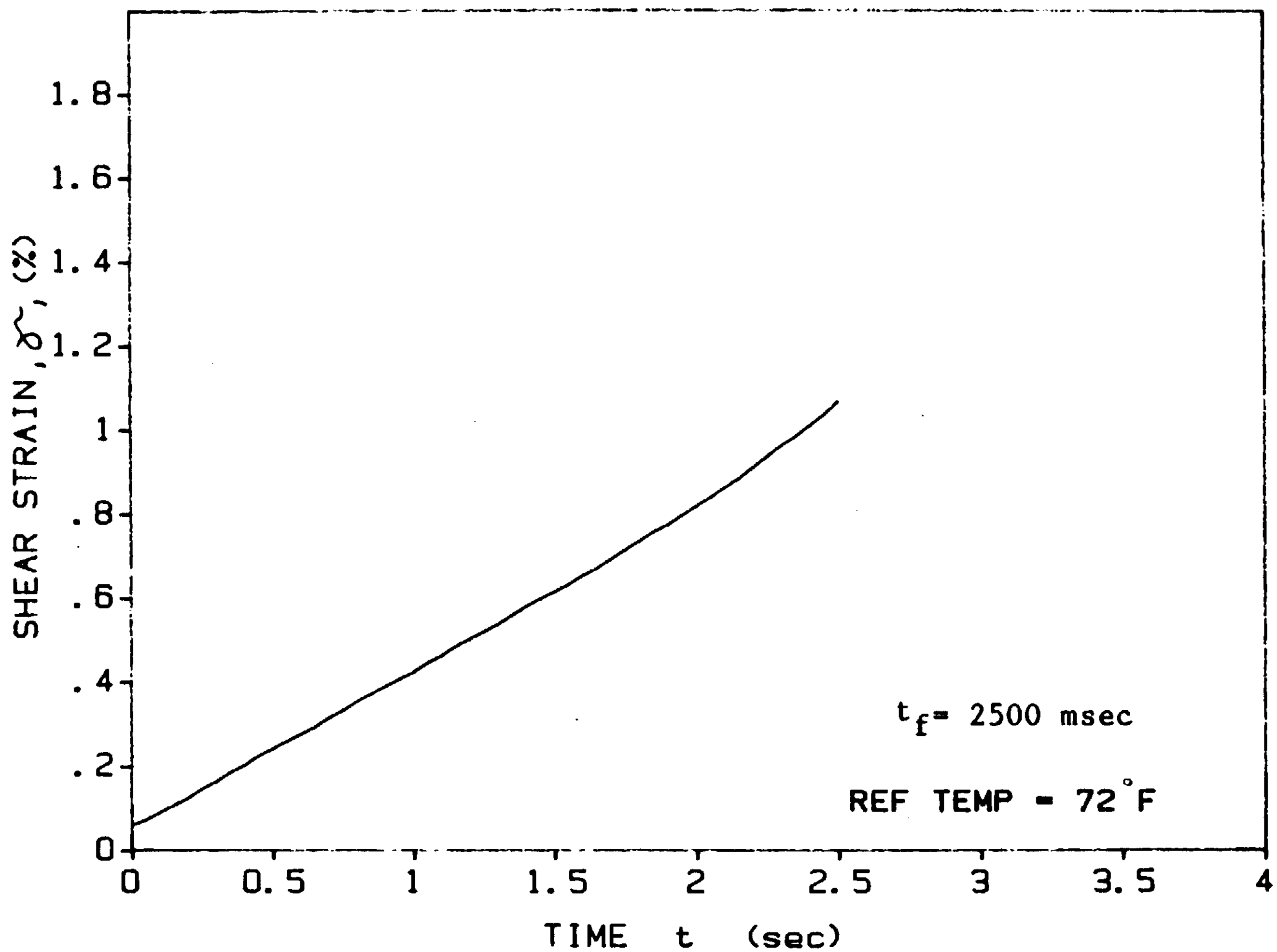


Fig. A-100. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-3L4 (T = 23°C (72°F))

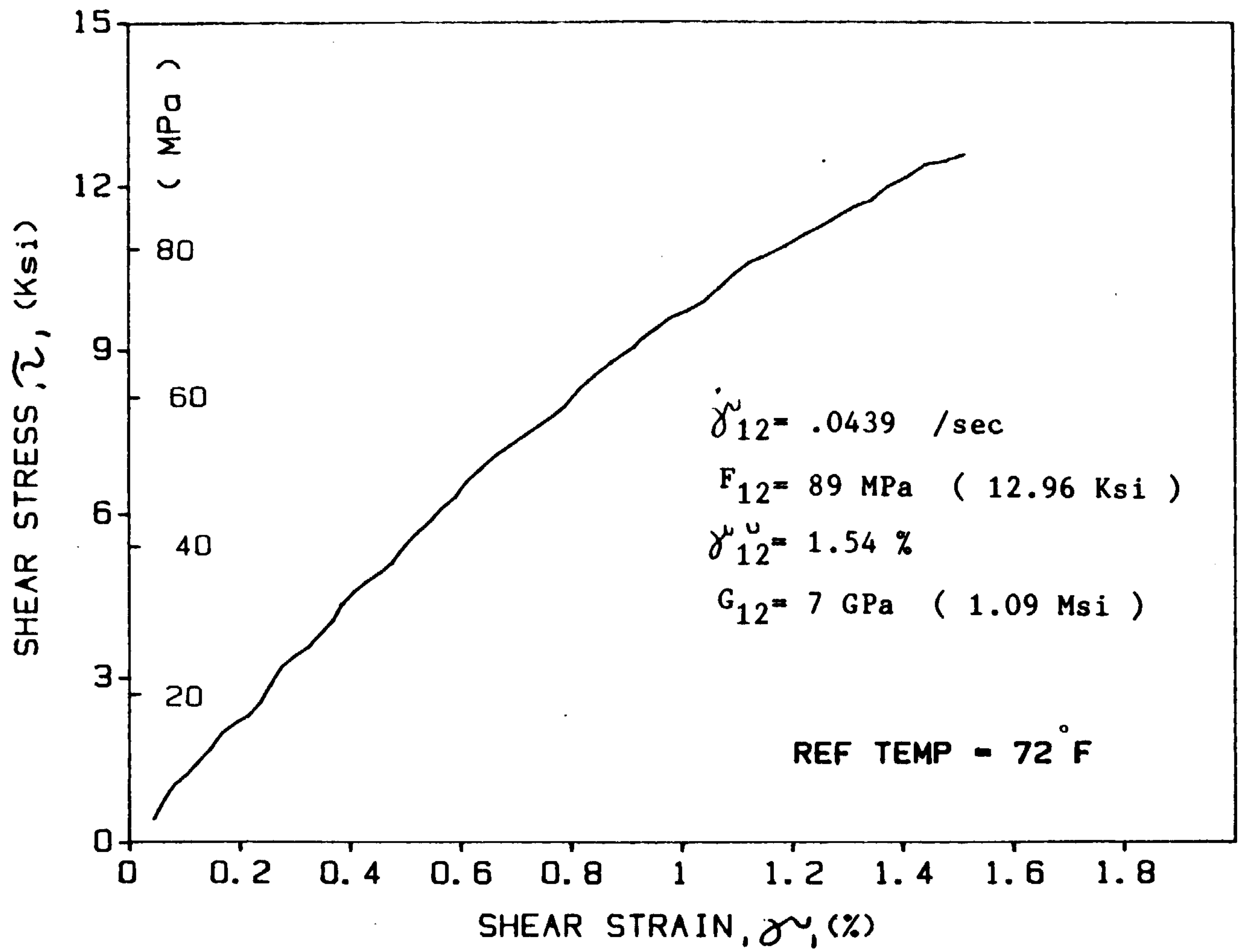


Fig. A-101. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L1 (T = 23°C (72°F))

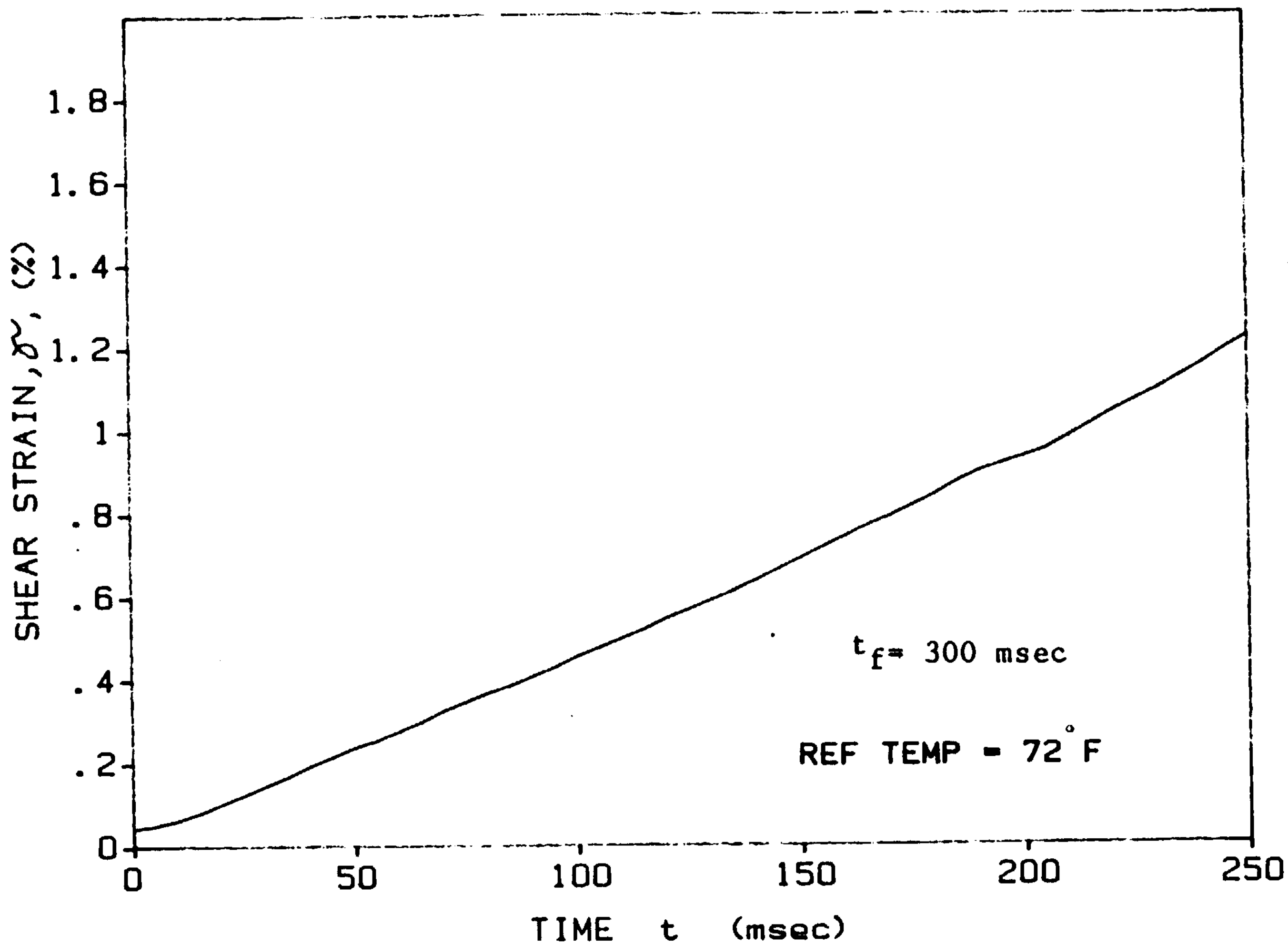


Fig. A-102. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L1 (T = 23°C (72°F))

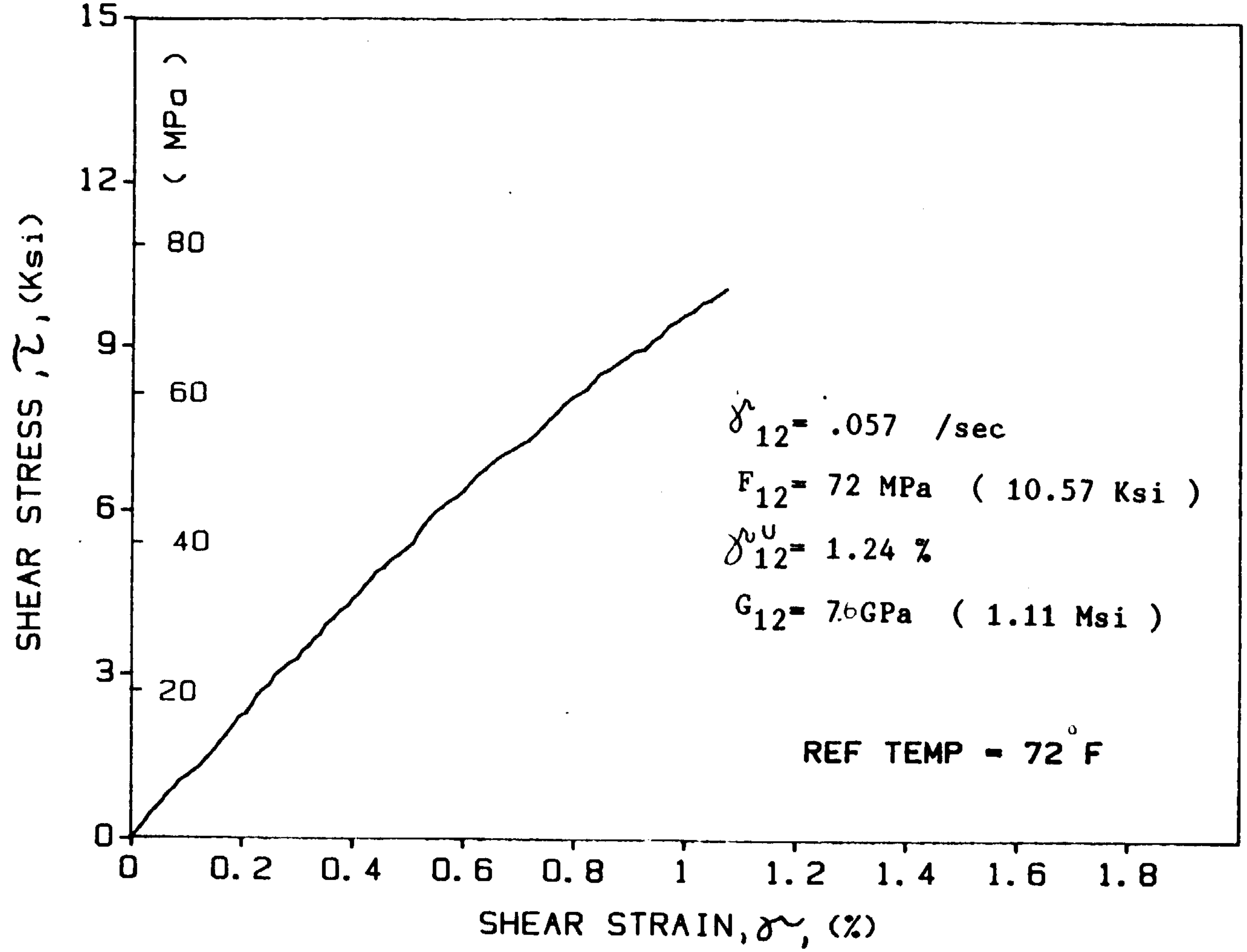


Fig. A-103. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L2 (T = 23°C (72°F))

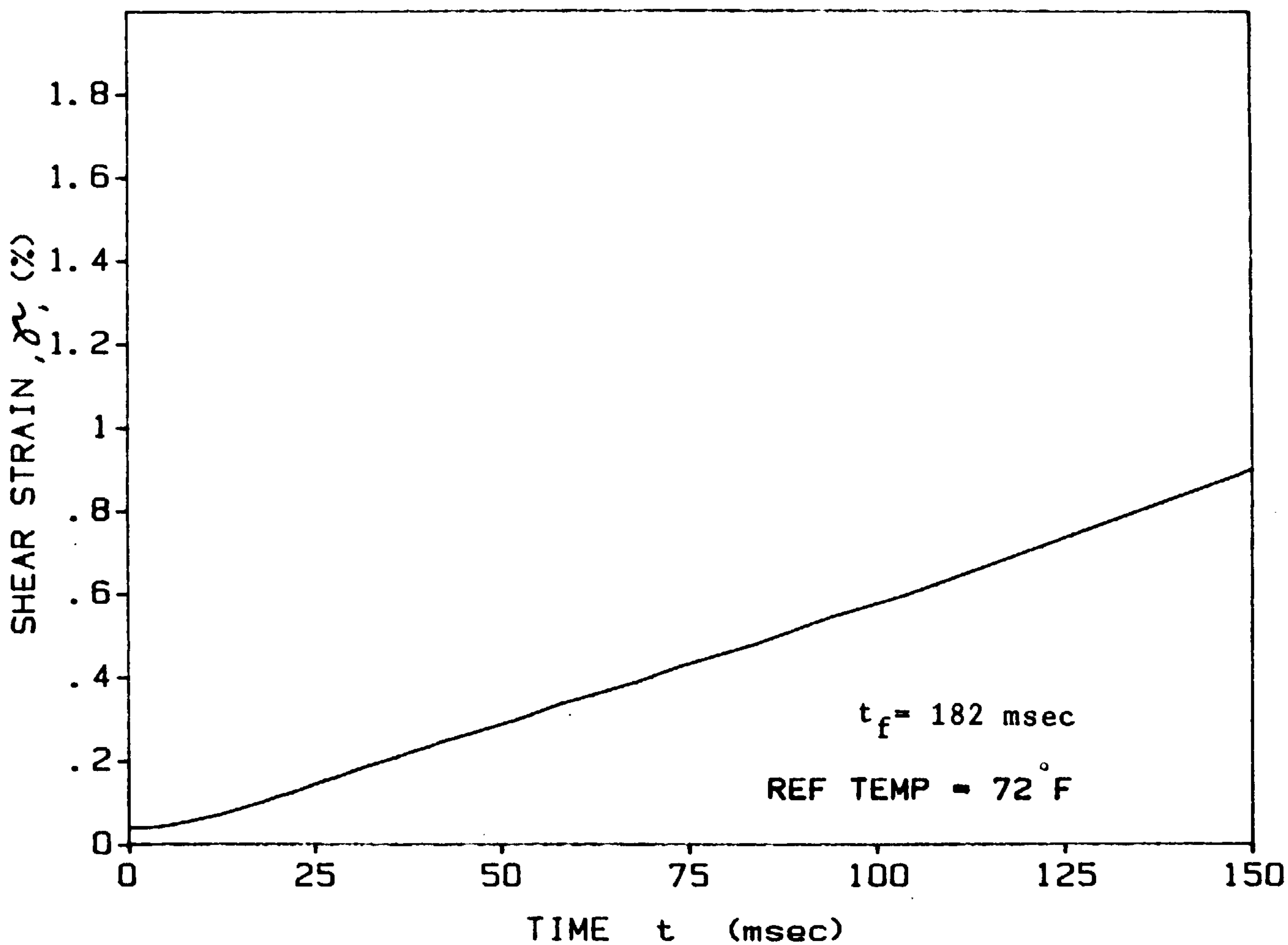


Fig. A-104. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L2 (T = 23°C (72°F))

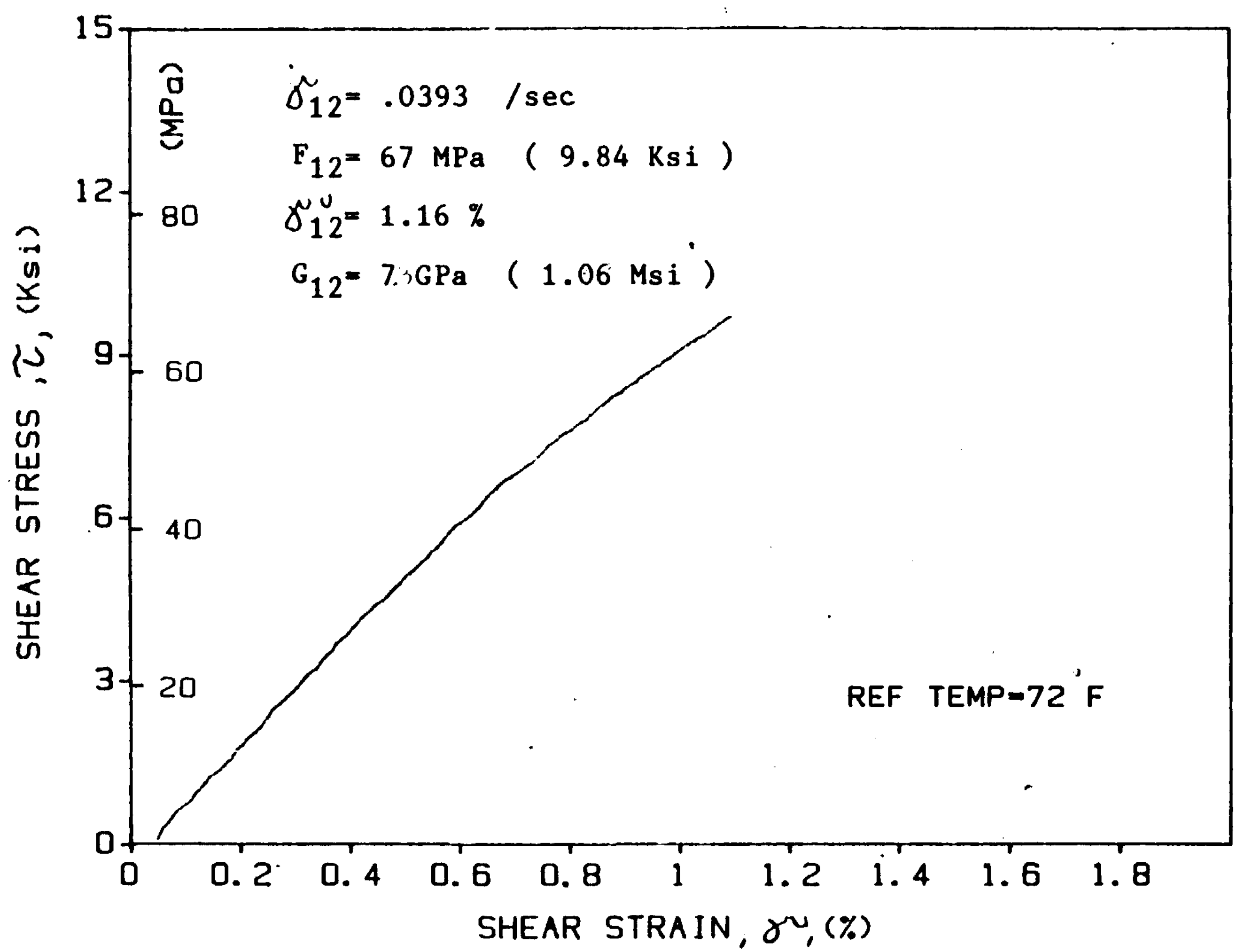


Fig. A-105. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L4 (T = 23°C (72°F))

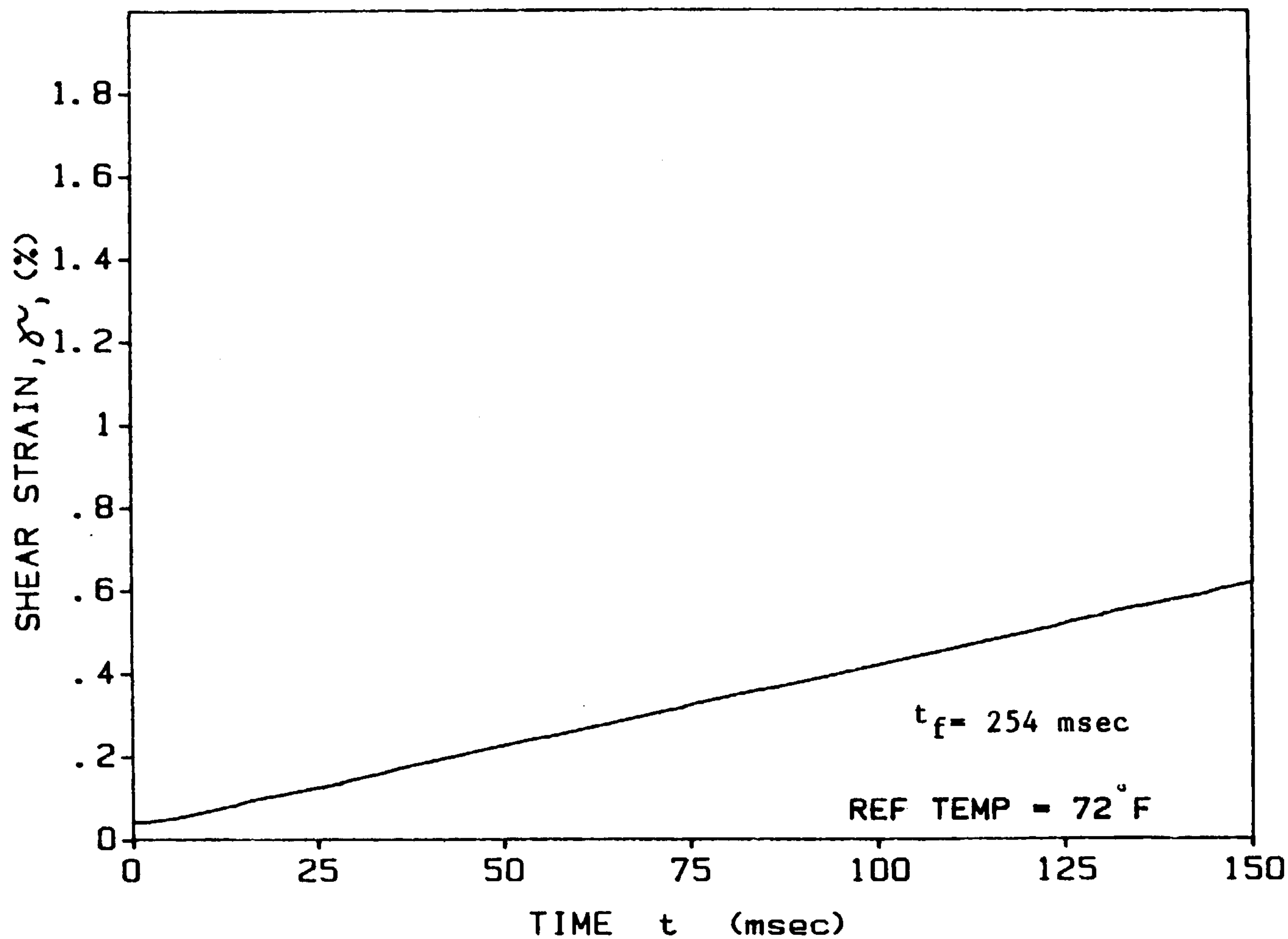


Fig. A-106. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L4 (T = 23°C (72°F))

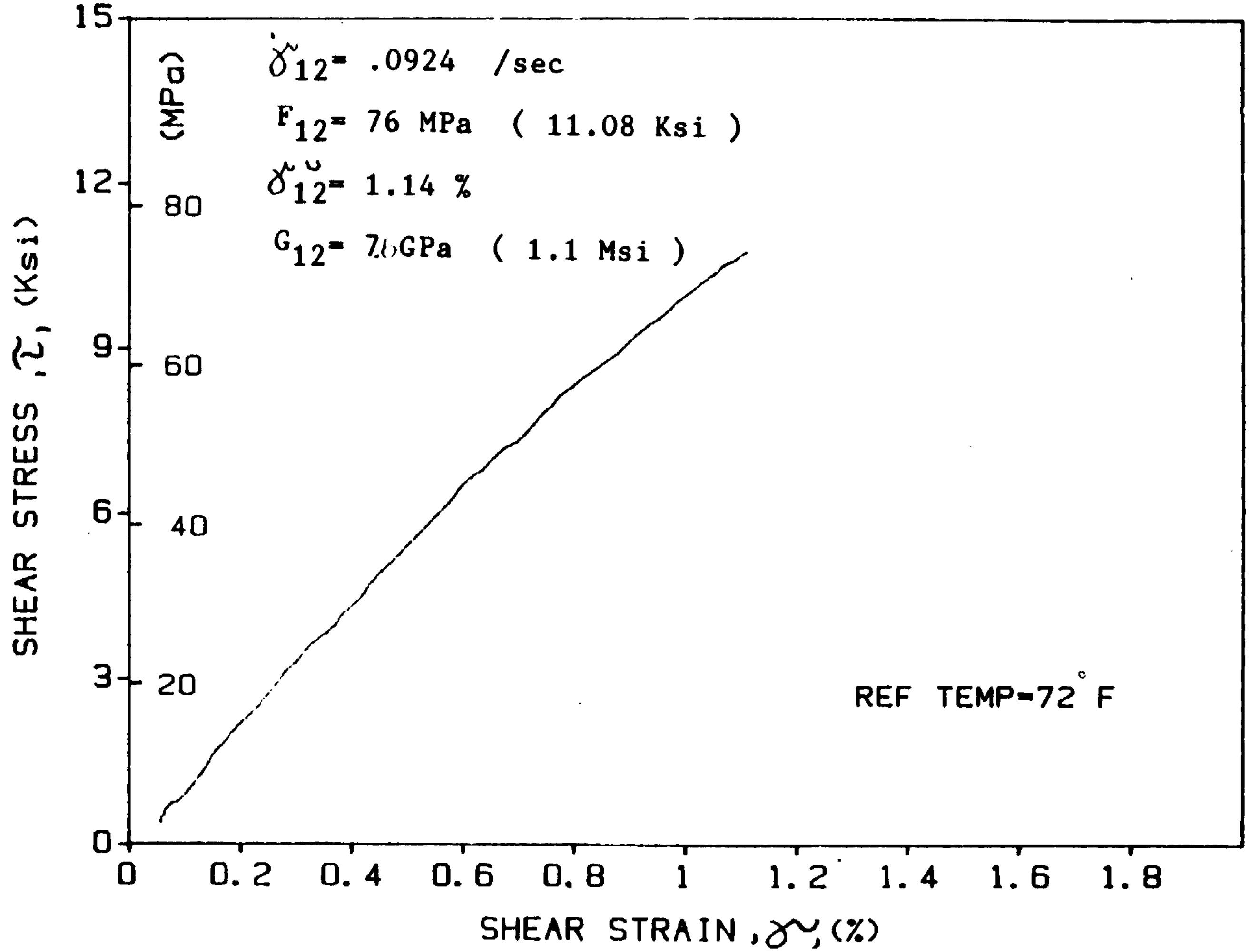


Fig. A-107. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L5 (T = 23°C (72°F))

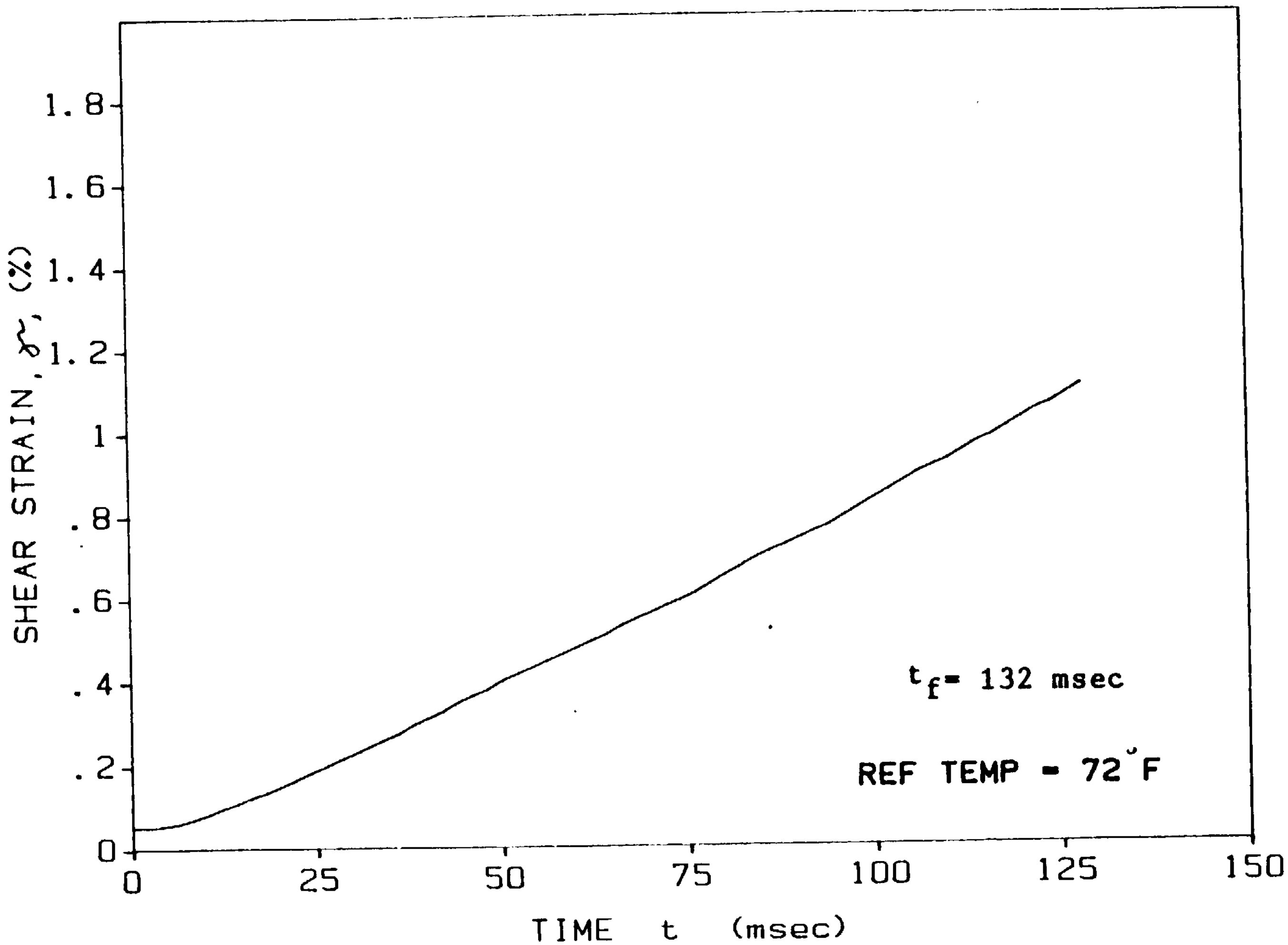


Fig. A-108. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L5 (T = 23°C (72°F))

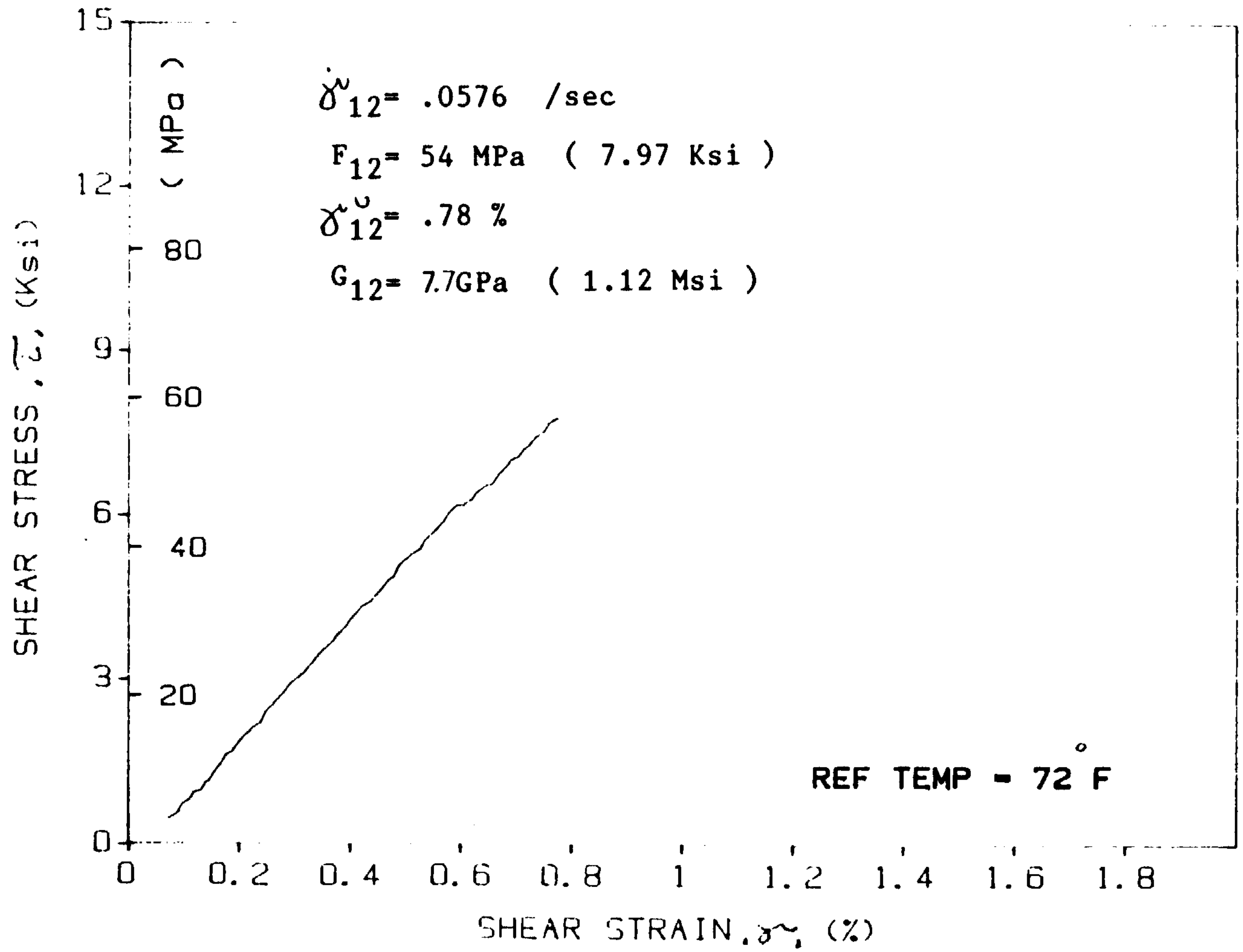


Fig. A-109. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L6 (T = 23°C (72°F))

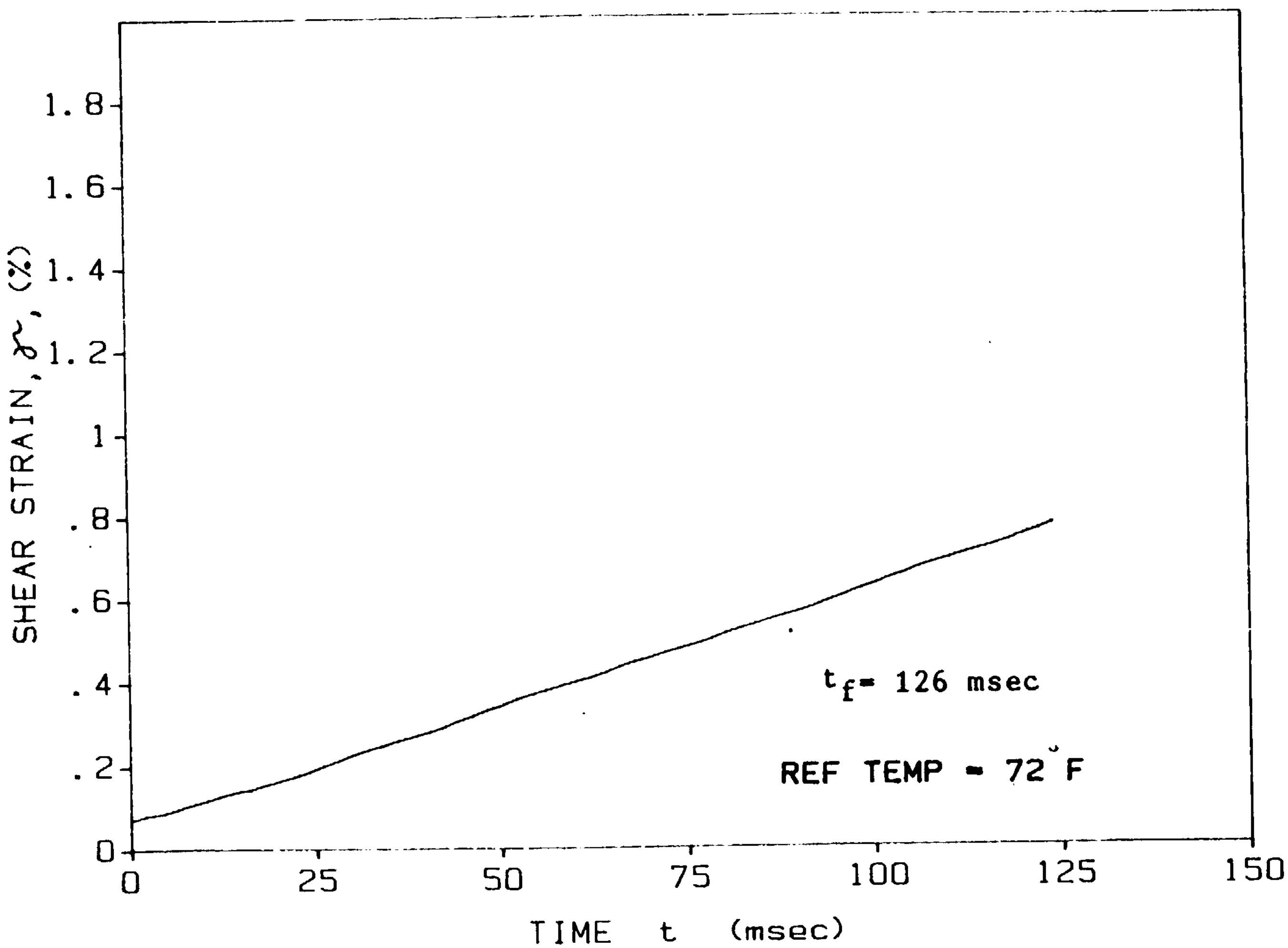


Fig. A-110. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L6 (T = 23°C (72°F))

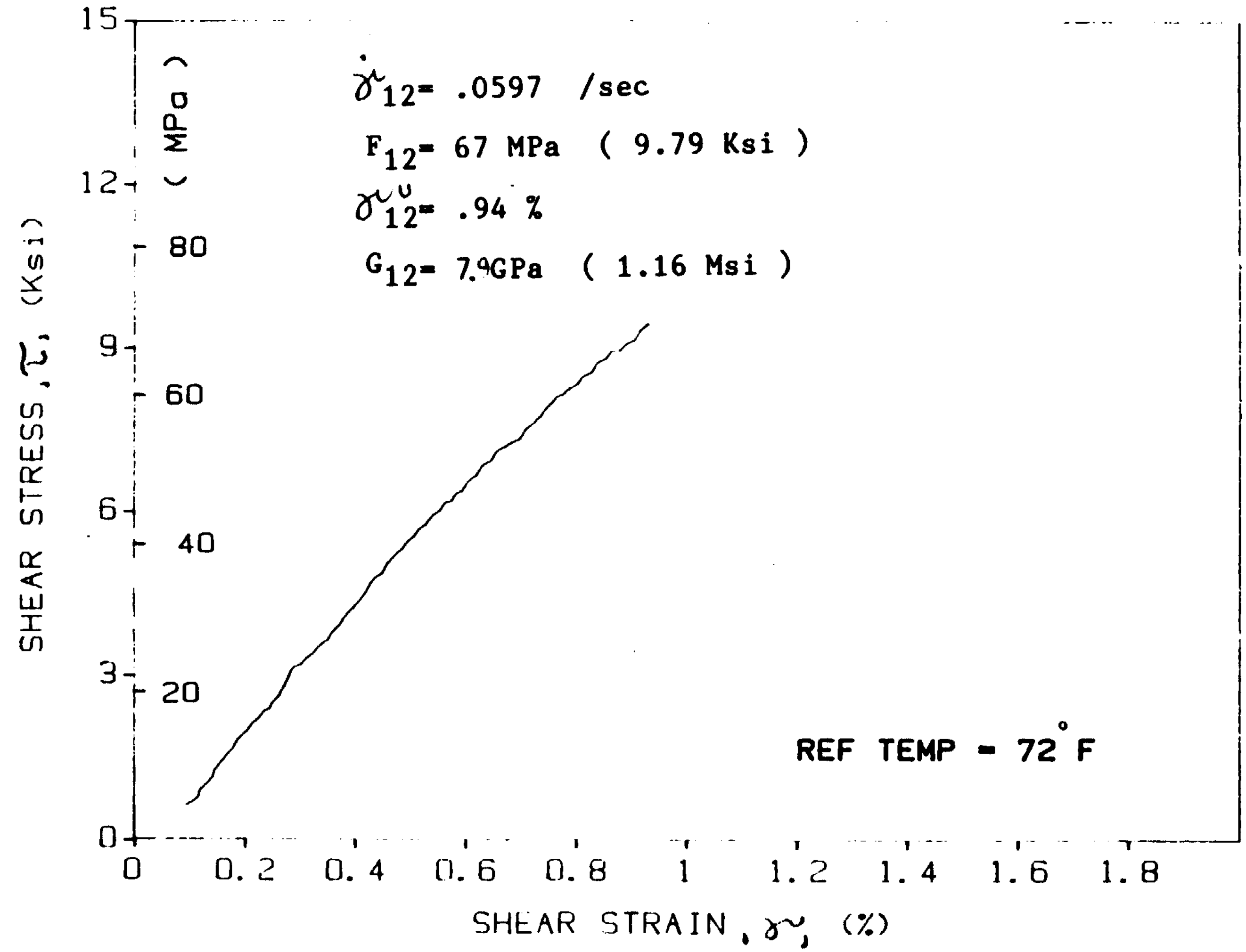


Fig. A-111. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L7 (T = 23°C (72°F))

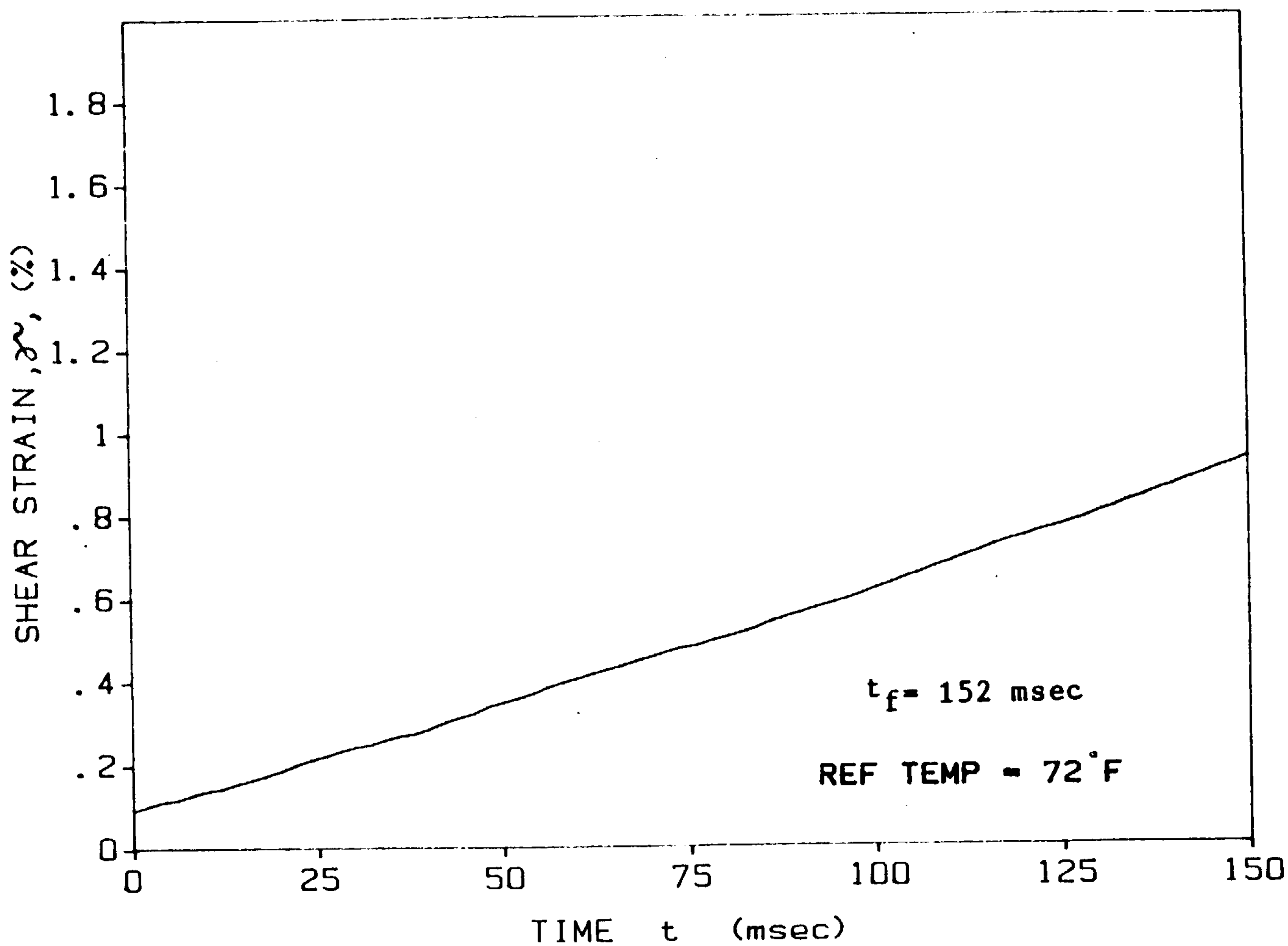


Fig. A-112. Shear Strain Vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L7 (T = 23°C (72°F))

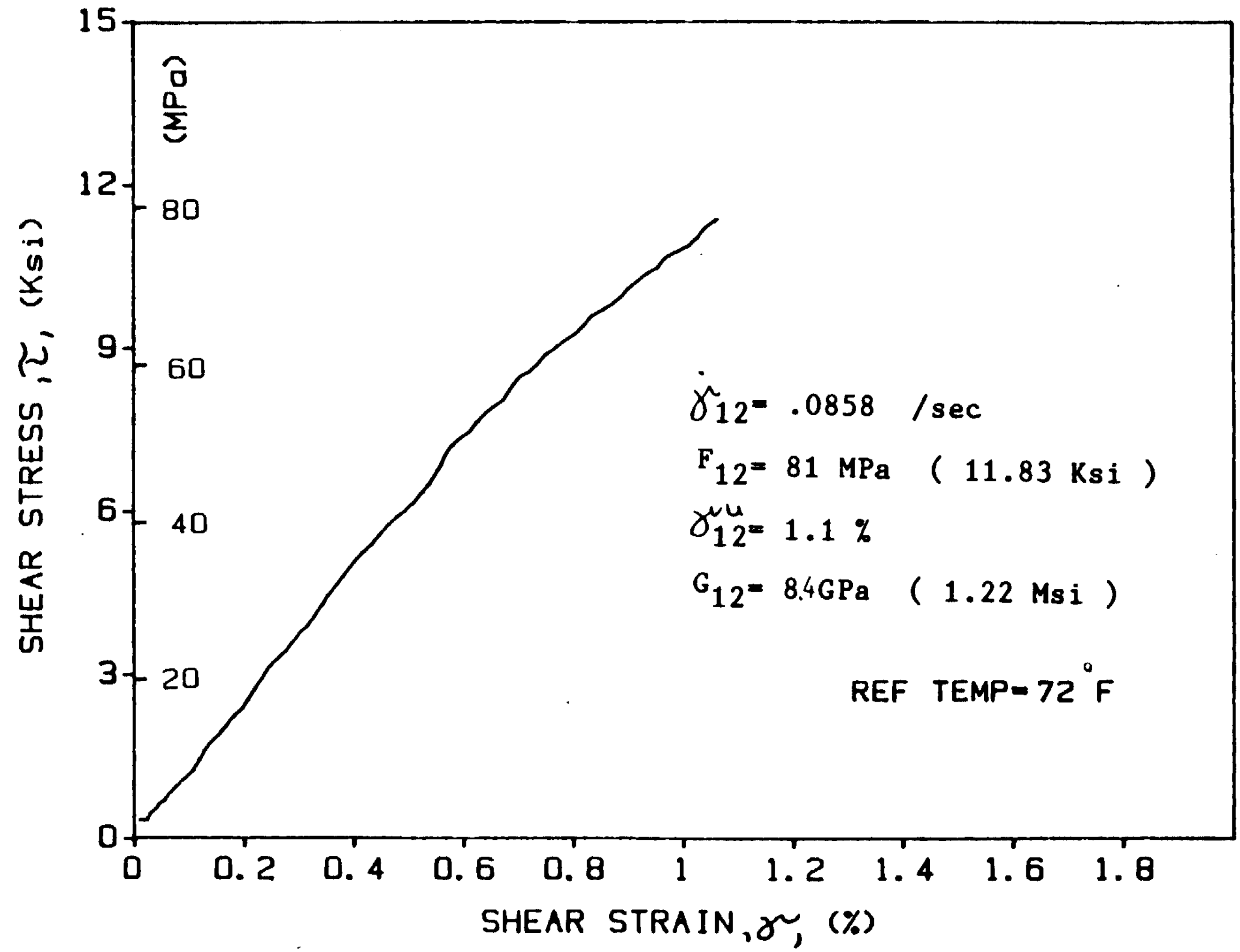


Fig. A-113. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L9 (T = 23°C (72°F))

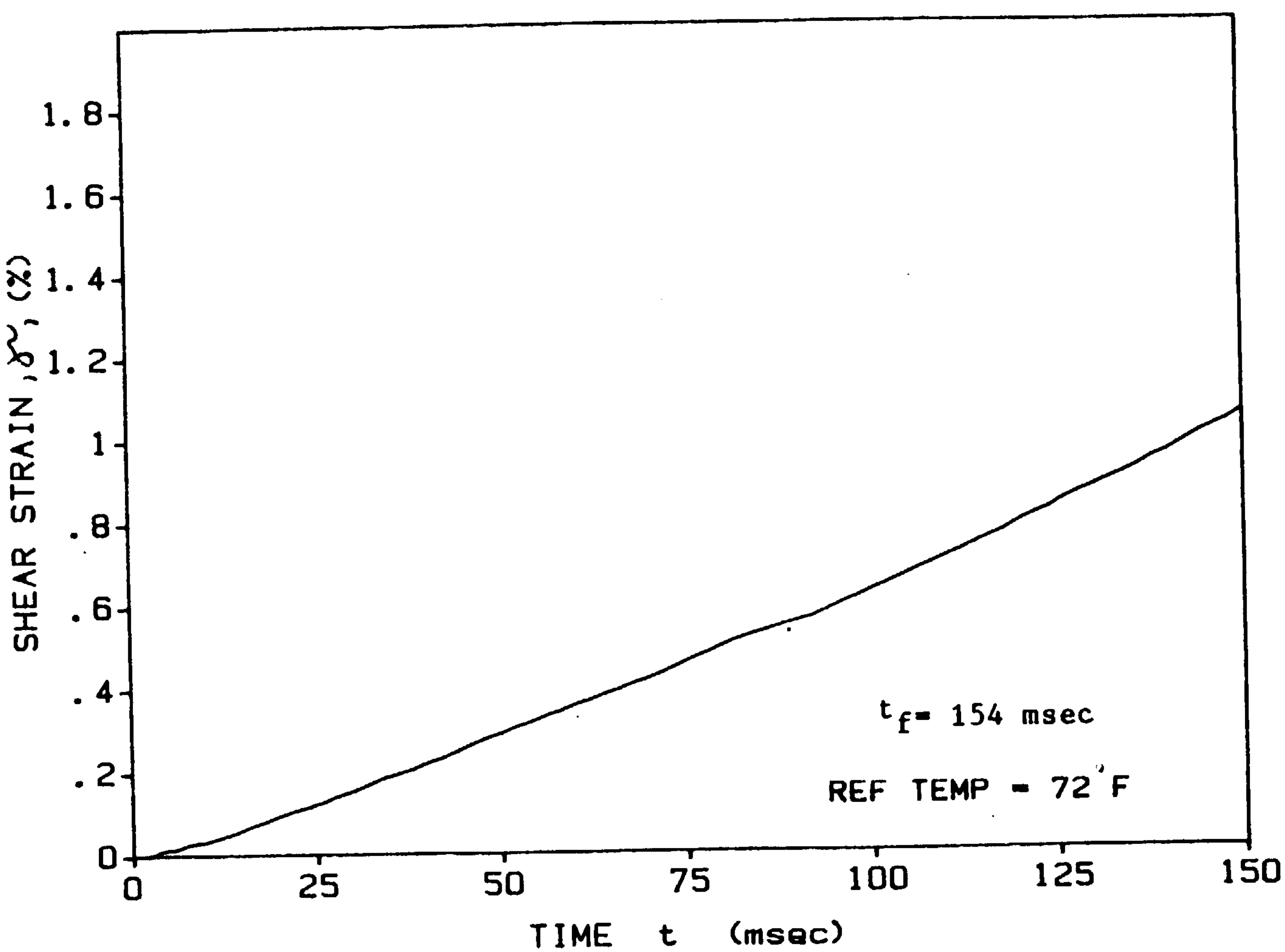


Fig. A-114. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L9 (T = 23°C (72°F))

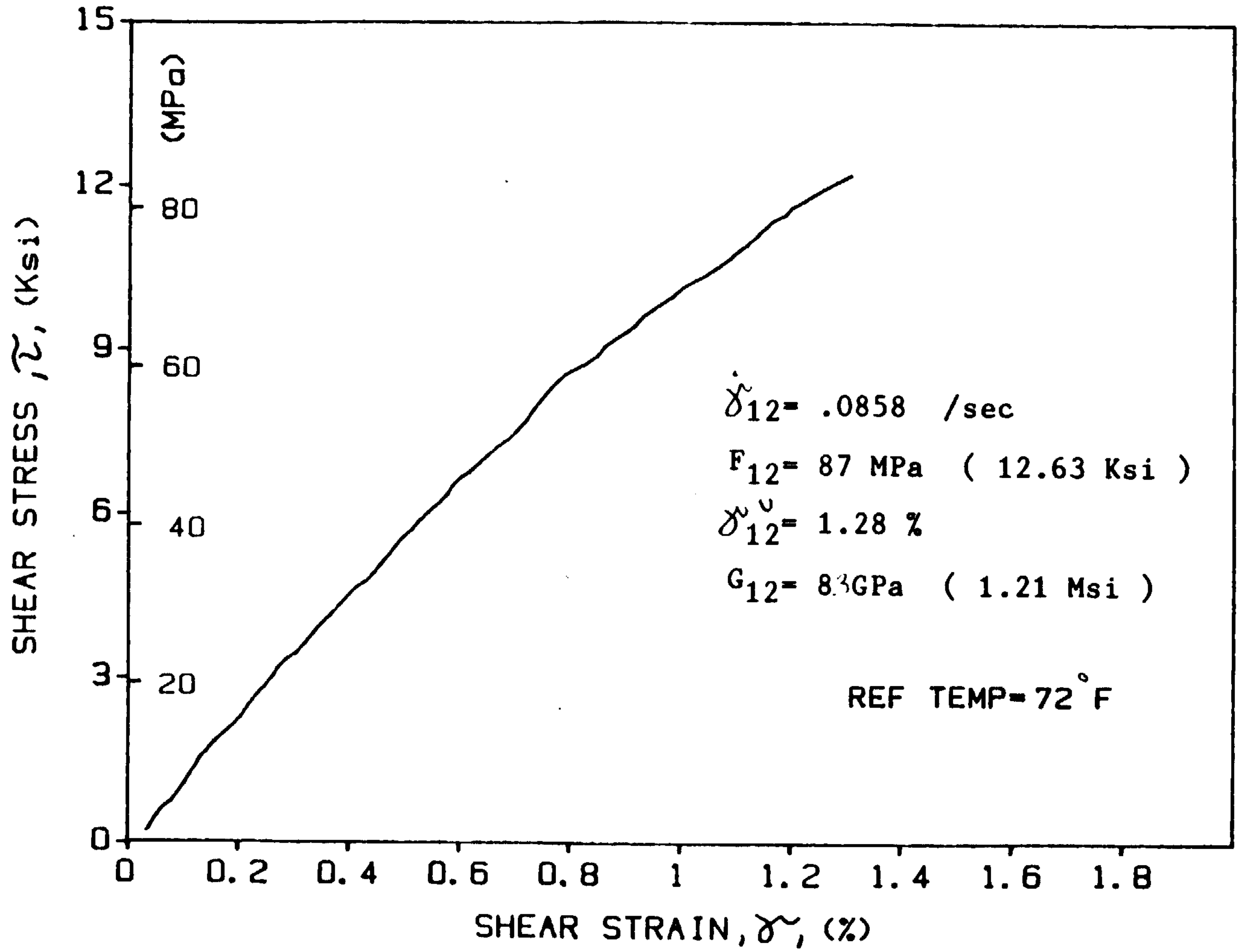


Fig. A-115. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L10 (T = 23°C (72°F))

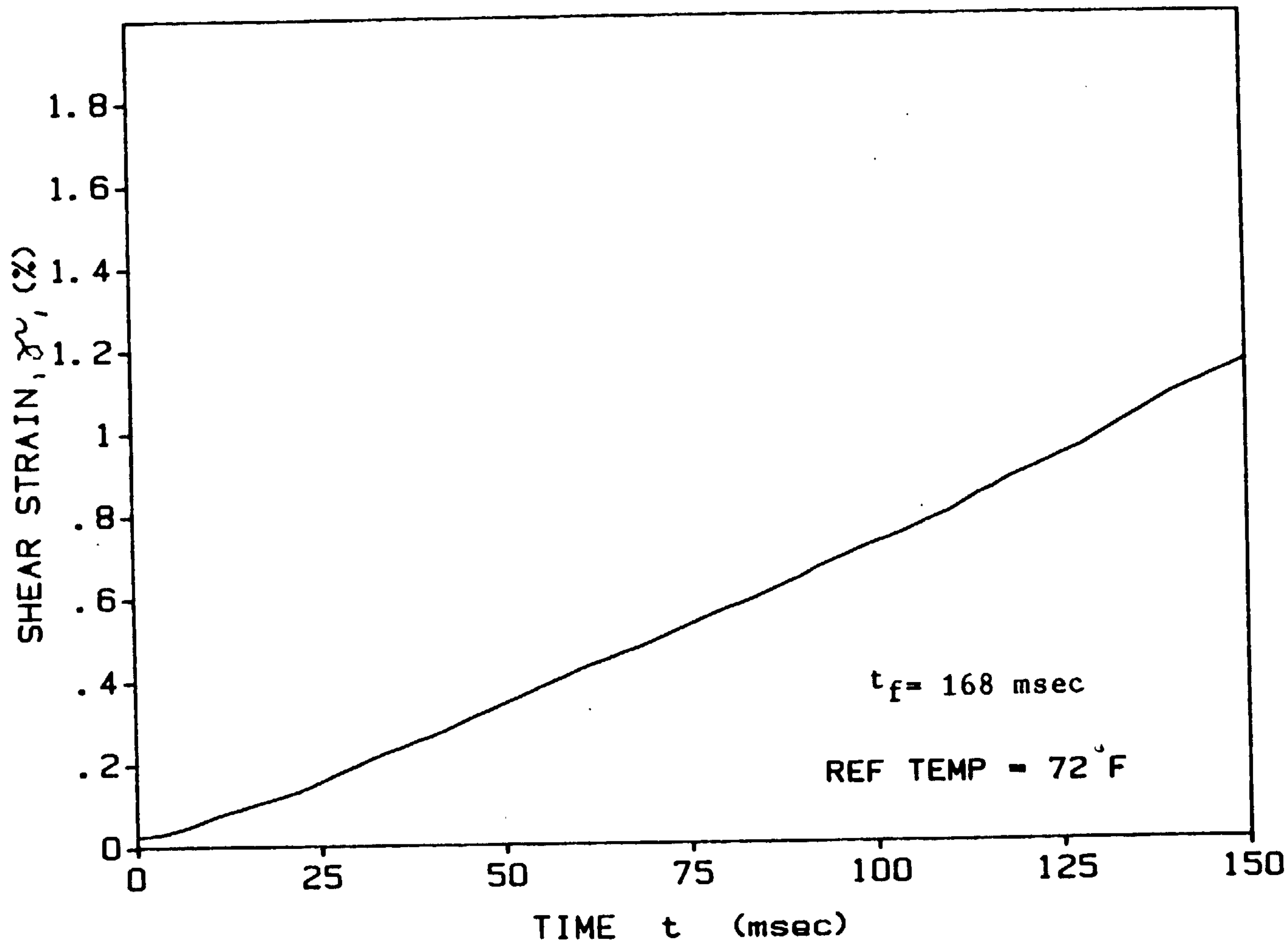


Fig. A-116. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2L10 (T = 23°C (72°F))

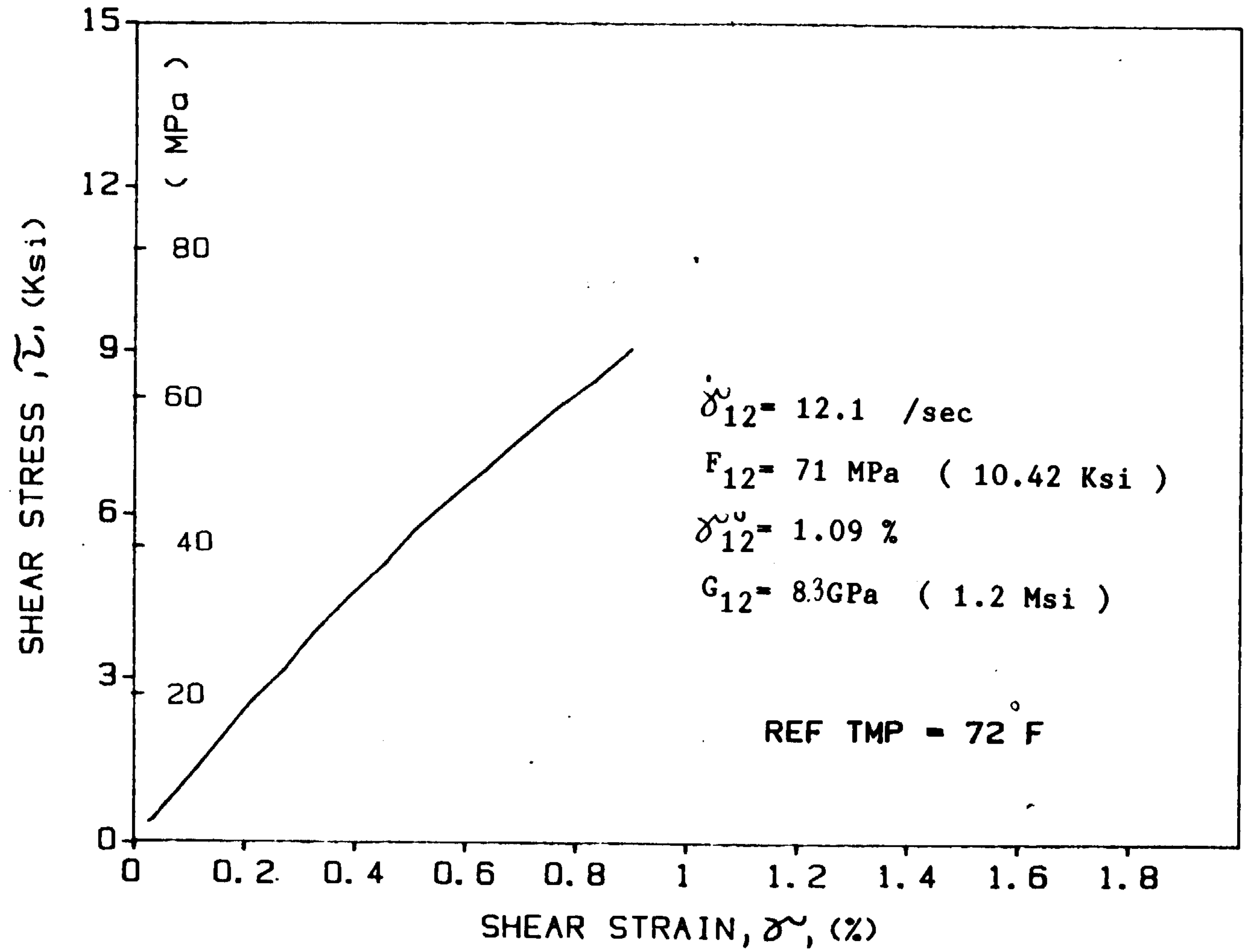


Fig. A-117. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-1L1 (T = 23°C (72°F))

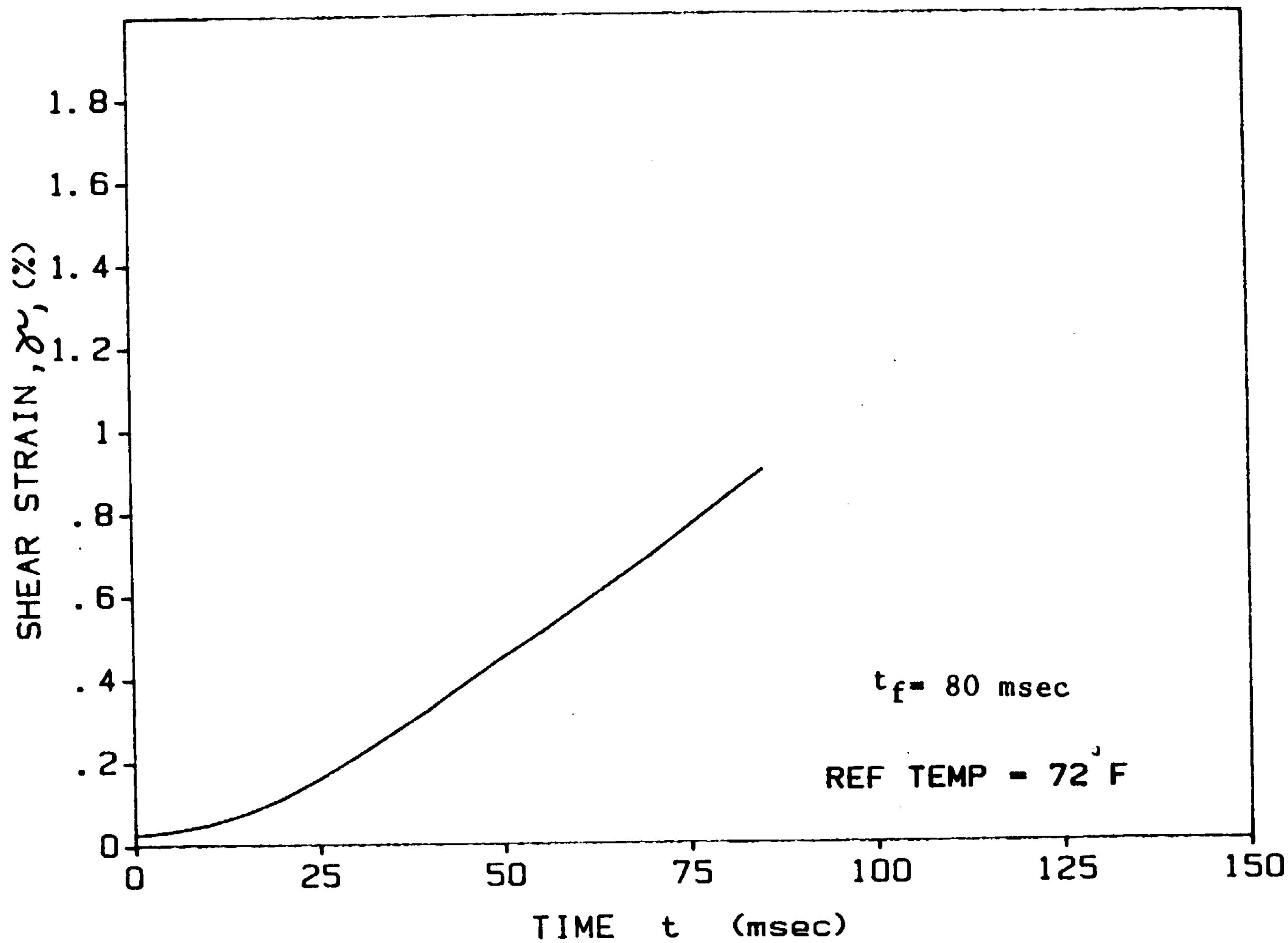


Fig. A-118. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-1L1 (T = 23°C (72°F))

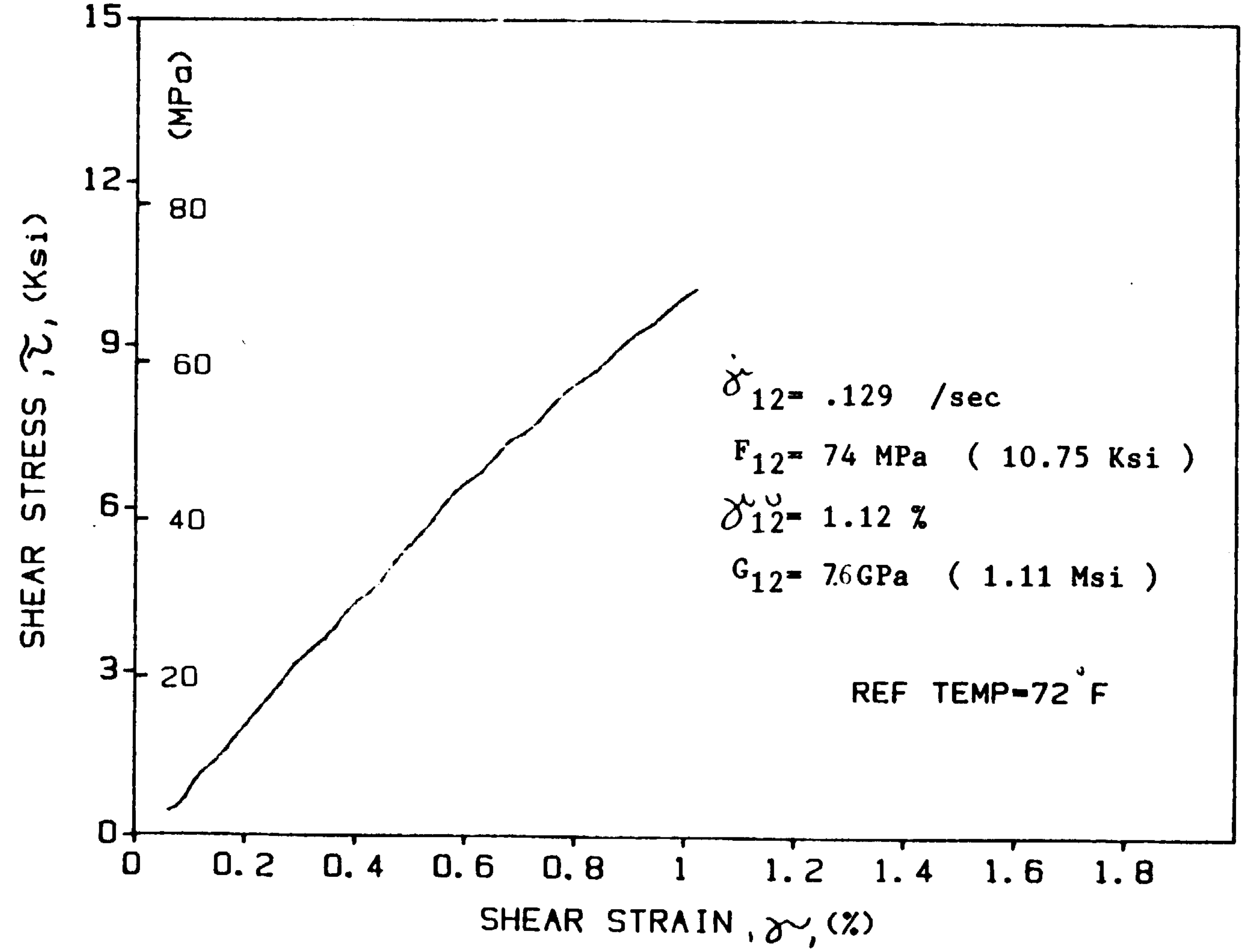


Fig. A-119. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-1L2 (T = 23°C (72°F))

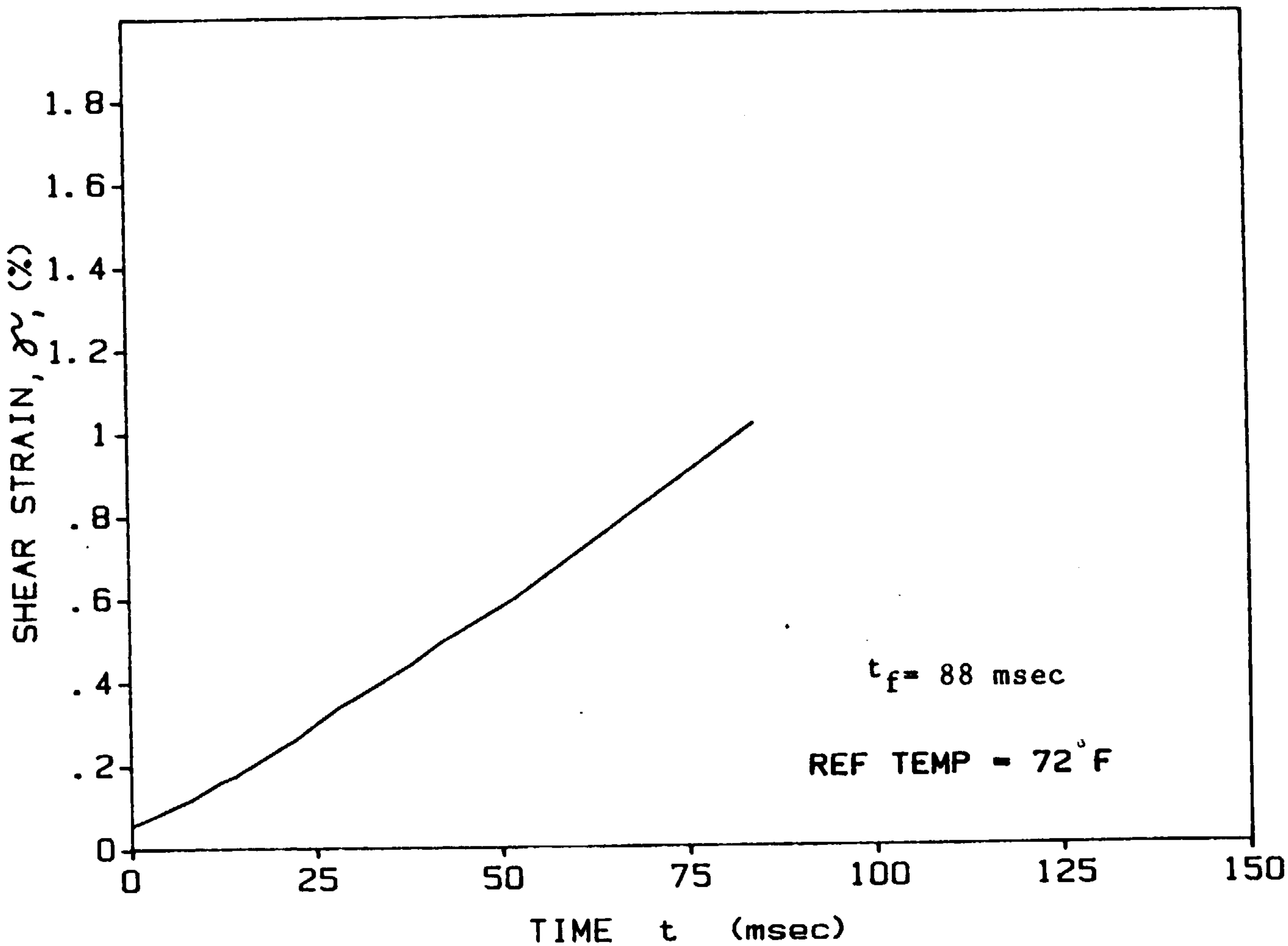


Fig. A-120. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-1L2 (T = 23°C (72°F))

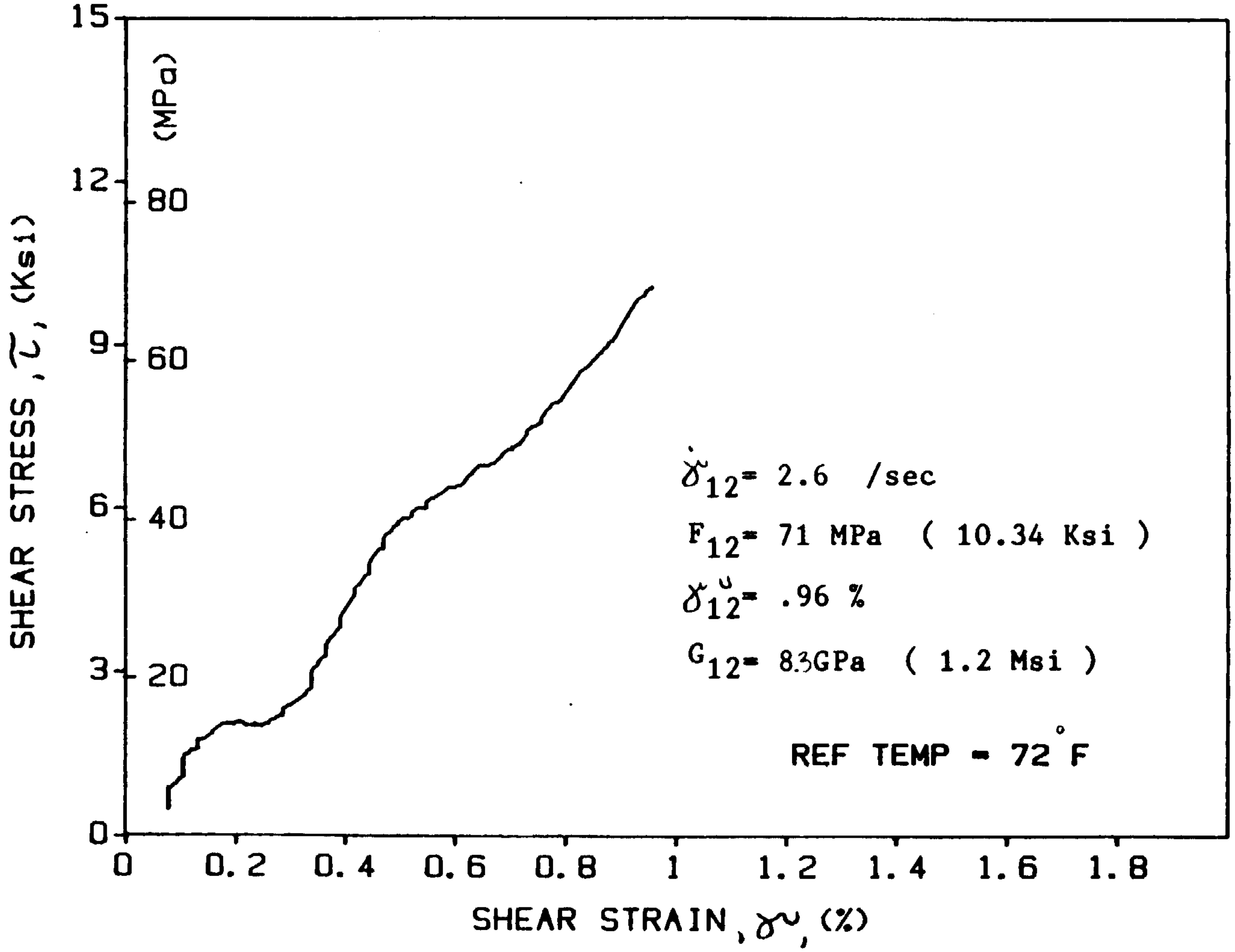


Fig. A-121. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L1 (T = 23°C (72°F))

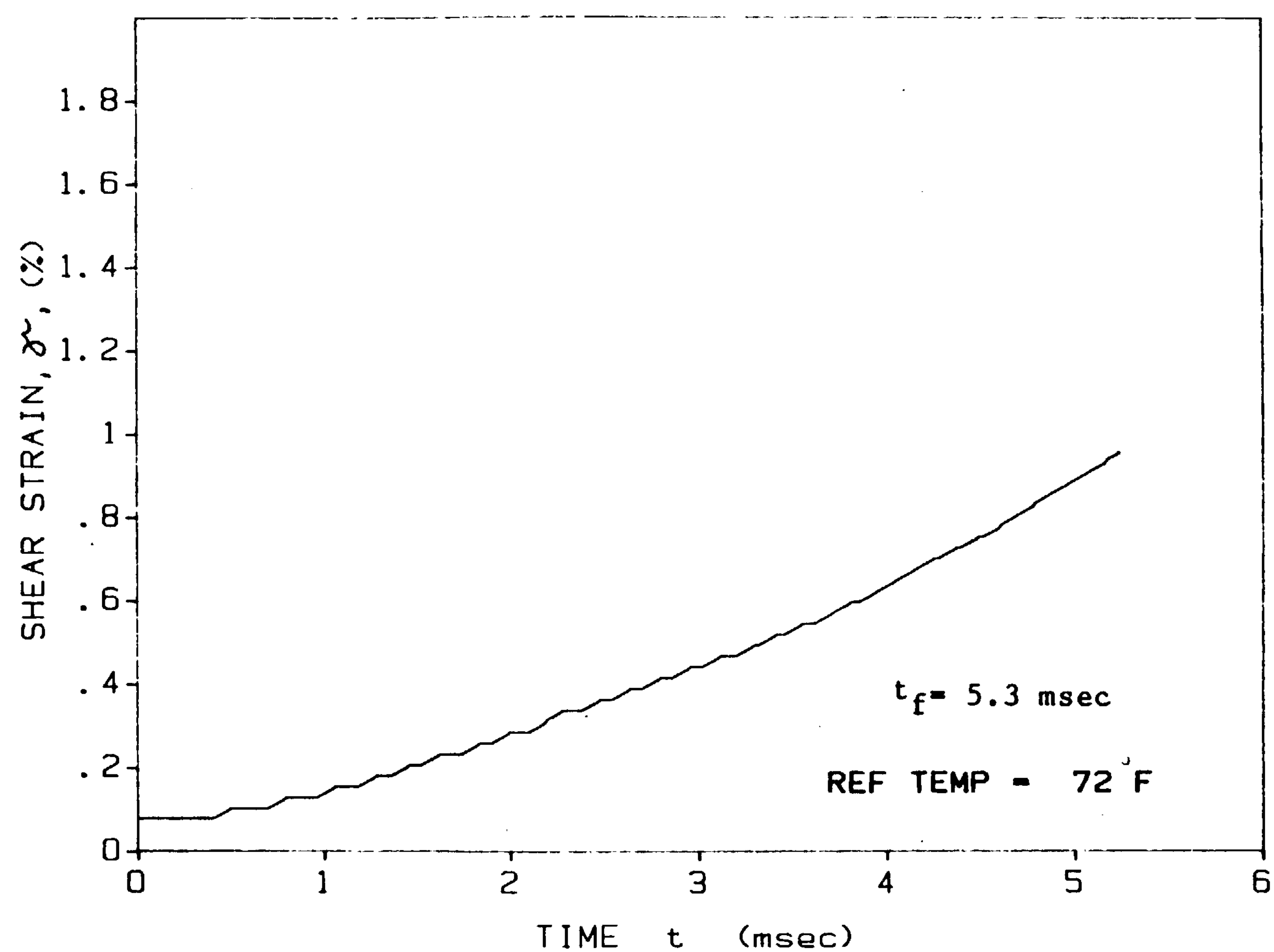


Fig. A-122. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L1 (T = 23°C (72°F))

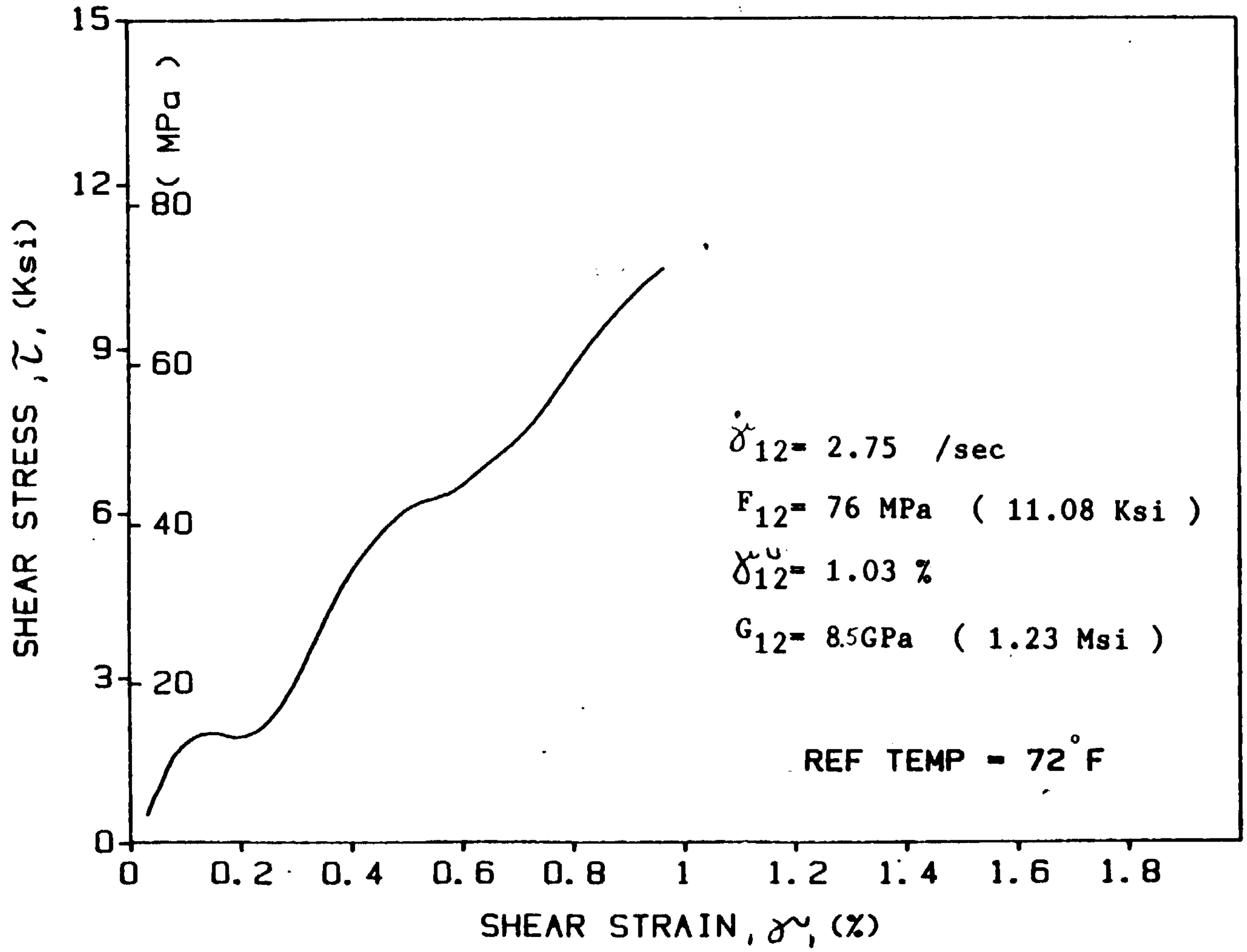


Fig. A-123. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L2 (T = 23°C (72°F)).

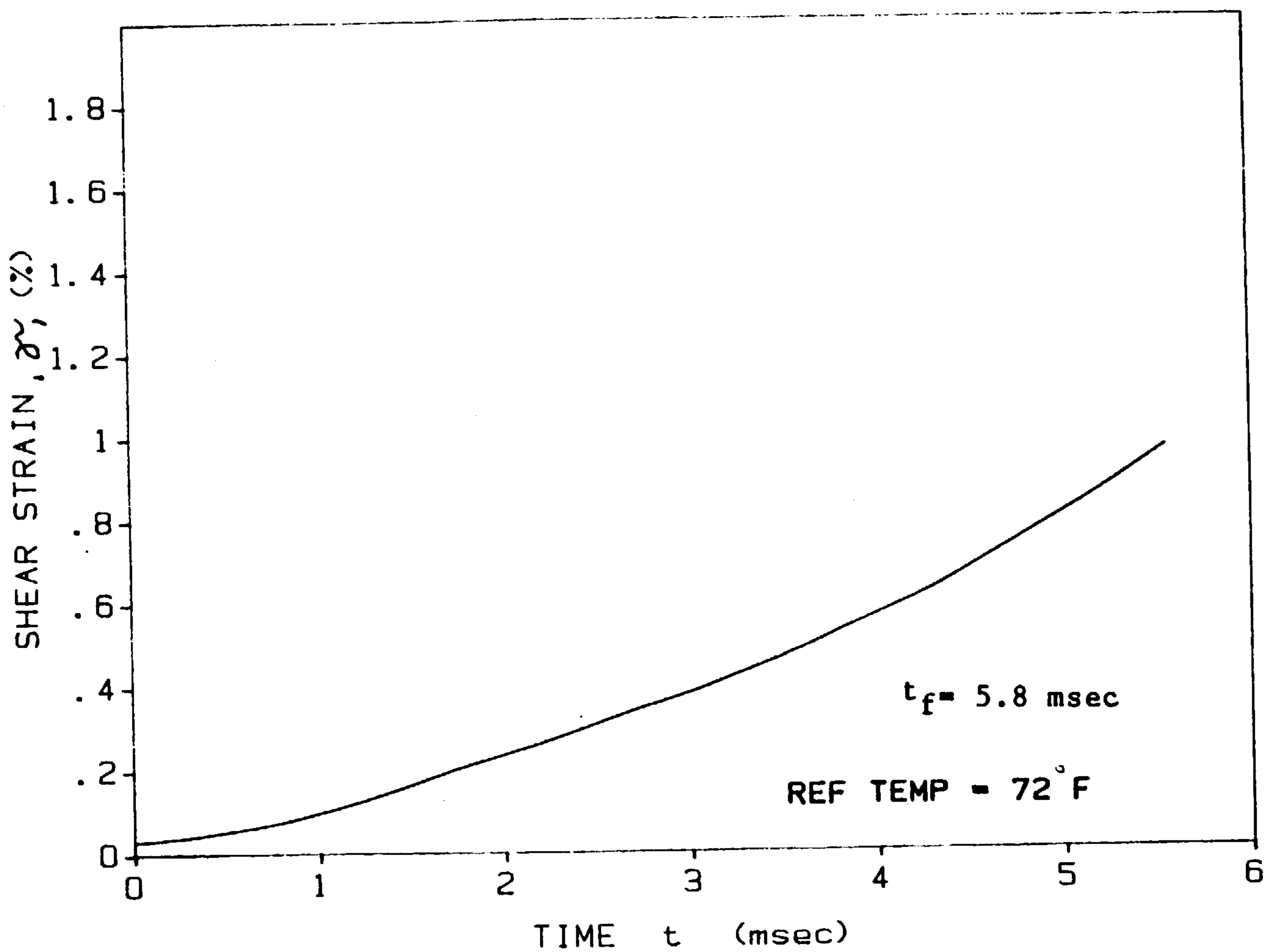


Fig. A-124. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L2 (T = 23°C (72°F))

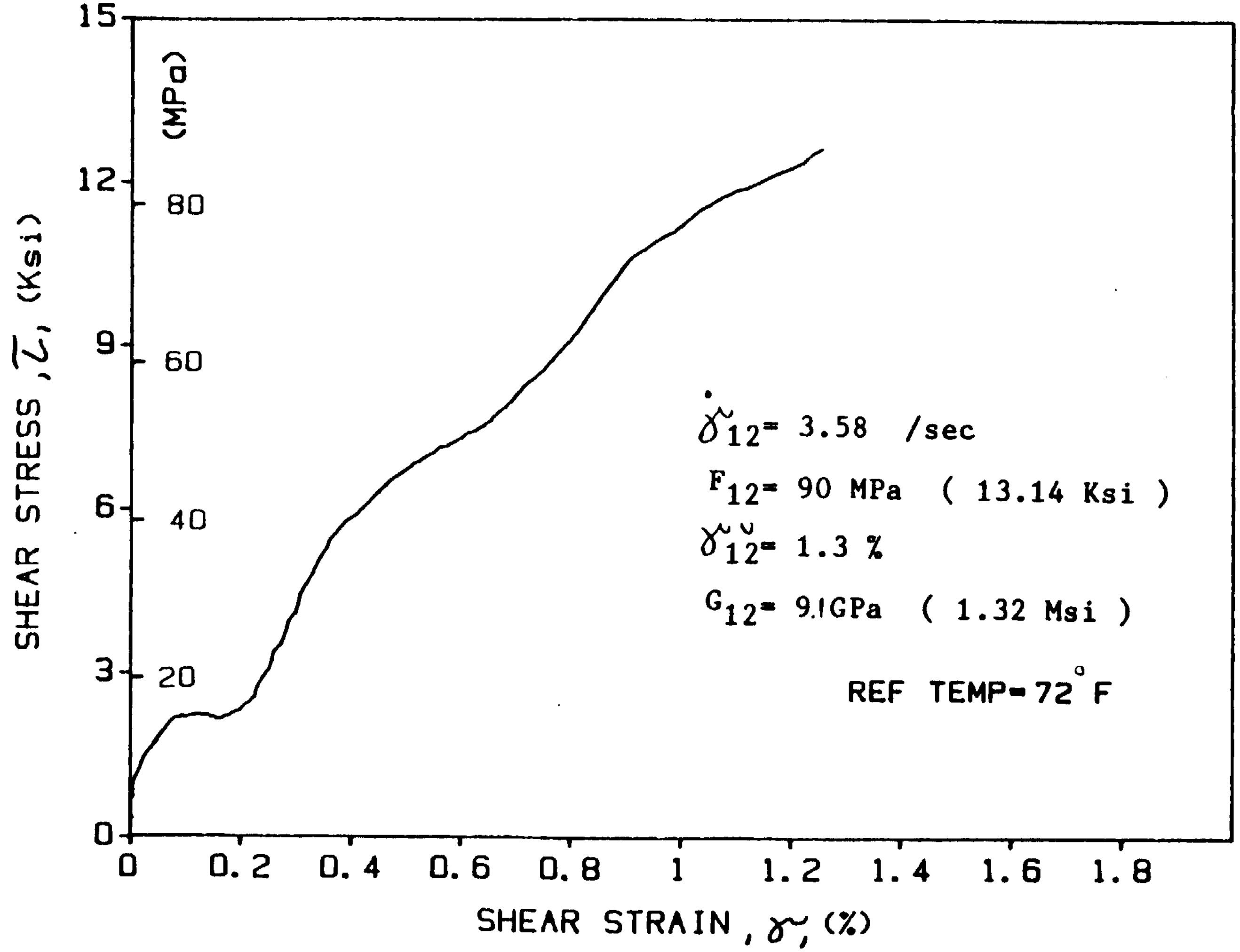


Fig. A-125. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L5 (T = 23°C (72°F))

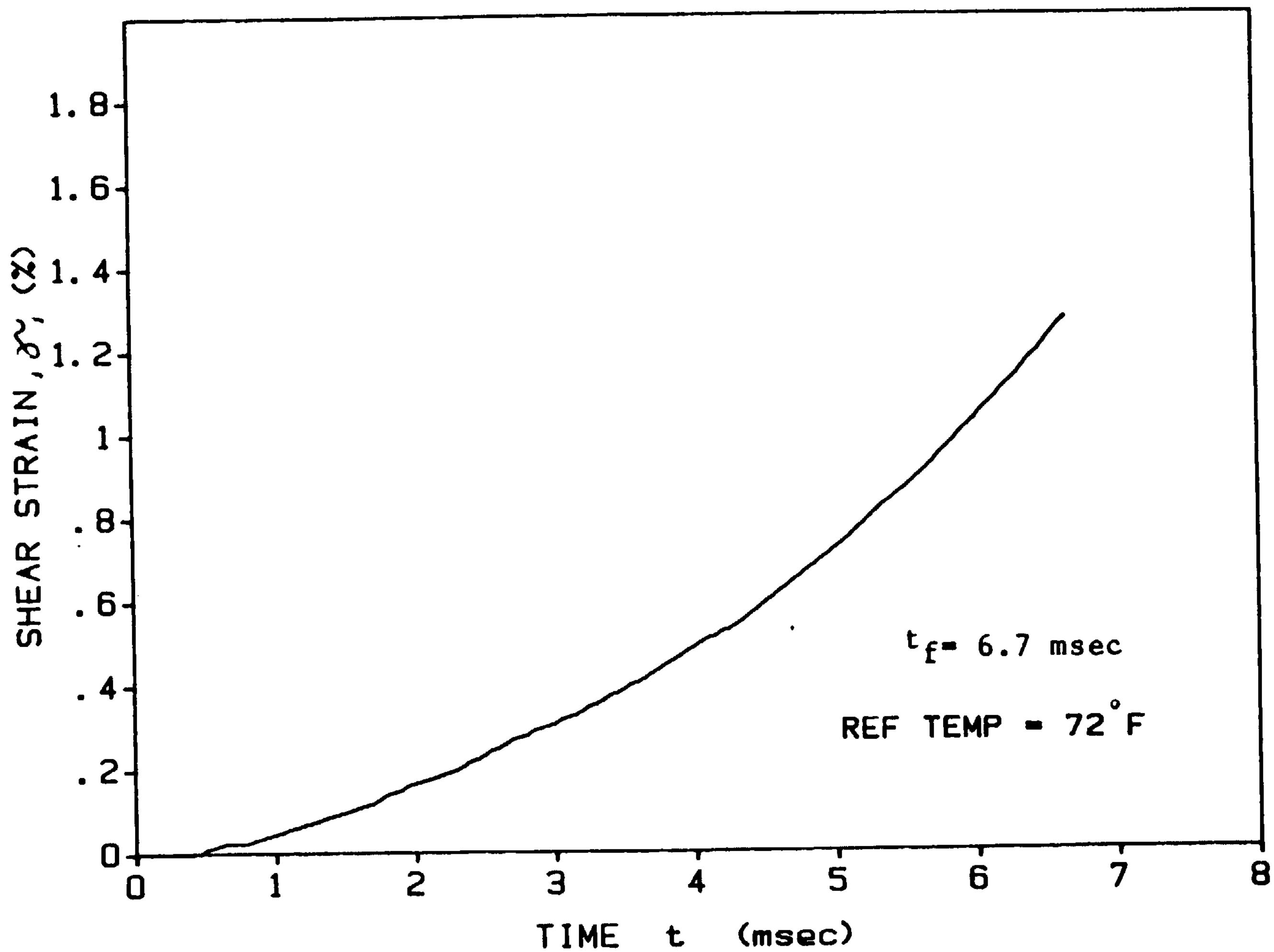


Fig. A-126. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L5 (T = 23°C (72°F))

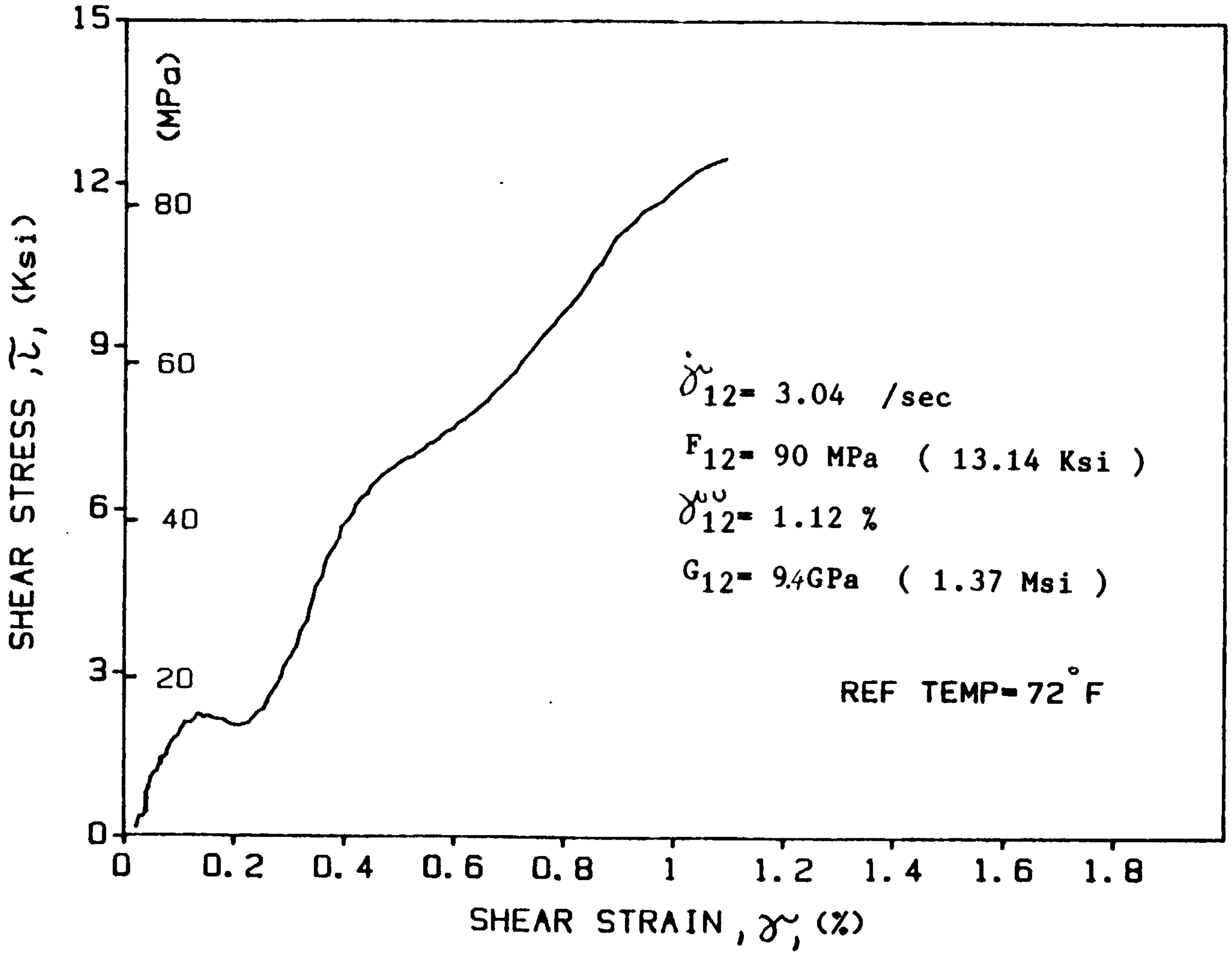


Fig. A-127. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L6 (T = 23°C (72°F))

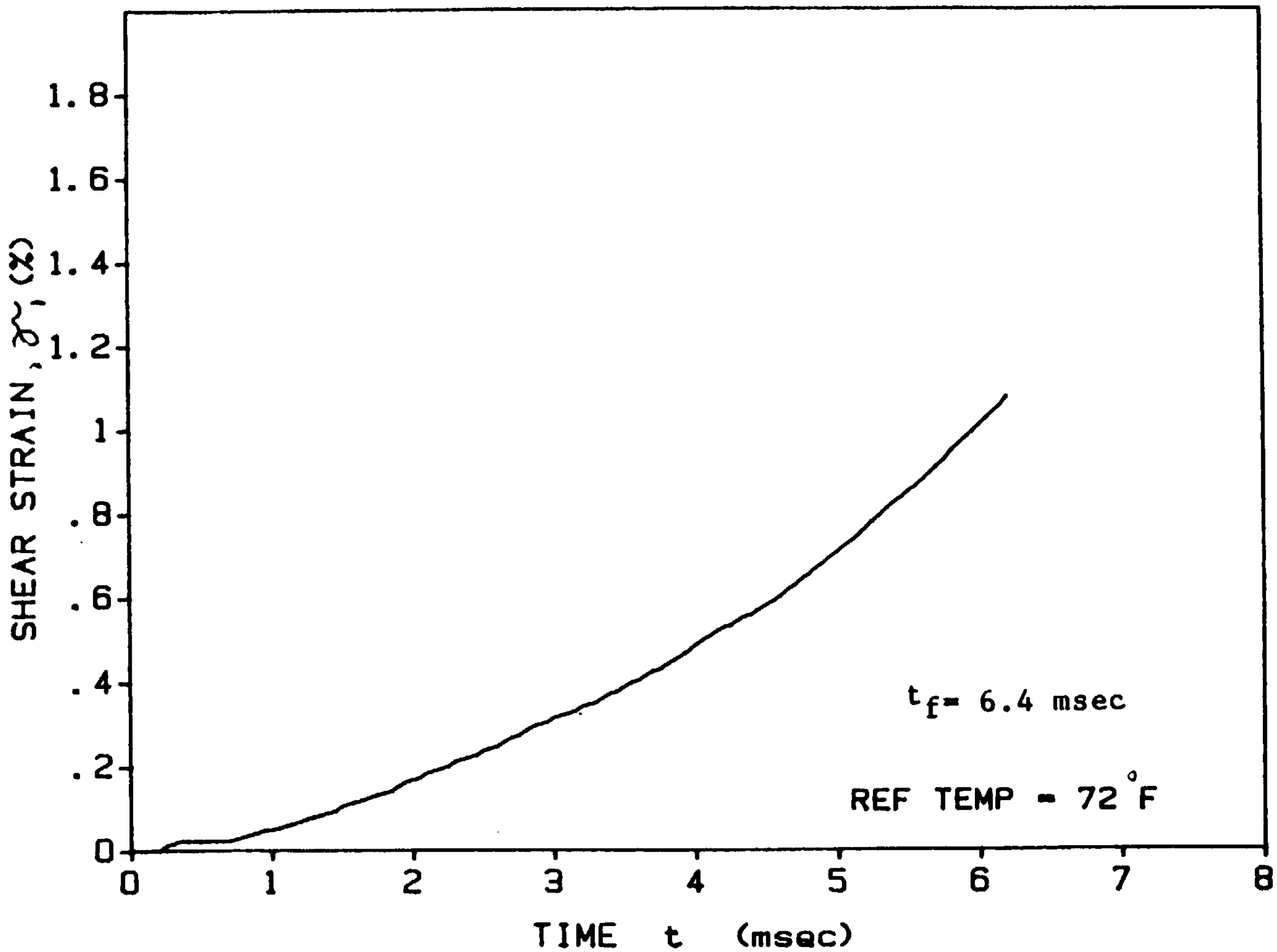


Fig. A-128. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L6 (T = 23°C(72°F))

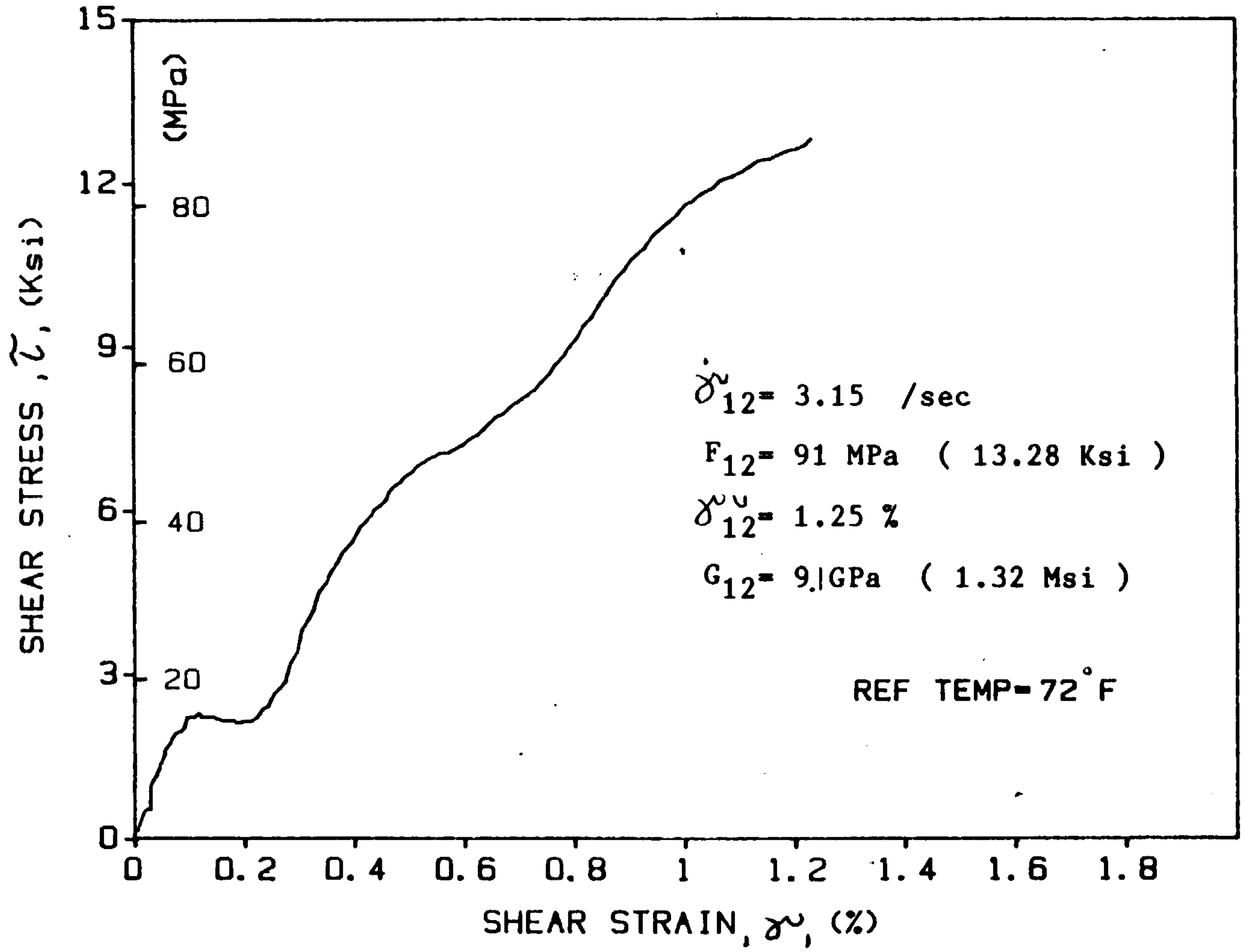


Fig. A-129. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L7 (T = 23°C (72°F))

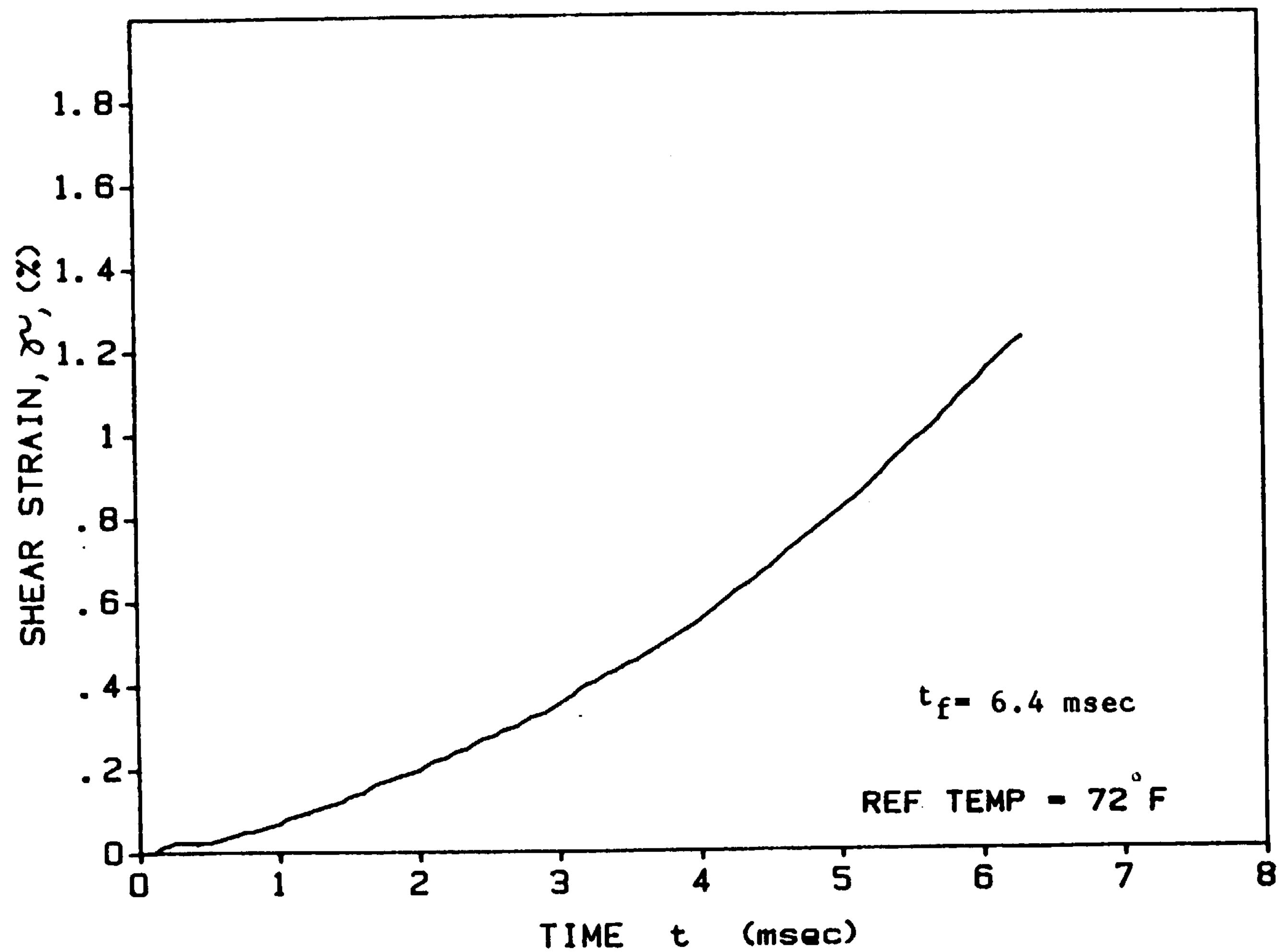


Fig. A-130. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L7 (T = 23°C (72°F))

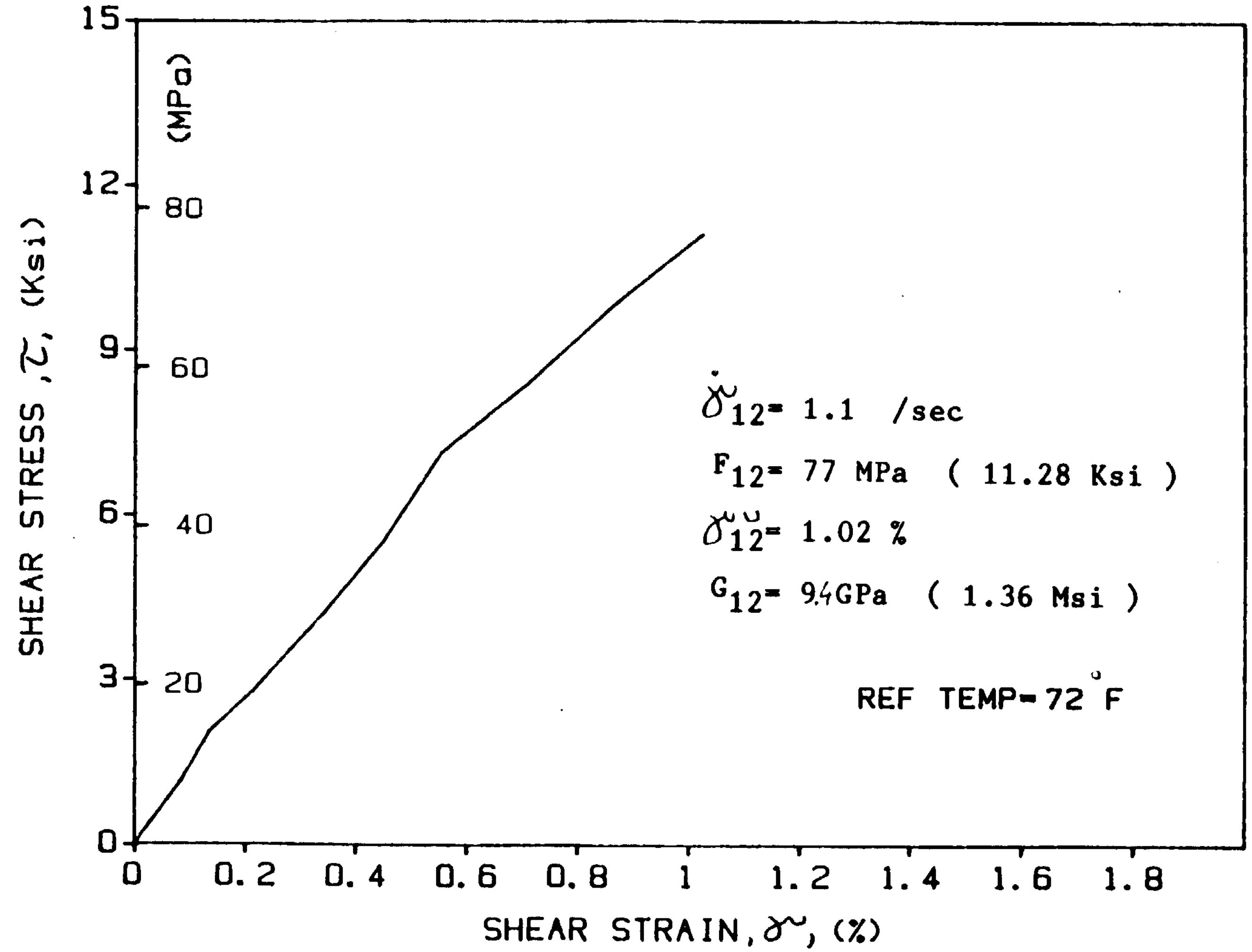


Fig. A-131. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L8 (T = 23°C (72°F))

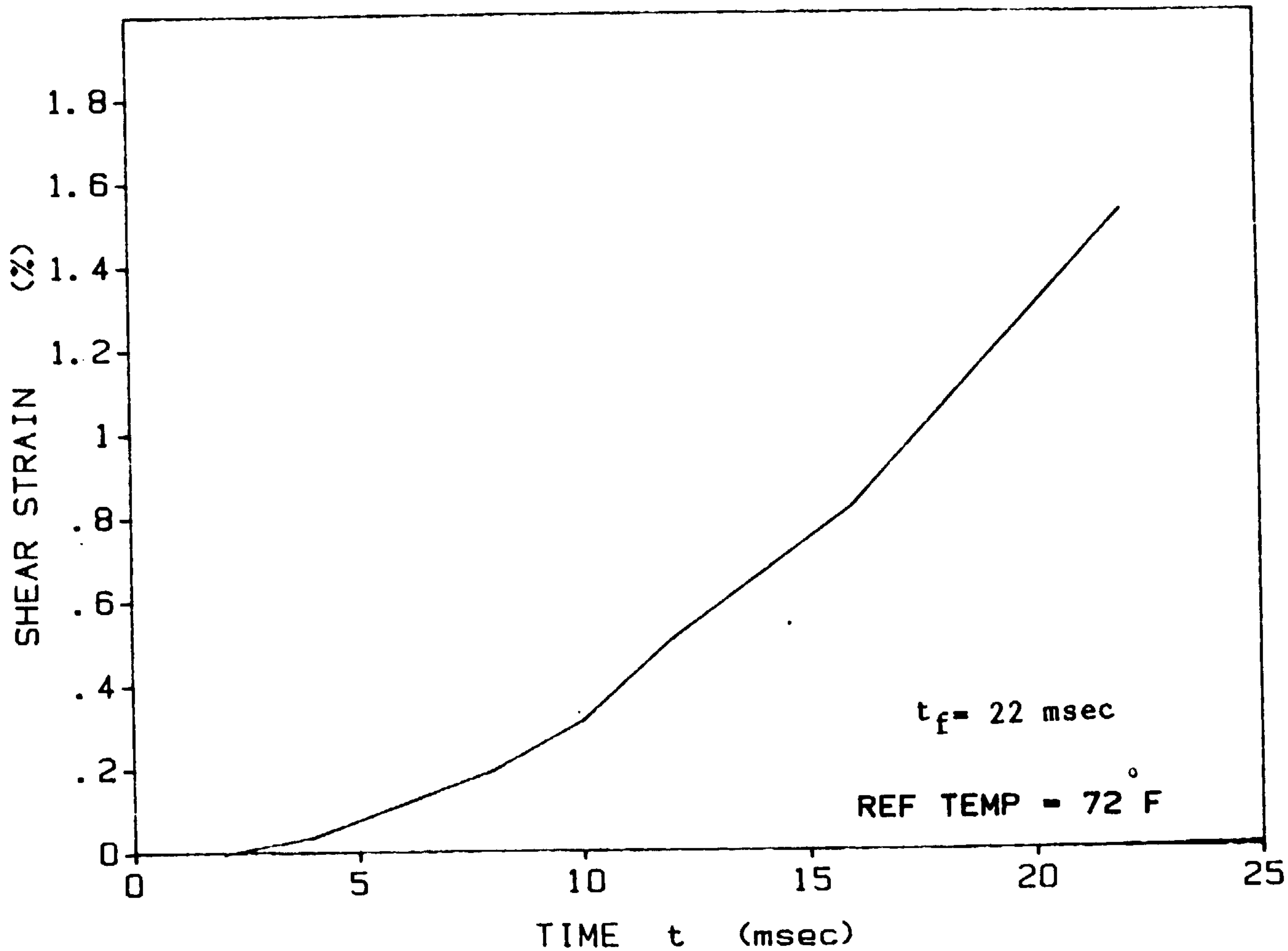


Fig. A-132. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0L8 (T = 23°C (72°F))

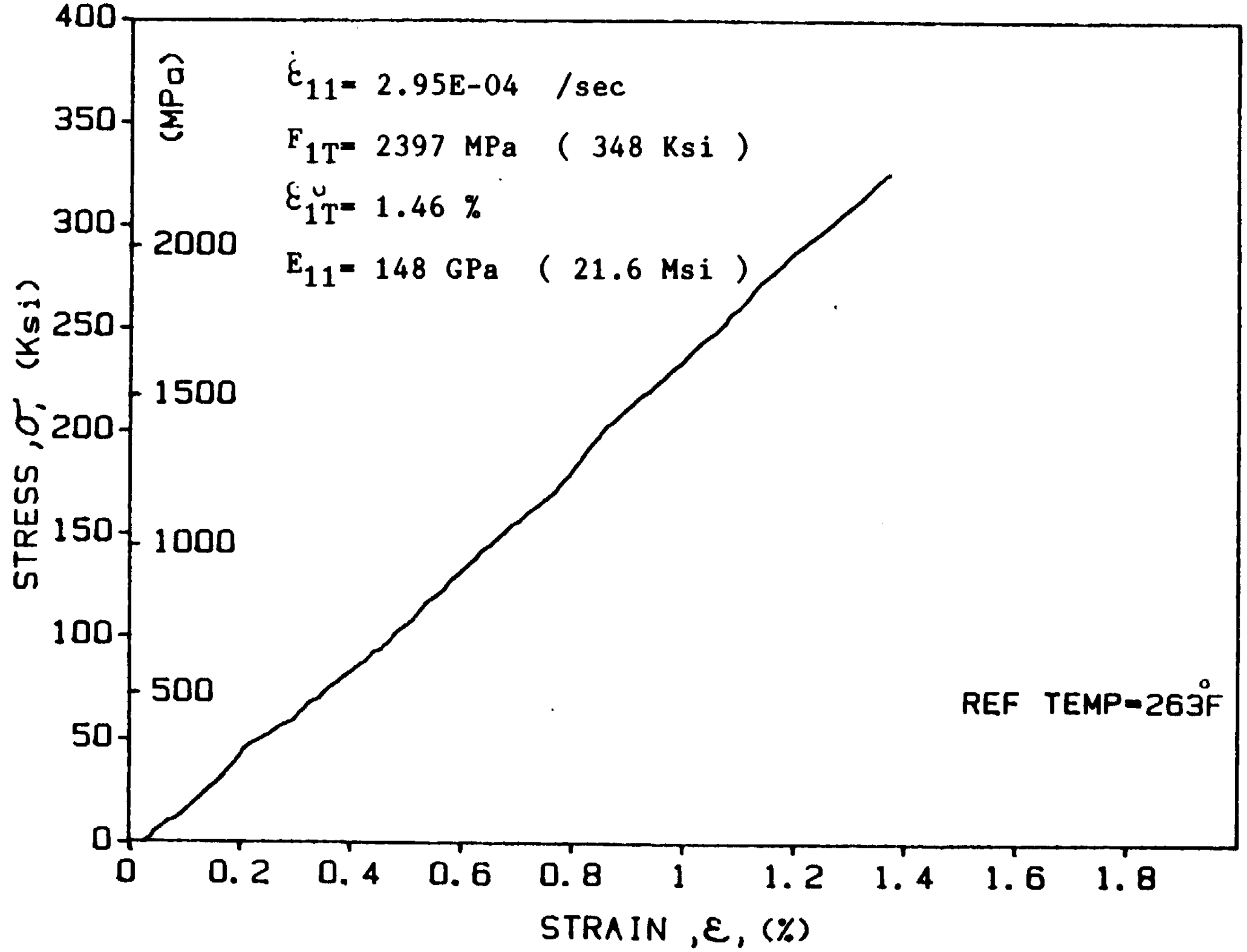


Fig. A-133. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H1 (T = 128°C (263°F))

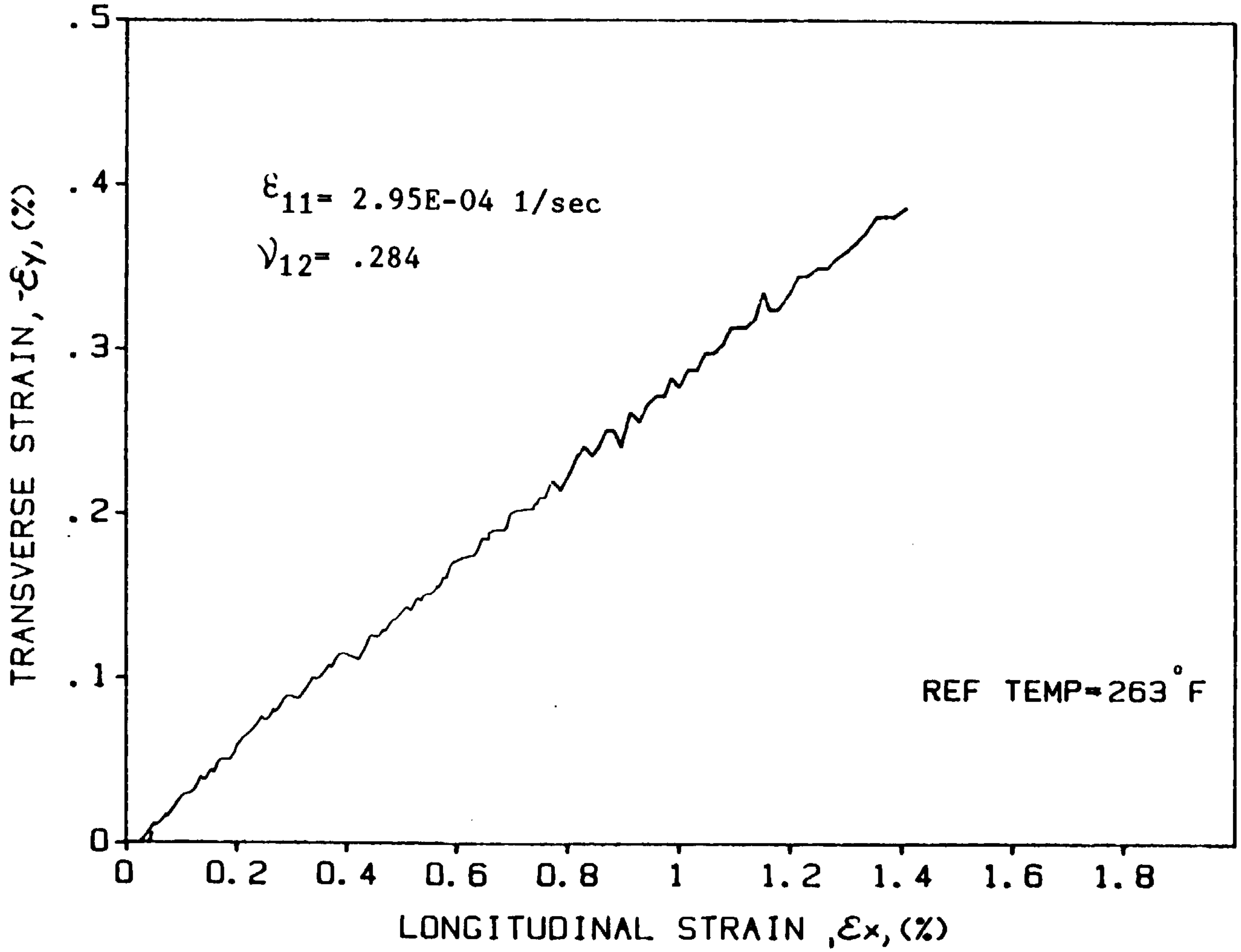


Fig. A-134. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H1 (T = 128°C (263°F))

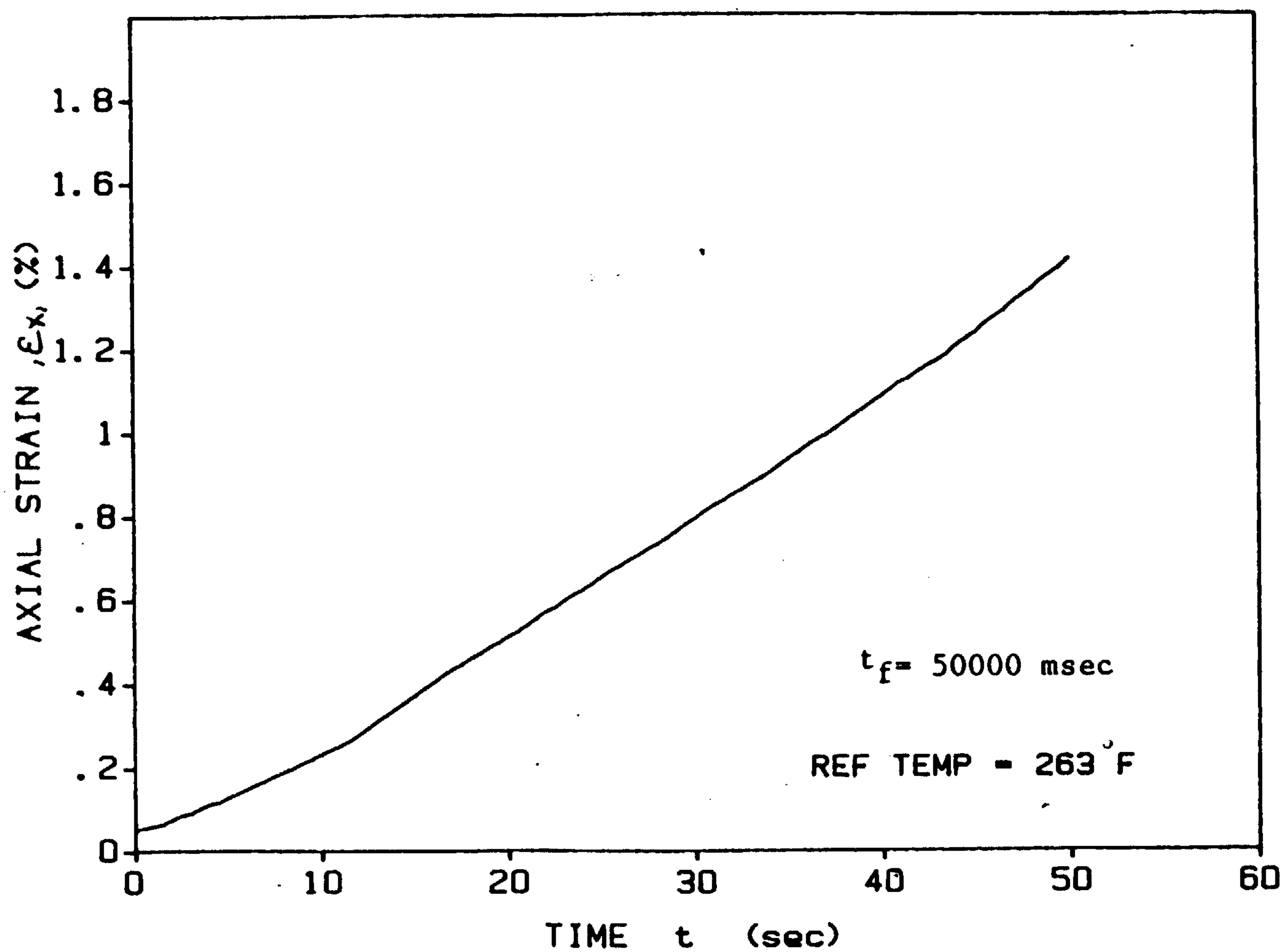


Fig. A-135. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H1 (T = 128°C (263°F))

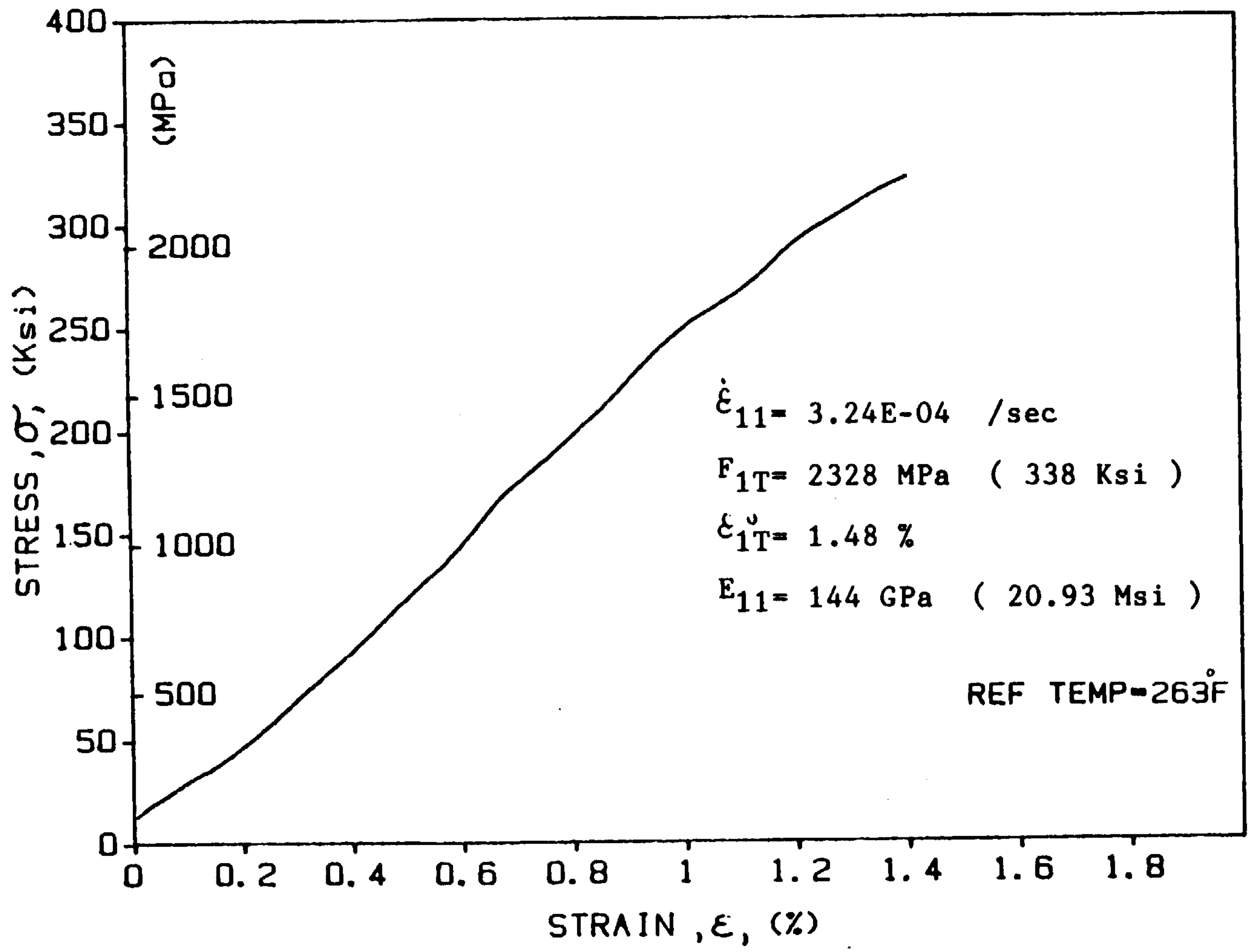


Fig. A-136. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H2 (T = 128°C (236°F))

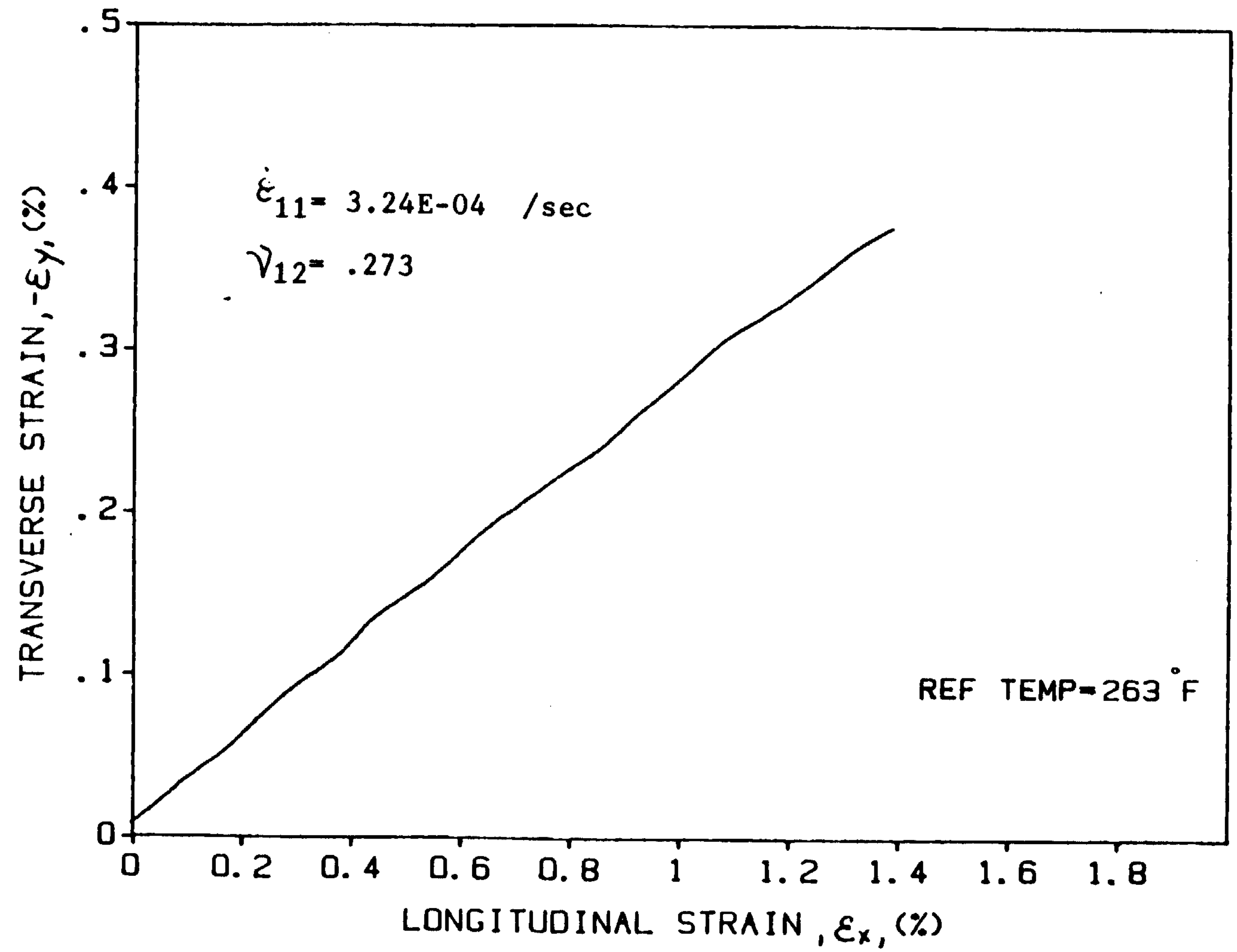


Fig. A-137. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H2 (T = 128°C (263°F))

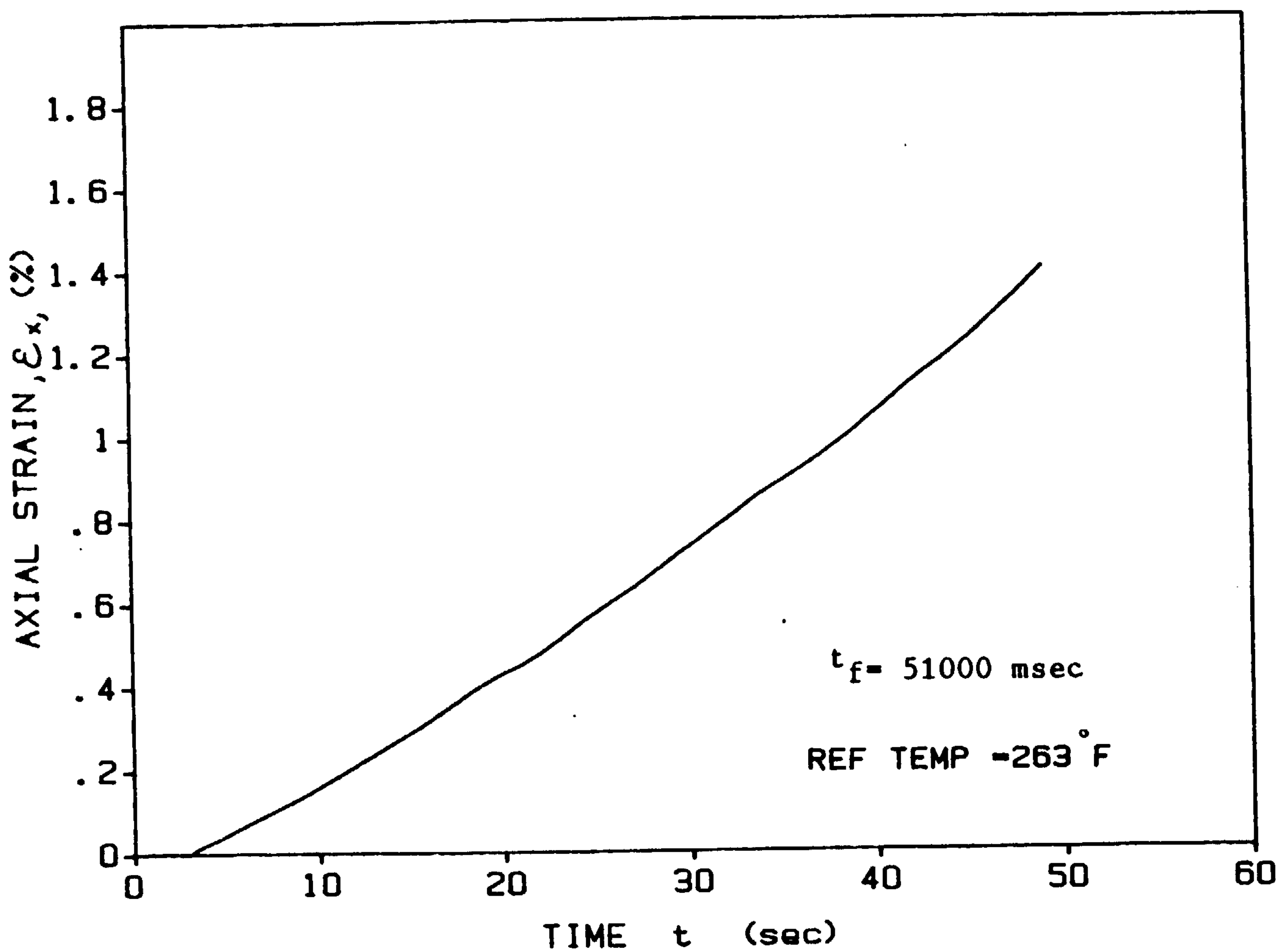


Fig. A-138. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H2 (T = 128°C (263°F))

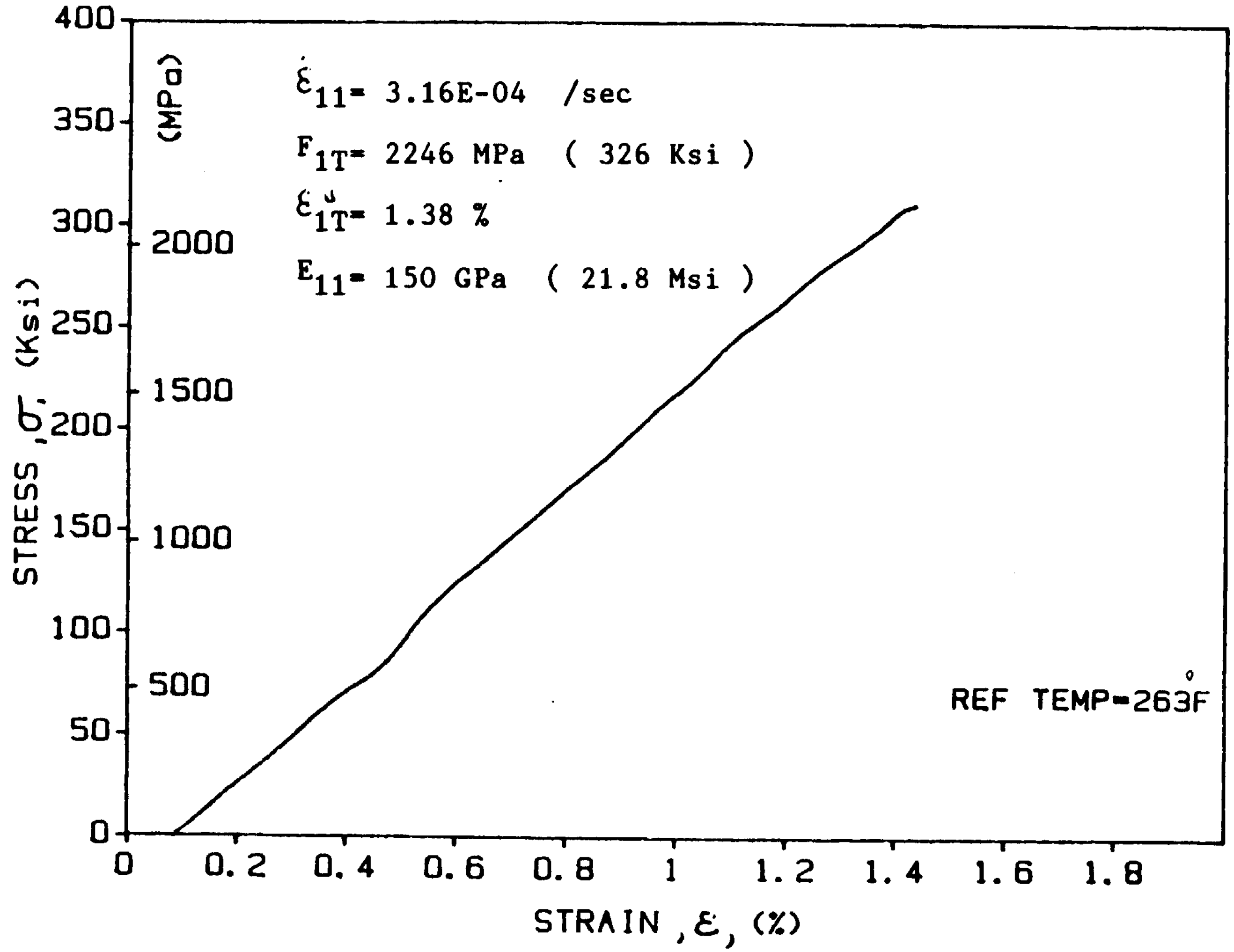


Fig. A-139. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H3 (T = 128°C (263°F))

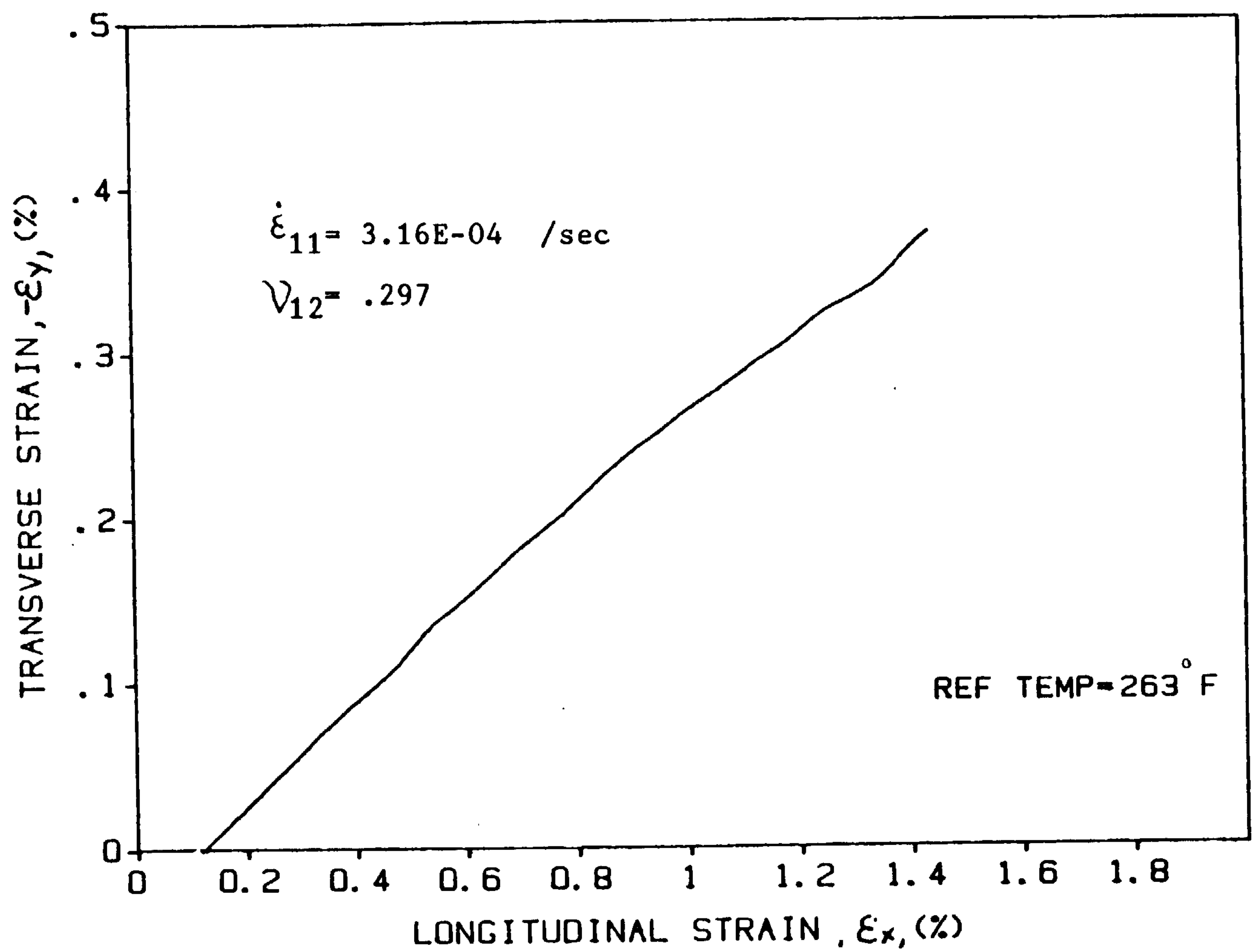


Fig. A-140. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 0/-4H3 (T = 128°C (263°F))

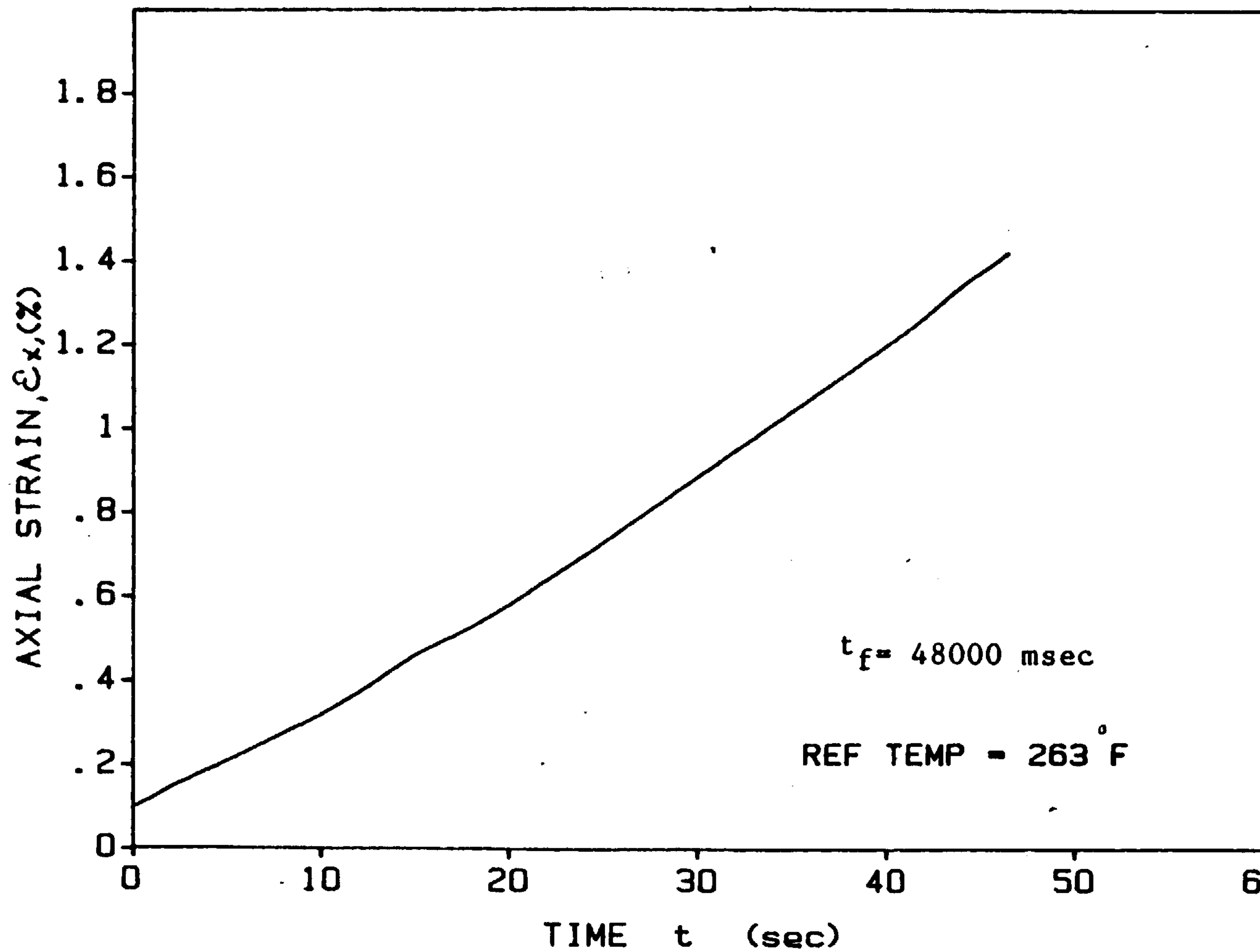


Fig. A-141. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/-4H3 (T = 128°C (263°F))

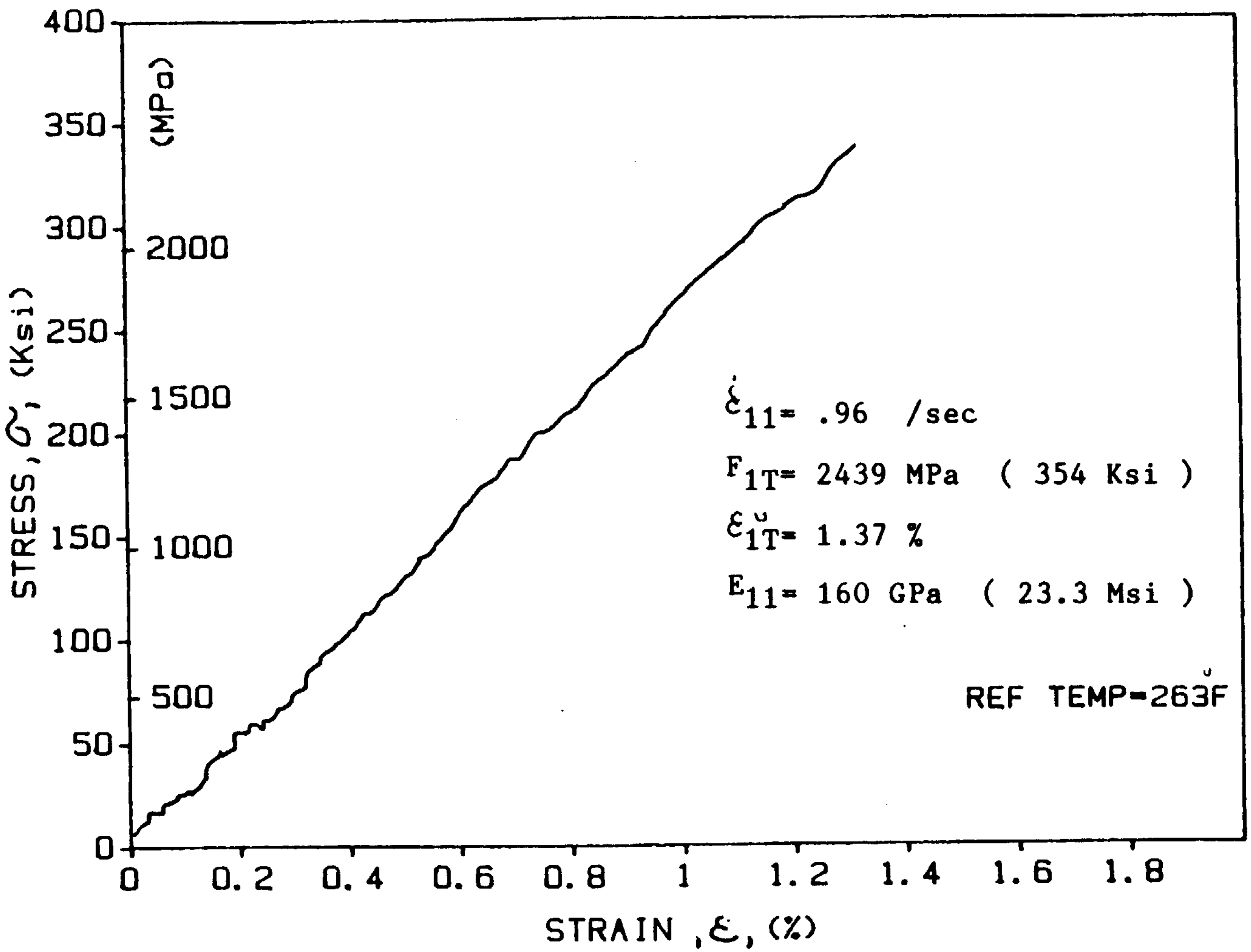


Fig. A-142. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H1 (T = 128°C (263°F))

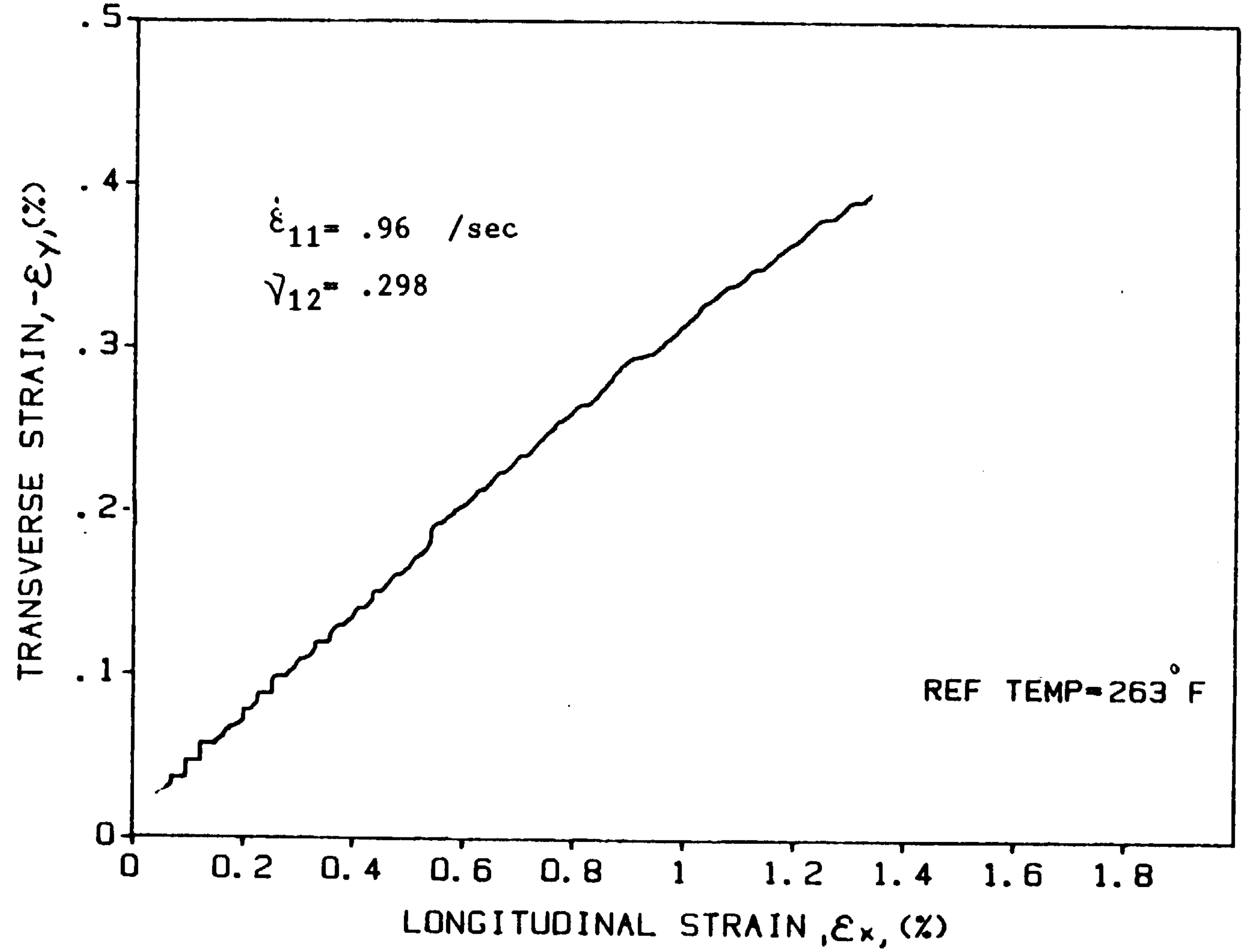


Fig. A-143. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H1 (T = 128°C (263°F))

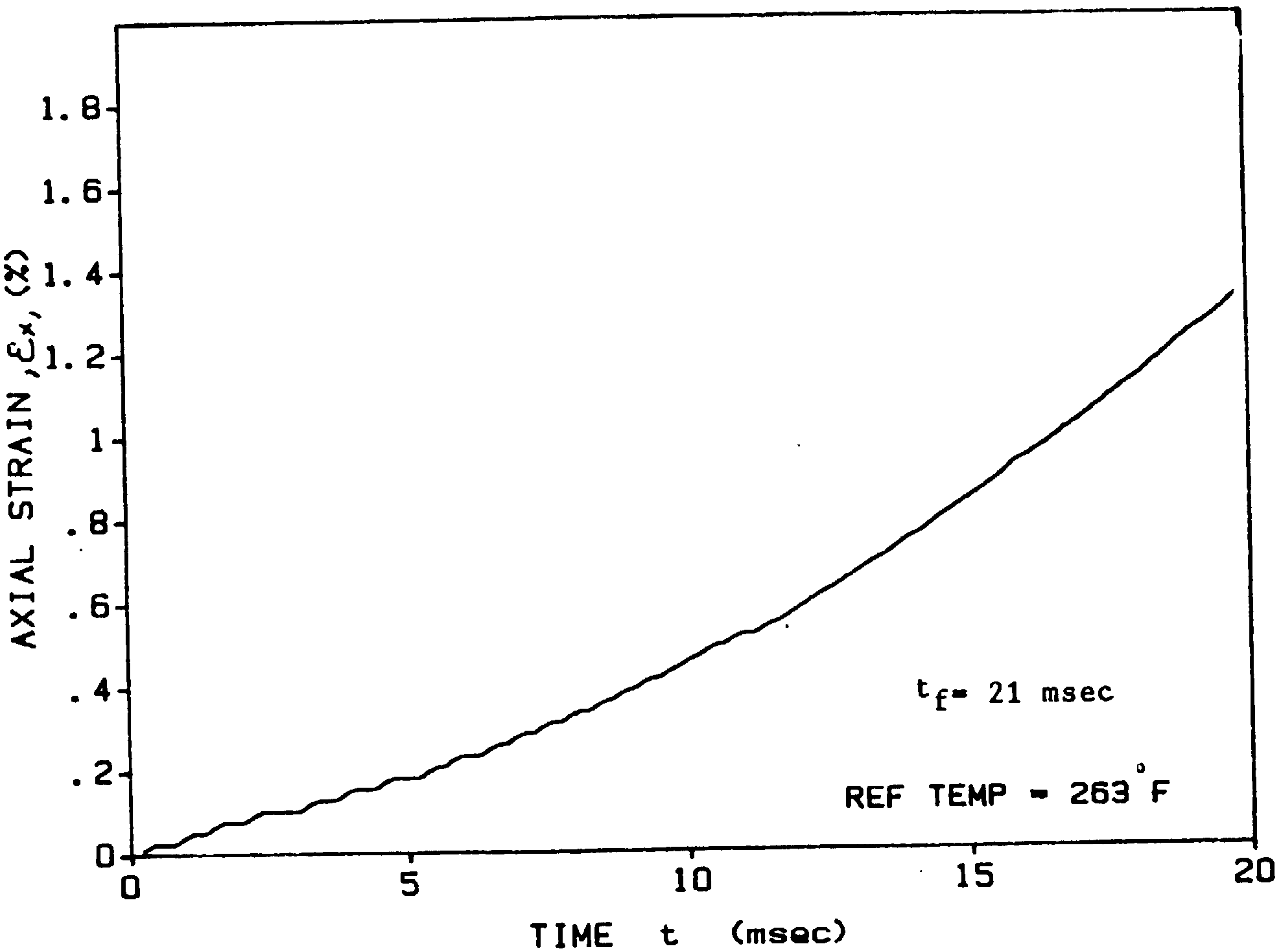


Fig. A-144. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H1 (T = 128°C (263°F))

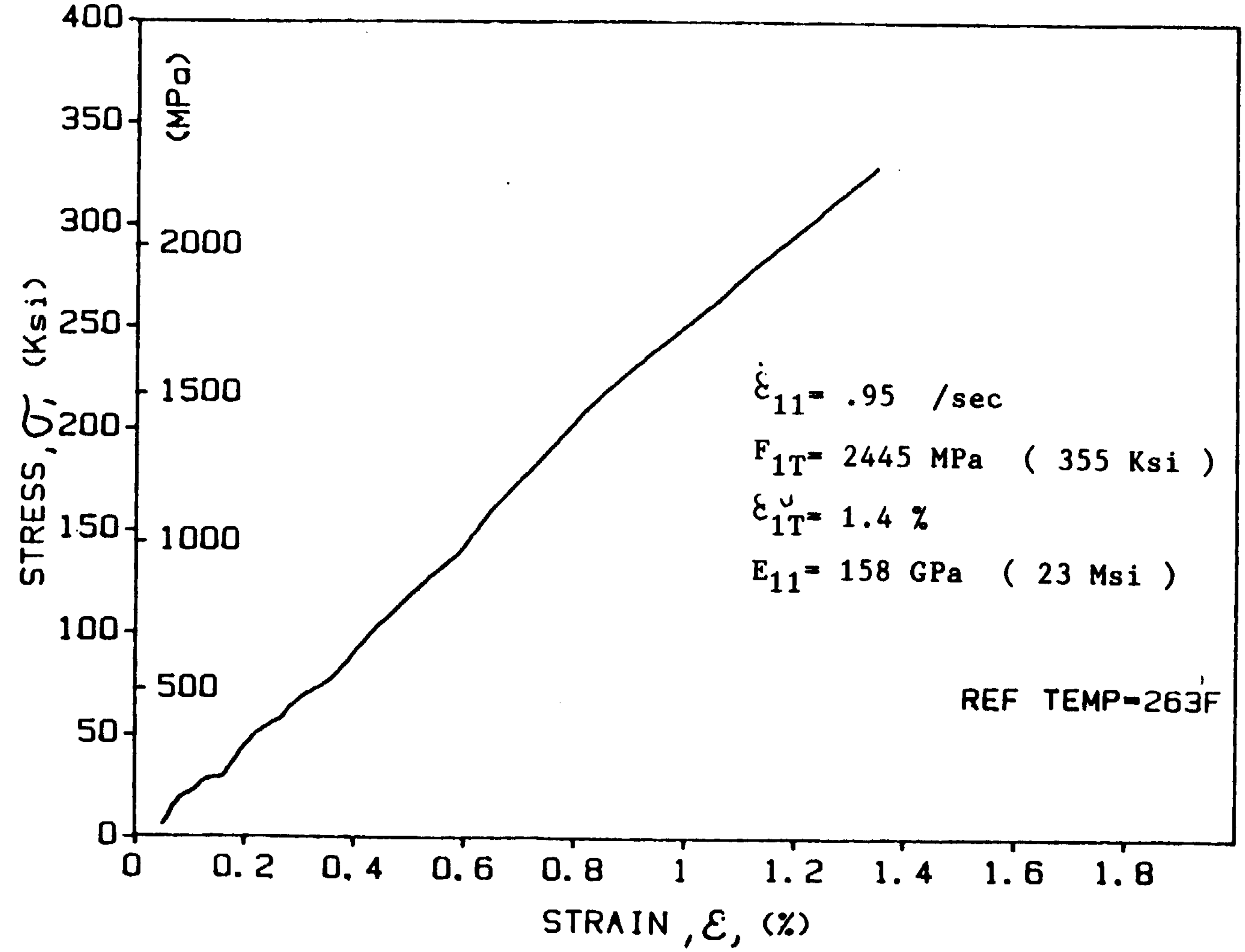


Fig. A-145. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H2 (T = 128°C (263°F))

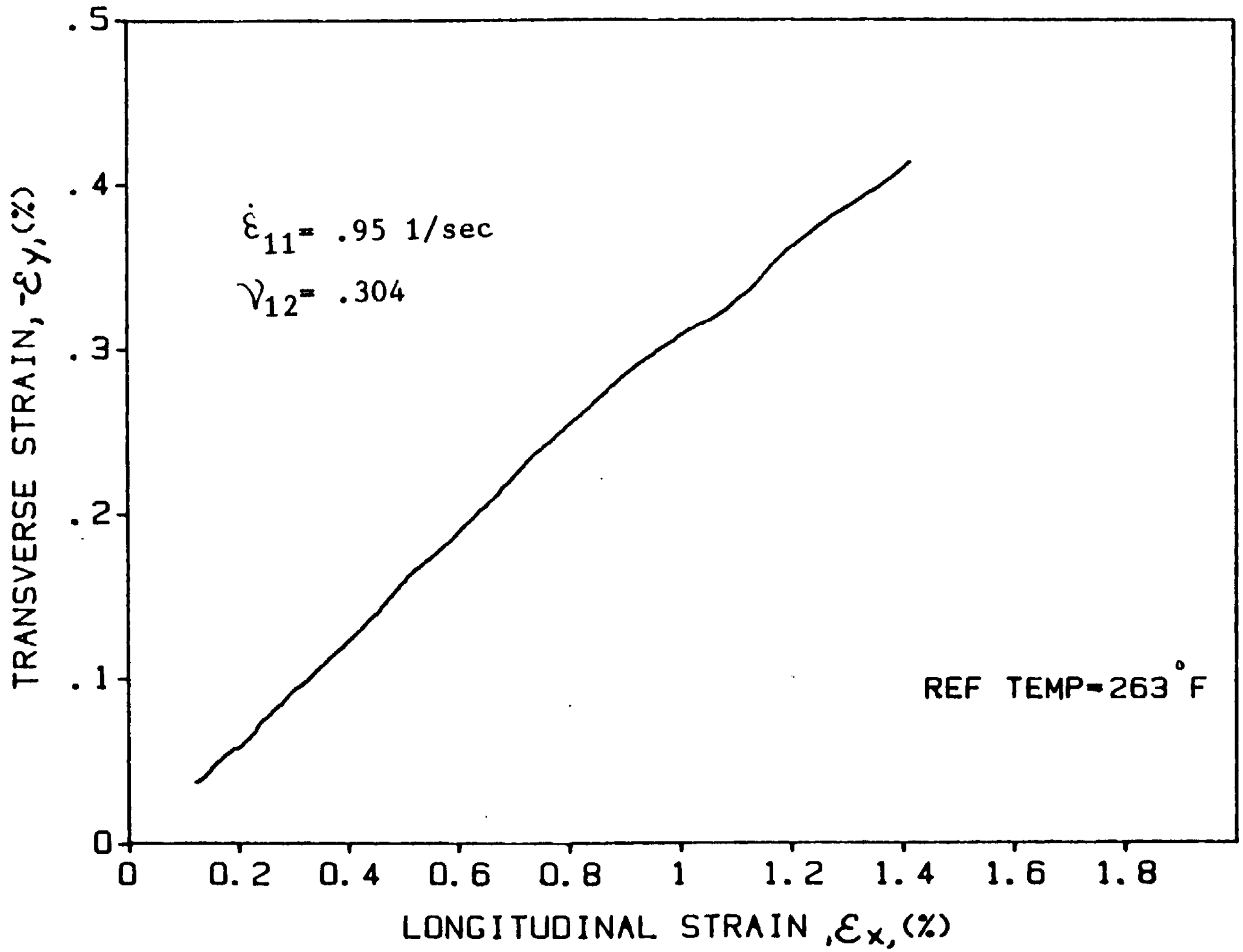


Fig. A-146. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H2 (T = 128°C (263°F))

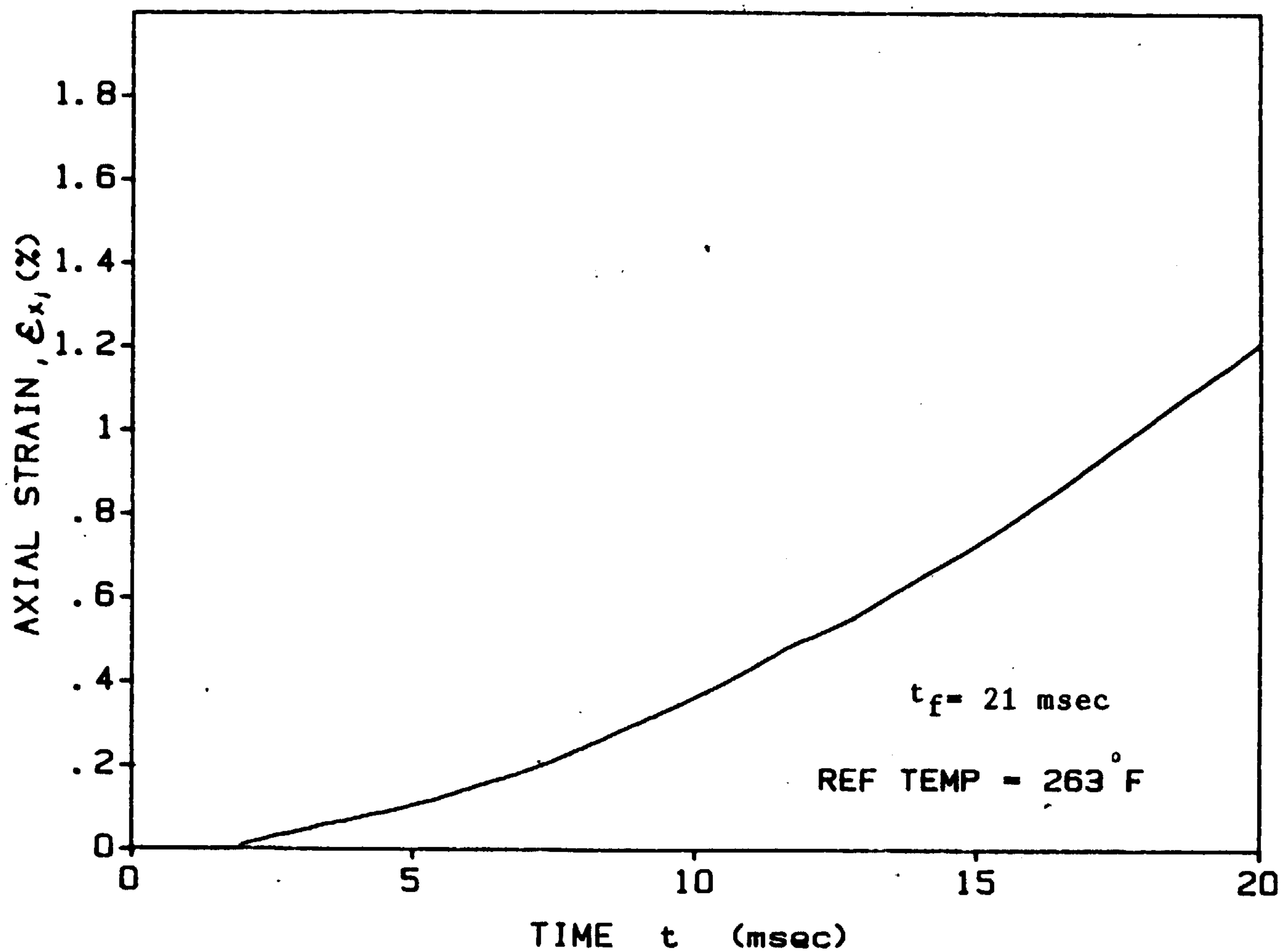


Fig. A-147. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H2 (T = 128°C (263°F))

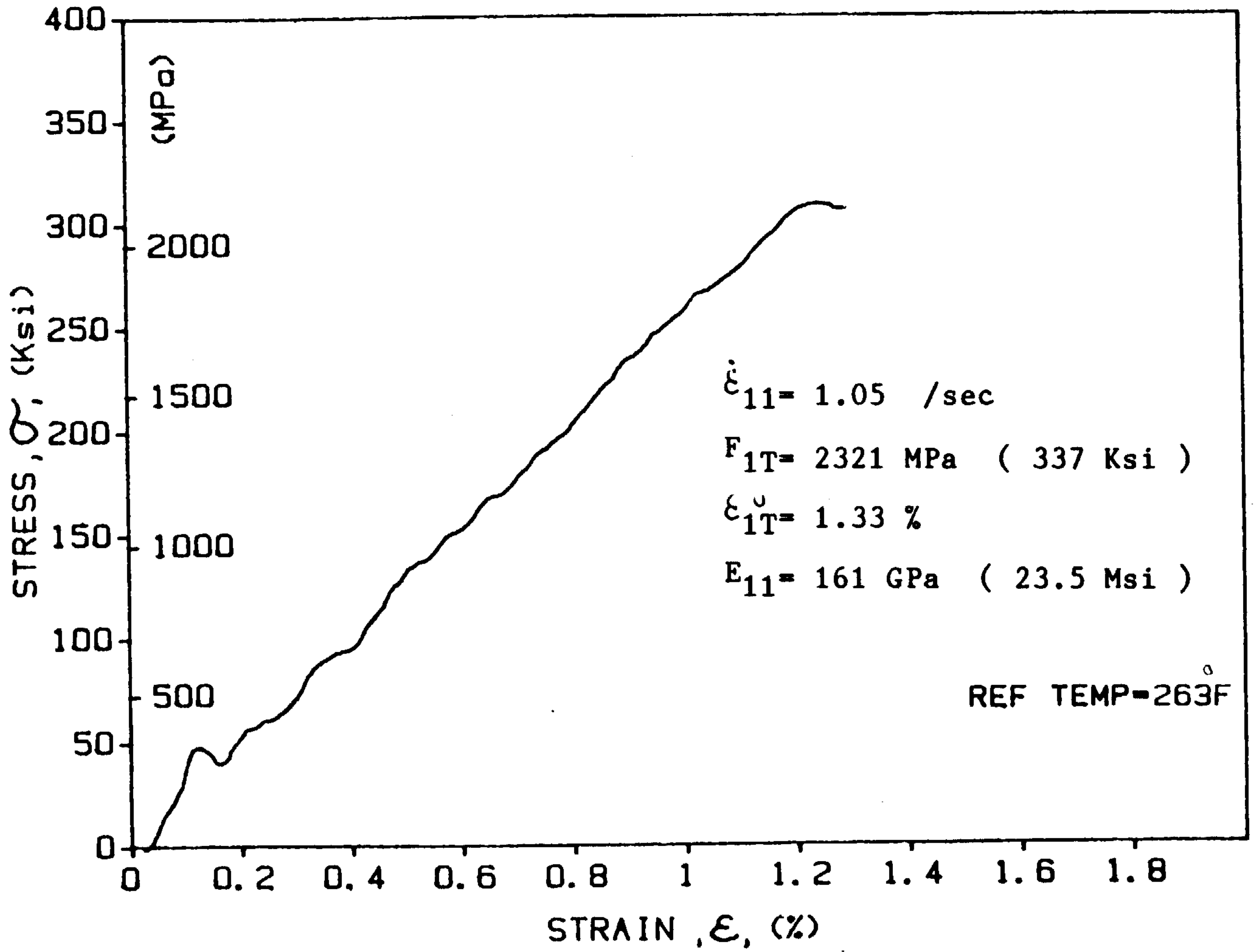


Fig. A-148. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H3 (T = 128°C (263°F))

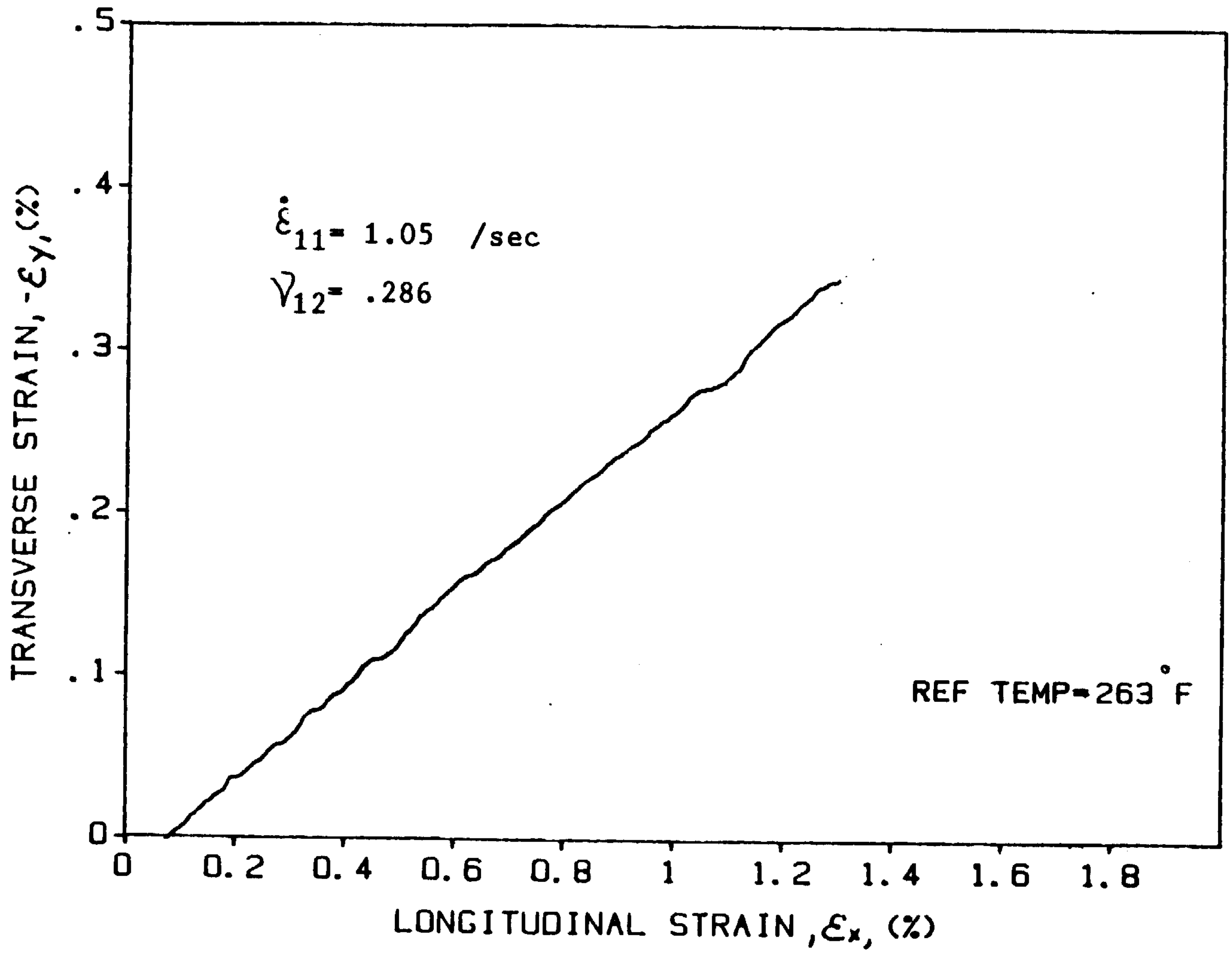


Fig. A-149. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H3 (T = 128°C (263°F))

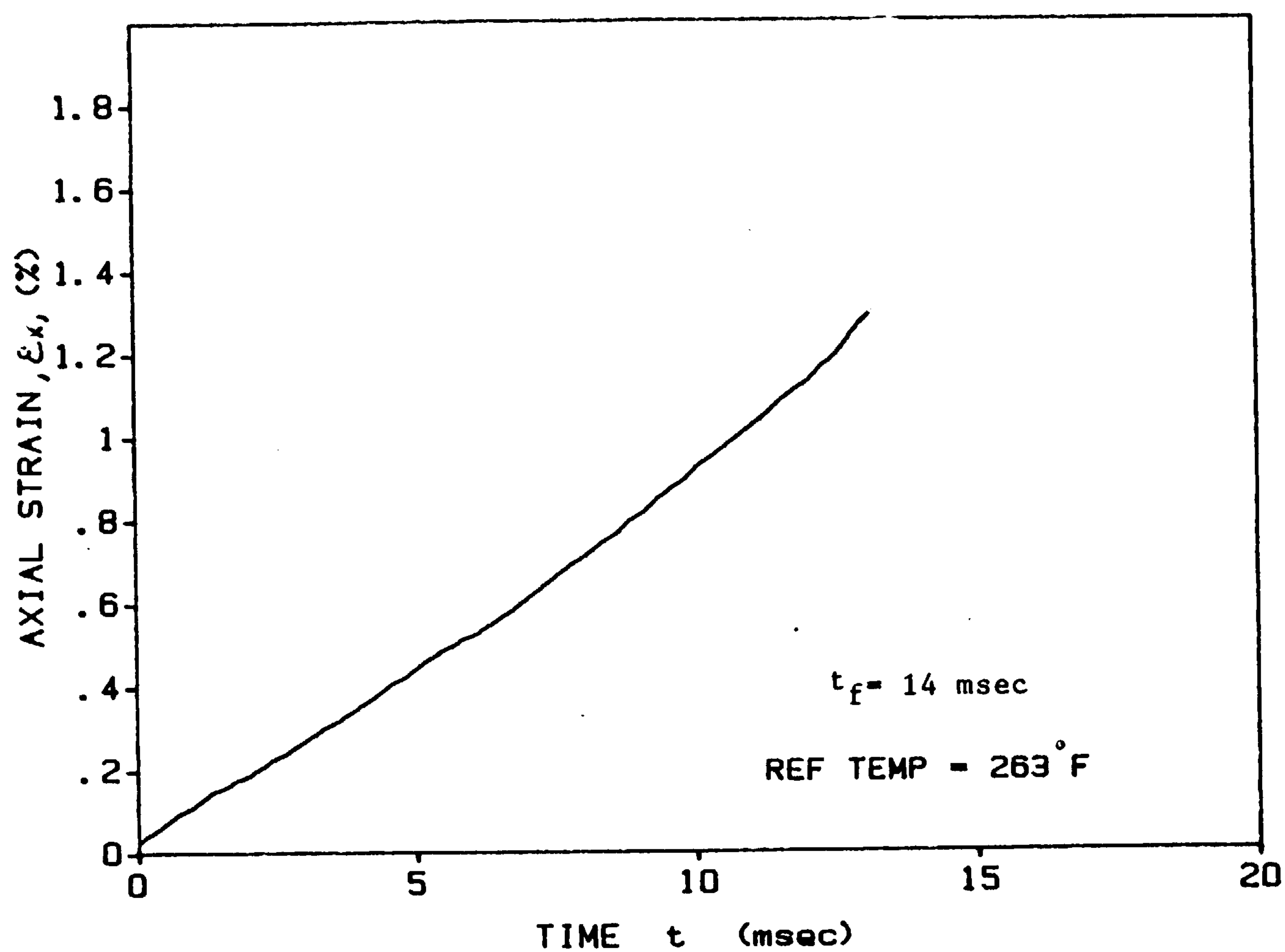


Fig. A-150. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H3 (T = 128°C (263°F))

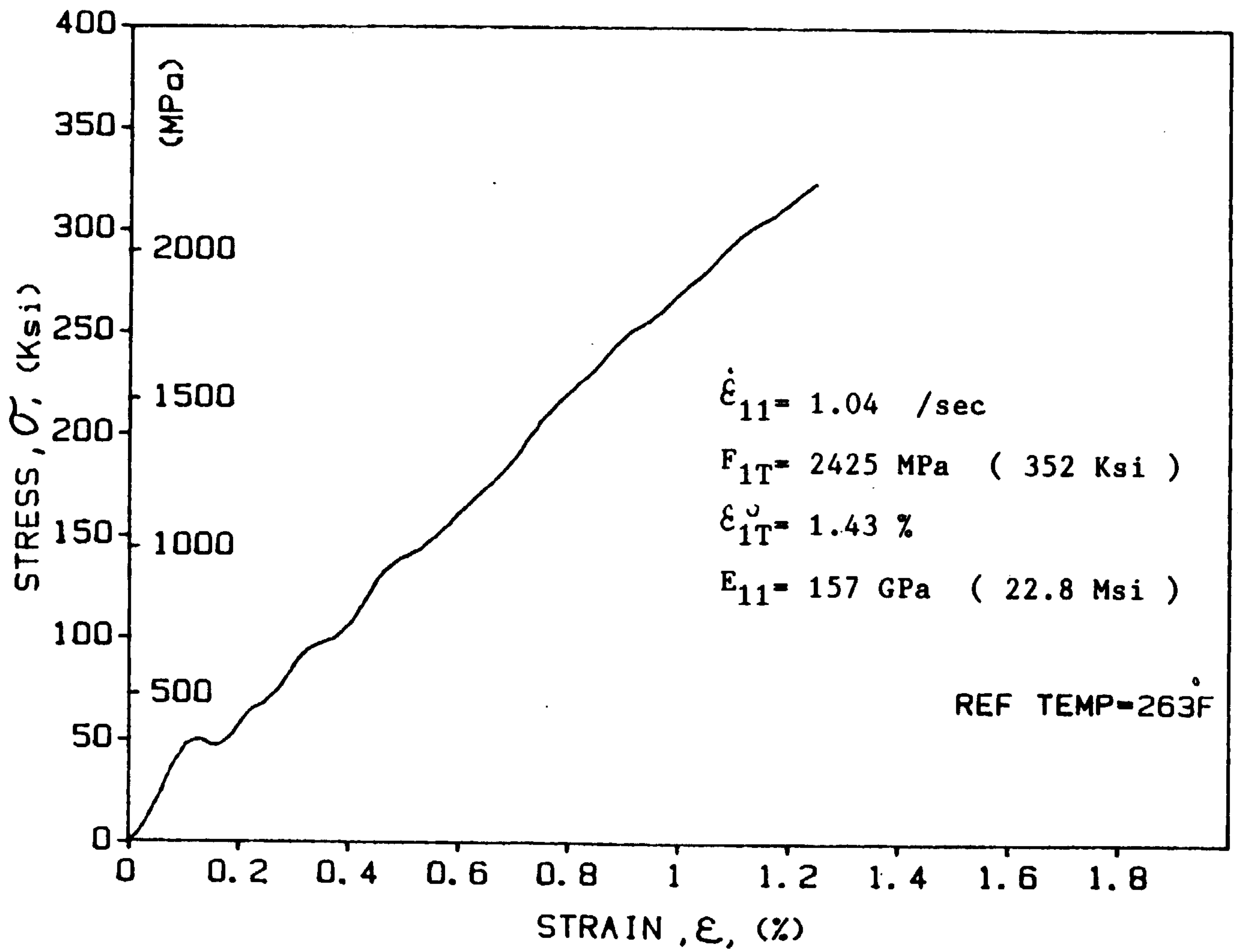


Fig. A-151. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H4 (T = 128°C (263°F))

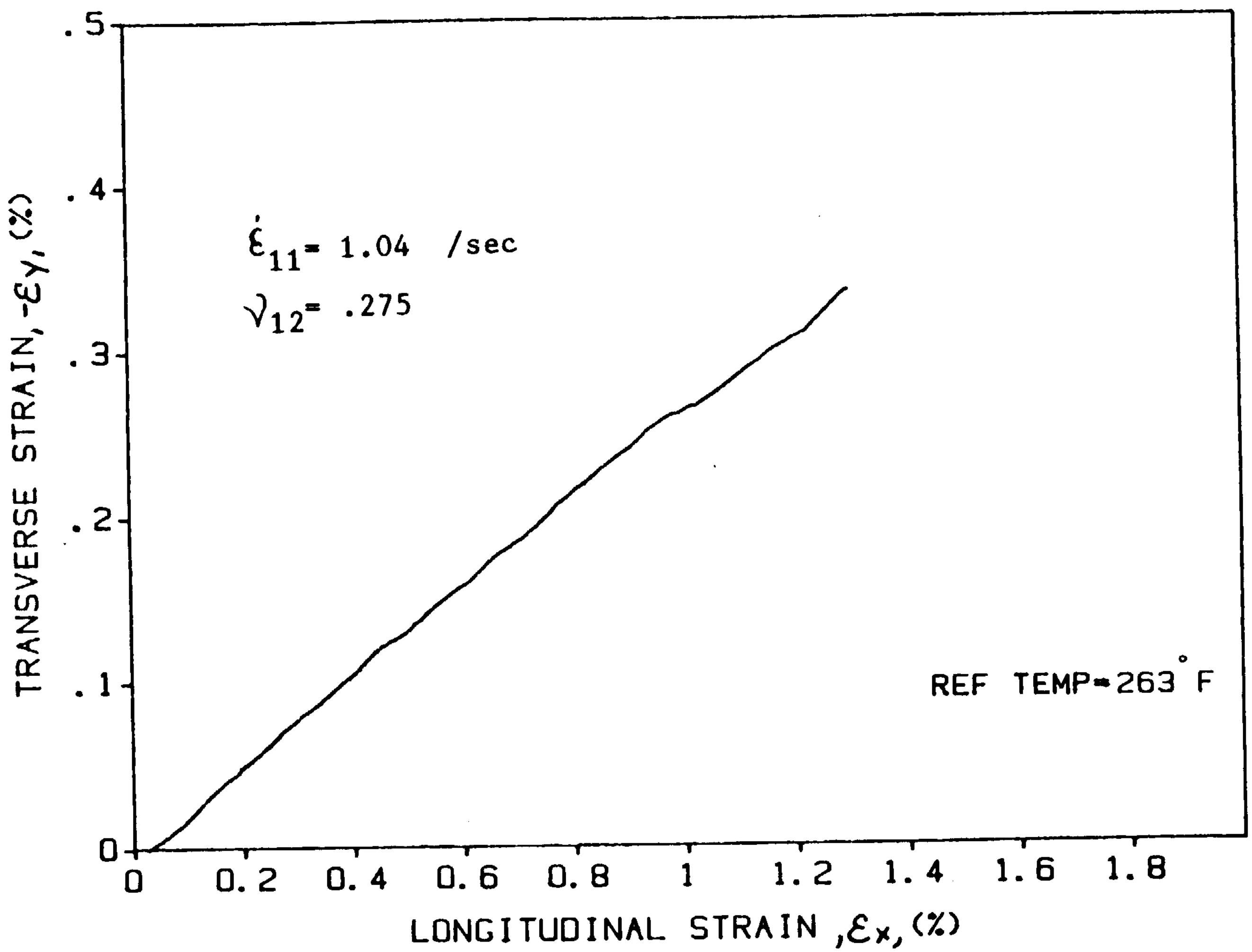


Fig. A-152. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 0/0H4 (T = 128°C (263°F))

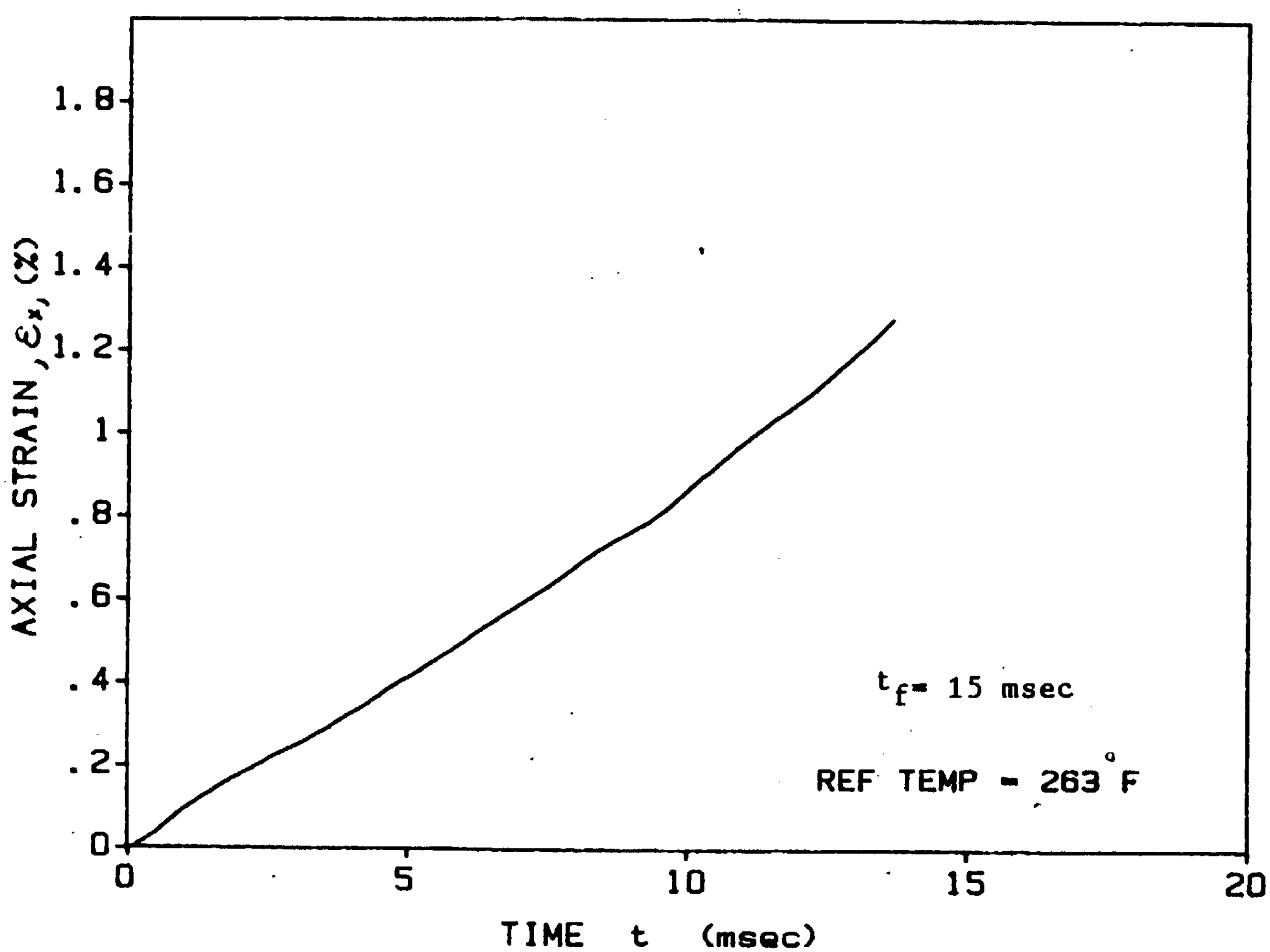


Fig. A-153. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H4 (T = 128°C (263°F))

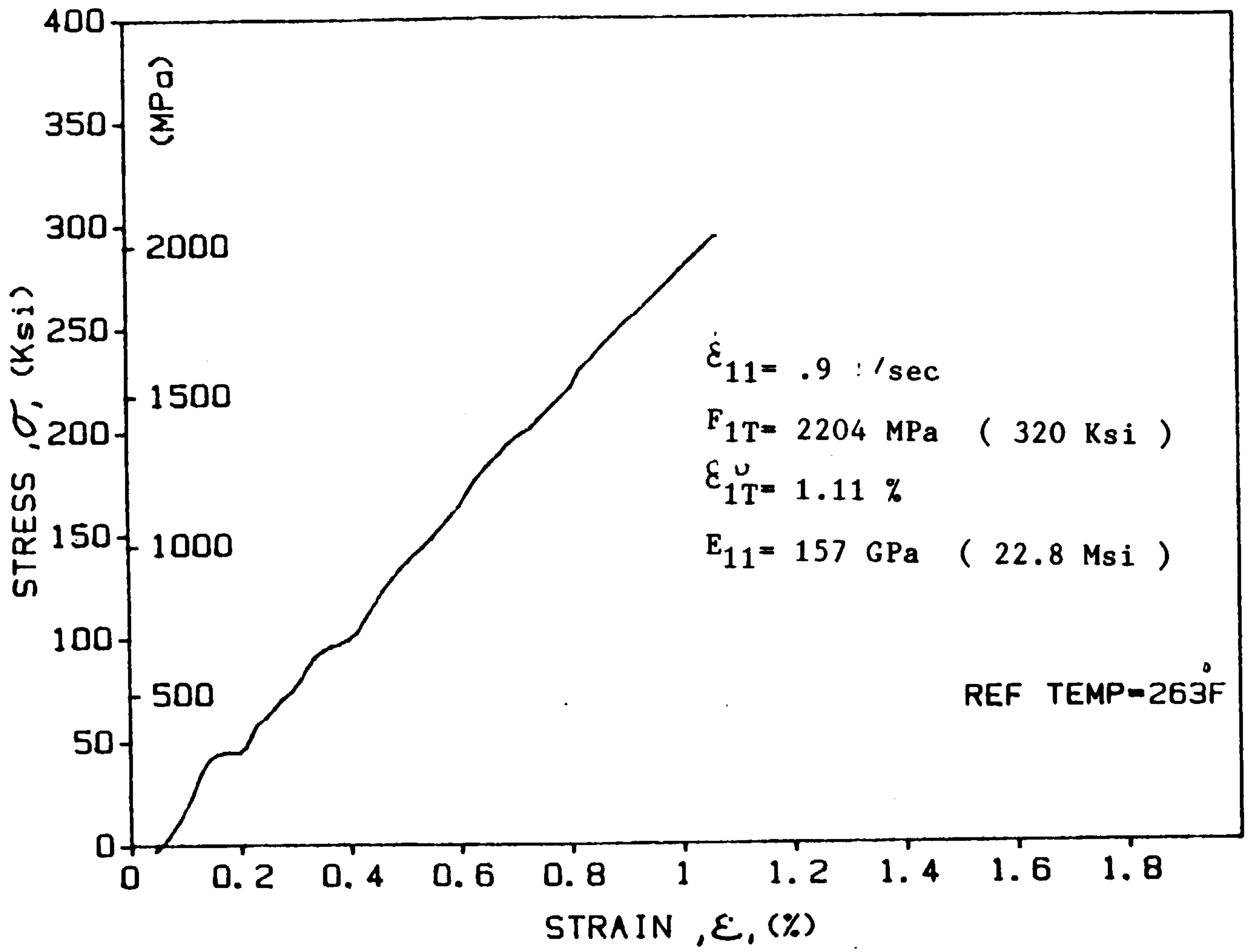


Fig. A-154. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H5 (T = 128°C (263°F))

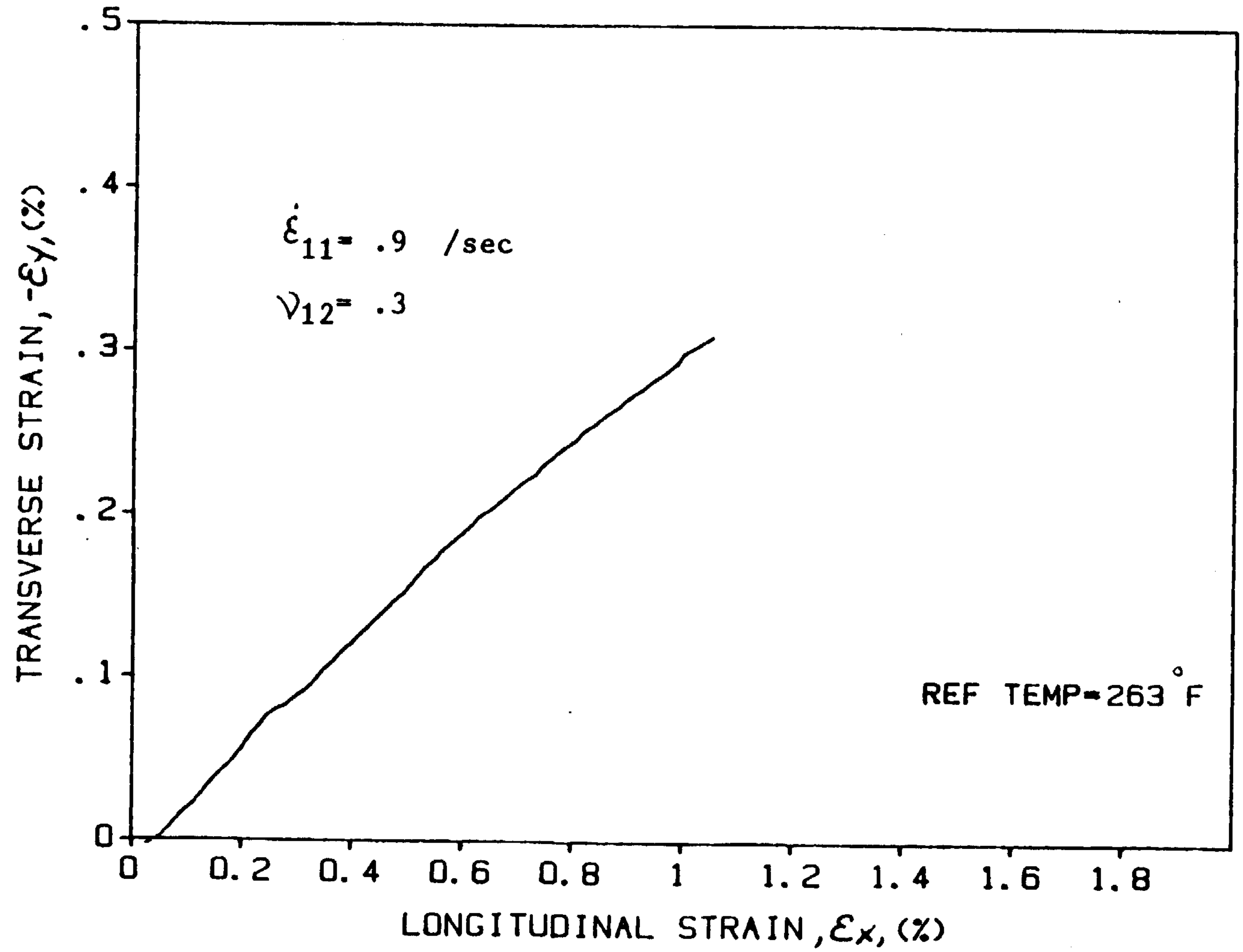


Fig. A-155. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H5 (T = 128°C (263°F))

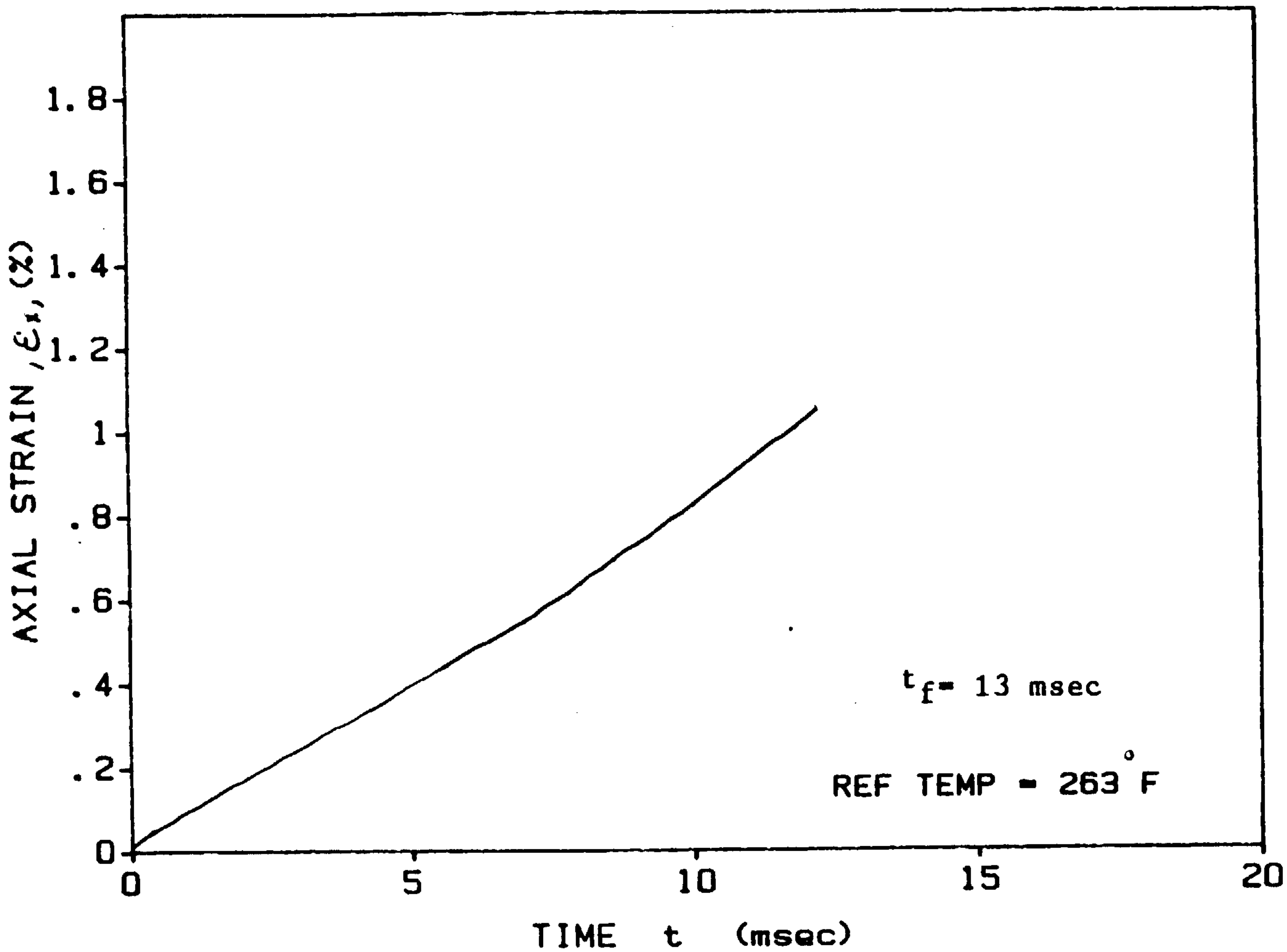


Fig. A-156. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H5 (T = 128°C (263°F))

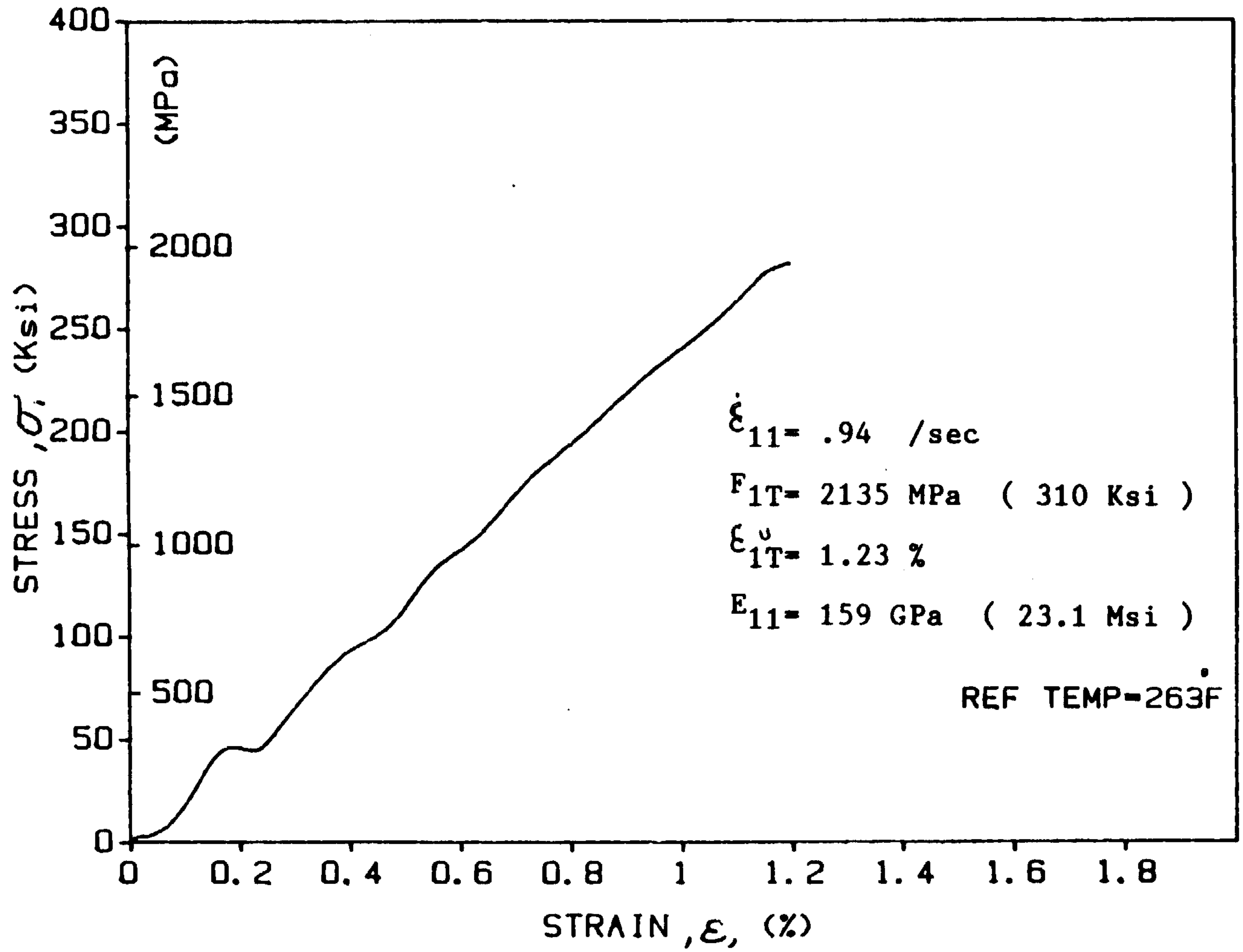


Fig. A-157. Stress-Strain Curve for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H6 (T = 128°C (263°F))

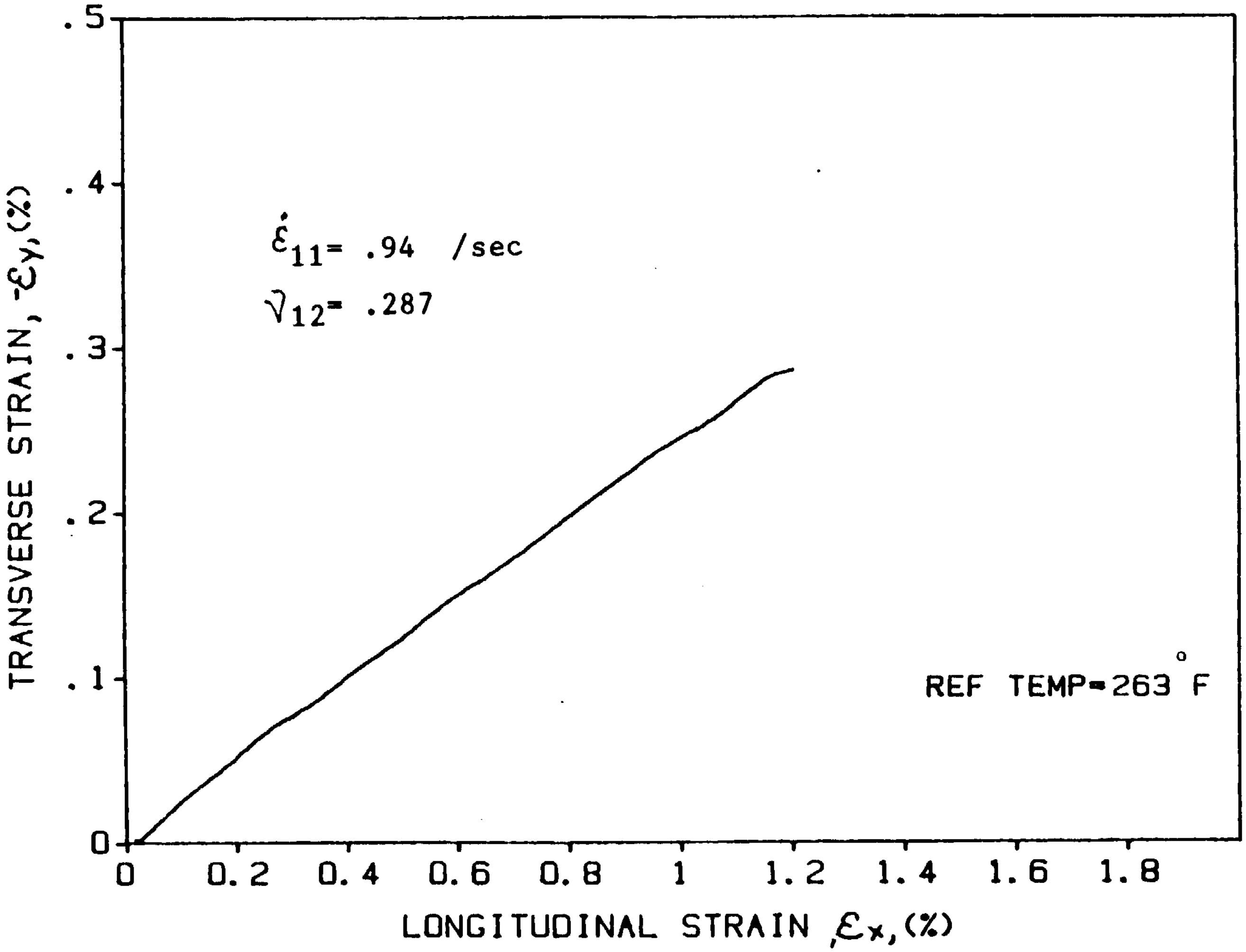


Fig. A-158. Transverse vs. Longitudinal Strain for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H6 (T = 128°C (263°F))

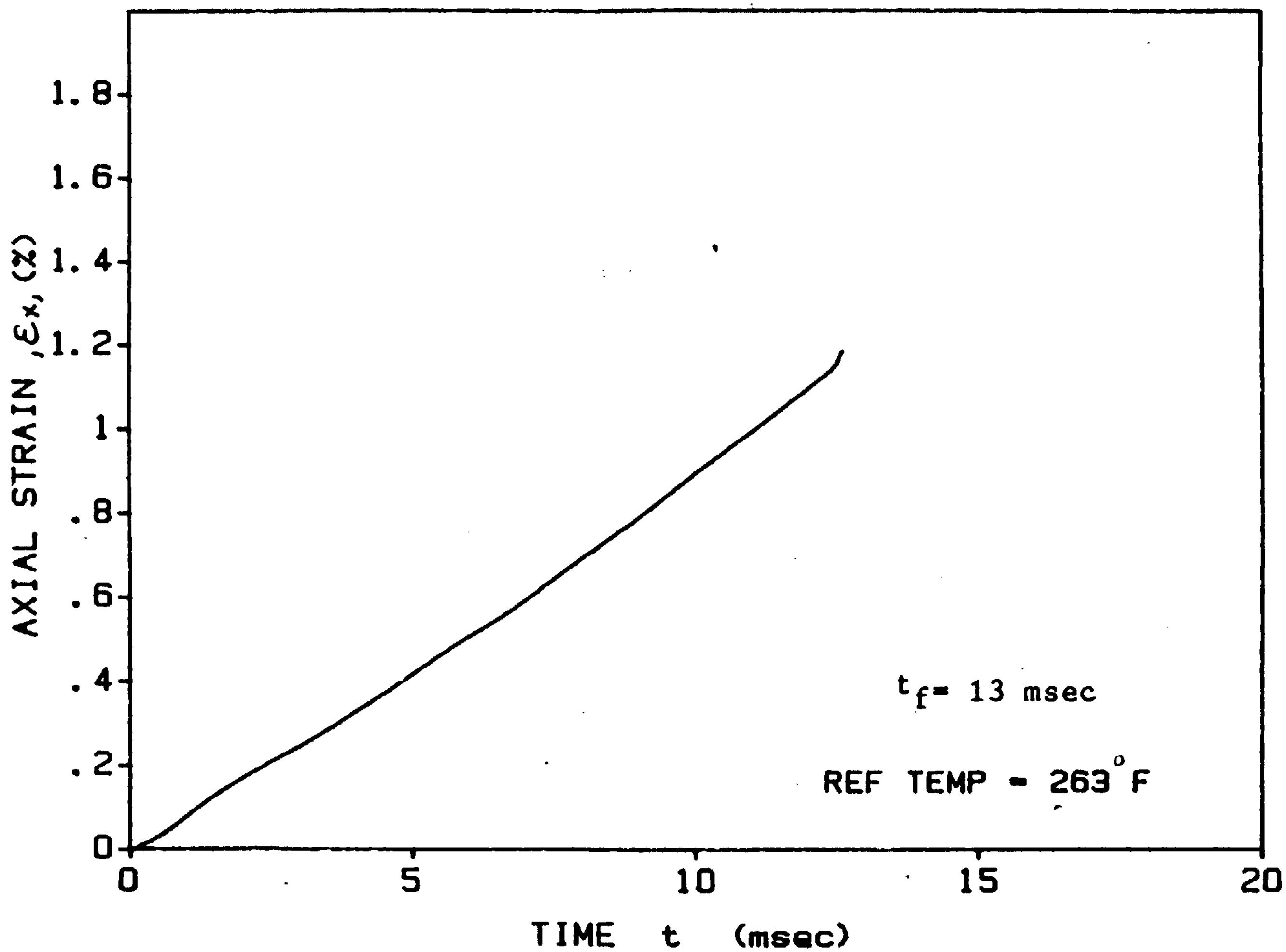


Fig. A-159. Axial Strain vs. Time for $[0_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 0/0H6 (T = 128°C (263°F))

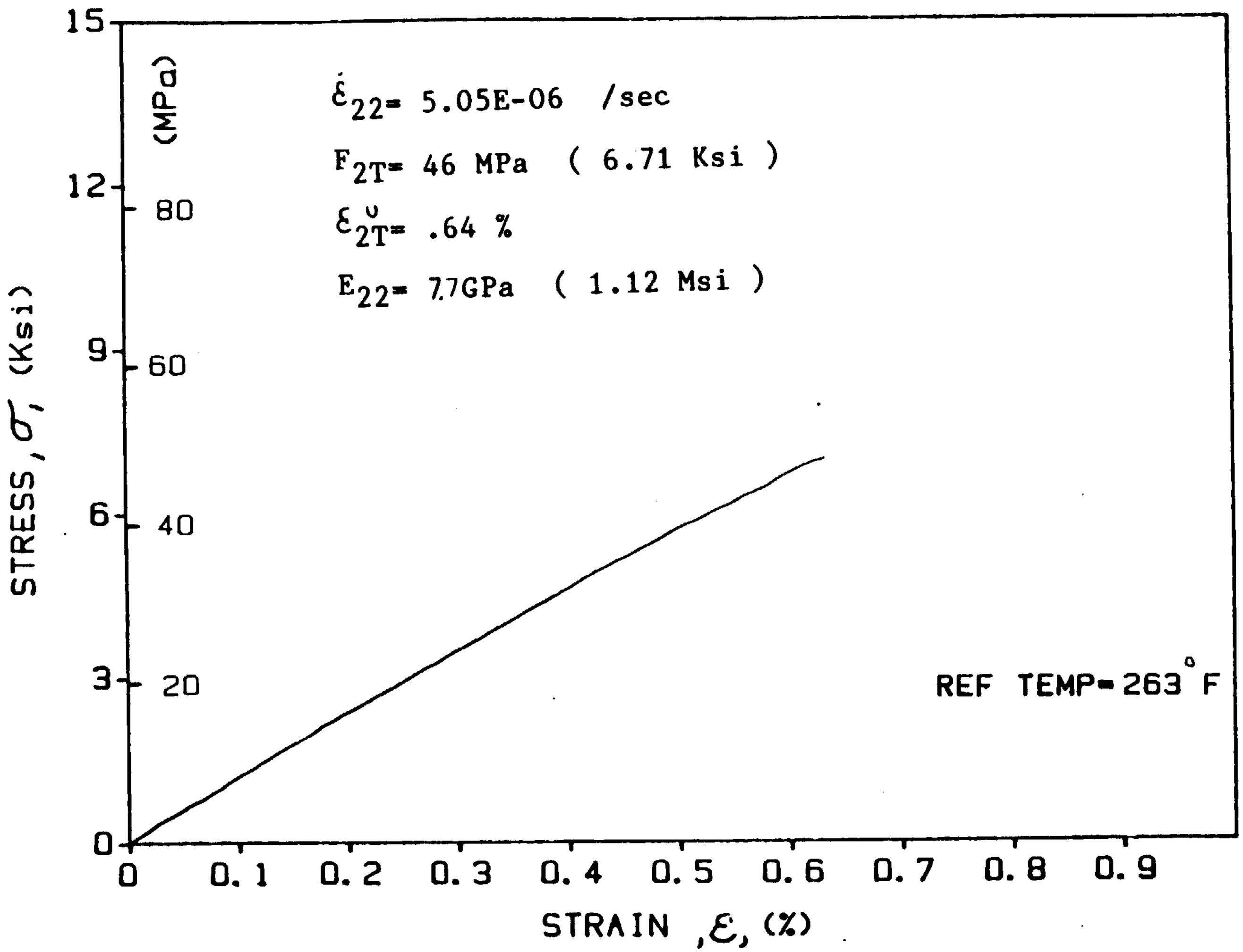


Fig. A-160. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-6H1 (T = 128°C (263°F))

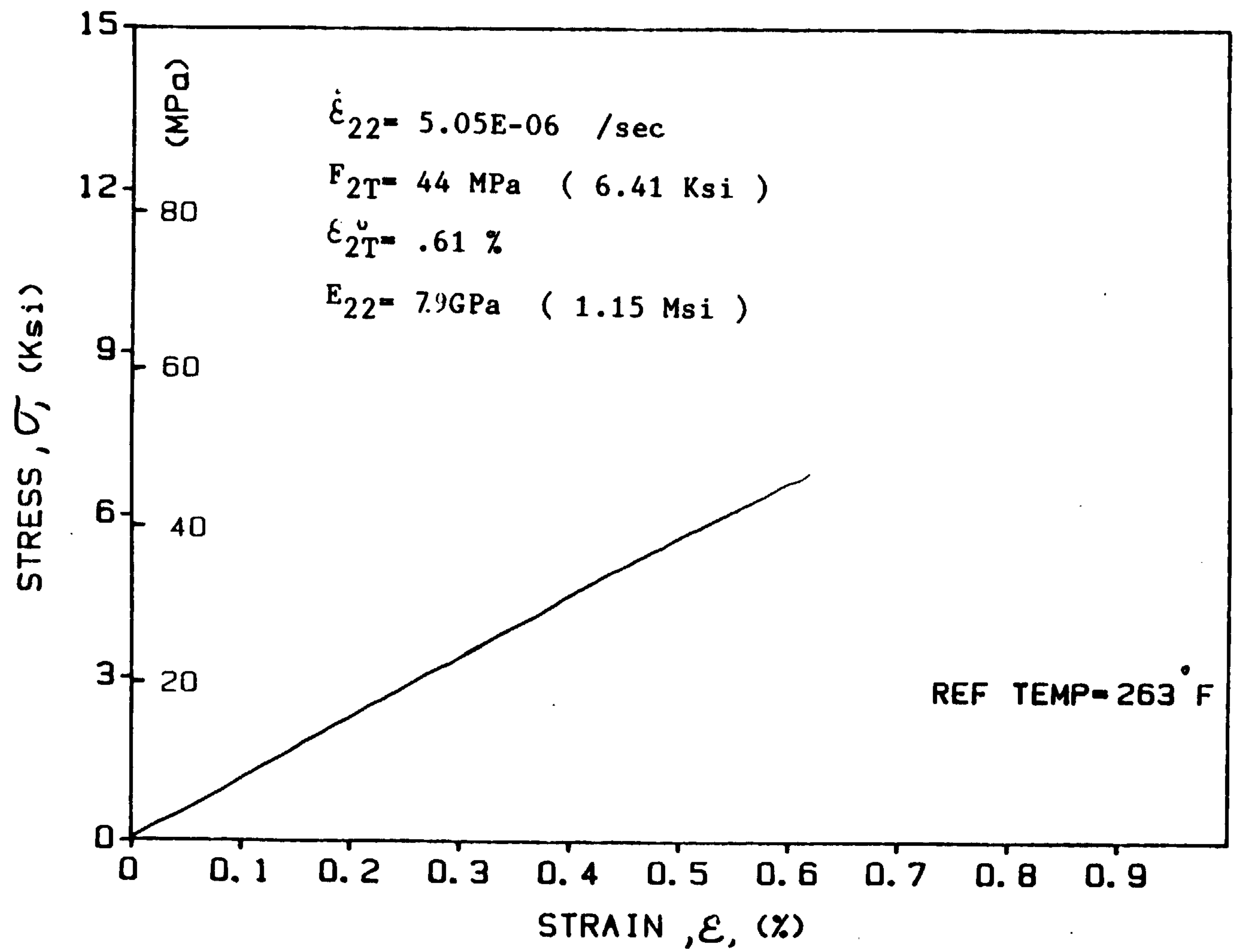


Fig. A-161. Stress-Strain Curve for $[90_8]$ AS4/3501-7 Graphite/Epoxy, Spec. 90/-6H2 (T = 128°C (263°F))

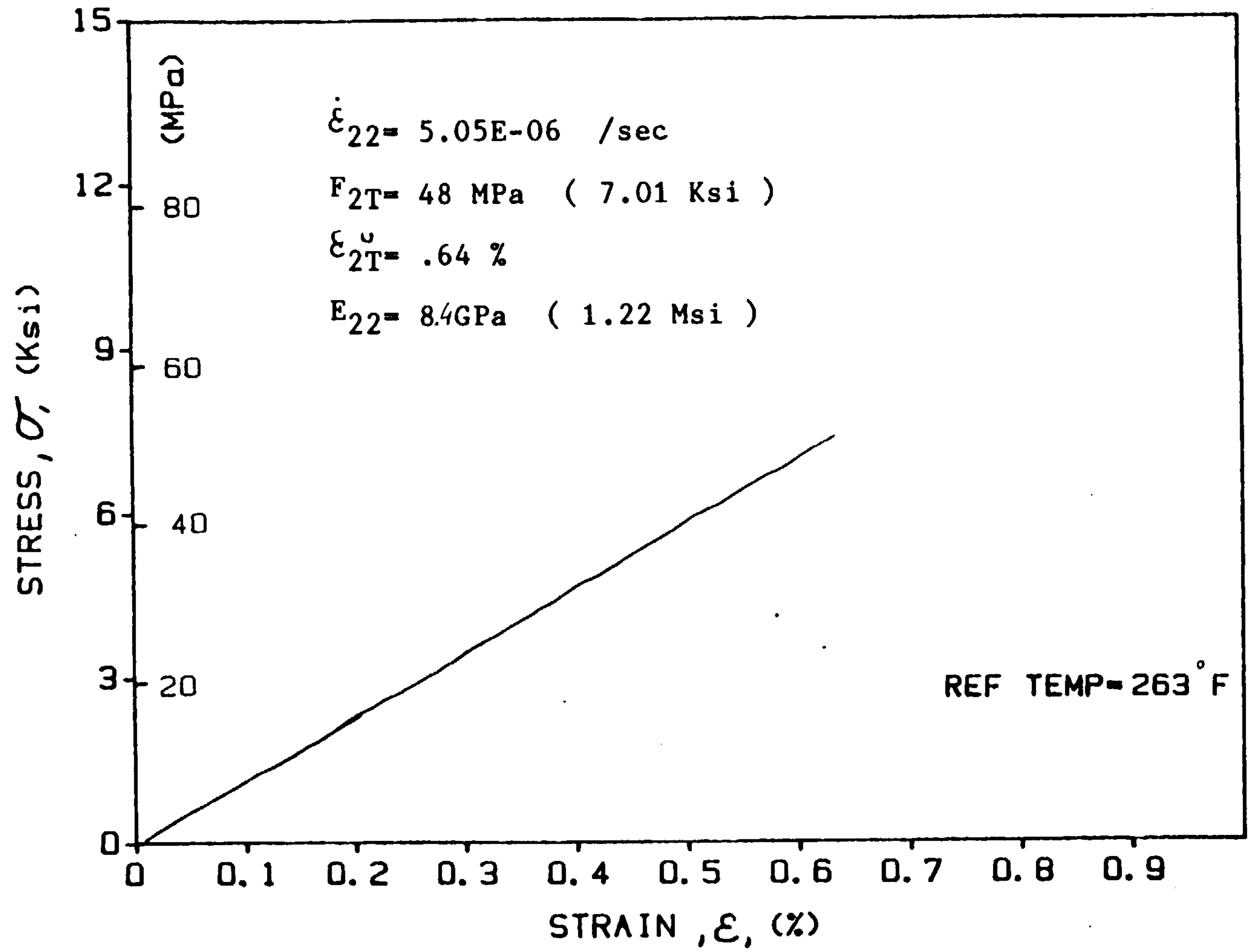


Fig. A-162. Stress-Strain Curve for $[90_8]$ AS4/3501-7 Graphite/Epoxy, Spec. 90/-6H3 (T = 128°C (263°F))

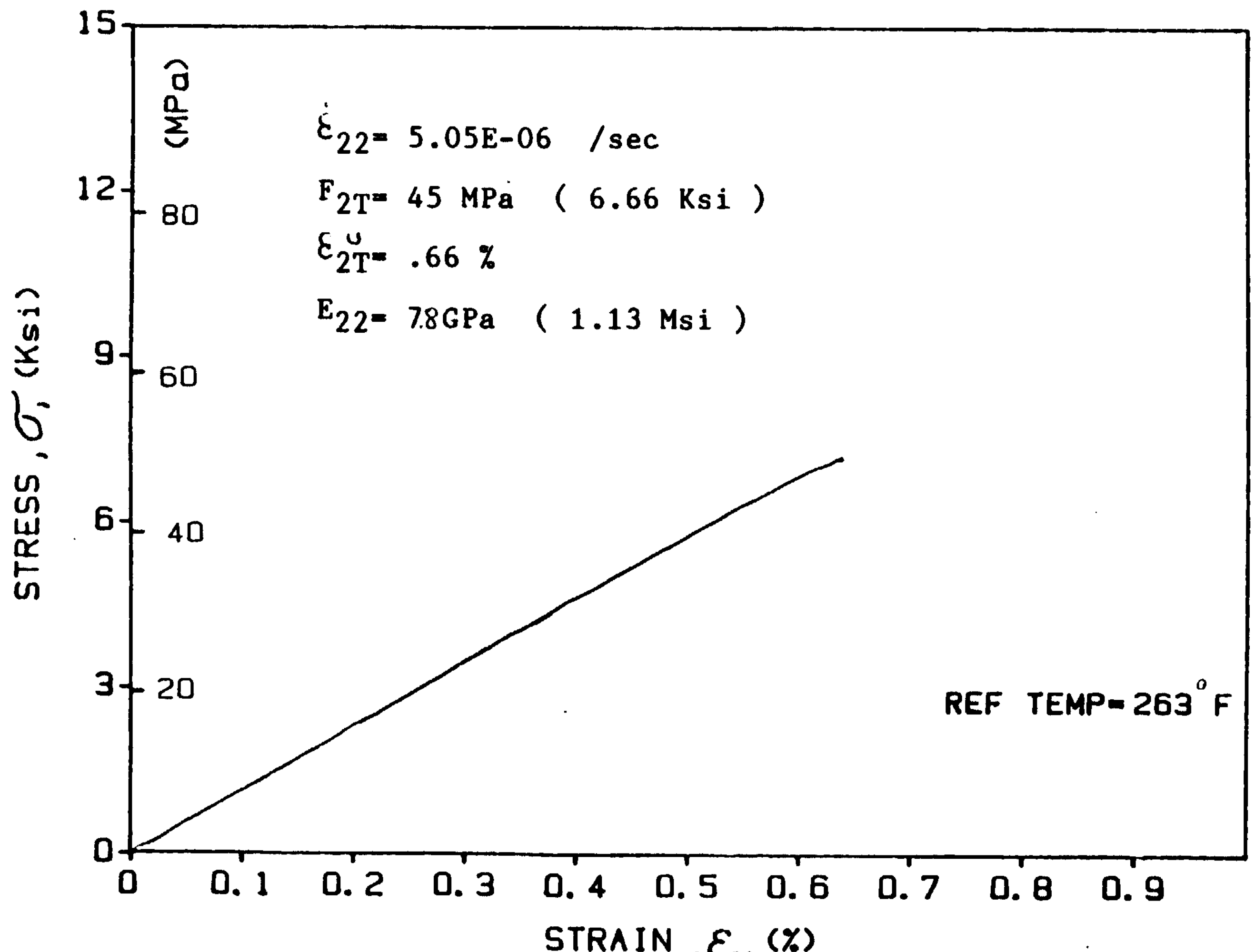


Fig. A-163. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-6H4 (T = 128°C (263°F))

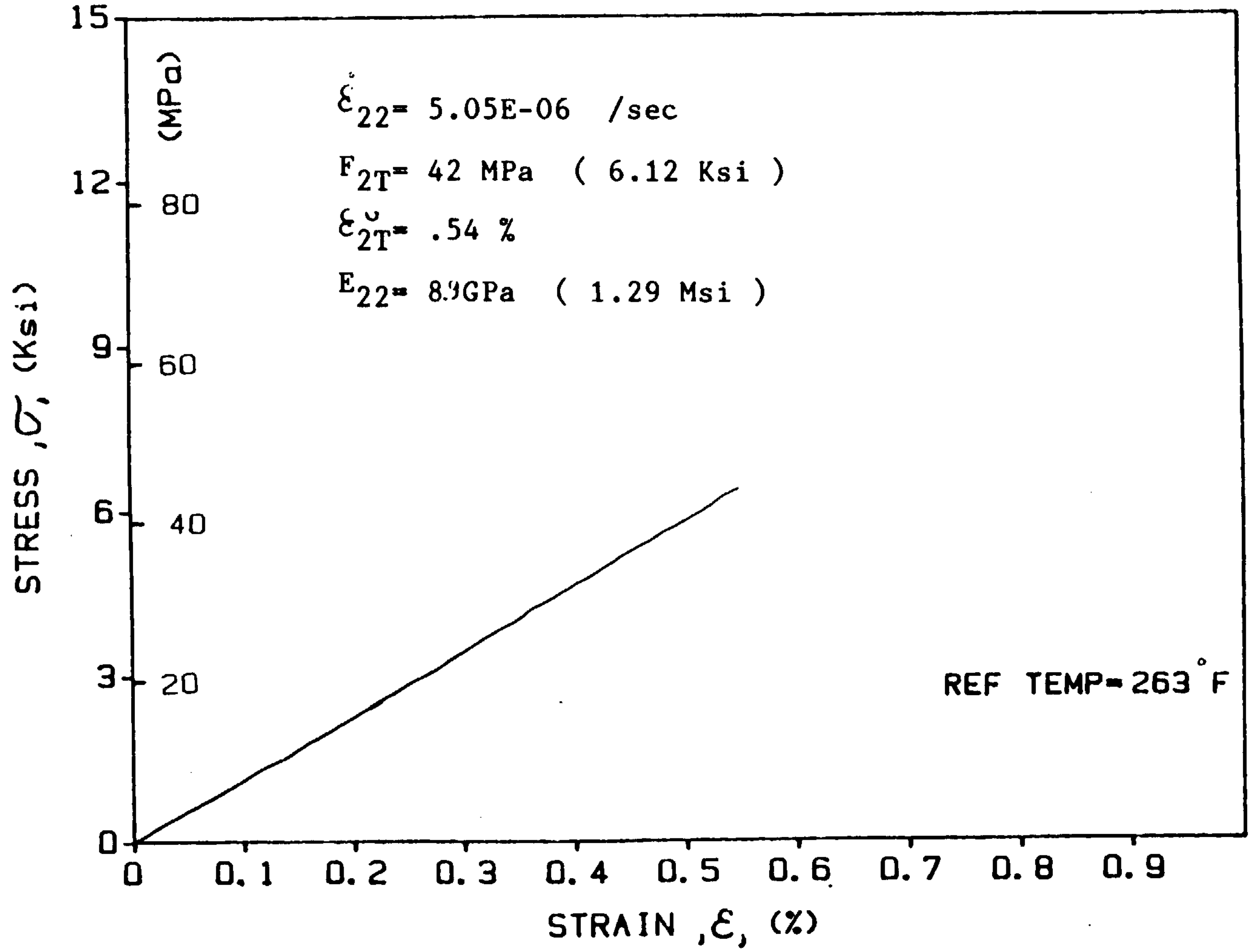


Fig. A-164. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-6H5 (T = 128°C (263°F))

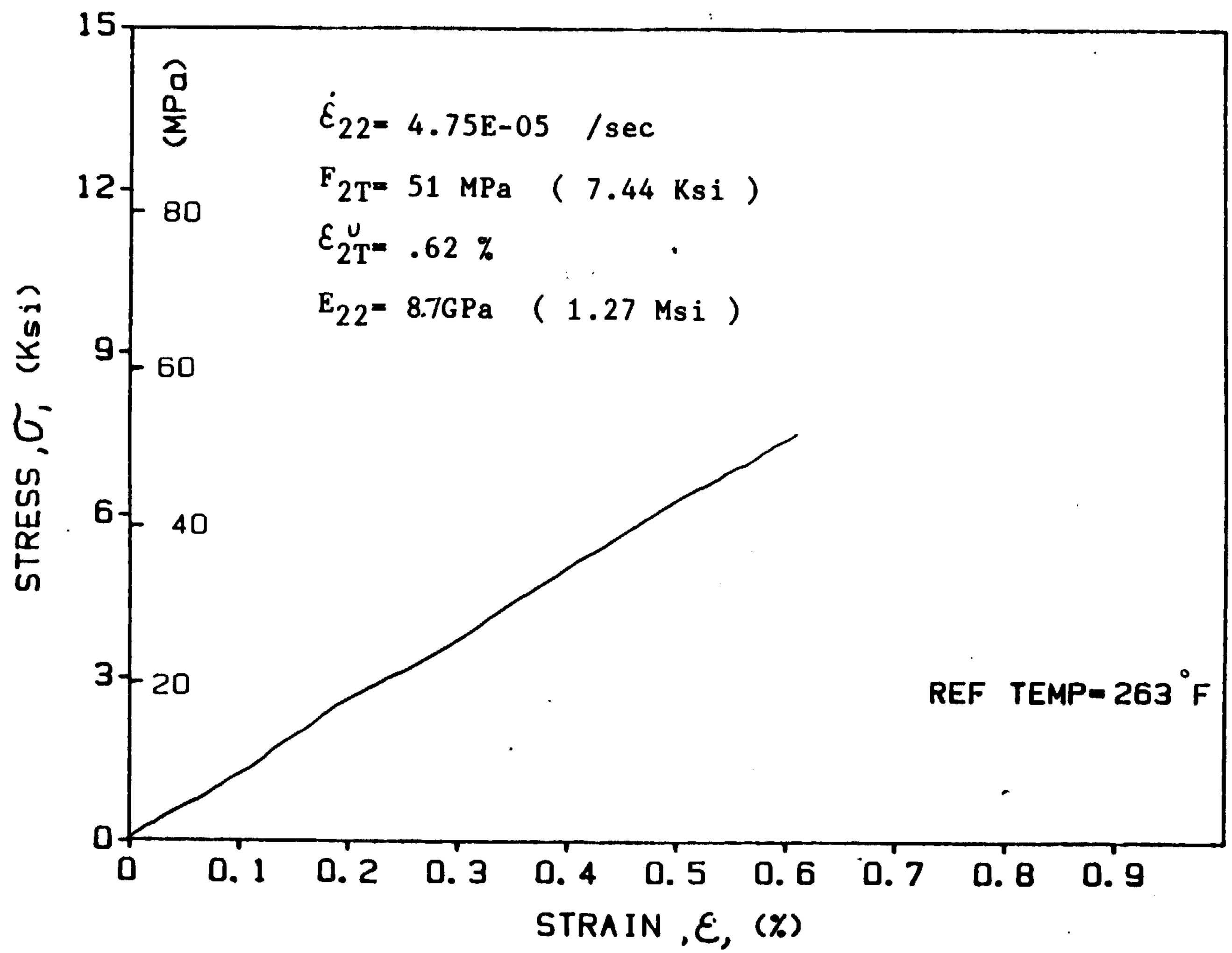


Fig. A-165. Stress-Strain Curve for [90_8] AS4/3501-6 Graphite/Epoxy, Spec. 90/-5H1 (T = 128°C (263°F))

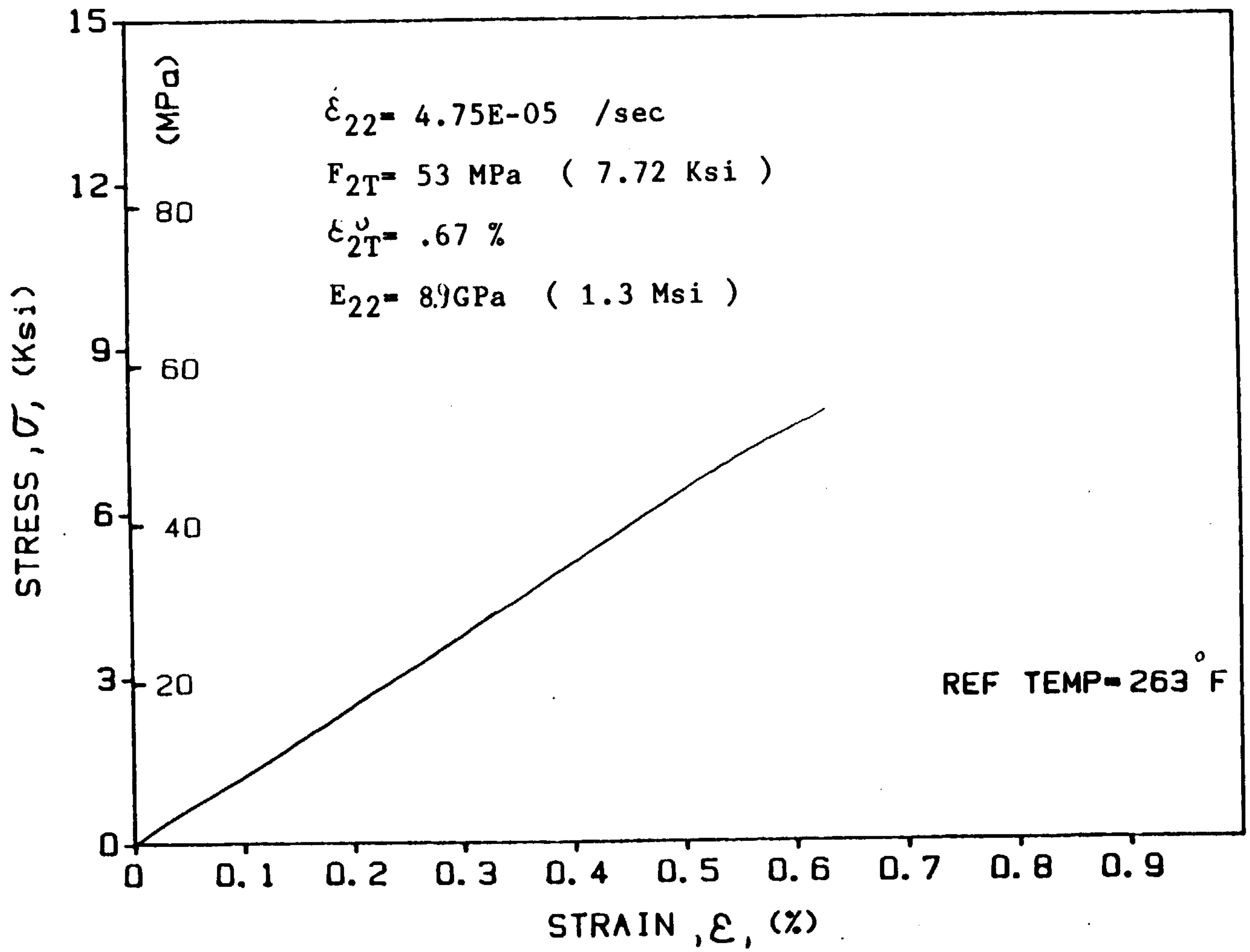


Fig. A-166. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5H2 (T = 128°C (263°F))

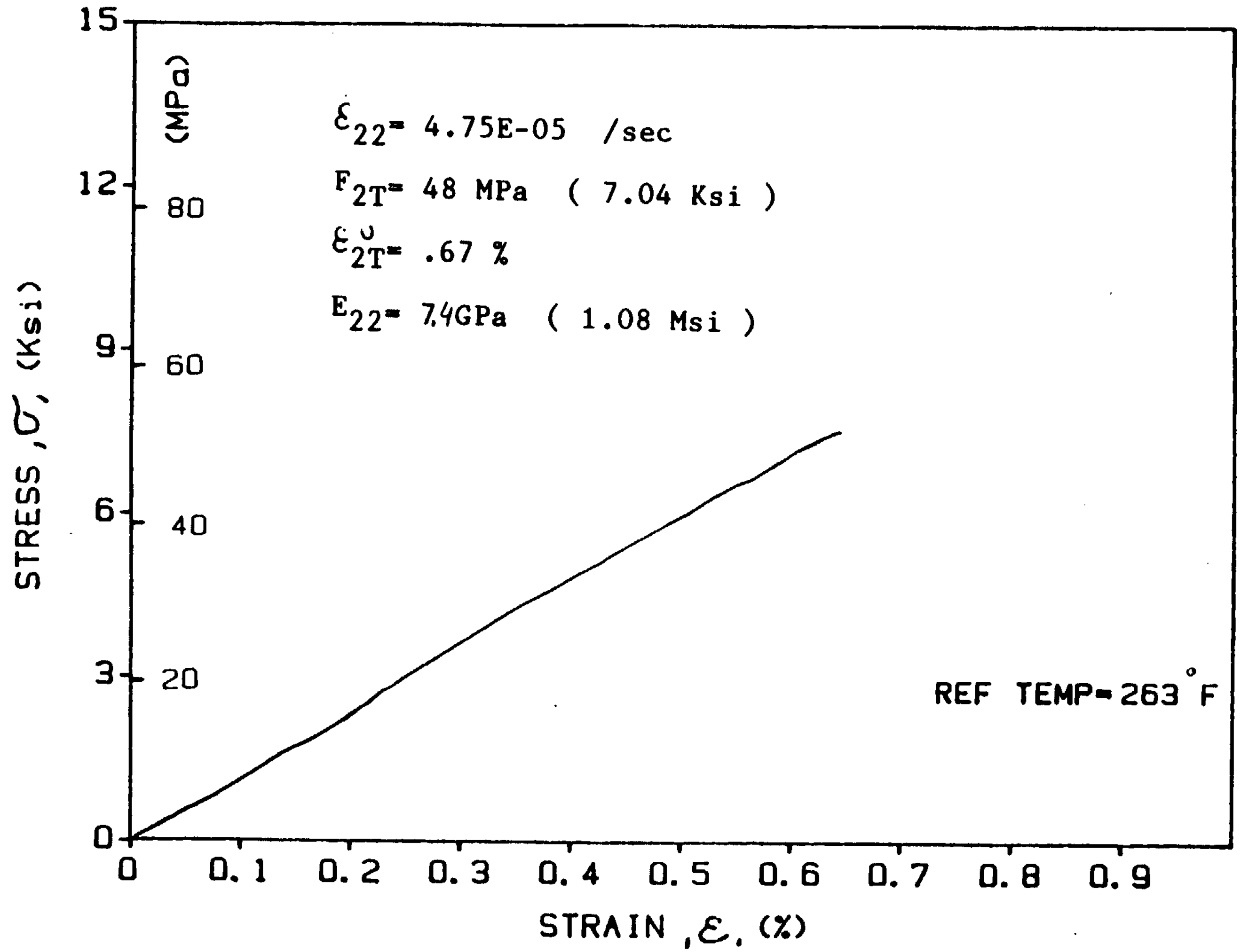


Fig. A-167. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5H3 (T = 128°C (263°F))

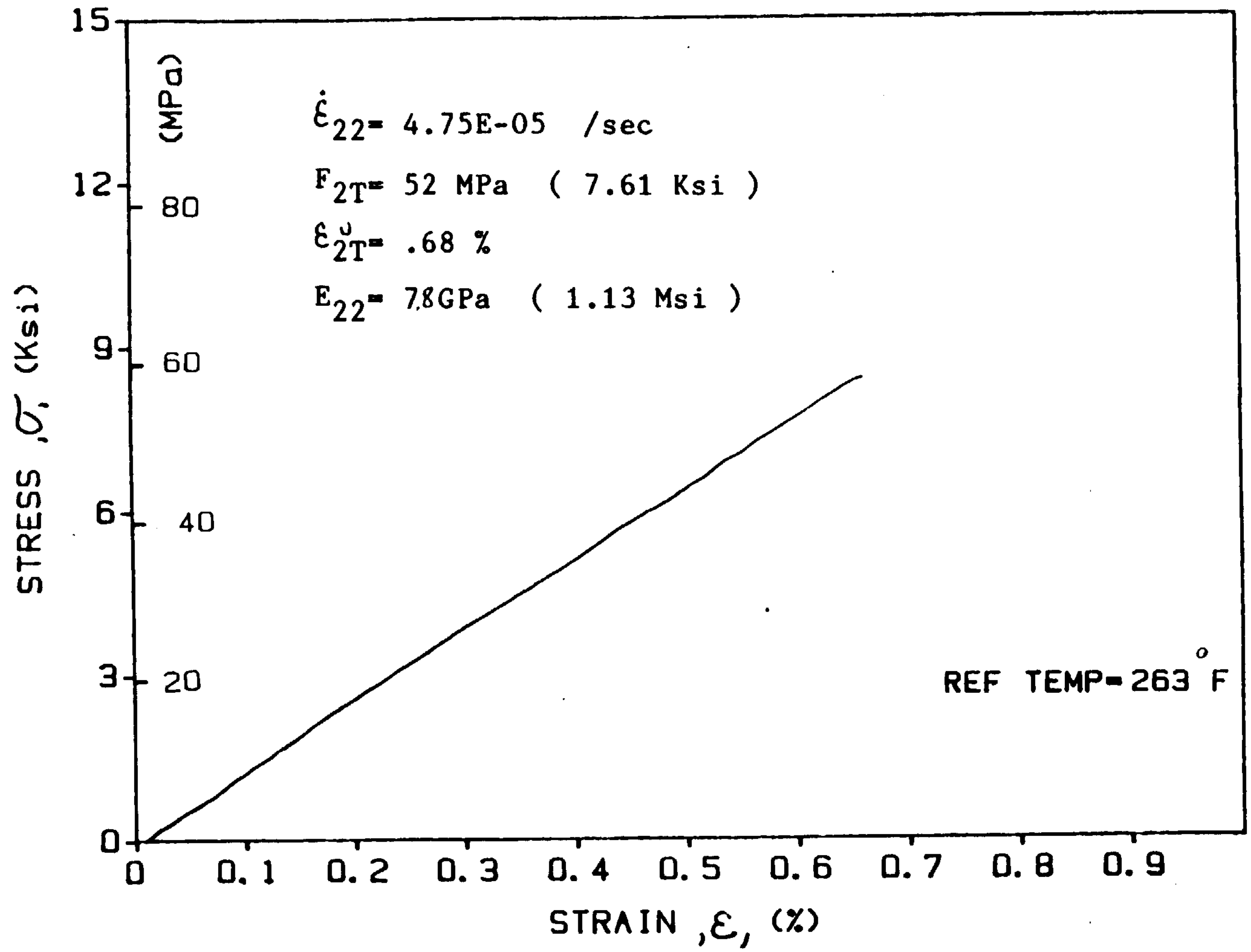


Fig. A-168. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5H4 (T = 128°C (263°F))

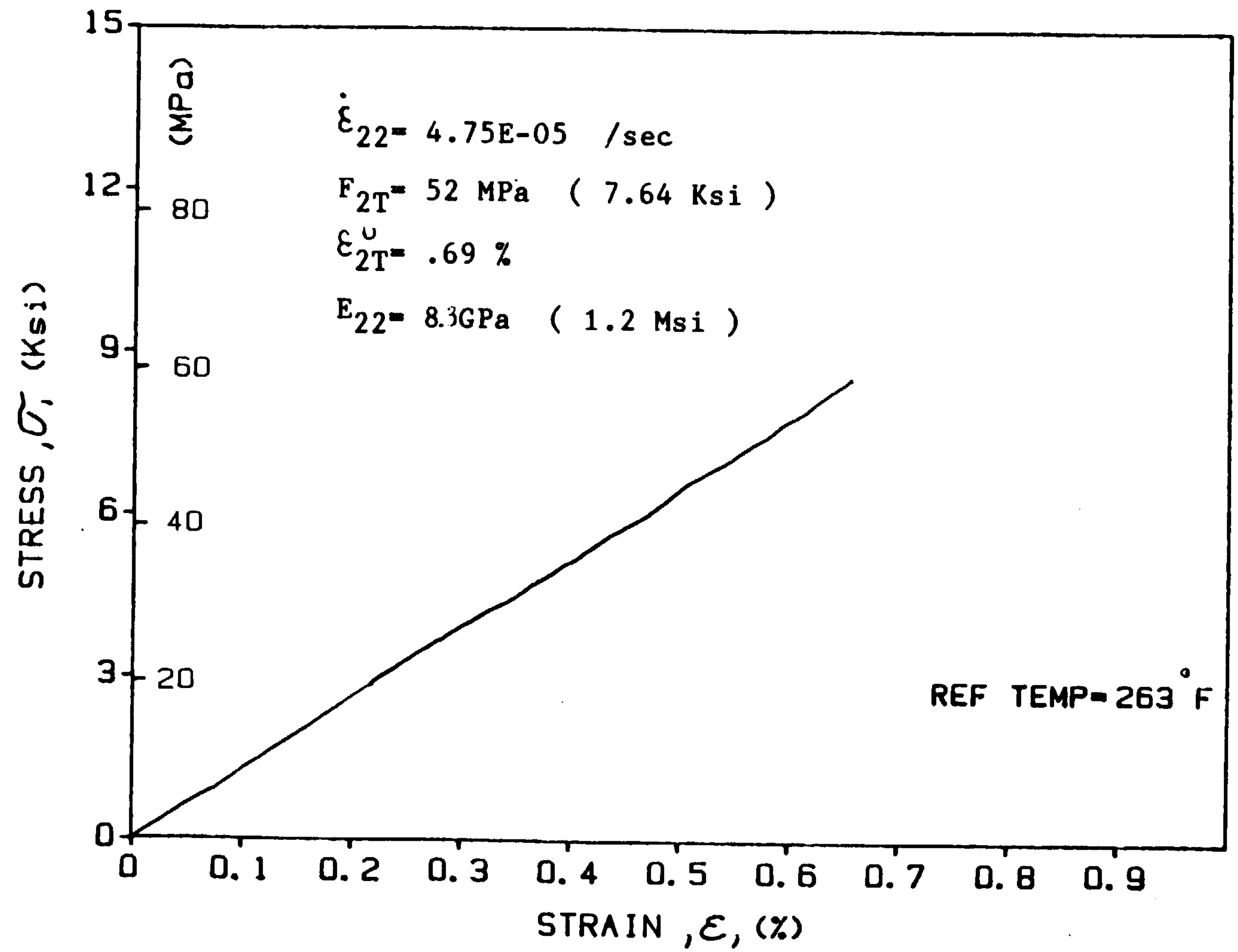


Fig. A-169. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-5H5 (T = 128°C (263°F))

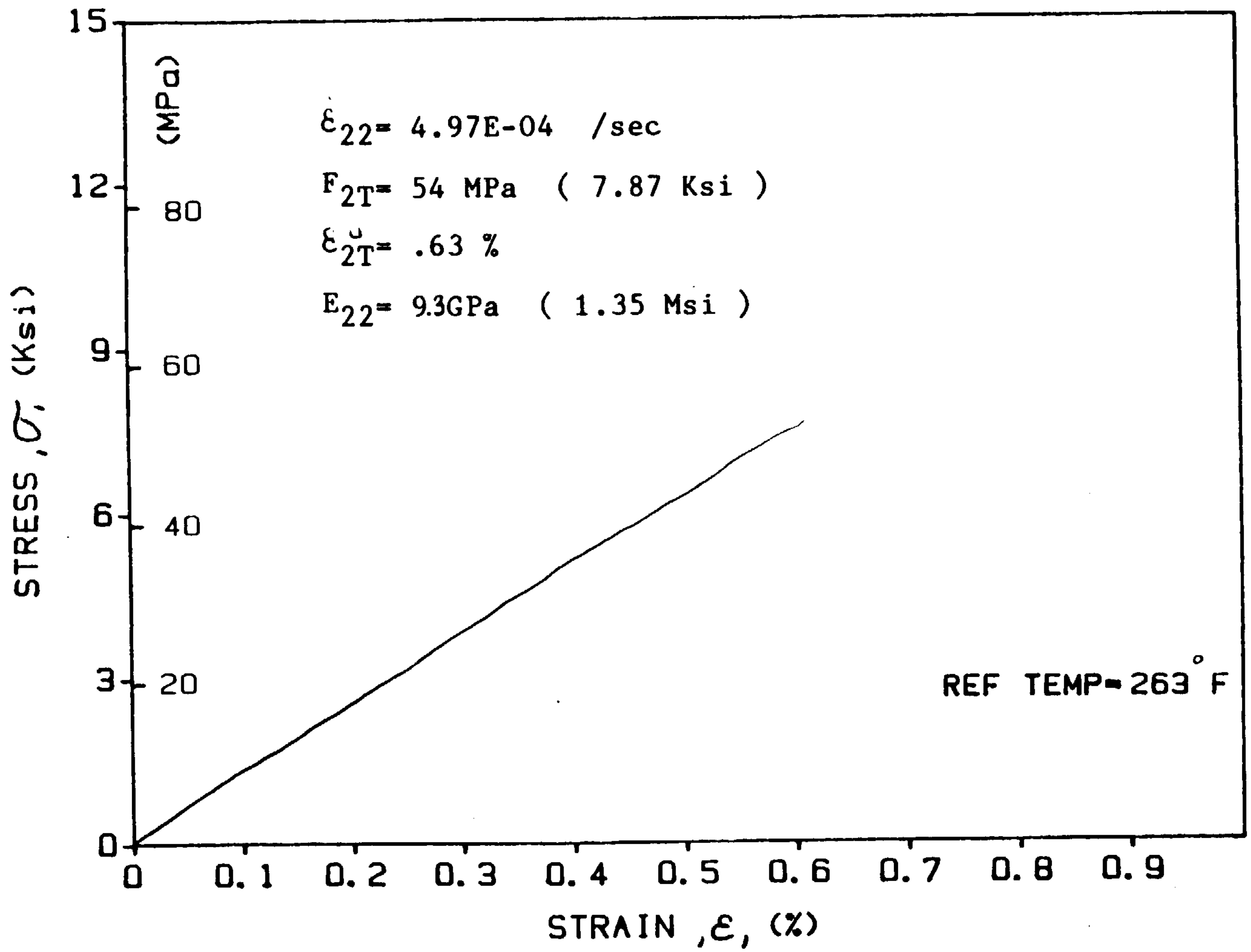


Fig. A-170. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-4H1 (T = 128°C (263°F))

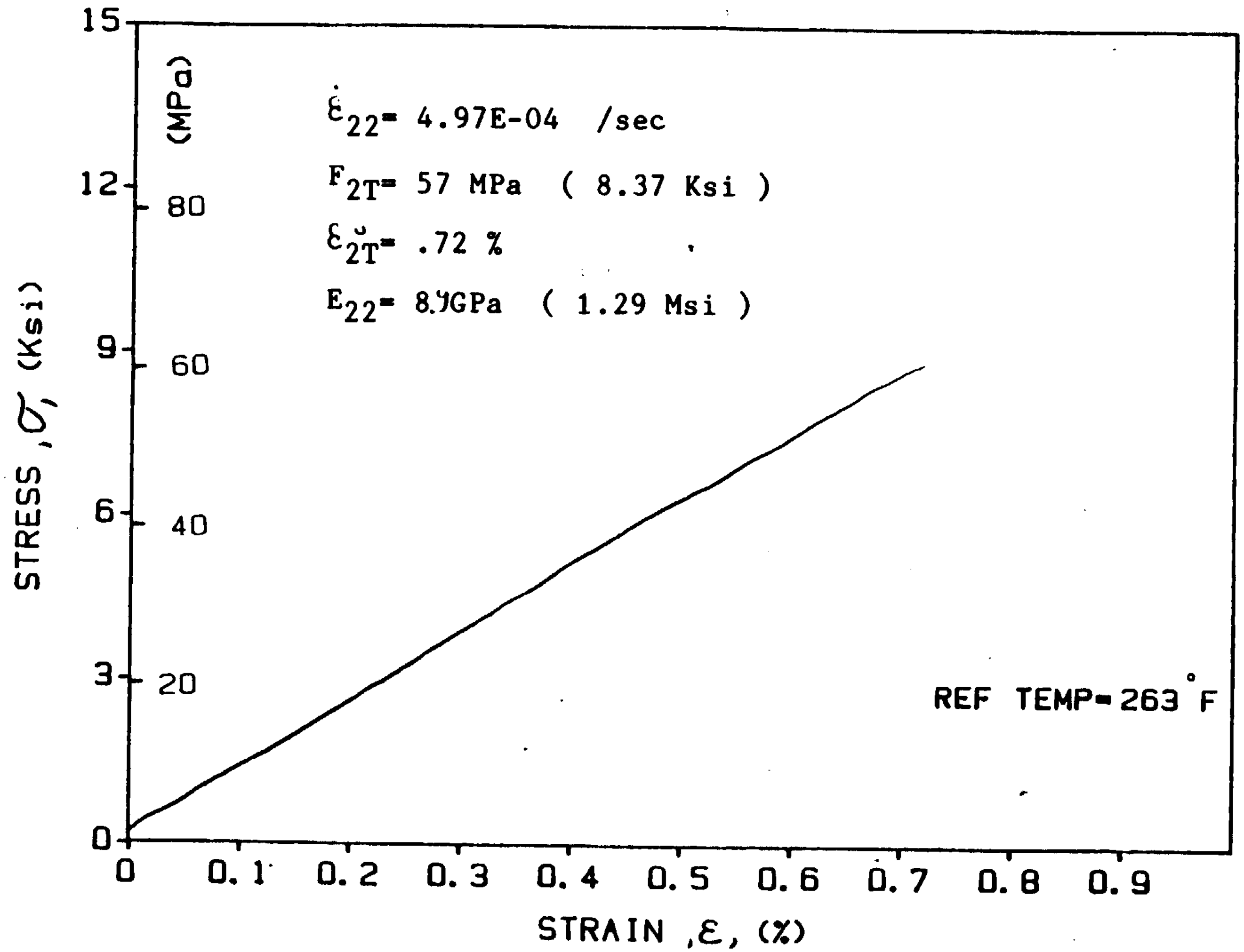


Fig. A-171. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-4H2 (T = 128°C (263°F))

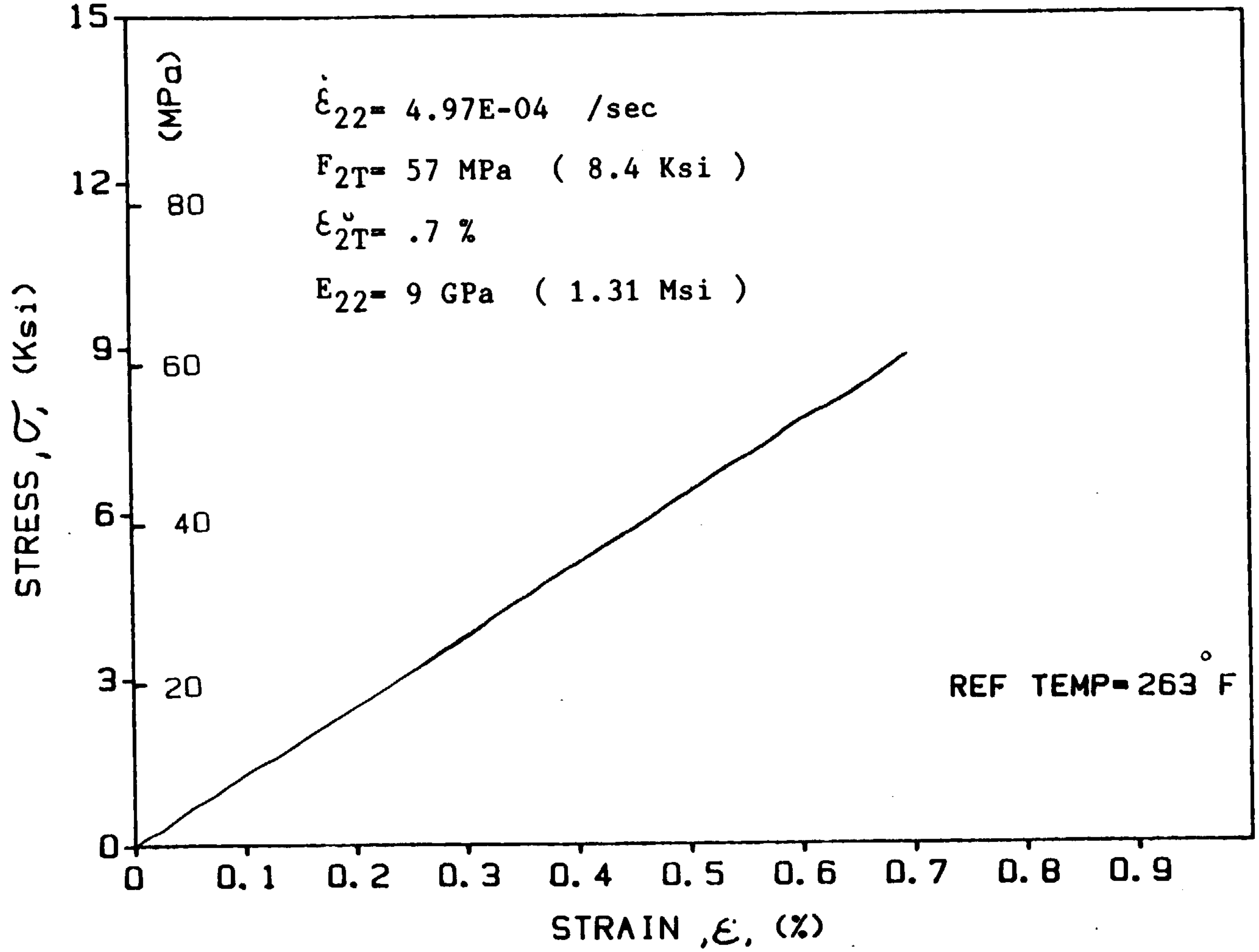


Fig. A-172. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-4H3 (T = 128°C (263°F))

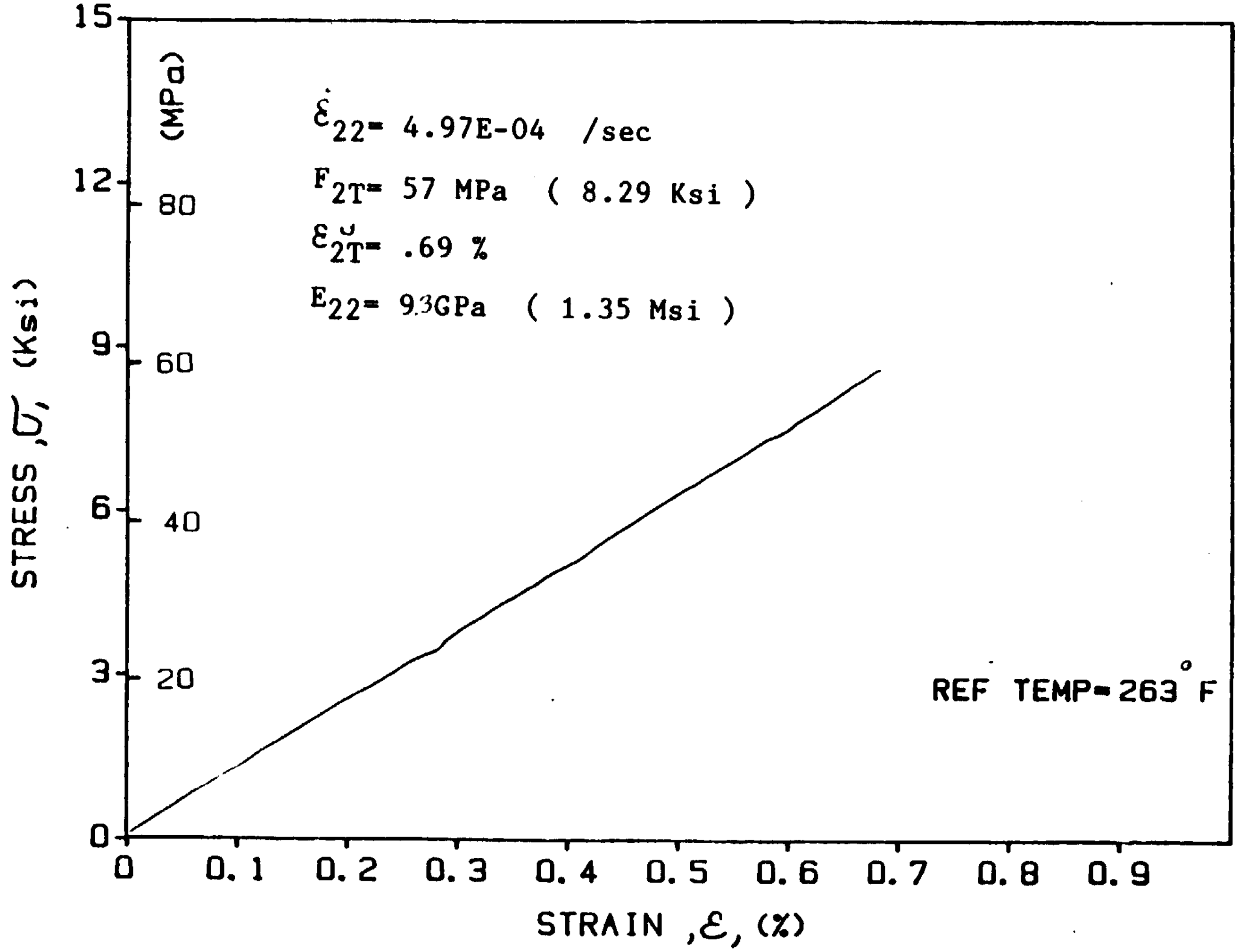


Fig. A-173. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-4H4 (T = 128°C (263°F))

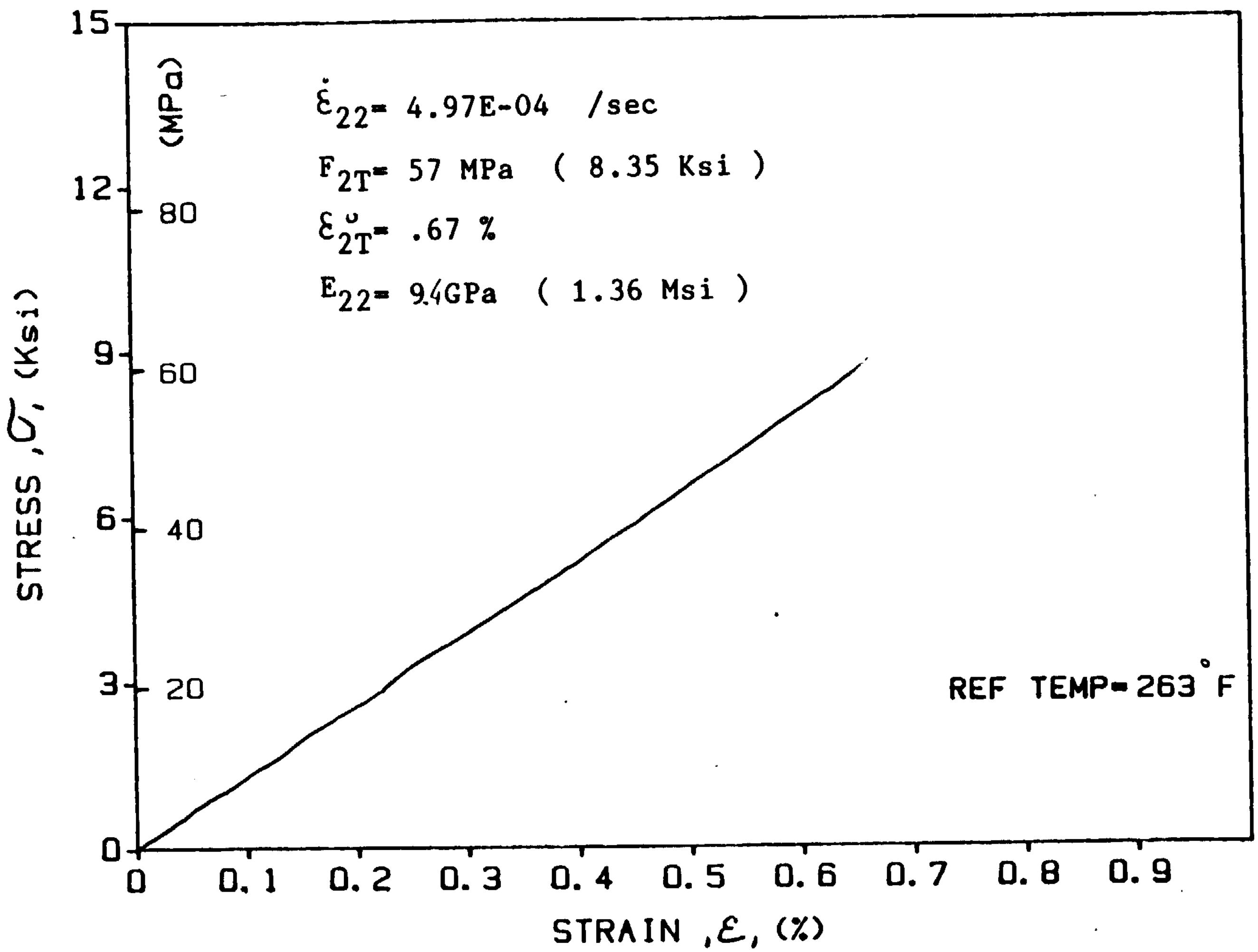


Fig. A-174. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-4H5 (T = 128°C (263°F))

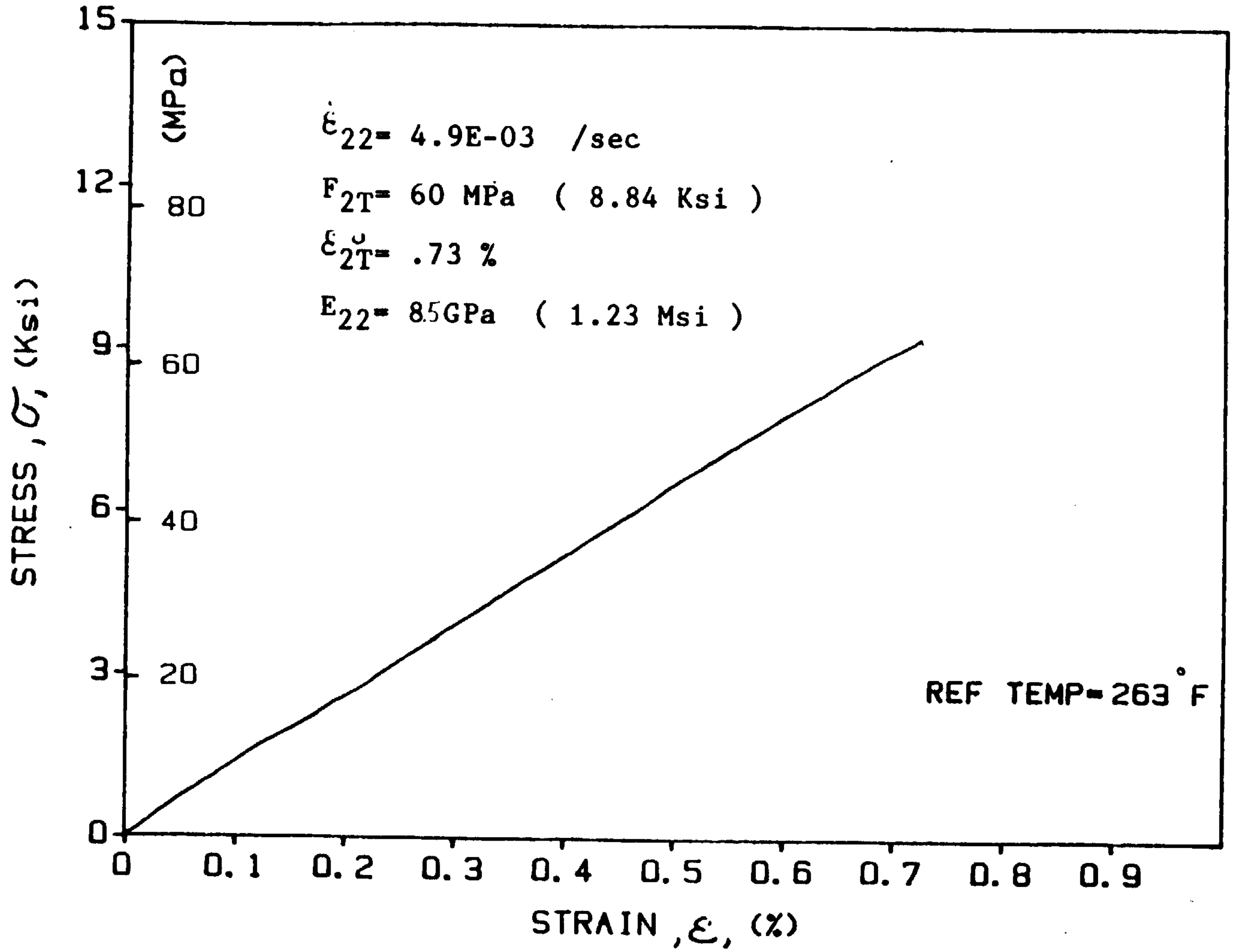


Fig. A-175. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3H1 (T = 128°C (263°F))

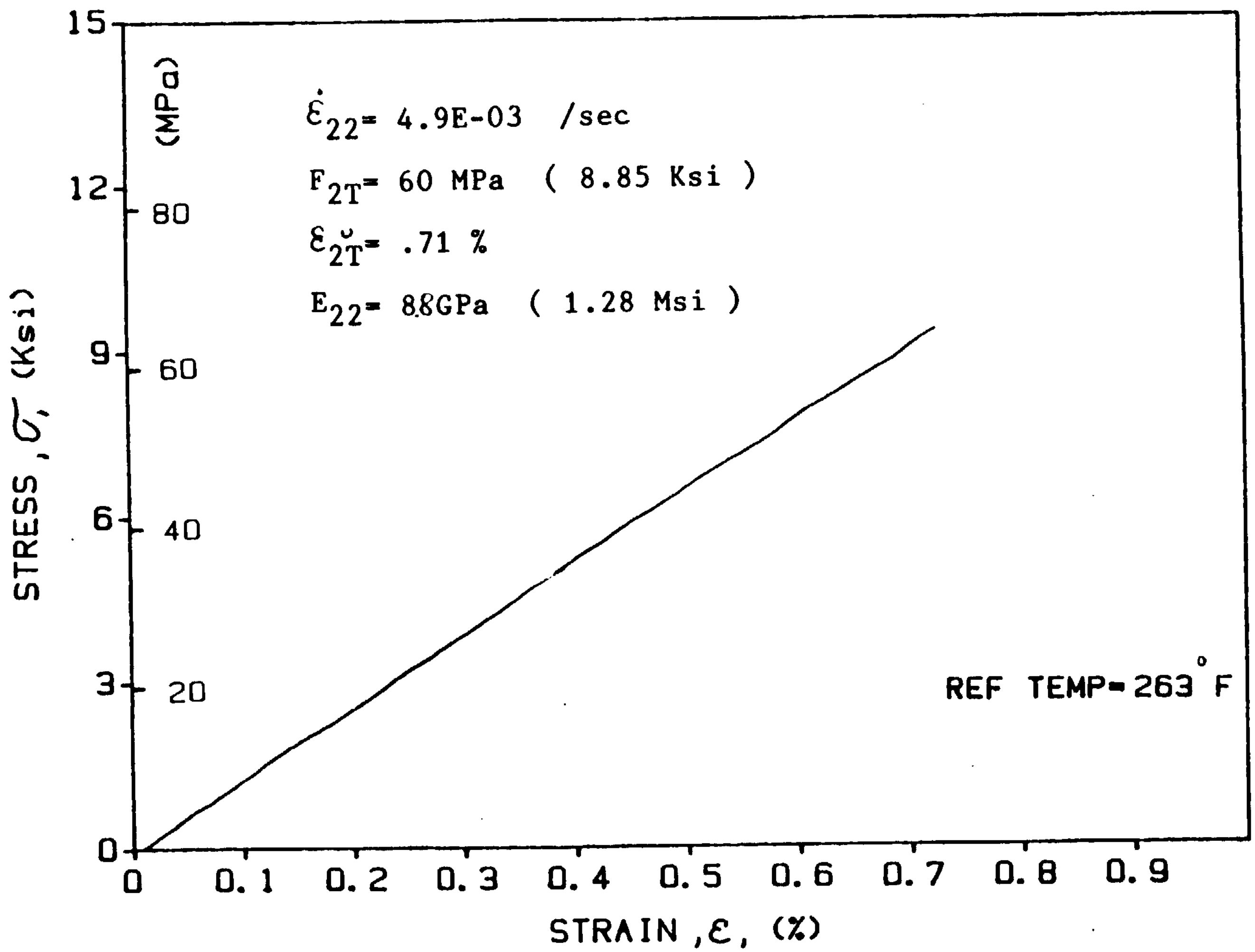


Fig. A-176. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3H2 (T = 128°C (263°F))

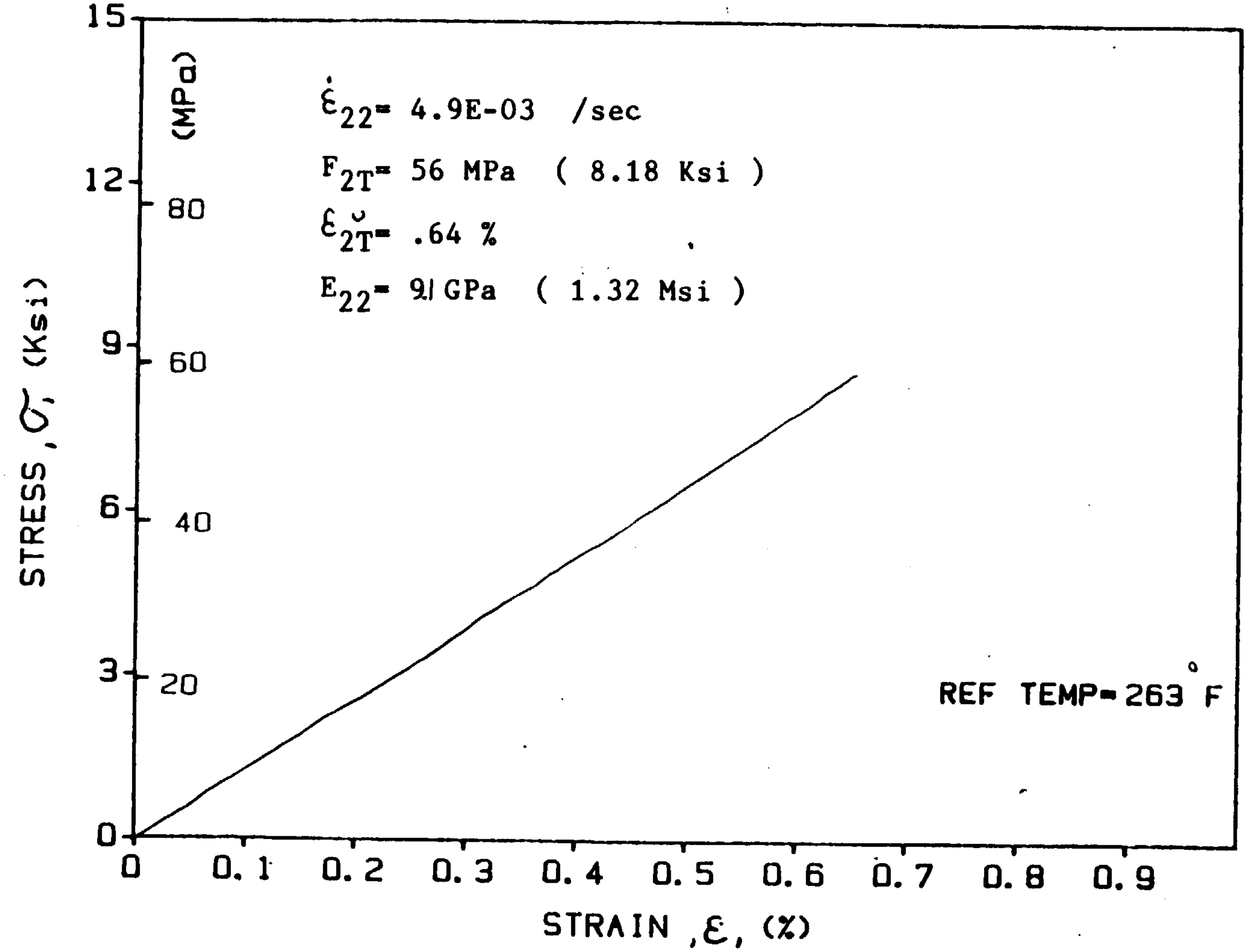


Fig. A-177. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3H3 (T = 128°C (263°F))

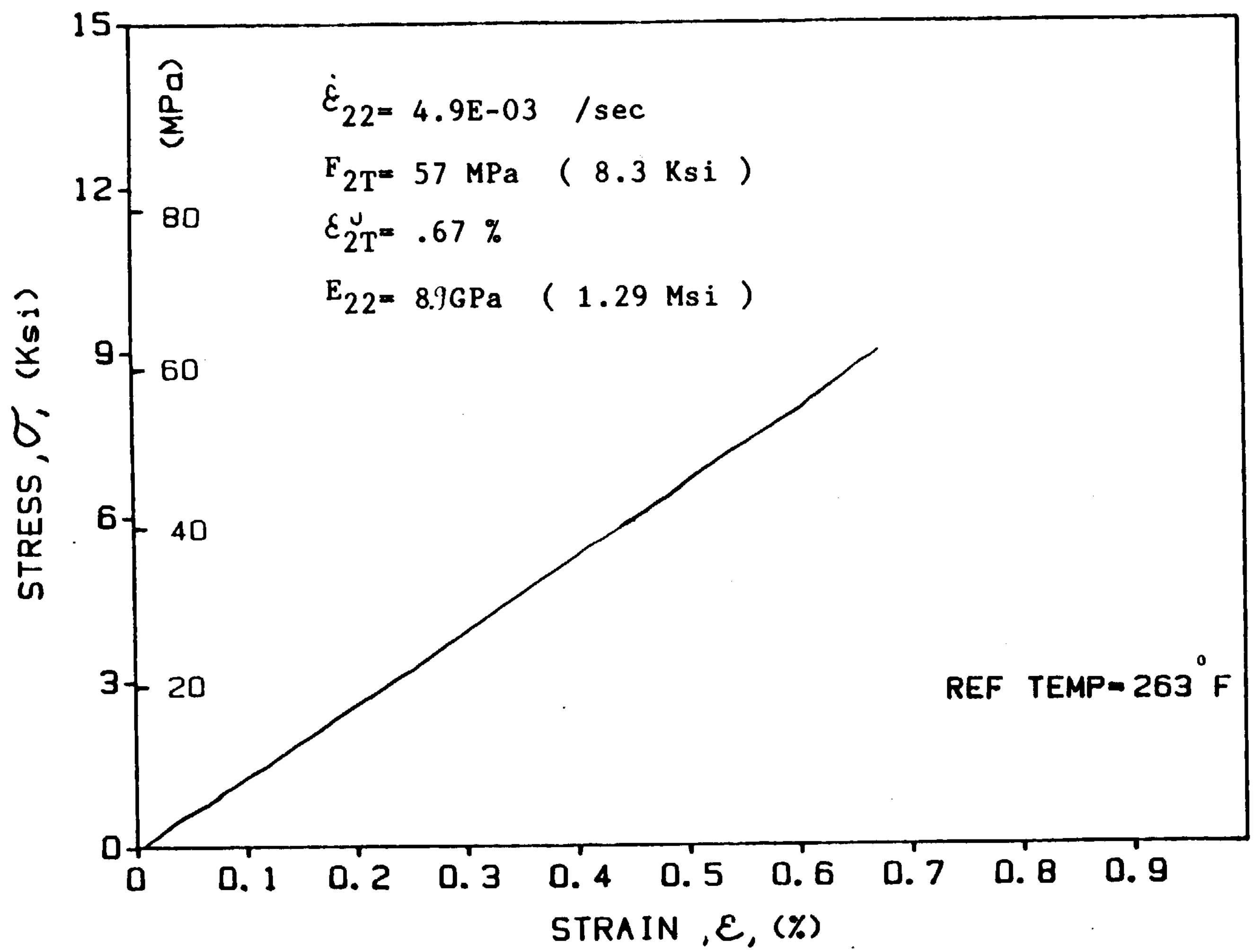


Fig. A-178. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3H4 (T = 128°C (263°F))

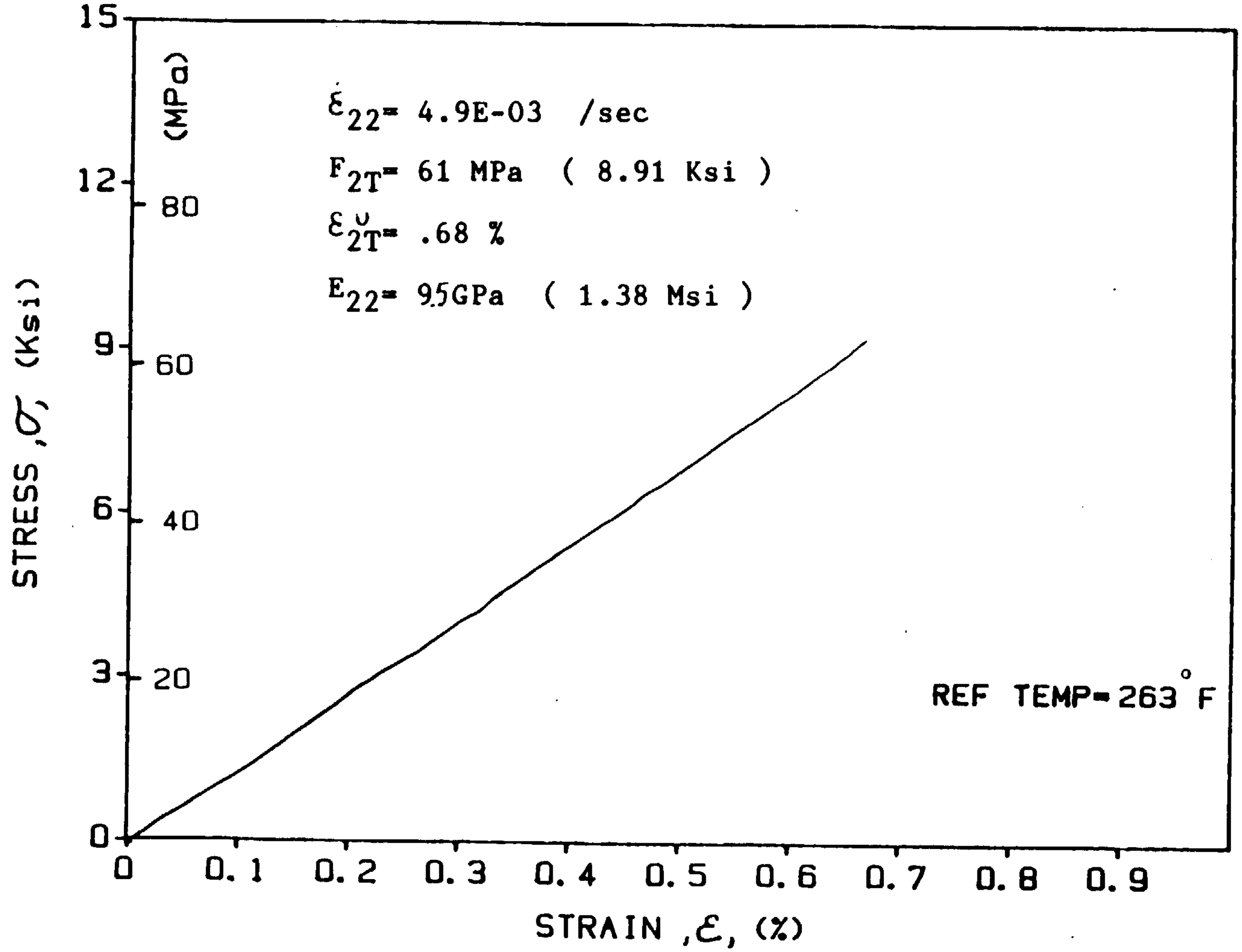


Fig. A-179. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-3H5 (T = 128°C (263°F))

C.4

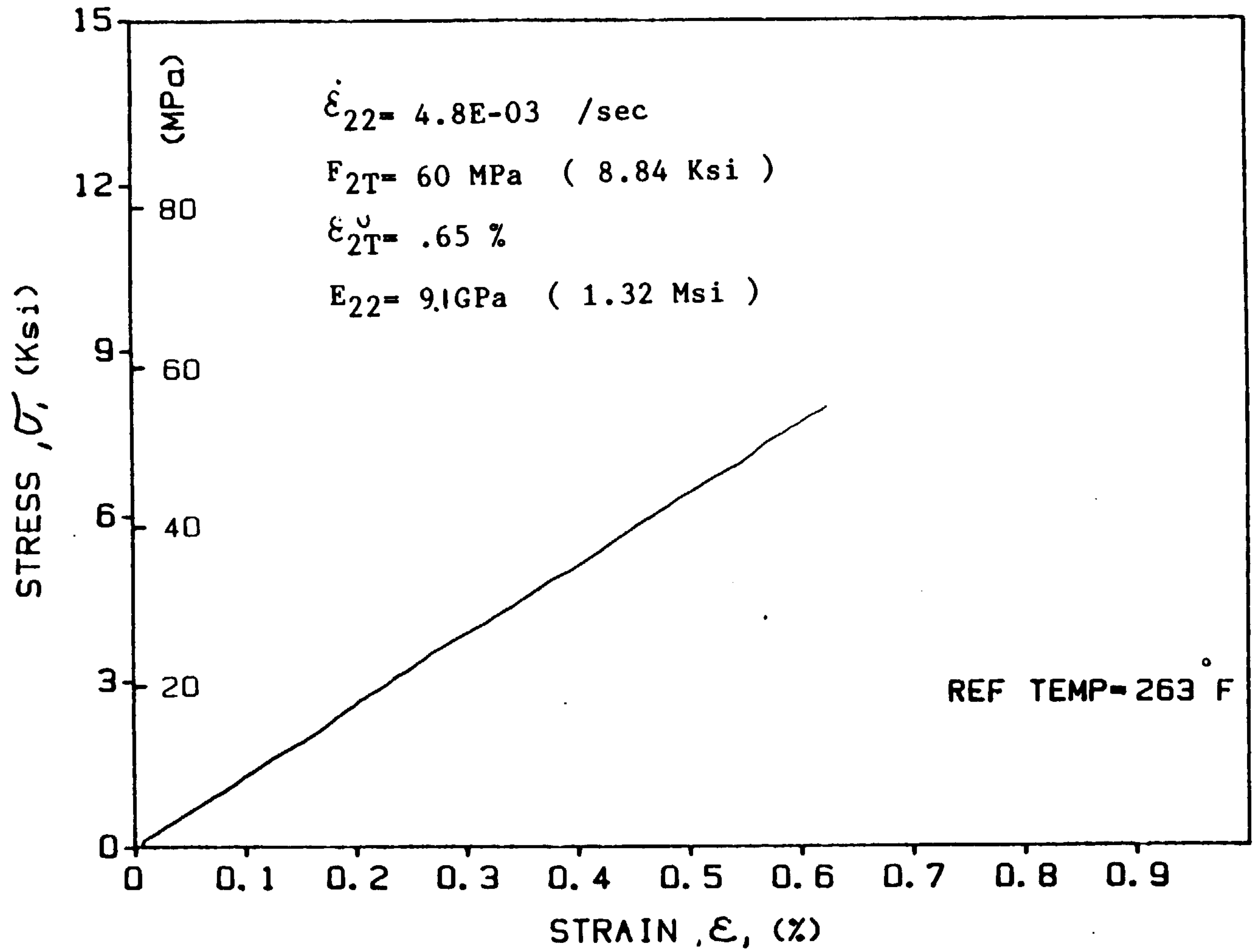


Fig. A-180. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epxoy, Spec. 90/-2H1 (T = 128°C (263°F))

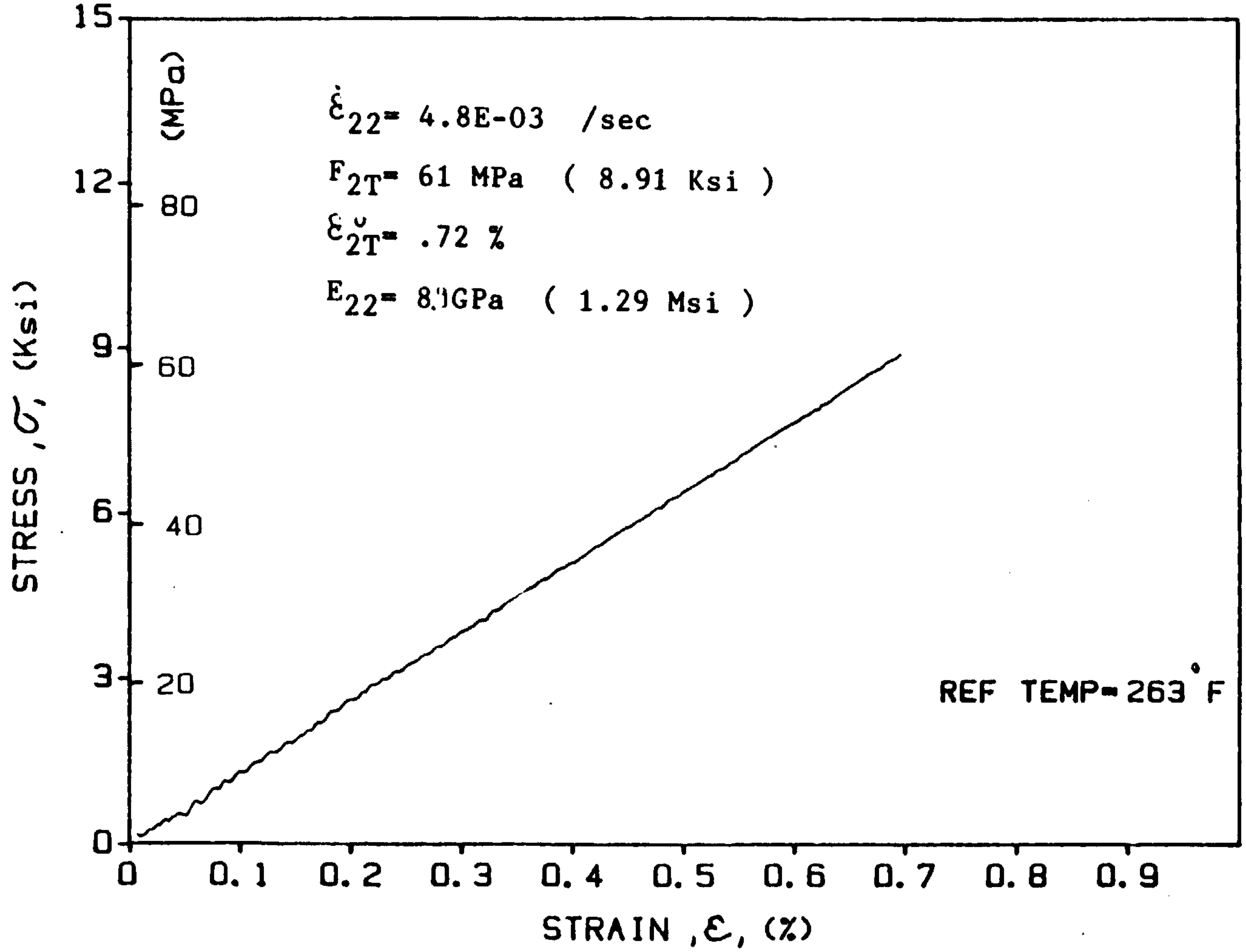


Fig. A-181. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2H2 (T = 128°C (263°F))

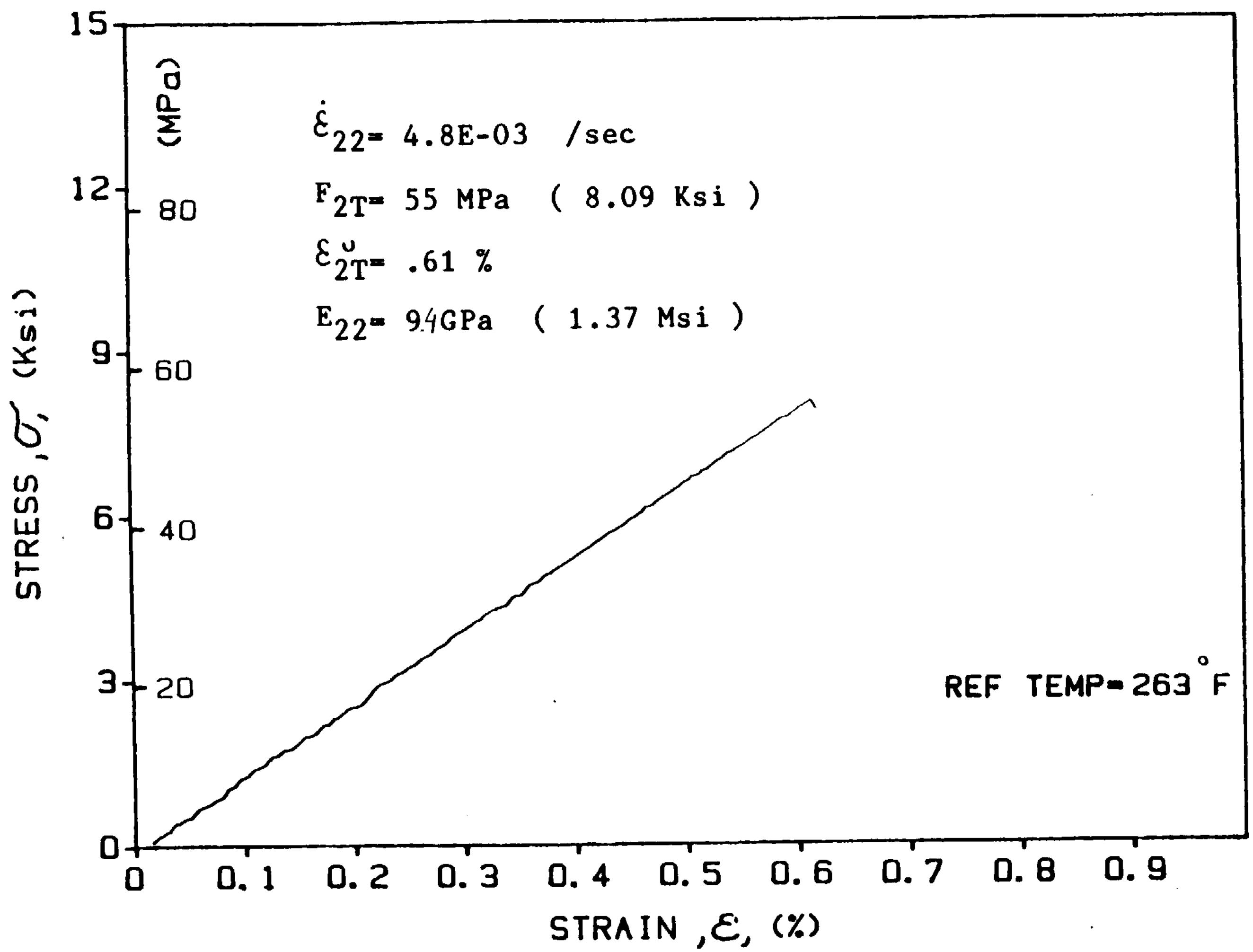


Fig. A-182. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2H3 (T = 128°C (263°F))

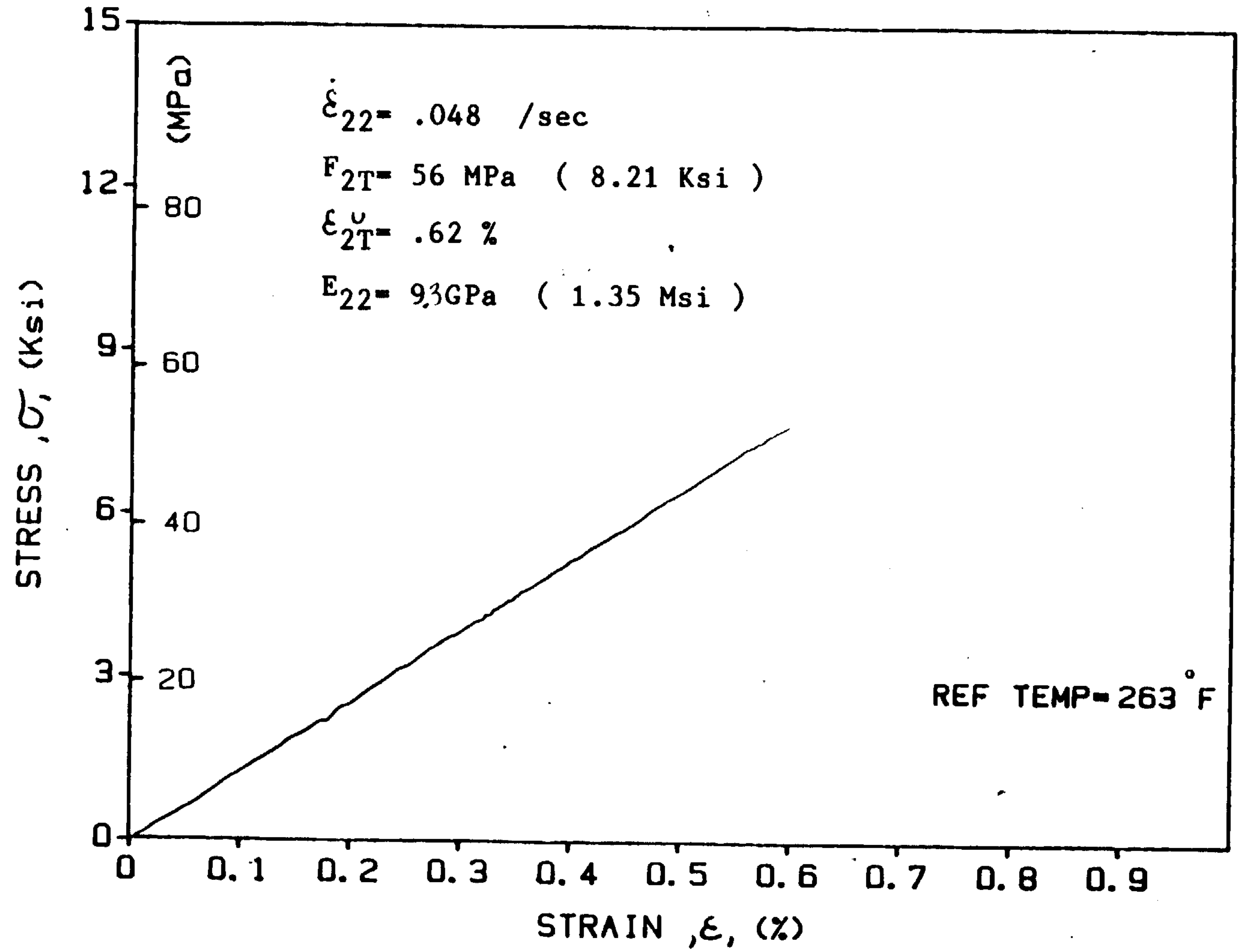


Fig. A-183. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2H4 (T = 128°C (263°F))

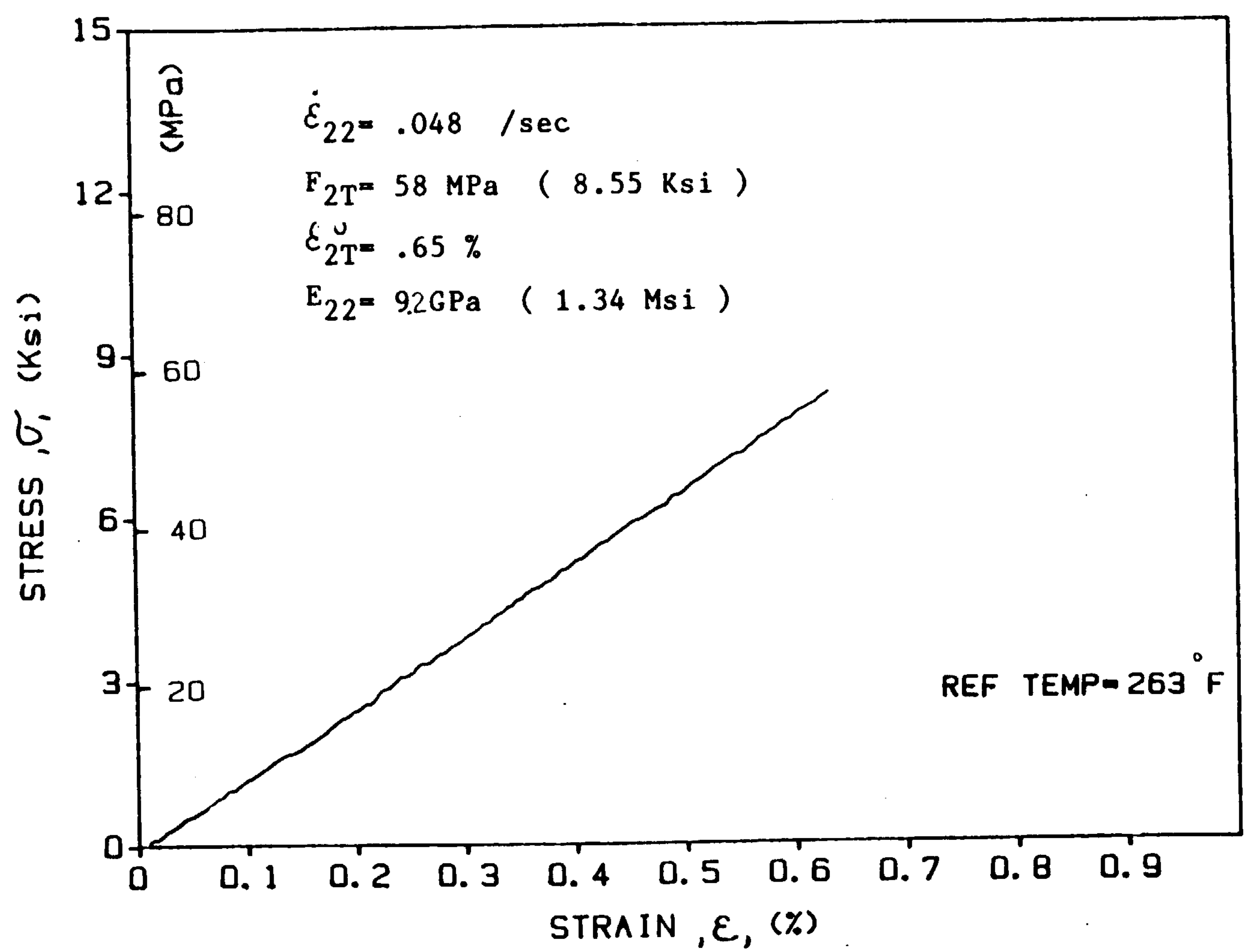


Fig. A-184. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-2H5 (T = 128°C (263°F))

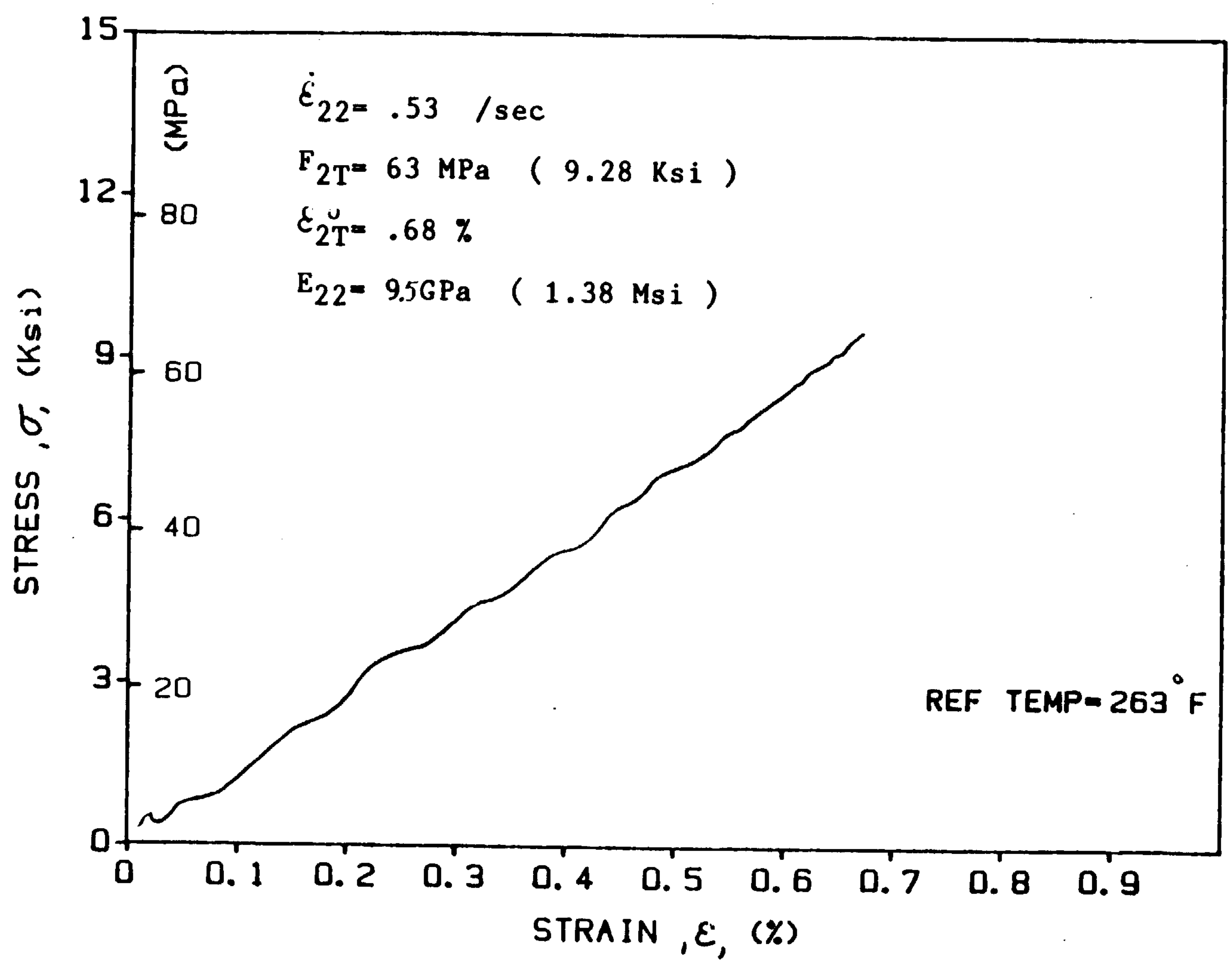


Fig. A-185. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1H1 (T = 128°C (263°F))

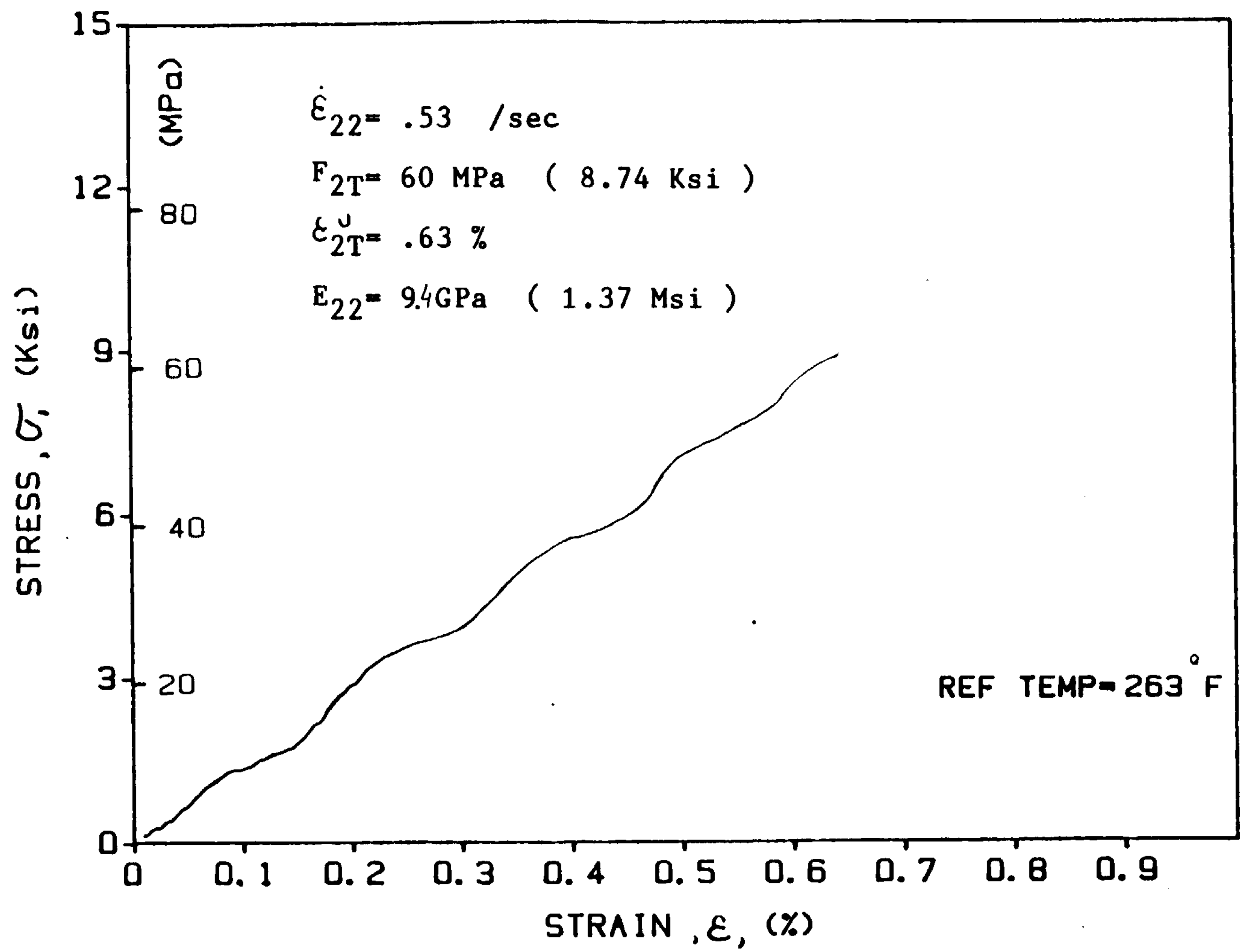


Fig. A-186. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1H2 (T = 128°C (263°F))

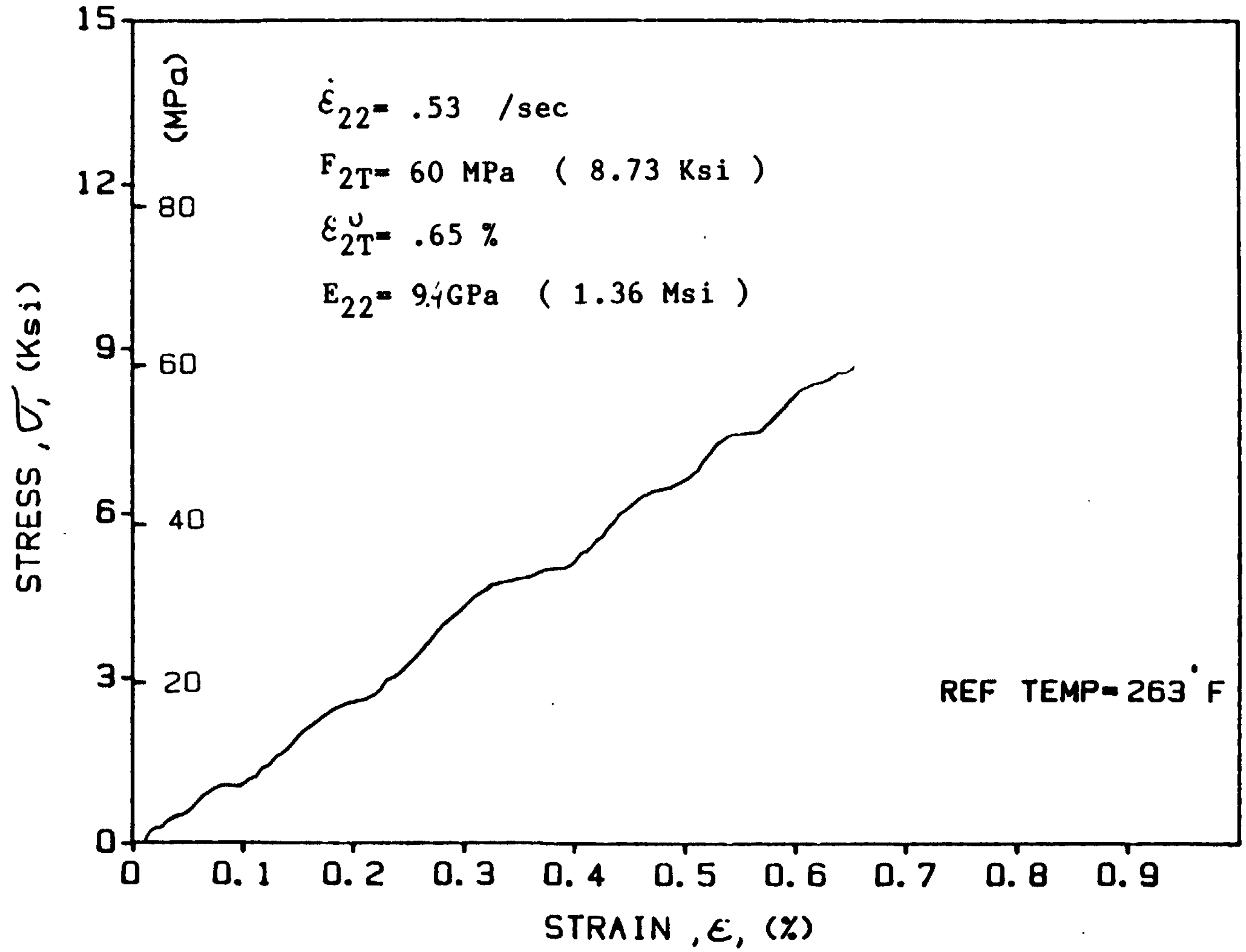


Fig. A-187. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1H3 (T = 128°C (263°F))

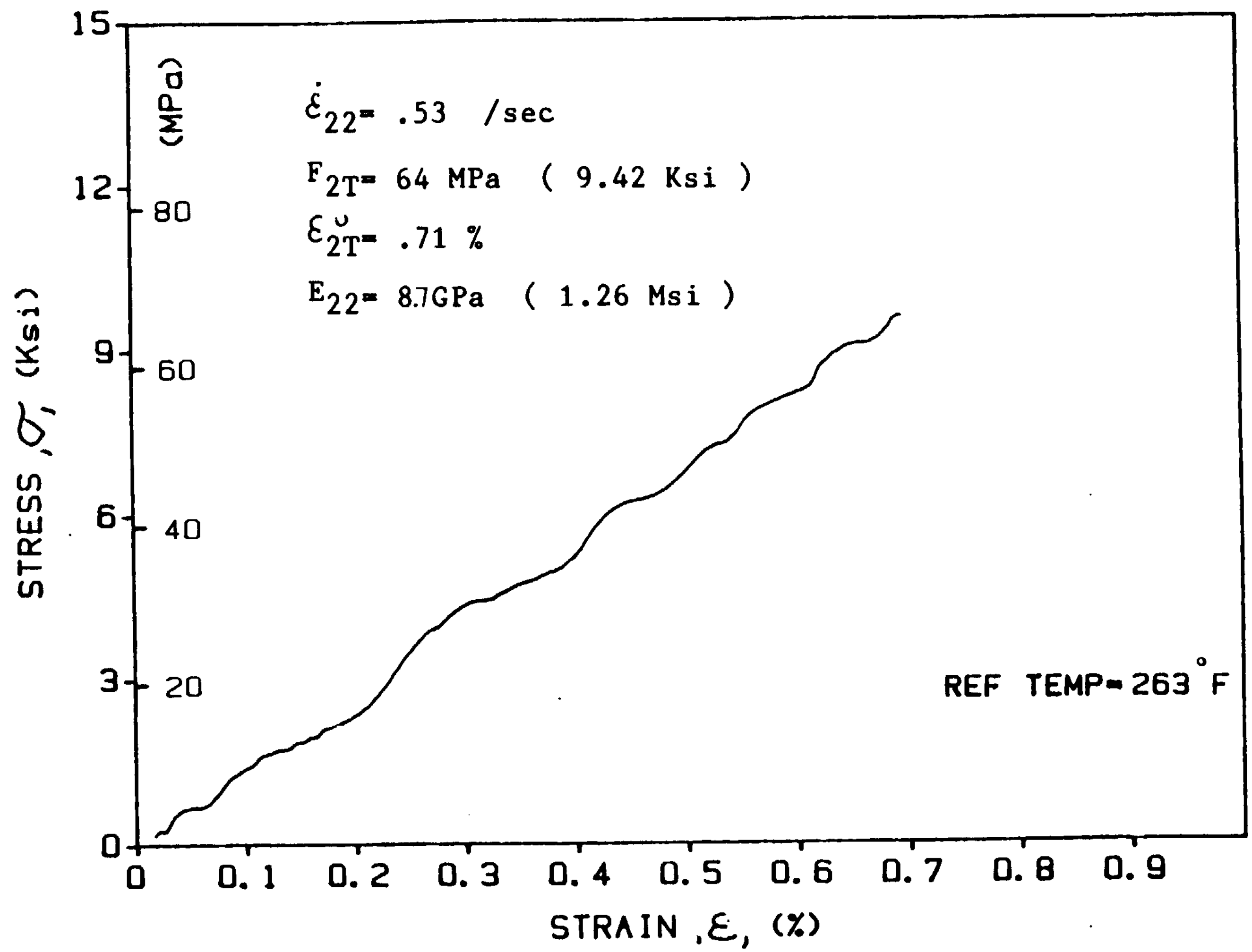


Fig. A-188. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1H4 (T = 128°C (263°F))

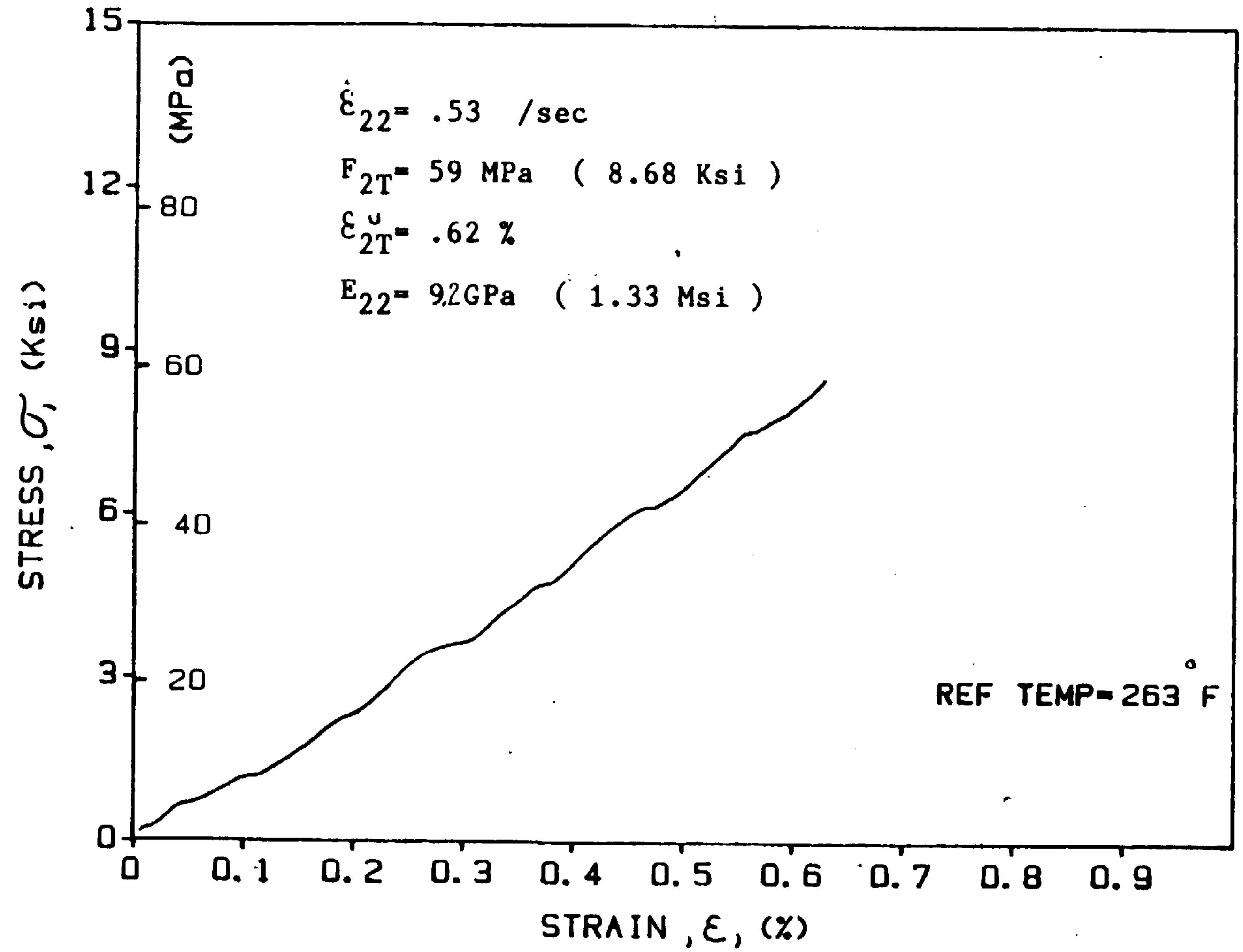


Fig. A-189. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/-1H5 (T = 128°C (263°F))

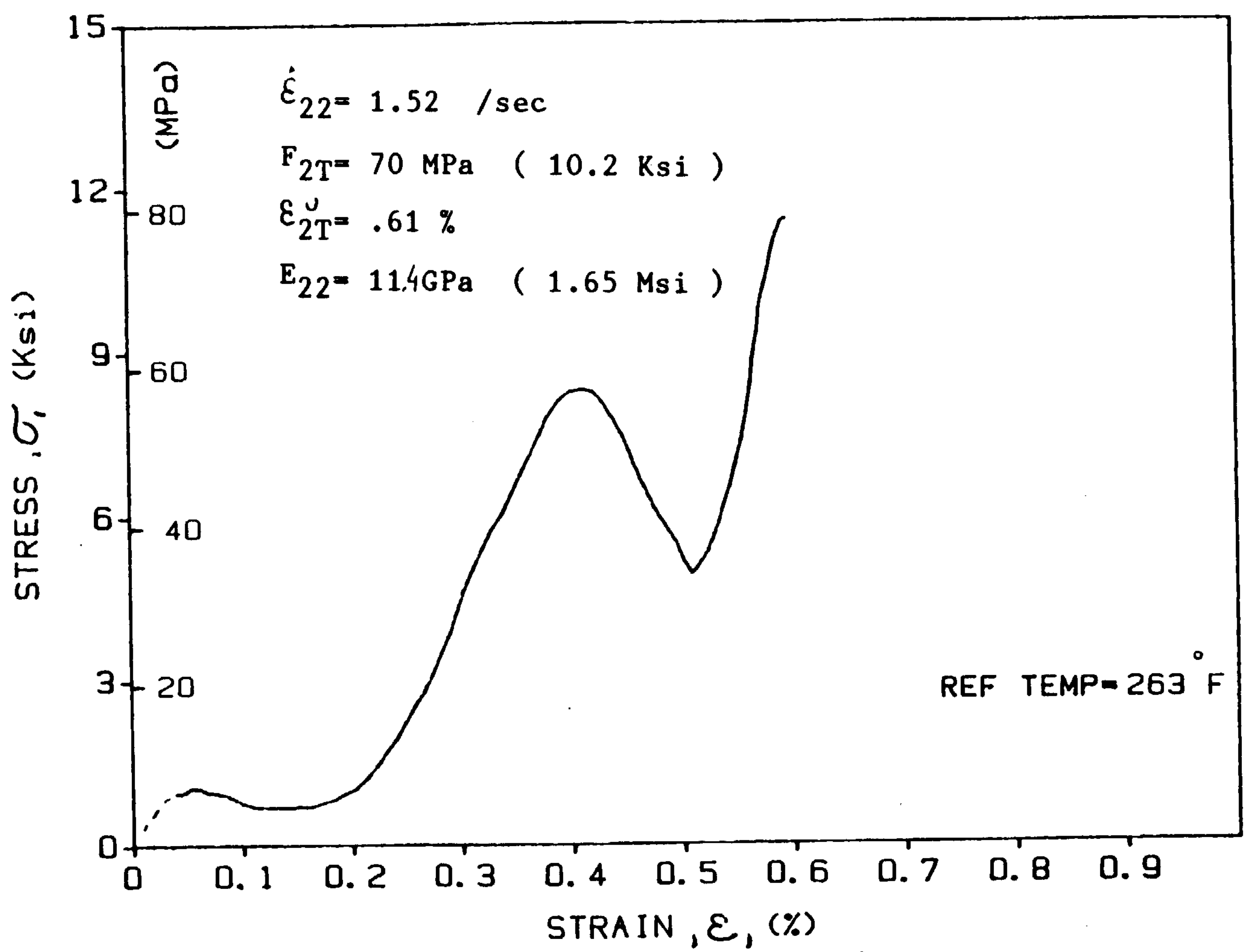


Fig. A-190. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H1 (T = 128°C (263°F))

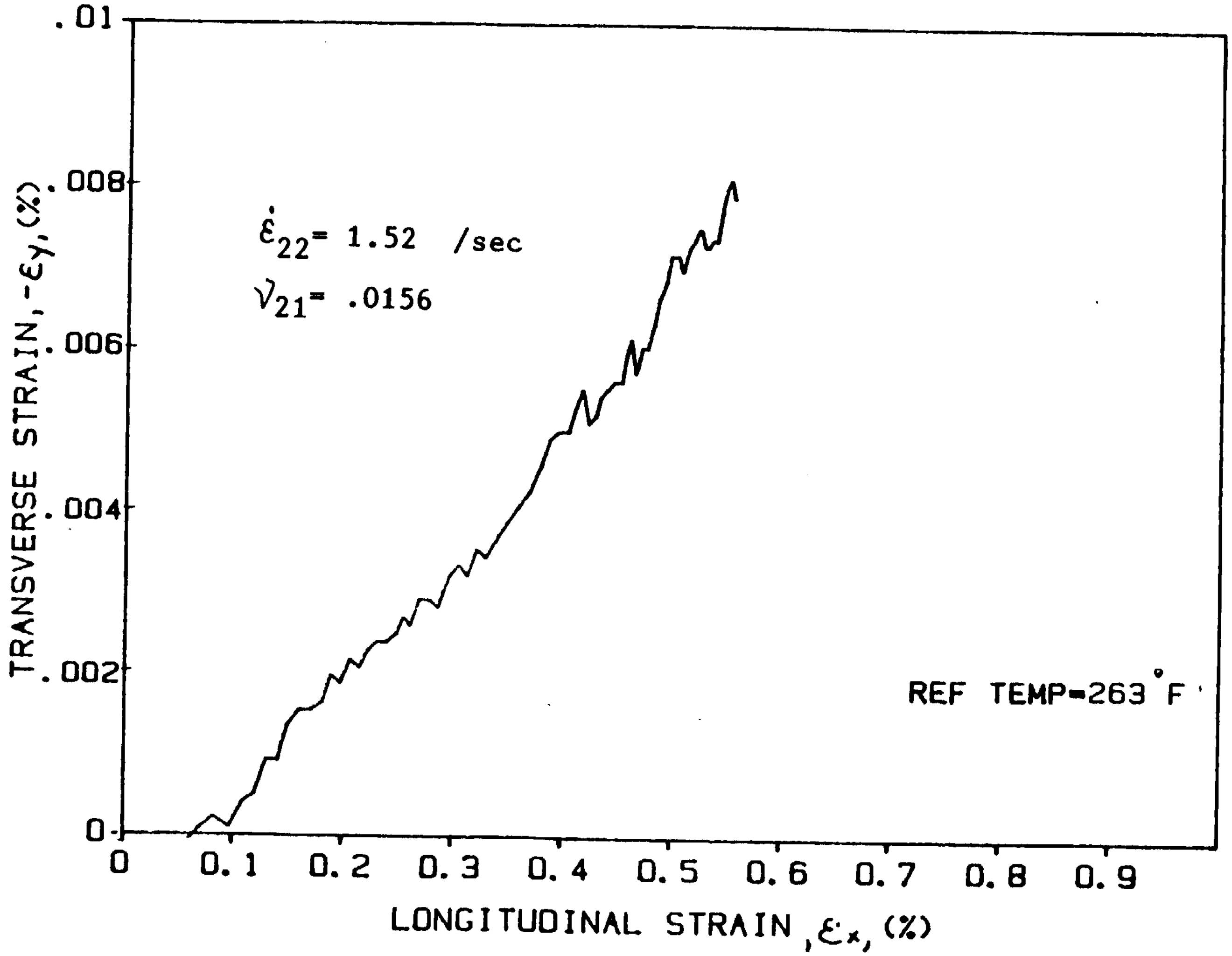


Fig. A-191. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H1 (T = 128°C (263°F))

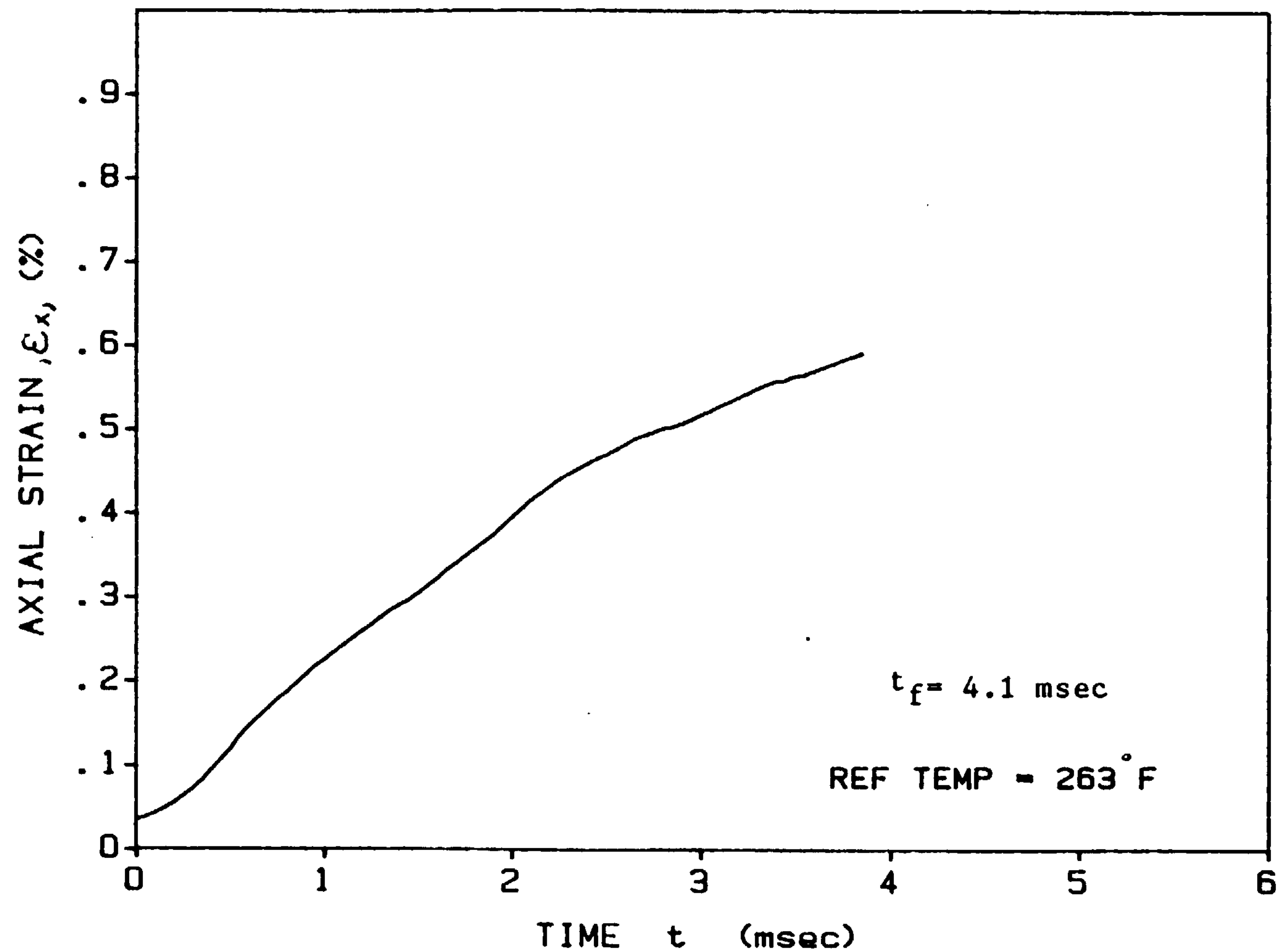


Fig. A-192. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, 90/OH1 (T = 128°C (263°F))

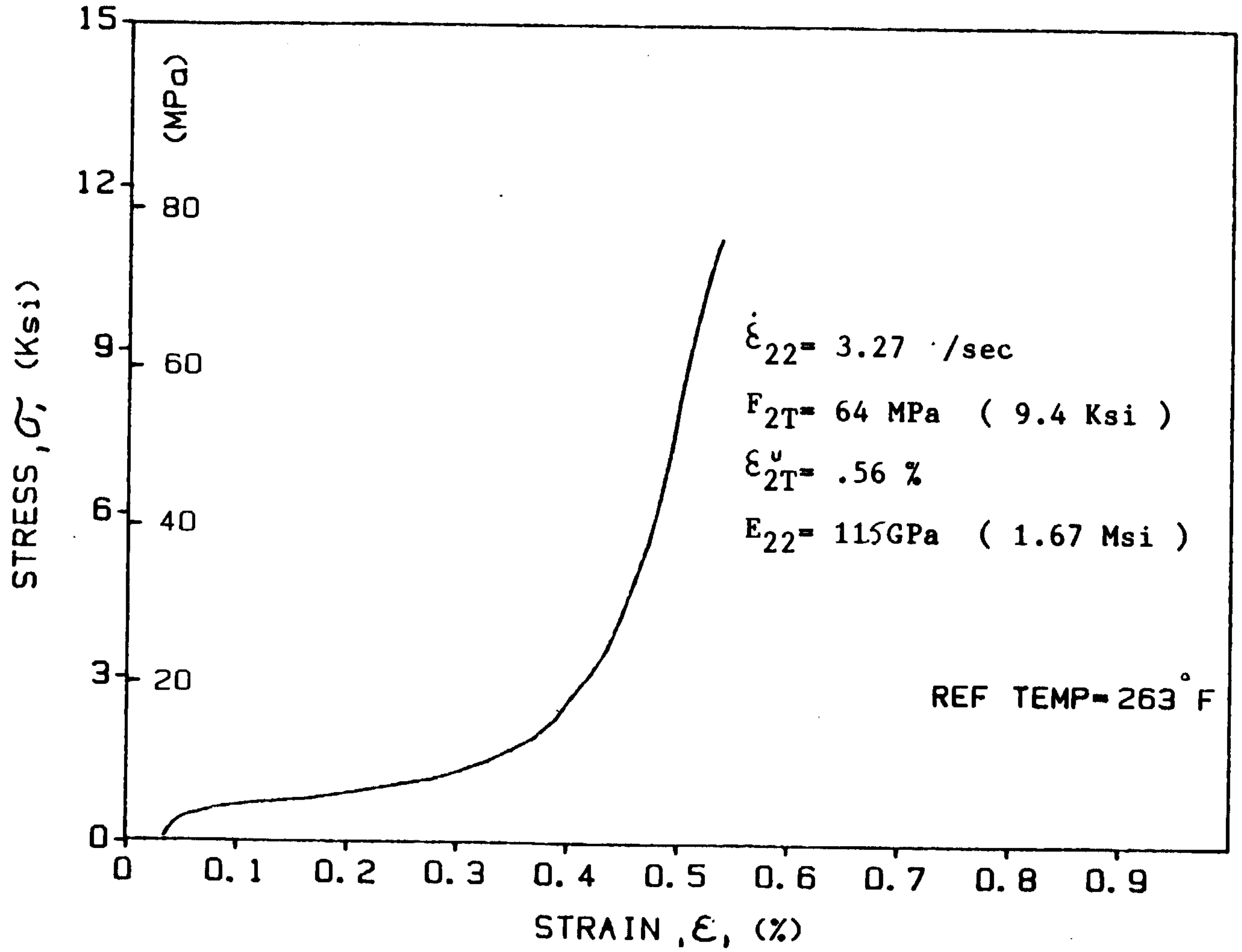


Fig. A-193. Stress-Strain Curve for [90_8] AS4/3501-6 Graphite/Epoxy, Spec. 90/0H2 (T = 128°C (263°F))

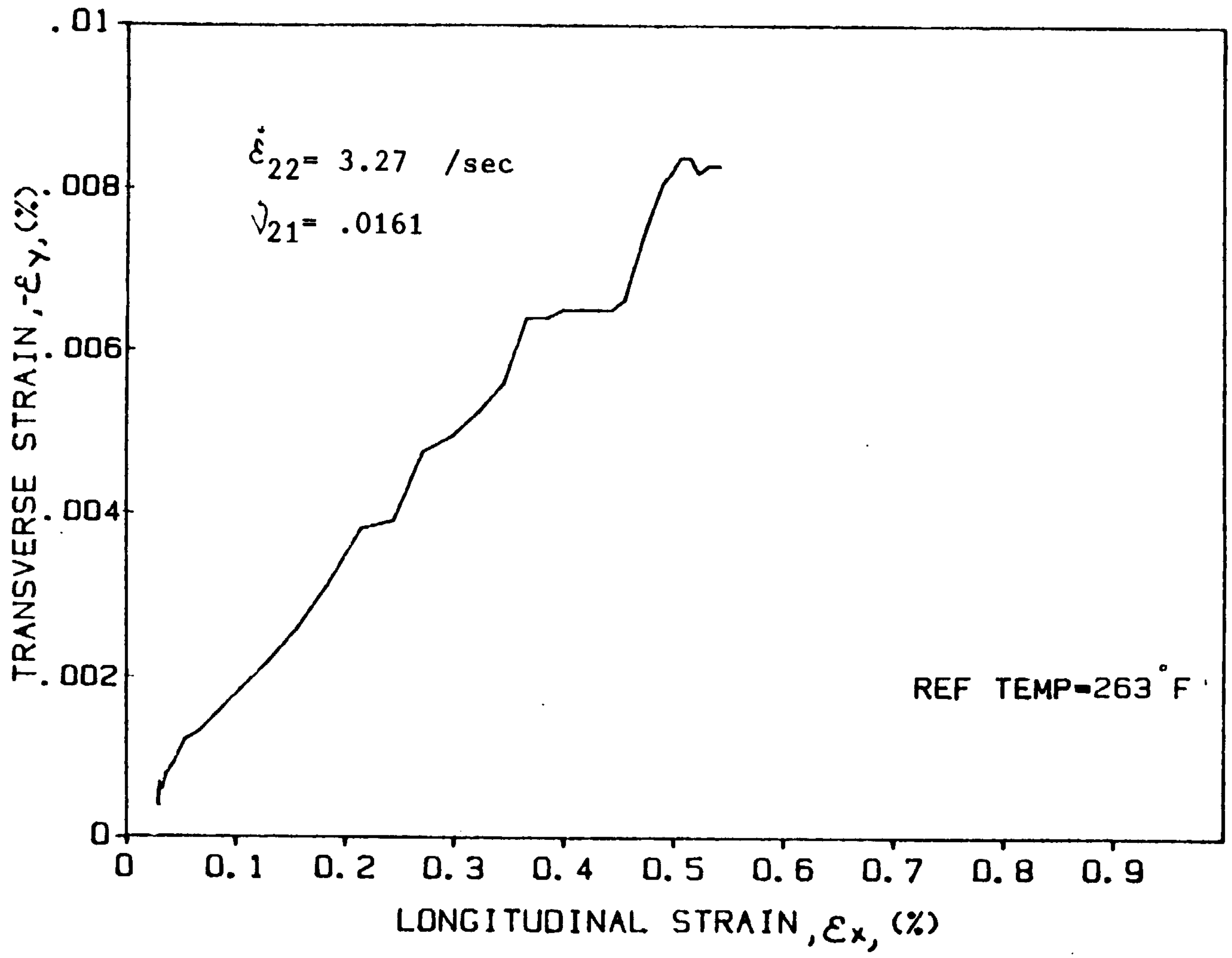


Fig. A-194. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H2 (T = 128°C (263°F))

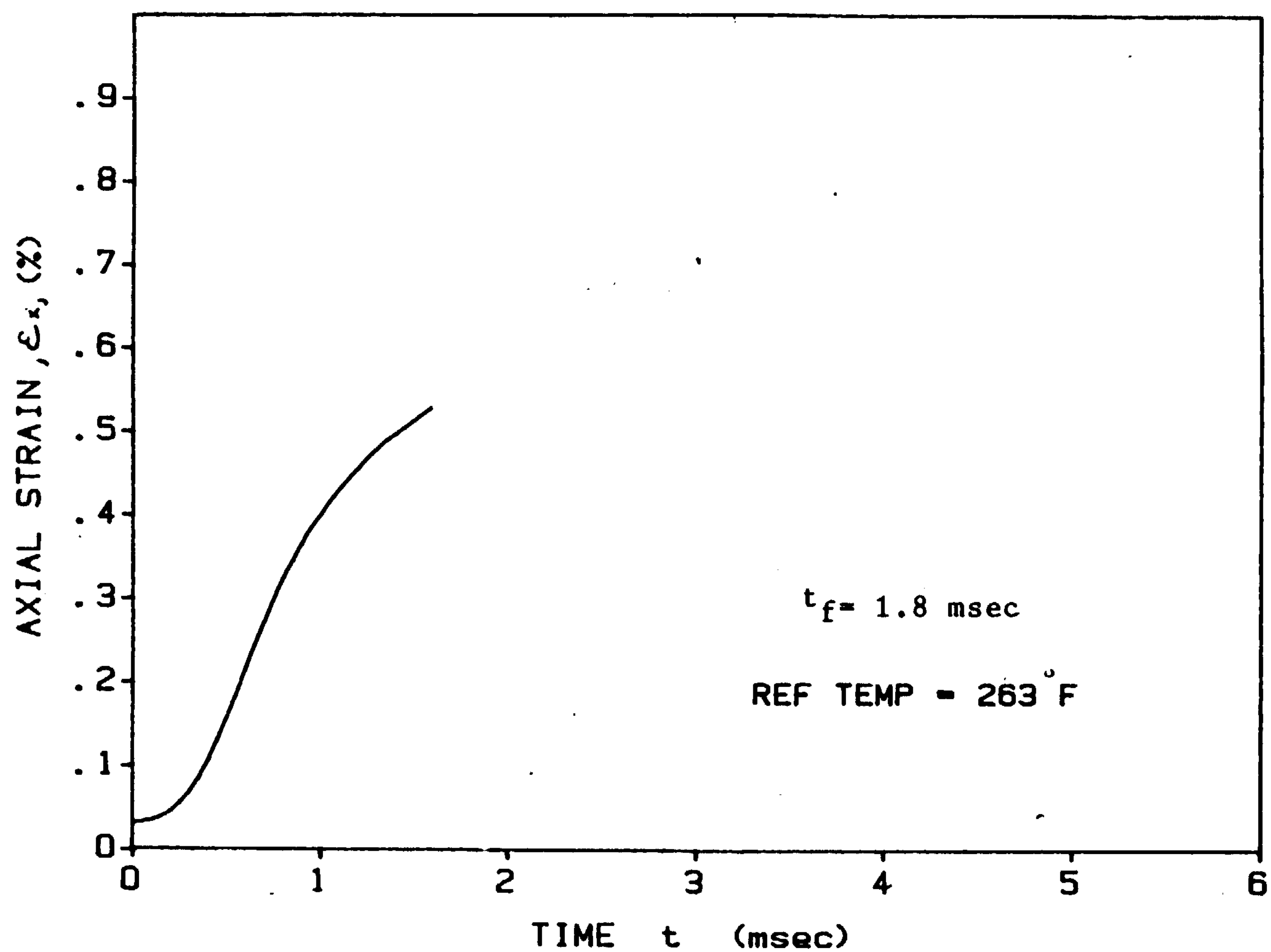


Fig. A-195. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H2 (T = 128°C (263°F))

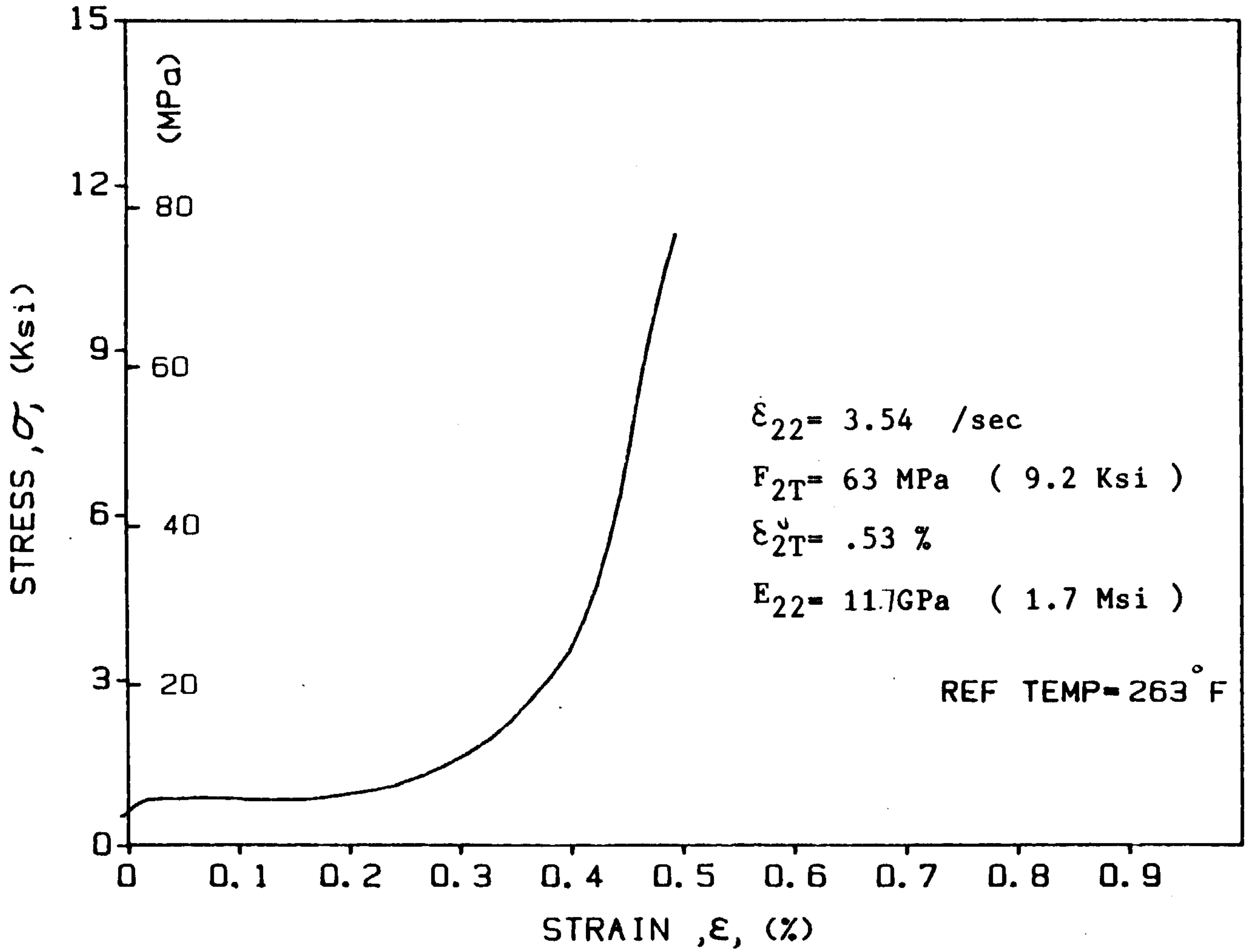


Fig. A-196. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H3 (T = 128°C (263°F))

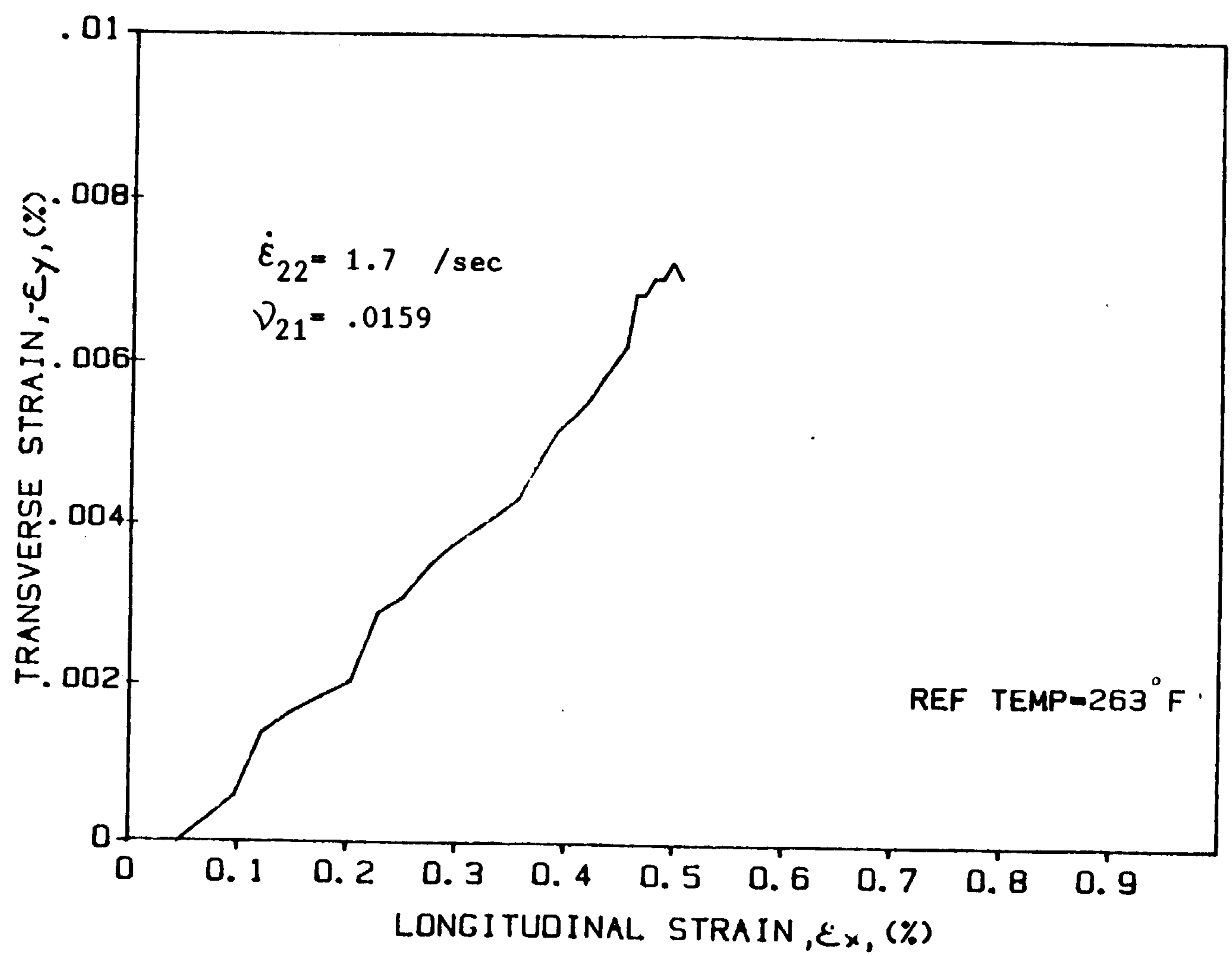


Fig. A-197. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H3 (T = 128°C (263°F))

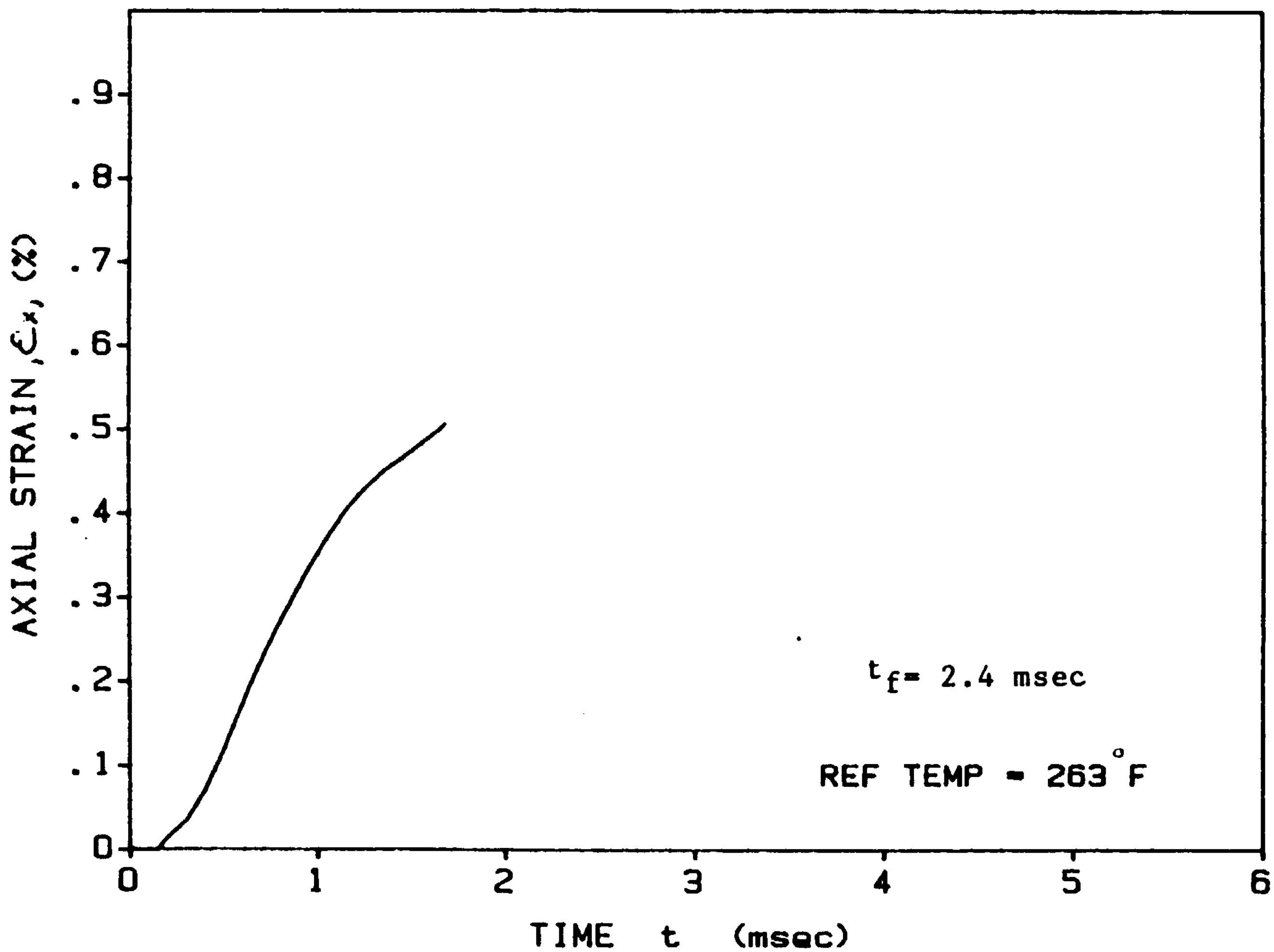


Fig. A-198. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H3 (T = 128°C (263°F))

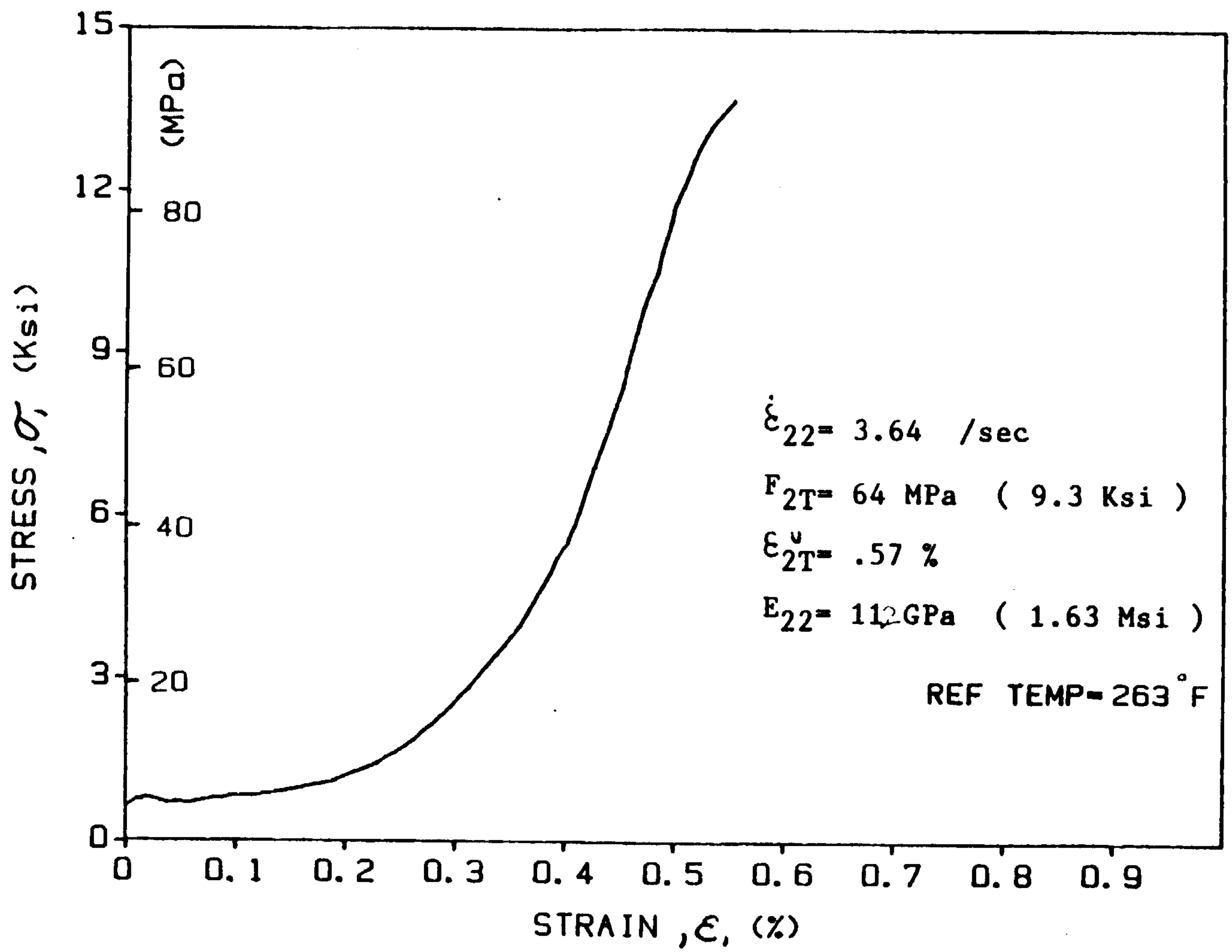


Fig. A-199. Stress-Strain Curve for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H4 (T = 128°C (263°F))

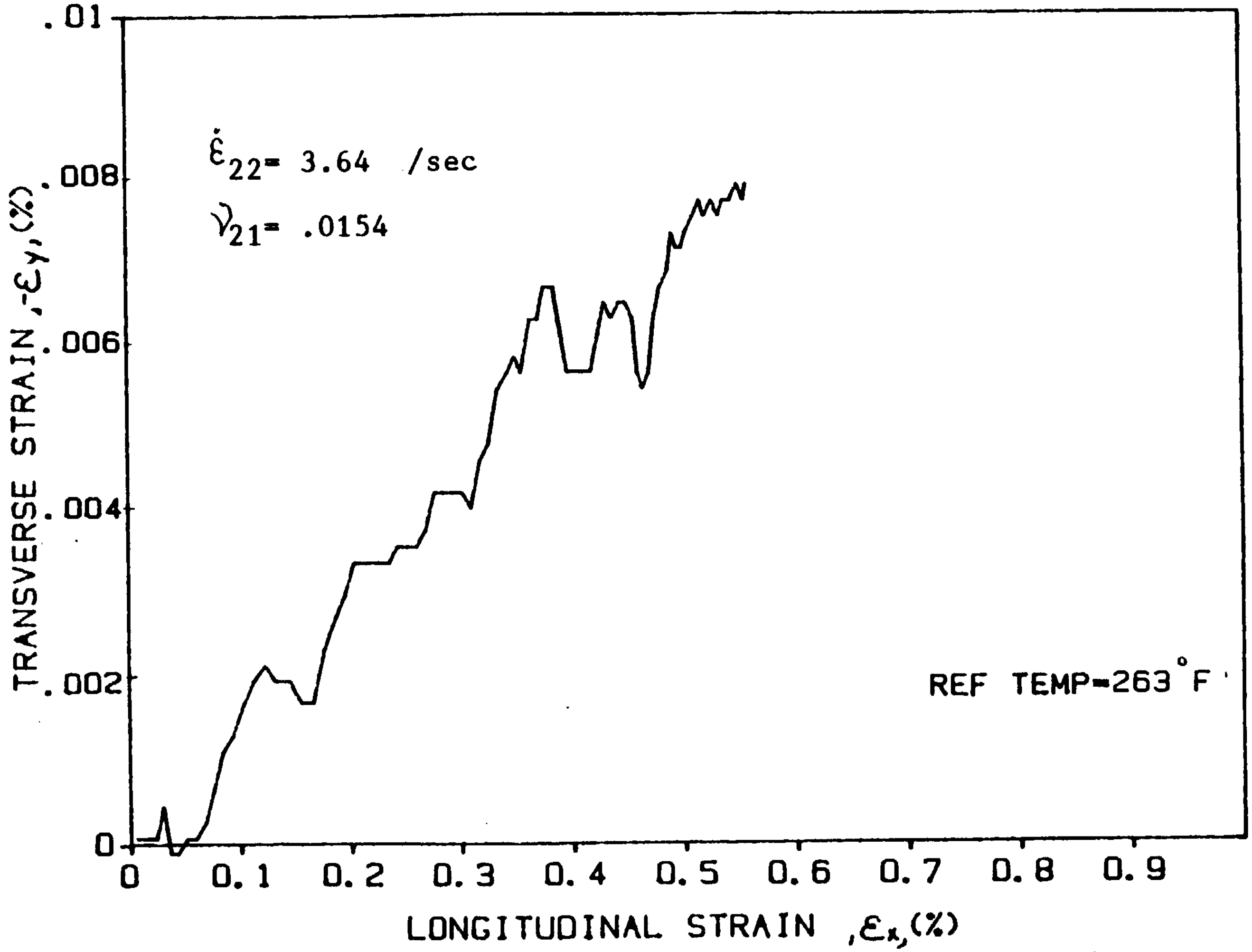


Fig. A-200. Transverse vs. Longitudinal Strain for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H4 (T = 128°C (263°F))

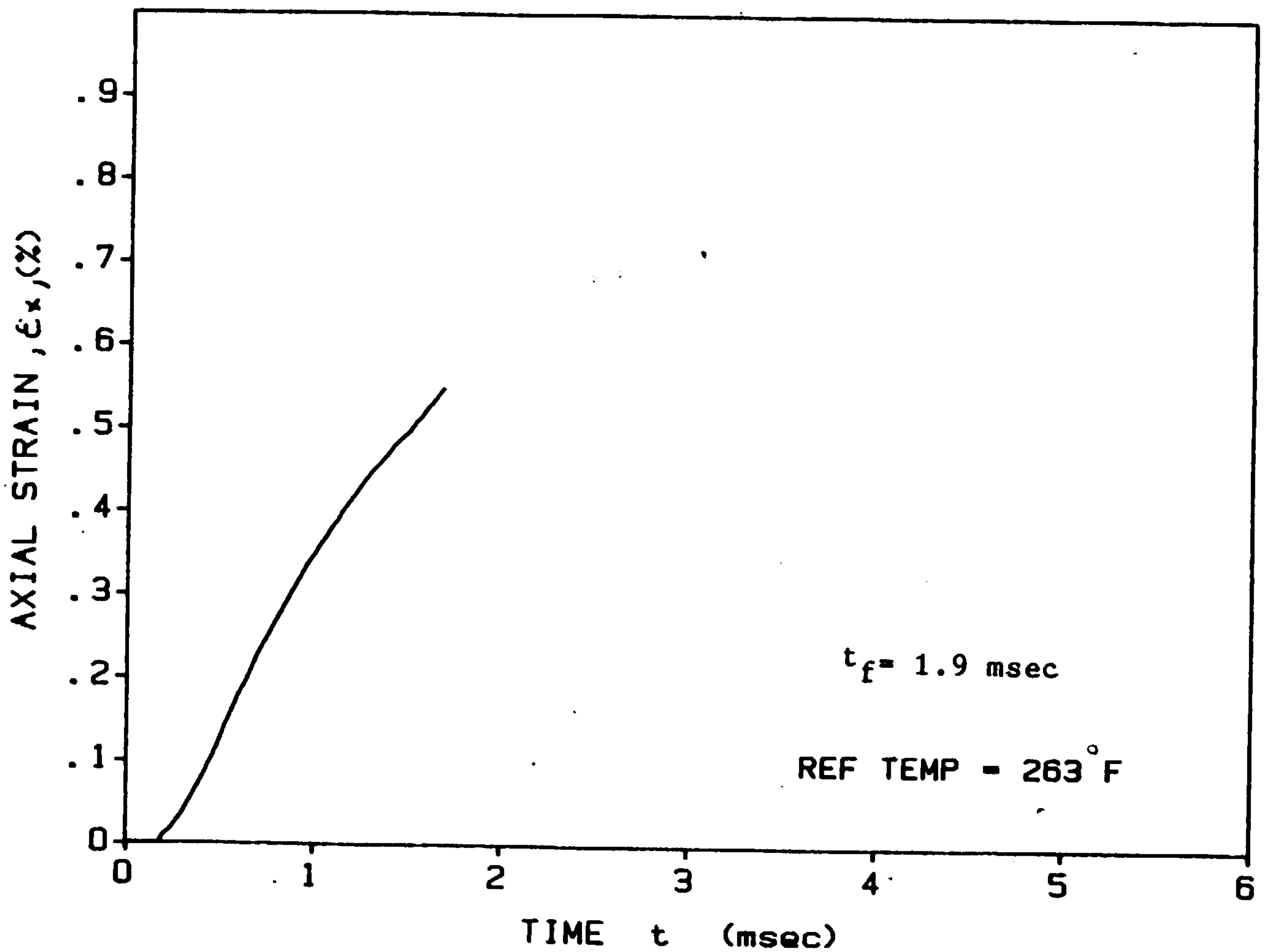


Fig. A-201. Axial Strain vs. Time for $[90_8]$ AS4/3501-6 Graphite/Epoxy, Spec. 90/0H4 (T = 128°C (263°F))

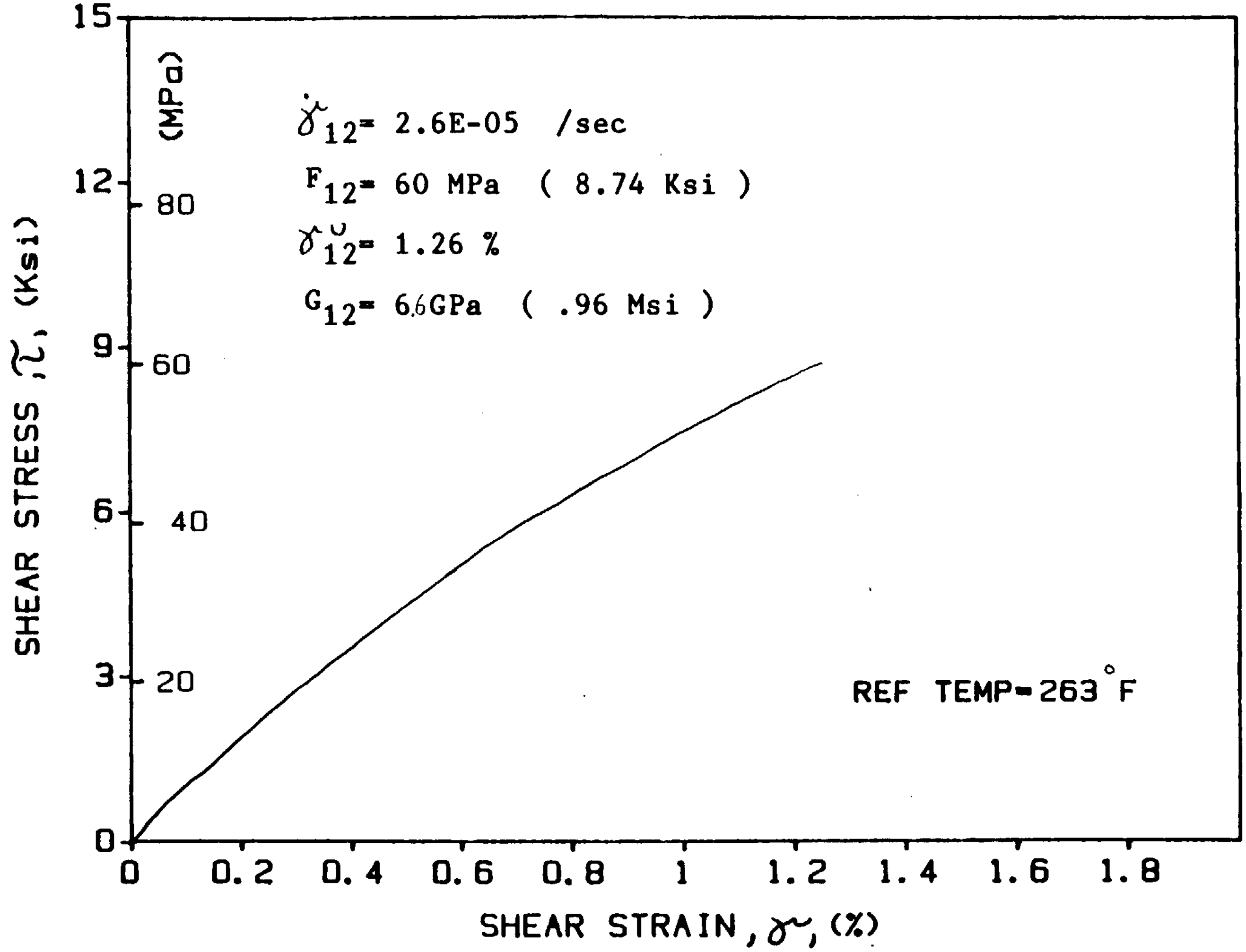


Fig. A-202. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-5H1 (T = 128°C (263°F))

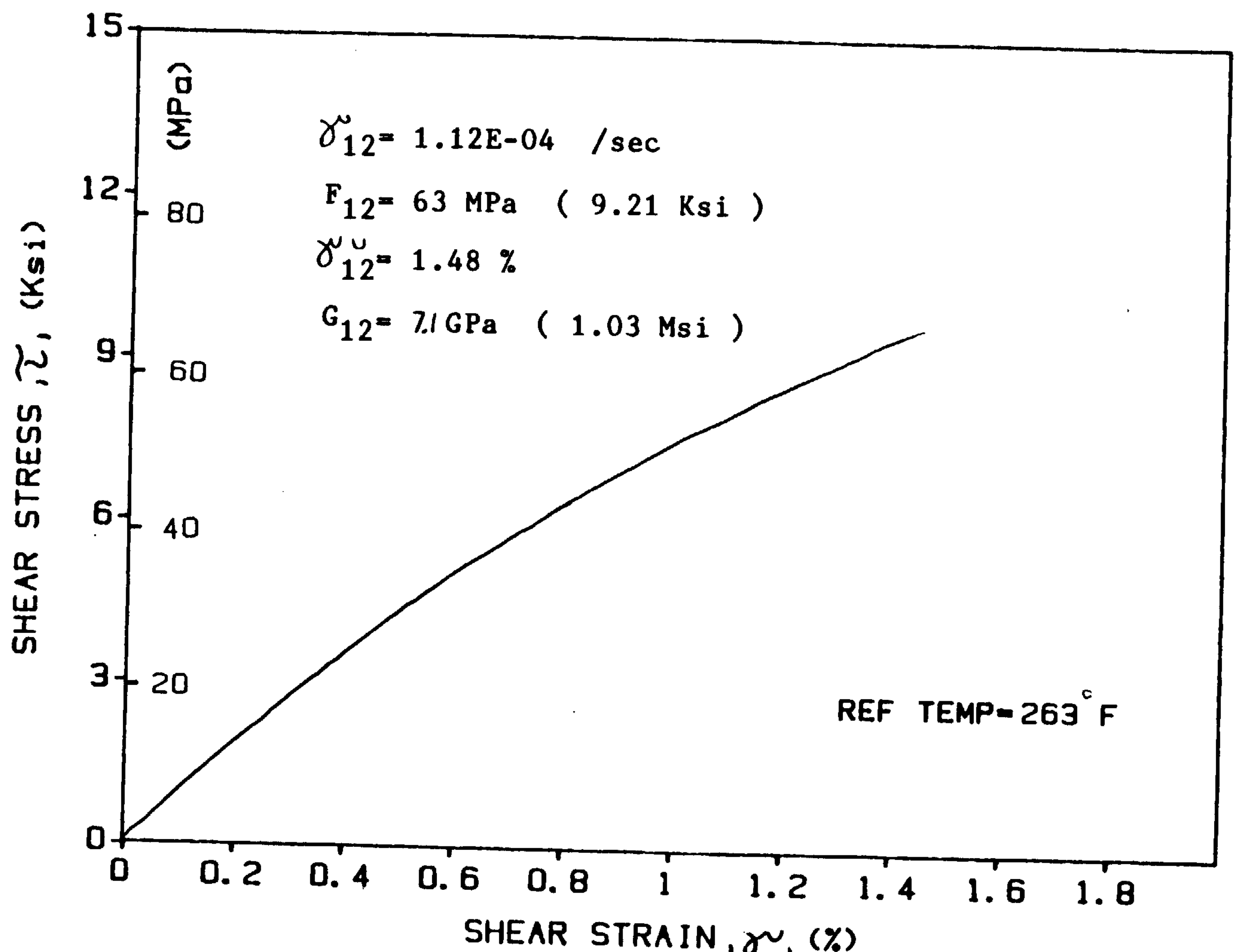


Fig. A-203. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-4H1 (T = 128°C (263°F))

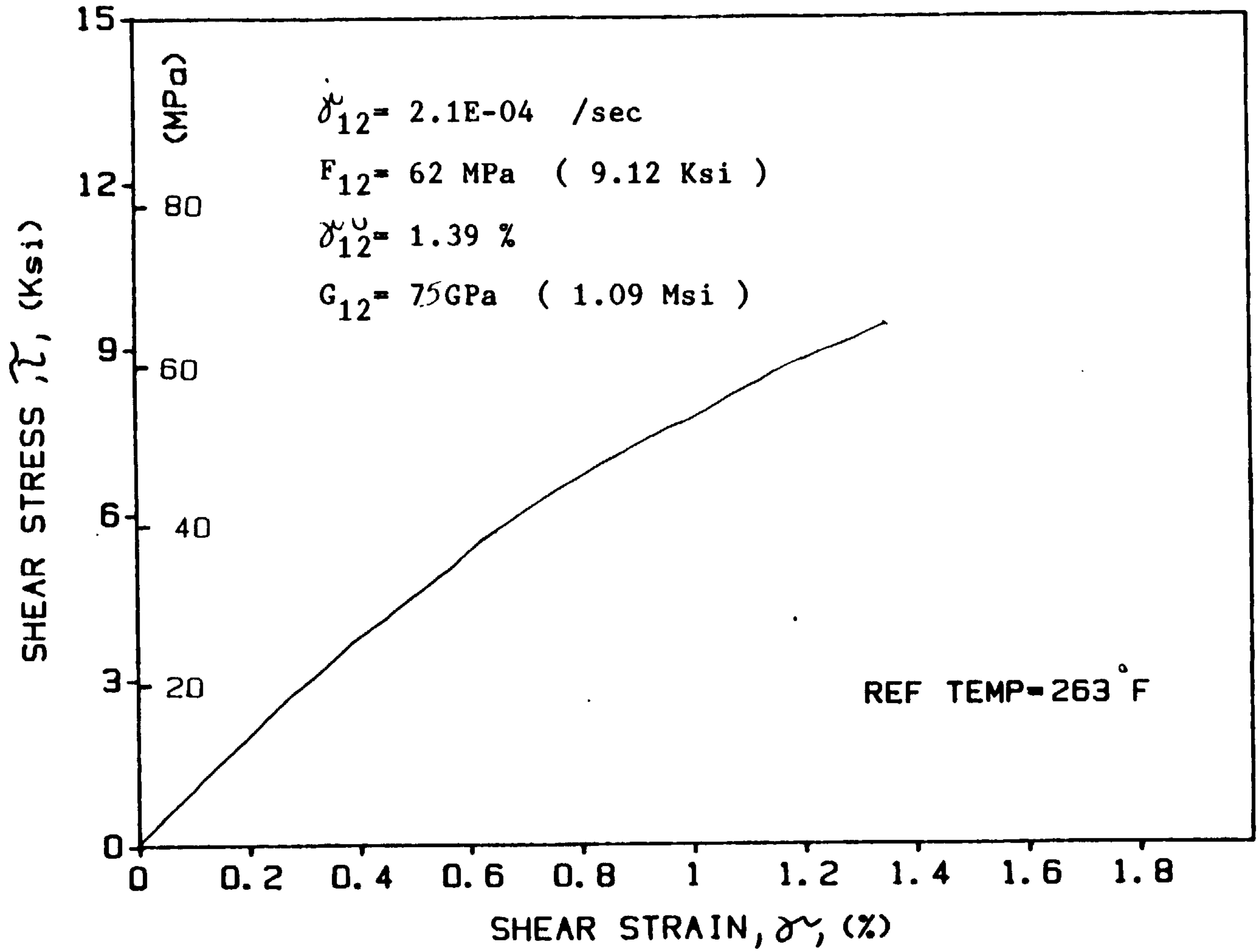


Fig. A-204. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-4H2 (T = 128°C (263°F))

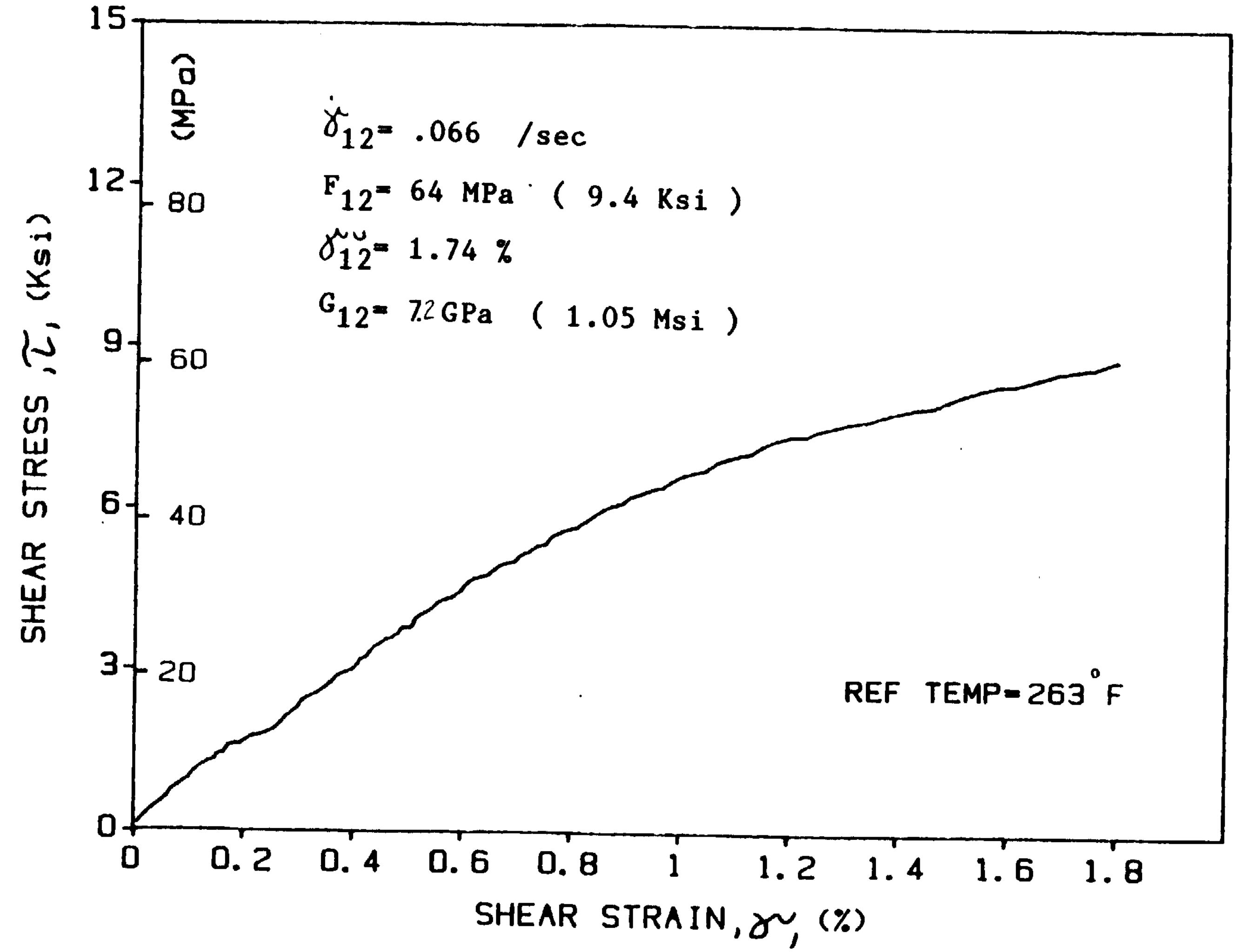


Fig. A-205. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H1 (T = 128°C (263°F))

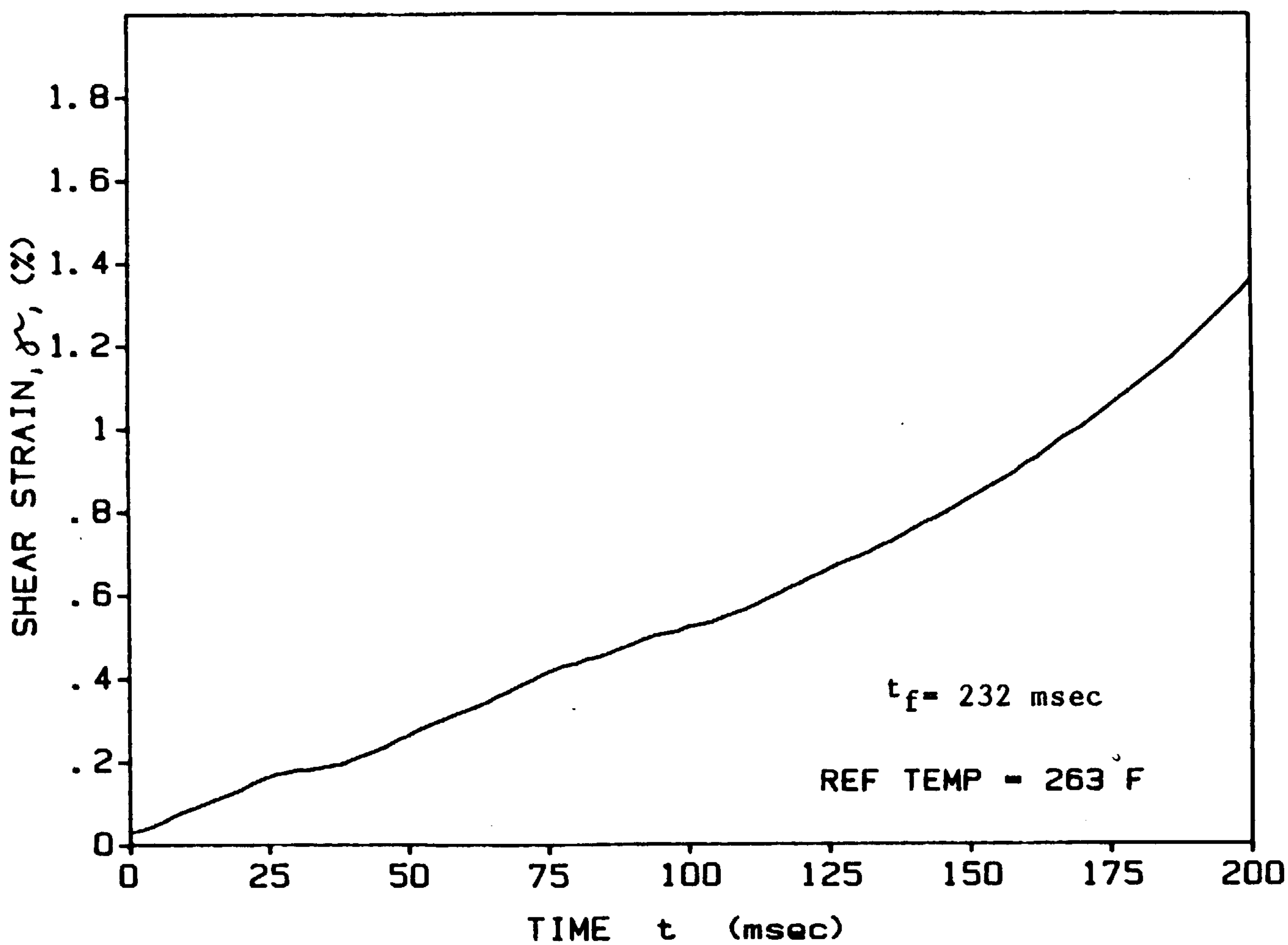


Fig. A-206. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H1 (T = 128°C (263°F))

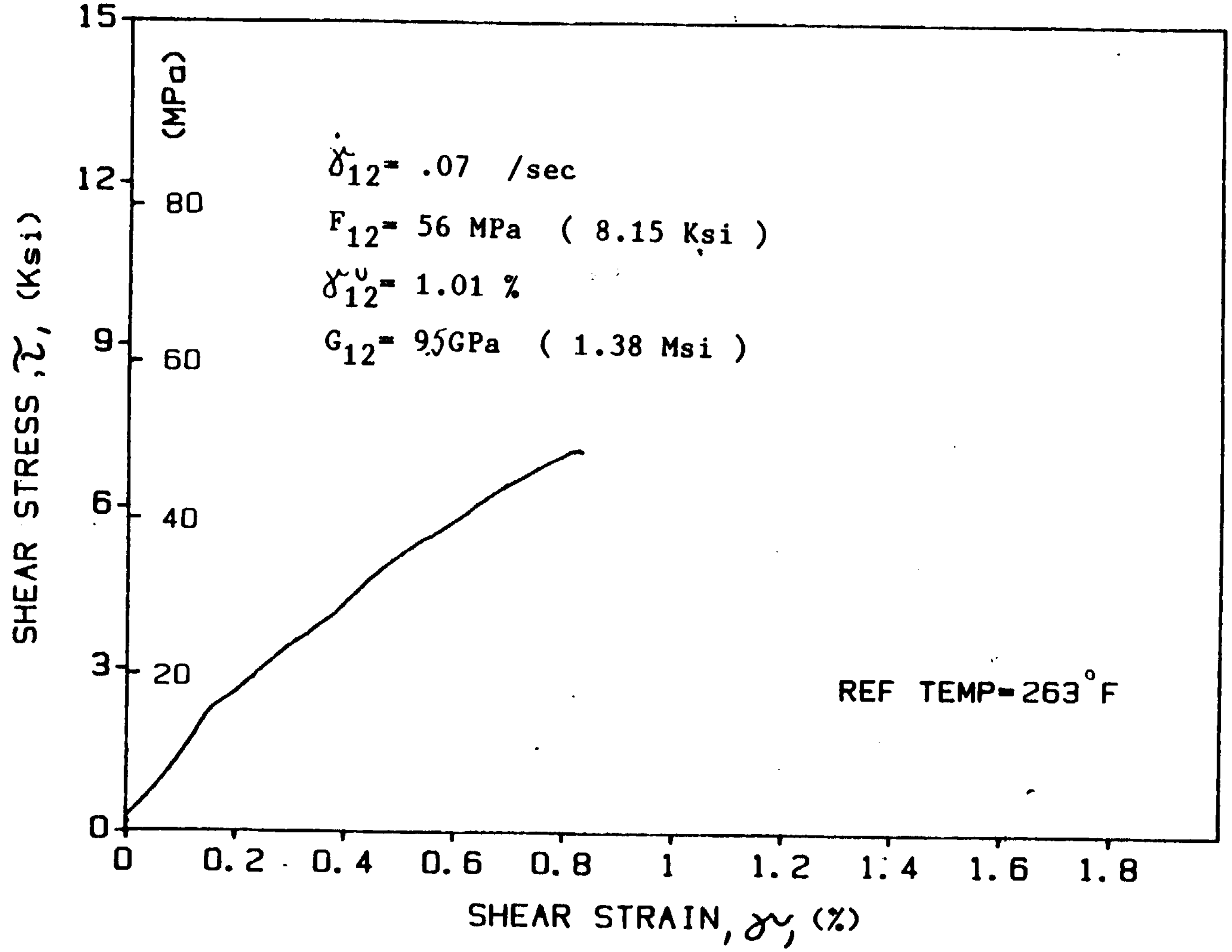


Fig. A-207. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H3 (T = 128°C (263°F))

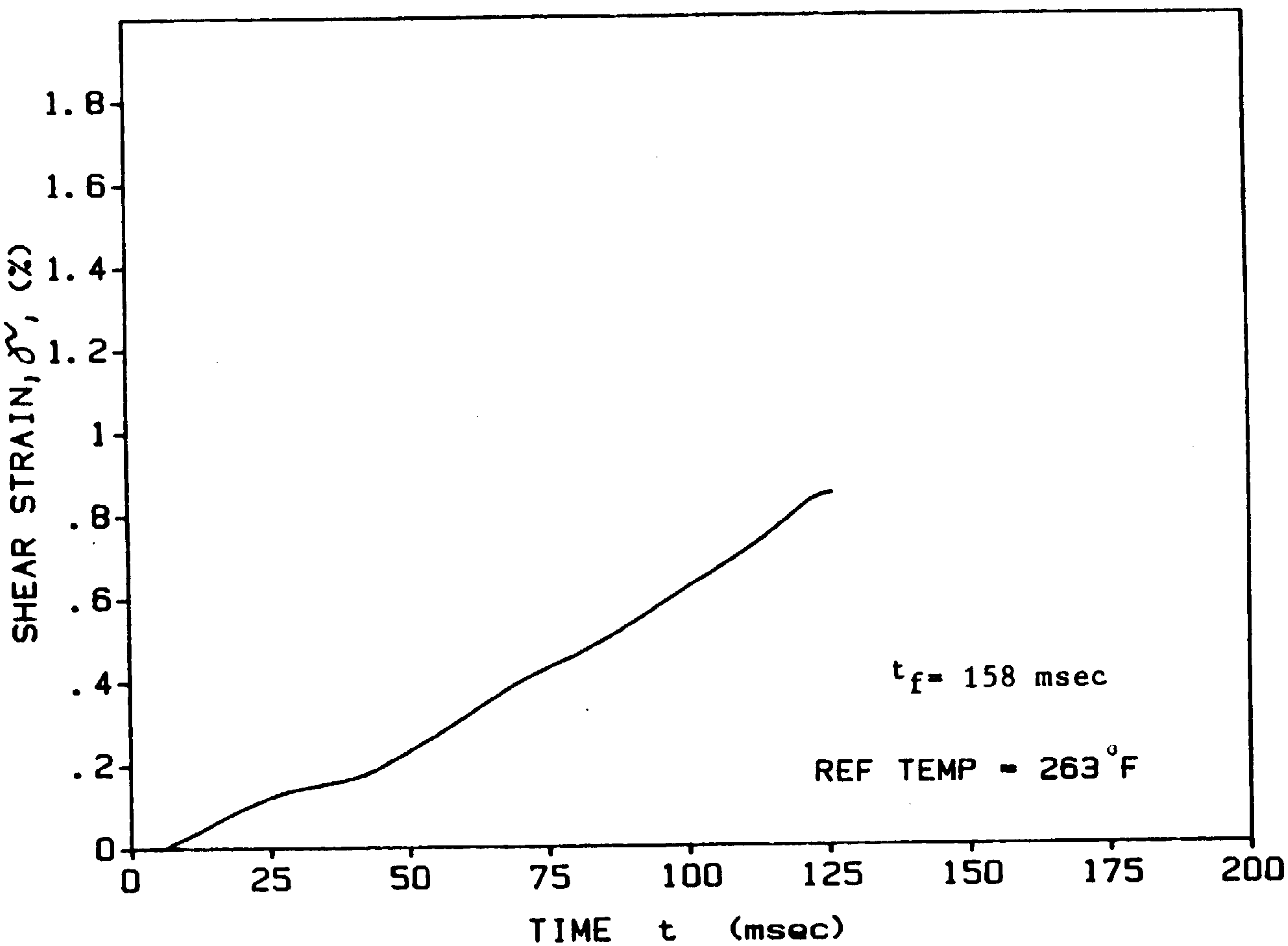


Fig. A-208. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H3 (T = 128°C (263°F))

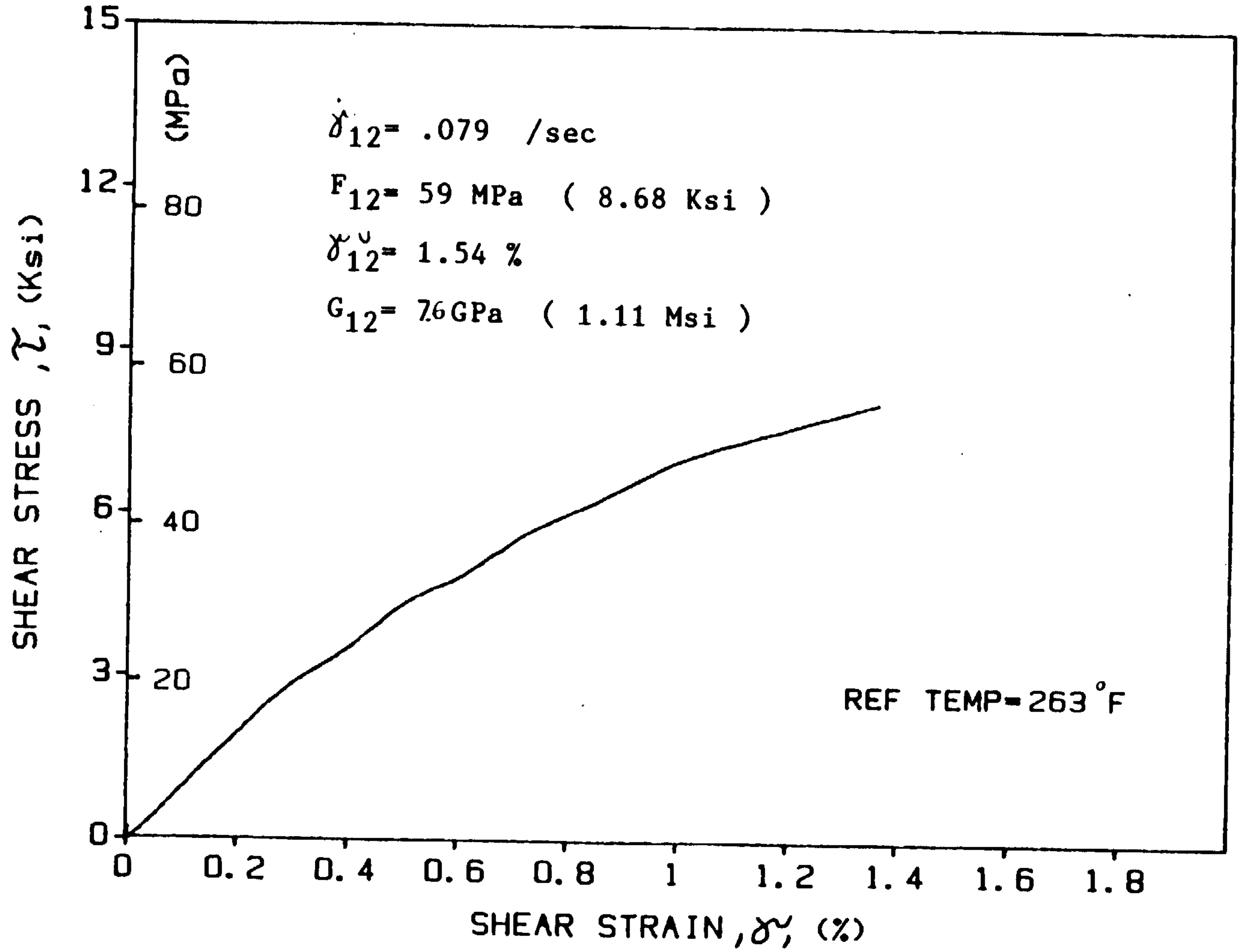


Fig. A-209. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H4 (T = 128°C (263°F))

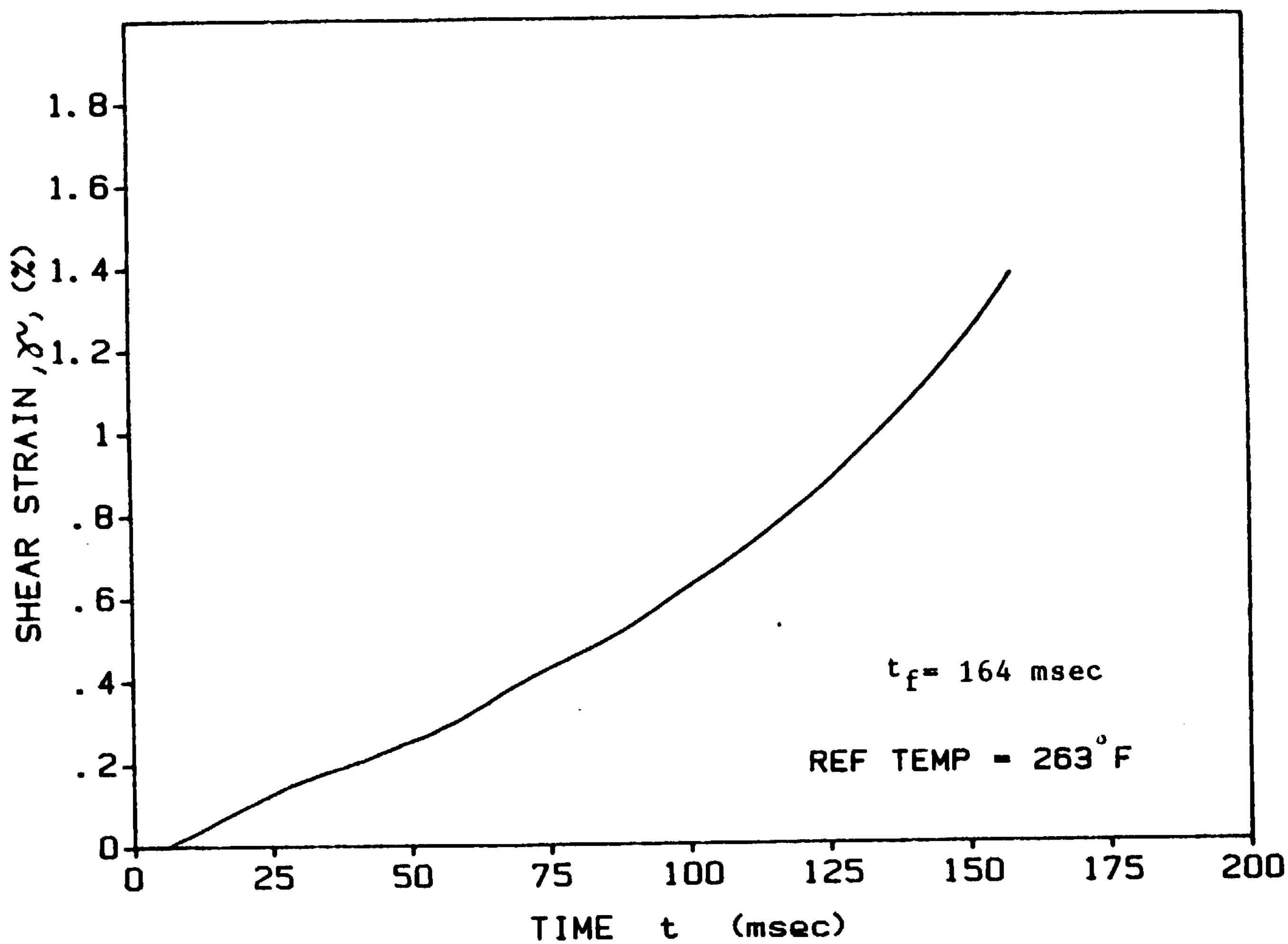


Fig. A-210. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H4 (T = 128°C (263°F))

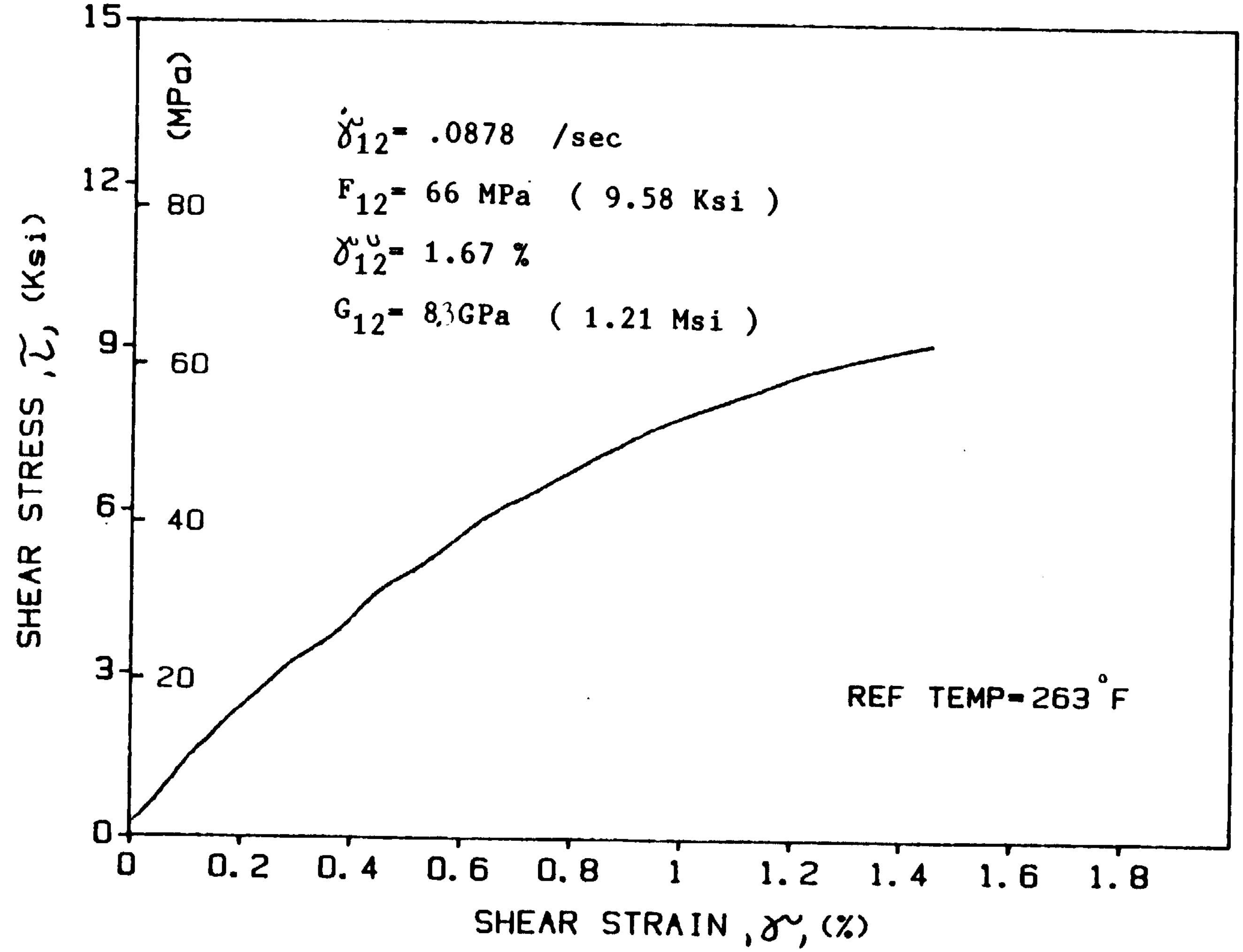


Fig. A-211. Shear Stress-Strain Curve for $[10_6]$ AS4/350106 Graphite/Epoxy, Spec. 10/-2H5 (T = 128°C (263°F))

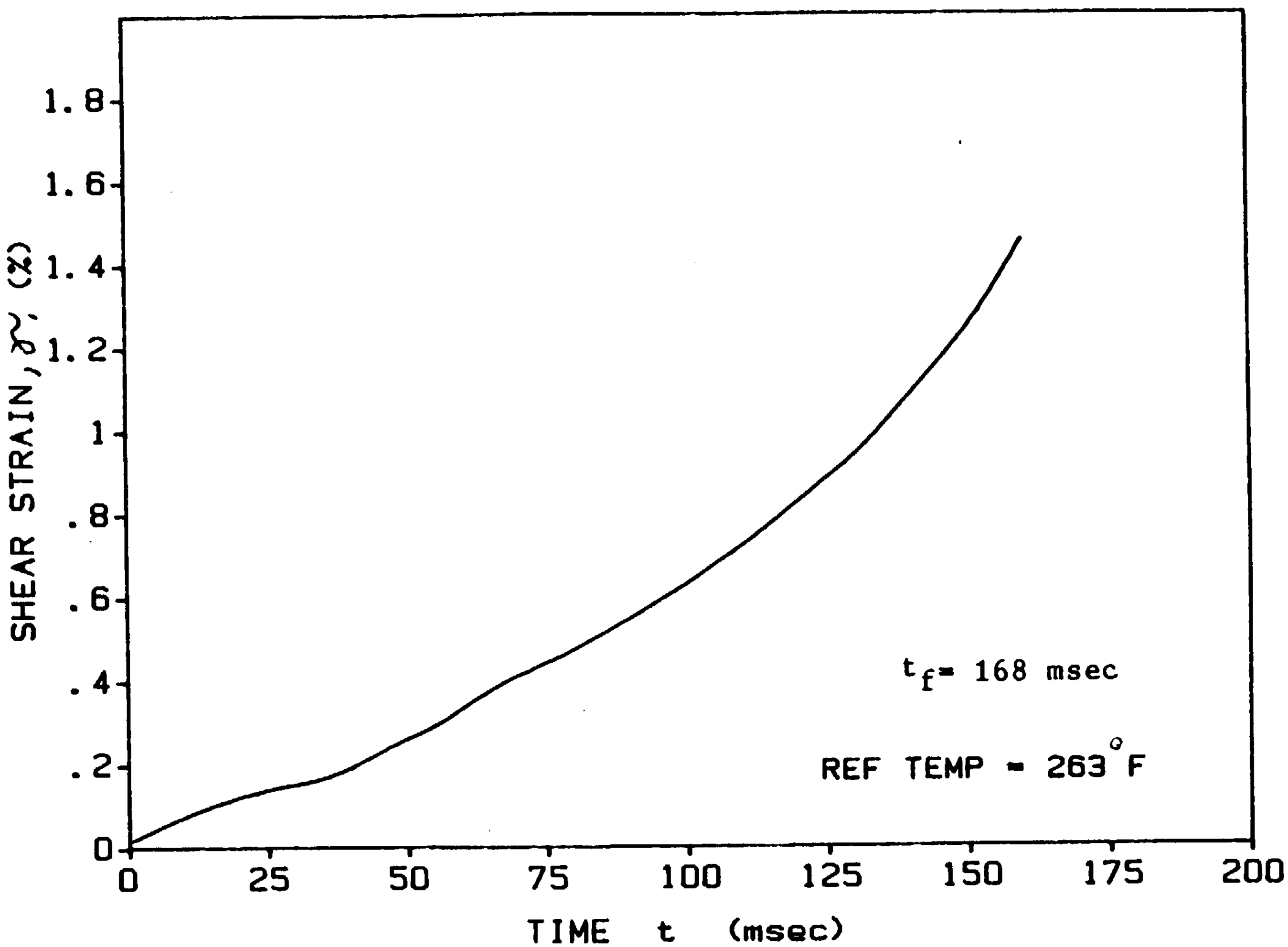


Fig. A-212. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H5 (T = 128°C (263°F))

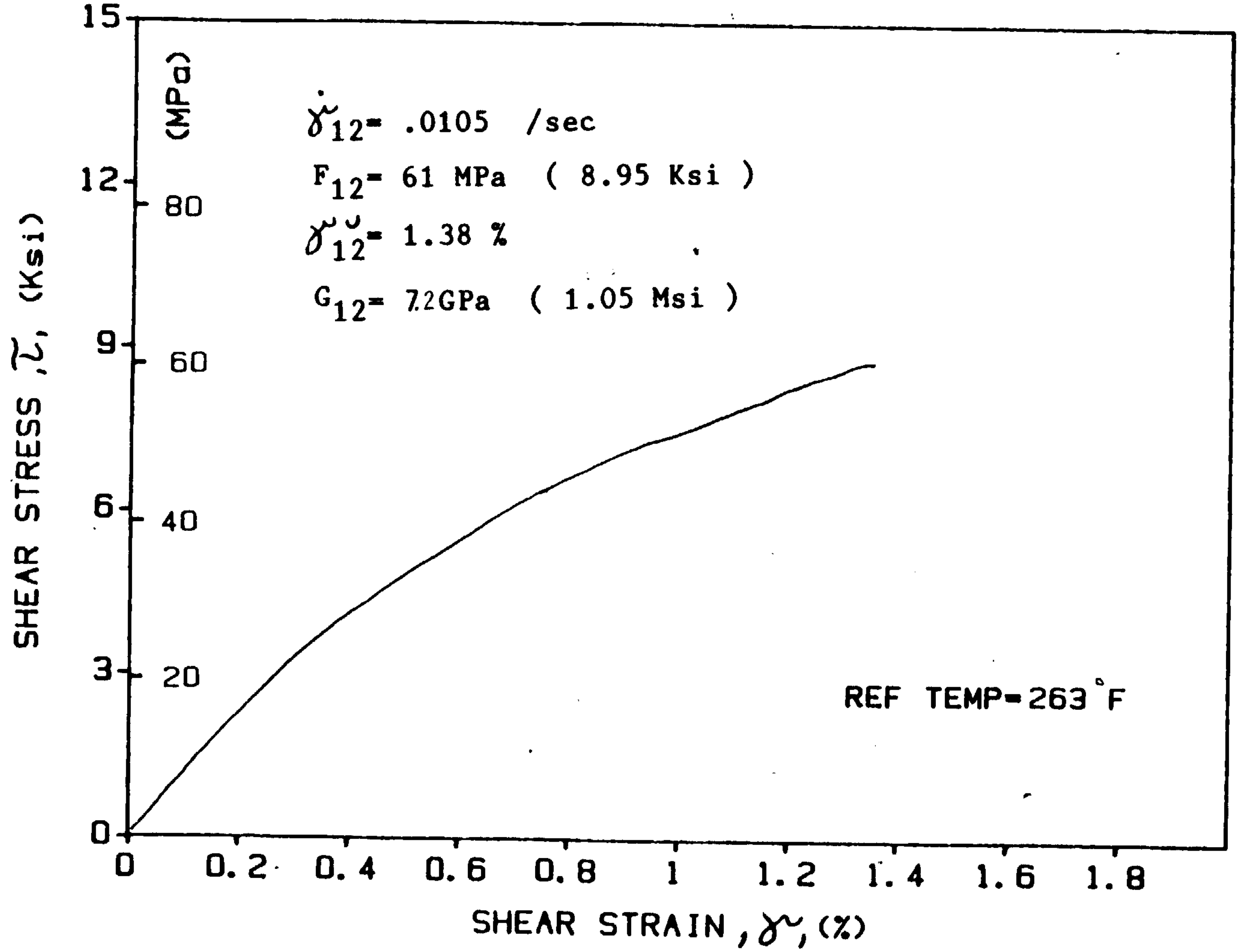


Fig. A-213. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H6 (T = 128°C (263°F))

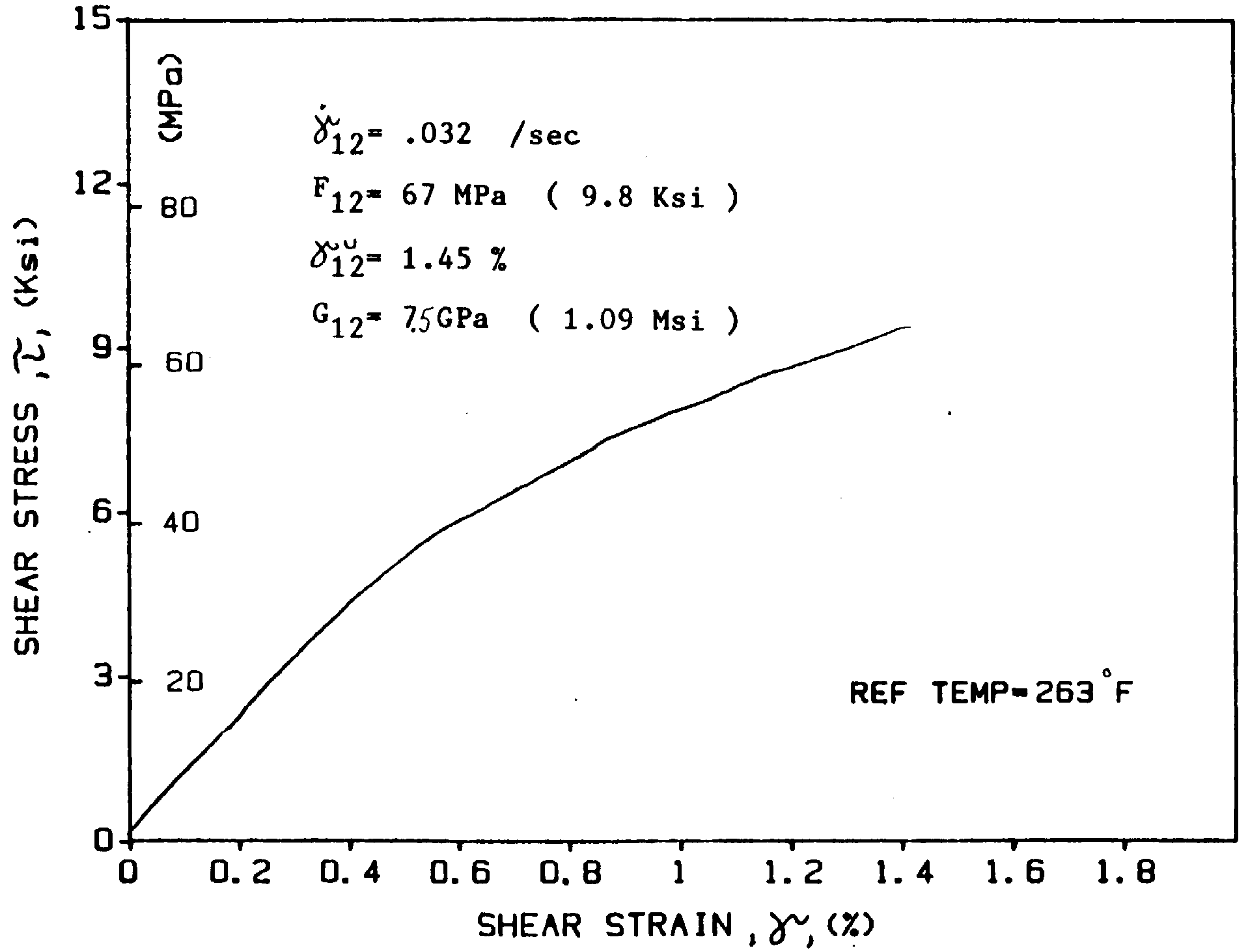


Fig. A-214. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H7 (T = 128°C (263°F))

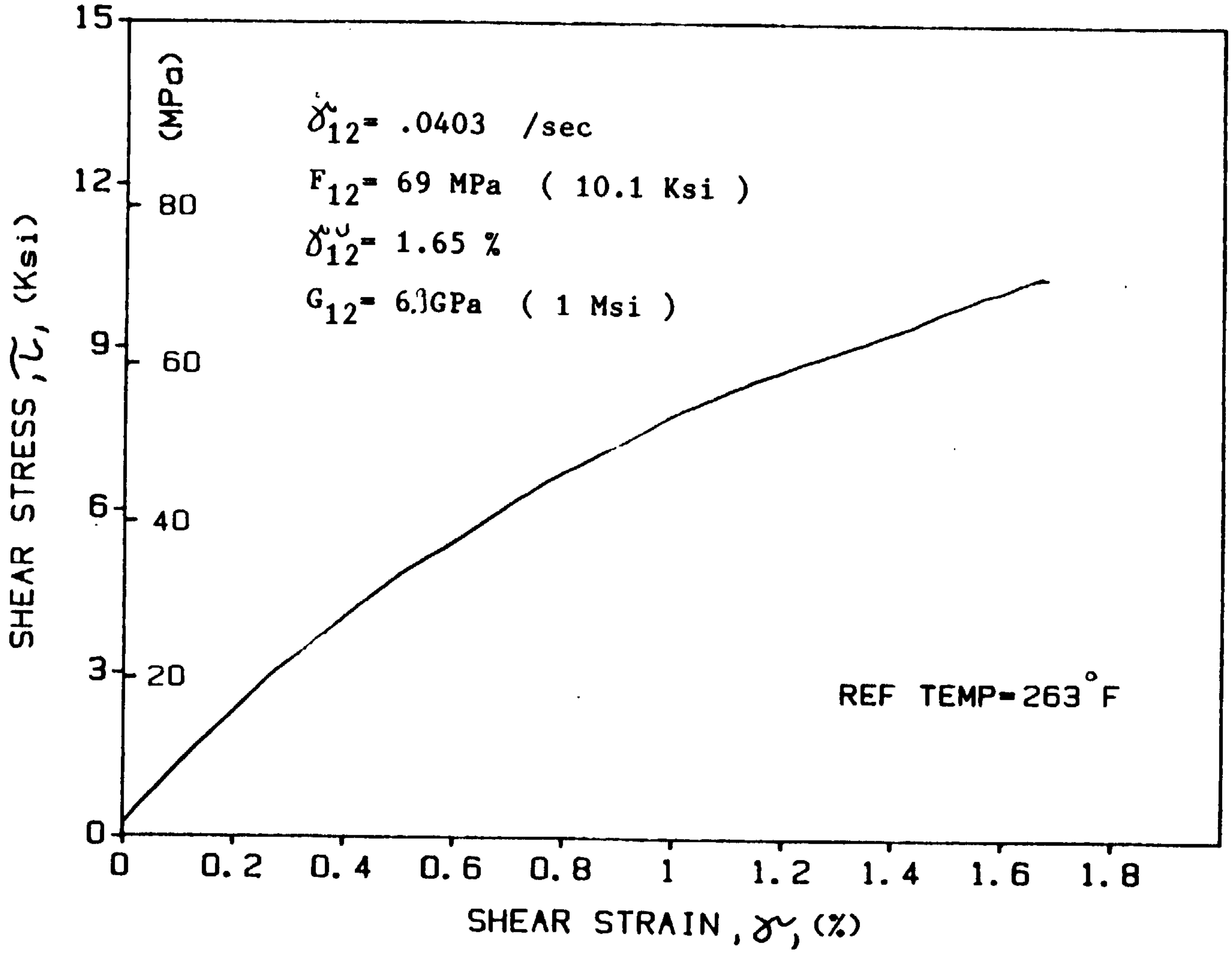


Fig. A-215. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-2H8 (T = 128°C (263°F))

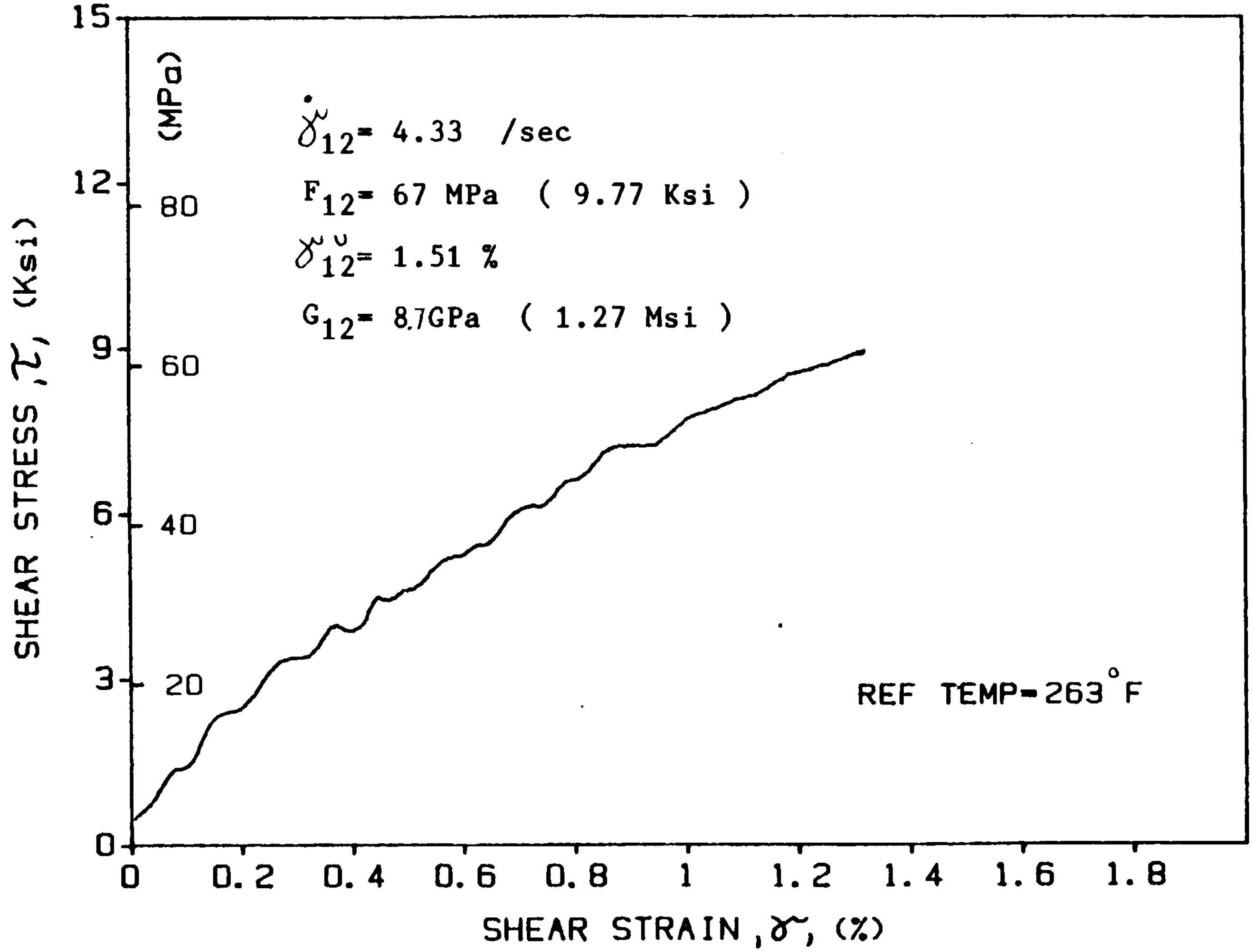


Fig. A-216. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-1H1 (T = 128°C (263°F))

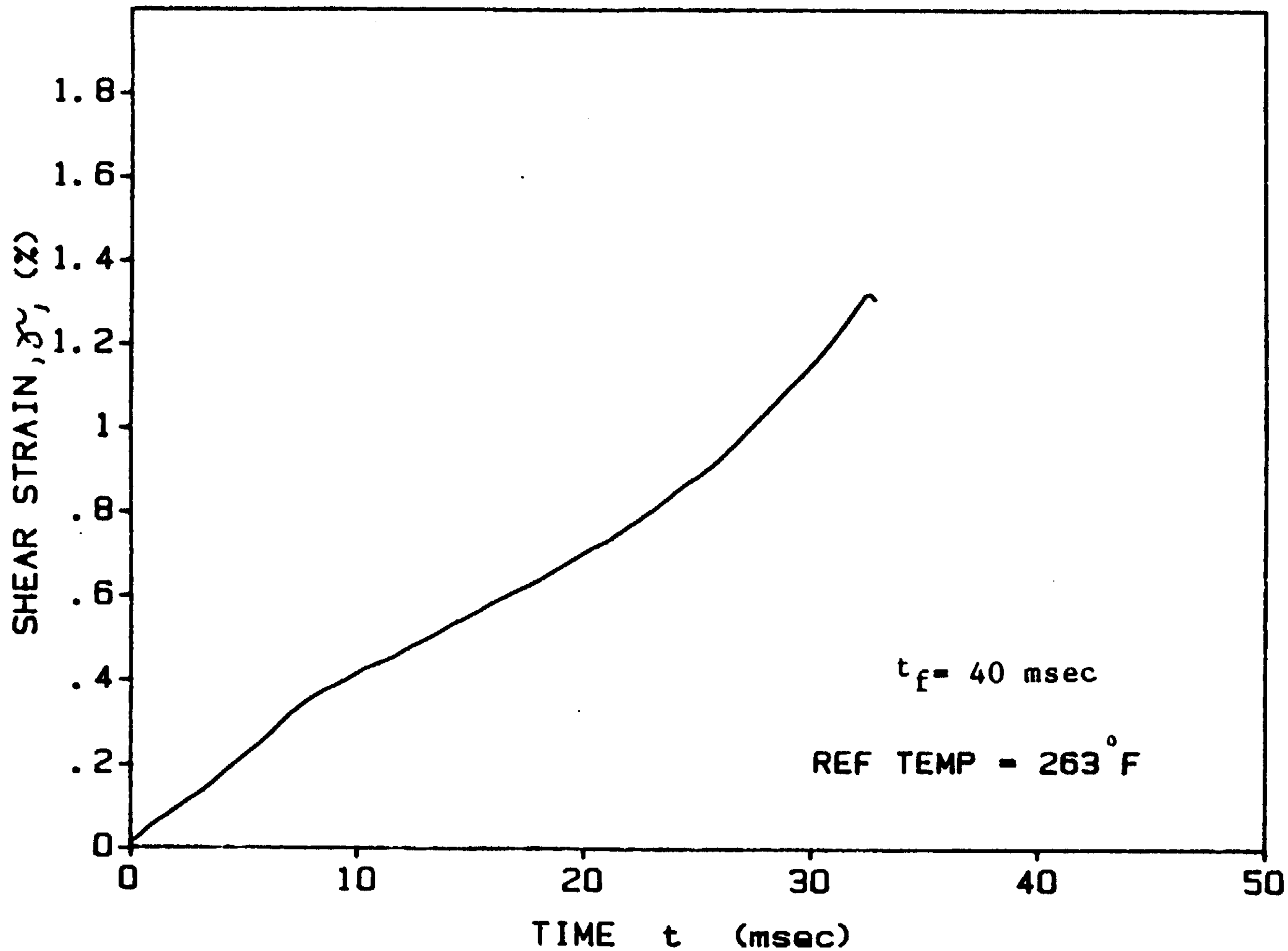


Fig. A-217. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy. Spec. 10/-1H1 (T = 128°C (263°F))

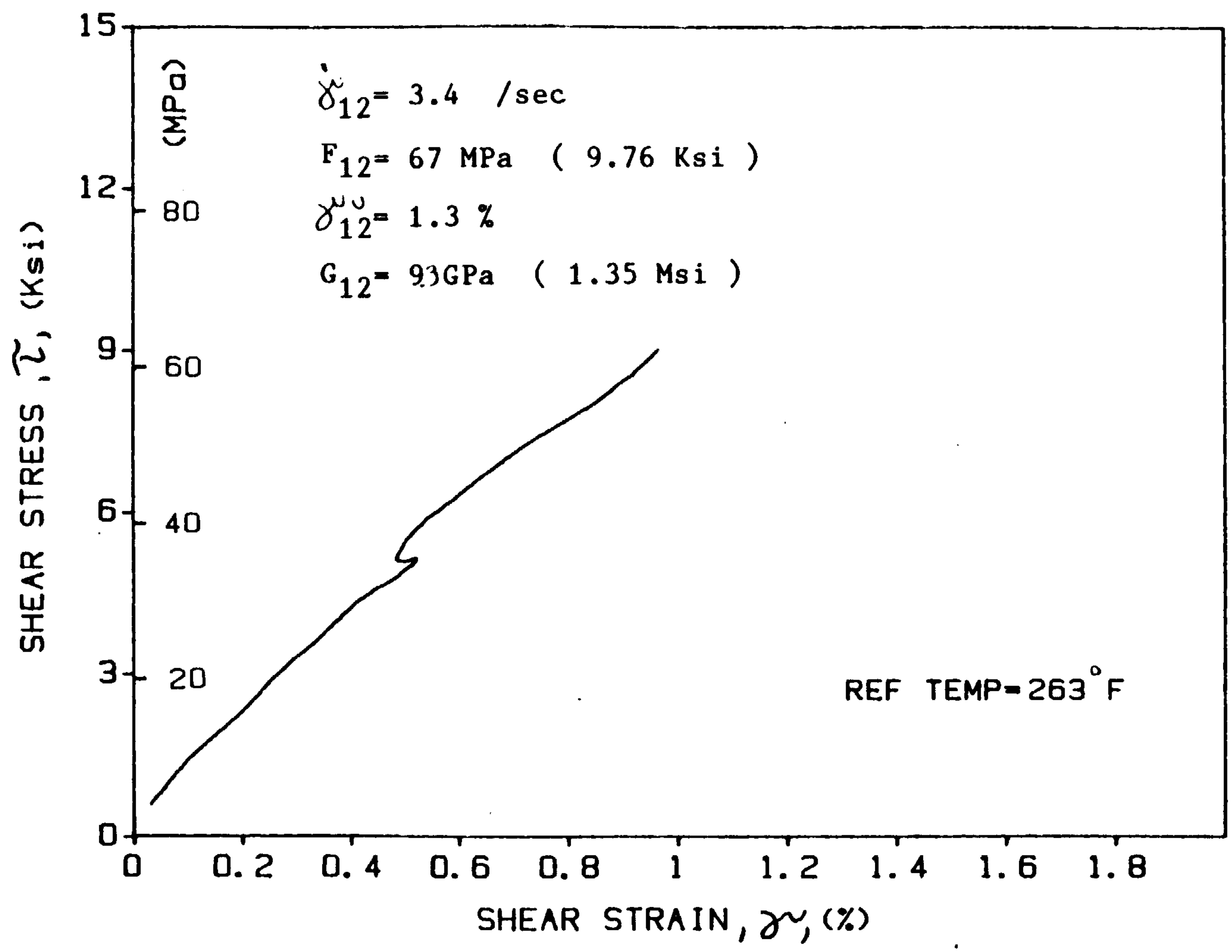


Fig. A-218. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-H2 (T = 128°C (263°F))

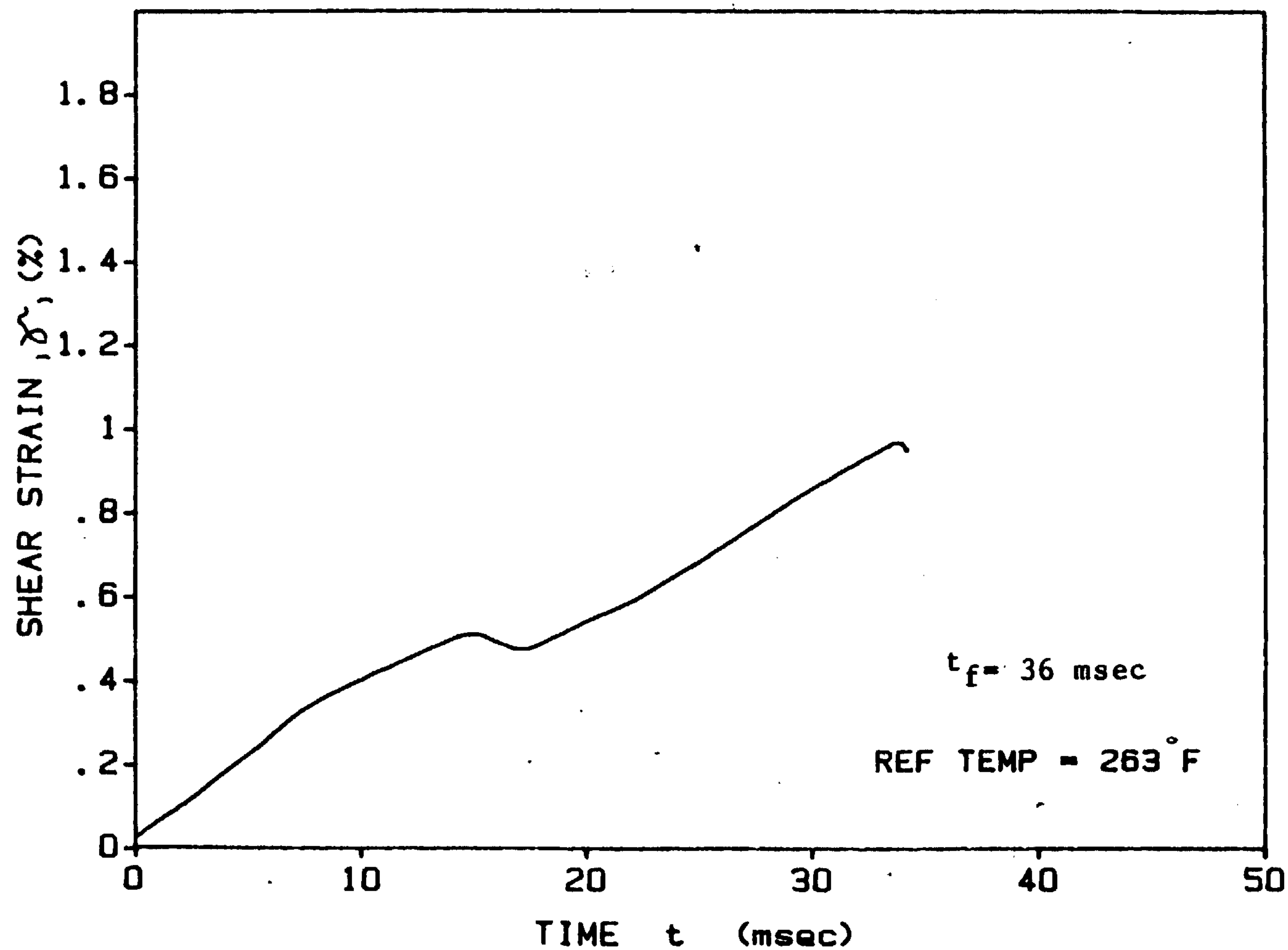


Fig. A-219. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-1H2 (T = 128°C (263°F))

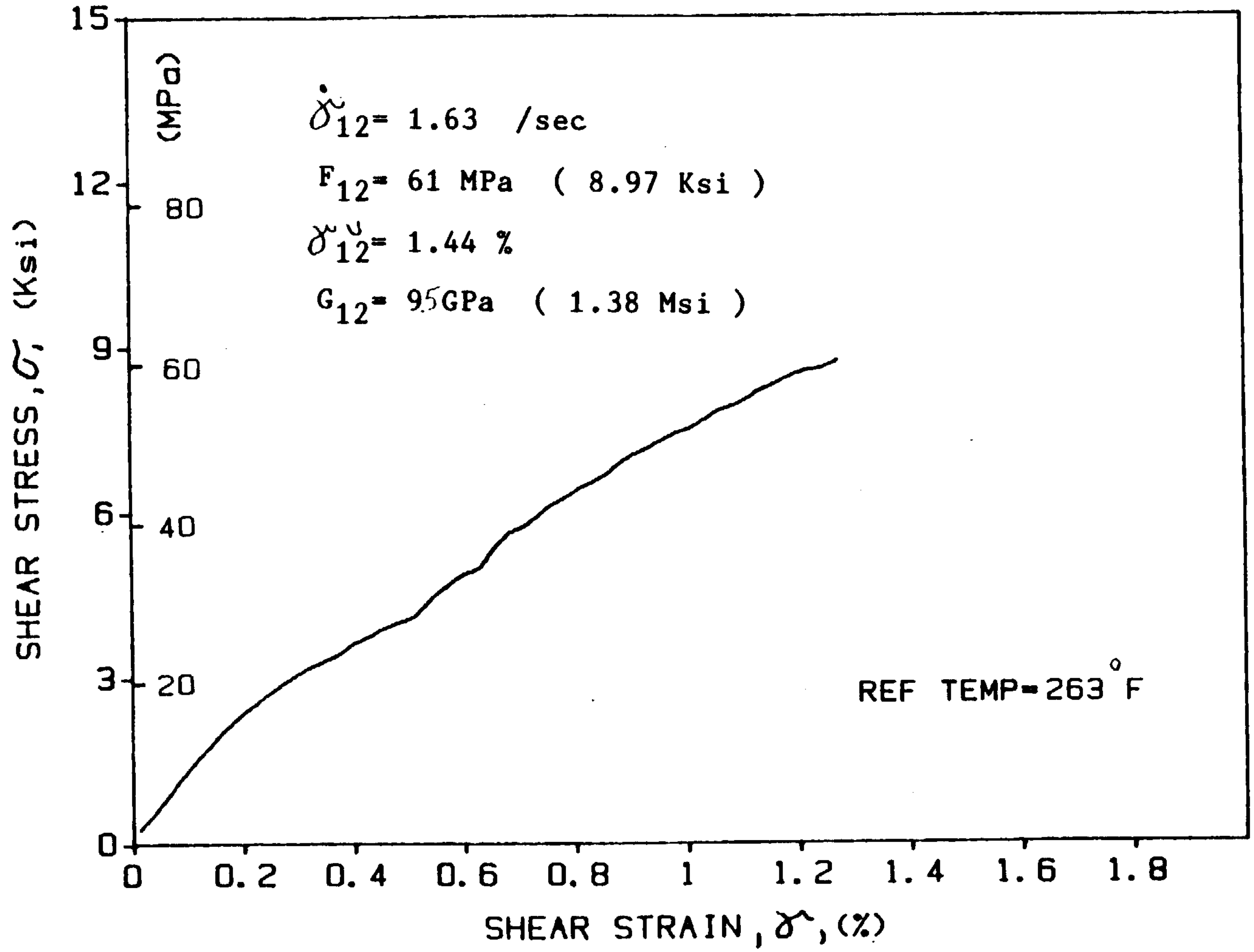


Fig. A-220. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/-1H4 (T = 128°C (263°F))

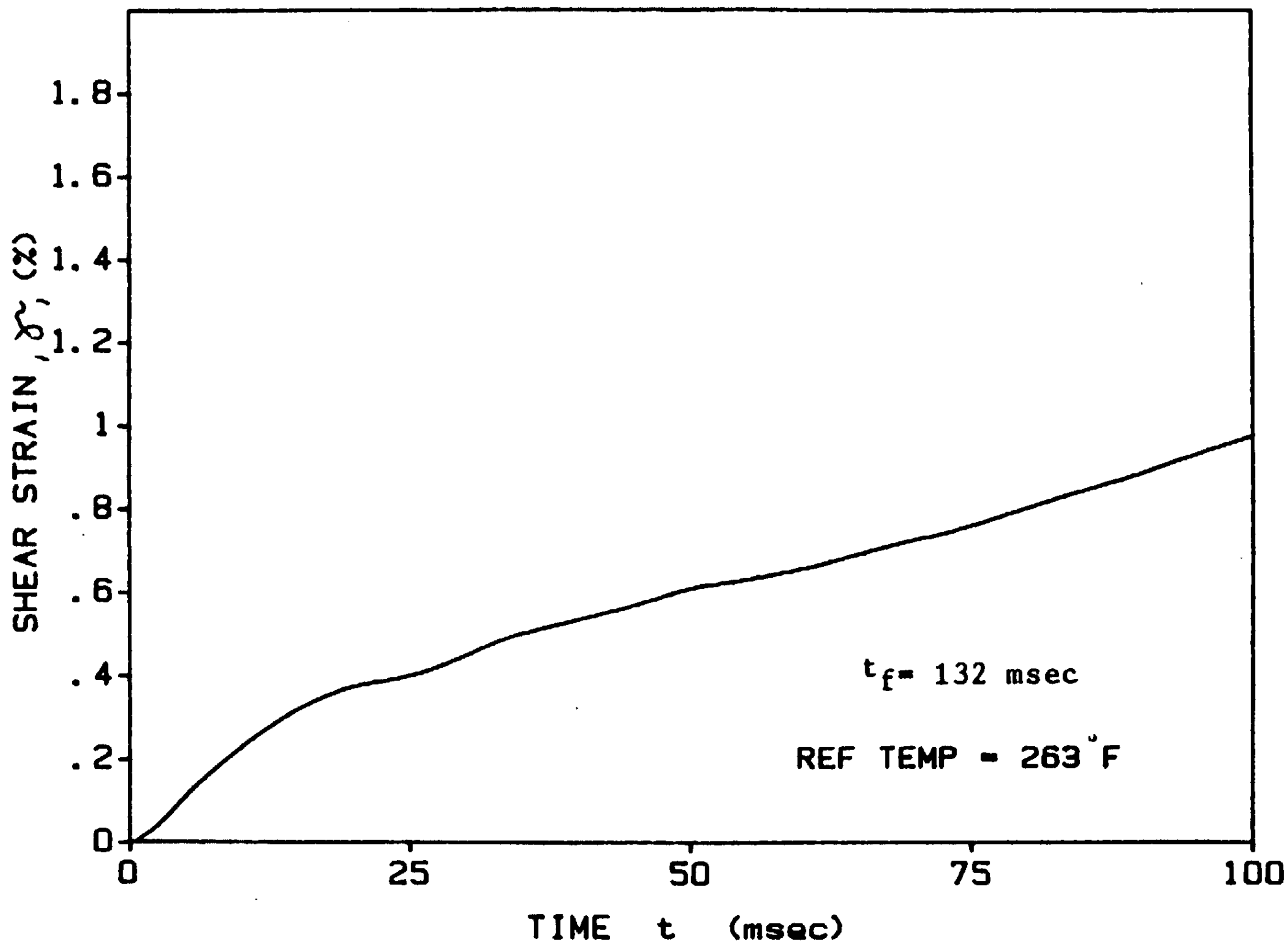


Fig. A-221. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy. Spec. 10/-1H4 (T = 128°C (263°F))

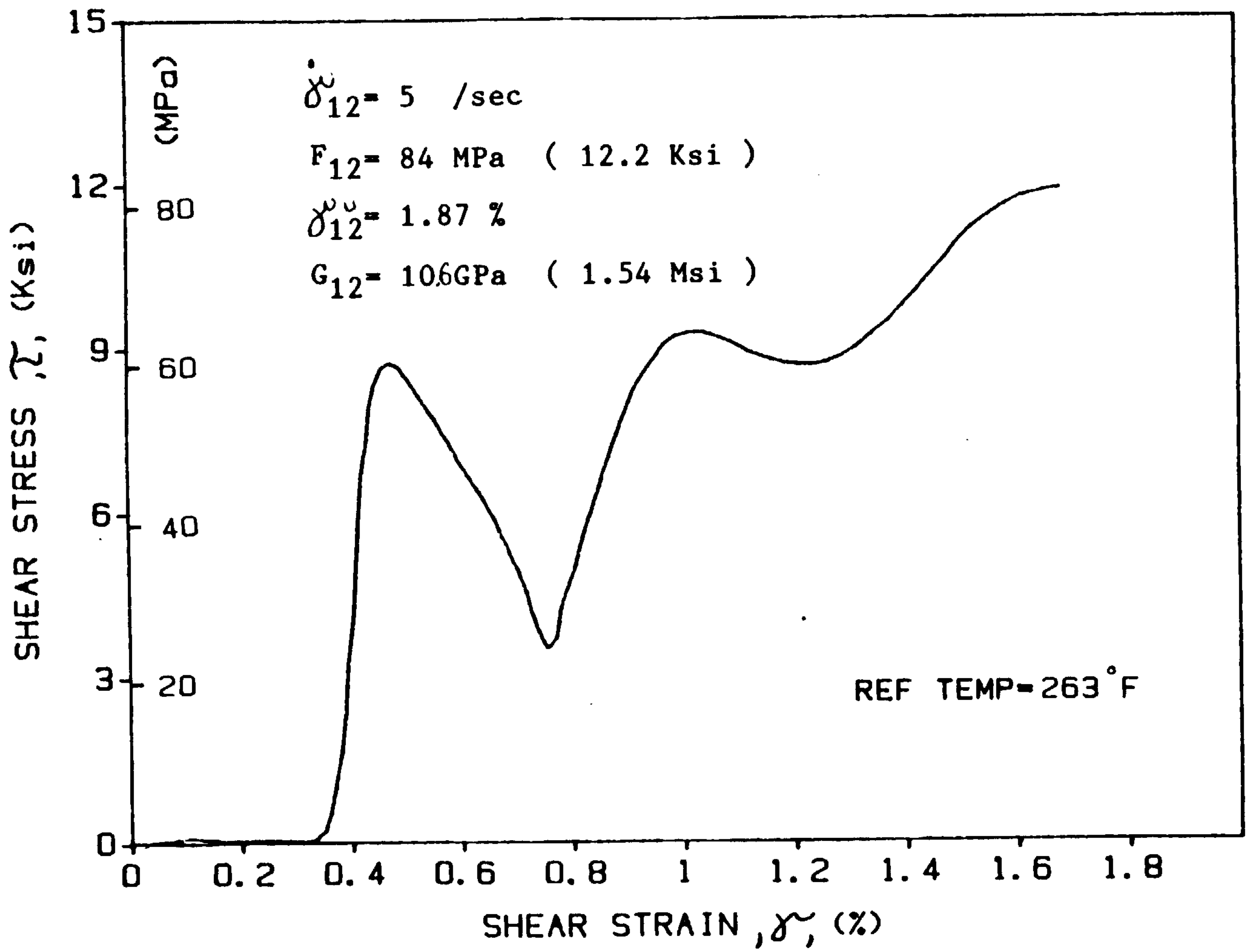


Fig. A-222. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H1 (T = 128°C (263°F))

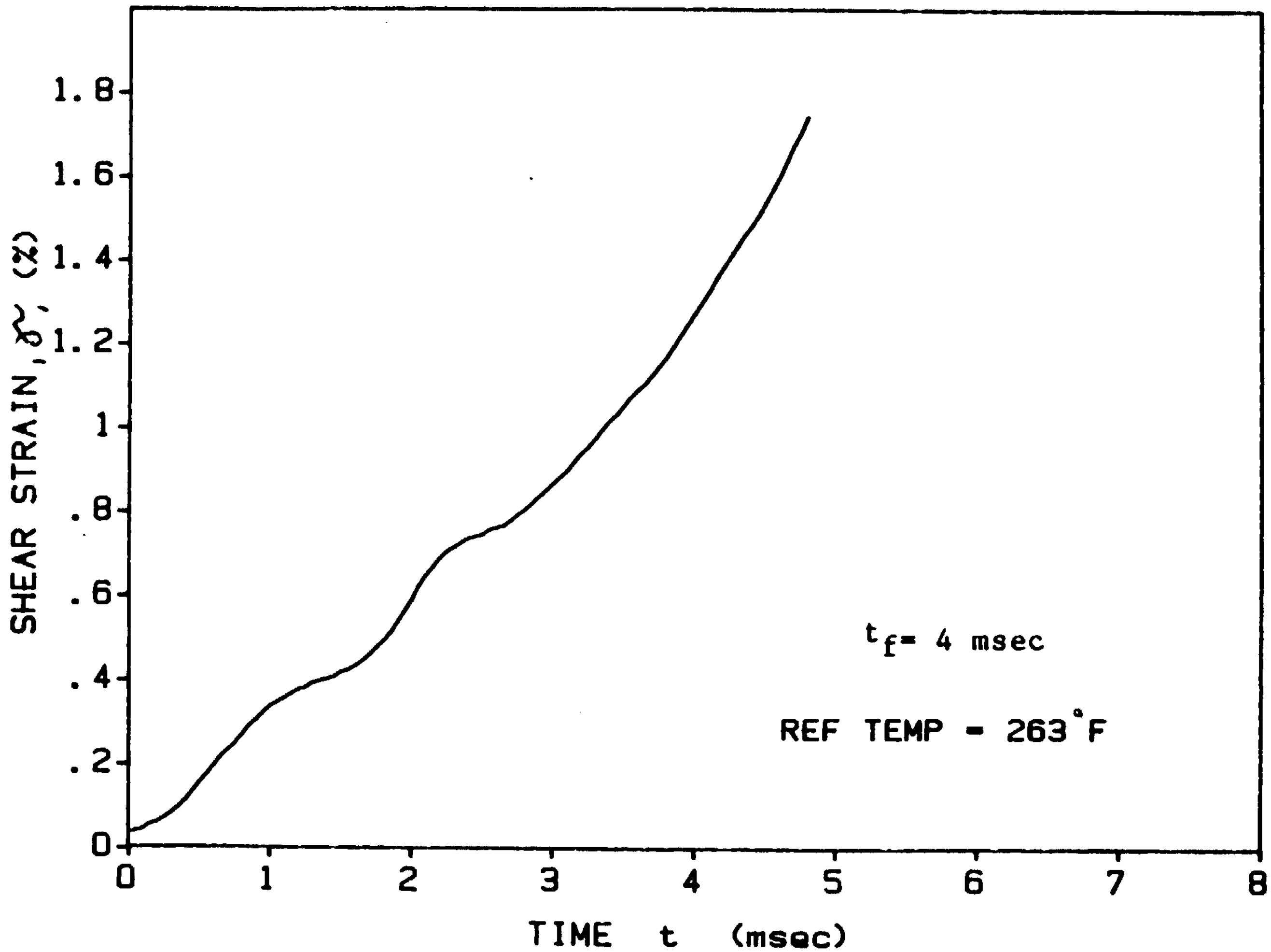


Fig. A-223. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H1 (T = 128°C (263°F))

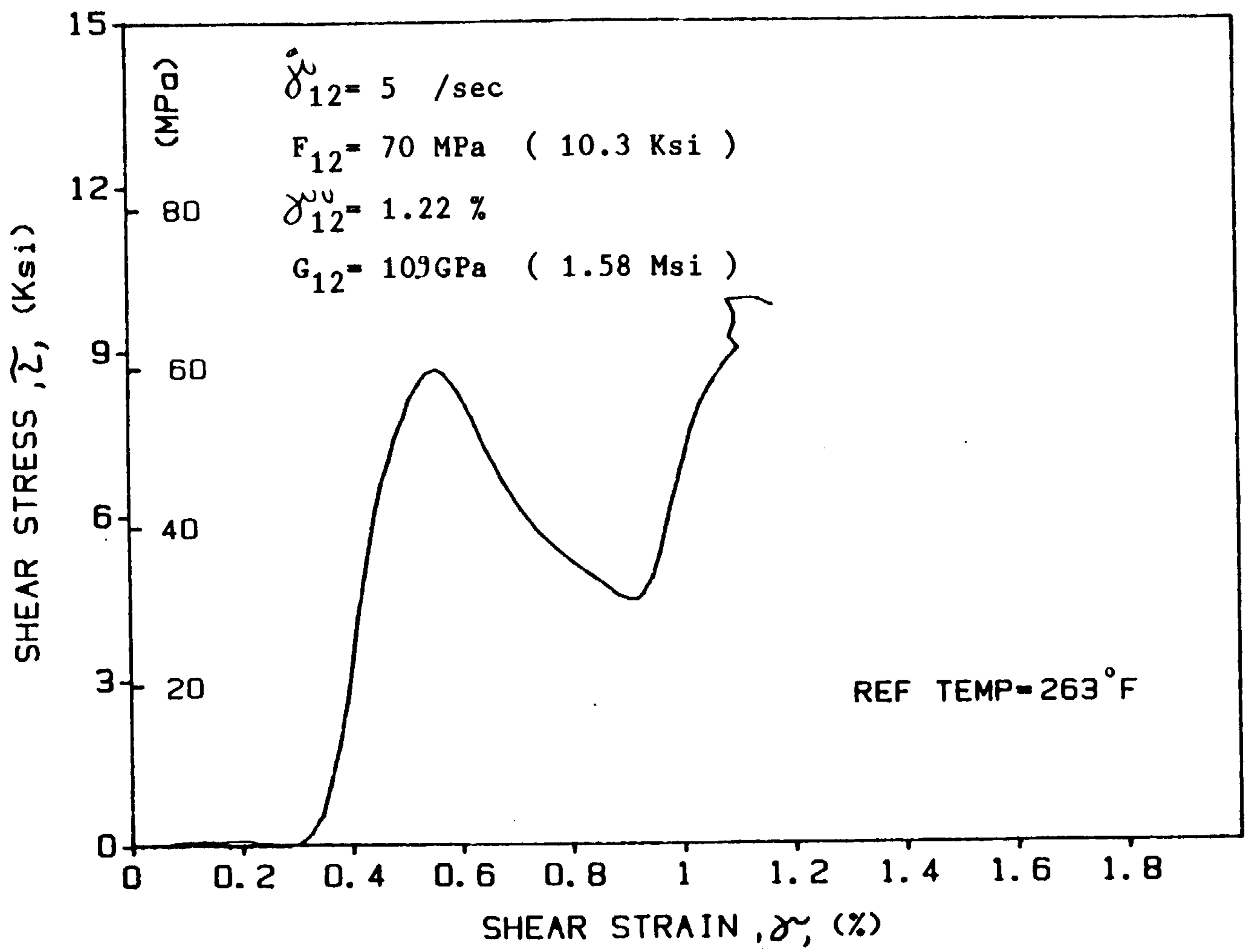


Fig. A-224. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H2 (T = 128°C (263°F))

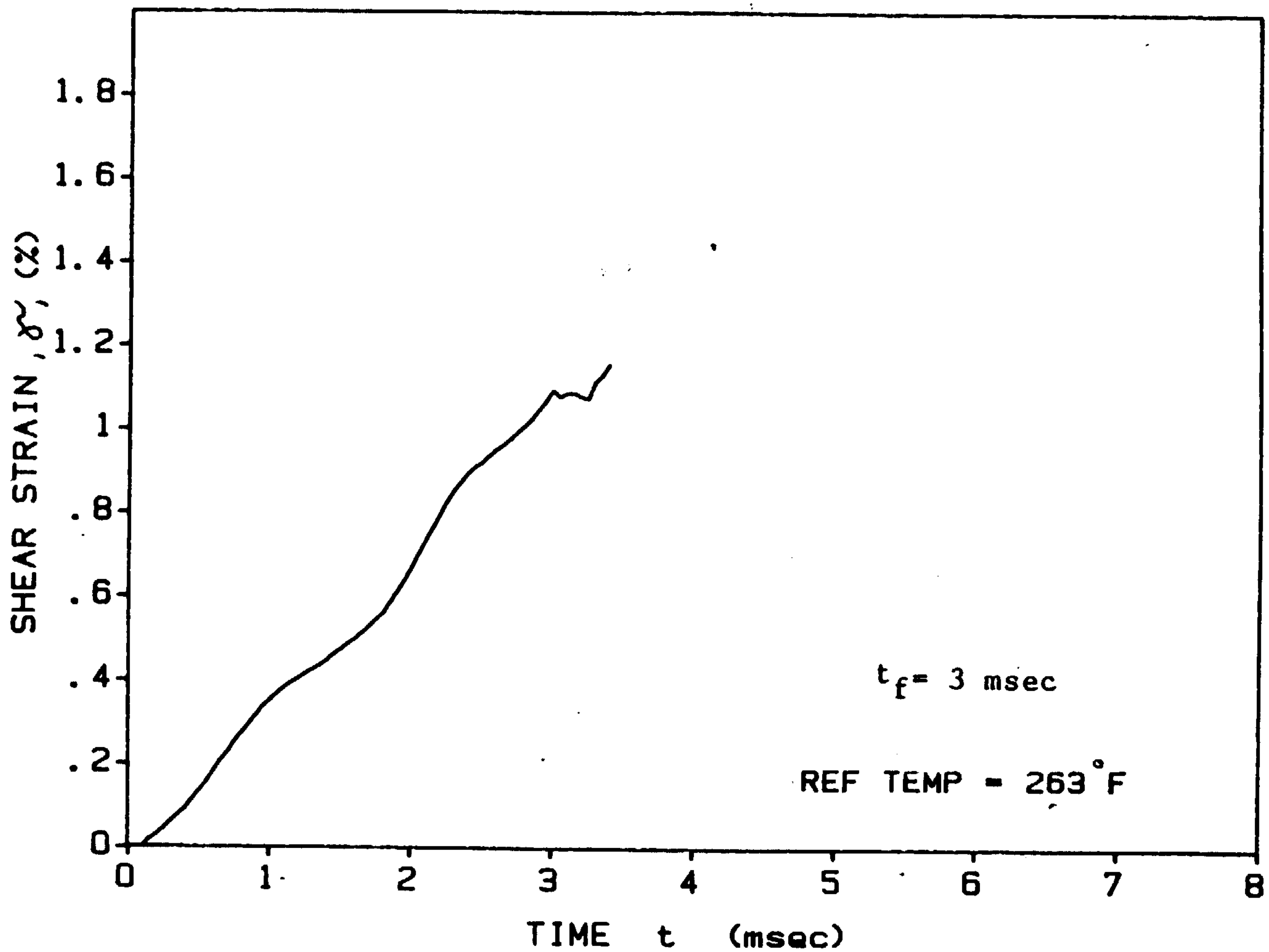


Fig. A-225. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H2 (T = 128°C (263°F))

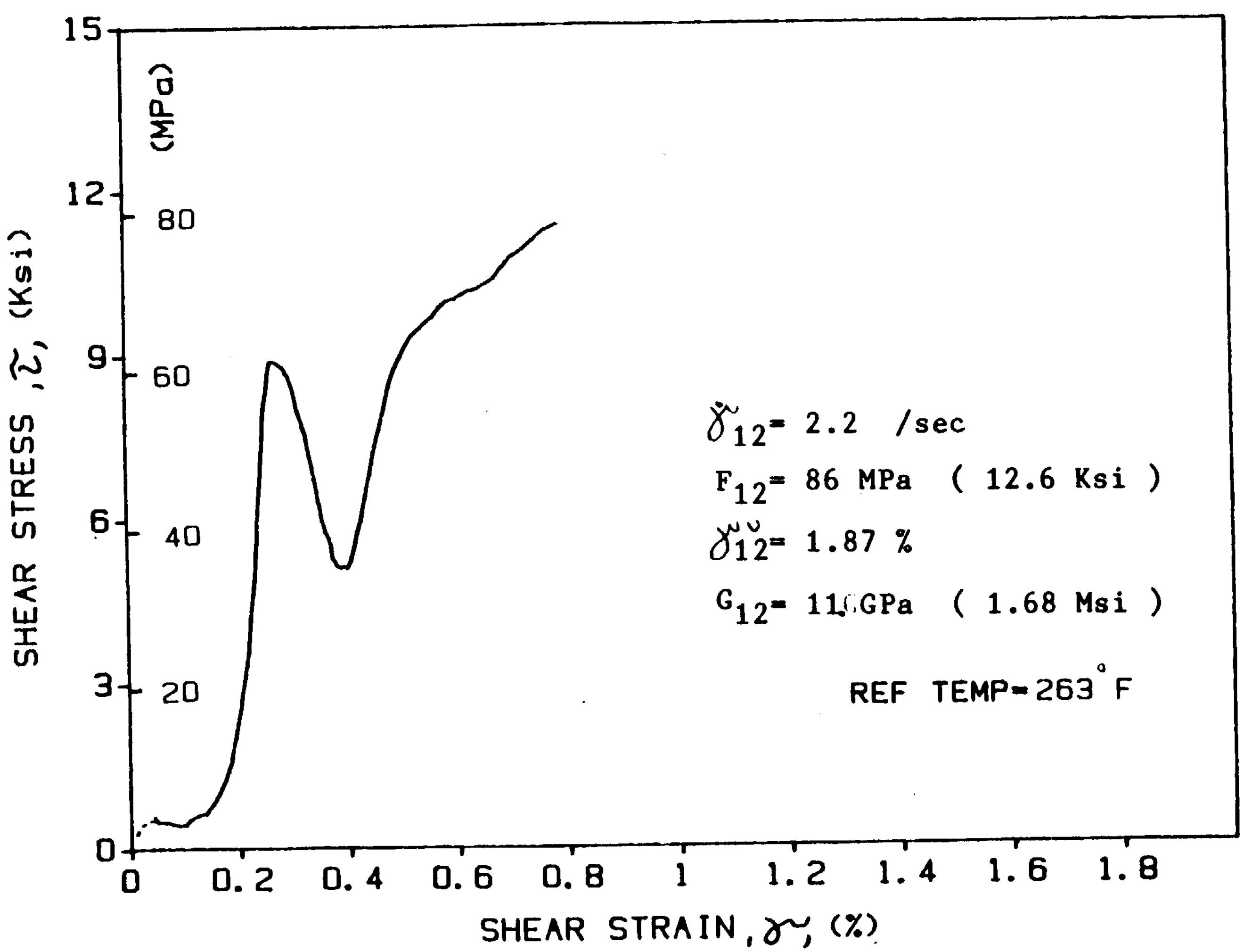


Fig. A-226. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 10/0H3 (T = 128°C (263°F))

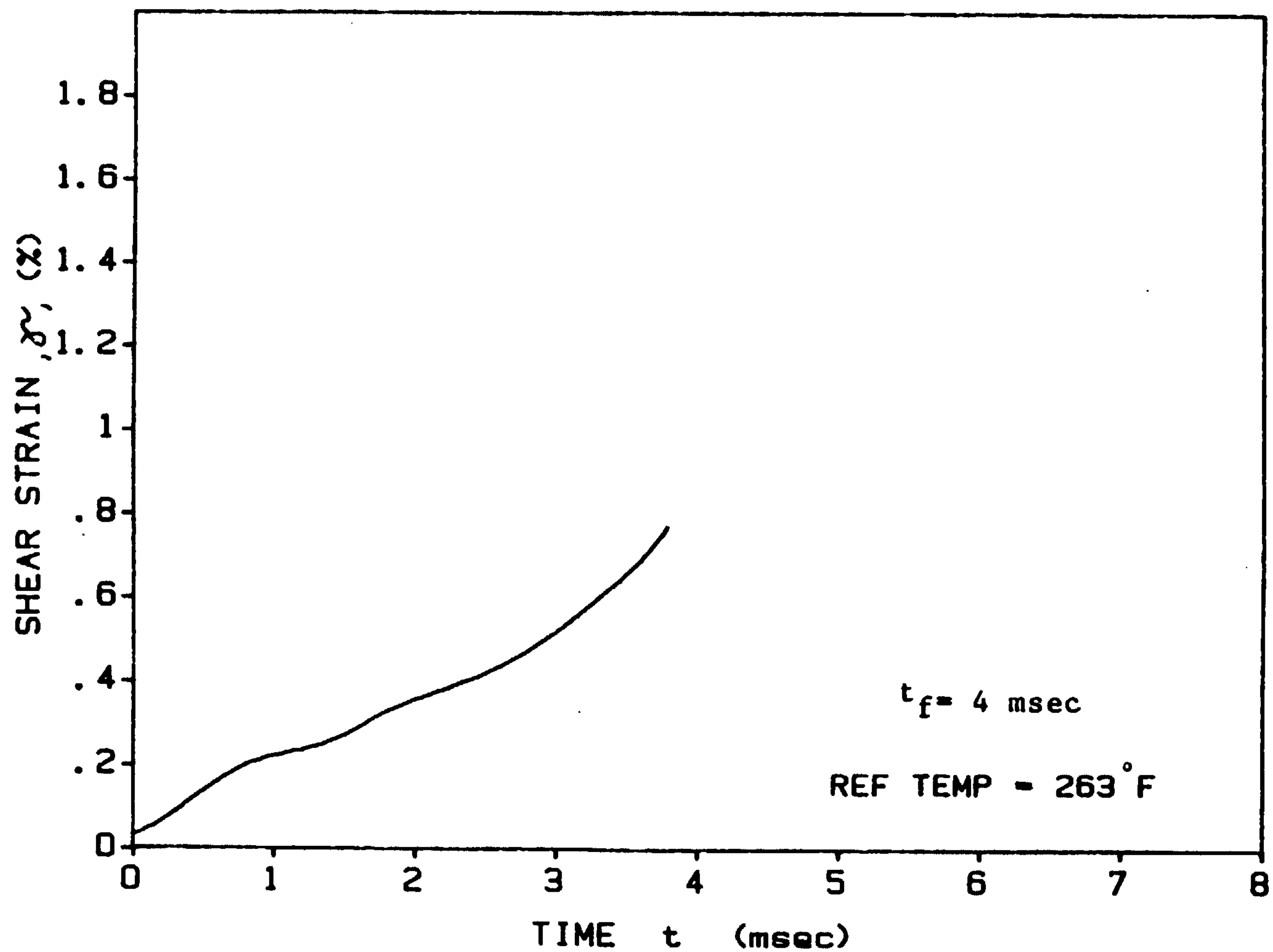


Fig. A-227. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H3 (T = 128°C (263°F))

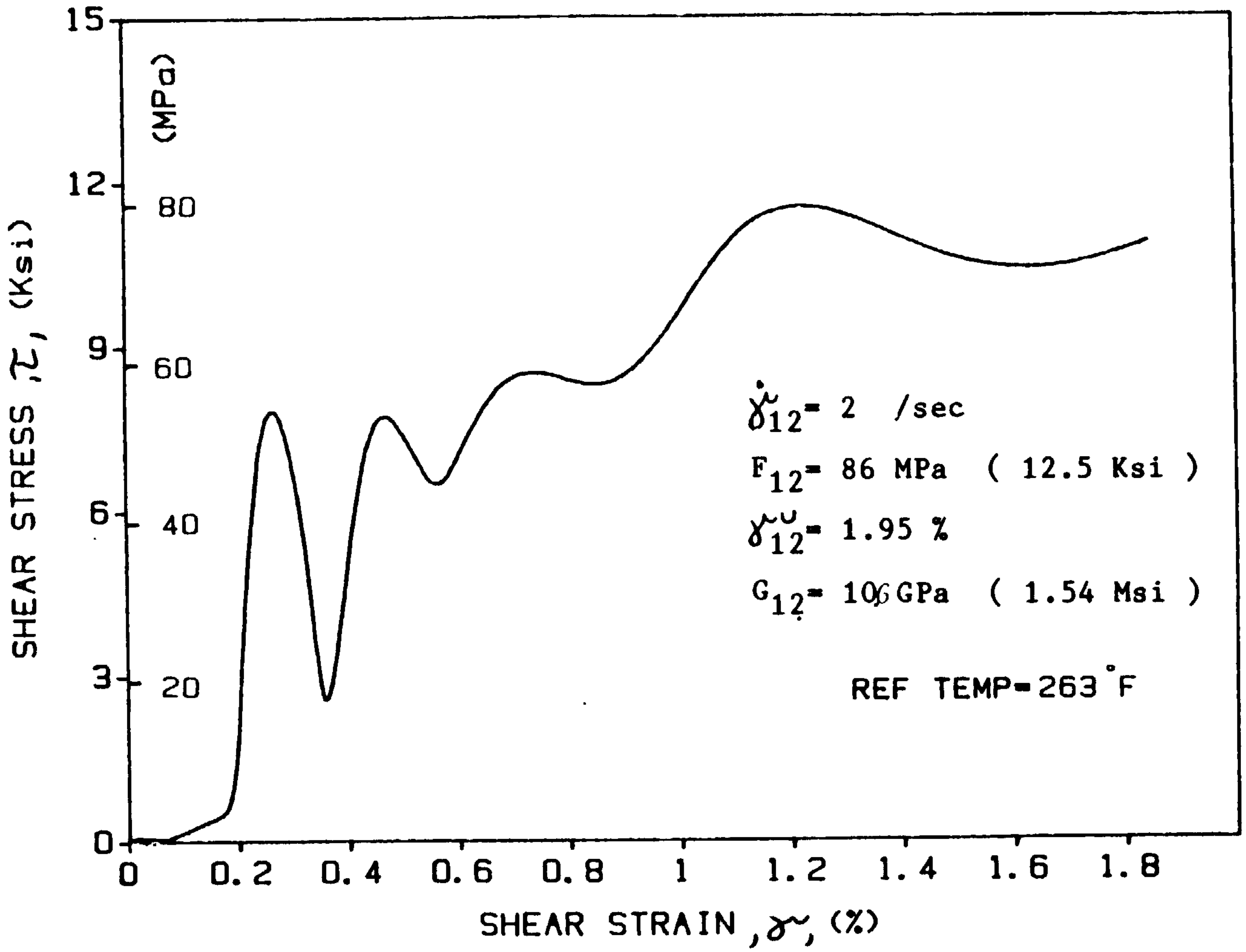


Fig. A-228. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 10/0H4 (T = 128°C (263°F))

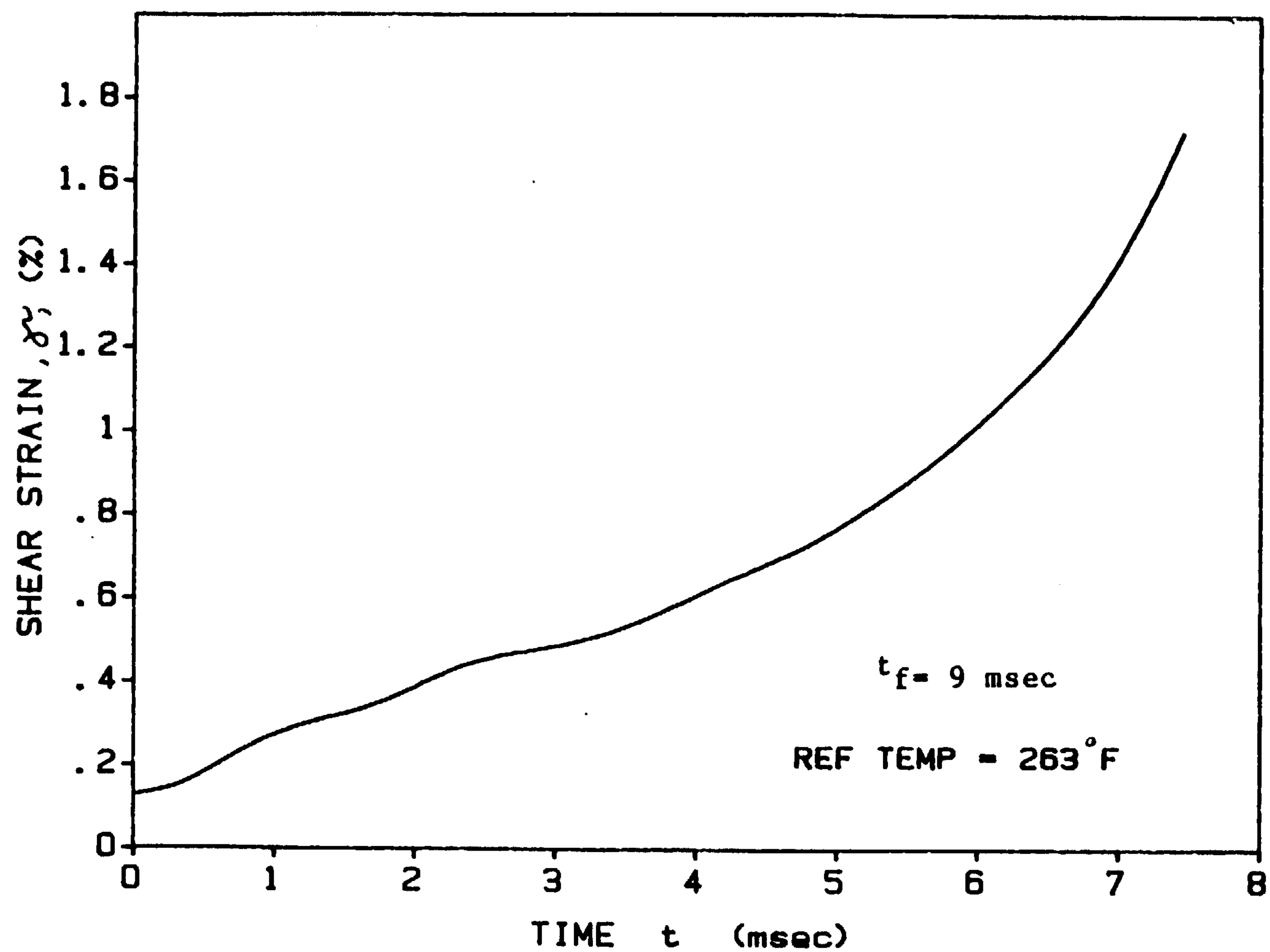


Fig. A-229. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H4 (T = 128°C (263°F))

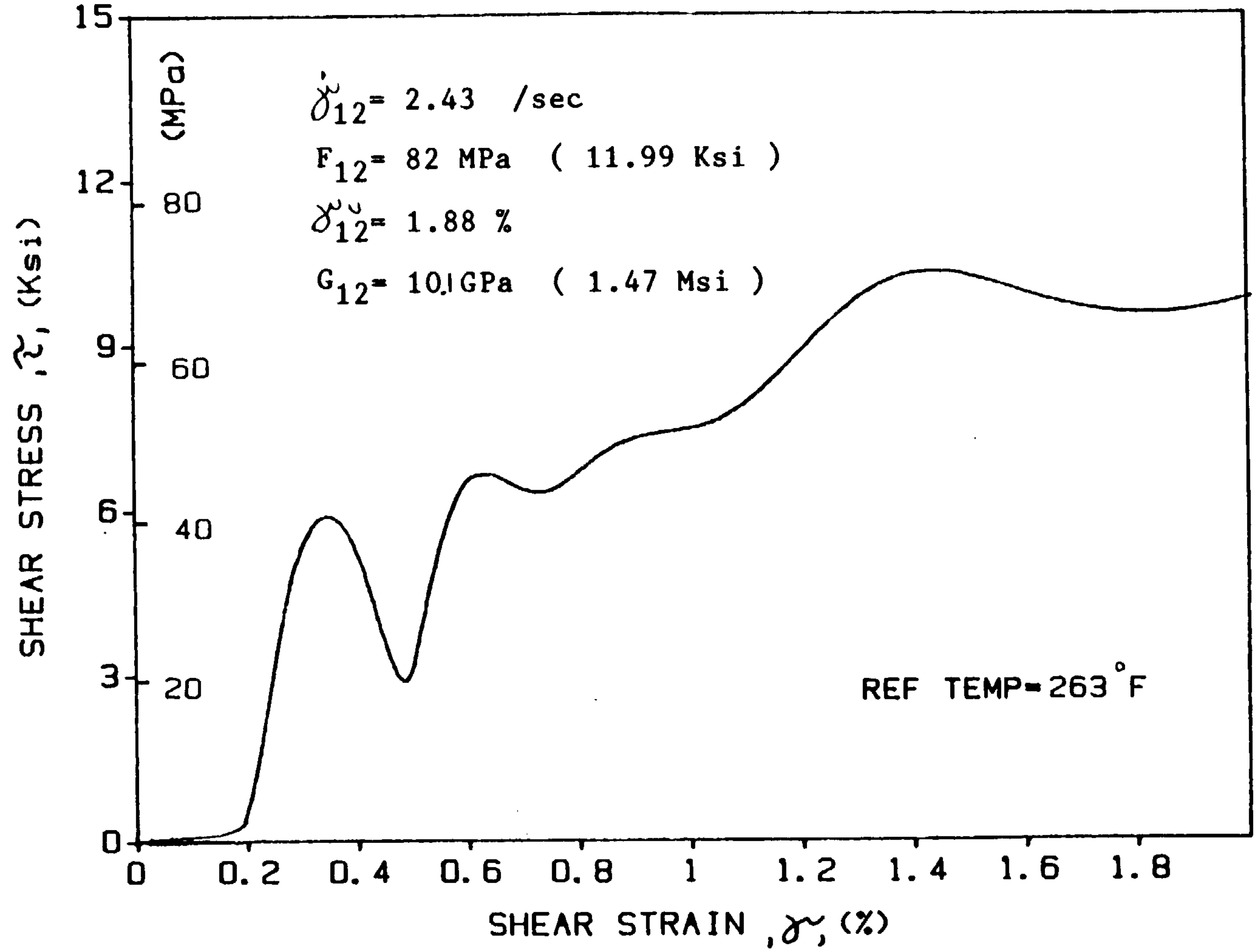


Fig. A-230. Shear Stress-Strain Curve for [10_6] AS4/3501-6 Graphite/Epoxy, Spec. 10/0H5 (T = 128°C (263°F))

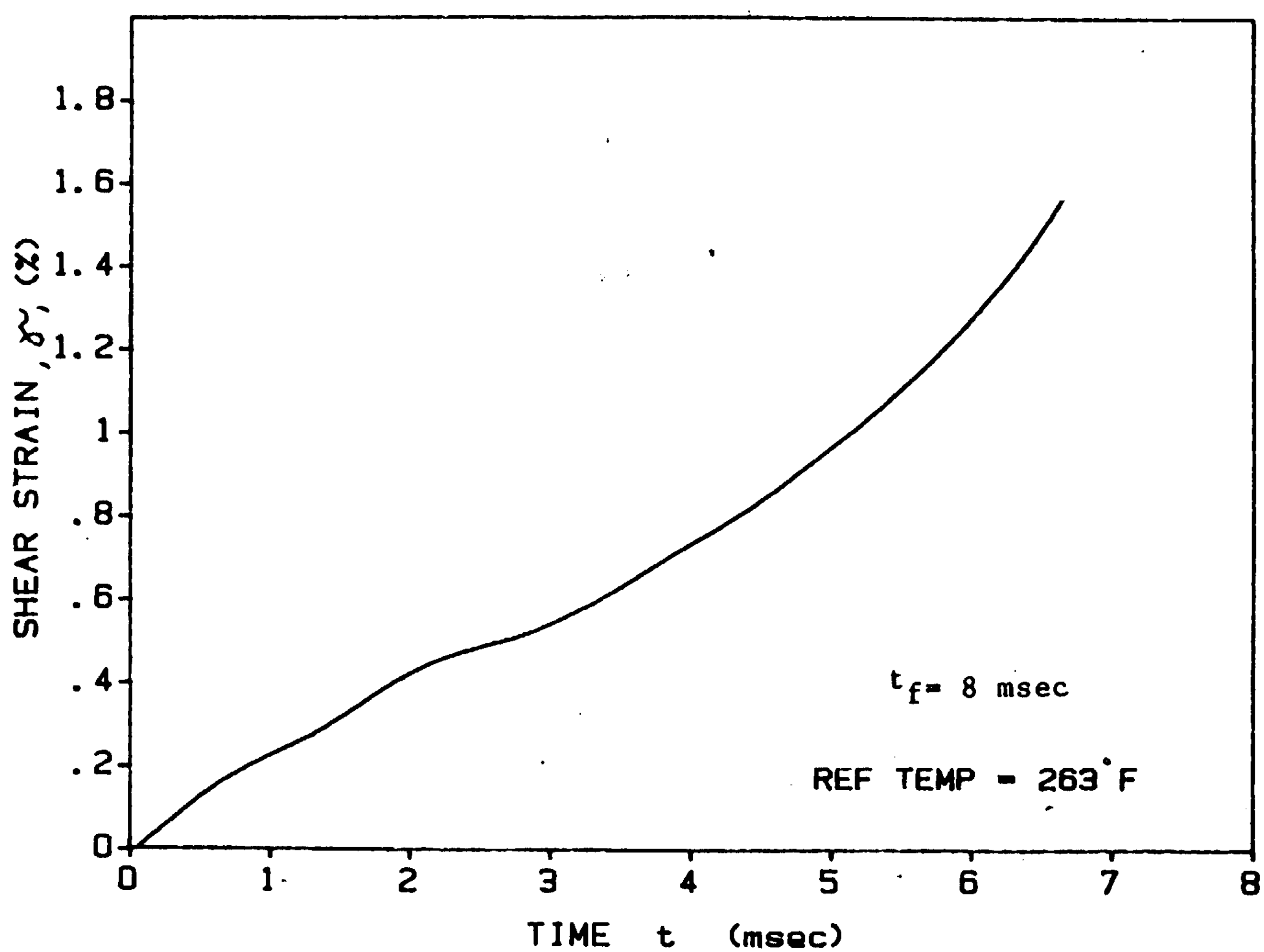


Fig. A-231. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H5 (T = 128°C (263°F))

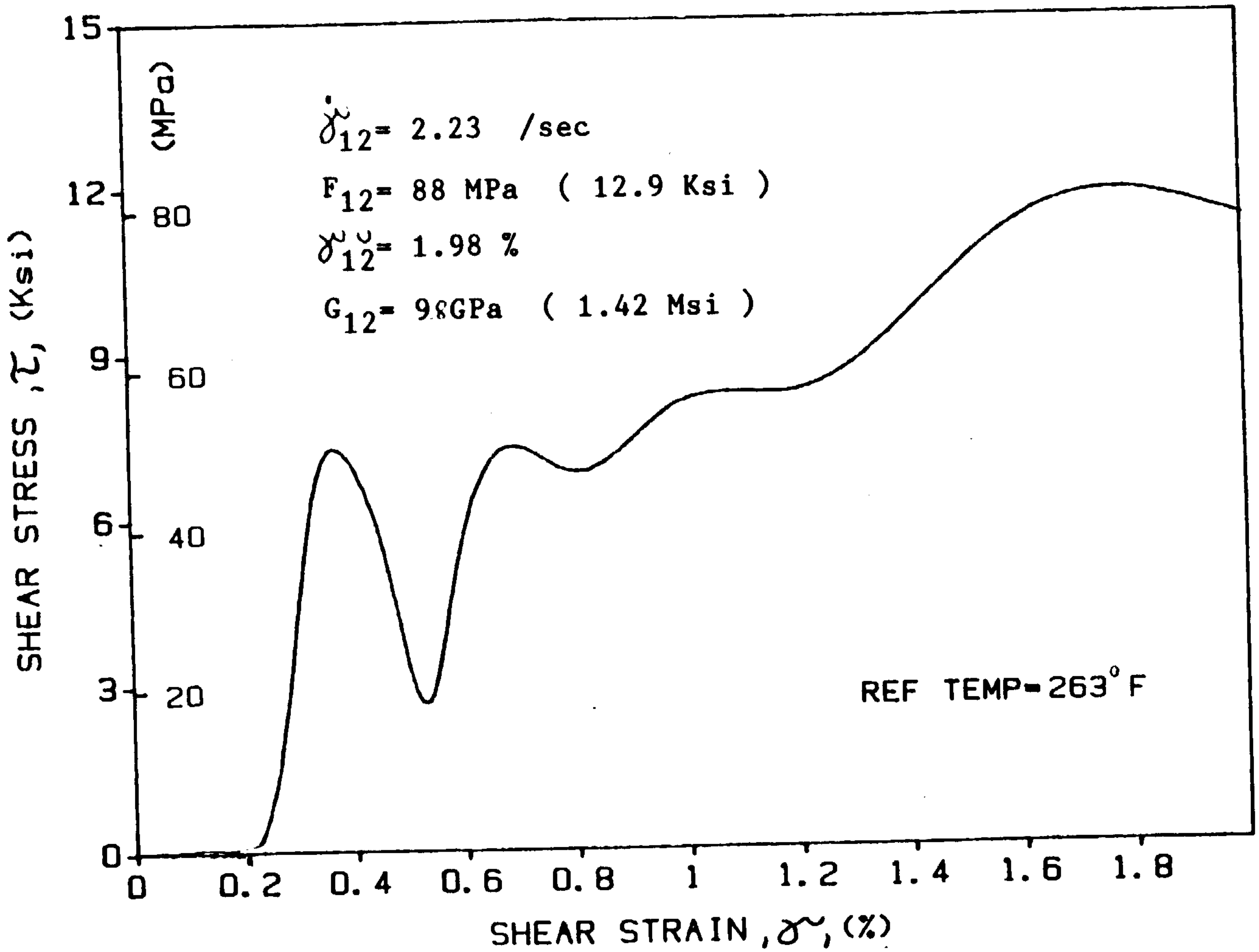


Fig. A-232. Shear Stress-Strain Curve for $[10_6]$ AS4/3501-6 Graphite/ Epoxy, Spec. 10/0H6 (T = 128°C (263°F))

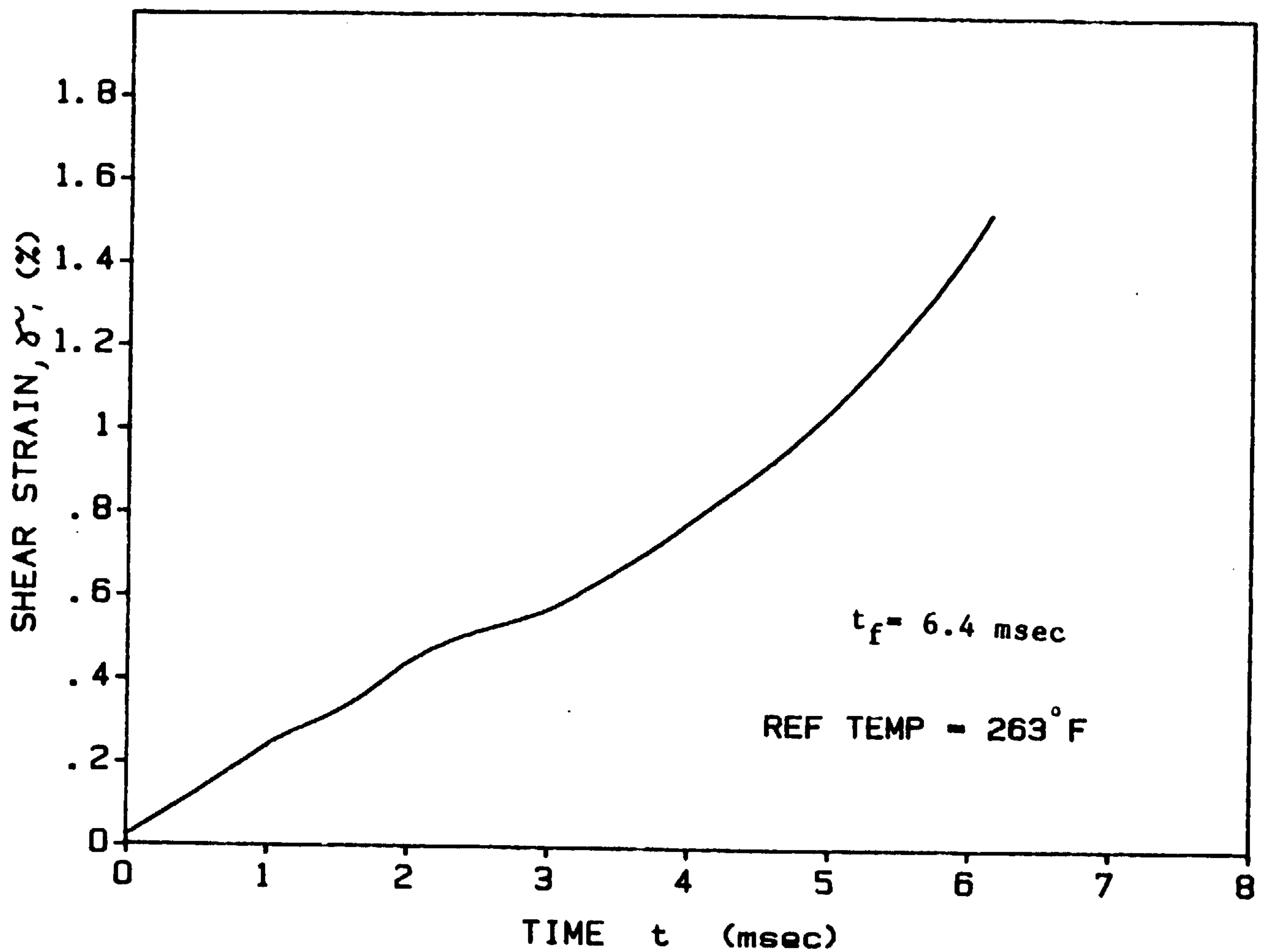


Fig. A-233. Shear Strain vs. Time for $[10_6]$ AS4/3501-6 Graphite/Epoxy, Spec. 10/0H6 (T = 128°C (263°F))

Table A-1. Tensile Properties of $[0_6]$ AS4/3501-6 Graphite/Epoxy at Low Strain-Rate - Room Temperature

Initial Properties

Specimen Number	Strain-Rate $(\dot{\varepsilon}_{11})$, S^{-1}	Modulus (E_{11}), GPa (Msi)	Poisson's Ratio (ν_{12})
0/-4L2	$3.12 \cdot 10^{-4}$	143 (20.80)	.265
0/-4L3	$3.67 \cdot 10^{-4}$	142 (20.65)	.269
0/-4L4	$3.47 \cdot 10^{-4}$	143 (20.80)	.270
0/-4L5	$3.37 \cdot 10^{-4}$	144 (21.00)	.267

Ultimate Properties

Specimen Number	Time to Failure (t_f), S	Strength (F_{1T}), MPa (Ksi)	Strain (ε^u_{1T}), %
0/-4L2	44	2404 (349)	1.55
0/-4L3	49	2356 (342)	1.54
0/-4L4	56	2452 (356)	1.58
0/-4L5	55	2404 (349)	1.55

Table A-2. Tensile Properties of $[0_6]$ AS4/3501-6 Graphite/ Epoxy at High Strain-Rate - Room Temperature

Initial Properties

Specimen Number	Strain Rate $(\dot{\varepsilon}_{11})$, S^{-1}	Modulus (E_{11}), GPa	(Msi)	Poisson's Ratio (ν_{12})
0/0L1	1.00	145	(21.10)	.272
0.0L2	1.02	145	(21.08)	.265
0/0L3	1.01	148	(21.50)	.270
0/0L3.1	1.03	150	(21.90)	.260
0/0L4	1.08	144	(20.90)	.267
0/0L5	1.19	148	(21.50)	.250

Ultimate Properties

Specimen Number	Time to Failure (t_f), mS	Strength (F_{1T}), MPa	(Ksi)	Strain (ε^u_{1T}), %
0/0L1	18	2349	(341)	1.42
0/0L2	18	2308	(335)	1.46
0/0L3	18	2335	(339)	1.42
0/0L3.1	19	2335	(339)	1.42
0/0L4	16	2273	(330)	1.39
0/0L5	14	2377	(345)	1.41

Table A-3. Tensile Properties of $[90_8]$ AS4/3501-6 Graphite/Epoxy at Low Strain-Rates - Room Temperature

Initial Properties

Specimen Number	Strain Rate $(\dot{\varepsilon}_{22})$, S^{-1}	Modulus (E_{22}), GPa	(Msi)	Poisson's Ratio (ν_{21})
90/-5L1	$4.75 \cdot 10^{-5}$	10.0	(1.46)	-
90/-5L2	$4.75 \cdot 10^{-5}$	10.4	(1.51)	-
90/-5L3	$4.75 \cdot 10^{-5}$	10.3	(1.50)	-
90/-5L4	$4.75 \cdot 10^{-5}$	10.1	(1.47)	-
90/-5L5	$4.75 \cdot 10^{-5}$	10.7	(1.55)	-

Ultimate Properties

Specimen Number	Time to Failure (t_f), S	Strength (F_{2T}), MPa	(Ksi)	Strain (ε^u_{2T}), %
90/-5L1	140	64	(9.42)	.67
90/-5L2	124	60	(8.79)	.61
90/-5L3	151	73	(10.60)	.75
90/-5L4	121	54	(7.85)	.55
90/-5L5	158	72	(10.50)	.78

Table A-4. Tensile Properties of $[90_8]$ and $[90_{16}]$ AS4/3501-6 Graphite/Epoxy at Intermediate Strain-Rates - Room Temperature

		Initial Properties		
Specimen Number	Strain Rate $(\dot{\varepsilon}_{22})$, S^{-1}	Modulus (E_{22}), GPa	(Msi)	Poisson's Ratio (ν_{21})
90/-3L1	$4.94 \cdot 10^{-3}$	10.9	(1.46)	-
90/-3L2	$4.90 \cdot 10^{-3}$	10.8	(1.57)	-
90/-3L3	$4.90 \cdot 10^{-3}$	10.9	(1.59)	-
90/-3L4	$4.90 \cdot 10^{-3}$	11.0	(1.60)	-
90/-3L5	$4.90 \cdot 10^{-3}$	11.0	(1.60)	-
90/-2L1	$6.70 \cdot 10^{-2}$	11.8	(1.71)	.0111
90/-2L2	$7.00 \cdot 10^{-2}$	11.4	(1.66)	.0108
90/-2L3	$6.77 \cdot 10^{-2}$	11.8	(1.71)	.0131
90/-2L4	$4.45 \cdot 10^{-2}$	11.8	(1.71)	.0086
90/-2L5	$3.33 \cdot 10^{-2}$	11.3	(1.64)	.0128
90/-2L6	$3.36 \cdot 10^{-2}$	11.2	(1.63)	.0133

Table A-4. (Cont'd) Tensile Properties of $[90_8]$ and $[90_{16}]$ AS4/3501-6 Graphite/Epoxy at Intermediate Strain-Rates - Room Temperature

Ultimate Properties

Specimen Number	Time to Failure (t_f), mS	Strength (F_{2T}), MPa	(Ksi)	Strain (ε^u_{2T}), %
90/-3L1	$.95 \cdot 10^3$	51	(7.48)	.48
90/-3L2	$1.31 \cdot 10^3$	67	(9.77)	.62
90/-3L3	$1.39 \cdot 10^3$	76	(11.10)	.71
90/-3L4	$1.28 \cdot 10^3$	68	(9.99)	.62
90/-3L5	$1.03 \cdot 10^3$	53	(7.78)	.50
90/-2L1	80	58	(8.47)	.53
90/-2L2	70	54	(7.90)	.50
90/-2L3	80	63	(9.22)	.54
90/-2L4	96	48	(6.98)	.42
90/-2L5	112	38	(5.56)	.39
90/-2L6	146	53	(7.75)	.49

Table A-5. Tensile Properties of $[90_8]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Room Temperature

Initial Properties

Specimen Number	Strain Rate $(\dot{\varepsilon}_{22})$, s^{-1}	Modulus (E_{22}), GPa	(Msi)	Poisson's Ratio (ν_{21})
90/-1L1	$2.95 \cdot 10^{-1}$	11.9	(1.73	.0120
90/-1L2	$3.13 \cdot 10^{-1}$	11.7	(1.70)	.0118
90/-1L3	$3.13 \cdot 10^{-1}$	11.6	(1.68)	.0135
90/-1L4	$2.95 \cdot 10^{-1}$	11.8	(1.71)	.0115
90/-1L5	$3.65 \cdot 10^{-1}$	11.8	(1.71)	.0120
90/-1L6	$4.43 \cdot 10^{-1}$	11.8	(1.72)	.0111
90/-1L6	$4.26 \cdot 10^{-1}$	11.7	(1.70)	.0117
90/0L1	1.00	12.2	(1.77)	.0197
90/0L2	1.10	11.7	(1.70)	.0110
90/0L3	1.48	11.9	(1.73)	.0160
90/0L4	1.49	11.9	(1.73)	.0142
90/0L5	1.30	11.9	(1.73)	.0114
90/0L6	1.28	11.9	(1.73)	.0170

Table A-5. (Cont'd) Tensile Properties of $[90_8]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Room Temperature

Specimen Number	Time to Failure (t_f), mS	Strength (F_{2T}), MPa	(Ksi)	Strain (ϵ^u_{2T}), %
		Ultimate Properties		
90/-1L1	19	51	(7.53)	.44
90/-1L2	18	59	(8.66)	.53
90/-1L3	17	48	(7.08)	.43
90/-1L4	18	52	(7.55)	.44
90/-1L5	15	57	(8.35)	.49
90/-1L6	15	56	(8.15)	.44
90/-1L7	14	54	(7.96)	.46
90/0L1	4.2	38	(5.66)	.35
90/0L2	3.9	38	(5.62)	.35
90/0L3	5.6	69	(10.09)	.59
90/0L4	5.5	68	(9.94)	.59
90/0L5	5.0	53	(7.75)	.49
90/0L6	5.3	63	(9.13)	.51

Table A-6. Shear Properties of $[10_6]$ AS4/3501-6 Graphite/Epoxy at Low Strain-Rates - Room Temperature

Initial Properties

Specimen Number	Strain Rate ($\dot{\gamma}_{12}$), s^{-1}	Modulus (G_{12}), GPa	(Msi)
10/-5L1	$2.0 \cdot 10^{-5}$	6.9	(1.0)
10/-5L2	$2.9 \cdot 10^{-5}$	7.0	(1.02)
10/-5L3	$2.9 . 10^{-5}$	7.2	(1.05)
10/-5L4	$2.9 \cdot 10^{-5}$	7.0	(1.02)

Ultimate Properties

Specimen Number	Time to Failure (t_f), mS	Strength (F_{12}), MPa	(Ksi)	Strain (γ_{12}^u), %
10/-5L1	-	63	(9.25)	1.06
10/-5L2	-	63	(9.24)	1.05
10/-5L3	-	66	(9.59)	1.26
10/-5L4	-	64	(9.36)	1.15

Table A-7. Shear Properties of $[10_6]$ AS4/3501-6 Graphite/Epoxy at Intermediate Strain-Rates - Room Temperature

	Initial Properties		
Specimen Number	Strain Rate ($\dot{\gamma}_{12}$), s^{-1}	Modulus (G_{12}), GPa	(Msi)
10/-3L1	$3.17 \cdot 10^{-3}$	6.5	(.94)
10/-3L2	$2.65 \cdot 10^{-3}$	7.9	(1.15)
10/-3L3	$4.00 \cdot 10^{-3}$	8.4	(1.22)
10/-3L4	$3.78 \cdot 10^{-3}$	9.0	(1.31)
10/-3L5	$1.66 \cdot 10^{-3}$	7.4	(1.08)
10/-3L6	$1.95 \cdot 10^{-3}$	7.4	(1.08)
10/-3L7	$1.81 \cdot 10^{-3}$	7.4	(1.08)
10/-2L1	$4.39 \cdot 10^{-2}$	7.5	(1.09)
10/-2L2	$5.70 \cdot 10^{-2}$	7.6	(1.11)
10/-2L4	$3.93 \cdot 10^{-2}$	7.3	(1.06)
10/-2L5	$9.24 \cdot 10^{-2}$	7.6	(1.10)
10/-2L6	$5.76 \cdot 10^{-2}$	7.7	(1.12)
10/-2L7	$5.97 \cdot 10^{-2}$	8.0	(1.16)
10/-2L9	$8.58 \cdot 10^{-2}$	8.4	(1.22)
10/-2L10	$8.58 \cdot 10^{-2}$	8.3	(1.21)

Table A-7. (Cont'd) Shear Properties of $[10_6]$ AS4/3501-6 Graphite/Epoxy at Intermediate Strain-Rates Room Temperature

	Ultimate Properties			
Specimen Number	Time to Failure (t_f), mS	Strength (F_{12}), MPa	(Ksi)	Strain (γ_{12}^u), %
10/-3L1	$3.6 \cdot 10^3$	67	(9.78)	1.28
10/-3L2	$3.1 \cdot 10^3$	59	(8.62)	.96
10/-3L3	$2.4 \cdot 10^3$	73	(10.73)	1.08
10/-3L4	$2.5 \cdot 10^3$	79	(11.59)	1.10
10/-3L5	-	83	(12.00)	1.56)
10/-3L6	-	81	(11.80)	1.55)
10/-3L7	-	82	(11.90)	1.55
10/-2L1	300	89	(12.96)	1.54
10/-2L2	182	72	(10.57)	1.24
10/-2L4	254	67	(9.84)	1.16
10/-2L5	132	76	(11.08)	1.14
10/-2L6	126	54	(7.97)	.78
10/-2L7	152	67	(9.79)	.94
10/-2L9	154	81	(11.83)	1.10
10/-2L10	168	87	(12.63)	1.28

Table A-8. Shear Properties of $[10_6]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Room Temperature

	Initial Properties		
Specimen Number	Strain Rate $(\dot{\gamma}_{12})$, s^{-1}	Modulus (G_{12}) GPa	(Msi)
10/-1L1	$1.21 \cdot 10^{-1}$	8.3	(1.20)
10/1L2	$1.29 \cdot 10^{-1}$	7.6	(1.11)
10/-1L3	$3.79 \cdot 10^{-1}$	8.4	(1.22)
10/-1L4	$3.79 \cdot 10^{-1}$	8.4	(1.22)
10/-1L5	$3.80 \cdot 10^{-1}$	8.4	(1.22)
10/0L1	2.60	8.3	(1.20)
10/0L2	2.75	8.5	(1.23)
10/0L3	3.02	8.9	(1.29)
10/0L5	3.58	9.1	(1.32)
10/0L6	3.04	9.4	(1.37)
10/0L7	3.15	9.1	(1.32)
10/0L8	1.10	9.4	(1.36)

Table A-8. (Cont'd) Shear Properties of $[10_6]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Room Temperature

Specimen Number	Time to Failure (t_f), mS	Strength (F_{12}), MPa	(Ksi)	Strain (γ_{12}^u), %
	Ultimate Properties			
10/-1L1	80	71	(10.42)	1.09
10/-1L2	88	74	(10.75)	1.12
10/-1L3	-	90	(13.00)	1.45
10/-1L4	-	87	(12.60)	1.27
10/-1L5	-	88	(12.85	1.36
10/0L1	5.3	71	(10.34)	.96
10/0L2	5.8	76	(11.08)	1.03
10/0L3	5.8	78	(11.36)	1.13
10/0L5	6.7	90	(13.14)	1.30
10/0L6	6.4	90	(13.14)	1.12
10/0L7	6.4	91	(13.28)	1.25
10/0L8	22	77	(11.28)	1.02

Table A-9. Tensile Properties of $[0_6]$ AS4/3501-6 Graphite/Epoxy at Low Strain-Rates - Elevated Temperature 128°C (263°F)

Initial Properties

Specimen Number	Strain Rate $(\dot{\varepsilon}_{11})$, S^{-1}	Modulue (E_{11}), GPa	(Msi)	Poisson's Ratio (ν_{12})
0/-4H1	$2.95 \cdot 10^{-4}$	148	(21.60)	.284
0/-4H2	$3.24 \cdot 10^{-4}$	144	(20.93)	.273
0/-4H3	$3.16 \cdot 10^{-4}$	150	(21.80)	.297
0/-4H4	$3.32 \cdot 10^{-4}$	147	(21.45)	.282

Ultimate Properties

Specimen Number	Time to Failure (t_f), S	Strength (F_{1T}), MPa	(Ksi)	Strain (ε^u_{1T}), %
0/-4H1	50	2397	(348)	1.46
0/-4H2	51	2328	(338)	1.48
0/-4H3	48	2246	(326)	1.38
0/-4H4	52	2405	(349)	1.44

Table A-10. Tensile Properties of $[0_6]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Elevated Temperature 128°C (263°F)

Initial Properties

Specimen Number	Strain Rate $(\dot{\varepsilon}_{11})$, S^{-1}	Modulus (E_{11}), GPa	(Msi)	Poisson's Ratio, (ν_{12})
0/0H1	.96	160	(23.3)	.298
0/0H2	.95	158	(23.0)	.304
0/0H3	1.05	161	(23.5)	.286
0/0H4	1.04	157	(22.8)	.275
0/0H5	.90	157	(22.8)	.300
0/0H6	.94	159	(23.1)	.287

Ultimate Properties

Specimen Number	Time to Failure (t_f), mS	Strength (F_{1T}), MPa	(Ksi)	Strain (ε^u_{1T}), %
0/0H1	21	2439	(354)	1.37
0/0H2	21	2445	(355)	1.40
0/0H3	14	2321	(337)	1.33
0/0H4	15	2425	(352)	1.43
0/0H5	13	2204	(320)	1.11
0/0H6	13	2135	(310)	1.23

Table A-11. Tensile Properties of $[90_8]$ AS4/3501-6 Graphite/ Epoxy at Low Strain-Rates - Elevated Temperature 128°C (263°F)

	Initial Properties		
Specimen Number	Strain Rate $(\dot{\varepsilon}_{22})$, S^{-1}	Modulus (E_{22}), GPa (Msi)	Poisson's Ratio (ν_{21})
90/-6H1	$5.05 \cdot 10^{-6}$	7.7 (1.12)	-
90/-6H2	$5.05 \cdot 10^{-6}$	7.9 (1.15)	-
90/-6H3	$5.05 \cdot 10^{-6}$	8.4 (1.22)	-
90/-6H4	$5.05 \cdot 10^{-6}$	7.8 (1.13)	-
90/-6H5	$5.05 \cdot 10^{-6}$	8.9 (1.29)	-
90/-5H1	$4.75 \cdot 10^{-5}$	8.7 (1.27)	-
90/-5H2	$4.75 \cdot 10^{-5}$	8.9 (1.30)	-
90/-5H3	$4.75 \cdot 10^{-5}$	7.4 (1.08)	-
90/-5H4	$4.75 \cdot 10^{-5}$	7.8 (1.13)	-
90/-5H5	$4.75 \cdot 10^{-5}$	8.3 (1.20)	-
90/-4H1	$4.97 \cdot 10^{-4}$	9.3 (1.35)	-
90/-4H2	$4.97 \cdot 10^{-4}$	8.9 (1.29)	-
90/-4H3	$4.97 \cdot 10^{-4}$	9.0 (1.31)	-
90/-4H4	$4.97 \cdot 10^{-4}$	9.3 (1.35)	-
90/-4H5	$4.97 \cdot 10^{-4}$	9.4 (1.36)	-

Table A-11. (Cont'd) Tensile Properties of $[90_8]$ AS4/3501-6 Graphite/Epoxy at Low Strain-Rates - Elevated Temperature 128°C (263°F)

Ultimate Properties

Specimen Number	Time to Failure (t_f), S	Strength (F_{2T}), MPa	(Ksi)	Strain (ε^u_{2T}), %
90/-6H1	1325	46	(6.71)	.64
90/-6H2	1250	44	(6.41)	.61
90/-6H3	1332	48	(7.01)	.64
90/-6H4	1285	45	(6.66)	.66
90/-6H5	1140	42	(6.12)	.54
90/-5H1	124	51	(7.44)	.62
90/-5H2	136	53	(7.72)	.67
90/-5H3	131	48	(7.04)	.67
90/-5H4	145	52	(7.61)	.68
90/-5H5	146	52	(7.64	.69
90/-4H1	11	54	(7.87)	.63
90/-4H2	14	57	(8.37)	.72
90/-4H3	13	57	(8.40)	.70
90/-4H4	12	57	(8.29)	.69
90/-4H5	12	57	(8.35)	.67

Table A-12. Tensile Properties for $[90_8]$ AS4/3501-6 Graphite/Epoxy at Intermediate Strain-Rates - Elevated Temperature 128°C (263°F)

	Initial Properties		
Specimen Number	Strain Rate ($\dot{\varepsilon}_{22}$), S^{-1}	Modulus (E_{22}), GPa (Msi)	Poisson's Ratio (ν_{21})
90/-3H1	$4.90 \cdot 10^{-3}$	8.5 (1.23)	-
90/-3H2	$4.90 \cdot 10^{-3}$	8.8 (1.28)	-
90/-3H3	$4.90 \cdot 10^{-3}$	9.1 (1.32)	-
90/-3H4	$4.90 \cdot 10^{-3}$	8.9 (1.29)	-
90/-3H5	$4.90 \cdot 10^{-3}$	9.5 (1.38)	-
90/-2H1	$4.80 \cdot 10^{-2}$	9.1 (1.32)	-
90/-2H2	$4.80 \cdot 10^{-2}$	8.9 (1.29)	-
90/-2H3	$4.80 \cdot 10^{-2}$	9.4 (1.37)	-
90/-2H4	$4.80 \cdot 10^{-2}$	9.3 (1.35)	-
90/-2H5	$4.80 \cdot 10^{-2}$	9.2 (1.34)	-

Table A-12. (Cont'd) Tensile Properties for $[90_8]$ AS4/3501-6 Graphite/Epoxy at Intermediate Strain-Rates - Elevated Temperature 118°C (263°F)

	Ultimate Properties			
Specimen Number	Time to Failure (t_f), mS	Strength (F_{2T}), MPa	(Ksi)	Strain (ε^u_{2T}), %
90/-3H1	$1.4 \cdot 10^3$	60	(8.84)	.73
90/-3H2	$1.4 \cdot 10^3$	60	(8.85)	.71
90/-3H3	$1.3 \cdot 10^3$	56	(8.18)	.64
90/-3H4	$1.3 \cdot 10^3$	57	(8.30)	.67
90/-3H5	$1.4 \cdot 10^3$	61	(8.91)	.68
90/-2H1	122	60	(8.84)	.65
90/-2H2	139	61	(8.91)	.72
90/-2H3	119	55	(8.09)	.61
90/-2H4	120	56	(8.21)	.62
90/-2H5	127	58	(8.55)	.65

Table A-13. Tensile Properties for $[90_8]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Elevated Temperature 128°C (263°F)

	Initial Properties		
Specimen Number	Strain Rate $(\dot{\varepsilon}_{22})$, S^{-1}	Modulus (E_{22}), GPa (Msi)	Poisson's Ratio (ν_{21})
90/-1H1	$5.3 \cdot 10^{-1}$	9.5 (1.38)	-
90/-1H2	$5.3 \cdot 10^{-1}$	9.4 (1.37)	-
90/-1H3	$5.3 \cdot 10^{-1}$	9.4 (1.36)	-
90/-1H4	$5.3 \cdot 10^{-1}$	8.7 (1.26)	-
90/-1H5	$5.3 \cdot 10^{-1}$	9.2 (1.33)	-
90/0H1	1.52	11.4 (1.65)	.0156
90/0H2	3.27	11.5 (1.67)	.0161
90/0H3	3.54	11.7 (1.70)	.0159
90/0H4	3.64	11.2 (1.63)	.0154

Table A-13. (Cont'd) Tensile Properties for $[90_8]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Elevated Temperature 128°C (263°F)

	Ultimate Properties			
Specimen Number	Time to Failure (t_f), mS	Strength (F_{2T}), MPa	(Ksi)	Strain (ε^u_{2T}), %
90/-1H1	13	63	(9.28	.68
90/-1H2	11	60	(8.74)	.63
90/-1H3	11	60	(8.73)	.65
90/-1H4	12	64	(9.42)	.71
90/-1H5	11	59	(8.68)	.62
90/0H1	4.1	70	(10.2)	.61
90/0H2	1.8	64	(9.4)	.56
90/0H3	2.4	63	(9.2)	.53
90/0H4	1.9	64	(9.3)	.57

Table A-14. Shear Properties of $[10_6]$ AS4/3501-6 Graphite/Epoxy at Low Strain-Rates - Elevated Temperature 128°C (263°F)

Initial Properties

Specimen Number	Strain Rate $(\dot{\gamma}_{12})$, s^{-1}	Modulus (G_{12}), GPa	(Msi)
10/-5H1	$2.60 \cdot 10^{-5}$	6.6	(.96)
10/-4H1	$1.12 \cdot 10^{-4}$	7.1	(1.03)
10/-4H2	$2.10 \cdot 10^{-4}$	7.5	(1.09)

Ultimate Properties

Specimen Number	Time to Failure (t_f), s	Strength (F_{12}), MPa	(Ksi)	Strain (γ^u_{12}), %
10/-5H1	935	60	(8.74)	1.26
10/-4H1	31	63	(9.21)	1.48
10/-4H2	25	62	(9.12)	1.39

Table A-15. Shear Properties of $[10_6]$ AS4/3501-6 Graphite/ Epoxy at Intermediate Strain-Rates - Elevated Temperature 128°C (263°F)

Initial Properties

Specimen Number	Strain Rate $(\dot{\gamma}_{12})$, S^{-1}	Modulus (G_{12}), GPa	(Msi)
10/-2H1	$6.60 \cdot 10^{-2}$	7.2	(1.05)
10/-2H2	$7.70 \cdot 10^{-2}$	8.4	(1.22)
10/-2H3	$7.00 \cdot 10^{-2}$	9.5	(1.38)
10/-2H4	$7.90 \cdot 10^{-2}$	7.6	(1.11)
10/-2H5	$8.78 \cdot 10^{-2}$	8.3	(1.21)
10/-2H6	$1.05 \cdot 10^{-2}$	7.2	(1.05)
10/-2H7	$3.20 \cdot 10^{-2}$	7.5	(1.09)
10/-2H8	$4.03 \cdot 10^{-2}$	6.9	(1.00)

Ultimate Properties

Specimen Number	Time to Failure (t_f), mS	Strength (F_{12}), MPa	(Ksi)	Strain (γ_{12}^u), %
10/-2H1	232	64	(9.40)	1.74
10/-2H2	174	68	(9.87)	1.72
10/-2H3	158	56	(8.15)	1.01
10/-2H4	164	59	(8.68)	1.54
10/-2H5	168	66	(9.58)	1.67
10/-2H6	1314	61	(8.95)	1.38
10/-2H7	510	67	(9.80)	1.45
10/-2H8	370	69	(10.10)	1.65

Table A-16. Shear Properties for $[10_6]$ AS4/3501-6 Graphite/Epoxy at High Strain-Rates - Elevated Temperature 128°C (263°F)

	Initial Properties	
Specimen Number	Strain Rate ($\dot{\gamma}_{12}$), s^{-1}	Modulus (G_{12}), GPa (Msi)
10/-1H1	$4.33 \cdot 10^{-1}$	8.7 (1.27)
10/-1H2	$3.40 \cdot 10^{-1}$	9.3 (1.35)
10/-H3	$1.00 \cdot 10^{-1}$	9.2 (1.34)
10/-1H4	$1.63 \cdot 10^{-1}$	9.5 (1.38)
10/0H1	5.00	10.6 (1.54)
10/0H2	5.00	10.9 (1.58)
10/0H3	2.20	11.6 (1.68)
10/0H4	2.00	10.6 (1.54)
10/0H5	2.43	10.1 (1.47)
10/0H6	2.23	9.8 (1.42)

Table A-16. (Cont'd) Shear Properties for $[10_6]$ AS4/350106 Graphite/Epoxy at High Strain-Rates - Elevated Temperature 128°C (263°F)

	Ultimate Properties			
Specimen Number	Time to Failure (t_f), mS	Strength (F_{12}), MPa	(Ksi)	Strain (γ_{12}^u), %
10/-1H1	40	67	(9.77)	1.51
10/-1H2	36	67	(9.76)	1.30
10/-1H3	220	65	(9.45)	1.30
10/-1H4	132	61	(8.97)	1.44
10/0H1	4	84	(12.20)	1.87
10/0H2	3	70	(10.30)	1.22
10/0H3	4	86	(12.60)	1.87
10/0H4	9	86	(12.50)	1.95
10/0H5	8	82	(11.99)	1.88
10/0H6	8	88	(12.90)	1.98

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A unidirectional graphite/epoxy material (AS4/3501-6) was characterized at strain rates ranging from 5×10^{-6} s^{-1} to 5 s^{-1}, at room temperature and at 128 °C (263 °F). Results are presented in the form of stress-strain curves to failure. The longitudinal properties remain nearly unchanged with strain rate and temperature. The transverse modulus increases with strain rate but decreases with temperature. The transverse strength and transverse ultimate tensile strain have a positive rate sensitivity at low rates which changes to negative at intermediate rates and returns to positive rate sensitivity at the highest rates tested. A temperature-time equivalence principle was applied and master curves were obtained for the transverse mechanical properties. The in-plane shear modulus and in-plane shear strength have a positive rate sensitivity. The ultimate intralaminar shear strain has a positive rate sensitivity at low rates, which changes to negative at high rates. At the elevated temperature of 128 °C (263 °F) the ultimate shear strain is 25-30% higher than the room-temperature value, but its strain rate dependence is moderate.

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