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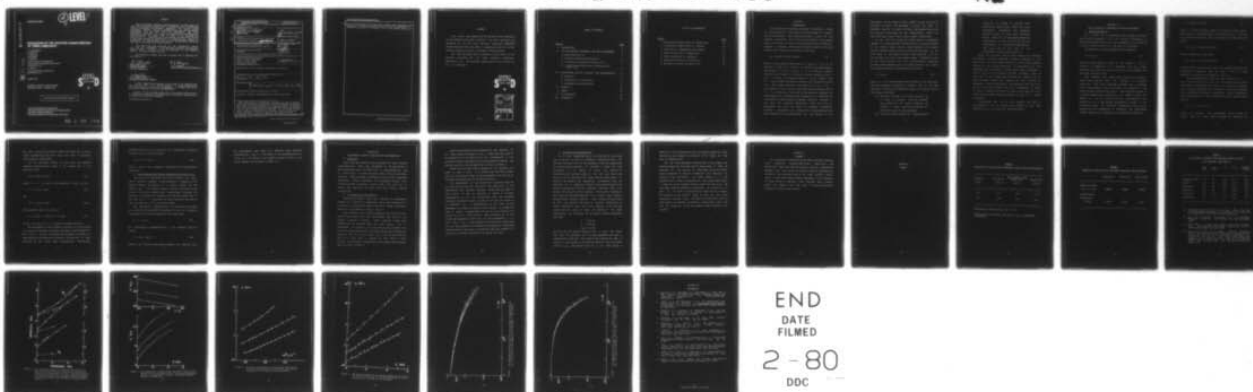
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EVALUATION OF THE TRACTON CHARACTERISTICS OF THREE LUBRICANTS.(U)
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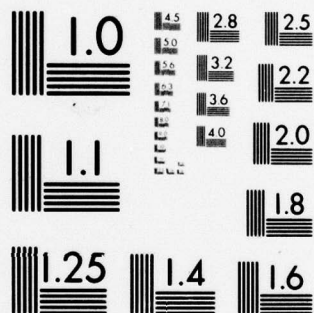
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EVALUATION OF THE TRACTION CHARACTERISTICS OF THREE LUBRICANTS

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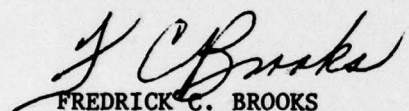
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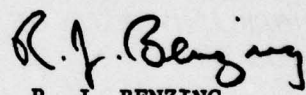
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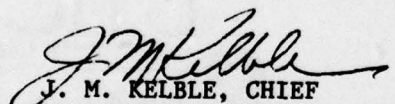
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in all three fluids and in one case a rather broad relaxation time spectrum. The other viscoelastic factors that are important in determining traction are found to be in a quite normal range. ←

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PREFACE

This report was prepared by the Vitreous State Laboratory of The Catholic University of America. The work described was sponsored by the Air Force Materials Laboratory (AFML/MBT) Wright-Patterson AFB, Ohio 45433 in cooperation with the Office of Naval Research, Code 473, Arlington, Virginia 22271.

The work described herein represents a joint effort of The Catholic University and the Naval Research Laboratory, Washington, DC. The principal investigator on the project was Dr. C. J. Montrose.

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SECTION I

INTRODUCTION

In 1976 Montrose, Moynihan and Sasabe¹ presented a model for the behavior of a viscoelastic fluid entrained in a concentrated line contact. Their calculation gave a result for the traction coefficient (the ratio of the tractive to the normal force) at low slip in terms of an average effective viscosity $\bar{\mu}$. Assuming a Hertzian semi-elliptic pressure profile in the EHD contact their result can be written in the form

$$C_T = (8R/\pi hE) [2\bar{\mu}/t_0] (\Delta U/U). \quad (1)$$

Here C_T is the traction coefficient, $R = R_1 R_2 / (R_1 + R_2)$ is an effective radius for the disk pair (simple twin disk geometry was assumed), of radii R_1 and R_2 , E is an effective elastic modulus for the disks (E is related to Young's modulus E_0 by $E = E_0 (1 - \nu^2)$ where ν is Poisson's ratio), t_0 is the transit time of a fluid element through the contact, the thickness of which is $2h$. The average velocity of the disks is U , i.e., $U = (U_1 + U_2)/2$ where U_1 and U_2 are the individual disk velocities, and $\Delta U = U_1 - U_2$ is the slip. The thrust of the Montrose, Moynihan and Sasabe paper was to determine what properties of a lubricant are instrumental in determining the average effective viscosity $\bar{\mu}$ and thus the traction coefficient. With this kind of information one could (at least in principle) molecularly engineer a lubricant with viscoelastic characteristics that would optimize $\bar{\mu}$ and concomitantly C_T . The details of the

calculation do not concern us here (indeed a recent revision of the model by Heyes and Montrose² in which the result is expressed entirely in terms of directly measureable quantities will be used in this paper for the calculations); rather, we shall make use of only a few of their general conclusions.

As the lubricant enters the contact zone it is subjected suddenly to a large pressure increase causing structural changes in the liquid; these lead to a large increase in the characteristic liquid relaxation times of the fluid and thus, on the time scale of the process (transit times typically $\sim 10^{-4}$ s), the lubricant acts like a solid shear stress transmitting pad. If one could presume that this liquid-to-glass transition occurred instantaneously upon the fluid's entering the contact the average effective viscosity would be given by

$$\bar{\mu} = G_{\infty} t_0 / 2, \quad (2)$$

where G_{∞} is the instantaneous shear rigidity of the lubricant. From the standpoint of maximizing traction this is the most desirable situation and immediately leads to two general lubricant design principles:

- (1) The shear rigidity of the fluid G_{∞} should be as large as possible. Since G_{∞} increases with pressure as the liquid traverses the contact, a large value of the pressure coefficient $\partial G_{\infty} / \partial P$ is also desirable.
- (2) The fluid should undergo the liquid-to-glass

transition as rapidly as possible after entering the contact zone. There are three viscoelastic parameters that primarily control the rate at which this transition occurs: these are (a) the pressure-viscosity coefficient, $\alpha = \partial(\ln \eta)/\partial P$; (b) the ratio of instantaneous to equilibrium compressibilities κ_{∞}/κ_0 ; and (c) the form of the viscoelastic relaxation function $\phi(t)$.

There are, of course, several other factors that influence the behavior. From the viewpoint of simply maximizing $\bar{\mu}$, one would want the inlet shear viscosity η_0 to be large; however, insofar as η_0 is of major importance in determining the film thickness, one is limited to a rather small range of feasible η_0 values. The ratio of structural to shear relaxation times is also one of the factors that determines $\bar{\mu}$. However, for the type of organic fluids that satisfy the other criteria of acceptable traction performance, one generally finds this ratio to lie in the range of about one to ten. Attempting to design or find a material for which the ratio is less than 10^{-2} or so (which would increase traction somewhat) is just not a viable alternative.

Consequently our aim in this research has been to characterize a set of liquids with respect to the four properties (G_{∞} , α , ϕ , and κ_{∞}/κ_0) described above.

SECTION II

THE VISCOELASTIC PARAMETERS AND THEIR MEASUREMENT

A. Shear Rigidity, G_∞ .

For a given set of conditions (rolling speed, slip-roll ratio, Hertzian pressure, etc.) the traction coefficient is essentially proportional to G_∞ , and consequently it is desirable to have as large a value of G_∞ (and $\partial G_\infty / \partial P$) as possible.

To measure G_∞ we take advantage of the expression

$$G_\infty = \rho V_{T,\infty}^2, \quad (3)$$

giving the shear modulus in terms of the density ρ and the velocity of propagation of a transverse wave $V_{T,\infty}$, under conditions for which the period of the wave is much shorter than the shear relaxation time.

High frequency wave speeds (both transverse and longitudinal) were measured using the technique of Brillouin scattering. Here one illuminates the sample with a collimated beam of monochromatic light and observes the spectrum of the light scattered through some angle θ . This spectrum consists of a triplet symmetrically placed about the incident light frequency, ω_0 ; the two shifted Brillouin lines appear at frequencies $\omega_0 \pm \omega_L$ if the incident polarization is normal to the scattering plane. The Brillouin frequencies ω_T and ω_L give, respectively, the frequencies of transverse and longitudinal thermal phonons with a wavevector k satisfying the condition

$$k = (4\pi n/\lambda) \sin(\theta/2) \quad (4)$$

where n is the refractive index of the material under investigation and λ is the wavelength of the incident light. Thus from the measured Brillouin shifts one obtains the transverse wave speed

$$V_T = \omega_T/k = (\omega_T \lambda / 4\pi n) / \sin(\theta/2) \quad (5)$$

and the longitudinal wave speed

$$V_L = \omega_L/k = (\omega_L \lambda / 4\pi n) / \sin(\theta/2). \quad (6)$$

At sufficiently high pressures and/or low temperatures where the viscoelastic relaxation times are long ($> 10^{-9}$ s), these approach the limiting wave speeds $V_{T,\infty}$ and $V_{L,\infty}$.

In our measurements an argon ion laser operating at $\lambda = 514.5$ nm was used as the source and a piezoelectrically scanned Fabry-Perot interferometer was used as the spectrum analyzer. The scattering angle was 90° . Refractive indices were measured using a modified Abbe-Grauer refractometer. These measurements were extrapolated to high pressures using the Lorenz-Lorentz formula

$$(n^2 - 1) / (n^2 + 2) = \gamma \rho,$$

where γ is a constant. The extrapolated indices agreed to within about 0.1% with values obtained by measuring the

deflection of the laser beam when a small prism was in the high pressure cell. The values of $V_{T,\infty}$ obtained are estimated to be accurate to about $\pm 1\%$. Densities were measured at atmospheric pressure to an accuracy of $\pm 0.1\%$ using a pycnometer. At elevated pressures a densitometer essentially similar to that described by McDuffie et al.³ was used to obtain values accurate to $\pm 0.2\%$. The overall precision of the measured-shear moduli is better than $\pm 3\%$.

B. Pressure-Viscosity Coefficient, α

Because large traction coefficients are obtained when the lubricant becomes glassy soon after entering the contact zone, the pressure variation of the viscosity is crucial in determining the lubricant's traction characteristics. For the materials being reported here (and for many other lubricant fluid candidates), the pressure dependence of the viscosity is described reasonably well by the simple Barus formula

$$\eta = A \exp(\alpha P),$$

where A is a constant and $\alpha = \partial(\ln \eta)/\partial P$ is called the pressure-viscosity coefficient. Shear viscosities in this work were measured at atmospheric pressure to an accuracy of ± 0.1 in $\log_{10} \eta$ using a Cannon-Fenske viscometer. At higher pressures a "falling slug" viscometer described by McDuffie and Barr⁴ was employed.

C. Viscoelastic Relaxation Function, $\phi(t)$

The dynamic response of the lubricant to shearing and compression is described by time-dependent relaxation functions. In the simplest case the relaxation functions take the form of a simple exponential decay:

$$\phi(t) = \exp(-t/\tau). \quad (7)$$

Usually this simple form is inadequate to describe the behavior and a sum or continuous distribution of such exponentials is used:

$$\phi(t) = \sum_i g_i \exp(-t/\tau_i) + \int_0^\infty d\tau g(\tau) \exp(-t/\tau). \quad (8)$$

The width of the distribution function $g(\tau)$ is an important factor in determining the traction coefficient--the narrower is $g(\tau)$, i.e., the closer $\phi(t)$ is to an exponential decay, the larger will be C_T . A convenient parameter characterizing this width is the variance B defined by

$$B = [\langle \tau^2 \rangle - \langle \tau \rangle^2]^{1/2} \langle \tau \rangle, \quad (9)$$

where

$$\langle \tau \rangle \equiv \int_0^\infty d\tau \phi(\tau) = \int_0^\infty d\tau g(\tau) \tau; \quad (10a)$$

$$\langle \tau^2 \rangle \equiv \int_0^\infty d\tau \phi(\tau) \tau^2 = \int_0^\infty d\tau g(\tau) \tau^2. \quad (10b)$$

For most traction lubricants B ranges from about one to three; values substantially less than unity will lead to unusually large traction coefficients.

For the materials studied in this work the measured relaxation functions were found to fit rather well to the empirical form⁵

$$\phi(t) = \exp[-(t/\tau_0)^\beta], \quad (11)$$

where $0 < \beta < 1$. In terms of the parameters τ_0 and β one has

$$\langle \tau \rangle = (\tau_0/\beta) \Gamma(1/\beta), \quad (12a)$$

and

$$\langle \tau^2 \rangle = (\tau_0^2/\beta) \Gamma(1/\beta). \quad (12b)$$

The relaxation width B is given by

$$B = [\beta \Gamma(2/\beta) - \Gamma(1/\beta)^2]^{1/2} / \Gamma(1/\beta). \quad (13)$$

In Eqs. (12) and (13), $\Gamma(\dots)$ denotes the gamma function.

The measurement of the relaxation function $\phi(t)$ was carried out using the technique of digital correlation spectroscopy.⁶⁻⁹ Here using a digital correlator one measures a function $F(t)$ describing the correlation of intensity fluctuations of light scattered by the liquid under investigation. The directly

measured function $F(t)$ is related to the viscoelastic relaxation function $\phi(t)$ by the relationship

$$F(t) = a + b \phi(t)^2, \quad (14)$$

where a and b are constants determined by the experimental conditions.

D. Instantaneous-Equilibrium Compressibility Ratio κ_{∞}/κ_0 .

The ratio κ_{∞}/κ_0 determines the extent to which the lubricant's structure changes "instantaneously" in response to the pressure impulse encountered as it passes through the EHD contact zone. The largest possible traction coefficient would result if the entire response were instantaneous allowing the viscosity to increase more rapidly; this behavior would occur in the limit $\kappa_{\infty}/\kappa_0 \rightarrow 1$. Typically for fluid lubricants one finds a value of about 0.5 to 0.6 to be more common.

The equilibrium compressibility was obtained by carrying out ultrasonic "sing-around" measurements of the low frequency sound speed v_0 ¹⁰ and then employing the relationship

$$\kappa_0 = 1 / \rho v_0^2. \quad (15)$$

The instantaneous compressibility κ_{∞} was obtained from the formula

$$\kappa_{\infty} = [M_{\infty} - 4G_{\infty}/3]^{-1}, \quad (16)$$

where M_{∞} , the limiting longitudinal modulus, was obtained from

the longitudinal wave speed $V_{L,\infty}$ measured using Brillouin scattering ($M_\infty = \rho V_{L,\infty}^2$). The errors in the determination of κ_0 ($\pm 2\%$), M_∞ ($\pm 2\%$) and G_∞ ($\pm 3\%$) combine so that the ratio κ_∞/κ_0 can be judged to be accurate to about $\pm 6\%$.

SECTION III

EXPERIMENTAL RESULTS, ANALYSIS AND INTERPRETATION

A. Materials

Three lubricant materials were evaluated for their traction characteristics. They were designated as (a) MLO-78-187, a MIL-L-7808 base stock, (b) MLO-77-127, a polyalphaolefin, and (c) MLO-76-136a, a narrow molecular weight (574 avg) petroleum fraction. These materials, provided by the Air Force Materials Laboratory, Fluids, Lubricants and Elastomers Branch, were filtered through a Millipore filter (pore size 0.65 μm) to remove dust particles and were then used without further purification.

B. Presentation of the Results

Longitudinal modulus data were obtained at atmospheric pressure as a function of temperature and at room temperature as a function of pressure for each of the three sample materials. These data are presented in Figs. 1 and 2.

Shear modulus data could be obtained only for two of the three liquids (MLO-77-127 and MLO-76-136a) and only at the highest pressures studied. Lower pressure values were extrapolated by assuming that the ratio $G_{\infty}/(M_{\infty} - M_0)$ is independent of pressure as is the case for many liquids. For the third liquid, MLO-78-187, the shear modulus was estimated by assuming that the ratio $G_{\infty}/(M_{\infty} - M_0) \approx 0.35$ as was found for MLO-77-127. This value is typical of that found in many liquids. The measured, extrapolated and estimated shear modulus data are given in Table I.

Density measurements versus temperature and pressure for the three liquids are shown in Fig. 3. These data were used in the computation of the moduli and in the extrapolation of the refractive indices according to the Lorenz-Lorentz formula. The relevant data for this extrapolation are given in Table 2.

Shear viscosity data versus temperature and pressure are shown in Figs. 4 and 5. It is evident from the latter figure that over the pressure range of the measurements the data can be described reasonably well by the Barus formula.

The measurements of the viscoelastic relaxation function $\phi(t)$ were carried out for MLO-78-187 and MLO-77-127 at low temperatures and elevated pressures. These data are shown in Figs. 6 and 7. It was not possible to obtain an accurate determination of $\phi(t)$ for MLO-76-136a since the scattered intensity increased by nearly a factor of ten over the course of an eight-hour run. A determination of the cause of this phenomenon is outside the scope of this program. An attempt was made to obtain an approximate form for $\phi(t)$ by carrying out a "quick" run at 21° C and 0.48 GPa. These data were fit to the fractional exponential form in Eq. (11) with parameters $\tau_0 = 8 \times 10^{-5}$ s and $\beta = 0.4$. In the analysis given below the forms found for $\phi(t)$ were assumed to be pressure and temperature independent and the pressure variation of relaxation times was assumed to be similar to the shear viscosity as is usually the case.

C. Analysis and Interpretation

As we have emphasized above, the objective of this study was to evaluate, in terms of fundamental viscoelastic data, the traction characteristics of the candidate fluids for application to rolling bearing analysis. To establish a basis for this evaluation, it is useful to recall the results of characterization studies similar to this one that have been carried out on lubricants with large traction coefficients. In Table III we summarize the appropriate viscoelastic data for Santotrac 40 (a commercial traction fluid manufactured by the Monsanto Corporation) and the synthetic lubricant 5P4E (five phenyl rings joined by ether bridges). We have also included in this table the corresponding data for a short chain methyl-phenylsiloxane polymer MPS-710. (Dow Corning silicone fluid No. 710). The slopes of the plots of traction coefficient C_T versus slide-roll ratio $\Delta U/U$ were computed in the low slip region using the model of Heyes and Montrose.² For these computations the following set of typical external parameters were used:

$$R = 1.91 \text{ cm}$$

$$E = 233 \text{ GPa}$$

$$P_{HZ} = 1.0 \text{ GPa}$$

The fact that the traction slope of 5P4E is about 30% higher than that of Santotrac 40 is in rough agreement with what is experimentally observed. The larger value obtained for 5P4E is primarily attributable to the smaller value of B and the larger value of κ_∞/κ_0 . The smaller value of G_∞ for 5P4E causes a

reduction in the difference of the two traction slopes (if equal values of G_0 are assumed, the traction is 50% larger for 5P4E than for Santotrac 40).

For the three materials characterized in this report, the traction slopes are less than half of those found in 5P4E and Santotrac 40. The origins of these lower values are rather easily understood in terms of a comparison with Santotrac 40. Consider first MLO-78-187. Its shear modulus is 1.1 GPa compared with 1.9 GPa for Santotrac 40. This alone would effect a reduction of the computed traction slope from 102 to 61. The very small pressure viscosity coefficient for MLO-78-187 (15 GPa^{-1} vs. 40 GPa^{-1} for Santotrac 40) leads also to a roughly 50% reduction in the traction slope as does the very broad relaxation function width. For MLO-77-127 and MLO-76-136a the shear moduli are somewhat, although not drastically, lower than that for Santotrac 40 and this leads to some reduction in the traction.

SECTION IV

SUMMARY

The viscoelastic properties of the three potential traction fluid candidates studied--MLO-78-187, MLO-77-127, and MLO-76-136a --have been found to predict traction coefficients somewhat less than those of the best traction lubricants now available. The principal cause of the lower traction coefficients is the rather small pressure dependence of the viscosity for these fluids; in addition, their measured shear rigidity moduli are slightly less than those in fluids specifically designed to achieve high traction.

SECTION V

TABLES

TABLE 1

SHEAR MODULI FOR THE THREE CANDIDATE LIQUIDS UNDER INVESTIGATION

Pressure (GPa)	Shear Modulus (GPa)		
	MLO-78-187 (21° C)	MLO-77-127 (22° C)	MLO-76-136a (21° C)
0.2	0.7*	1.4 ⁺	1.7 ⁺
0.4	1.1*	2.0	2.2

*Estimated by taking $G_{\infty}/(M_{\infty} - M_0) = 0.35$

⁺Extrapolated by assuming that $G_{\infty}/(M_{\infty} - M_0)$ is independent of pressure.

TABLE 2

REFRACTIVE INDEX DATA FOR THE THREE CANDIDATE LIQUIDS STUDIED

	MLO-78-187	MLO-77-127	MLO-76-136a
Refractive index (20° C, 1 atm)	1.48661	1.49301	1.48975
Lorenz-Lorentz coefficient, γ (cm ³ /g)	0.3090	0.3491	0.3371

TABLE 3
VISCOELASTIC PARAMETERS AND COMPUTED TRACTION SLOPES
FOR CANDIDATE LUBRICANTS^(a)

	G_{∞} (GPa)	α (GPa ⁻¹)	B	κ_{∞}/κ_0	Traction slope
Santotrac 40 ^(b)	1.9	40	1.33	0.5	102
5P4E ^(c)	1.6	45	0.88	0.74	129
MPS-710 ^(d)	1.4	45	≥ 2.5 ~	0.52	≤ 45
MLO-78-187	0.7	14	7.5	0.66	18
MLO-77-127	1.4	16.5	1.4	0.58	48
MLO-76-136a	1.7	23	2.1	0.41	50

- (a) Parameters given are for 20° C, 0.2 GPa. Where data was not specifically available at this pressure it was obtained by extrapolation from higher or lower pressure.
- (b) Data from R. Moeller, R. Meister, and C. J. Montrose, Technical Report #8, ONR Contract No. N0017-75-C-0585 (1978).
- (c) Data from J. F. Dill, P. W. Drake, and T. A. Litovitz, Trans. ASLE 18, 209 (1975); Tech. Reports Nos. 2 and 3, ONR Contract N00017-67-A-0377-0018.
- (d) Data from B. Dom, Ph. D. thesis, Catholic University (1977). The form of $\phi(t)$ is found to be a superposition of that given in Eq. (11) with $\beta \approx 0.40$ plus a long time tail varying as t^{-n} with $n \approx 0.25$. This latter feature was neglected in the computation of B and of the traction slope. The traction slope thus obtained represents an upper bound.

SECTION VI

ILLUSTRATIONS

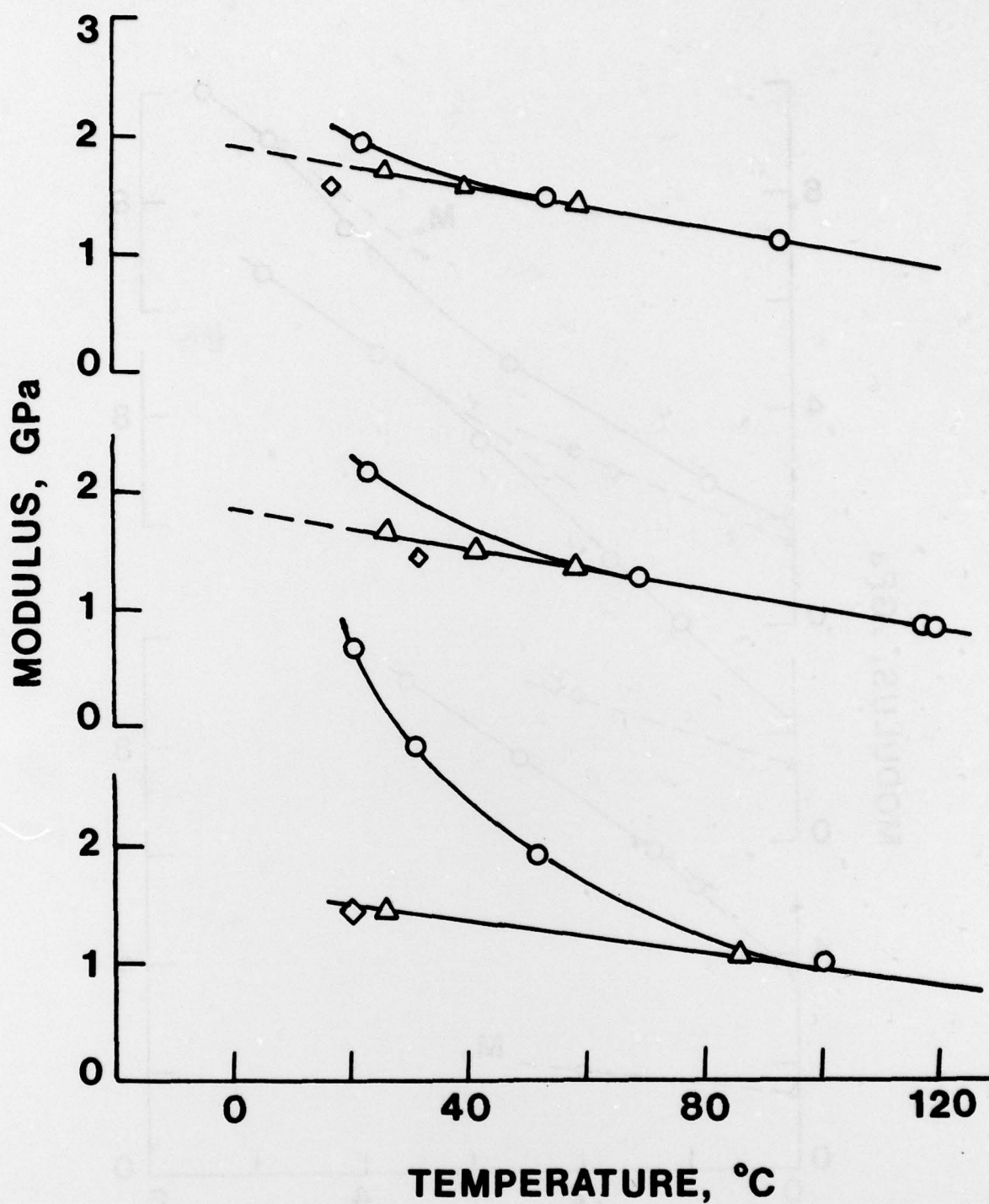


FIGURE 1. The longitudinal moduli of (reading down) ML-78-187, MLO-77-127 and MLO-87-136a are shown as a function of temperature. Triangles indicate values determined from ultrasonic velocity measurements; circles indicate values from Brillouin light scattering experiments; diamonds indicate values from density vs. pressure data (Fig. 3).

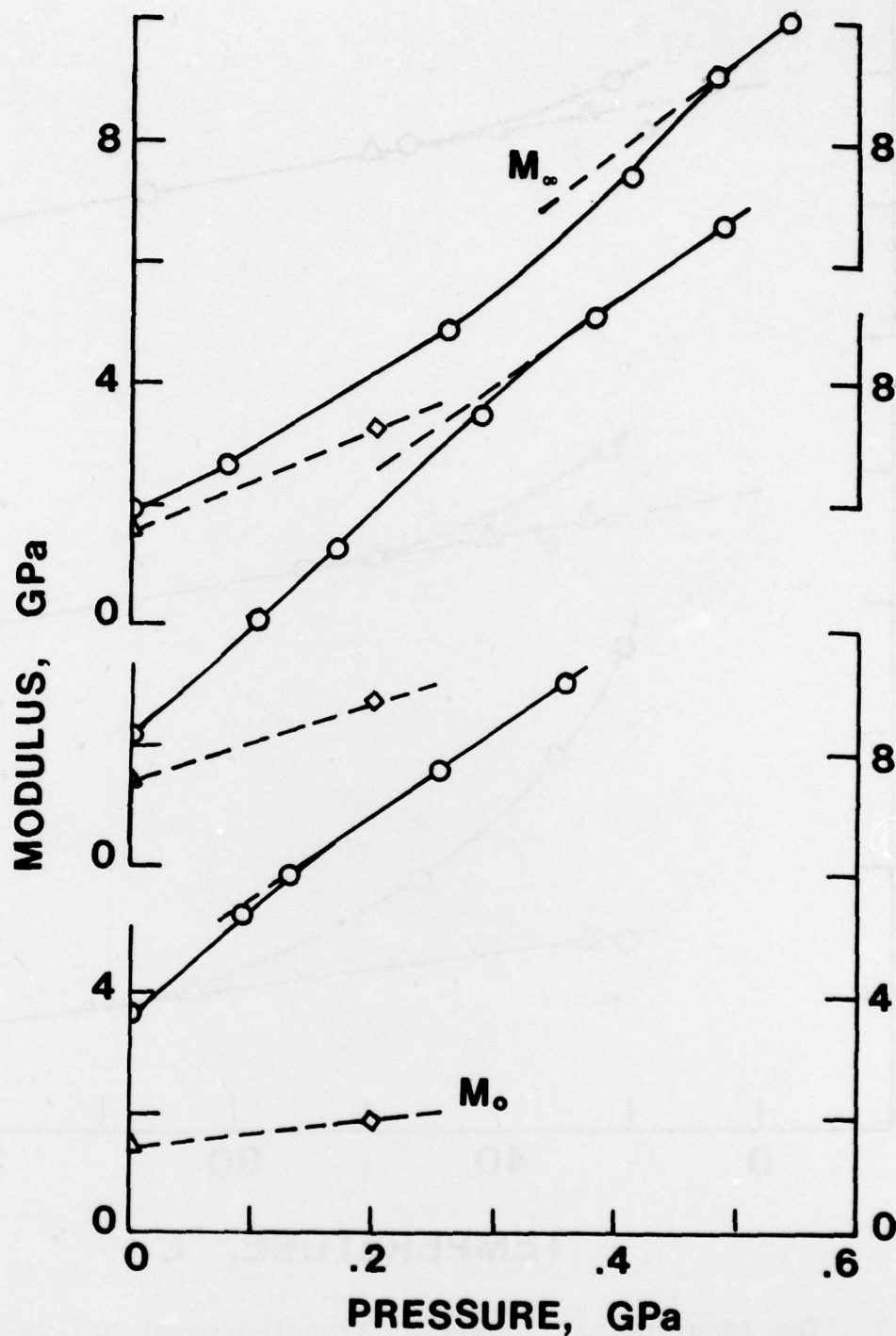


FIGURE 2. The longitudinal moduli of (reading down) MLO-78-187 MLO-77-127 and MLO-76-136a are shown as functions of pressure for a temperature of 20°C. The extrapolations of the instantaneous (M_{∞}) and equilibrium (M) moduli are shown as broken lines; diamonds indicate⁰ isothermal modulus data obtained from density vs. pressure data (Fig. 3).

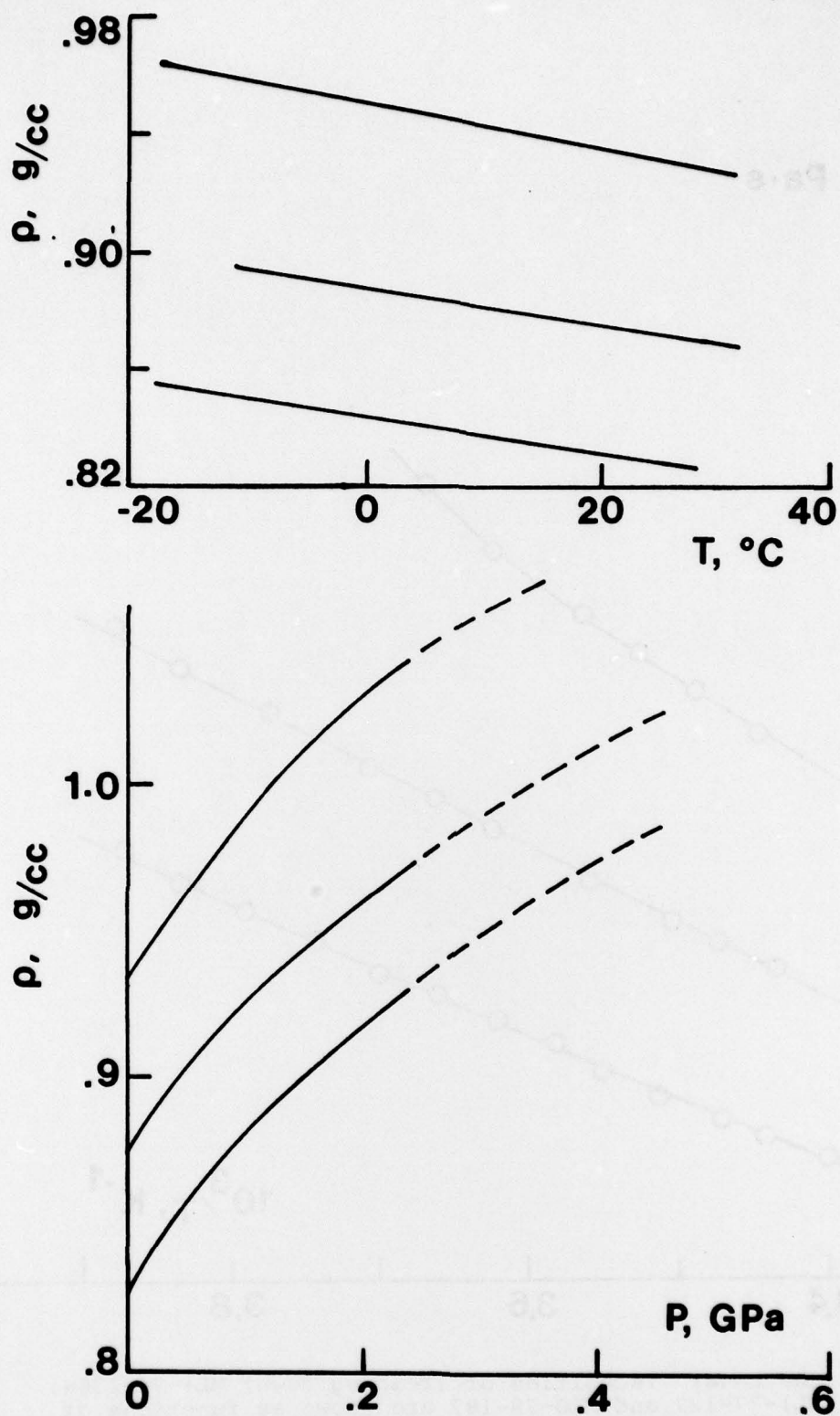


FIGURE 3. The densities of (reading down) MLO-78-187, MLO-76-136a, and MLO-77-127 are shown (a) as a function of temperature and (b) as a function of pressure. Extrapolations are shown as a broken line.

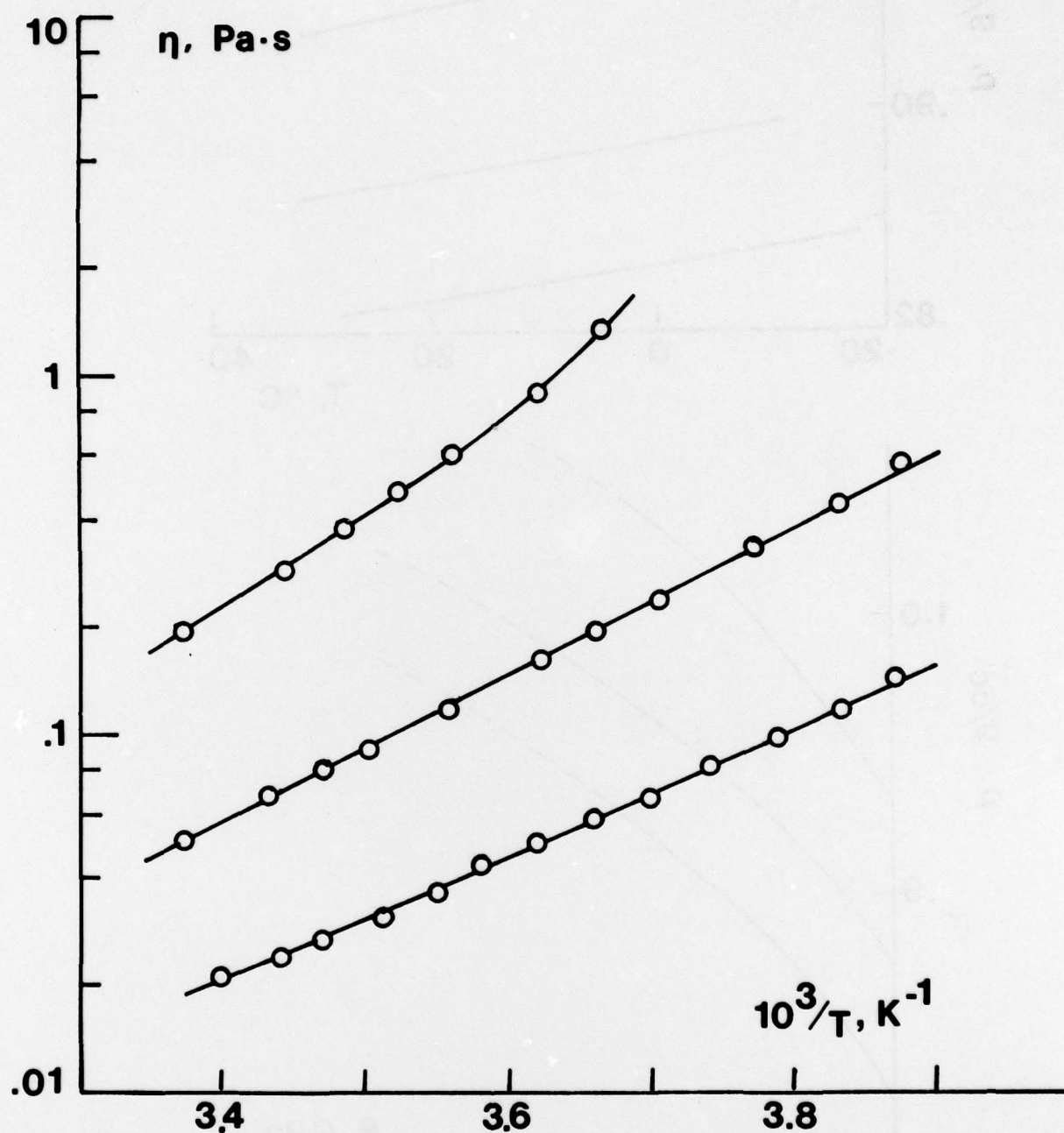


FIGURE 4. The shear viscosities of (reading down) ML)-76-136a, ML)-77-127 and MLO)-78-187 are shown as functions of temperature at a pressure of one atmosphere.

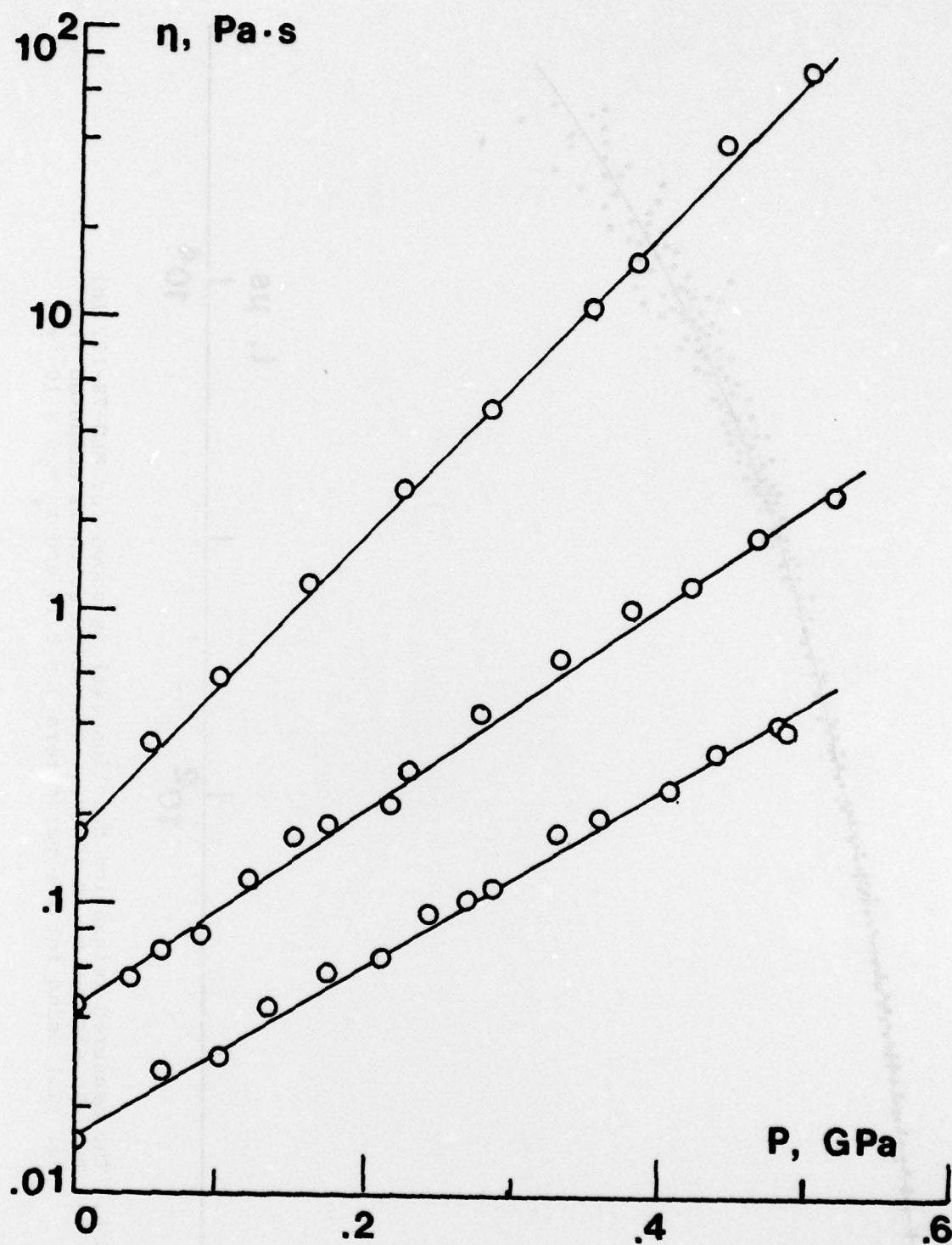


FIGURE 5. The shear viscosities of (reading down) MLO-76-136a at 24.7°C, MLO-77-127 at 23.5°C and MLO-78-187 at 23.1°C are shown as functions of the pressure.

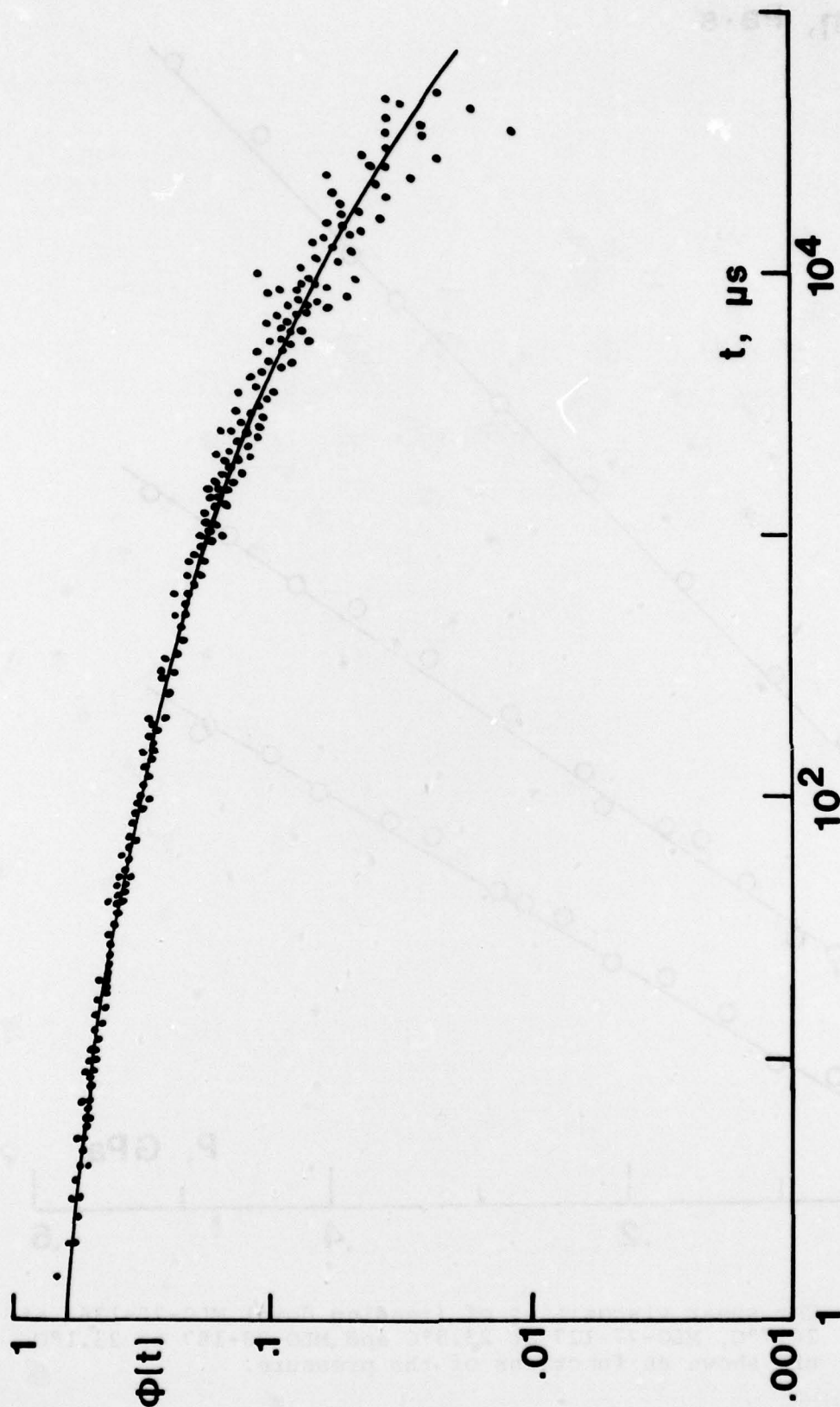


FIGURE 6. The measured relaxation function $\phi(t)$ is shown for MLO-78-187 for $T = -25.6^\circ\text{C}$ and $P = 0.49$ GPa. The solid curve is computed from Eq. (11) using for the parameters $\beta = 0.19$ and $\tau_0 = 5 \times 10^{-5}$ s.

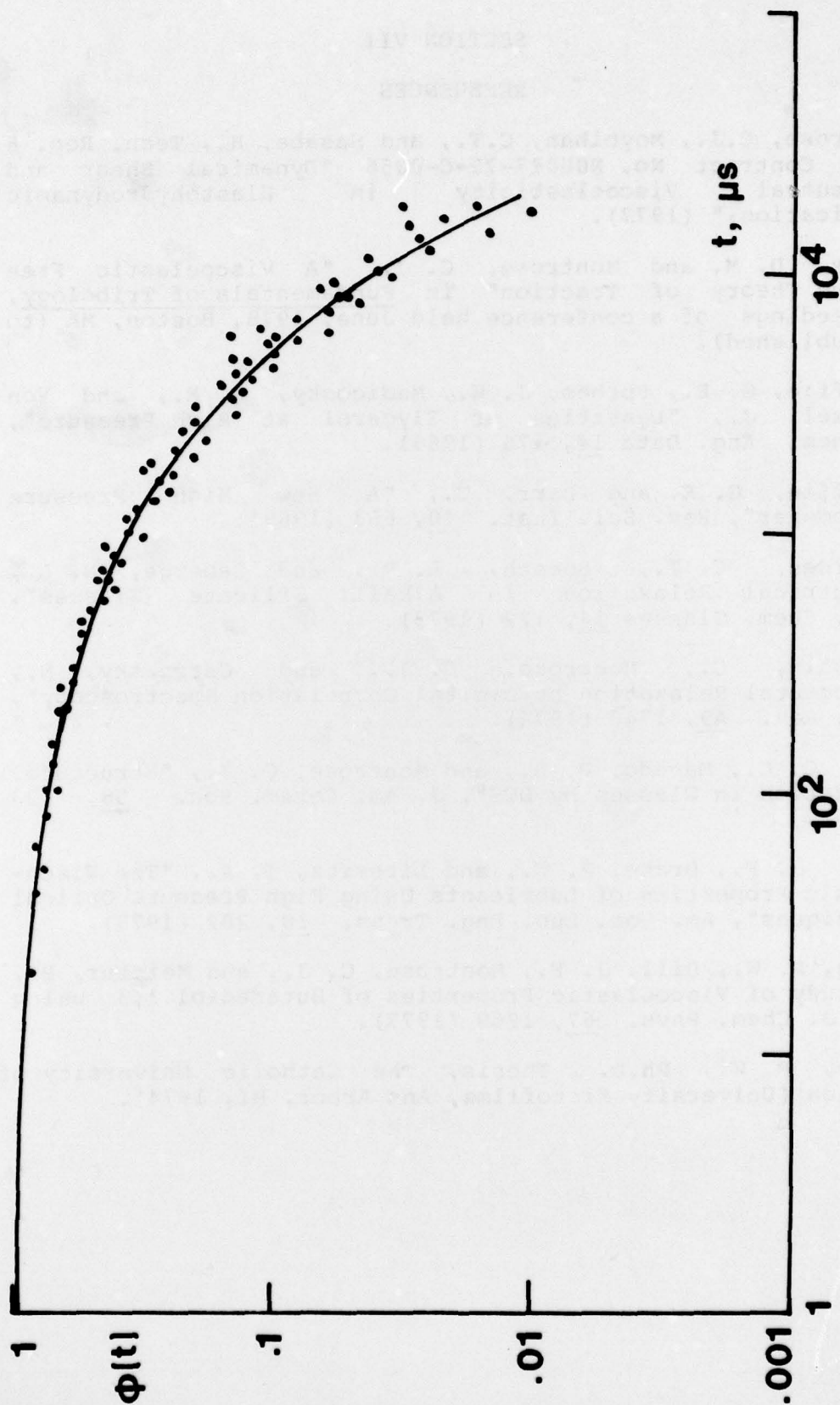


FIGURE 7. The measured relaxation function $\phi(t)$ is shown for MLO-77-127 for $T = -16^\circ\text{C}$ and $P = 0.48$ GPa. The solid curve is computed from Eq. (11) using the parameters $\beta = 0.5$ and $\tau_0 = 9.5 \times 10^{-4}$ s.

SECTION VII

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