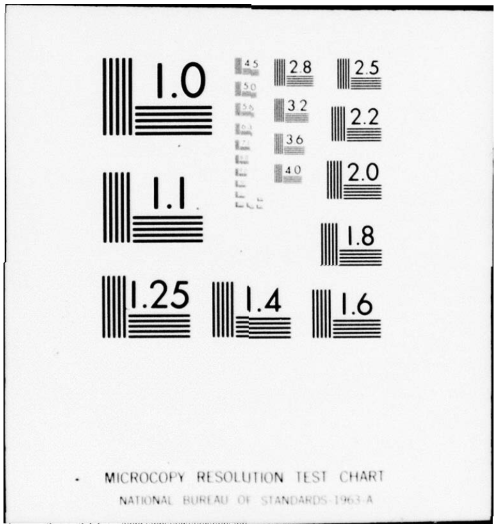
AD-A041 902 MIDWEST RESEARCH INST KANSAS CITY MO F/G 11/8
HIGH PRESSURE AND TEMPERATURE EFFECTS ON THE VISCOSITY, DENSITY--ETC(U)
DEC 76 V HOPKINS, P J HOGAN F33615-75-C-5116
UNCLASSIFIED AFML-TR-76-240 NL

1 OF 1
ADA041902

END

DATE
FILMED
8 - 77


1.0
4.5
5.0
5.6
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFML-TR-76-240

(13)

HIGH PRESSURE AND TEMPERATURE EFFECTS ON THE VISCOSITY, DENSITY, AND BULK MODULUS OF TWO LIQUID LUBRICANTS

MIDWEST RESEARCH INSTITUTE
KANSAS CITY, MISSOURI 64110

DECEMBER 1976

FINAL REPORT OCTOBER 1975 - MARCH 1976

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

F C Brooks
Frederick C. Brooks
Project Monitor

FOR THE DIRECTOR

Larry L. Fehrenbacher
LARRY L. FEHRENBACHER, MAJOR, USAF
Chief, Lubricants and Tribology Branch
Nonmetallic Materials Division

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

(19) REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

(18) 1. REPORT NUMBER: AFML-TR-76-240

2. GOVT ACCESSION NO. (9)

3. RECIPIENT'S CATALOG NUMBER

(6) 4. TITLE (and Subtitle): High Pressure and Temperature Effects on the Viscosity, Density, and Bulk Modulus of Two Liquid Lubricants,

5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report, October 1975 [redacted] March 1976,

6. PERFORMING ORG. REPORT NUMBER

(10) 7. AUTHOR(s):
Vern Hopkins
Patrick J. Hogan

(15) 8. CONTRACT OR GRANT NUMBER(s): F33615-75-C-5116 nlu

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

(16) 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
Project No.: 7343
Task No.: 734301
PE 62102F

11. CONTROLLING OFFICE NAME AND ADDRESS:
DCASO-Kansas City
Room 201, Noland Plaza Office Building
3675 South Noland Road
Independence, Missouri 64055

(11) 12. REPORT DATE: December 1976

13. NUMBER OF PAGES: 27 (12) 33p.

14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*:
Air Force Materials Laboratory
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright Patterson Air Force Base, Ohio 45433

15. SECURITY CLASS. *(of this report)*: Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited. (17) 01

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Lubrication, Lubricating Oil, Viscosity, Density, Bulk Modulus, High Pressure, Pressure Viscosity, Pressure Temperature Viscosity

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Absolute viscosity, kinematic viscosity, density, and secant bulk modulus values determined for two lubricating fluids are presented. The determinations were made with a falling weight viscometer at temperatures of 38°C (100°F), 99°C (210°F) and 149°C (300°F) and at pressures ranging from atmospheric to 965 MPa (140,000 psi). Plots of absolute viscosity, density, and bulk modulus are given, and all results are discussed. The equipment used to make the determinations is described, and the procedures followed to collect data and reduce to fluid property values are outlined. The fluids were designated ATL 4102 and ELO 67-22.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

230350

dB

FOREWORD

The purpose of this work has been to determine viscosity, density, and bulk moduli of two liquid lubricants. The work has been conducted at Midwest Research Institute, 425 Volker Boulevard, Kansas City, Missouri 64110, for the Air Force Materials Laboratory (MBT), under Contract No. F33615-75-C-5116 (January 2, 1975 to April 1, 1978), Project No. 7343, Task No. 434303, MRI Project No. 4023-L.

Per CAT/1498 search [illegible]

Mr. Frederick C. Brooks of the Lubricants and Tribology Branch, Air Force Materials Laboratory (AFML/MBT), has been the project engineer. Messrs. Vern Hopkins and Patrick Hogan prepared this report. Mr. Hogan conducted the laboratory work. Mr. Karl Mecklenburg is the project leader for the overall program.

The report was submitted by the authors in November 1976.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

Viscosity, the constant of proportionality relating fluid shear stress to shear strain for Newtonian liquids, is generally considered to be most important property of liquid lubricants and hydraulic fluids. Because of the relationship between viscosity and fluid-film thickness in elastohydrodynamic lubrication, this property is significant in determining friction loss, mechanical efficiency, heat generation, fluid flow, load-carrying capacity, and wear of machine components such as bearings and gears. Viscosity will vary appreciably because of the large pressure and temperature changes that occur within liquid films which move in and out of the concentrated contact zone of such machine elements.

This work was undertaken to determine the effect of changes in pressures to 965 MPa (140,000 psi) and temperatures to 149°C (300°F) on the viscosity, density, and bulk modulus characteristics of two liquid lubricants. Data on these fluids were taken with a falling-weight viscometer and a compressibility fixture. Fall time and compressibility measurements were generally made at 138 MPa (20,000 psi) intervals of pressure and at temperatures of 38°C (100°F), 99°C (210°F), and 149°C (300°F). These data were then used to determine values for absolute and kinematic viscosity, density, and bulk modulus.

The following sections of this report describe the equipment used (II); outline the procedures followed to collect the data (III); present viscosity, density, and bulk modulus values determined for both fluids, and discuss the characteristics of the fluids (IV).

SECTION II

DESCRIPTION OF EQUIPMENT

An advanced version of the high-pressure, high-temperature falling weight viscometer, described in the 1953 ASME Pressure Viscosity Report (Ref. 1), is used to measure the viscosity nnd compressibility of lubricating fluids (see Figure 1). The falling-weight viscometer is designed to operate at temperatures from 0°C (32°F) to 204°C (400°F) and pressures from 0 to 1,724 MPa (0 to 250,000 psig). Compressibility data and fall time data are measured and used to calculate absolute and kinematic viscosity, density, and bulk modulus of the fluids tested. The viscometer unit consists of: (1) a hydraulic system to provide the high-pressure environment; (2) a liquid bath to provide the thermal environment; (3) falling weight and compressibility fixtures; (4) instrumentation to collect data; and (5) a roll-over system to cause the falling weight to fall alternately from one end of the viscometer tube to the other.

A. Hydraulic System

A schematic diagram of the hydraulic circuit of the viscometer is shown in Figure 2. Items 8 through 26 of Figure 2 are all part of a rotating assembly.

The high-pressure environment in the high-pressure chamber (21), which contains either the viscosity or the compressibility fixture, is built in three stages. The air-operated hydraulic pump (8) is first used to increase the pressure in the high-pressure chamber, transition tube, and high-pressure cylinder (18) directly to 48 to 55 MPa (7,000 to 8,000 psig). The 10:1 intensifier (16) is then actuated to increase the pressure to about 345 MPa (50,000 psig). Items (18), (21), and the connecting tubing (transition tube) now contain all the hydraulic fluid that will be added to them. The low-pressure cylinder (14), which has an area about 49 times that of the high-pressure cylinder (18), is actuated for the final increase in pressure. As the piston (19) for the high-pressure cylinder advances because of loading by the low-pressure cylinder piston, the port used to introduce hydraulic fluid (into 18) below 345 MPa (50,000 psig) is vented to the atmosphere, and the fluid in (18) and (21) is trapped. Very high pressures can now be developed in (18) and (21), with only moderate increases of pressure in the low-pressure cylinder (14). On decreasing pressure, the piston for the high-pressure cylinder will retract the low-pressure cylinder most of the way as the hydraulic and test fluids expand. Complete return of the low-pressure cylinder piston is accomplished by pressurizing the backup cylinder (13). This cylinder mechanically forces the return of the piston in the low-pressure cylinder (14).

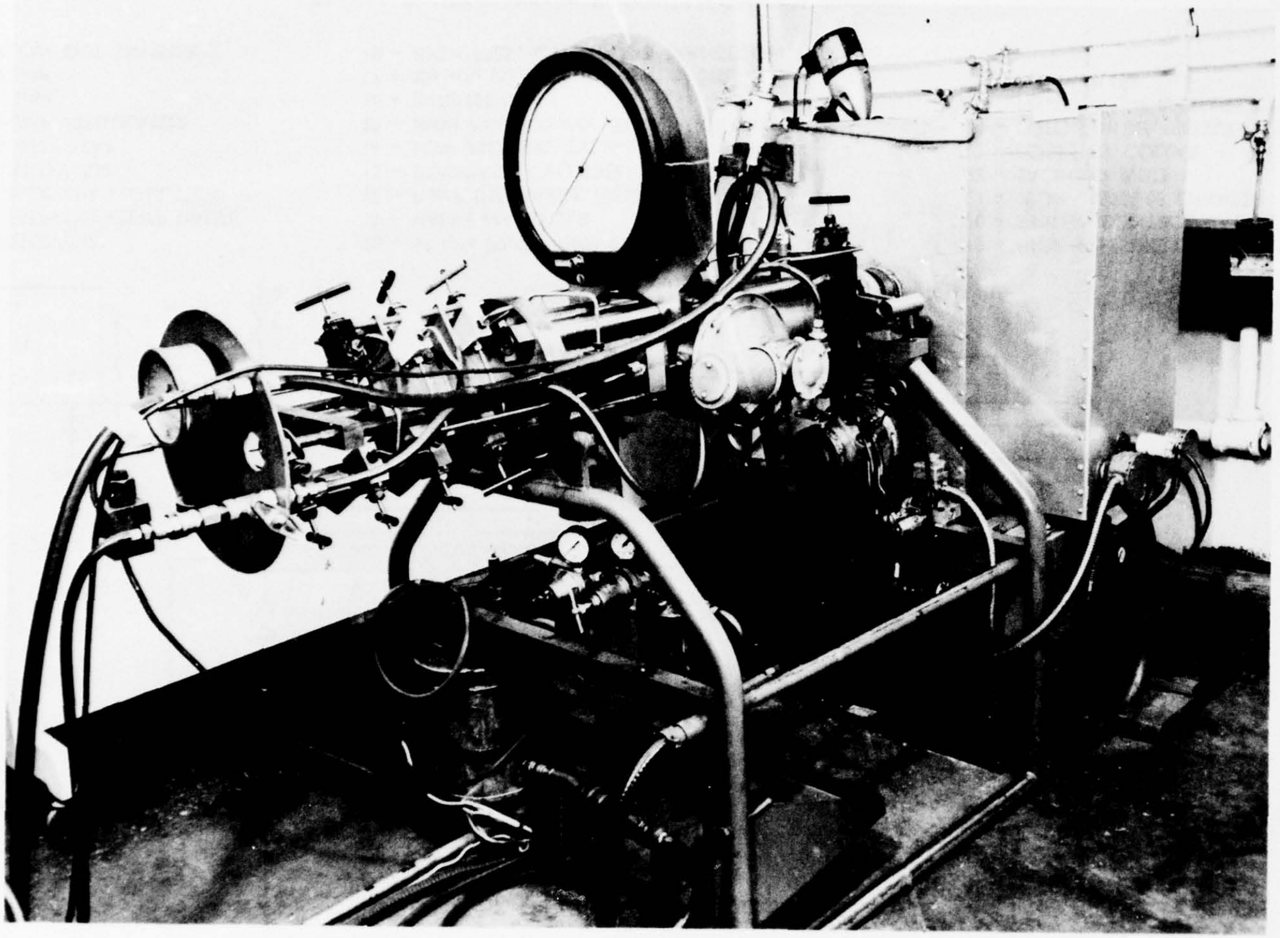
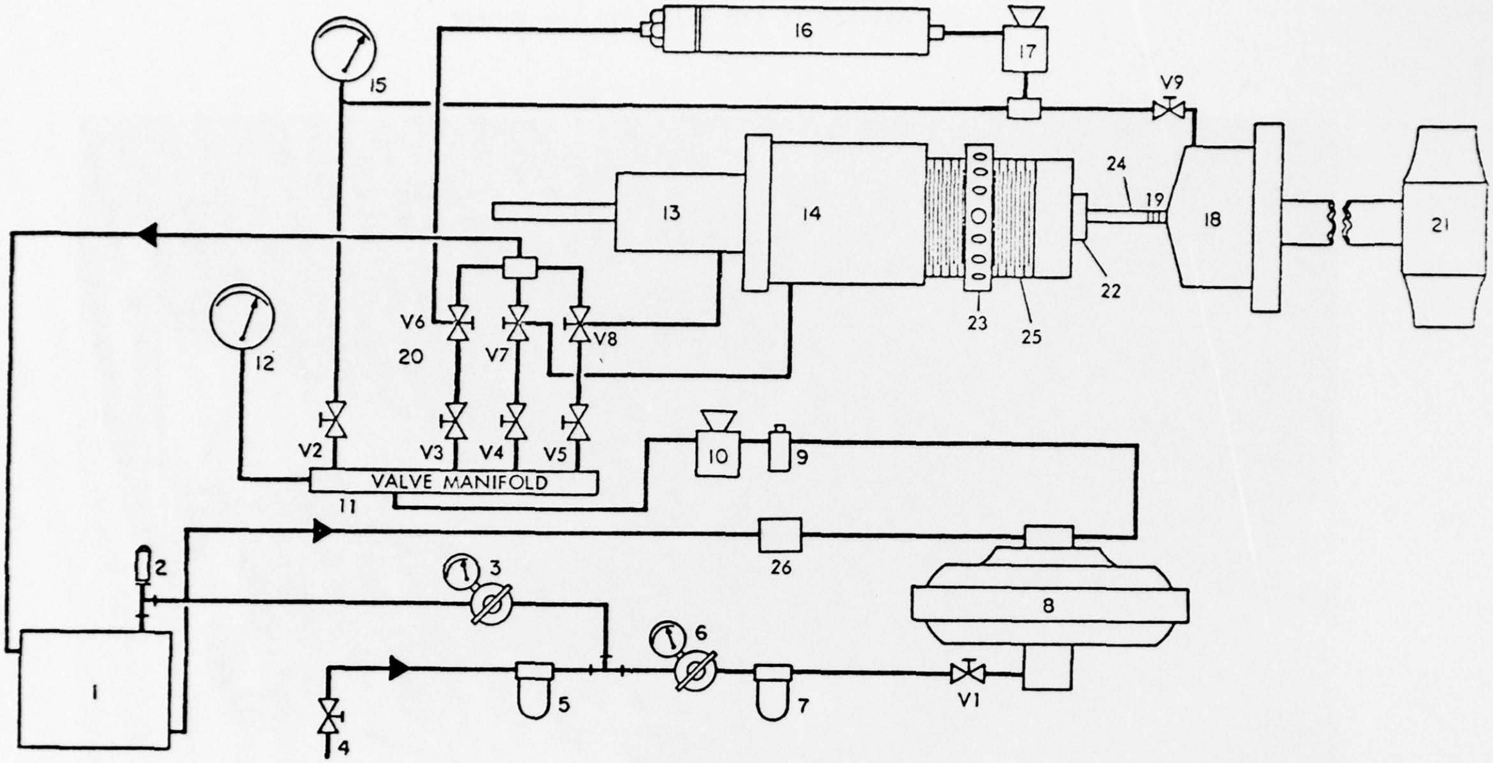


Figure 1 - High Pressure Viscometer



1 - RESERVOIR
2 - RESERVOIR RELIEF VALVE
3 - RESERVOIR REGULATOR
4 - UTILITY AIR
5 - WATER TRAP
6 - PUMP - REGULATOR
7 - OILER
8 - PUMP
9 - BLOW OUT SNUBBER
10 - 69 MPa (10,000 PSIG) RUPTURE DISC
11 - VALVE MANIFOLD
12 - PUMP DISCHARGE PRESSURE
13 - DRAWBACK CYLINDER
14 - LOW PRESSURE CYLINDER
15 - HIGH PRES. 345 MPa (50,000 PSIG) HEISE GAGE
16 - INTENSIFIER
17 - 379 MPa (55,000 PSIG) RUPTURE DISC
18 - HIGH PRES. CYLINDER & TRANSITION TUBE
19 - HIGH-PRESSURE CYLINDER PISTON HEAD
20 - SYSTEM CONTROL VALVES
21 - HIGH PRESSURE CHAMBER
22 - BACKING PIECE
23 - LOCKING COLLAR
24 - PISTON-HIGH PRESSURE CYLINDER
25 - PISTON-LOW PRESSURE CYLINDER
26 - FLUID FILTER

Figure 2 - Viscometer Hydraulic-Control System

The level of the high-pressure environment in the high-pressure cylinder and chamber (18 and 21) is indicated either by a Bourdon-tube pressure gage (below 345 MPa (50,000 psi)), or by the change in resistance of a manganin wire coil located in the high-pressure cylinder. The manganin wire transducer has a linear resistance change as a function of pressure. This linear pressure-resistance characteristic is useful from atmospheric pressure to 2,930 MPa (425,000 psi). The calibration constant of the coil is checked at pressures up to 689 MPa (100,000 psi) with a precision Bourdon-tube pressure gage. Pressures above 689 MPa (100,000 psi) are measured by extrapolation.

B. Bath

A stirred constant-temperature bath, shown at the right end of Figure 1, provides the thermal environment for the high-pressure chamber. This chamber (Item 21 in Figure 2) contains either the viscosity or compressibility fixture. A phenyl-methyl silicone (QF-258) is used as a bath fluid at temperatures above 10°C (50°F). The bath vessel is equipped with a coil for tap water, an evaporator coil for a small refrigeration unit, three 1,500 w electric heaters, and one 500 w electric heater.

At 20°C (68°F) and above, one or more of three 1,500 w heaters are used to supply the bulk of the heat required. These heaters are controlled by a solid-state power supply. The output of this power supply is controlled by a thermocouple in the bath liquid. In order to have positive control near room temperature, both the heaters and the refrigeration system may be operated at the same time. The coil for tap water is used primarily to hasten cooling of the bath. The bath liquid temperature is measured by ASTM extended-range thermometers.

An electric-motor-driven pump and 0.114 m^3 (30-gal.) drum were connected to the temperature controlled bath to transfer and hold the bath fluid while changing specimens. This arrangement prevents the loss of bath fluid, and minimizes the time required to change specimens or replace a seal.

C. Falling-Weight Viscosity and Compressibility Fixtures

The falling-weight viscosity and compressibility fixtures are the heart of the high-pressure viscometer apparatus. The remainder of the setup is designed to control the environment for these fixtures or to take data from them.

1. Falling-weight viscosity fixture: A cross section of the fixture is shown in Figure 3.* This device consists of a cylinder (1) in which slides a closely-fitted cylindrical falling weight (2). There is an insulated contact (3a) at each end of the tube. The contacts are locked in

---

* Reprinted from ASME Pressure-Viscosity Report and modified.

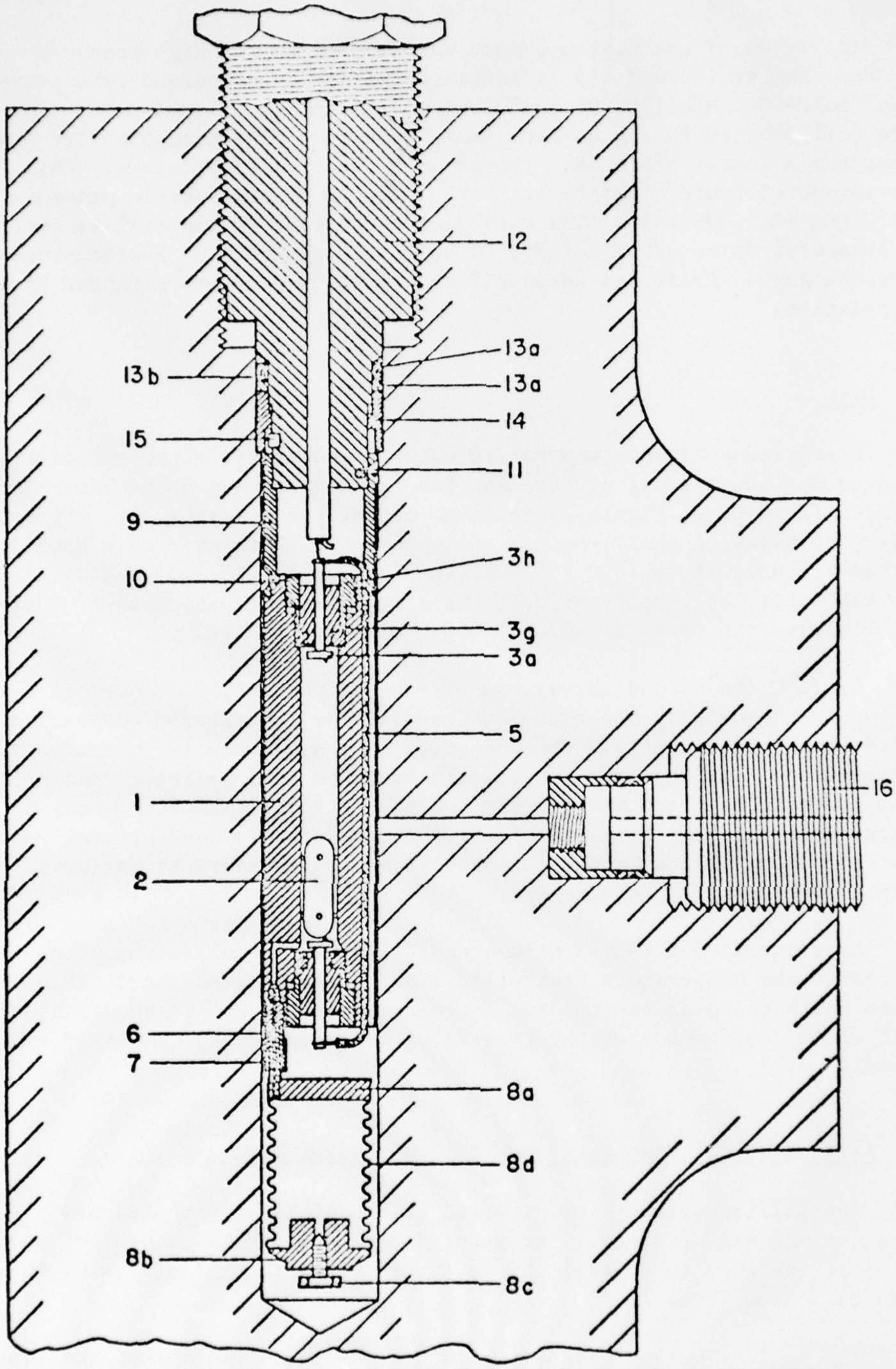


Figure 3 - Cross Section of the Falling Weight Fixture in Place

place by nuts (3h), and sealed by lead washers or O-rings (3g). The flexible bellows assembly (8), which is connected to the lower end of the viscometer cylinder by a tube (6) and union (7), serves as a reservoir to keep the viscometer tube filled with the test fluid, and to transmit the hydrostatic pressure outside the fixture to the test fluid without appreciable change. The insulted contacts (3a) are connected by a wire (5) which is attached to a lead extending through the terminal plug (12) which, with seals (13), closes the high-pressure chamber. The entire fixture is surrounded by the pressure-transmitting fluid introduced through the extension (16) of the high-pressure chamber. The pressure-transmitting fluid is a mixture of normal hexane containing 5% (by volume) SAE 20-20W motor oil.

Viscosity is proportional to the time required for the falling weight to descend vertically through the cylinder under the force of gravity. Repeat readings are taken by rotating the viscometer one-half revolution. This rotation is accomplished by turning the entire hydraulic system (except the reservoir) about its horizontal axis. The time of fall is indicated by a counter accurate to within 1/60 sec. The counter is started when the weight breaks contact with the upper cylinder and plug, and is stopped when contact is established by the weight touching both the cylinder and the bottom end plug.

The electrical leads through the terminal plug are in a swaged stainless-steel sheath which is silver-brazed to an air-quenched toosteel plug. Six conductors, four iron and two constantan, are contained in the 0.63 cm (1/4-in.) OD sheath and are insulated with very dense magnesium oxide. To reduce the chance of leakage of hexane, the MgO is impregnated with polyimide resin at roughly 345 MPa (50,000 psig) and then cured (about 1 hr at 107°C (225°F) and then 1 hr at 260°C (500°F)).

2. <u>Compressibility fixture</u>: A cross section of the compressibility fixture is shown in Figure 4.* The liquid test sample is sealed into the bellows (1) under vacuum. The bellows are welded to the end pieces (2) and (3), and contain the guides (4) and (5), which keep the bellows straight and assure a linear length/volume-change relationship for the bellows. This relationship was experimentally determined. The guides are held in place and the bellows ends sealed by silver solder. After filling the bellows with test fluid, the filling opening is sealed by a screw (8). The bellows assembly is then clamped to the sleeve (12) by the nut (13). A short length of polished high-resistance 0.45 mm (0.0179 in.) diameter Nirex wire (11) is attached to the upper end of the bellows and, as the pressure is increased, the bellows become shorter, causing the Nirex wire to slide over the insulated contact (15) which is fixed in the block (14) which in turn is clamped to the sleeve (12). Leads from the slide wire (11) and the insulated contact (15) are soldered to terminals (23) which are connected to the leads (30) extending through the

---

* Reprinted from ASME Pressure-Viscosity Report and modified.

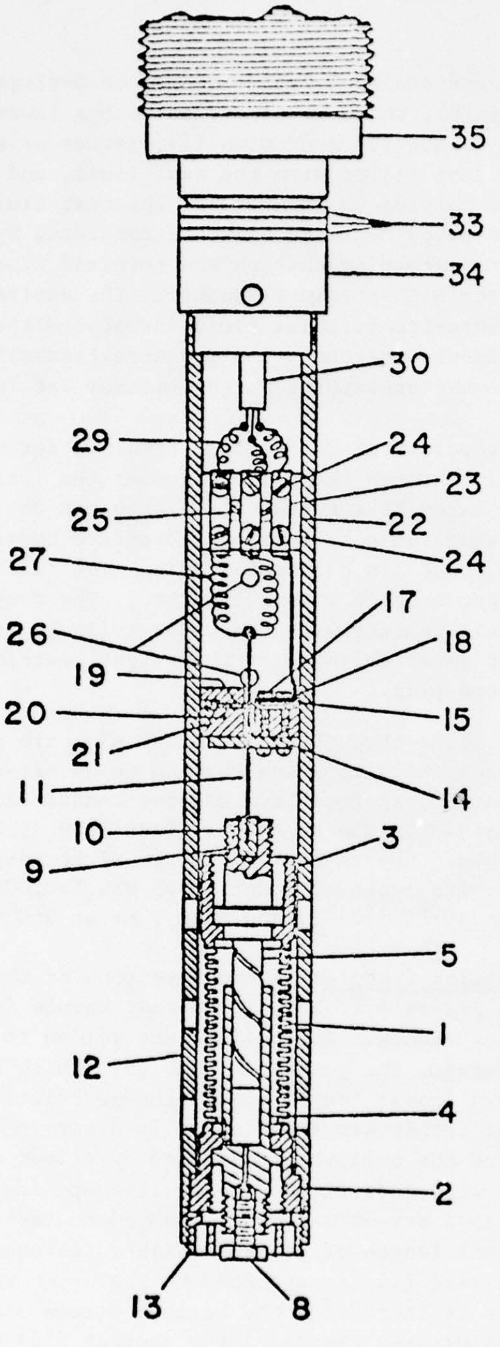


Figure 4 - Cross Section of the Compressibility Fixture

terminal plug. Identical terminal plugs are used for the viscosity and compressibility fixtures.

The motion of the slide wire over the insulated contact is measured by determining the voltage drop between the contact soldered to the end of the Nirex wire and the insulated contact. Separate leads are used to measure the voltage drop and to supply the bias voltage to the Nirex wire. The relationship between voltage drop change and bellows-length change is established experimentally at the various test temperatures, using a micrometer head and a small oven. The relationship between bellows-length change and bellows-volume change is experimentally determined by use of a micrometer head with a precision capillary tube that measures the change in bellows volume caused by a known length change.

Additional information concerning the development of the present viscometer will be found in Refs. 2-5.

D. Instrumentation

A schematic diagram of the instrumentation used to measure: (1) pressures with a manganin coil transducer; (2) compressibility with a slide wire transducer; and (3) the time required for the falling weight to fall from one end of the viscometer tube to the other is shown in Figure 5.

All electrical measurements except fall time were made on a Leeds and Northrup K-3 potentiometer. To measure voltages, leads were connected to the potentiometer through Leeds and Northrup instrumentation switches having less than 0.1 μv of thermal noise. Fall time measurements were made with a Hewlett-Packard 5325 Counter.

The manganin-coil pressure-measuring system uses a 4-wire system to permit the leads carrying current to the coil to be separated from the voltage measuring leads to the potentiometer. A 100-ohm precision resistor connected in series with the manganin coil was used to monitor the current through the coil. This current can be monitored with a potentiometer or a separate microvoltmeter. Calibration of the microvoltmeter was checked before each test to assure the stability of the manganin coil current. Calibration of the manganin coil pressure-measuring system was checked many times during the course of this work. The coil did not change base resistance or sensitivity to pressure at any time during this work. It was established that results of the manganin-coil pressure-measuring system were reproducible to ± 0.35 MPa (± 50 psi) from 0 to 689 MPa (0 to 100,000 psig).

The Nirex wire compressibility measuring system is a 4-wire system; one pair supplies the bias current, while the second pair is used to measure the voltage. The voltage drop across a 10 ohm precision resistor is used to monitor the current. A second microvoltmeter can be used to monitor the

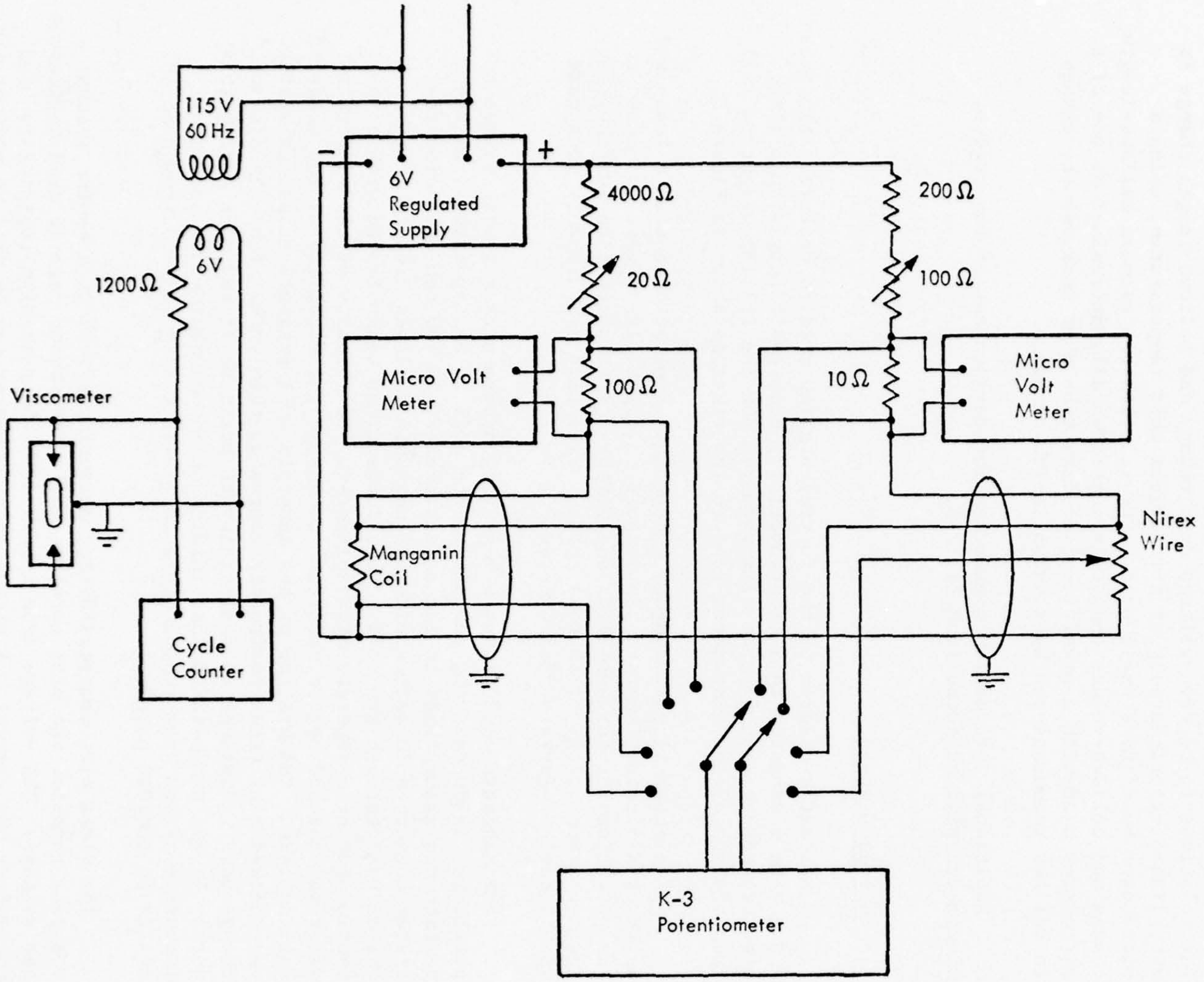


Figure 5 - Schematic Diagram of Viscometer Instrumentation

current while the potentiometer is being used to measure the Nirex wire voltage.

The laboratory in which the viscometer is located is equipped with an air-conditioning system capable of holding the room temperature constant within ± 0.25°C (± 0.5°F). Temperatures varied less than ± 0.1°C (± 0.2°F) inside the instrument console where the critical electrical measuring components are located. This control of laboratory temperature permits accurate measurements to be made in an efficient manner.

E. Roll-Over System

This falling-weight viscometer is equipped with a remotely operated rotating device to provide uniform rates of rotation of the viscometer fixture, and to permit the operator to remain away from dangerous areas during high-pressure runs. The system is pneumatic and uses 0.41 to 0.62 MPa (60 to 90 psig) air pressure. A partial revolution air motor turns the entire hydraulic system 180 degrees in less than 1 sec, and thereby causes the weight to fall through the viscometer tube filled with test fluid. The air motor, which is connected to the rotating assembly through a timing belt, is supplied with air through one of two ports. The direction of rotation is controlled by the position of a four-way solenoid valve.

Cam-operated valves sense the position of the rotating assembly and adjust the air flow rate to permit deceleration of the assembly to a smooth, but firm, halt on one of the two adjustable stops. Adjustments can be independently made in: (1) the angular position of the test chamber, the cams, and the stop arm with respect to the transition (hydraulic fluid supply) tube; (2) the actuating air pressure; (3) the stop positions; and (4) the settings of the air snubbers.

SECTION III

PROCEDURES

The procedures followed to determine high-pressure viscosity, density, and bulk modulus values consisted of three steps. The first step involves calibrating transducers. During the second step the overall unit is operated to collect data. In the third step, data are reduced to viscosity, density, and bulk modulus values.

A. Calibration

The high-pressure viscometer incorporates two measuring transducers which require regular checks of calibration and occasional recalibration. In addition, the viscometer tube has two pointed electrical contacts which must be occasionally resharpened.

The calibration of the manganin-coil pressure transducer was checked at least once for each fluid tested. The resistance of the coil was calibrated against a 689 MPa (100,000 psi) Heise bourdon tube gage which was certified to 0.1% of full scale. The base resistance and sensitivity of the manganin coil transducer did not change during this work.

The calibration of the Nirex wire compressibility transducer was checked at least once for each fluid tested. The resistance/displacement characteristic of the wire is measured with a potentiometer and a 0 to 2.54 cm (0 to 1 in.) micrometer graduated in 2.5 μm (0.0001-in.) increments. The Nirex wire was replaced twice during specimen changes. The replacement resulted in three different reference currents being used for the compressibility measurements with each wire replacement. No changes in calibration were ever detected in the Nirex wire transducer.

Fall length must be measured each time the electrical contacts in the viscometer tube are sharpened because the distance which the weight can fall is altered. The length is measured with an adjustable plug gage, which is in turn measured with a 0 to 5 cm (0 to 2 in.) micrometer graduated in 25 μm (0.001-in.) increments. The length of the falling weight is subtracted from the length of the plug gage to obtain the fall length.

Bath temperatures are set by using ASTM extended range thermometers, and are held constant within ± 0.05°C (± 0.1°F) by a three-mode temperature controller.

The vertical position of the viscometer tube axis is checked after each change of specimens. The position is set within 1 min of vertical, using a precision level (± 30 sec) positioned on a machined surface of the high pressure chamber.

B. Data Collection

Data required for the viscosity determination are the fall time and the density of the fluid in the viscometer at each temperature and pressure of the test schedule. The test schedule called for temperatures of 38°C (100°F), 99°C (210°F), and 149°C (300°F) and pressures from atmospheric to 965 MPa (140,000 psig). At each temperature, the pressure was increased in increments of 138 MPa (20,000 psi) to a maximum of 1,103 MPa (160,000 psig) or until the fall time exceeded 750 sec. In some cases smaller increments of pressures were used to permit taking at least four data points at each test temperature.

The time required for the weight to fall the length of the viscometer tube filled with the test fluid was recorded to the nearest 1/60 of a second. At least five readings of fall time were taken when the viscometer was rolled to the left and five when it was rolled to the right, except at the longest fall time (greater than 10 min). Only two or three fall times were taken at the longest fall times.

The volume of a known weight of test fluid was measured in the compressibility fixture at each of the temperatures and pressures of the test schedule. Pressure limits were those established during the fall time measurements.

Density of the test fluid, at atmospheric pressure for each temperature of the test schedule, was measured concurrently with the compressibility measurements, using two different makes of specific-gravity bottles immersed in the temperature-controlled bath. The simultaneous density and compressibility measurements are expected to eliminate any possible error due to different bath temperatures.

Measurements were made in order of increasing temperature and pressure, and rechecks of selected points were made on decreasing pressure.

C. Data Reduction

Three computer programs are used to reduce the data to values of density, bulk modulus and viscosity. The programs are helpful in reducing the number of errors and the cost of the computations.

The computer programs are written to accept some of the data in the English system of units. Once the data have been reduced, the programs make necessary conversions to S.I. units and then output the data in that form.

1. <u>Density</u>: Data at atmospheric pressure are smoothed by fitting them to an equation of the form

$$\rho_O = a + bT \tag{1}$$

where ρ_O = density at temperature T and atmospheric pressure, g/ml

T = temperature, degrees Fahrenheit

a and b = constants determined by a linear regression curve fit procedure.

Densities at test pressures are calculated from the atmospheric pressure density data and the compressibility data using the equation

$$\rho = \frac{1}{\frac{1}{\rho_O} - \frac{(V_O - V)}{W}} \tag{2}$$

where ρ = density at temperature T and pressure P , g/ml

ρ_O = density at temperature T and atmospheric pressure, g/ml

$(V_O - V)$ = volume change of test fluid sample at temperature T , and subjected to an increase in pressure from atmospheric pressure to the test pressure P, ml

W = weight of sample, g.

An equation is fitted to the density-pressure-temperature data to smooth it in a way that all data points will have equal weight. It has been found that a suitable equation will have the form

$$\rho = \frac{\rho_O \gamma}{\gamma - \ln\left(1 + \frac{P}{\alpha + \frac{\beta}{T_R}}\right)} \tag{3}$$

where P = pressure, psig

T_R = temperature, degrees Rankine

α, β and γ = constants dependent upon the fluid.

2. <u>Bulk modulus</u>: Bulk modulus values are calculated from the constants α , β and γ determined above using the relationship

$$\bar{B}_T = \frac{\gamma P}{\ln\left(1 + \frac{P}{\alpha + \frac{\beta}{T_R}}\right)} \tag{4}$$

where $\bar{B}_T$ is the isothermal secant bulk modulus.

3. <u>Viscosities</u>: Absolute viscosity and kinematic viscosity are calculated from the fall time data, the density data and the form factors for the viscometer, using the equation presented in the 1953 ASME Pressure Viscosity Report (Ref. 1):

$$\mu = (C_f\ C'\ C_b\ C_d)\ T/L \tag{5}$$

where μ = absolute viscosity, centipoise

C_f = form factor or calibration constant

C' = factor related to the geometry of falling weight and viscometer tube

C_b = correction for bouyancy of sinker in the test fluid

C_d = correction for thermal expansion and compressibility effects on viscometer

L = distance sinker falls

T = time for sinker to travel distance L at constant velocity; measured fall time corrected for time to accelerate sinker to final velocity.

Kinematic viscosity is the ratio of absolute viscosity to the density.

$$\nu = \frac{\mu}{\rho} \tag{6}$$

where ν = kinematic viscosity, centistokes.

SECTION IV

RESULTS AND DISCUSSION

Changes in absolute and kinematic viscosity, as well as density and bulk modulus, have been determined for two lubricants at high pressures and temperatures. Data to determine these properties were taken at test conditions listed in Table 1.

Values of absolute and kinematic viscosity, density, and bulk modulus determined for two fluids are presented in Tables 2 and 3. Values of absolute viscosity density and isothermal secant bulk modulus as functions of pressure and temperature were plotted and are presented in Figures 6, 7, 8, 9, 10, and 11. Each figure contains a curve for temperatures of 38°C (100°F), 99°C (210°F), and 149°C (300°F).

ELO 67-22 is a higher viscosity liquid than ATL 4102, and has a steeper slope with pressure. ELO 67-22 also exhibits a greater viscosity change with temperature than does ATL 4102. Viscosity results for both of these lubricants were compared to values given in AFML-TR-74-195 for seven lubricants obtained under nearly identical conditions. The viscosity of ATL 4102 is nearly identical to that reported for ATL-3144. The viscosity of ELO 67-22 is only slightly greater than that obtained for MLO-73-91. However, the densities of ATL 4102 and ELO 67-22 were noticeably less than ATL-3144 and MLO-73-91, respectively.

ELO 67-22 is less dense than ATL 4102. It also appears that the curves for the density of ELO 67-22 tend to get closer together as pressure increases. This trend is believed to be the result of a small experimental error. Checks made on the equipment and an examination of the lubricant for contamination by the pressurizing media did not turn up a reason for this unusual trend.

The 38°C (100°F) bulk modulus of ATL 4102 is less than the 38°C (100°F) bulk modulus of ELO 67-22. The values of both lubricants at 149°C (300°F) are nearly identical. The slopes of the bulk modulus curves for both lubricants with pressure are nearly the same. Temperature has a greater effect on bulk modulus of ATL 4102 than it does on ELO 67-22.

The probable error of the density and bulk modulus values reported in Tables 2 and 3 is estimated to be no greater than ± 0.8%. Of the 41 density determinations, 39 are within ± 0.8% of the value calculated by Eq. (3). The computer programs for reducing the density data also calculate the standard error of the estimate for Eqs. (1) and (3). The standard error for all of the atmospheric density data combined is 0.52% and the standard error for all of the high-pressure density measurements combined is 0.7%.

TABLE 1

HIGH-PRESSURE VISCOSITY AND DENSITY TEST CONDITIONS

Temperature		Pressure		Liquid Lubricants	
°C	(°F)	MPa	(psig)	ELO 67-22	ATL 4102
38	100	0	0	X	X
		34.4	5,000	X	
		68.9	10,000	X	
		103.4	15,000	X	
		137.9	20,000	X	X
		172.4	25,000	X	
		206.8	30,000	X	
		275.8	40,000		X
		413.7	60,000		X
99	210	0	0	X	X
		137.9	20,000	X	X
		275.8	40,000	X	X
		413.7	60,000	X	X
		482.6	70,000	X	
		551.6	80,000	X	X
		689.5	100,000		X
		827.4	120,000		X
		965.3	140,000		X
149	300	0	0	X	X
		137.9	20,000	X	X
		275.8	40,000	X	X
		413.7	60,000	X	X
		551.6	80,000	X	X
		689.5	100,000	X	X
		827.4	120,000	X	X
		896.3	130,000	X	
		965.3	140,000		X

TABLE 2

HIGH-PRESSURE VISCOSITY DATA FOR FLUID ELO 67-22

Test Temperature °C	Test Temperature (°F)	Test Pressure MPa	Test Pressure (psi)	Density kg/m^3	Density (g/mℓ)	Bulk Modulus MPa	Bulk Modulus (psi)	Absolute Viscosity mNs/m^2	Absolute Viscosity (CPS)	Kinematic Viscosity μm^2/s	Kinematic Viscosity (CST)
37.8	100	0.000	0	862.300	0.8623	1665.254	241,525	132.302	132.30	153.429	153.43
37.8	100	34.474	5,000	878.507	0.8785	1868.679	271,029	289.402	289.40	329.425	329.43
37.8	100	68.948	10,000	892.173	0.8922	2059.180	298,659	600.240	600.24	672.784	672.78
37.8	100	103.421	15,000	904.042	0.9040	2239.891	324,869	1153.598	1153.60	1276.045	1276.05
37.8	100	137.895	20,000	914.568	0.9146	2412.839	349,953	2212.599	2212.60	2419.283	2419.28
37.8	100	172.369	25,000	924.049	0.9240	2579.427	374,114	4014.960	4014.96	4344.964	4344.96
37.8	100	206.843	30,000	932.692	0.9327	2740.674	397,501	7397.740	7397.74	7931.602	7931.60
98.9	210	0.000	0	827.500	0.8275	1208.499	175,278	13.111	13.11	15.844	15.84
98.9	210	137.895	20,000	891.092	0.8911	1932.265	280,251	92.545	92.55	103.856	103.86
98.9	210	275.790	40,000	928.554	0.9286	2534.152	367,548	445.869	445.87	480.175	480.18
98.9	210	413.685	60,000	955.987	0.9560	3077.956	446,420	1803.131	1803.13	1886.146	1886.15
98.9	210	482.633	70,000	967.497	0.9675	3335.407	483,760	3542.934	3542.93	3661.959	3661.96
98.9	210	551.581	80,000	977.949	0.9779	3585.386	520,016	6772.161	6772.16	6924.860	6924.86
148.9	300	0.000	0	798.000	0.7980	933.173	135,345	5.790	5.79	7.256	7.26
148.9	300	137.895	20,000	871.475	0.8715	1635.549	237,216	22.869	22.87	26.241	26.24
148.9	300	275.790	40,000	911.863	0.9119	2208.652	320,338	78.667	78,67	86.270	86.27
148.9	300	413.685	60,000	940.849	0.9408	2724.662	395,179	226.068	226.07	240.280	240.28
148.9	300	551.581	80,000	963.835	0.9638	3205.789	464,960	613.533	613.53	636.554	636.55
148.9	300	689.476	100,000	983.063	0.9831	3662.522	531,204	1564.275	1564.27	1591.225	1591.22
148.9	300	827.371	120,000	999.695	0.9997	4100.845	594,777	3846.255	3846.26	3847.430	3847.43
148.9	300	896.318	130,000	1007.262	1.0073	4314.347	625,743	5920.827	5920.83	5878.141	5878.14

TABLE 3

HIGH-PRESSURE VISCOMETER DATA FOR FLUID ATL 4102

Test Temperature		Test Pressure		Density		Bulk Modulus		Absolute Viscosity		Kinematic Viscosity	
°C	(°F)	MPa	(psi)	kg/m^3	(g/mℓ)	MPa	(psi)	mNs/m^2	(CPS)	µm^2/s	(CST)
37.8	100	0.000	0	973.700	0.9737	1943.930	281,943	28.828	28.83	29.607	29.61
37.8	100	137.895	20,000	1025.515	1.0255	2729.194	395,836	180.541	180.54	176.049	176.05
37.8	100	275.790	40,000	1059.528	1.0595	3404.560	493,790	810.228	810.23	764.707	764.71
37.8	100	413.685	60,000	1085.388	1.0854	4020.219	583,083	3136.007	3136.01	2889.296	2889.30
98.9	210	0.000	0	930.200	0.9302	1269.437	184,116	7.320	7.32	7.870	7.87
98.9	210	137.895	20,000	998.256	0.9983	2022.667	293,363	26.665	26.66	26.712	26.71
98.9	210	275.790	40,000	1038.273	1.0383	2649.551	384,285	74.525	74.52	71.777	71.78
98.9	210	413.685	60,000	1067.517	1.0675	3216.035	466,446	182.693	182.69	171.138	171.14
98.9	210	551.581	80,000	1090.886	1.0909	3744.652	543,116	423.597	423.60	388.306	388.31
98.9	210	689.476	100,000	1110.508	1.1105	4246.451	615,896	932.474	932.47	839.682	839.68
98.9	210	827.371	120,000	1127.514	1.1275	4727.857	685,718	2006.585	2006.59	1779.654	1779.65
98.9	210	965.266	140,000	1142.580	1.1426	5193.017	753,184	4191.090	4191.09	3668.093	3668.09
148.9	300	0.000	0	894.900	0.8949	862.861	125,147	3.576	3.58	3.996	4.00
148.9	300	137.895	20,000	980.333	0.9803	1582.338	229,499	8.930	8.93	9.109	9.11
148.9	300	275.790	40,000	1025.566	1.0256	2164.613	313,951	19.752	19.75	19.260	19.26
148.9	300	413.685	60,000	1057.657	1.0577	2688.293	389,904	39.690	39.69	37.526	37.53
148.9	300	551.581	80,000	1082.946	1.0829	3176.521	460,715	75.799	75.80	69.994	69.99
148.9	300	689.476	100,000	1104.015	1.1040	3640.069	527,947	138.844	138.84	125.763	125.76
148.9	300	827.371	120,000	1122.183	1.1222	4085.041	592,485	251.016	251.02	223.686	223.69
148.9	300	965.266	140,000	1138.226	1.1382	4515.307	654,890	434.916	434.92	382.099	382.10

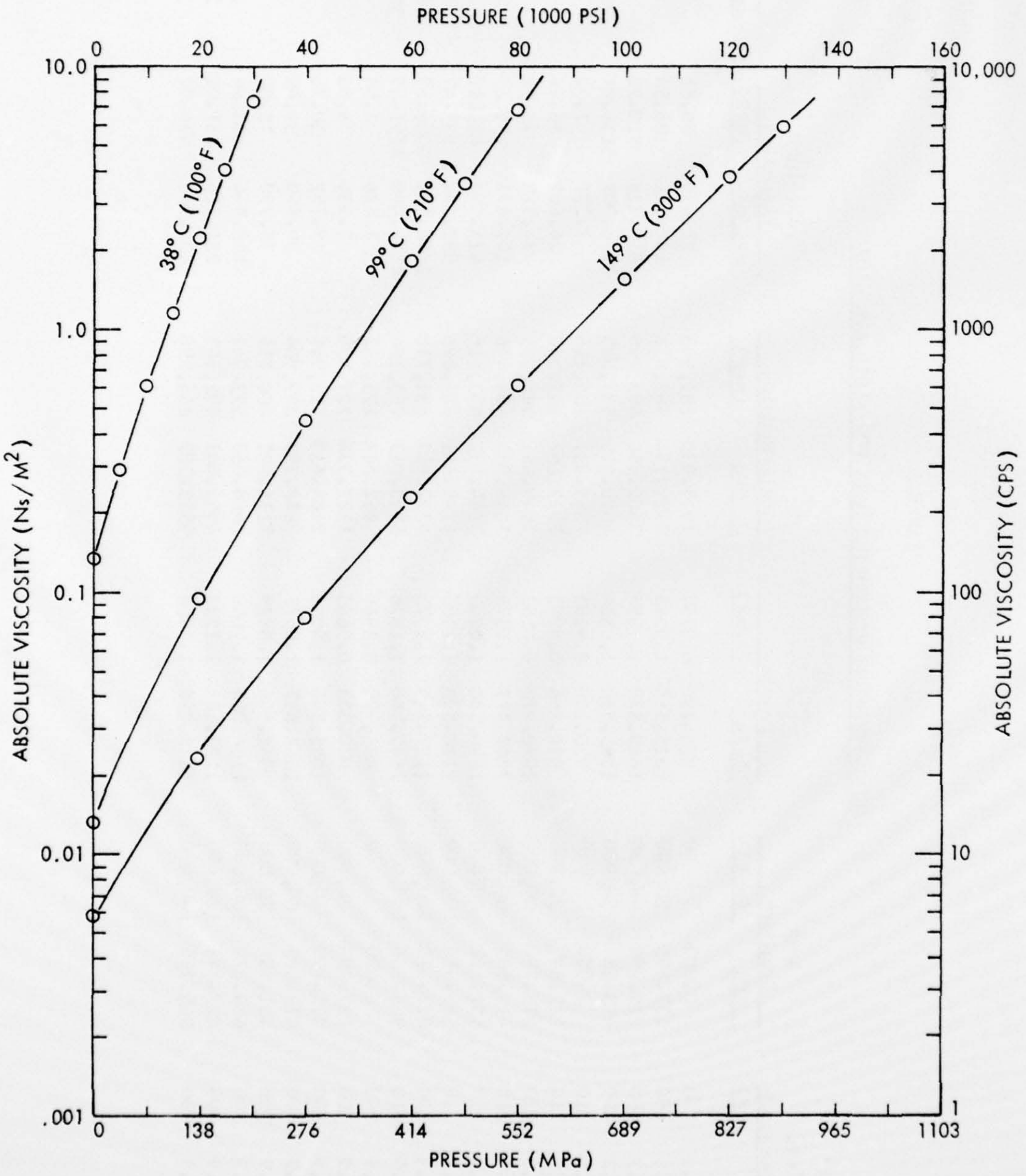


Figure 6 - Absolute Viscosity Versus Pressure - ELO 67-22

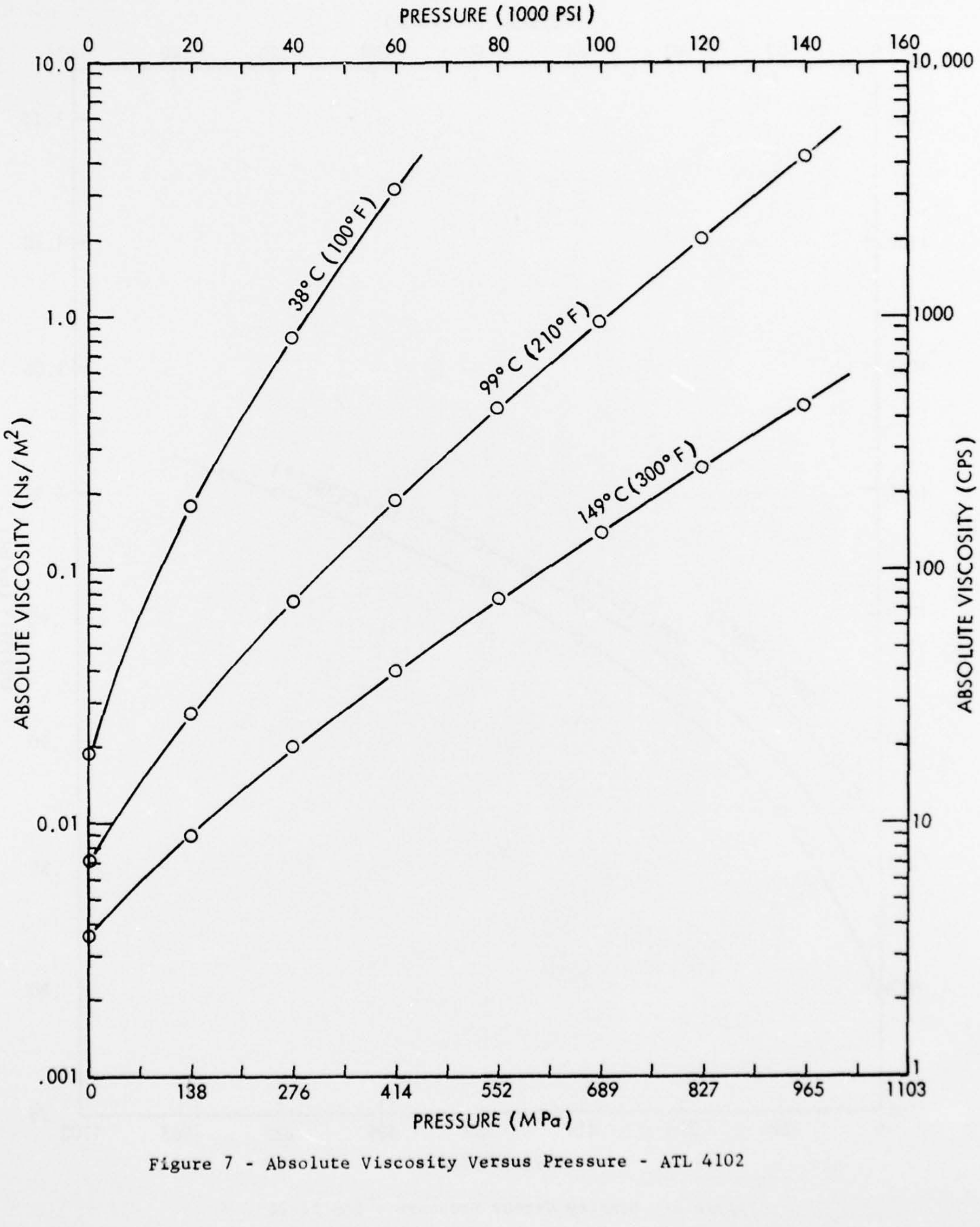


Figure 7 - Absolute Viscosity Versus Pressure - ATL 4102

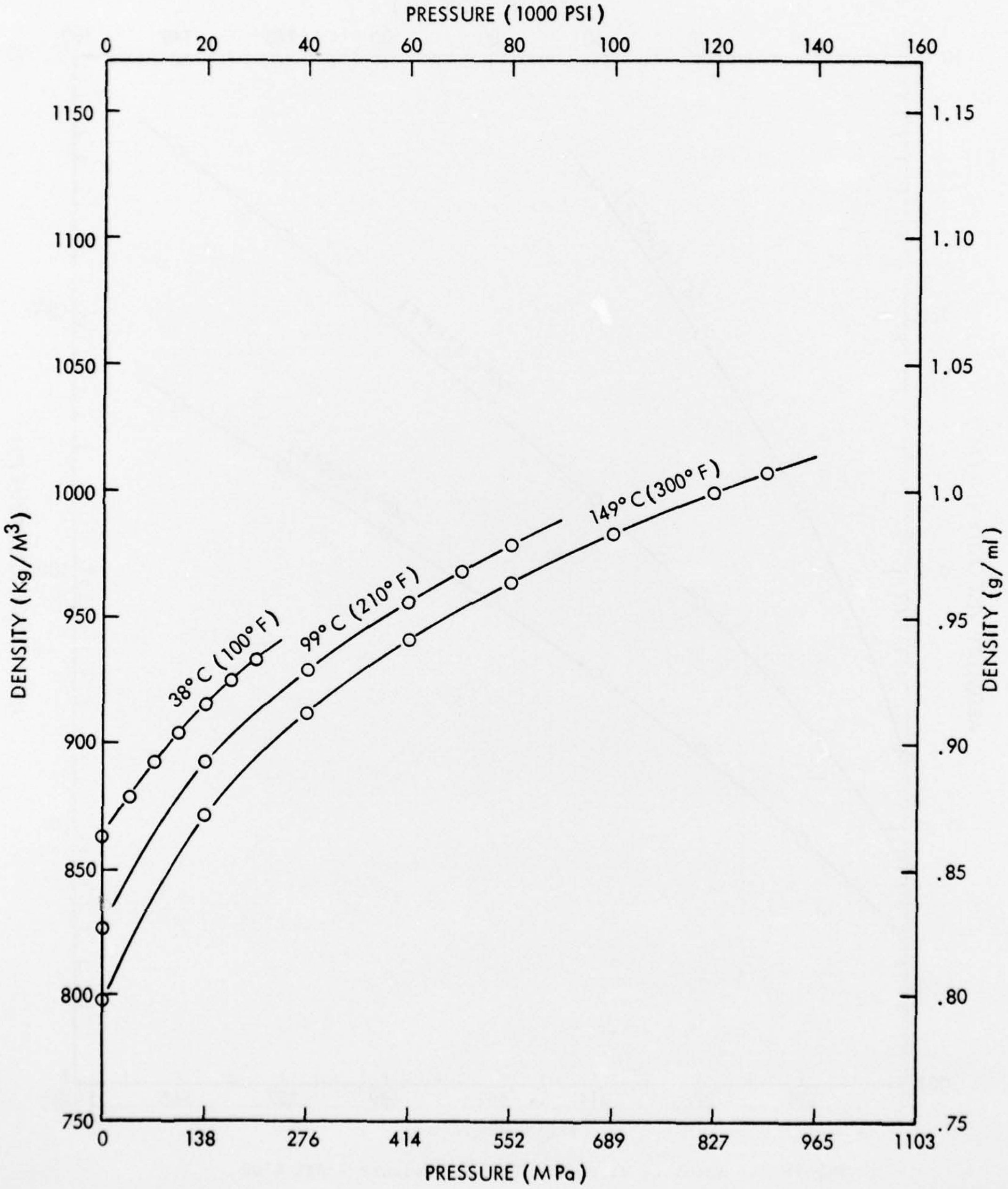


Figure 8 - Density Versus Pressure - ELO 67-22

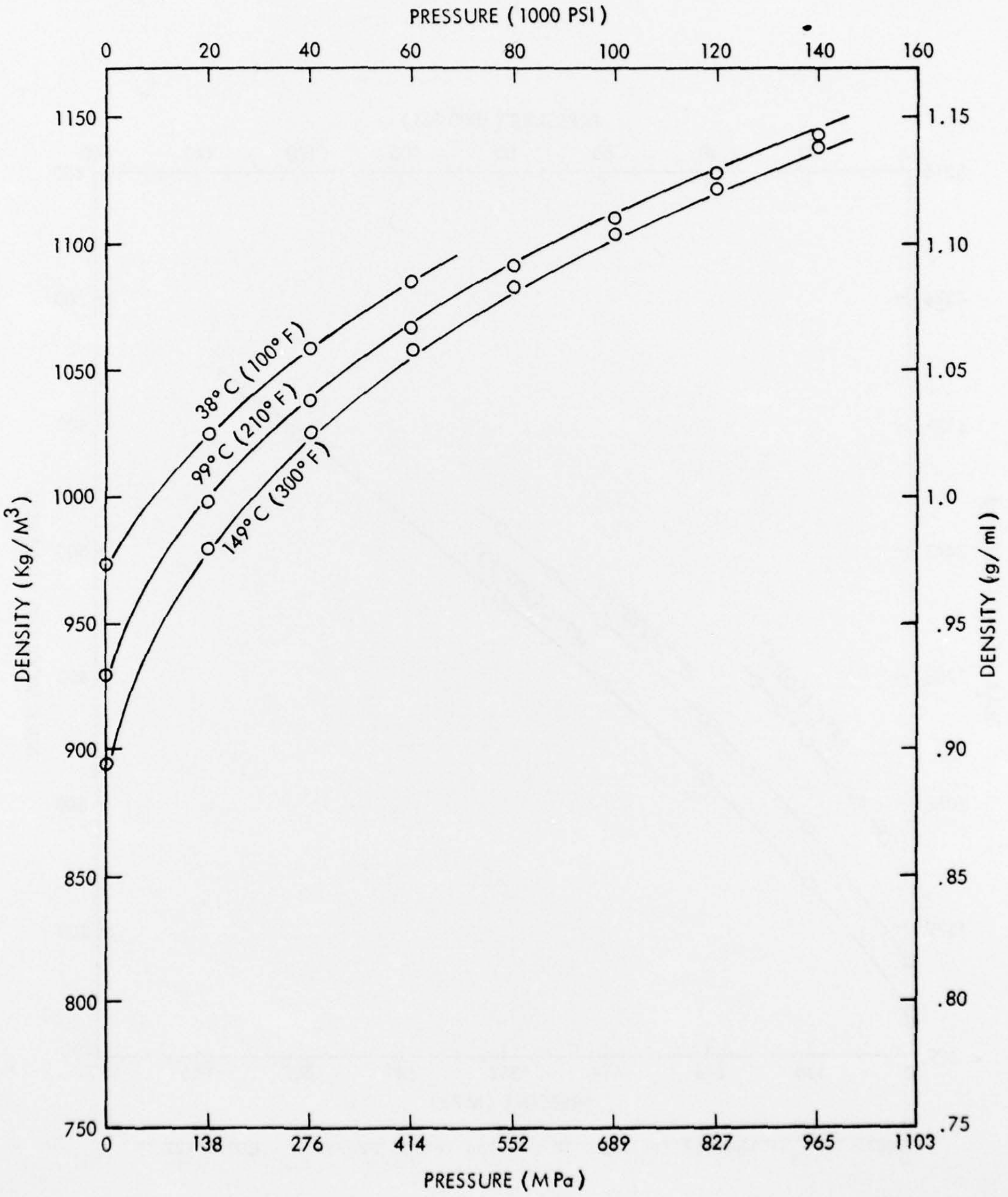


Figure 9 - Density Versus Pressure - ATL 4102

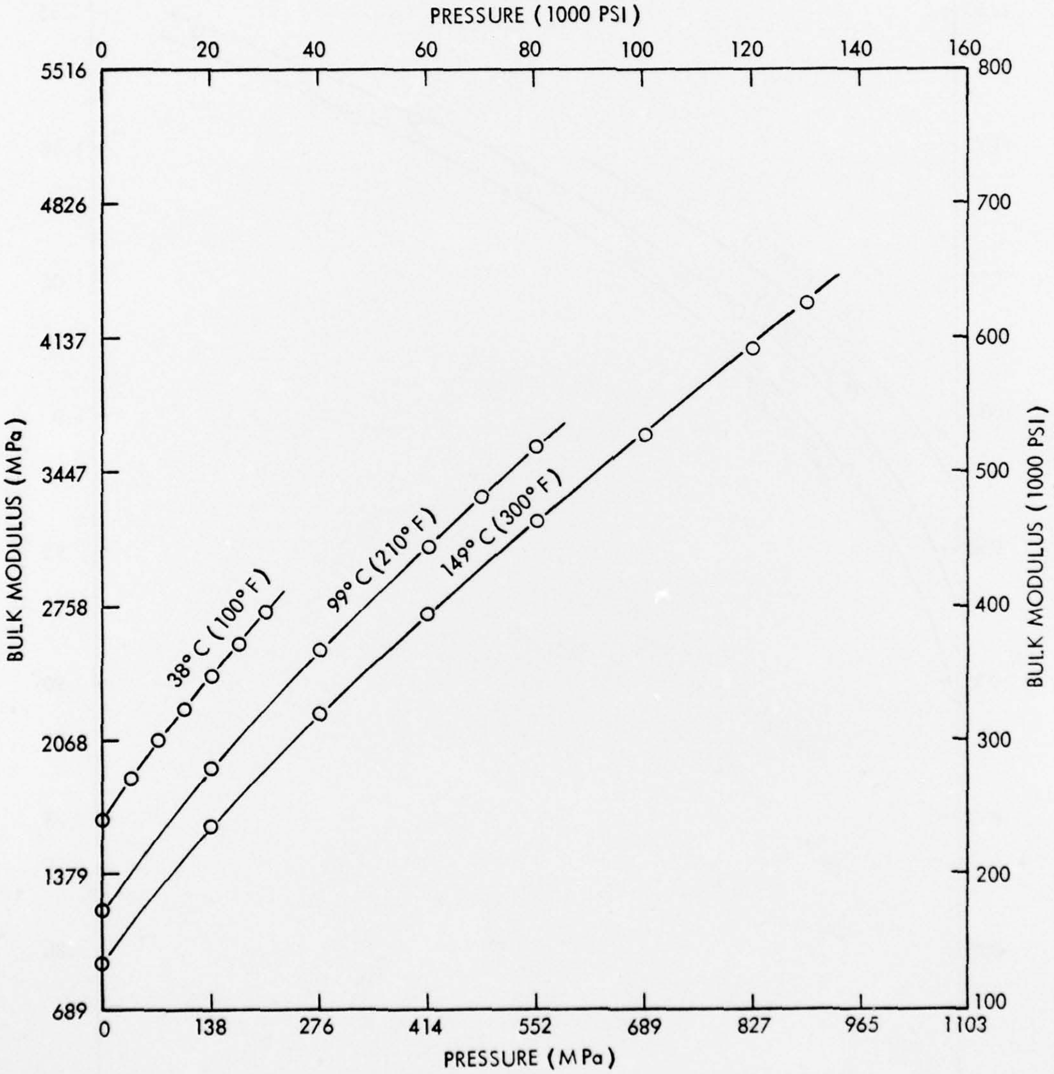


Figure 10 - Isothermal Secant Bulk Modulus Versus Pressure - ELO 67-22

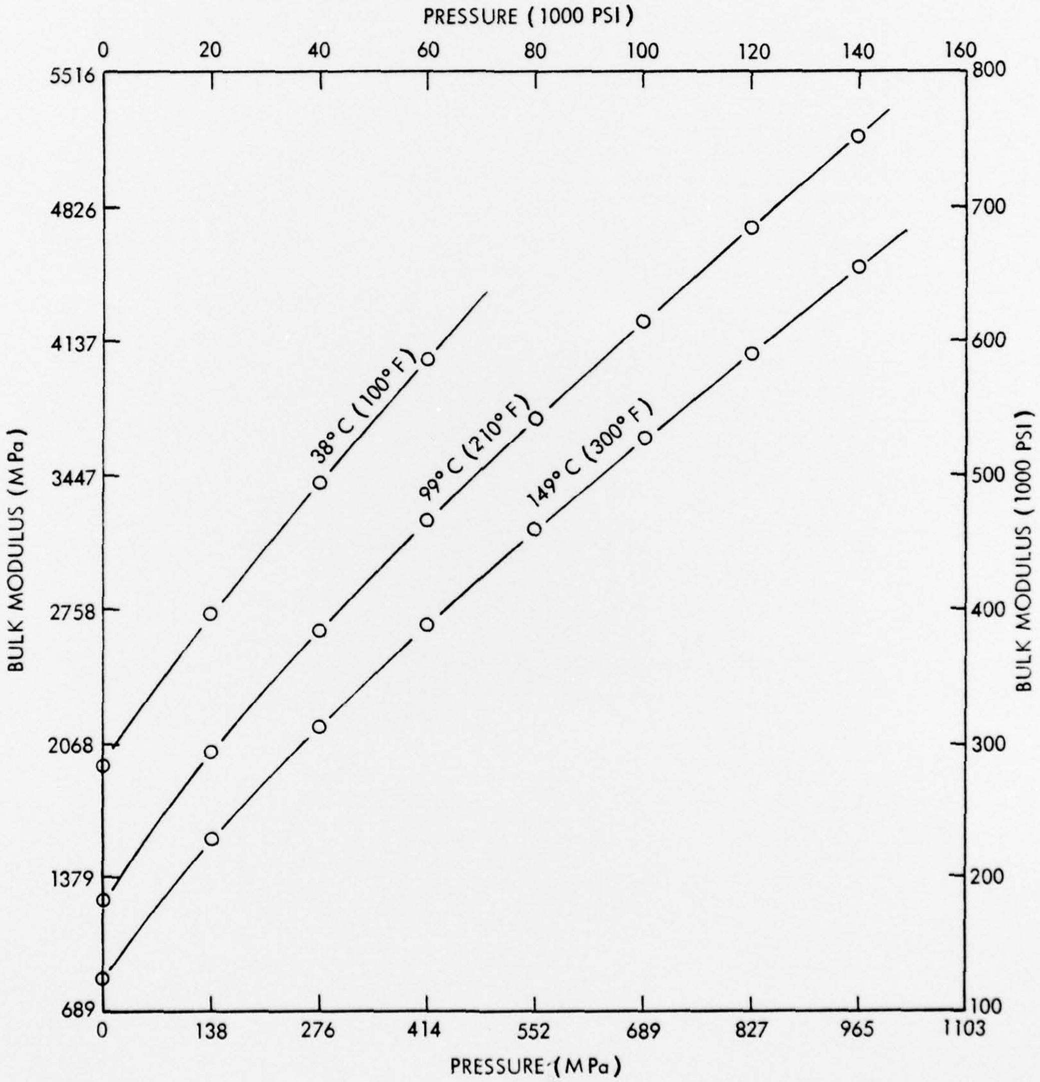


Figure 11 - Isothermal Secant Bulk Modulus Versus Pressure - ATL-4102

The probable error of the viscosity values reported in Tables 2 and 3 is estimated to be no greater than ± 5%. This estimate is based on the variation of fall times in the viscometer and the repeatability of the fall times. At present, no procedures are used to smooth the viscosity data; however, plots of viscosity as a function of pressure, Figures 6 and 7, tend to support this estimate.

REFERENCES

1. "Viscosity and Density of Over 40 Lubricating Fluids of Known Composition at Pressures to 150,000 psi and Temperatures to 425°F," ASME (1953).

2. Wilson, D. R. et al., "Effect of Extreme Environments on the Behavior of Fluids and Lubricants," ML-TDR-64-12, Part III, February 1966.

3. Wilson, D. R., "Effect of Extreme Conditions on the Behavior of Lubricants and Fluids," AFML-TR-67-8, Part III, February 1969.

4. Wilson, D. R., "Exploratory Development on Advanced Fluids and Lubricants in Extreme Environments by Mechanical Characterization," AFML-TR-70-32, Part I, March 1970.

5. Wilson, D. R., "Exploratory Development on Advanced Fluids and Lubricants in Extreme Environments by Mechanical Characterization," AFML-TR-70-32, Part II, February 1971.

6. Bossert, A. J., and V. Hopkins, "Determination of Changes in Lubricant Viscosities at High Pressures and Temperatures," AFML-TR-74-195, October 1974.

☆ U. S. GOVERNMENT PRINTING OFFICE: 1977 — 757-001/509