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By Mayo D. Hersey

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In the development of Diesel engine fuel injection systems it is necessary to have an approximate knowledge of the absolute viscosity of the fuel oil under high hydrostatic pressures. This report has been prepared by the Special Research Committee on Lubrication of the American Society of Mechanical Engineers at the request of the National Advisory Committee for Aeronautics, and presents the results of experimental tests conducted by Mr. Jackson Newton Shore,* utilizing the A.S.M.E. high pressure equipment which had previously been described in a paper (Reference 1) by Mayo D. Hersey and Henry Shore.***

Experimental Method

Reference should be made to the paper cited (Reference 1) for a detailed description of the apparatus used. The viscometer itself is of the rolling ball type originally due to Dr. Alan E. Flowers.**** The pump, leakproof fittings and other high pressure equipment are similar to those originally developed by Professor P. W. Bridgman of Harvard University.

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For pressure up to 12,000 pounds per square-inch it was found unnecessary to use the intensifier or the manganin coil gauge. Pressures were produced by the pump and measured on a calibrated Bourdon tube gauge. The pump was connected direct to the viscometer by means of a six-foot length of Shelby tubing and the entire system was filled with the sample under test.

The principal change made for the purpose of the present tests consisted in replacing the standard 1/4 inch steel ball by a 3/8 inch ball. This was done in order to adapt the viscometer for liquids of much lower viscosity than had been tested hitherto. Since the bore of the viscometer tube is 27/64 inch, the 3/8 ball reduced the radial clearance to 3/128 inch, thus introducing a sufficient amount of viscous resistance to appreciably retard the motion of the ball and permit accurate time observations.

Under these new conditions it was necessary to recalibrate the viscometer, since the published calibration curve (Fig. 6, of Reference 1), applies only to the 1/4 inch ball.

Calibration was accomplished by the use of five liquids whose viscosities were already known at atmospheric pressure, viz., methyl alcohol, water, kerosene, the Diesel fuel oil sample, and a white mineral oil. The calibration curve thus obtained checked almost perfectly with similar data obtained by the use of P. W. Bridgman's values for the relative viscosities of kerosene under various pressures (Reference 2) up to 15,000 pounds per square-inch, as shown by Figure 1 herewith.

Description of the Fuel Oil

The sample submitted from the Langley Memorial Aeronautical Laboratory had been purchased in conformity with Government Specifications* and in addition, possessed the following characteristics:

Viscosity (absolute) at 20°C	0.061 poises
" " " 30°C	0.46 "
Density at 20°C	0.864 g/cm³
" " 30°C	0.858 "

Computations of the density of the sample ρ, as a function of pressure and temperature, which are necessary for interpreting the readings of the viscometer, were made in accordance with the published formula (Reference 1)

$$\rho = \rho_o \left(1 + \frac{p}{E} - \frac{\theta}{A}\right) \qquad (1)$$

in which ρ_o denotes the density at atmospheric pressure $p = 0$, and at a temperature of 25°C, while θ represents the temperature elevation above 25°C. From the density values tabulated above, ρ_o was found equal to 0.861 g/cm³, and A (reciprocal of thermal expansivity) equal to 1350°C. The bulk modulus of elasticity E, was taken equal to 284,000 lb./sq.in., a mean

*Bureau of Mines Technical Paper 323B.

between published values for kerosene and for lubricating oils, which is considered a safe approximation since this factor enters only as a small correction term.

From equation (1) the maximum density occurring in the present tests was found to be $\rho = 0.898$ at 22.6°C under a pressure of 12,000 lb./sq.in., and the minimum $\rho = 0.850$ at 100°C under atmospheric pressure.

Numerical Data and Results

The actual stop-watch readings, uncorrected for initial acceleration of the ball, are recorded in Table I, where T_o denotes the observed roll-time in seconds and p the corrected gauge pressure in pounds per square inch above atmospheric pressure. Each time reading is the mean of several observations.

TABLE I. Original Time Observations

Temp. 22.6°C			Temp. 50°C			Temp. 100°C		
Test No.	Press. lb./sq.in.	T_o sec.	Test No.	Press. lb./sq.in.	T_o sec.	Test No.	Press. lb./sq.in.	T_o sec.
1	0	6.13	11	0	4.60	20	0	3.60
2	12000	20.5	12	3000	5.17	21	3000	4.00
3	0	6.27	13	6000	5.57	22	6000	4.17
4	12000	20.7	14	9000	6.87	23	9000	4.70
5	0	6.50	15	12000	8.20	24	12000	4.87
6	3000	8.13	16	9000	7.57	25	9000	4.47
7	6000	11.0	17	6000	6.10	26	6000	4.20
8	9000	15.5	18	3000	5.20	27	3000	4.00
9	12000	21.3	19	0	4.60	28	0	3.67
10	0	6.60						

Corrections for acceleration were made by equation (1) (Reference 1) and were never as large as 1 per cent. A re-examination of the derivation of this formula showed that the constant k is independent of the ball diameter, directly proportional to the sine of the angle above the horizontal, and inversely proportional to the length of path through which the ball moves. The same value as before was therefore used. Corrections for change of path due to compression of the rubber washers were also made as before, and the combined correction for acceleration and compression was never greater than 1 per cent.

From the corrected time values and the density values according to equation (1) above, a table was computed showing the values of ST for each of the 28 tests, where S denotes $\sqrt{\frac{\rho_o}{\rho} - 1}$, taking ρ_o as before = 7.9 g/cm³ for the ball density. From the calibration chart (Fig. 1), the corresponding U/S values were read off, where U is the kinematic viscosity, i.e., μ/ρ. Knowing ρ, the absolute viscosity is now obtained from the slide rule.

The absolute viscosities thus determined, and their logarithms, are recorded in Table II and the latter are plotted in Figure 2 herewith.

TABLE II. Original Viscosity Values

Test No.	Pressure lb./sq.in.	Viscosity, poises	
		μ	$\log \mu$
	Tests 1-10 incl. at 22.6°C		
1	0	.0498	$\bar{2}.6972$
2	12000	.239	$\bar{1}.3784$
3	0	.0526	$\bar{2}.7210$
4	12000	.240	$\bar{1}.3802$
5	0	.0563	$\bar{2}.7505$
6	3000	.0794	$\bar{2}.8998$
7	6000	.119	$\bar{1}.0755$
8	9000	.179	$\bar{1}.2529$
9	12000	.284	$\bar{1}.4533$
10	0	.0578	$\bar{2}.7619$

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TABLE II. Original Viscosity Values (Cont.)

Test No.	Pressure lb./sq.in.	Viscosity, poises	
		μ	$\log \mu$
Tests 11-19 incl. at 50°C			
11	0	.0292	$\bar{2}.4654$
12	3000	.0361	$\bar{2}.5575$
13	6000	.0421	$\bar{2}.6243$
14	9000	.0610	$\bar{2}.7853$
15	12000	.0782	$\bar{2}.8932$
16	9000	.0708	$\bar{2}.8500$
17	6000	.0502	$\bar{2}.7007$
18	3000	.0367	$\bar{2}.5647$
19	0	.0278	$\bar{2}.4579$
Tests 20-28 incl. at 100°C			
20	0	.0128	$\bar{2}.1072$
21	3000	.0188	$\bar{2}.2742$
22	6000	.0211	$\bar{2}.3243$
23	9000	.0287	$\bar{2}.4579$
24	12000	.0316	$\bar{2}.4997$
25	9000	.0255	$\bar{2}.4065$
26	6000	.0218	$\bar{2}.3385$
27	3000	.0188	$\bar{2}.2742$
28	0	.0139	$\bar{2}.1430$

Graphical Presentation of Results

Values of $\log \mu$ from the smooth curves of Figure 2 are replotted in Figure 3 against $\log t^\circ F$ in the form of constant pressure curves (isopiestics), at intervals of 2000 pounds per square-inch, over the temperature range from 20° to 120°C. The use of $\log t^\circ F$ rather than $\log t^\circ C$ has the advantage of giving nearly straight lines.

Interpolating on Figure 3, at equally spaced Centigrade temperatures, viz., 20°, 40°, 60°, 80°, 100°, and 120°C, provides data for Figure 4, in which the approximate absolute viscosity in poises has been represented as a function of pressure up to 12,000 pounds per square-inch, at the temperatures stated. For convenience, two more isothermal curves have been added at intermediate temperatures, 25° and 30°C.

Absolute viscosities read from Figure 4, are believed to be accurate within 5 per cent at every point.

June 21, 1929.

References

1. Hersey, Mayo D. and Shore, Henry : Viscosity of Lubricants Under Pressure. Mech. Eng., Vol. 50, 1928, pp.231-232.

2. Bridgman, P. W. : Proc. Am. Acad. Arts Sci., Vol. 61, No. 3, 1926, pp.57-99 (see p.82).

Calibration of high pressure viscometer
(Ball 3/8" diam., angle 16°10', path 9-5/8")

T=Corrected time, seconds.
U=Kinematic viscosity, C.G.S.
S=$\sqrt{R-1}$ where
R=Ratio of ball density to liquid density.
Dot circles=Kerosene at high pressures.
Open circles=Various liquids, atmosph.press.

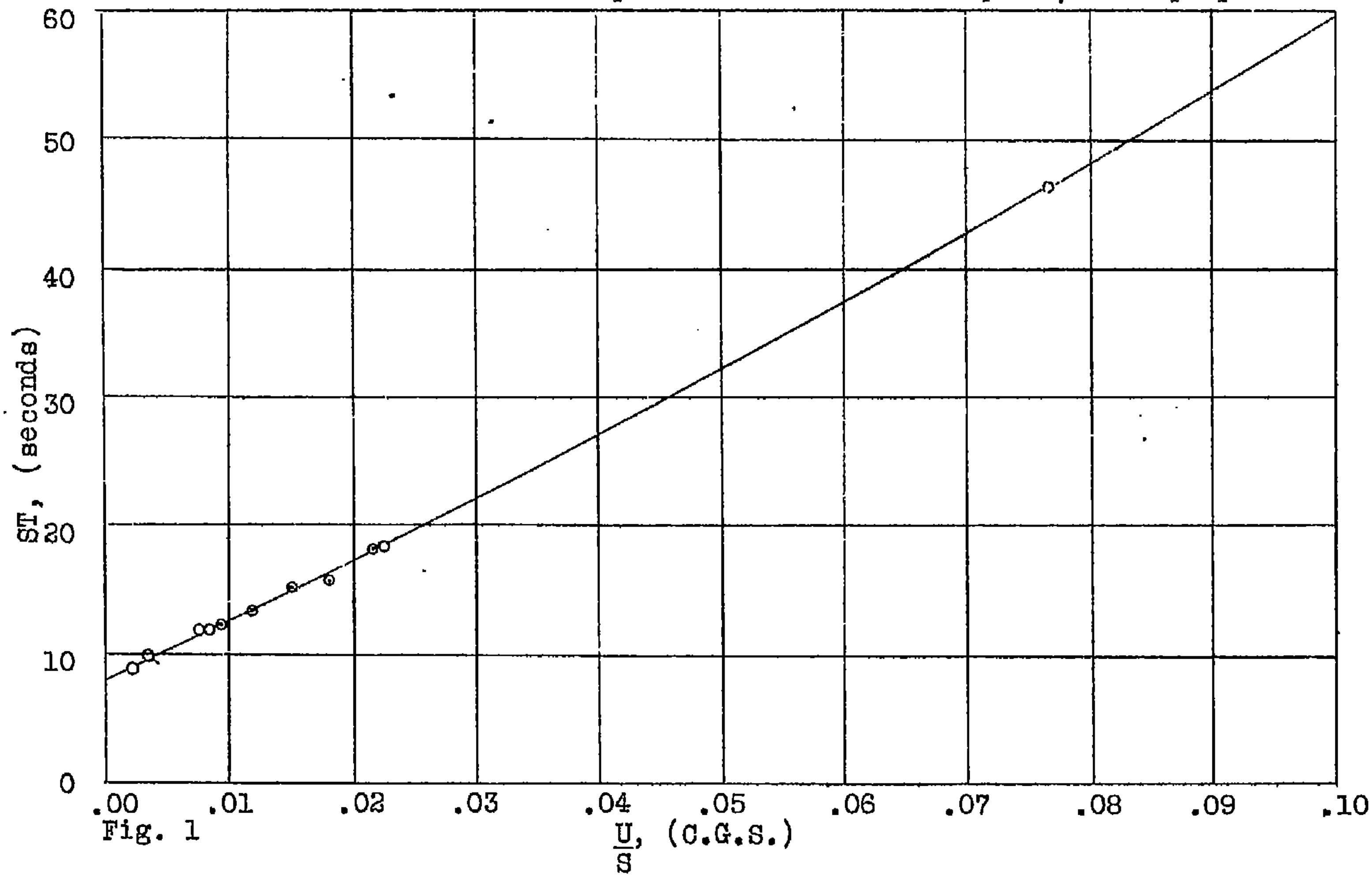


Fig. 1

N.A.C.A. Diesel engine fuel oil

Plot showing the original observations
at three temperatures

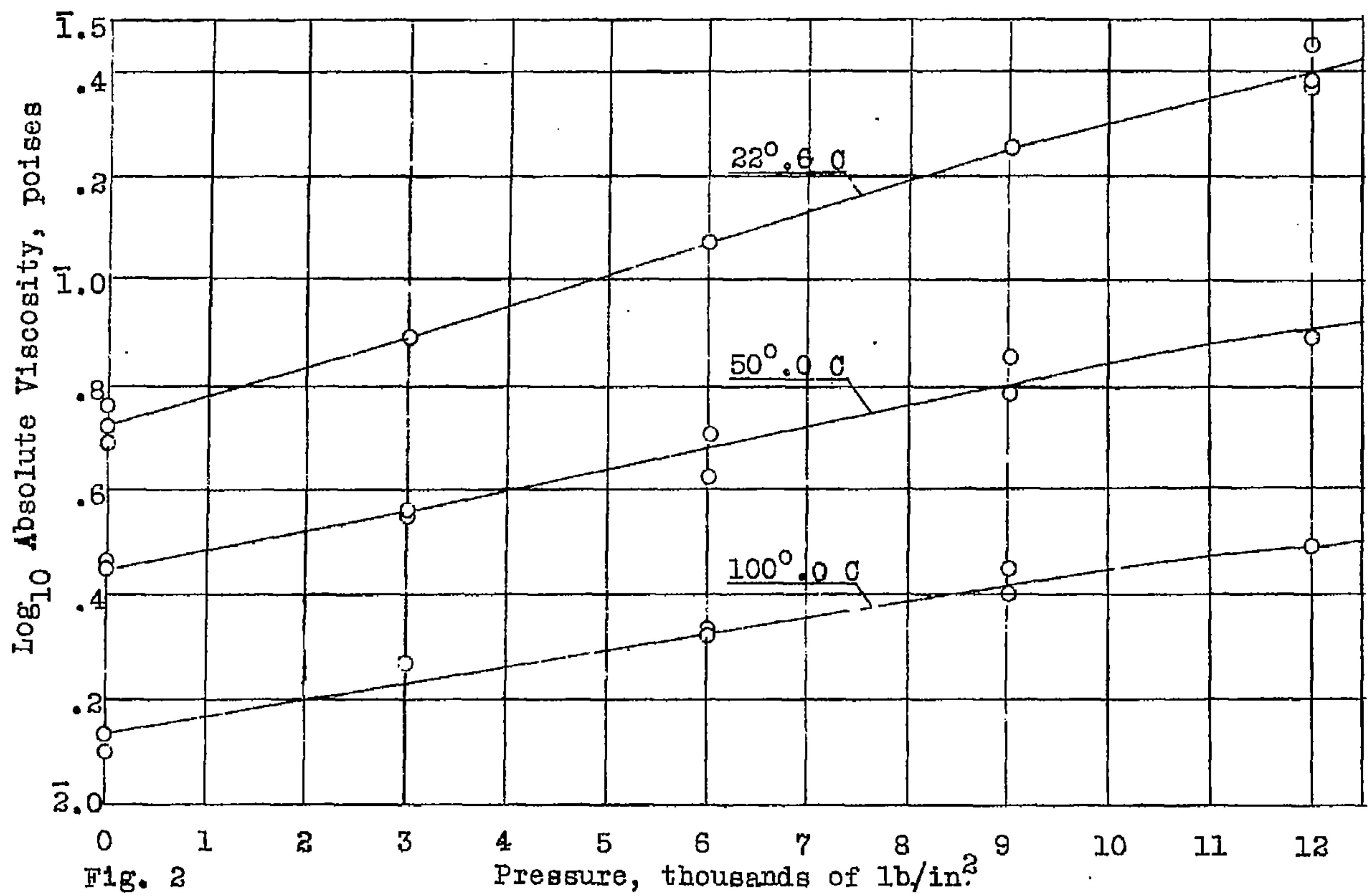
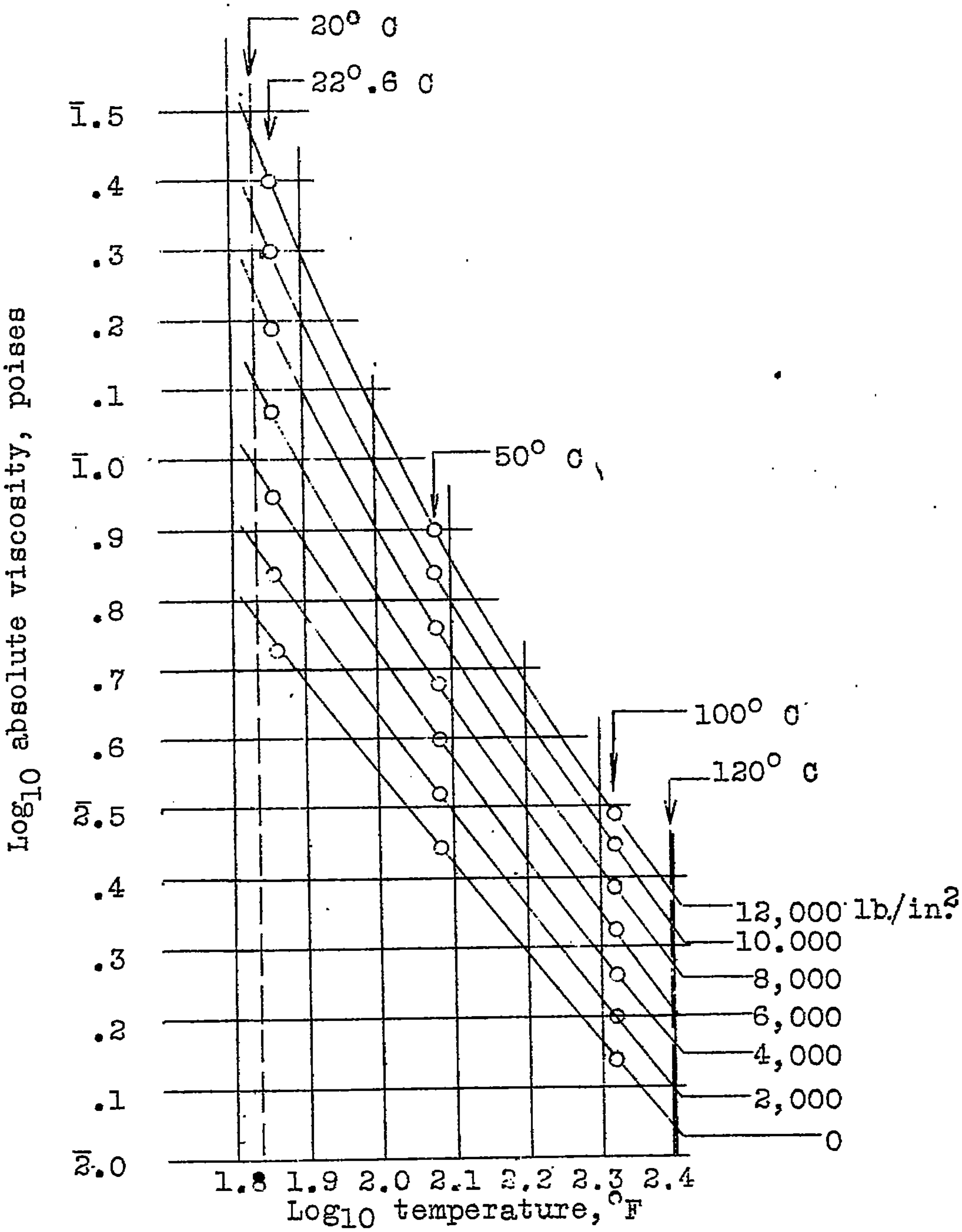


Fig. 2

N.A.C.A. Diesel engine fuel oil:
Log plot showing relation
of viscosity to temperature
at various constant pressures.



N.A.C.A. Diesel engine fuel oil

Chart showing viscosity as a function of pressure for temperatures from 20° to 120° C

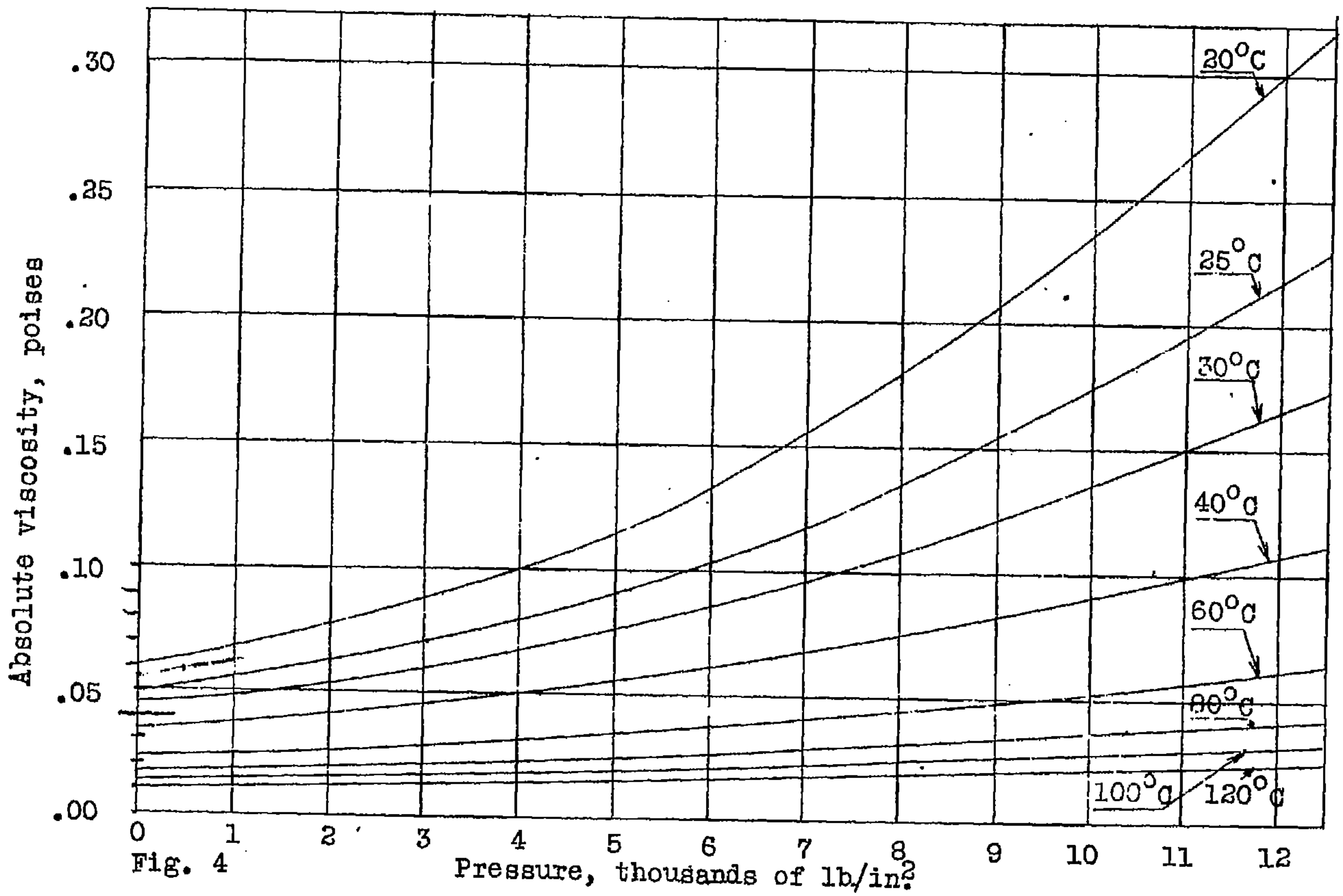


Fig. 4