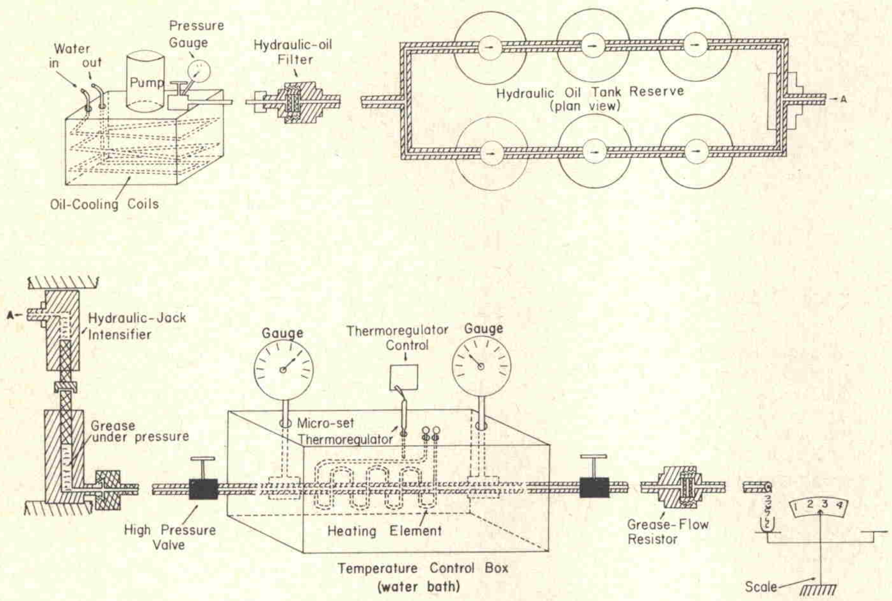

FIG. 15. Schematic of high-pressure apparatus.

leaks. The grease is injected with a grease gun through a port containing a ball valve.

The grease is ejected through a high-pressure stainless steel tube into a stainless steel capillary whose internal diameter is 0.083 in. The test capillary is provided with two pressure gauges, exactly 40 in. apart, for measuring the initial pressure P_i and final pressure P_f.

3. Temperature Control

The capillary is kept in a temperature controlled refrigeration (−45°C) and water bath unit (Fig. 16 G) fitted with heating coils controlled by a Micro-set thermoregulator through a thermorelay. A "reservoir" capillary coil is incorporated in the temperature control unit, just before the initial-pressure gauge, to gain thermo-equilibrium of grease in the test capillary.

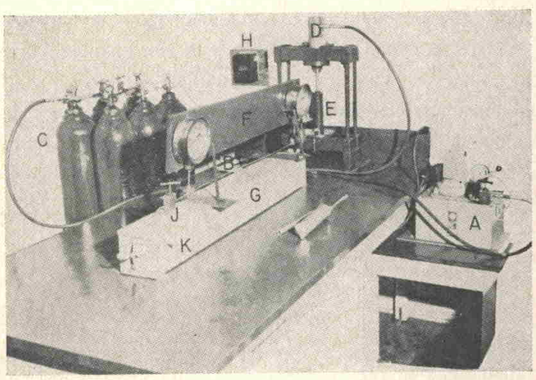

FIG. 16. Photograph of apparatus: (A) model Y26-A Vanguard 5-cylinder, axial-piston pump supercharged by a gear pump, (B) hydraulic-oil filter, (C) war-surplus cylinders—oxygen and/or nitrogen—filled with hydraulic oil, (D) OTC single-acting 20-ton hydraulic ram, (E) pressure chamber, (F) pressure gauges, (G) temperature-control refrigeration (−45°C) and water bath unit, (H) thermoregulator control, (J) high pressure valve, (K) bath water outlet.

MEASUREMENTS

1. Newtonian Flow

The pressure drops through the 40-in. capillary between the two gauges are obtained by controlling the initial pressure P_i and the final pressure P_f, for a constant average pressure of $(P_i+P_f)/2$. Thus, various pressure drops are obtained under the same hydrostatic pressure $(P_i+P_f)/2$.

The pressure P_i and P_f on the gauges are controlled by the pump—reserve-tank arrangement and the outlet valve (Fig. 16 J), respectively. With some greases at the higher pressures (15 to 30 000 psi) one outlet valve did not completely control fluctuation at the "final-pressure" gauge. Excellent control was achieved by putting in series with the outlet valve a coiled and a "filter" type resistance to the grease flow plus a second valve. Proper adjustment of the two valves proved to be completely satisfactory for minimizing gauge fluctuation.

The weight of grease extruded under pressure through the capillary tube during a given time interval is a measure of flow rate Q. The flow rate Q through a tube of radius r and length L at a pressure drop ΔP is converted to shear stress f and shear rate $\dot{s}$ by the following relations:

$$f=r\Delta P/2L$$
$$\dot{s}=4Q/\pi r^3.$$

A plot of shear rates $\dot{s}$ against shear stress f shows the flow curves for a material.

2. Non-Newtonian Flow

Since 1884 investigators have worked[36,37] on theoretical relations for the non-Newtonian behavior of oils as a func-

[36] W. Warburg and S. Sachs, Am. J. Phys. 22, 518 (1884).
[37] C. Barass, Am. J. Sci. 45, 87 (1893).

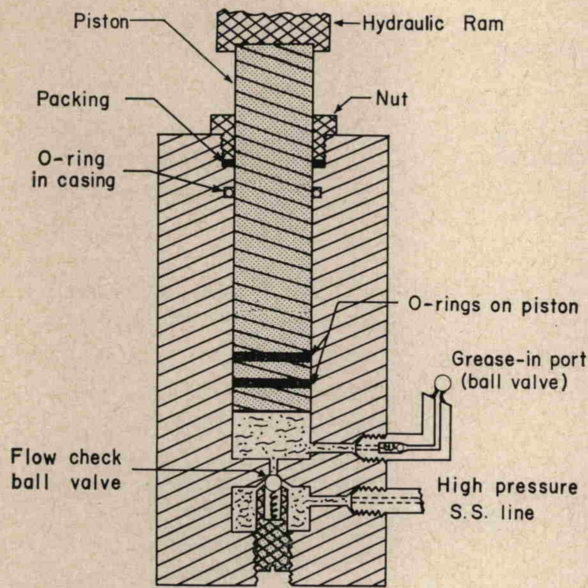

FIG. 17. Schematic of pressure chamber.

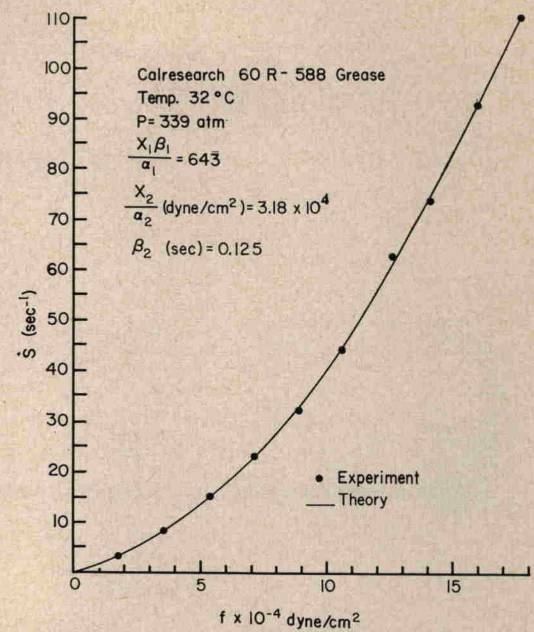

FIG. 18. Flow curve of Calresearch 60R-588 grease at 32°C.

tion of pressure. These were successively, but empirically, improved by later workers.[38–42] Ewell and Eyring[43] also Frish, Eyring, and Kincaid[44] have advanced a general theory of the effect of pressure on viscosity. The pressure effect is given as due to the volume change in passing from a normal to an activated state; e.g.,

$$\Delta F^{\ddagger}=\Delta F_1^{\ddagger}+P\langle\Delta V\rangle_{\mathrm{av}}^{\ddagger}, \qquad (22)$$

where $\langle\Delta V\rangle_{\mathrm{av}}$ is the average volume increase for passage from the normal to the activated state.

Present studies of the rate of shear as a function of shear stress $[\dot{s}=F(f)]$ are concerned with the flow mechanism of lubricants and high polymer solutions based on the assumptions that (a) stationary and viscous flow occurs where there is (b) no slippage on the wall and (c) the fluids are incompressible: For flow in a capillary, consider a cylindrical liquid surface of radius r and length L under a shear stress f (in dyn/cm²). For both Newtonian and non-Newtonian units, the resultant force, due to longitudinal traction, $2\pi rLf$, on the cylindrical surface of the capillary wall, must be equal to the net driving force, $\pi r^2\Delta P$, i.e., $f=(\Delta P/2L)r$.

The rate of shear $\dot{s}$ is defined as the negative of the gradient of fluid velocity u or

$$\dot{s}=-du/dr. \qquad (23)$$

[38] H. Suge, Bull. Inst. Phys. Chem. Research (Tokyo) **12**, 643 (1933).
[39] S. J. Needs, Trans. ASME **60**, 347 (1938).
[40] E. K. Gatcombe, Trans. ASME **67**, 177 (1945).
[41] R. B. Dow, J. S. McCartney, and C. E. Fink, J. Inst. Petrol. **27**, 301 (1941).
[42] M. D. Hersey and D. B. Lowdenslager, Trans. ASME **72**, 035 (1950).
[43] H. Ewell and H. Eyring, J. Chem. Phys. **5**, 726 (1937).
[44] D. Frish, H. Eyring, and J. Kincaid, J. Appl. Phys. **11**, 75 (1940).

The flow rate Q is given by

$$Q=\int_0^R \pi r^2\dot{s}dr=8\pi L^3/P^3\int_0^{f_w}\phi f^3 df, \qquad (24)$$

where $f_w=RP/2L$ and is equal to the shearing stress at the wall of the capillary of radius R, and $\phi=\dot{s}/f$ is the fluidity (reciprocal of viscosity). In the Newtonian case ϕ is a constant.

Integrating Eq. (3) results in the well-known Hagen–Poiseville[45] equation $\phi=8LQ/\pi R^4P$. When ϕ is a function of f, as in the non-Newtonian case, $\dot{s}$ is given in terms of the flow rate as[35]

$$\dot{s}=1/\pi R^3[3Q+PdQ/dP]. \qquad (25)$$

The P and Q relationship is obtained from experiment, e.g., Fig. 18. Thus, all the quantities on the right side of Eq. (4) are known[46] since dQ/dP is the slope of the Q–P curve.

Based on the theory of rate processes, Eyring[47] derived an equation for a non-Newtonian system. The relation between shear stress f and shear rate $\dot{s}$ for a system composed of n flow units of different relaxation times is given by

$$f=\sum_n^{\infty} X_n/\alpha_n \sinh^{-1}\beta_n\dot{s}. \qquad (26)$$

[45] S. Glasstone, *Physical Chemistry* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1951), 2nd ed., p. 497.
[46] The capillary radius R is generally uniform. However, it has been determined that in some capillaries R varies, making it necessary to determine its "average value" by calibrating the capillary with a "standard" fluid.
[47] S. Glasstone, K. J. Laidler, and H. Eyring, *The Theory of Rate Processes* (McGraw-Hill Book Company, Inc., New York, 1941), pp. 477–551.