
REPORT No. 299

**INVESTIGATION OF DAMPING LIQUIDS
FOR AIRCRAFT INSTRUMENTS**

**By G. H. KEULEGAN
Bureau of Standards**

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SUMMARY

This report covers the results of an investigation carried on at the Bureau of Standards with the financial assistance of the National Advisory Committee for Aeronautics.

The choice of a damping liquid for aircraft instruments is difficult owing to the range of temperature at which aircraft operate. Temperature changes affect the viscosity tremendously. The investigation was undertaken with the object of finding liquids of various viscosities otherwise suitable which had a minimum change in viscosity with temperature. The new data relate largely to solutions.

The effect of temperature on the kinematic viscosity of the following liquids and solutions was determined in the temperature interval -18° to $+30^{\circ}$ C.

(1) Solutions of animal and vegetable oils in xylene. These were poppy seed oil, two samples of neat's-foot oil, castor oil and linseed oil.

(2) Solutions of mineral oils in xylene. These were Squibb's petrolatum of naphthene base and transformer oil.

(3) Glycerine solutions in ethyl alcohol and in mixture of 50-50 ethyl alcohol and water.

(4) Mixtures of normal butyl alcohol with methyl alcohol.

(5) Individual liquids; kerosene, mineral spirits, xylene, and recoil oil.

The apparatus consisted of four capillary-tube viscometers, which were immersed in a liquid bath in order to secure temperature control. The method of calibration and the related experimental data are presented in detail.

The viscosity data for the liquids are given in curves in which $\log_{10} \frac{t_{\theta}}{t_{30}}$ is plotted against temperature, where t_{30} and t_{θ} are respectively the times of discharge through the viscometer at 30° C. and θ° C. Except for a correction which is usually small, the following relation holds:

$$\log_{10} \frac{t_{\theta}}{t_{30}} = \log_{10} \frac{\nu_{\theta}}{\nu_{30}}$$

in which ν_{30} and ν_{θ} are respectively the kinematic viscosities at 30° C. and θ° C. The density at 30° C., the coefficient of cubical thermal expansion for each solution, and ν_{30} are given, together with other data, so that the absolute viscosity may be computed. The accuracy is within 1 per cent.

INTRODUCTION

This investigation was undertaken in order to obtain data on the viscosity and the change in viscosity with temperature of such liquids and solutions as may be suitable for damping purposes in aircraft instruments. Damping liquids in many cases must also have other characteristics, such as invariability with time, low volatility, and constancy of index of refraction and transparency for varying temperatures. These latter characteristics are not dealt with in this paper except incidentally.

Most of the liquids which were chosen for the tests are solutions of mineral, vegetable, and animal oil in xylene. The selection of xylene as a solvent for the heavier oils finds its reason in the fact that it has a low thermal coefficient of viscosity for the thermal range considered in

aircraft instruments, which is the range $+30^{\circ}\text{C.}$ to -30°C. The range of temperatures in the tests was somewhat smaller than this and was from $+30^{\circ}\text{C.}$ to -18°C.

An accuracy of 1 per cent was aimed at in the determination of viscosity at the temperature of 30° centigrade. Two considerations have discouraged possible effort for greater precision: First, it is a known fact that most oily solutions age with time, and therefore the viscosity of such solutions need not be accurately determined except for the purpose of showing that the viscosity changes (Reference 1); secondly, more precise determinations of viscosity for the particular range adopted can not be realized with a reasonable amount of attention and effort.

It is desired to acknowledge the valuable assistance of Dr. W. G. Brombacher and the substantial help of Mr. E. R. Melton in obtaining the experimental data.

APPARATUS AND EXPERIMENTAL PROCEDURE

VISCOMETERS

Consider the particular Ostwald-type viscometer which is shown in Figure 1. The discharging and receiving bulbs A and B are cylinders of equal radius and volume. The timing of the flow is made for the total discharge of liquid in the discharging bulb A . When this total discharge has taken place, the receiving bulb B is just full and the discharging bulb A is empty. Now if liquid flows under its own weight the following expression holds, which is Poiseuille's law applied to the present case (Reference 2):

$$\mu = \frac{\pi r^4 g \rho}{8 l_e Q} \frac{2 h_r}{\log_e \left(\frac{h_o + h_r}{h_o - h_r} \right)} t \quad (1)$$

where

μ = the absolute viscosity in poises.

t = the time of discharge in seconds.

Q = the volume of the discharging bulb in cm.^3 .

h_r = the height of B or of A (see fig. 1) in cm.

h_o = the vertical distance between the centers of the bulbs A and B in cm.

l_e = the effective length of the capillary tube in cm.

r = the radius of the capillary tube in cm.

ρ = the density of the liquid in grams per cm.^3

g = the acceleration of gravity in cm. per sec.²

In practice deviations are made from the viscometer just discussed, particularly in the design of the bulbs. The one which is adopted for the present work is shown in Figure 2. The discharging bulb is a combination of cone frustrums and a cylinder, while, the receiving bulb is a cylinder which has the same radius as the cylinder in the discharging bulb. The volume of the discharging bulb A is included between the marks M_2 and M_1 , which will be spoken of as the timing marks.

In order to compensate for the slight deviation from the ideal case, equation (1) is modified as follows:

$$\mu = \frac{\pi r^4 g \rho}{8 l_e Q} \frac{2 h_r t}{\log_e \left(\frac{h_o + h_r + C}{h_o - h_r + C} \right)} \quad (2)$$

or putting

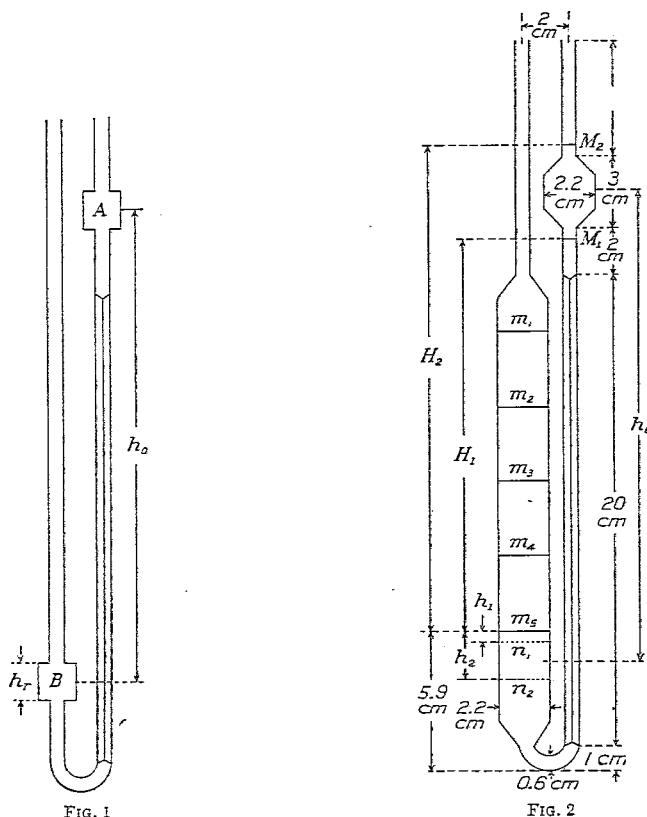
$$A_o = \frac{\pi r^4 g}{8 l_e Q} \quad (3)$$

$$\mu = \rho A_o \frac{2 h_r t}{\log_e \left(\frac{h_o + h_r + C}{h_o - h_r + C} \right)}$$

Here all of the quantities except h_o , h_r , and C have the same meaning as in equation (1). C is to be determined experimentally, while h_o and h_r are defined in the following paragraph.

The quantity C may involve a constant term and an expression dependent on h_0 . The latter would be small in comparison with the constant term and therefore can be neglected.

It will be supposed that when the liquid in the viscometer is in equilibrium under its own weight its free surface in the receiving tube B occupies the mark m_5 . (See fig. 2.) Such marks will be spoken of as the filling mark of the viscometer. When the liquid is forced to the level of the timing mark M_1 of the discharging bulb, the free surface of the liquid in the receiving tube will descend to a level n_1 . When the liquid is next forced to the timing mark M_2 , the corresponding level in the receiving tube will be n_2 . Denoting by H_1 and H_2 the vertical distances



of M_1 and M_2 from m_5 and by h_2 and h_1 the vertical distances of n_2 and n_1 from m_5 , the definitions of h_0 and h_r are

$$h_r = h_2 - h_1$$

$$h_0 = \frac{H_1 + H_2 + h_1 + h_2}{2} \quad (4)$$

Equations (2) and (3) hold only for slow rates of flow. If the velocity is fast, the following equation applies:

$$\mu = \rho \left[A_0 \frac{2h_r t}{\log_e \left(\frac{h_0 + h_r + C}{h_0 - h_r + C} \right)} - \frac{B}{t} \right] \quad (5)$$

where

$$B = \frac{mQ}{8\pi l_e} \quad (6)$$

The term $\frac{B\rho}{t}$ is known as the inertia term. The quantity m which appears in the definition of B is a constant quantity for a given viscometer; its value may vary from 1 to 2, depending on the configuration of the ends. (Reference 4.)

A relation proposed by Bond (Reference 3) is that equation (3) applies when

$$\frac{Q' \rho}{r \mu} = \frac{Q}{r} \frac{\rho}{\mu t} = \frac{Q}{r} B_c \leq 16 \quad (7)$$

and that equation (5) should be used for values in excess of 16. Q' is the volume rate of flow of the liquid, which is Q/t for all practical purposes. B_c may be called Bond's criterion. This relation was shown to hold only for short-length, thick-walled, and square-edged capillaries.

In capillaries with trumpet-shaped ends the quantity $\frac{Q}{r} B_c$ is larger than 16. (Reference 4.)

It should be noted that multiplying the quantity $\frac{Q}{r} B_c$ by $\frac{2}{\pi}$ gives the expression for the more familiar Reynolds Number; thus the criterion 16 is equivalent to a Reynolds Number of $\frac{32}{\pi}$.

The viscometers used during measurements were four in number. They were alike in design, except for the radii of the bores, and conform to the data given in the sketch in Figure 2. In each viscometer there were five filling marks, allowing five different rates of flow. Generally it is the lowest one—that is, m_5 , which was used during the tests. However, use was made of the other filling marks in the calibration of the viscometers. The proportions of the discharging bulb were designed for the smallest error in drainage (Reference 5), which requires that the height of the conical portion is at least equal to the height of the cylindrical portion. The distance between the timing marks was nearly 3.5 cm., while the distances between two consecutive filling marks were nearly 3 cm. Approximate essential dimensions, such as the radii of capillaries r , the volumes of discharging bulbs Q , the length of capillaries when the trumpetlike ends are excluded, l_2 , and when they are included, l_1 , are given in Table I. The dimension r was found by weighing the mercury contained in a measured length of the capillary tube and Q by weighing mercury both at a temperature of 23° C.

TABLE I

Viscometer	Radius of capillary r	Volume of bulb Q	Length of capillary	
			l_2	l_1
	<i>Cm.</i>	<i>Cm.³</i>	<i>Cm.</i>	<i>Cm.</i>
V ₁ -----	0.0519	6.37	19.6	20.2
V ₂ -----	.0641	5.84	19.6	20.2
V ₃ -----	.1085	6.81	19.5	20.2
V ₄ -----	.1283	6.28	19.3	20.0

CALIBRATION OF VISCOMETERS

Equation (5) is the working formula of the viscometers which shall be denoted by V₁, V₂, V₃, and V₄. There are three constants to be determined by calibration; these constants are A_o , B , and C . The equation (5) can be made linear in these constants if C is sufficiently small with respect to $h_o - h_r$. It will be assumed that this is the case. It can be shown that

$$\log_e \frac{h_o + h_r + C}{h_o - h_r + C} = \log_e \left(\frac{h_o + h_r}{h_o - h_r} \right) - \frac{2h_r C}{h_o^2 - h_r^2} + \frac{2h_r}{h_o^2 - h_r^2} \cdot \frac{h_o}{h_o^2 - h_r^2} C^2$$

or defining

$$N = \log_e \frac{h_o + h_r}{h_o - h_r}$$

$$M = \frac{2h_r}{h_o^2 - h_r^2}$$

$$L = \frac{h_o}{h_o^2 - h_r^2}$$

$$\left(\log_e \frac{h_o + h_r + C}{h_o - h_r + C} \right)^{-1} = \frac{1}{N} + \frac{M}{N^2} C - \frac{M}{N^2} \left(L - \frac{M}{N} \right) C^2 \quad (8)$$

TABLE II
DATA FOR EVALUATING THE EFFECTIVE HEAD

Viscometer	Filling mark	h_0	h_0	$\frac{1}{N}$	M	$\frac{M}{N^2}$	L
V ₁ -----	m_1	1.73	6.52	1.840	0.0881	0.296	0.1650
	m_2		9.59	2.743	.0387	.292	.1078
	m_3		12.59	3.621	.0223	.292	.0810
	m_4		15.59	4.498	.0143	.292	.0649
	m_5		18.60	5.362	.0101	.290	.0542
V ₂ -----	m_1	1.62	6.94	2.102	.0711	.314	.1524
	m_2		9.98	3.051	.0334	.311	.1029
	m_3		12.97	3.976	.0196	.309	.0738
	m_4		16.01	4.929	.0128	.309	.0631
	m_5		19.05	5.862	.0090	.301	.0529
V ₃ -----	m_1	1.92	6.98	1.771	.0853	.267	.1550
	m_2		9.99	2.569	.0399	.263	.1039
	m_3		12.98	3.358	.0233	.263	.0788
	m_4		15.98	4.142	.0152	.262	.0635
	m_5		19.04	4.948	.0107	.262	.0531
V ₄ -----	m_1	1.99	6.55	1.594	.1022	.260	.1682
	m_2		9.63	2.384	.0448	.255	.1085
	m_3		12.61	3.141	.0257	.253	.0814
	m_4		15.62	3.903	.0166	.253	.0651
	m_5		18.56	4.649	.0117	.253	.0545

The values of $\frac{1}{N} \frac{M}{N^2}$, M and L for each filling mark of the four viscometers appear in Table II. It is evident from this table that the term containing C^2 in equation (8) is insignificant. Accordingly (5) becomes

$$\frac{\mu}{\rho} = \nu = A'_0 \left[\frac{1}{N} + \frac{M}{N^2} C \right] t - \frac{B}{t} \quad (9)$$

where $A'_0 = 2h_r A_0$ and ν represent the kinematic viscosity. By definition kinematic viscosity is the ratio of the viscosity in absolute units to the density.

In equation (9) the quantities A'_0 , C , and B are constants for each viscometer, independent of the filling marks. The term $2h_r g \rho \left(\frac{1}{N} + \frac{M}{N^2} C \right)$ is the effective pressure of which $2h_r g \rho$ is constant for each viscometer and included in with A'_0 , while $\frac{1}{N} + \frac{M}{N^2} C$ varies for each filling mark.

Since each viscometer has five filling marks, one standard liquid would be sufficient to determine the three constants, A'_0 , C , and B , providing that t could be measured with sufficient accuracy. In the determination of these constants at least three appropriate standard liquids were used for each viscometer. The viscosities of these liquids at $+25^\circ \text{C}$., except that of water, were furnished by the friction and lubrication section of the Bureau of Standards. The majority of them were mineral oils, and their viscosity values perhaps had undergone slight variation before use was made of them as calibrating liquids. During the calibrations no particular effort was exerted to observe the flows exactly at 25°C . as long as the temperature of the liquid remained in the vicinity of 25°C . By previously determining the thermal coefficient of each standard liquid all the observed values of the time of flow were reduced to that at 25°C . These reduced values of t_{25} obtained for the various viscometers are given in Tables IV, V, VI, and VII. When the known values of ν_{25} and the observed values of t_{25} were substituted in equation (9), the substitutions gave concordant values for A'_0 and C on the supposition that $m = 1.1$. The values are given below:

All of the constants in equation (9) are now known for the viscometers.

Viscometer	C	A'_0
	<i>Cm.</i>	
V ₁ -----	-0.09	0.776×10^{-4}
V ₂ -----	-.30	1.891×10^{-4}
V ₃ -----	-.24	1.540×10^{-4}
V ₄ -----	-.34	3.557×10^{-4}

The following procedure was adopted in order to study the concordance of the observations given in Figures 5 to 7 and the values of the constants. This will place the results of the calibration in final form for use in measuring viscosities. Define

$$\nu_1 = A_1 t \quad (10)$$

where

$$A_1 = A'_0 \left(\frac{1}{N} + \frac{M}{N^2} C \right)$$

The values of A_1 for each filling mark in each viscometer are given in Table III. Equation (10) gives the value of the kinematic viscosity ν_1 neglecting the term $\frac{B}{t}$. Denoting by ν the correct value of the kinematic viscosity, the percentage error of the kinematic viscosities when formula (10) is used becomes $\frac{\nu_1 - \nu}{\nu} \times 10^2$. These errors for the calibration are given in Tables IV, V, VI, and VII and in Figures 3, 4, and 5. The ratio $\frac{1}{t\nu}$ is plotted against these errors. This procedure is substantially that proposed by Herschel (Reference 6), since $\frac{1}{t\nu}$ is proportional to Reynolds Number, which is in our notation $\frac{2Q}{\pi r \nu t}$.

TABLE III
CALIBRATION OF VISCOMETERS V_1 , V_2 , V_3 , AND V_4 —VALUE OF A_1

Viscometer	Filling mark	A_1	Viscometer	Filling mark	A_1
V_1 -----	m_5	4.141×10^{-4}	V_3 -----	m_5	7.524×10^{-3}
	m_4	3.470×10^{-4}		m_4	6.283×10^{-3}
	m_3	2.790×10^{-4}		m_3	5.074×10^{-3}
	m_2	2.109×10^{-4}		m_2	3.859×10^{-3}
	m_1	1.408×10^{-4}		m_1	2.630×10^{-3}
V_2 -----	m_5	1.091×10^{-3}	V_4 -----	m_5	1.623×10^{-2}
	m_4	$.9145 \times 10^{-3}$		m_4	1.358×10^{-2}
	m_3	$.7343 \times 10^{-3}$		m_3	1.090×10^{-2}
	m_2	$.5594 \times 10^{-3}$		m_2	$.8170 \times 10^{-2}$
	m_1	$.3799 \times 10^{-3}$		m_1	$.5357 \times 10^{-2}$

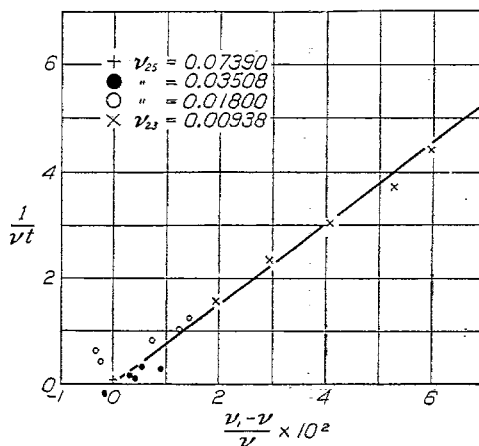


FIG. 3.—Calibration of viscometer No. 1

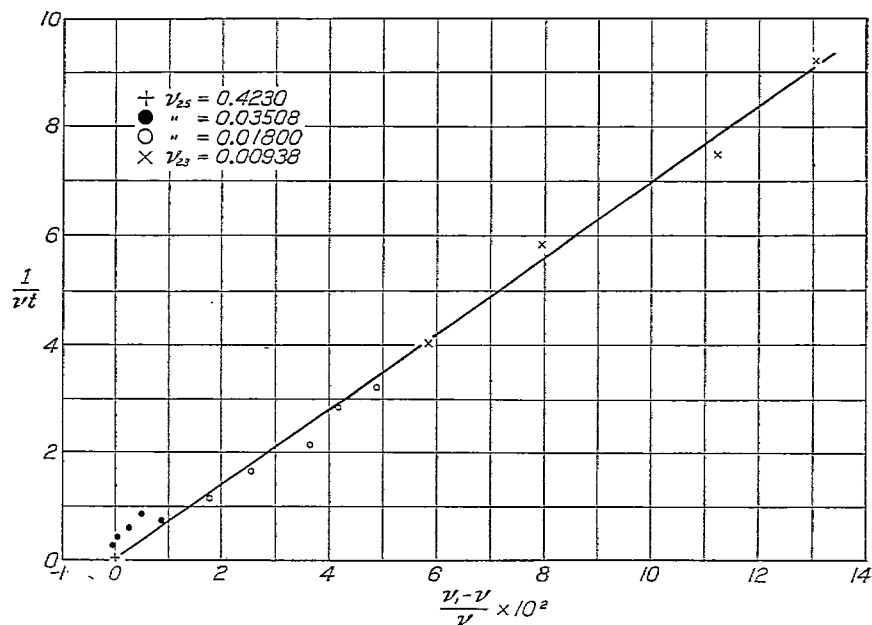


Fig. 4.—Calibration of viscometer No. 2

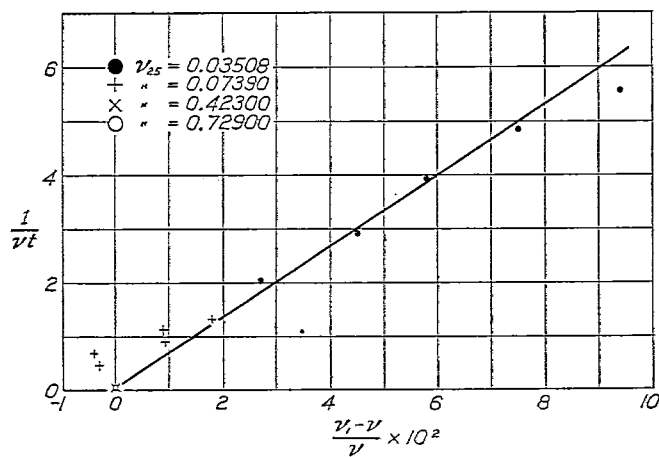


Fig. 5.—Calibration of viscometer No. 3

TABLE IV
CALIBRATION OF VISCOMETER V₁

Kinematic viscosity of liquid	Filling mark	Time t	Kinematic viscosity ν_1	Error $\frac{\nu_1 - \nu}{\nu} \times 10^2$	$\frac{1}{t\nu}$
$\nu_{25} = 0.07390$	m_5	Seconds 178.8	0.07404		0.07
$\nu_{25} = 0.03508$	m_5	85.2	.03528	0.56	.33
	m_4	102.0	.03540	.91	.28
	m_3	126.9	.03540	.91	.22
	m_2	166.9	.03519	.31	.17
	m_1	250.3	.03523	.42	.11
$\nu_{25} = 0.01800$	m_5	44.1	.01826	1.44	1.25
	m_4	52.5	.01822	1.22	1.05
	m_3	65.0	.01813	.72	.85
	m_2	85.1	.01794	-.32	.65
	m_1	127.6	.01796	-.22	.43
$\nu_{23} = 0.00938$	m_5	24.0	.00994	5.96	4.45
	m_4	28.4	.00986	5.24	3.77
	m_3	35.0	.00976	4.05	3.07
	m_2	45.8	.00966	2.98	2.35
	m_1	67.9	.00956	1.92	1.58

TABLE V
CALIBRATION OF VISCOMETER V₂

Kinematic viscosity of liquid	Filling mark	Time t	Kinematic viscosity ν_1	Error $\frac{\nu_1 - \nu}{\nu} \times 10^2$	$\frac{1}{t\nu}$
$\nu_{25} = 0.4230$	m_5	<i>Seconds</i> 386.6	0.4229	0	0.01
$\nu_{25} = 0.03508$	m_5	32.3	.03526	.50	.88
	m_4	38.7	.03539	.89	.74
	m_3	47.9	.03517	.26	.60
	m_2	62.7	.03507	.03	.45
	m_1	92.3	.03506	.06	.31
$\nu_{25} = 0.01800$	m_5	17.3	.01888	4.89	3.20
	m_4	20.5	.01875	4.17	2.72
	m_3	25.4	.01865	3.61	2.16
	m_2	33.0	.01846	2.55	1.67
	m_1	48.2	.01831	1.72	1.16
$\nu_{25} = 0.00938$	m_5	9.9	.01080	15.02	10.80
	m_4	11.6	.01061	13.02	9.22
	m_3	14.2	.01043	11.20	7.50
	m_2	18.1	.01012	7.98	5.89
	m_1	26.1	.00992	5.81	4.07

TABLE VI
CALIBRATION OF VISCOMETER V₂

Kinematic viscosity of liquid	Filling mark	Time t	Kinematic viscosity ν_1	Error $\frac{\nu_1 - \nu}{\nu} \times 10^2$	$\frac{1}{t\nu}$
$\nu_{25} = 0.7290$	m_5	<i>Seconds</i> 96.9	0.7290	0.00	0.01
$\nu_{25} = 0.4230$	m_5	56.2	.4232	.00	.04
	m_4	67.3	.4231	.00	.03
	m_3	83.3	.4230	.00	.03
	m_2	109.6	.4229	.00	.02
	m_1	161.2	.4230	.00	.01
$\nu_{25} = 0.07390$	m_5	10.0	.07525	1.83	1.35
	m_4	11.9	.07454	.86	1.15
	m_3	14.7	.07458	.92	.92
	m_2	19.1	.07361	-.39	.71
	m_1	28.0	.07370	-.27	.48
$\nu_{25} = 0.03508$	m_5	5.1	.03838	9.4	5.53
	m_4	6.0	.03771	7.5	4.84
	m_3	7.3	.03704	5.8	3.91
	m_2	9.5	.03666	4.5	3.00
	m_1	13.7	.03604	2.7	2.05

TABLE VII
CALIBRATION OF VISCOMETER V_4

Kinematic viscosity of liquid	Filling mark	Time t	Kinematic viscosity ν_1	Error $\frac{\nu_1 - \nu}{\nu} \times 10^2$	$\frac{1}{t\nu}$
$\nu_{25} = 0.729$		<i>Seconds</i>			
	m_5	44.8	0.727	-0.28	0.030
	m_4	53.9	.736	+.96	.025
	m_3	66.3	.720	-1.25	.021
	m_2	89.1	.728	-.14	.016
	m_1	135.5	.726	-.42	.009
$\nu_{25} = 0.783$	m_5	48.0	.780	-.38	.027
	m_4	57.4	.779	-.51	.022
	m_3	71.6	.781	-.26	.018
	m_2	95.2	.778	-.64	.013
	m_1	145.5	.780	-.38	.009
$\nu_{25} = 0.423$	m_5	26.2	.425	+.47	.0902
	m_4	31.3	.425	+.47	.076
	m_3	39.1	.426	+.71	.062
	m_2	52.0	.425	+.47	.045
	m_1	79.3	.425	+.47	.028

The graphs which are straight lines were made to pass through the origin. This procedure of permitting the straight lines to pass through the origin is quantitatively contrary to Bond's criterion. The criterion was ignored purposely in this respect, as the errors of the calibration were sufficiently large to eclipse its importance. For from equation (7) Bond's criterion B_c for the viscometers V_1 , V_2 , V_3 , and V_4 becomes $\frac{1}{t\nu} B_c = 0.13, 0.17, 0.26$, and 0.33 , respectively. As all the observations made with V_4 were below the value of Bond's criterion, the data of Table VII are not plotted.

Now it remains to be seen if the assumed value of $m=1.1$ during the determinations of A'_0 and C is in accordance with the graphs in Figures 2, 3, and 4. As

$$\nu_1 = A_1 t$$

and $\nu = A_1 t - \frac{B}{t}$

then $\nu_1 - \nu = \frac{B}{t}$

or $\frac{\nu_1 - \nu}{\nu} = \frac{B}{t\nu}$ (10A)

This gives $B \times 10^2 = \frac{1}{\tan \alpha}$

where $\tan \alpha$ is the slope of the straight lines in Figures 3, 4, and 5. (See References 6, 7, and 8.) Finally, if l_e is supposed not to differ much from l_2 , expression (6) gives

$$m = \frac{8\pi l_2}{Q} \times \frac{10^{-2}}{\tan \alpha} \quad (11)$$

Calculations from the data of the calibration graphs gave $m=1.00, 1.18$, and 1.11 for viscometers V_1 , V_2 , and V_3 , respectively. This shows that the values of B when determined from the calibration graph would have an accuracy of 10 per cent. On the other hand, the values of A_1 which are given in Table III have an accuracy of 0.5 per cent at least as judged from the individual observations of the calibration.

MEASUREMENT OF KINEMATIC VISCOSITY

The procedure in evaluating ν for some particular liquid consisted in determining ν_1 by means of equation (10) after the time of discharge t was observed. The values of ν_1 against temperature are given in graphs, as described later. In order to determine the values of ν given in this report, the quantity $\frac{1}{t\nu_1}$ was computed and the error e read from the calibration graph for the viscometer used. (Fig. 3 to 5.) The value of ν then becomes

$$\nu = \nu_1 (1 - e) \quad (12)$$

DENSITY AND THERMAL COEFFICIENT OF CUBICAL EXPANSION

When t_θ is known for a given liquid, formula (10) gives the kinematic viscosity ν_θ for the temperature θ . To obtain the absolute viscosity μ_θ from the known value of ν_θ the density ρ_θ at the temperature θ must be known. To obtain the density ρ_θ in the temperature range $+30^\circ \text{C.}$ to -20°C. with an accuracy adequate for the purpose of the present paper, it suffices to measure ρ_{30} and the average thermal coefficient of cubical expansion α for the range $+30^\circ \text{C.}$ to 0°C. The definition of α is

$$\alpha = \frac{V_{30} - V_0}{30 \times V_{30}} \quad (13)$$

where V_0 represents the volume of a given mass of liquid at the temperature 0°C. Then the density ρ_θ is given by

$$\rho_\theta = \rho_{30} [1 + \alpha (30 - \theta)] \quad (14)$$

The determinations of the density ρ_{30} and the coefficient of expansion were carried out in the well-known orthodox manner; no other comment need be made except the statement that ρ_{30} is determined with an accuracy of 0.2 per cent and α with an accuracy of 3 per cent. The results are given in Table VIII, in which α is the coefficient for temperatures in degrees centigrade.

The values of the change in density per degree centigrade for petroleum oils against specific gravity based on the National Standard Petroleum Oil Tables (Reference 10) are given in convenient form in Reference 9. The data in Table VIII are in agreement within the experimental error.

TEMPERATURE CONTROL

The four viscometers $V_1, V_2, V_3,$ and V_4 arranged in a plane were held parallel to each other by means of two pairs of wooden clamps. To insure fixity of position, a single arm of each clamp was rigidly attached to the two vertical sides of a rectangular brass frame. A heavy rectangular plate was attached to the upper edge of the frame so as to be perpendicular to the vertical plane containing the axis of the viscometers. This plate will be spoken of as the holding plate. When the holding plate is kept horizontal, the axis of the capillaries are in a vertical position. The description so far given relates to the viscometer assembly. Next consider the bath of the viscometers. It consisted of a rectangular glass vessel of over-all dimensions 13 by 22 by 31 centimeters, placed in a wooden frame. The frame embraced the bottom and the two narrow sides of the glass vessel. It also provided a smooth rectangular brim to the glass vessel. The liquid of the bath was a mixture of water and alcohol.

When the viscometer assembly was immersed in the bath, the holding plate rested evenly on the wooden brim of the vessel. Thus if the brim was horizontal, the axis of capillaries would be vertically submerged in the bath. Eight holes in the holding plate allowed the ends of the viscometers to protrude. Two thermometers were employed to measure the temperature of the bath in the lower and upper portion of the vessel. An agitator in the form of a small propeller was placed in the bath for the equalization of temperature.

The viscometer assembly and the bath together constituted the viscometer box of the tests.

In order to control the temperature of the viscometer bath, the viscometer box was placed in a temperature chamber in which the reduction of temperature was effected by the use of an ammonia refrigeration system. An electric heater was the source of heat in the chamber.

Because of the large mass of liquid in the bath, it generally took seven hours to reduce the temperature of the bath from an initial value of 0°C. to -18°C. , when the temperature of the chamber was held continually at its lowest temperature, that is, -23°C. This property of the apparatus is the factor limiting the lowest values of the temperature realized during the tests.

ERRORS OF THE MEASUREMENTS

Three main sources of experimental error exist; calibration, observation of time of flow, and determination of temperature. As remarked previously, errors of calibration did not appear to be greater than 0.5 per cent. The errors of measurement of time need be considered only in connection with the observation of small values of the time, t_{θ} . In the tests the smallest values of t_{θ} were in the neighborhood of 10 seconds. To reduce the error, measurements of time for a given temperature were made three times or more and the average noted. Quite generally in runs in which t_{30} was approximately 10 seconds individual observations of t_{θ} did not differ more than 0.1 second from the average. It follows that viscosity determinations for the lowest value of t_{30} are open to an error of not more than 1 per cent. Temperature errors may arise in two ways: First, that during a flow measurement the temperature of the bath had a temperature gradient along the capillaries; secondly, that the average temperature of the bath was not the same in the beginning of the flow as at the end. However, the temperature error was minimized by taking the averages of the average temperature of the bath at the beginning and at the end of the flow period. For most of the observations the temperature errors were not more than $\pm 0.5^{\circ}\text{C.}$

RESULTS OF INVESTIGATION

SAMPLES

The solutions and liquids may be classified as follows:

- (1) Solutions of animal and vegetable oils in xylene. These were poppy-seed oil, two samples of neat's-foot oil, castor oil, and linseed oil.
- (2) Solutions of mineral oil in xylene. These were Squibbs' petrolatum of naphthene base and transformer oil.
- (3) Glycerin solutions in ethyl alcohol and in mixture of 50-50 ethyl alcohol and water.
- (4) Mixtures of normal butyl alcohol with methyl alcohol.
- (5) Individual liquids; kerosene, mineral spirits, xylene, recoil oil.

The following information is available regarding the source, purity, and physical properties of the liquids:

XYLENE

The following data were obtained from the label of the container: Chemical composition, $\text{C}_6\text{H}_4(\text{CH}_3)_2$; molecular weight, 106.12; specific gravity, 0.86; boiling point, $138^{\circ}\text{--}139^{\circ}\text{C.}$ It was found that the freezing point of the sample was below -35°C. Thorpe and Rodger's values of the viscosity for meta xylol were obtained from the Smithsonian Physical Tables (1920).

Temperature ($^{\circ}\text{C.}$)	Viscosity (poise)
0	0.00806
10	.00702
20	.00620
30	.00552

These values are about 2 per cent greater than the values found for the sample.

Xylene has been extensively used as the liquid for bubble levels for use on aircraft sextants and other instruments. Owing to its relatively low viscosity, low rate of change with temperature, and to the fact that the temperature at the melting point is below ordinary conditions of aircraft use, xylene is well adapted for use as a solvent. In this way solutions may be obtained which meet a variety of viscosity requirements.

POPPY-SEED OIL

A sample was purchased without specifications from a wholesale dealer. This had a density at 15° C. of 0.92 gram per cm.³ compared with a value of 0.924 to 0.926 given in the International Critical Tables (Vol. II, 1927). The sample was found to have a cloud point of +7° C. and to freeze at -16° C.; the tables give -16° to -18° C. as the freezing point. The coefficient of viscosity of the sample was found to be 0.797 poise at 15.5° C. as compared with the value 0.789 poise given in the International Critical Tables.

The index of refraction of the sample was determined at two temperatures by the optical-instrument section of the Bureau of Standards. The values are given below, including also data on solutions of poppy-seed oil in xylene.

Poppy-seed oil (per cent, by weight)	Xylene (per cent, by weight)	Index of refraction, N_D		Temperature coefficient of index per degree C.
		10.0° C.	30.0° C.	
100	0	1.4806	1.4731	-0.00038
75	25	1.4862	1.4779	-.00042
50	50	1.4914	1.4825	-.00045
25	75	1.4964	1.4867	-.00049

Poppy-seed oil and xylene solutions have found some use in dashpots of special aircraft instruments. As poppy-seed oil is a semidrying oil it requires frequent replacement.

NEAT'S-FOOT OIL

Two samples of neat's-foot oil were furnished through the courtesy of the research department of Armour & Co. The samples are a "wintered" product and are known respectively as 20° and 30° F. (-6.7° C. and -1.1° C.) cold or flow test neat's-foot oil. The 20° F sample became cloudy at -14° C. and froze at about -16.5° C. The 30° F. sample became cloudy at -5° C. and froze at a temperature of -8° C.

The International Critical Tables (Vol. II, 1927) give 0.987 to 1.13 poises for the value of the viscosity at 15.5° C., compared with 1.15 poises for the 30° F. sample and slightly less for the 20° F. sample.

Neat's-foot oil is nonoxidizing in character, which is a desirable property in the selection of a liquid for use in an open dashpot.

CASTOR OIL

The sample has not been analyzed for purity. The International Critical Tables (Vol. II, 1927) state that castor oil becomes turbid at -12° C. and solid at -17° C. to -18° C. The sample commenced freezing at -15° C. and was solid at -17° C. The density and viscosity are as follows according to the above reference:

Temperature (° C.)	Density (grams/cm. ³)	Viscosity (poises)
5	0.9707	37.60
10	.9672	24.18
20	.9603	9.86
25	.9569	6.51
30	.9534	4.51

A comparison of the above viscosity data with that for the sample (given later) shows good agreement as regards the change in viscosity with temperature, but the viscosity of the sample is substantially 8 per cent greater.

LINSEED OIL

The sample was raw linseed oil, purchased under United States Government Master Specification for Raw Linseed Oil. This specification is published as Bureau of Standards Circular No. 82 (third edition, issued April 26, 1927). The density of the sample is 0.932 gram per

cm.³ at 15.5° C., which is within the specific-gravity tolerance of 0.9300 to 0.935 (15:5°/15:5° C.), which is equivalent to the density interval 0.929 to 0.934 gram per cm.³ The cloud point of the sample is approximately -7° C., freezing in the interval -14° to -17° C. The International Critical Tables (Vol. II, 1927) give the freezing point as -19° to -27° C. and the viscosity at 15.5° C. as 0.55 poises, while the value found for the sample is 0.585 poises.

SQUIBBS' MINERAL OIL (LIQUID PETROLATUM)

This oil is a commercial product sold for medical use. The label on the bottle states that the oil is refined from California crude petroleum (naphthene base) and that it is free from paraffin, inorganic matter, and organic sulphur compounds. The sample froze at a temperature of -21° to -22° C.

TRANSFORMER OIL

This oil is a sample of transformer oil which, contrary to expectations, froze in the temperature range -32° to -33° C.

GLYCERINE

If the density of the sample is taken as the criterion, then the glycerine of our tests contained 4 per cent water, for, according to the International Critical Tables (Vol. III) the density of 96 per cent aqueous solution of glycerol at 25° C. is 1.2477, and for the same temperature the density of the sample was found to be 1.2480 grams per cm.³ Shöttner's values of the viscosity of glycerol are given in the Physico-Chemical Tables (Vol. II). According to these tables the viscosity of glycerol at 26.5° C. is 4.939 poises. Our determination of the same quantity gives 3.909 poises. The considerable difference between these two values is due to the water content in our sample.

ETHYL ALCOHOL

The sample initially contained less than 2 per cent of water. It should be noted that measurements on a given sample of liquid extended over a period of three days. In the case of hygroscopic liquids and solutions such as alcohol and glycerine some change in water content may have occurred.

N. BUTYL ALCOHOL

The sample was purchased from the Eastman Kodak Laboratories. Two grades of the substance are available; one is known as technical and has a boiling point of 114° to 118° C.; the other is a purer product and has a boiling point of 116° to 118° C. The latter product was used in the tests.

The International Critical Tables (Vol. I, 1926) give the melting point as -89.8° C. and the density as 0.810 gram per cm.³ at 20° C. The values of the viscosity found by Thorpe and Rodger (1894) as given in Landolt-Börnstein Tables (Vol. I, 1923) agree within 1 per cent with the values found for the sample. Thorpe and Rodger's values are:

Temperature (° C.)	Viscosity (poise)
0.27	0.0515
10.69	.0380
21.83	.0280

METHYL ALCOHOL

The sample (CH₃OH) was of reagent quality. The manufacturer's label gave the following analysis:

	Per cent		Per cent
Acetone.....	0	Empyreuma.....	0.001
Aldehyde.....	0	Reaction to litmus.....	Neutral.
Chloroform.....	.01	Reducing matter.....	0

The International Critical Tables (Vol. I, 1926) give the melting point of methyl alcohol as -97.8° C. This alcohol when mixed with butyl alcohol has been proposed for use in rolling ball inclinometers.

KEROSENE

The sample of kerosene had a density of 0.810 gram per cm.³ at 30° C. and a freezing point of -15° C.

MINERAL SPIRITS

This is a petroleum product also known as Varnolene, which is used as a paint thinner. It is generally used as the damping liquid in aircraft compasses. The sample is commercial, most likely a naphthene (asphalt) base. Its density is 0.769 gram per cm.³ at 30° C. A specification of mineral spirits based on its use as a paint thinner is given in Bureau of Standards Circular No. 98.

The sample was found to remain clear when at a temperature of -35° C.

RECOIL OIL

This sample conforms to the specification for recoil oil, light grade, given in United States Master Specification for Lubricants and Liquid Fuels, Bureau of Mines Technical Paper 323-B. It was found to remain unfrozen at a temperature of -30° C.

2. EXPERIMENTAL RESULTS

Figures 6 to 17, inclusive, show the effect of temperature on the kinematic viscosity of the various solutions and liquids. The concentrations of the solutions are noted in the figures and refer to weight.

The ordinates n_θ are the quantities defined by

$$n_\theta = \log_{10} \frac{t_\theta}{t_{30}} \quad (15)$$

where t_θ is the observed time of discharge at temperature θ . Here t_{30} was not observed generally but was evaluated from the observed t_θ in the temperature range 30° C. to 15° C. Thus the value of t_{30} is more probable than that of a single observation made at 30° C.

Now, denote by n'_θ the quantity

$$n'_\theta = \log_{10} \frac{\nu_\theta}{\nu_{30}} \quad (16)$$

where ν_θ is the kinematic viscosity at the temperature θ . The quantity n' will have the same value as n_θ if the inertia term is negligible in the flows of time t_θ and t_{30} . Strictly speaking, this was not the case, particularly for the measurements of t_{30} made with the viscometer V₁. For many purposes the differences $n'_\theta - n_\theta$ being small can be neglected; with this restriction, then, the curves in Figures 6 to 17, inclusive, are representative of the temperature effect on kinematic viscosity.

The magnitudes of the differences $n'_\theta - n_\theta$ are always less than the value for e given in the graphs, as is evident from equation (18) below, and therefore the values of n_θ are, on the whole, except for the data on Figures 15 and 16, within 1 per cent of n'_θ . The data for the 50-50 butyl-methyl alcohol in Figure 15 shows an extreme error e of 9.5 per cent. If the values of n_θ given in the graph are used to compute ν , the result is in error 0.5 per cent at +10° C. and 6.5 per cent at -15° C.

Assuming that the difference of $n'_\theta - n_\theta$ is negligible, the viscosity ν_θ can be computed from the relation

$$n_\theta = \log \frac{\nu_\theta}{\nu_{30}}$$

in which n_θ is read from the proper graph (figs. 6 to 17), and ν_{30} is obtained from the tables given in the same figures.

The absolute viscosity μ_θ is given by the relation

$$\mu_\theta = \rho_\theta \nu_\theta$$

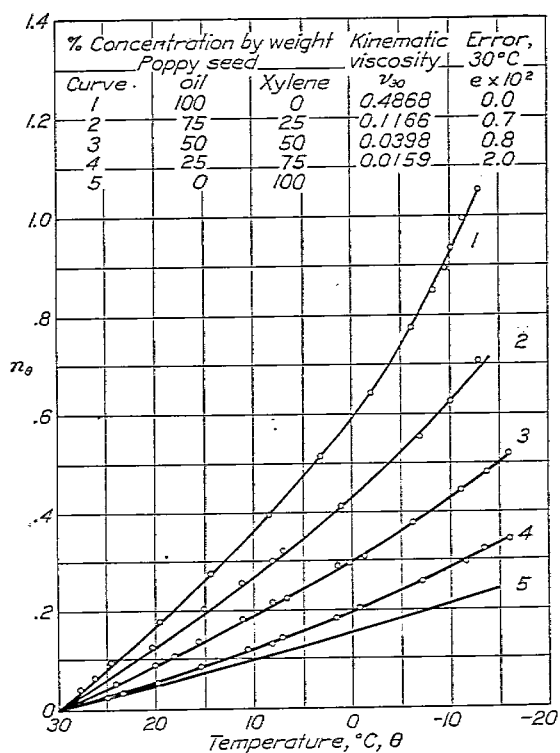


Fig. 6.—Change of kinematic viscosity with temperature. Poppy-seed oil and xylene

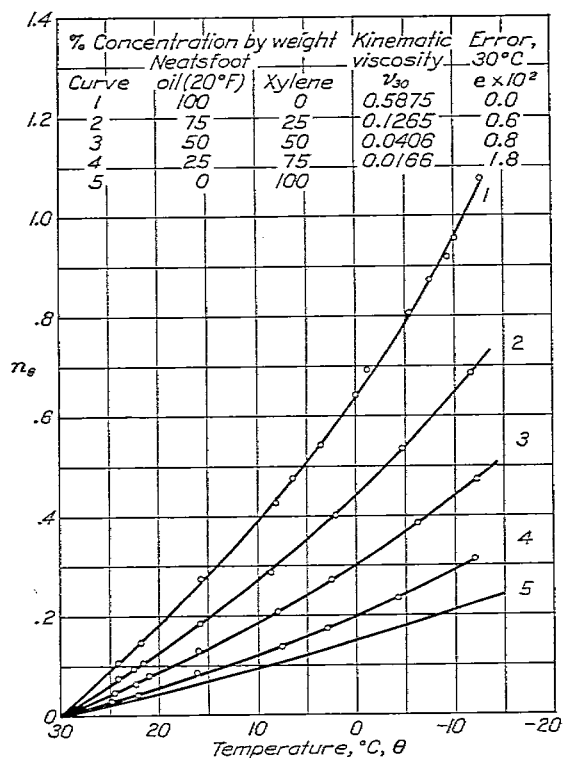


Fig. 7.—Change of kinematic viscosity with temperature. Neat's-foot oil and xylene

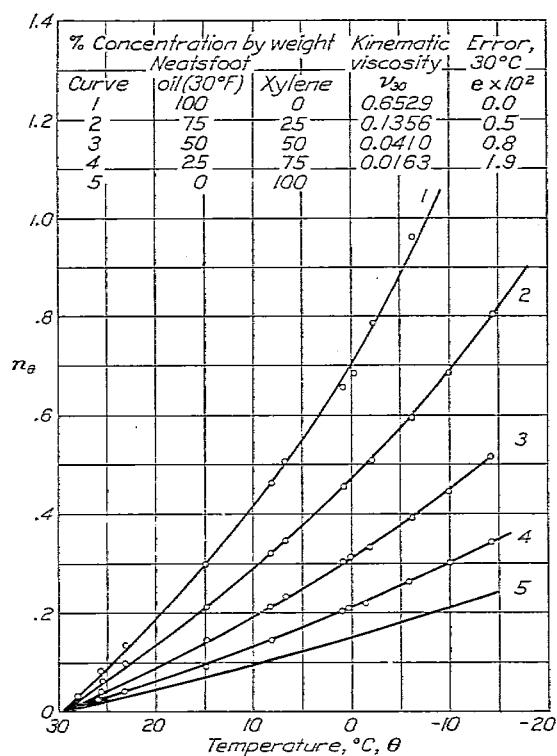


Fig. 8.—Change of kinematic viscosity with temperature. Neat's-foot oil (30° F.) and xylene

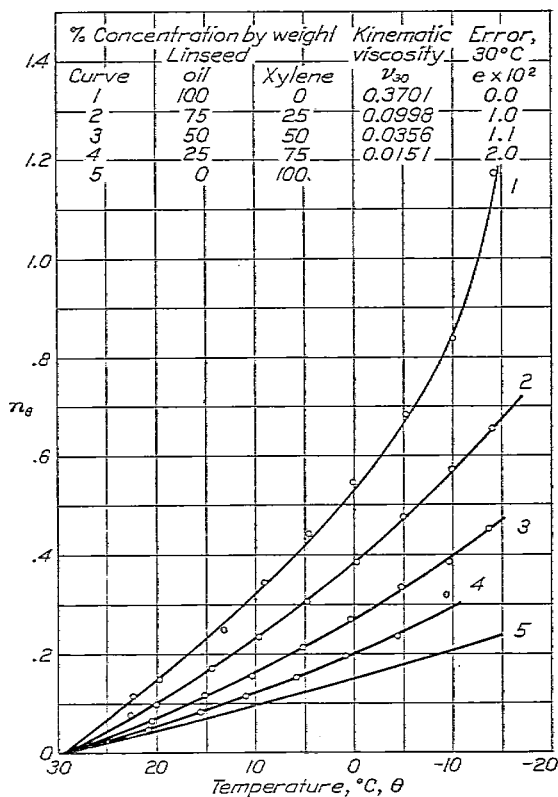


Fig. 9.—Change of kinematic viscosity with temperature. Linseed oil and xylene

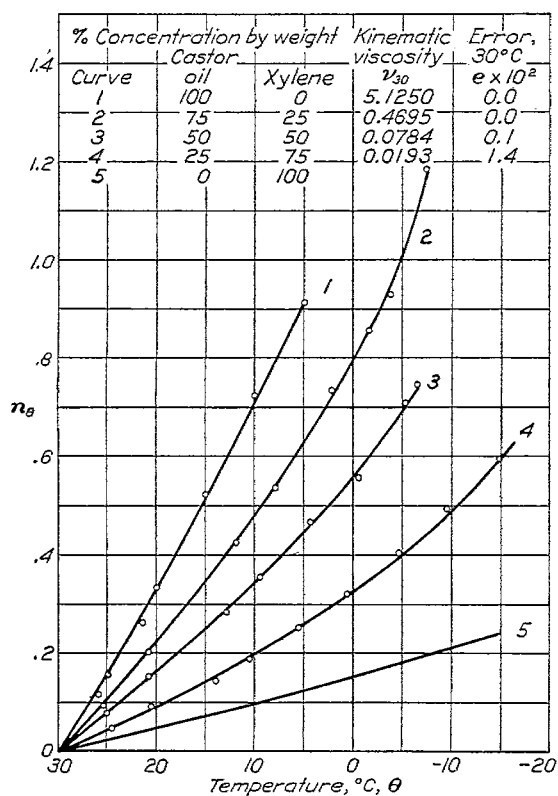


FIG. 10.—Change of kinematic viscosity with temperature. Castor oil and xylene

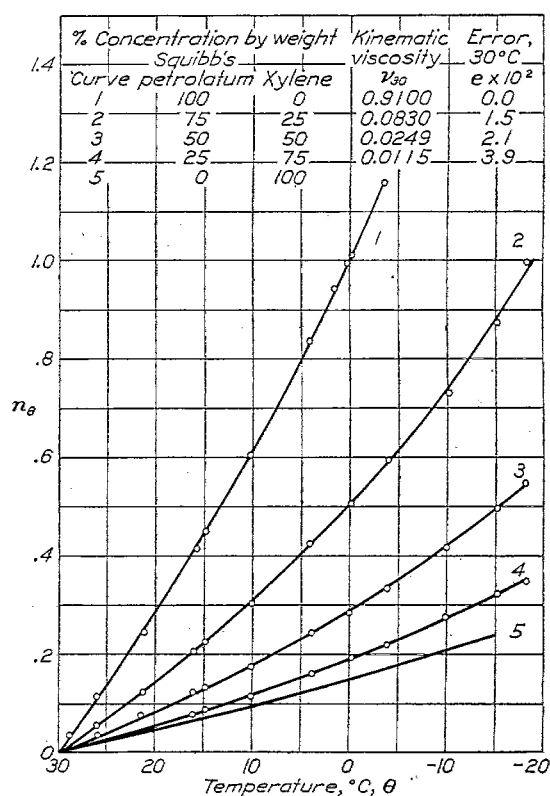


FIG. 11.—Change of kinematic viscosity with temperature. Squibb's petroleum and xylene

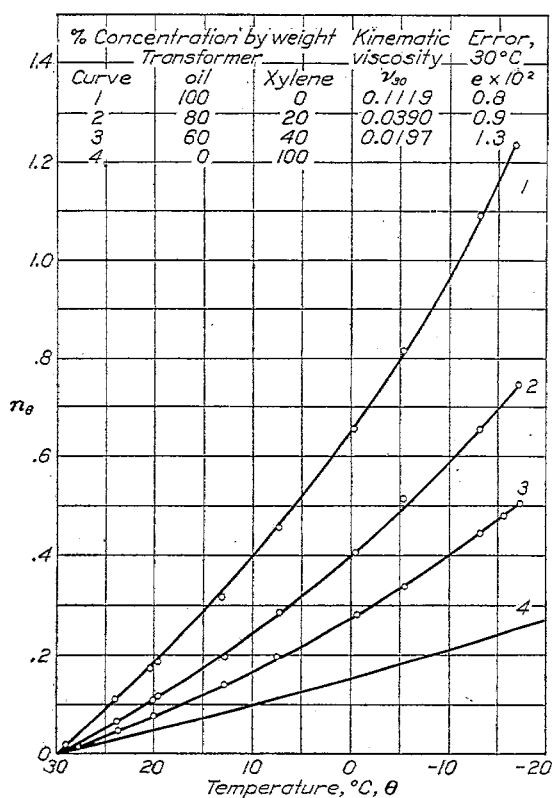


FIG. 12.—Change of kinematic viscosity with temperature. Transformer oil and xylene

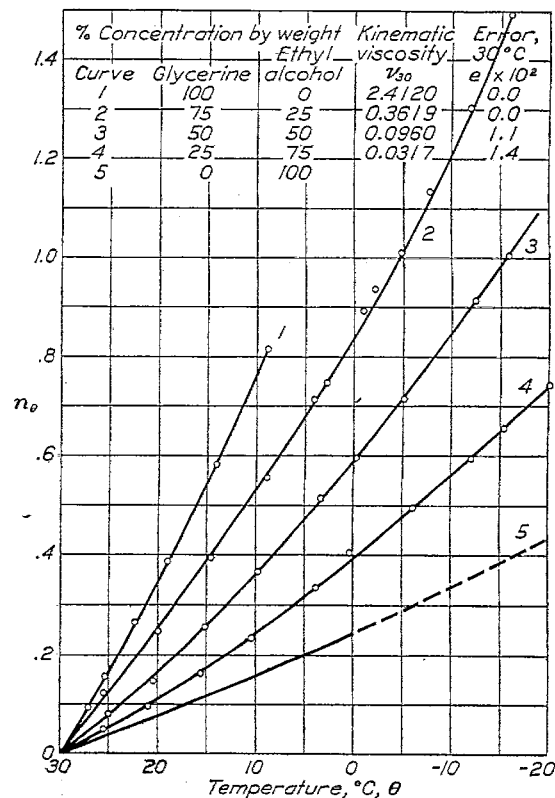


FIG. 13.—Change of kinematic viscosity with temperature. Glycerine and ethyl alcohol

For the purpose of determining the density at $\theta^\circ\text{C}$., the values of ρ_{30} and the coefficient of volume expansion α are given in Table VIII. Equation (14) then serves to calculate the value of ρ_θ .

In cases such that the difference $n'_\theta - n_\theta$ can not be ignored, the same procedure given above is followed except that n'_θ must be computed and used instead of n_θ .

Let e_θ as given in equation (10A) represent the proportional error in ν_θ , when ν_θ is evaluated by formula (12). Putting $e_{30}=e$, it can be shown that

$$n'_\theta - n_\theta = \log_{10} (1 + e - e_\theta) \quad (17)$$

where e_θ satisfies to the first order the relation derived from equation (10A) and the definition of n_θ

$$\log_{10} e_\theta = \log_{10} e - 2n_\theta \quad (18)$$

Thus to evaluate n'_θ one needs to consider only the quantities e and n_θ . The values of e are given for each liquid in tabular form in Figures 6 to 17, inclusive.

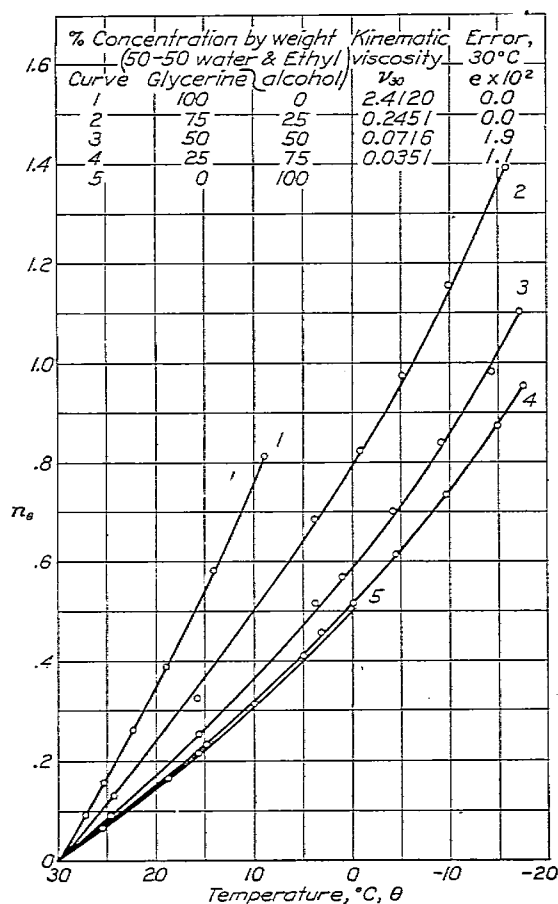


FIG. 14.—Change of kinematic viscosity with temperature. Glycerine and 50-50 water and ethyl alcohol

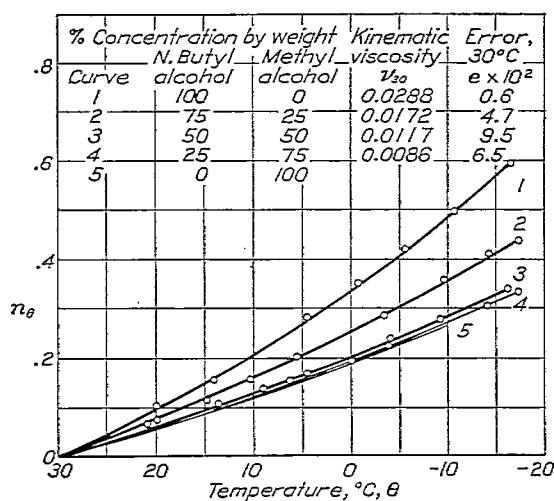


FIG. 15.—Change of kinematic viscosity with temperature. N. butyl alcohol and methyl alcohol

As an illustration, suppose that n'_θ , ν_θ , and μ_θ are required for xylene at $\theta = -15^\circ\text{C}$. From the graph for xylene, No. 3, Figure 16, it is seen that $e = 0.038$ and $n_\theta = 0.24$; then by formula (18) $e_\theta = 0.013$, by formula (17) $n'_\theta - n_\theta = 0.01$, and $n'_\theta = 0.25$. The kinematic viscosity ν_{-15} is given by

$$\nu_{-15} = \nu_{30} \text{ antilog } n'_\theta$$

From the table in Figure 16, ν_{30} equals 0.0066 and $\nu_{-15} = 0.0117$. From Table VIII $\rho_{30} = 0.855$ and $\alpha = 0.00095$. Then $\rho_{-15} = 0.892$ and $\mu_{-15} = 0.0104$ poise.

Two tables are presented which summarize the experimental work. Table VIII gives data on the viscometers used coupled with the time of flow at 30° and 25° C. for each individual solution. The data required for determining the density ρ_θ , namely, ρ_{30} and α , are included in this table.

Table IX gives the viscosity μ at 25° C. and the values of the ratio n at +20° and -15° C. for each solution. This affords a convenient rough comparison of the values of the viscosity μ of the liquids at one temperature and of the change of their kinematic viscosity ratio n in the temperature interval -15° to +20° C. The solution corresponding to any desired value of μ may be found by interpolation and then n at -15° and +20° C. also found by interpolation thus enabling the proper liquid to be selected. The selection should be made bearing in mind the other properties such as given in the description of the samples.

Comparative data on the various solutions is given in Table X. These data are derived by interpolation from Table IX and Figures 6 to 17, inclusive, and give the composition of the solutions against the viscosity at +25° C., varying by convenient steps. The logarithms of the kinematic viscosity ratio are given for five temperatures, neglecting the error e , and also the

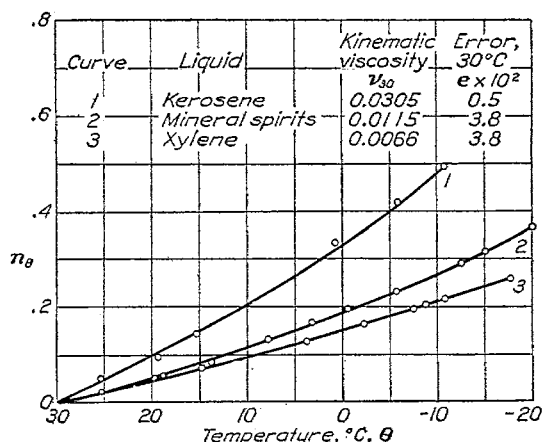


FIG. 16.—Change of kinematic viscosity with temperature. Kerosene, mineral spirits, xylene

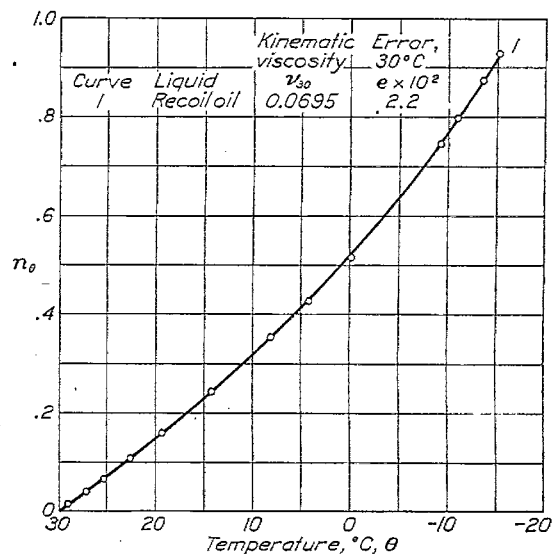


FIG. 17.—Change of kinematic viscosity with temperature. Recoil oil

temperature at which the logarithms of the kinematic viscosity ratio n equals 0.7. At this temperature the viscosity is very closely five times the value at 30° C., which for many purposes sets the lowest temperature at which the liquid can be used.

SUMMARY

Table X summarizes the data in convenient form. The solutions and liquids of a given viscosity are compared directly as to lowest temperature at which it is useful and the effect of temperature on the kinematic viscosity.

Inclinometers of the rolling-ball type contain for damping a solution of 40 per cent glycerine and 60 per cent absolute (ethyl) alcohol. This solution is seen to have a viscosity between 0.05 and 0.10 (0.065) poise and to become five times as viscous at about -10° C. as at 30° C. A 50-50 solution of N. butyl and methyl alcohol has been proposed for use in order to secure satisfactory operation at lower temperatures. The data in Table X shows that at -20° C. the solution is less than two and one-half times as viscous as at 30° C., but that the viscosity at +25° C. is only one-sixth that of the glycerine-alcohol solution.

Mineral spirits are used to fill magnetic compasses. Only xylene appears to have better temperature properties.

The uses considered above relate to cases in which the liquid is entirely inclosed. When a liquid is desired for use in an open dashpot, other properties, such as evaporation and oxidation, become as important as the effect of temperature. No oily liquid has been found which is by itself satisfactory at low temperatures. It is seen in Table X that all liquids at 25° C. with a

viscosity greater than 0.05 have an excessive temperature effect, the viscosity at -20°C . exceeding more than fivefold that at 30°C . Of the liquids investigated the "wintered" neat's-foot-oil solutions appear to be the best. Their temperature properties are substantially as good as those of other solutions of the same viscosity but these solutions have the advantage of being relatively nonoxidizing. The use of xylene as a solvent introduces the factor of evaporation, but possible solvents with the necessary properties of low viscosity and small change with temperature appear to have an appreciable vapor pressure.

TABLE VIII

DATA FOR EVALUATING μ_{25} THE VISCOSITY AT 25°C ., THE KINEMATIC VISCOSITY AT 30°C ., AND ρ_{30} THE DENSITY AT 30°C .

Proportions, by weight		Viscometer		Time of flow		Density	Thermal coefficient of cubical expansion $\alpha \times 10^3$
		No.	Mark	t_{30} (sec.)	t_{25} (sec.)	ρ_{30} (gr./cm. ³)	
Poppy-seed oil:	Xylene:						
	100	0	V_3 m_5	64.7	79.1	0.914	0.70
	75	25	V_3 m_5	15.6	17.7	.900	.76
	50	50	V_2 m_5	36.7	41.6	.886	.82
Neat's-foot oil (20° sample):	25	75	V_1 m_5	39.2	41.6	.871	.89
	100	0	V_4 m_5	36.2	44.5	.905	.66
	75	25	V_3 m_5	16.9	19.5	.893	.73
	50	50	V_2 m_5	37.5	41.6	.881	.80
Neat's-foot oil (30° sample):	25	75	V_1 m_5	40.8	43.5	.869	.87
	100	0	V_4 m_5	40.2	50.1	.909	.70
	75	25	V_3 m_5	18.1	21.4	.896	.76
	50	50	V_2 m_5	37.8	41.9	.883	.82
Castor oil:	25	75	V_1 m_5	40.0	42.9	.870	.89
	100	0	V_4 m_5	31.6	44.7	.954	.74
	75	25	V_3 m_5	62.4	79.5	.928	.79
	50	50	V_2 m_5	72.6	87.7	.903	.85
Linseed oil:	25	75	V_1 m_5	47.3	52.7	.879	.89
	100	0	V_4 m_5	22.8	27.0	.922	.73
	75	25	V_3 m_5	13.4	15.1	.905	.78
	50	50	V_2 m_5	33.0	34.8	.889	.84
Petrolatum:	25	75	V_1 m_5	37.1	39.5	.872	.90
	100	0	V_4 m_5	56.1	78.0	.878	.69
	75	25	V_3 m_5	11.2	13.3	.871	.75
	50	50	V_2 m_5	23.3	25.7	.866	.82
Transformer oil:	25	75	V_1 m_5	28.9	30.8	.860	.88
	100	0	V_3 m_5	15.0	18.4	.896	.73
	80	20	V_2 m_5	36.0	40.6	.887	.77
	60	40	V_1 m_5	48.1	52.5	.879	.82
Glycerine:	Ethyl alcohol:						
	100	0	V_4 m_5	148.6	217.3	1.2455	.45
	75	25	V_4 m_5	22.3	29.7	1.102	.62
	50	50	V_3 m_5	12.9	15.5	.993	.75
Glycerine:	25	75	V_2 m_5	29.4	33.4	.888	.88
	Ethyl alcohol and water (50-50):						
	75	25	V_4 m_5	15.1	19.6	1.141	.55
	50	50	V_3 m_5	9.7	11.8	1.052	.61
N. butyl alcohol:	25	75	V_2 m_5	32.5	38.5	.975	.68
	100	0	V_1 m_5	70.1	78.0	.811	.82
	75	25	V_2 m_5	18.5	18.0	.803	.90
	50	50	V_2 m_5	11.8	12.6	.797	.97
Xylene	25	75	V_1 m_5	22.1	23.6	.789	1.05
	Kerosene		V_1 m_5	49.1	52.1	.855	.95
	Mineral spirits		V_1 m_5	74.0	82.8	.810	.80
	Recoil oil		V_1 m_5	28.9	30.8	.769	.99
			V_3 m_5	9.4	11.1	.883	.74

TABLE IX

DATA FOR COMPARING THE VISCOSITY AND THE EFFECT OF TEMPERATURE ON THE VISCOSITY OF THE VARIOUS SOLUTIONS

Proportions, by weight		Viscosity μ_{25} (poise)	Logarithm of the kinematic viscosity ratio	
			n_{20}	n_{15}
Poppy-seed oil: 100 75 50 25	Xylene: 0 25 50 75	0.5460 .1197 .0401 .0148	0.175 .130 .090 .055	>1.20 .735 .500 .335
Neat's-foot oil (20° sam- ple): 100 75 50 25	Xylene: 0 25 50 75	.6560 .1310 .0399 .0156	.180 .125 .085 .055	>1.10 .770 .520 .330
Neat's-foot oil (30° sam- ple): 100 75 50 25	Xylene: 0 25 50 75	.7420 .1433 .0403 .0153	.190 .140 .095 .065	>1.15 .820 .525 .350
Castor oil: 100 75 50 25	Xylene: 0 25 50 75	6.94 .5550 .0867 .0191	.335 .225 .165 .090	>1.50 >1.20 .85 .600
Linseed oil: 100 75 50 25	Xylene: 0 25 50 75	.4060 .1023 .0335 .0140	.150 .100 .070 .055	>1.25 .675 .475 .350
Petrolatum: 100 75 50 25	Xylene: 0 25 50 75	1.1150 .0866 .0239 .0106	.290 .150 .085 .055	>1.25 .880 .495 .325
Transformer oil: 100 80 60	Xylene: 0 20 40	.1238 .0392 .0190	.188 .110 .075	1.16 .695 .475
Glycerine: 100 75 50 25	Ethyl alcohol: 0 25 50 75	4.400 .5325 .1151 .0321	.345 .255 .165 .110	----- 1.44 .985 .650
Glycerine: 75 50 25	Ethyl alcohol and water (50-50): 25 50 75	.3640 .0924 .0408	.240 .175 .155	1.36 1.02 .885
N. butyl alcohol: 100 75 50 25	Methyl alcohol: 0 25 50 75	.0263 .0152 .0101 .00733	.095 .085 .060 .055	.565 .410 .330 .310
Xylene..... Kerosene..... Mineral spirits..... Recoil oil.....	----- ----- ----- -----	.00595 .0278 .00940 .0728	.047 .095 .055 .146	.240 >.500 .315 .918

TABLE X

Absolute viscosity 25° C.	Liquid	Temperature at which $n=0.7$	Logarithm of kinematic viscosity ratio				
			n_{30}	n_{10}	n_0	n_{-10}	n_{-20}
Poises: 6.0	98 per cent D.....	° C. 9.5	0	0.68	-----	-----	-----
4.0	96 per cent D.....	8.5	0	.66	-----	-----	-----
	98 per cent H.....	11.0	0	-----	-----	-----	-----
	99 per cent K.....	11.0	0	.74	-----	-----	-----
2.0	90 per cent D.....	7.0	0	.60	-----	-----	-----
	90 per cent H.....	8.5	0	.65	-----	-----	-----
	96 per cent K.....	9.5	0	.69	-----	-----	-----
1.0	83 per cent D.....	5.5	0	.53	0.89	-----	-----
	99 per cent F.....	7.5	0	.59	.96	-----	-----
	82 per cent H.....	6.0	0	.58	.91	-----	-----
	90 per cent K.....	8.0	0	.63	-----	-----	-----
.742	30° neat's-foot oil.....	0	0	.42	.70	1.1	-----
.656	20° neat's-foot oil.....	-2.0	0	.39	.64	.96	-----
.6	99 per cent B.....	-2.5	0	.39	.63	.95	-----
	97 per cent C.....	-1.0	0	.40	.68	1.05	-----
	76 per cent D.....	+3.0	0	.48	.80	-----	-----
	77 per cent H.....	5.0	0	.55	.87	-----	-----
	82 per cent K.....	5.5	0	.55	.87	-----	-----
	94 per cent F.....	4.0	0	.50	.81	-----	-----
.546	Poppy-seed oil.....	-4.0	0	.36	.59	.92	-----
.4	94 per cent A.....	-5.8	0	.34	.56	.84	-----
	95 per cent B.....	-4.0	0	.37	.60	.89	-----
	91 per cent C.....	-3.0	0	.38	.62	.94	-----
	71 per cent D.....	+2.0	0	.46	.76	-----	-----
	90 per cent F.....	1.0	0	.48	.80	-----	-----
	70 per cent H.....	2.5	0	.49	.77	-----	-----
	75 per cent K.....	3.0	0	.50	.79	1.14	-----
.4	Linseed oil.....	-6.0	0	.32	.53	.85	-----
.2	82 per cent A.....	-9.8	0	.28	.48	.70	-----
	83 per cent B.....	-8.5	0	.31	.49	.74	-----
	81 per cent C.....	-7.2	0	.33	.53	.78	-----
	63 per cent D.....	-1.0	0	.41	.69	1.05	-----
	87 per cent E.....	-10.0	0	.27	.45	.70	-----
	85 per cent F.....	-2.5	0	.40	.65	.94	-----
	60 per cent H.....	-1.0	0	.41	.67	.96	-----
	62 per cent K.....	-1.0	0	.43	.68	.99	-----
.1238	Transformer oil.....	-3.0	0	.40	.65	.96	1.5
.1	72 per cent A.....	-14.5	0	.25	.41	.60	-----
	70 per cent B.....	-15.0	0	.25	.42	.61	-----
	65 per cent C.....	-15.0	0	.26	.42	.59	.82
	50 per cent D.....	-5.0	0	.34	.56	.90	-----
	75 per cent E.....	-16.0	0	.24	.38	.57	-----
	78 per cent F.....	-6.5	0	.34	.54	.79	-----
	98 per cent G.....	-2.5	0	.39	.63	.93	-----
	48 per cent H.....	-6.0	0	.34	.56	.81	-----
	53 per cent K.....	-3.5	0	.38	.61	.89	-----
.0728	Recoil oil.....	-7.5	0	.32	.52	.76	-----
.05	57 per cent A.....	-20.0	0	.20	.34	.48	.66
	57 per cent B.....	-20.0	0	.21	.34	.50	.69
	52 per cent C.....	-20.0	0	.20	.32	.47	.64
	44 per cent D.....	-8.5	0	.31	.51	.75	-----
	60 per cent E.....	-20.0	0	.20	.32	.46	.64
	63 per cent F.....	-17.0	0	.24	.39	.55	.78
	86 per cent G.....	11.0	0	.28	.45	.67	-----
	35 per cent H.....	-12.5	0	.28	.46	.65	-----
	30 per cent K.....	7.5	0	.33	.53	.77	-----
.0278	Kerosene.....	-15.0	0	.20	.33	.48	-----

TABLE X—Continued

Absolute viscosity 25° C.	Liquid	Temperature at which $\eta = 0.7$	Logarithm of kinematic viscosity ratio				
			η_{30}	η_{10}	η_0	η_{-10}	η_{-20}
Poisés— Contd. 0.025	38 per cent A.....	¹ —20.0	0	0.16	0.25	0.36	0.49
	35 per cent B.....	¹ —20.0	0	.15	.24	.35	.49
	38 per cent C.....	¹ —20.0	0	.17	.27	.38	.52
	30 per cent D.....	—16.0	0	.22	.37	.55	0
	42 per cent E.....	¹ —20.0	0	.15	.25	.37	.51
	52 per cent F.....	¹ —20.0	0	.19	.31	.44	.61
	68 per cent G.....	¹ —20.0	0	.19	.32	.47	-----
	18 per cent H.....	¹ —20.0	0	.20	.32	.47	.63
	15 per cent K.....	—10.0	0	.31	.50	.70	-----
	98 per cent L.....	—21.5	0	.20	.32	.46	.66
.01	15 per cent C.....	¹ —20.0	0	.12	.19	.26	.41
	10 per cent D.....	¹ —20.0	0	.13	.22	.32	.44
	20 per cent G.....	¹ —20.0	0	.12	.19	.26	.35
	50 per cent L.....	¹ —20.0	0	.13	.20	.28	.37
.01	Ethyl alcohol.....	¹ —20.0	0	.16	.24	.33	.43
.094	Mineral spirits.....	¹ —20.0	0	.12	.19	.27	.37
.00595	Xylene.....	¹ —20.0	0	.10	.15	.21	.26

¹ Below.

A..... Poppy-seed oil and xylene.

B..... Neat's-foot oil (20°F.) and xylene.

C..... Neat's-foot oil (30°F.) and xylene.

D..... Castor oil and xylene.

E..... Linseed oil and xylene.

F..... Petrolatum and xylene.

G..... Transformer oil and xylene.

H..... Glycerine and ethyl alcohol.

K..... Glycerine and 50-50 solution of ethyl alcohol and water.

L..... N. butyl alcohol and methyl alcohol.

The percentage given in the table refers to the amount, by weight, of the first-named liquid.

BUREAU OF STANDARDS,

WASHINGTON, D. C., May 16, 1928.

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