

Therefore, other methods of correlation which are proved valid for the region investigated are required to estimate values outside the region with definable accuracy.

Use of several methods of extrapolation of viscosity values is possible. The rigorous kinetic theory for dilute gases correlates atmospheric viscosity with great accuracy for many gases (6). Extrapolation to higher temperatures by use of this theory should be possible. However, this application is restricted to the relatively small density range for which the gas can be considered dilute. For the dense gas and liquid regions, the dense-gas viscosity theory developed by Enskog should be applicable. By appropriate adjustments in a single parameter, and utilizing the Benedict-Webb-Rubin equation of state, the Enskog theory yields accurate values of propane viscosity at elevated pressures (14). There are other approaches to this problem. The best available extrapolative technique is believed to be a method which transforms the problem of extrapolation into the less sensitive problem of interpolation. This method, based on the residual viscosity concept, has been utilized previously for ethane and propane.

The residual concept applied here was derived by Abaszade (1), who verified the theory of Predvoditelev (9) for the thermal conductivity of liquids and gases. Thodos and coworkers extended the application to viscosity (2, 12). The residual viscosity, defined as the difference between the viscosity at a given pressure and temperature, and the viscosity at one atmosphere and the same temperature, has been shown to be only a function of density at high densities for a number of materials. The fundamental significance of the method will be discussed separately.

Residual *n*-butane viscosity values calculated from the experimental data of the present investigation yield a single

smooth curve when plotted vs. density (Figure 6). This is significant, considering the wide range of temperatures and pressures involved. For most points the residual viscosity-density plot predicts values of viscosity which are within  $\pm 1\%$  of the experimental data, the exception being for densities below 0.10 gram/cc. For these low densities, residual viscosity is evidently dependent upon temperature (5). The density values used for constructing Figure 4 are those of Sage and Lacey (10).

The problem of predicting *n*-butane viscosity for temperatures and pressures outside the region of the experimental investigation has thus been transformed from a problem of extrapolation to one of interpolation. Since the residual viscosity is a pseudoinvariant with respect to temperature and pressure, the viscosity for any condition may be determined knowing the density and the atmospheric pressure viscosity. Experimental data for a sufficient range of densities and accurate atmospheric viscosity values such as obtained here are, of course, essential for application of the method.

#### SELECTION OF RECOMMENDED VALUES

Recommended values for the viscosity of *n*-butane for temperatures from 100° to 460° F. and pressures from atmospheric to 10,000 p.s.i.a. are presented in Table I. For the regions of temperature and pressure of this investigation, the recommended values were determined from smoothed large-scale viscosity-pressure, viscosity-temperature, and residual viscosity-density plots. The values from these respective plots were not significantly different for most points.

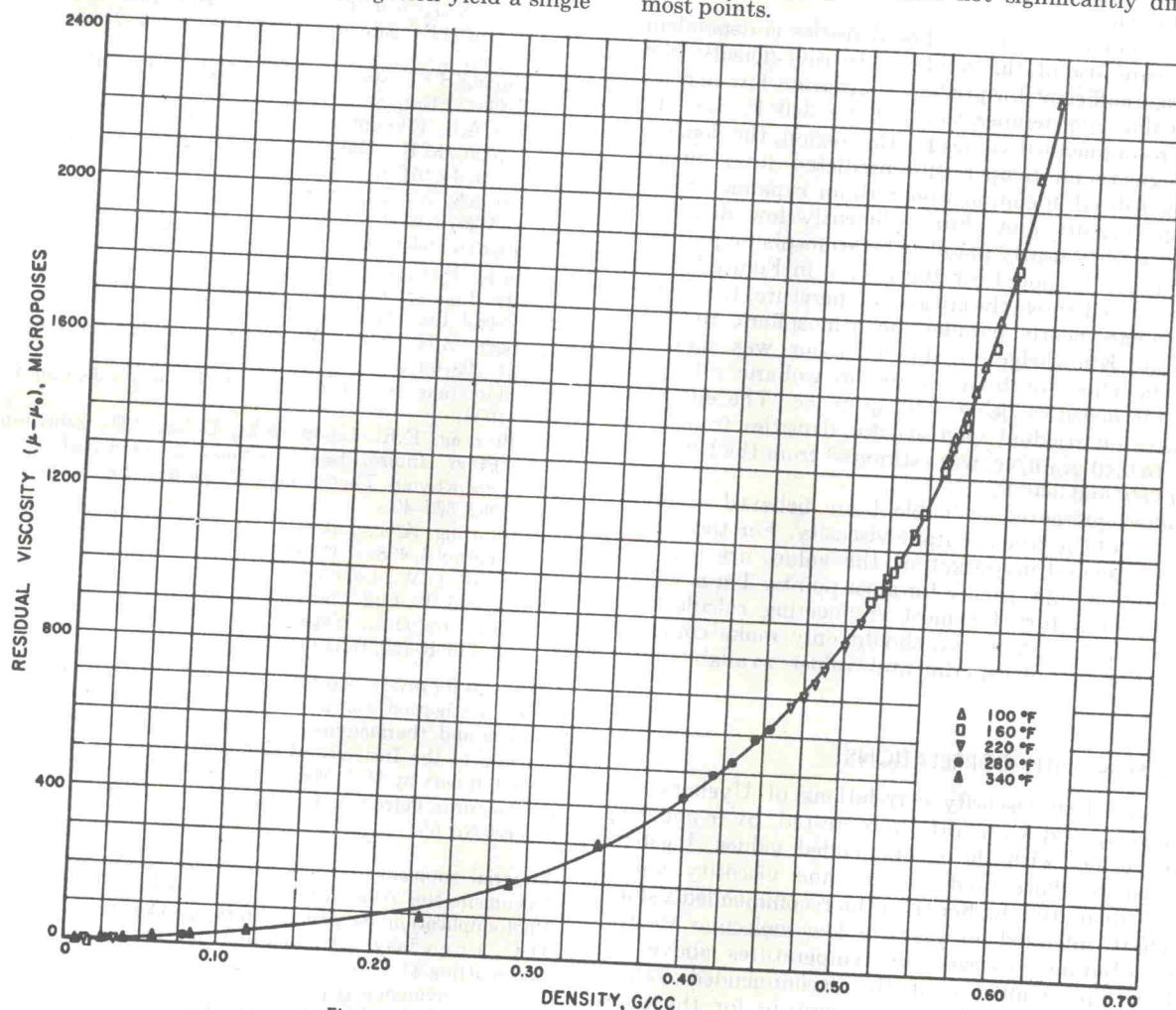


Figure 6. Residual *n*-butane viscosity vs. density



Table I. Recommended Values for the Viscosity of *n*-Butane, Micropoises

Pressure, p.s.i.a.	Temp. ° F.									
	100.0	130.0	160.0	190.0	220.0	250.0	280.0	340.0	400.0	460.0
14.7	80	84	88	92	96	101	105	112	120	127
100	1415	1205	90	94	97	102	106	113	121	128
200	1430	1220	1050	885	900	760	110	112	118	124
300	1445	1235	1065	915	775	615	122	124	128	132
400	1460	1250	1078	930	790	640	510	134	133	136
500	1472	1265	1092	945	805	665	535	152	142	142
600	1485	1278	1105	960	825	685	565	200	154	150
700	1500	1293	1120	975	840	705	590	294	166	158
800	1512	1305	1135	990	868	740	630	405	205	178
1000	1540	1335	1160	1005	890	820	715	530	360	255
1500	1610	1400	1225	1075	940	887	785	610	462	350
2000	1675	1465	1290	1140	1005	1010	905	740	600	492
3000	1795	1590	1412	1260	1125	1120	1015	842	703	595
4000	1920	1705	1522	1375	1233	1222	1115	938	795	680
5000	2035	1820	1632	1480	1337	1315	1208	1025	875	760
6000	2150	1930	1735	1580	1432	1405	1293	1105	952	832
7000	2270	2040	1838	1676	1528	1495	1375	1180	1022	896
8000	2375	2150	1940	1772	1618	1580	1455	1253	1090	960
9000	2480	2260	2040	1865	1705	1665	1535	1325	1155	1020
10000	2585	2370	2140	1960	1795					

Recommended values for temperatures and pressures beyond the experimental investigation and densities above 0.10 gram/cc. were determined from the residual viscosity-density plot. The values obtained in this manner yielded smooth continuations of the isotherms and isobars of the experimental data. Except for the extreme pressure for 100° F., all values determined from the residual viscosity-density plot were for densities within the range of the experimental data.

Because residual viscosity for low densities is dependent on temperature, use of the residual viscosity-density plot alone was not sufficient for predicting accurate low density viscosity values for temperatures above 340° F. (5). To determine recommended values for this region, the dependence of viscosity on temperature predicted from kinetic theory was utilized in conjunction with an expanded residual viscosity-density plot. For sufficiently low densities, isobars of viscosity nearly parallel the atmospheric pressure isobar. This can be noted for 100 p.s.i.a. in Figure 3. For temperatures well above the critical temperature, the higher pressure isobars nearly parallel the atmospheric pressure isobar, also. Knowledge of this behavior was used to estimate the effect of temperature on isobaric *n*-butane viscosity for densities below 0.04 gram/cc. The effect of temperature on residual viscosity for densities from 0.04 gram/cc. to 0.10 gram/cc. was estimated from the behavior noted for 280° and 340° F.

The values presented in Table I are believed accurate within  $\pm 2\%$  of the true *n*-butane viscosity. For the region of the experimental investigation, the values are believed to be accurate within  $\pm 0.5\%$  for most points. These values should be satisfactory for most engineering calculations. Other investigators, however, should only make comparisons with the actual experimental values available from ADI.

#### COMPARISON WITH CORRELATIONS

The generalized viscosity correlations of Uyehara and Watson (17), and Carr (3), were tested by comparing predicted values with the recommended values. Uyehara and Watson's chart predicts *n*-butane viscosity values which are about 10% higher than the recommended values. Carr's chart, intended for gases of low molecular weight, predicts *n*-butane viscosity for temperatures above the critical within about 5% of the recommended values. However, the lowest reduced temperature for the chart is 1.0.

#### ACKNOWLEDGMENT

R.D. Shaw assisted in the experimental program and calculations.

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RECEIVED for review September 7, 1962. Accepted January 28, 1963. This investigation was part of a continued study of hydrocarbon physical and thermodynamic properties under the basic research program of the Institute of Gas Technology. The work was supported in part by IGT Members and Contributors and in part by the American Petroleum Institute through Grant-in-Aid No. 77 and Project No. 65.

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