Table 8 Summary of the effectiveness of various methods for predicting viscosity at elevated pressures

Method		Mineral Oils No. of Fluids	Mineral Oils Avg. Dev., % All Values	Mineral Oils Avg. Dev., % 90% of Values	Pure Hydrocarbons No. of Fluids	Pure Hydrocarbons Avg. Dev., % All Values	Pure Hydrocarbons Avg. Dev., % 90% of Values	Nonhydrocarbons No. of Fluids	Nonhydrocarbons Avg. Dev., % All Values	Nonhydrocarbons Avg. Dev., % 90% of Values	All Fluids Studied No. of Fluids	All Fluids Studied Avg. Dev., % All Values	All Fluids Studied Avg. Dev., % 90% of Values
Chu-Cameron	(A)	31	49	38	11	96	69	14	38	34	56	55	44
Worster	(B)	31	27	22	11	16	14	14	20	18	56	23	18
Kouzel	(C)	31	21	12	11	21	15	14	27	25	56	23	16
Roelands, et al.	(D)	31	11	7	11	9	7	-	-	-	-	-	-
PRL Chart	(E)	30	9	6	11	11	7	13	14	11	54	11	7
PRL Equation	(F)	31	9	6	11	12	7	10	19	16	52	11	8

on data provided using fluids of that type alone. However, quite reasonable predictions for a rather wide variety of fluids of different chemical types and viscosity levels can be made using the PRL chart or equation.

Acknowledgment

This research was supported in part by the United States Air Force under Contracts AF33(657)-10374 and AF33(615)-3379 monitored by the Nonmetallic Materials Division, MANL, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

References

1 Bridgman, P. W., "Viscosities to 30,000 kg/cm²," *Proceedings of The American Academy of Arts and Sciences*, Vol. 77, 1949, p. 115.

2 Kuss, E., "The Viscosities of 50 Lubricating Oils Under Pressures up to 2000 Atmospheres," Report No. 17 on Sponsored Research (Germany), Department of Scientific and Industrial Research, London 1951.

3 ASME Pressure-Viscosity Report, ASME, New York, 1953.

4 Dixon, J. A., Webb, W., and Steele, W. A., "Properties of Hydrocarbons of High Molecular Weight," Research Project 42 Report to The American Petroleum Institute, The Pennsylvania State University, September 1962.

5 Klaus, E. E., Johnson, R. H., and Fresco, G. P., "Development of a Precision Capillary-Type Pressure Viscometer," *Trans. ASLE*, Vol. 9, 1966, p. 113.

6 Chu, P. S. Y., and Cameron, A., "Pressure Viscosity Characteristics of Lubricating Oils," *Journal of the Institute of Petroleum*, Vol. 48, No. 461, 1962, p. 147.

7 Worster, R. C., Discussion to paper by Bingham, A. E., "Some Problems of Fluids for Hydraulic Power Transmission," *Proceedings of The Institution of Mechanical Engineers*, Vol. 165, 1951, p. 269.

8 Roelands, C. J. A., Vlugter, J. C., and Waterman, H. I., *Trans. ASME*, 601, December 1963.

9 Kouzel, B., "How Pressure Affects Liquid Viscosity," *Hydrocarbon Proceedings and Petroleum Refiner*, Vol. 44, No. 3, 1965, p. 120.

10 van Nes, K., and van Westen, H. A., *Aspects of the Constitution of Mineral Oils*, Elsevier Publishing Co., New York, 1951.

11 Hirschler, A. E., "Molecular Weights of Viscous Hydrocarbon Oils: Correlation of Density with Viscosities," *Journal of the Institute of Petroleum*, Vol. 32, 1946, p. 267.

DISCUSSION

J. K. Appeldoorn[2]

The chart for predicting the pressure-viscosity coefficient, α, from viscosity and ASTM slope has some limitations that should be emphasized. First, as specified by the authors, it is not universal and cannot be applied to VI-improved oils nor to many of the nonhydrocarbon synthetics. Second, the pressure range is limited to about 10,000 psi. The chart is quite accurate in this range, which is sufficient for hydraulic oils or deep-diving submarines. But at 100,000 psi it can be in error as much as 100-fold, and so is not suitable for elastohydrodynamic calculations. Third, it uses kinematic viscosity (centistokes), whereas a bearing recognizes only absolute viscosity (centipoises).

The chart does show the advantage of a two-constant equation over a one-constant equation in correlation work. By using both the viscosity level and the viscosity-temperature slope, a family of curves is obtained that allows a much better prediction than a single curve can give. The Worster, Kouzel, and Chu-Cameron correlations are one-constant equations and try to predict α from viscosity alone. That is, they assume that all oils of the same viscosity have the same α; but this is true only in rough approximation. Nevertheless, the Kouzel and Worster equations do predict the behavior of naphthenic oils reasonably well, as shown in Fig. 3. The Chu-Cameron equation is based on a faulty assumption which results in a prediction that α *decreases* with increasing atmospheric viscosity; hence, it is worse than no correction at all. The Roelands' correlation, which is a two-constant equation, appears to be as good as the author's correlation. So is the relationship suggested by Hartung.[3]

The trouble with all such correlations is that they have already been done and done better. Roelands, in a remarkably comprehensive doctoral thesis at Delft, has considered virtually every

[2] Esso Research and Engineering Co., Linden, N. J.

[3] Hartung, H. A., "Prediction of the Viscosity of Liquid Lubricants Under Pressure," ASME Paper No. 55—Lub-18. Presented at the ASME-ASLE Lubrication Conference, Indianapolis, Ind., October 10–12, 1955.

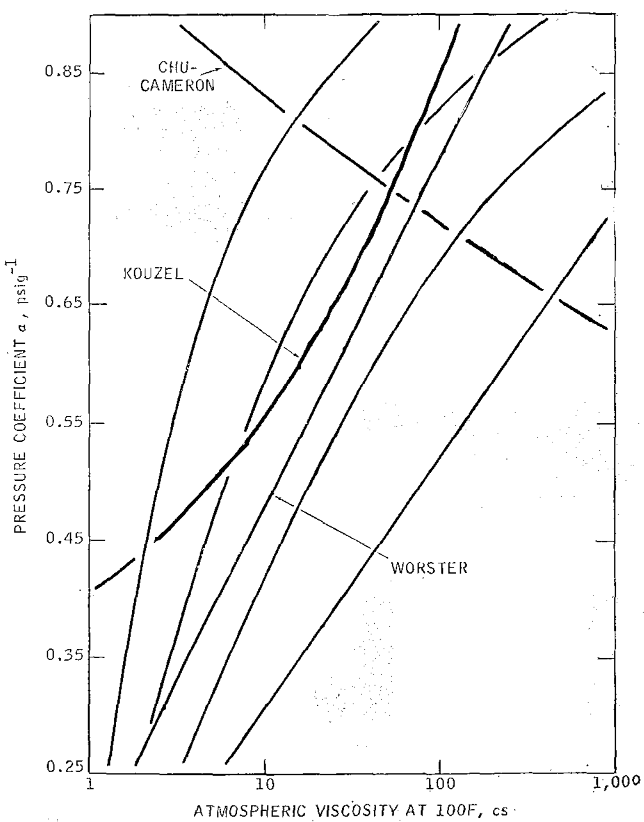

Fig. 3

aspect of the viscosity-temperature-pressure relationships. He first developed a new viscosity-temperature chart based on centipoises instead of the centistokes of the ASTM chart; then a new viscosity-pressure chart that does not show the downward curvature of the Barus equation; then a series of correlation charts which predict both viscosity-pressure and viscosity-temperature from the viscosity level and one of the following: density, refractive index, refractive index minus density and hydrocarbon composition. Included is a chart correlating viscosity-pressure to viscosity-temperature coefficient, which is of the same form as the author's chart. It is equally accurate and remains as accurate over a much larger pressure range.

Author's Closure

Mr. Appeldoorn's discussion brings out several interesting points. This correlation is designed for use in hydraulics. However, when correlations are developed and proven for use in the 100,000 to 1,000,000 psi range to correspond to the Hertz stresses found in many machine elements, the primary data for the many classes of synthetics as well as mineral oils which are presented in this paper may be used in these correlations. The conversion from centistokes to centipoise requires the density. The density-pressure function is a simple one as has been indicated by bulk modulus correlations developed by Klaus and O'Brien.[4]

The mention of a pamphlet paper by Hartung in the discussion brings up an interesting point. A 14-year old ASME Pamphlet paper may be indexed and readily available as a literature reference but such a paper is not available in most libraries and other locations where technical literature is kept. Roeland's doctoral thesis is also not readily available in this country. Theses are generally easier to obtain than ASME Pamphlet papers.

[4] Klaus, E. E., and O'Brien, J. A., "Precise Measurement and Prediction of Bulk-Modulus Values for Fluids and Lubricants," *Journal of Basic Engineering*, TRANS. ASME, Series D, Vol. 86, No. 3, Sept. 1964, pp. 469–474.