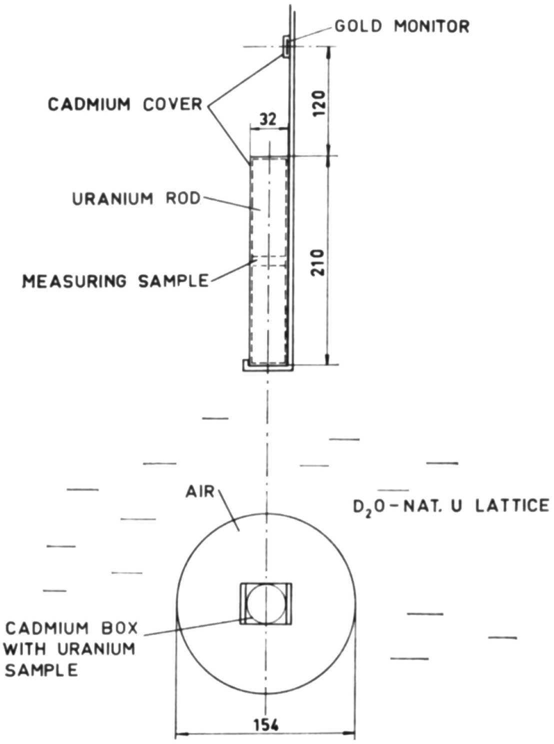

FIG. 1. Arrangement for the irradiations (all units in mm). D_2O–natural uranium lattice: hexagonal lattice, pitch 145 mm, rod diameter 29 mm, central rod missing.

resonance integrals calculated from the two formulas are ±5%.

This new result for metal gives a ratio of oxide to metal resonance integrals which is in better agreement with the value obtained by Smith *et al.* Unfortunately, a direct comparison of the two results is not possible because of the large difference in neutron energy distribution at the sample position for the two measurements.

The old measurements were less accurate than the new ones, and part of the discrepancy for the metal is explained by the common margin of errors. In addition, a minor systematic error has been discovered for the measurements described in (*2*). During the metal irradiations, one of the uranium rods in the inner ring of the reactor lattice had been removed by the reactor operators. This caused a slight decrease of the high energy tail of the neutron spectrum, which decreased the resonance absorption for the lumped uranium relative to that for the infinitely thin uranium standard. This effect is certainly small and it can hardly amount to more than about 1%. Finally, it may be pointed out that the use of different cross section standards for the two measurements makes it difficult to say if the old measured activities for the metal were too low or those for the oxide too high.

It has been argued against the method of measurement that the cadmium box (diam 30 mm, length 200 mm, Cd-thickness 0.8 mm) depresses the fission sources nearest to the samples and thus causes a depletion of high energy neutrons around the samples. To investigate the magnitude of this effect, threshold detectors (phosphor, sulphur, and aluminium) were successively irradiated inside the large cadmium box and inside a small one (diam 30 mm, length 10 mm). Gold was used as a flux monitor. The normalized activities from the detectors inside the small box were about 1% larger than those from the large box. Thus, the depression of the very high energy flux (above 1–2 Mev) is quite small and there is no reason to believe that it should be considerably larger at lower energies.

More details about the experiments described and some additional ones concerning the epithermal absorption in samples, being part of a noncadmium covered rod, will be given in a company report, AE-64.

REFERENCES

1. G. G. SMITH, J. HARDY, D. KLEIN, AND J. A. MITCHELL, *Nuclear Sci. and Eng.* **9,** 421 (1961).
2. E. HELLSTRAND, *J. Appl. Physics* **28,** 1493 (1957).
3. E. HELLSTRAND AND J. WEITMAN, *Nuclear Sci. and Eng.* **9,** 507 (1961).

E. HELLSTRAND
G. LUNDGREN

AB Atomenergi,
Stockholm, Sweden

Received November 3, 1961

The Temperature Dependence of the Viscosity of Liquid Metals

A knowledge of the thermophysical properties of liquid metals is essential to the effective use of these elements as working fluids or as high-temperature coolants in nuclear power plants. In this connection, viscosity is an important property because of its relation to pumping power requirements and heat transfer characteristics of the system (*1*). Experimental difficulties are so great that direct measurements of viscosity have been made on only a fraction of the metals of the Periodic Table, and methods to estimate unknown viscosities from measurement of simpler more basic properties are desirable both for preliminary assessment of practical applicability and for improving our understanding of the liquid metallic state. Although attempts have been made to correlate viscosities and their temperature coefficients with other properties of the elements (*2–16*), no completely satisfactory viscosity–temperature relation for liquid metals has been formulated. However, Andrade's equation for the estimation of viscosities of liquid metals at their melting temperatures (*14*)[1] gives values which are generally in reasonably good agreement with those determined experimentally, this being especially true for metals whose structures do not deviate greatly from cubic close packing (*14*). If a temperature dependence factor could be incorporated into Andrade's expression for η_m, the resulting equation would offer a means to estimate viscosities as a function of temperature for liquid metals for which experimental data are not available. Among the more promising equations proposed for the calculation of temperature coefficients are those of Eyring (*3*, *7*), Fürth (*5*), and Hrbek (*9*). While each of those equations (*3*, *5*, *9*) has

---

[1] This equation is: $\eta_m = 0.57\ (MT_m)^{1/2}V_m^{-2/3}$, where η_m is the viscosity, in millipoises, at the Kelvin melting temperature, T_m, M is the atomic weight, and V_m is the atomic volume at T_m.

TABLE I
SOURCES OF VISCOSITY DATA

Element	Method of measurement	References	Element	Method of measurement	References	Element	Method of measurement	References
Ag	a, c	24, 32, 33	Fe	b, c	20, 38	Ni	d	38, 40
Al	c	10, 30, 31, 36	Ga	a, c	41, 60	Pb	c	26, 29, 36, 55
Au	c	23	Hg	a, e	42–49	Rb	d	21
Bi	a, c	26, 34, 35	In	c, d	50, 60	Sb	a, c	26, 36, 39, 56
Ca	d	37	K	a, d	32, 44	Sn	a, c, e	24, 26, 27
Cd	a, c	29, 32			51–53			29, 32, 35
Co	c	38	Li	d	21			36, 38, 44, 45
Cs	d	21	Mg	c, d	37, 54			54, 56, 57
Cu	a, c	22, 39, 40	Na	a, d	52, 53	Zn	a, c	30, 32, 36, 44, 58

a—capillary, b—rotating crucible, c—oscillating crucible, d—oscillating sphere, e—oscillating disc.

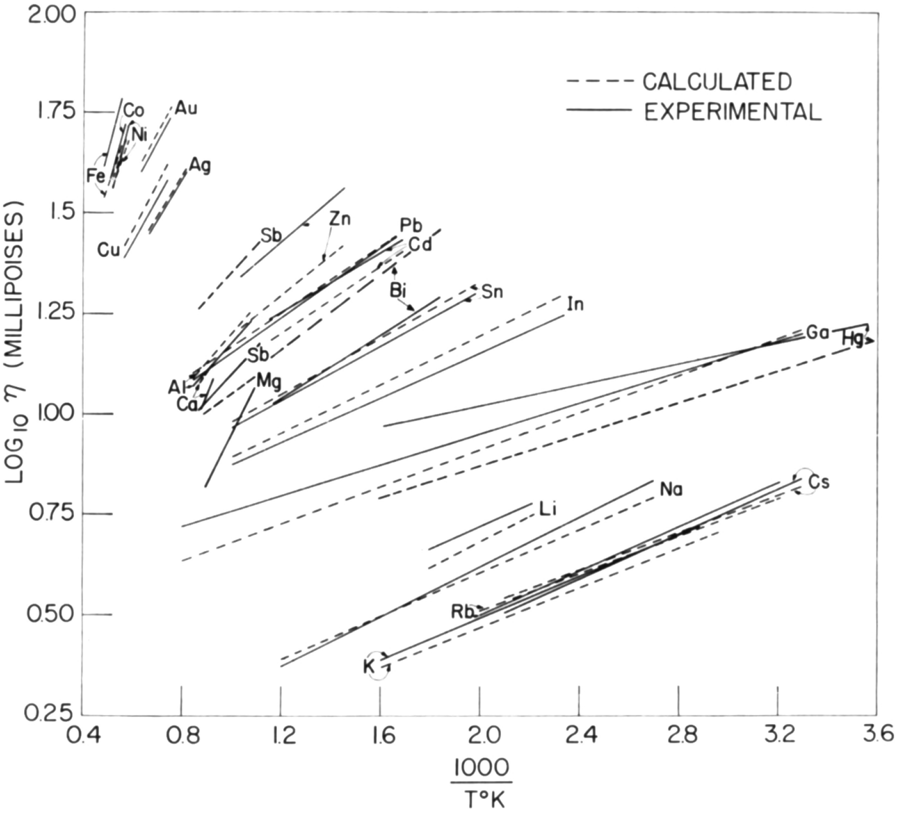

FIG. 1. Log viscosity–reciprocal absolute temperature plots for liquid metals.

some merit, there is room for improvement. The present investigation was carried out, therefore, to determine if a suitable expression for the estimation of temperature coefficients of viscosity could be obtained, and the results are given in the present paper.

A general viscosity-temperature relation for liquid metals (*6*) can be expressed in the form

$$\log \eta = \frac{A}{T} + B, \qquad (1)$$

where η is the viscosity at the temperature T°K, and A and B are constants. Various forms of this equation which contain a volume term have been proposed (*6*), but there is little advantage in departing from the simplicity of Eq. (1) for considering experimental data (*6, 7*). Some investigators (*17–20*) have reported that there is a sudden increase in viscosity as the freezing point of the metal is approached, while others (*21–29*) have shown that a linear relation of log η versus $1/T$ obtains down to the freezing point. In the present investigation, the latter was assumed correct. From Eq. (1) and Andrade's expression for η_m (*14*), it can be shown readily that

$$\log \eta = \log\left[0.57(MT_m)^{1/2}V_m^{-2/3}\right] + \frac{A(T_m - T)}{TT_m}. \qquad (2)$$

This equation contains only one unknown parameter, A, assuming that liquid metal densities are available or may be estimated from densities of the solid metals.

Viscosity data taken from the literature, the sources of which are referred to in Table I, were plotted as log η versus $1/T$, and the temperature coefficient, A, was determined from the slope of the line drawn through the plotted points.[2] The factors which made it difficult to evaluate the reported viscosity data include (a) for some metals, Ca (*39*) and Cs (*21*), for example, only one set of data was available, and (b) for other metals, Ga (*41*, *60*) and Al (*10*, *30*, *31*, *36*), for example, inconsistencies were found between results obtained by different investigators for the same metal. In those cases where such inconsistencies existed and where it was not apparent whose data were most reliable, average values were used.

The temperature coefficients obtained in the manner described above were compared with such physical parameters of the metals as atomic size, heats of fusion, heats of vaporization, ionization potentials, and melting and critical temperatures. The most promising correlation was obtained by comparing the square root of the temperature coefficients with the Kelvin melting temperatures of the metals. A least-square treatment of the data, omitting the values for Ca, Hg, and Mg, whose points on an $A^{1/2}$ versus T_m plot showed the largest deviations, yielded the empirical relation

$$A = (1.79 \times 10^{-2} T_m + 9.73)^2. \qquad (3)$$

By combining Eq. (3) with Eq. (2) we get the following η–T relation which, in exponential form, is

$$\eta = 0.57\ (MT_m)^{1/2} V_m^{-2/3} \exp\left[(2.72 \times 10^{-2} T_m + 14.77)^2 (T_m - T)/TT_m\right]. \qquad (4)$$

Equation (4) was tested by comparing experimental and calculated viscosities of the metals listed in Table I, and the results are plotted as log η versus $1/T$ in Fig. 1.[3] Over the temperature ranges for which experimental data were available, the differences between experimental and calculated viscosities were (a) up to about 34, 51, and 80% for Bi, Mg, and Sb, respectively, (b) less than 30% for Ca, Fe, Ga, Hg, and Zn, and (c) less than 11% for the remaining 15 metals. Most of the metals in groups (a) and (b), which show the largest differences between experimental and calculated viscosities, show anomalous behavior in other respects (*14*, *61*). Finally, it is interesting to note that whereas none of the metals in group (a) and only 2 metals in group (b) are cubic, most of the metals in group (c) have cubic crystals structures.

REFERENCES

1. J. A. Lane, H. G. MacPherson, and F. Maslan (editors), "Fluid Fuel Reactors," p. 837. Addison-Wesley, Reading, Massachusetts, 1958.

2. J. R. Partington, "An Advanced Treatise on Physical Chemistry. Vol. 2. "The Properties of Liquids," pp. 70–127. Longmans, Green, New York, 1955.

3. S. Glasstone, K. J. Laidler, and H. Eyring, "The Theory of Rate Processes," Chap. 9. McGraw-Hill, New York, 1941.

4. R. C. Reid and T. K. Sherwood, "The Properties of Gases and Liquids," pp. 202–218. McGraw-Hill, New York, 1958.

5. R. Furth, *Proc. Camtridge Phil Soc* **37,** 252–290 (1941).

6. R. W. Ewell, *J. Appl. Phys.* **9,** 252–269 (1938).

7. R. W. Ewell and H. Eyring, *J. Chem. Phys.* **5,** 726–736, (1937).

8. J. F. Kincaid, H. Eyring, and A. E. Stearn, *Chem. Revs.* **28,** 301–365 (1941).

9. A. Hrbek, *Z. Metallk.* **48,** 134–137, 603–605 (1957).

10. A. M. Korol'kov, *Izvest. Akad. Nauk. SSSR Otdel. Tekh. Nauk Met i Toplivo* No. 5, 123–126 (1959).

11. K. Furukawa, *Sci. Repts. Research Insts., Tohoku Univ.* **Ser A, 12,** 368–383 (1960).

12. J. H. Simons and W. H. Wilson, *J. Chem. Phys.* **23,** 613–617 (1955).

13. D. R. MacRae and E. F. Johnson, Project Squid, Technical Report PR-81-R (1958).

14. E. N. da C. Andrade, *Endeavour* **13,** 117–127 (1954); *Phil. Mag.* **17,** 497, 698 (1934).

15. A. N. Solov'yev, *Atomnaya Energ.* **3,** 550–552 (1957).

16. S. Peter, *Z. Naturforsch.* **9A,** 98–104 (1954).

17. W. R. D. Jones and W. L. Bartlett, *J. Inst. Metals* **81,** 145-152 (1952).

18. T. P. Yao and V. Kondic, *J. Inst. Metal* **81,** 17–24 (1952).

19. D. Saito and T. M. Matsukawa, *Mem. Coll. Eng., Kyoto Imp. Univ.* **7,** 49–114 (1932).

20. R. N. Barfield and J. A. Kitchener, *J. Iron Steel Inst.* **180,** 324–329 (1955).

21. E. N. da C. Andrade and E. R. Dobbs, *Proc. Roy. Soc.* **A211,** 12–30 (1952).

22. E. Gebhardt and M. Becker, *Z. Metallk.* **42,** 111–117 (1951).

23. E. Gebhardt and G. Worwag, *Z. Metallk.* **42,** 358–361 (1951); *ibid.* **43,** 106–108 (1952).

24. E. Gebhardt, M. Becker, and E. Trager, *Z. Metallk.* **44,** 379–382 (1953).

25. E. Gebhardt, M. Becker, and S. Dorner, *Z. Metallk.* **44,** 510–514 (1953).

26. E. Gebhardt and K. Kostlin, *Z. Metallk.* **48,** 601–602 (1957).

27. V. H. Stott, *Proc. Phys. Soc.*, **45,** 530–544 (1933).

28. V. A. Konstantinov, *Zhur. Fiz. Khim.* **24,** 953–954 (1950).

29. H. J. Fisher and A. Phillips, *J. Metals* **9,** 1060–1070 (1954).

30. E. Gebhardt and K. Detering, *Z. Metallk.* **50,** 379–384 (1959).

31. E. G. Shvidkovski, "Certain Problems of the Viscosity of Liquid Metals", p. 175. State Publishers for Technical and Theoretical Literature, Moscow, 1955.

32. K. Gering and F. Sauerwald, *Z. anorg. Chem.* **223,** 204–208 (1935).

33. W. Radecker and F. Sauerwald, *Z. anorg. Chem.* **203,** 156–158 (1931).

34. R. Arpi, *Z. Metallographie* **5,** 142–167 (1914).

---

[2] The available viscosity data for Ga (*41*, *60*) indicate a possible change in the value of A at about 320°C (*60*) or 400°C (*41*) above the melting point. However, in the absence of additional experimental evidence regarding this apparent anomaly, a single line was drawn through the data on the log η versus $1/T$ plot from which A was determined.

[3] Values for V_m in Eq. (4) were calculated using density data given in ref. *59*; the density of liquid Au was taken from ref. *23*.

35. F. Sauerwald and K. Toppler, *Z. anorg. Chem.* **157,** 117–137 (1926).
36. T. P. Yao, *Giesserei Tech.-Wiss.* **2,** 837–851 (1956).
37. M. F. Culpin, *Proc. Phys. Soc.* **70,** 1079–1088 (1957).
38. G. Cavalier, National Phys. Lab. Symp. No. 9, "The Physical Chemistry of Metallic Solutions and Intermetallic Compounds," Vol. 2, Section 4D. Her Majesty's Stationery Office, London, 1959.
39. A. Bienias and F. Sauerwald, *Z. anorg. Chem.* **161,** 51–75 (1927).
40. A. A. Vertman and A. M. Samarin, *Doklady Akad. Nauk SSSR* **132,** 572–575 (1960).
41. K. E. Spells, *Proc. Phys. Soc.* **48,** 299–311 (1936).
42. C. E. Fawsitt, *Proc. Roy. Soc.* **80A,** 290–298 (1908).
43. S. Koch, *Wied. Ann.* **14,** 1 (1881).
44. "Landolt-Bornstein Physikalisch-Chemische Tabellen," Vol. 4, Part 1. Springer, Berlin, 1955.
45. A. J. Lewis, *Proc. Phys. Soc.* **48,** 103–110 (1936).
46. J. E. P. Wagstaff, *Proc. Cambridge Phil. Soc.* **21,** 11–13 (1922).
47. E. C. Bingham and T. R. Thompson, *J. Am. Chem. Soc.* **50,** 2878–2883 (1928).
48. S. Erk, *Z. Physik* **47,** 886–894 (1928).
49. R. Shuhrman and E. O. Winter, *Z. Naturforsch.* **10A,** 985–996 (1955).
50. M. F. Culpin, *Proc. Phys. Soc.* **70,** 1069–1078 (1957).
51. F. Sauerwald, *Z. Metallk.* **26,** 259–260 (1934).
52. Y. S. Chiong, *Proc. Roy. Soc.* **A157,** 264–277 (1936).
53. C. T. Ewing, J. A. Grand, and R. R. Miller, *J. Phys. Chem.* **58,** 1086–1088 (1954).
54. E. Gebhardt, M. Becker, and H. Sebastian, *Z. Metallk.* **46,** 669–672 (1955).
55. A. Knappwost and G. Horz, *Z. physik. Chem.* **22,** 139–157, (1959).
56. H. Esser, F. Greis, and W. Bungardt, *Arch. Eisenhüttenw.* **7,** 385–388 (1934).
57. M. Pluss, *Z. anorg. Chem.* **93,** 1–44 (1915).
58. M. R. Hopkins and T. C. Toye, *Proc. Phys. Soc.* **63,** 773–782 (1950).
59. J. F. Elliott and M. Gleiser, "Thermochemistry for Steelmaking," Vol. 1, pp. 7–12, Addison-Wesley, Reading, Massachusetts, 1960.
60. G. I. Gorjaga and M. V. Morgunova, *Nauch. Doklady Vyssh. Shkoly (Fiz.-Mat. Nauk* **1,** 180 (1958)).
61. S. W. Strauss, *Nuclear Sci. and Eng.* **8,** 362–363 (1960).

Simon W. Strauss

Physical Metallurgy Branch
Metallurgy Division
U. S. Naval Research Laboratory Washington 25, D. C.

Received October 23, 1961

Measured Slowing Down Distribution at the Indium Resonance from a Line Source of Fission Neutrons in Heavy Water*

Although a number of measurements have been reported (*1–4*) of the slowing down distribution at the indium resonance from a point source of fission neutrons in heavy water, no corresponding measurements seem to have been made for a line source.[1] Such line source distributions are of considerable interest since they are often the starting point for the calculation of flux distributions of resonance neutrons in heterogeneous reactor lattice theory (*5, 6*). The integration of measured point source distributions to obtain line source distributions is unreliable since it assumes knowledge of the point source distribution far beyond the region of measurement. For these reasons, the line source distribution has been measured directly in the Process Development Pile (PDP). This measurement also permitted a new determination of the neutron age to the indium resonance in heavy water.

TABLE I

Corrected Epicadmium Indium Activations Using a Single Enriched Uranium Rod as a Source

Distance from center of rod, r(cm)	Foil activities, A(arbitrary Units)	
	Totals counts	Background Corrected
6.41	70,340	70,220
10.41	56,960	56,840
14.41	42,530	42,410
18.41	28,940	28,820
22.41	18,530	18,410
26.41	11,670	11,540
30.41	7207	7065
34.41	4292	4140
39.2	2300	2140
43.2	1366	1180
47.2	824	608

The Process Development Pile is a heavy-water-moderated, unreflected reactor with an inner tank diameter of 494 cm and a moderator height adjustable up to 466 cm. The pile loading used in this experiment consisted of a driver lattice of natural uranium fuel assemblies surrounding a central heavy water region about 245 cm in diameter. The critical moderator height with this loading was about 200 cm. A rod one inch in diameter composed of 5% enriched uranium (93.2% U^{235}) alloyed with aluminum was placed at the center of the reactor to simulate a line source of fission neutrons with a cosine-shaped strength distribution. The moderator purity was 99.70 mol % D_2O, and the moderator temperature was 22°C.

The detectors were ½-in. diam foils of a lead–indium alloy containing 5.87% indium by weight. Each foil contained 5.6 mg/cm² of indium and was enclosed in cadmium 0.020 in. thick. The foils were placed at approximately 4-cm intervals on a lightweight aluminum tube which was perpendicular to the fission source rod at the center of the pile. At these intervals, mutual shadow shielding between samples was negligible. The plane of the foils was parallel to the fission source. A similar foil irradiation was later made with the source rod replaced by a solid aluminum rod, to obtain the background distribution of pile neutrons at the indium resonance.

---

* The information contained in this article was developed during the course of work under contract AT(07-2)-1 with the U. S. Atomic Energy Commission.

[1] Referred to in what follows as "Point (line) source distributions."