

for the "permanent" gases, hydrogen-bonded liquids and many ordinary compounds,  $H_\eta$  is found to equal  $\Delta U_{\text{vap.}}/2.45$ .

The viewpoint *does not hold in the case of metals*,\* however. A simple example of the two low melting metals, *mercury and gallium*, but boiling far apart, illustrates this point, as shown below:

|         | Melting point (°K) | $H_\eta$ (Cal/g atom) | $\Delta U_{\text{vap.}}$ (Cal/g atom) | Normal b.p. (°K) |
|---------|--------------------|-----------------------|---------------------------------------|------------------|
| Mercury | 234                | 600                   | 12,884                                | 630              |
| Gallium | 303                | 988                   | 56,200                                | 2510             |

$H_\eta$  for mercury and gallium (taken from Table 1) and  $\Delta U_{\text{vap.}}$  for these metals are compared in the table above. Whereas the  $H_\eta$ 's show only a small difference, the corresponding values for  $\Delta U_{\text{vap.}}$  are far apart; there is no simple relationship between  $H_\eta$  and  $\Delta U_{\text{vap.}}$  for metals.

It was found, however, that a *simple relationship exists between  $H_\eta$  and the melting point of the metal*. This is shown graphically in Fig. 2,  $H_\eta$  increases as a monotonic function of the melting point of the metal. All known metals for which  $H_\eta$  data are available lie on or close to the smooth curve. Low melting metals, such as mercury, gallium or the alkali metals have low energies of activation  $H_\eta$ , while silver, copper and iron, melting above 1000°K, have high activation energies for viscous flow. The highest values are expected for the refractory metals, such as tantalum, rhenium and tungsten.

Use of this empirical relationship thus makes it possible to estimate the change of a metal's viscosity with temperature.

It should be understood that this empirical relationship represents a first approximation only. A more precise relationship will have to take into consideration the different changes in specific volume or density with temperature for various metals. Thus, for example, although the melting points of cesium and gallium are very close (see Table 1), their temperature coefficients  $dD/dt$  are quite different, since the critical temperatures<sup>(2)</sup> of cesium (2150°) and gallium (7620°K), are quite far apart. This empirical relationship can be expressed algebraically. However, it would be desirable to first obtain viscosity data on the high temperature branch of the curve, i.e., above the melting point of iron. It would be particularly interesting to get viscosity data for such high melting metals as molybdenum, tantalum and tungsten.

As has been shown also by ANDRADE<sup>(10)</sup>, the viscosity of a liquid metal *at the melting point*, provided it has a close packed crystal structure, is given by the simple expression:

$$\eta_{\text{m.p.}}(\text{poise}) = \frac{5.7 \times 10^{-4} \cdot \sqrt{(A \cdot T_{\text{m.p.}})}}{V_A^{2/3}}$$

\* We are grateful to the reviewer for informing us that according to EYRING'S latest development of the theory of significant liquid structures<sup>(9)</sup> the viscosity of metals involves the introduction of holes of *ionic size* rather than of atomic or molecular size, as in the case of *non-metallic* atoms or molecules. Thus a relationship similar to the one expressed in this article may be expected theoretically.

<sup>(9)</sup> H. EYRING and T. REE, *Proc. Nat. Acad.* 47, 562 (1961).

<sup>(10)</sup> E. N. DA C. ANDRADE, *Phil. Mag.* 17, 497-511 (1934).