Discussion

G. E. McIntosh.[8] The authors are to be commended for their work. Devising this clever sinusoidal temperature input has enabled them to approach the problem of direct measurement of thermal diffusivity in the most logical manner. The results obtained appear to be good and the temperature range is significant, although values from 1000 to 2000 F and above are in greater demand at many activities.

In critically viewing the paper, the writer has the following specific comments and questions:

1 It is believed that the paper would be strengthened by stating the results of an error analysis and relating the maximum expected error to measurements on a standard specimen.

2 How reproducible are the data obtained from the authors' apparatus?

3 How many man-hours are required to determine a thermal diffusivity value at, for instance, 500 F, if one were to start with a piece of bar stock of approximately the correct OD?

In closing, the authors are urged to make further use of their apparatus. If at all possible, the work should be extended to higher temperature ranges.

W. L. Sibbitt.[9] The authors are to be congratulated for an excellent example of analytical and experimental research. An error analysis of this experimental method would be of interest. The composition and mean temperature are not sufficient to identify the state of the test specimen. Thermal diffusivity is also a function of the energy gradient, the load stresses, and the number of dislocations in the metal. The fact that the metal has been held for a few hours at a temperature above the recrystallization temperature does not necessarily mean that it is in a fully annealed state.

There is a great need for the thermal properties of materials in the temperature region close to their melting points. Metals are now used in applications where they are subjected to extremely high-temperature gradients and moderate load stresses for a total service life of the order of 1 min. The data on specific heats and densities are acceptable; however, there is very little information on thermal conductivities.

Authors' Closure

The authors wish to express their appreciation to Dr. McIntosh and Professor Sibbitt for their kind remarks and pertinent comments on the paper.

Both discussers expressed the desirability of performing an error analysis which was not done owing to the complexity of the problems involved. Instead, a direct comparison with diffusivity values calculated from published data on K, c, and ρ was made whenever feasible. Nevertheless, during the course of investigation, the following sources of error were noted and efforts had been made to keep them to a minimum:

1 The equations derived in the paper were based upon tubular specimens of uniform cross section. Installation of thermocouples at the temperature-measuring stations would produce some local disturbance on the supposedly linear heat flow in the specimen. Accurate analysis is difficult, but the error was presumed to be small since any excess deposit of the brazing alloy was carefully removed afterwards. Conduction error along thermocouple leads had been estimated and found to be insignificant.

2 The impervious boundary condition at the unheated end of the specimen used in the analysis was a simplification. Calculation showed that it introduced little error if (a) the specimen material were of relatively good conductors, such as those used in the present investigation and (b) the thermocouples were installed at sufficient distance from that end.

3 Inaccuracies in wave shape were within narrow limits, as they were checked frequently by comparing the recorded temperature wave with the theoretical sine wave. In this connection, it may be remarked that the photoelectric potentiometer-type recorders used in the experiment showed noticeable error (2 to 3 per cent) when readings were taken in the range over $^3/_4$ of the full-scale deflection. Corrections were then applied by calibration with precision, manually balanced potentiometers.

4 One obvious source of error in the present apparatus was the discrepancy obtained in the measured period (or frequency) of the temperature waves. To illustrate, data obtained from a typical test run on the 1.1 per cent C tool-steel specimen are given for reference in Table 1.

TABLE 1 TEST-RUN DATA

Voltage of feeding variac, volts	80.0
Manometer reading, in.	0.03
Period of sinusoidal heater,[a] sec per cycle	540
Bucking emf for 1st measuring station, mv	14.65
Bucking emf for 2nd measuring station, mv	14.60
Time averaged temperature at 1st station, deg F	534
Time averaged temperature at 2nd station, deg F	525

(i) Amplitude ratio — A_{12}

Difference between maxima and minima of temperature wave at first station (average of 5 rdgs., mean deviation ± 1 per cent), mv	0.745
As above but at second station, mv	0.382

Thus

$$A_{12} = \frac{0.745}{0.382} = 1.95$$

(ii) Phase shift $\frac{(\Delta\phi)_{12}}{\omega}$ sec

Time at which temperature wave crosses mid-axis, measured from some arbitrarily chosen zero

First measuring station	Second measuring station	$\frac{(\Delta\phi)_{12}}{\omega}$
55 sec	107 sec	52 sec
320	371	51
592	643	51
857	907	50
1126	1177	51
	Avg.	51.0 sec

[a] Obtained by using stop watch and counting the number of revolutions of the driving cam (Fig. 3, item 10).

The half-periods obtained with the temperature wave at the first measuring station are, respectively, 265, 272, 265, and 269 sec. Corresponding values for the second measuring station are 264, 272, 264, and 270 sec. These values indicate a maximum deviation of +0.7 to —2.2 per cent when compared with the half-period of the sinusoidal heater, the latter being 270 sec.

While, under certain conditions as expounded in the paper, the use of amplitude ratio of the temperature waves is preferable to phase shift in diffusivity calculations, data reported herewith represent the mean value obtained by using both measurements. In general, the agreement is good. For the case of 1.1 per cent C tool steel cited in the foregoing $\alpha = 0.368$ and 0.370 sq ft per hr as computed, respectively, from the amplitude ratio and phase shift. More representative, however, is the result acquired from subsequent tests on AISI Type 430 stainless steel. At a mean temperature of 913 F, the corresponding diffusivity values are 0.242 and 0.250 sq ft per hr, indicating a mean deviation of ±1.6 per cent.

During the course of the investigation, it was immediately learned that fluctuations in air pressure had a serious effect on wave shape. The air was delivered from a compressor which was also the source of air supply to other laboratories. During

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the daytime, the surge-tank pressure fluctuated between 68 and 75 psig. Satisfactorily steady condition was achieved by conducting all test runs in late evening and by bleeding the compressor at the same time. Under these controlled conditions, reproducibility of data was checked on Type 430 stainless-steel specimen and had been found to be within $3^1/_2$ per cent among three different runs.

Perhaps one of the major shortcomings of the present apparatus is the large number of man-hours involved. If one were to start with a piece of bar stock of approximately the correct OD, it is estimated that at least 7 to 10 man-hours will be required to obtain a single diffusivity value at a specified temperature. This does not include the computation work.

Extension to higher temperature ranges seems possible but must be accompanied with modifications. The copper tubing and other parts which deteriorate rapidly at higher temperatures will have to be replaced by heat-resistant alloys. To date, no actual tests have been conducted above 1200 F.

With reference to Professor Sibbitt's comment on the effect of load stress, energy gradient, etc., on the thermal diffusivity of metals, the authors wish to point out that the present apparatus is inherently not suitable for studies of such type, for instance, the determination of stress-conductivity relations. In the first place, the present apparatus necessitates a state of equilibrium, i.e., heating of specimens at higher temperature for a considerable length of time. This usually entails changes in microstructure. It is clear that for metals which are designed for short service life, say, of the order of 1 min, but subjected to high-temperature gradients and load stresses, one has to resort to true transient methods.

As early as 1923 Bridgman[10] reported data on the effect of tension on thermal conductivity of metals, ranging from about 0.39 per cent for a 2050 kg/cm^2 ($\sim$29,000 psi) load in Fe to 0.015 per cent for a 770 kg/cm^2 ($\sim$10,900 psi) load in Pd. Evidently, for such study, an accuracy of better than $^1/_2$ per cent is required. In view of the foregoing discussion, one could not expect an accuracy of better than 2 to 3 per cent from the present apparatus.

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[10] "Effect of Tension on the Thermal and Electrical Conductivity of Metals," by P. W. Bridgman, Proceedings of the American Academy of Arts and Sciences, vol. 59, 1923, p. 127.