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HIGH TEMPERATURE THERMAL DIFFUSIVITY
MEASUREMENTS BY THE FLASH TECHNIQUE

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ABSTRACT

The pulse technique was applied to the measurement of the thermal diffusivity of tantalum and three grades of graphite over the 800° to 2200°C temperature range. A ruby laser system was used as the pulsed energy source; a photomultiplier tube detected the transient time-temperature response of the back face of a thin sample. Corrections for the heat loss and finite pulse-time are included in the calculations for thermal diffusivity. The data for tantalum are in good agreement with literature values. The laser pulse technique was found to be a convenient, rapid, and precise method for routinely measuring the thermal diffusivity of small samples of solid materials. The extension of the technique to 3000°C and the simultaneous measurements of specific heat are discussed.

INTRODUCTION

The nuclear rocket program at Los Alamos Scientific Laboratory requires the utilization of refractory materials at extremely high temperatures. One phase of the materials development involves the measurement of thermal properties (thermal diffusivity and specific heat) at temperatures corresponding to those expected in advanced nuclear rocket motors. A number of presently existing steady-state and non steady-state methods are being used to measure these parameters. The length of time to make

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reliable measurements and large sample size requirements impose intolerable limitations on the routine use of these methods to measure production variables.

A particularly simple technique for measuring thermal diffusivity has been developed in recent years based on the time it takes for an applied heat pulse to travel through a thin sample. Parker et al⁽¹⁾ measured the thermal diffusivity, α , by exposing a thin slab of material to a very short pulse of light from a xenon flash tube. With the rapid development of laser technology in the last few years, investigators^{(2)*} active in the field suggested that the basic characteristics of the ruby laser make it well suited for applying a quick pulse of high energy to the surface of a small sample. The laser beam is well collimated and can be directed into a tube furnace some distance from the flash source. This property makes possible measurements on radioactive samples in a hot cell or even the study of samples while they are being exposed to a neutron flux within a reactor.

In the following, the basic mathematical relations derived from the Fourier Heat Conduction equation are analyzed and applied to measurements made by the flash technique on samples of tantalum and graphite in the 800° to 2200°C temperature range.

One considers a sample in the shape of a disc, one face of which is to receive a uniformly distributed pulse of energy from a laser beam. The heat flow in the sample is governed by the general Fourier equation:

$$-\nabla^2 T(x, r, t) + \alpha^{-1} \frac{\partial T(x, r, t)}{\partial t} = k^{-1} q(x, r, t) \quad (1)$$

where the front and back surfaces of the sample are denoted by $x = 0$ and $x = a$ and the radius r_0 . The temperature is denoted by T , q is the heat source term, α is the thermal diffusivity, k is the thermal conductivity, t is the time, and ∇^2 is the Laplacian operator in cylindrical coordinates (assuming no angular dependence).

*References appear under the heading REFERENCES

In the pulse method for thermal diffusivity measurements as developed by Parker et al, several simplifying assumptions were made in the analytical solution of the general equation. These include: one dimensional heat flow, energy pulse absorbed in a very thin layer of the sample surface in a time very short compared to the propagation of the heat wave through the material, thermal properties α and k independent of the temperature, and no heat losses by conduction or radiation from the faces. These assumptions lead to a simple equation,

$$\alpha = \frac{0.139 \, l^2}{t_{1/2}} \quad (2)$$

where

α = thermal diffusivity (cm^2/sec).

l = sample thickness (cm).

$t_{1/2}$ = time required for back face temperature to reach one-half its maximum value (sec).

Equation (2) has been used in several recent papers to calculate the thermal diffusivity of Armco Iron by G. L. Denman⁽³⁾ and R. E. Taylor et al⁽⁴⁾ (with finite pulse-time corrections), and irradiated graphite⁽⁵⁾ and technetium metal⁽⁶⁾ by D. E. Baker.

A more general solution of Equation (1) to account for heat losses from both faces of the sample is given by Cowan.⁽⁷⁾ The dimensionless temperature response at the back face ($x = 0$) is:

$$\rho C_p \theta(x, t) = 2 \sum_{n=0}^{\infty} \gamma_n^2 \frac{\cos(\gamma_n x/l) + [\gamma_n(1+r)] \sin(\gamma_n x/l)}{D_n \exp(\alpha \gamma_n^2 t/l^2)} \quad (3)$$

where

$\theta(x, t)$ = temperature above ambient,
i. e., furnace temperature ($^{\circ}\text{C}$).

ρ = density (gm/cm^3).

Q = total energy of pulse
(cal/cm^2).

C_p = specific heat ($\text{cal}/\text{gm } ^{\circ}\text{C}$).

γ_n is the solution in the range $n\pi < \gamma < (n+1)\pi$

of $\cot \gamma = y/a - b/ay$,

$C_x = [(\partial W / \partial T) / k]_x, \quad x = 0, \quad l$

where W is the power loss per unit area at the surface $x = 0$ or l due to thermal radiation and/or convection losses,

and

$$a = 1 (C_0 + C_1) = 1 C_0 (1 + r), \quad r = C_1/C_0$$

$$b = 1^2 C_0 C_1 = r a^2 / (1 + r)^2$$

$$D_n = y_n (\sin y_n) [1 + a - (2 b/a) + y_n^2 / a + (b/y_n^2) + (b^2/a y_n^2)].$$

In the general case where neither "a" nor "b" is small, the values of "a" and "r" must be determined, at least, approximately. Since "a" is a function of the magnitude of the surface heat losses, its experimental determination is very difficult. However, "a" can be eliminated by obtaining a long time solution to Equation (3) as well as the half-time solution. Experimental convenience dictates the use of a solution at some multiple of the half-time. The coefficient of Equation (2) is defined as $0.139 = \alpha t_{1/2} / 1^2$ for the case of no heat losses but will be re-defined as $\omega = \alpha t_{1/2} / 1^2$ for the more general case in the solution of Equation (3).

In Figure 1, a plot of ω as a function of the ratio of the solution, $\theta(0, t)$, at 5 and 10 times $t_{1/2}$ to $\theta(0, t)$ at $t_{1/2}$ is plotted. For zero heat losses this ratio is equal to two and the value of ω is 0.139. A value of $r = 1$ has been assumed for both curves in Figure 1 as suggested by Cowan. The emittance of both faces is certainly the same and only radiation losses need be considered at the high temperatures measured in this work. Therefore

$$r \approx \left(\frac{T_1}{T_0} \right)^3$$

and since T_1 and T_0 differ by only a few degrees at the most, "r" is very close to one.

Denman⁽³⁾ anticipated that radiation heat losses from the edge of the sample might invalidate the assumptions of the simple boundary conditions and require the application of the more stringent boundary conditions as discussed by Cape and Lehman.⁽⁸⁾ The radial heat losses can be reduced by decreasing the sample thickness and/or the viewing area on the back face of the sample. However, as the sample thickness is decreased, the pulse time of the laser beam may become a relatively large fraction of the half-time of the heat pulse. Taylor and Cape^(4, 8)

have presented an adequate mathematical treatment of this finite pulse-time effect. The experimental application of heat losses and finite pulse-time effect is discussed under results.

EXPERIMENTAL TECHNIQUES

The schematic diagram in Figure 2 and the photograph in Figure 3 show the over-all apparatus used in measurements of thermal diffusivity to 2200°C. The 20 joule ruby laser system consists of a 2000 joule power supply and firing circuit (Raytheon Model LPS2) and elliptical cavity laser head (Raytheon Model LH5) with a 6 5/8 inch long by 3/8 inch diameter ruby, mirrored on one end. The cavity containing the ruby and the xenon flash lamp is flushed with dry nitrogen gas to prevent moisture condensation due to the low temperatures resulting from the liquid nitrogen cooling of the ends of the ruby crystal.

The water cooled high temperature furnace (Figure 4) has a 5/8" O. D. 15 mil wall tantalum tube heating element wrapped with 6 layers of 3 mil Ta sheet for radiation shielding. A continuously variable powerstat and 14 KVA stepdown transformer constitute the power supply for the furnace. The furnace vacuum system, a model 1402 Duo-Seal fore pump and 4 inch CVC oil diffusion pump, has the capacity of producing a vacuum of 1×10^{-5} torr with 10 minutes of pumping. This vacuum is necessary for the elimination of convective heat losses and for protection of the tantalum furnace parts from oxidation. Both furnace windows are of 1/8 inch quartz. One end of the furnace is hinged for easy withdrawal of the sample holder assembly.

The one-half inch diameter samples varying in thickness from .020 to .090 inches (0.05 to 0.23 cm) are held in a tantalum tube which extends to the center of the heater tube. The cold end of this sample holder is held away from the heater tube by boron nitride rings to prevent the leakage of laser light between the holder and heater. The samples are held against a shoulder at the hot end by a threaded tantalum ring which has been carbided and then coated with thorium oxide to prevent self-welding to the mating threads. Light-proof seals between the sample and its holder, and the holder and its enclosing heater are necessary to prevent any laser light from reaching the detection system directly. It was observed experimentally that if 0.02% of sample area could be penetrated by direct laser light, the heat pulse response of the detection system was completely obliterated.

The temperature response of the back face of the sample is monitored by a RCA-6655A multiplier phototube mounted on an optical bench as shown in Figure 5. The wave length of maximum spectral response of this tube is listed as 4400 ± 500 angstroms which should have resulted in negligible response to the ruby laser light at 6943 angstroms. In actual practice, however, the phototube did detect the laser light to a very appreciable extent. A Power Designs Pacific Company Model HV-1565, high voltage, regulated DC power supply is used to supply anode voltage to the phototube.

The optical bench is designed to provide a high degree of flexibility in making measurements of the light emitted from the incandescent sample in the furnace. Provision is made to scan the surface of the sample in order to determine the uniformity of temperature response across it, and to operate at different wave lengths in order to determine how the signal amplitude, signal linearity, and signal-to-noise ratio vary with wave length. This is accomplished by bringing the desired light from the incandescent sample to the photomultiplier tube through a series of lenses, filters and apertures. Between-the-lens mounting of filters, fixed apertures, and a continuously variable iris diaphragm is provided to permit control of both the intensity and wave length of the light being measured.

The laser head, furnace, and optical bench are rigidly mounted in perfect alignment on a long laboratory bench. Each unit is designed so it can be adjusted or opened without disturbing the alignment of the light path from the laser to the photomultiplier tube. A length of 1/4" diameter lucite tube is installed to pipe a portion of the laser fluorescent light around the furnace directly into the covered optical bench. This small pulse of light provides a fiducial point on the oscilloscope trace for a zero time indication. This simple device obviates the necessity of having delay circuits in the laser triggering circuitry.

The sample temperature is measured by elevating a prism into the light path as it enters the optical bench. The back face of the sample is observed with a Leeds and Northrup optical pyrometer which was calibrated against a NBS standard tungsten filament lamp. Corrections are also made for the quartz window and prism absorption. The emissivity of the carbon samples was found to be approximately unity by drilling black body holes into a thick sample and comparing the temperature within the holes to the surface temperature. No appreciable difference could be observed. The same procedure was performed with a tantalum sample and an emissivity correction curve developed. All tantalum temperatures were corrected in this manner.

The amplified signal from the photomultiplier tube is divided in order to improve the tube operation in the presence of high background light levels. A portion of the phototube output flows through a one megohm resistor to a positive power supply (Barnes Corporation Model 32-101). This positive voltage is then varied to bring the anode voltage back to ground potential at whatever background light is being emitted from the furnace at a particular temperature. This modified phototube response is then displayed on a Tektronix Type 564 storage oscilloscope having a 3A1 plug-in amplifier and a 3B3 plug-in time base generator. The oscilloscope displays are photographed with a Polaroid Land Camera (Model C-12) using type 46L positive transparency film. The film is projected onto 5 x 5 to 1/2 inch grid paper from a distance such that the oscilloscope screen grid coincides with the paper grid. The projected display is traced on the graph paper and then the appropriate data are read. This enlarging technique greatly facilitates the data acquisition as the original films are too small for accurate measurements.

RESULTS

The thermal diffusivity of tantalum was measured from 800° to 2200°C. The results of measurements on three samples of different thicknesses are shown in Table 1 and Figure 6. Tantalum was chosen for the first test of the system because it was readily available from high purity, easily machined 3/4 inch diameter round stock. Tantalum also has a relative freedom from the effects of heat treatment and has no phase changes over the temperature range studied. A spectrochemical qualitative analysis of the tantalum is listed in Table 2.

The 40 data points as plotted on Figure 6 show essentially no dependence on sample thickness and a relatively small scatter. The solid line curve is slightly concave downward and is very similar to a curve (dashed line) as shown by Taylor and Nakata.⁽⁹⁾ All results were calculated on the basis of Equation (3) using Cowan's value of ω from Figure 1. In a few cases the θ_{10}/θ_1 curve for ω was used instead of the θ_5/θ_1 curve. Typical photographs of oscilloscope traces from the three runs are shown in Figure 7. The laser pulse is the small spike which appears and dies away before the heat pulse response starts to rise. Zero time for purposes of measurement is taken at a point 0.2 milliseconds before the peak of the laser pulse.

The thermal diffusivities of three different grades of graphite over the same temperature range are shown on Figures 8 through 11 and Tables 3 through 6. ATJ graphite was measured in the longitudinal and transverse grain direction. Only transversely oriented TS-699 and EP-192C graphite samples were measured. ATJ is a National Carbon Company graphite with a bulk density of 1.73 gm/cm^3 and a room temperature thermal conductivity of $1.17 \text{ watt/cm } ^\circ\text{C}$ (longitudinal) and $0.89 \text{ watt/cm } ^\circ\text{C}$ (transverse). The EP-192C graphite is made by the Pure Oil Company. Its density is 1.55 gm/cm^3 . The TS-699 graphite is the production grade of National Carbon Company experimental graphite originally labeled B-2691. Its density is higher, i. e., 1.85 gm/cm^3 .

Various thicknesses of tantalum and each type of graphite were measured to verify the boundary conditions used to solve Equation (1). In general, one can observe from Figures 6 through 11 that samples of .040 to .080 inches thickness exhibit no dependence of thermal diffusivity on thickness. All values lie within the random scatter of results. The use of Cowan's method to correct for radiation heat losses from the sample faces was necessary as can be observed by the negative slope of the heat pulses shown in Figure 7. Values of ω , the correction term, varied from 0.139, no correction, to 0.110, a correction of 21%, depending on the temperature and sample thickness.

A major advantage of the laser flash method for thermal diffusivity measurements is the rapidity with which a sample can be analyzed. The furnace temperature can be varied in approximately 100°C intervals over the 800 to 2200°C range with temperature equilibrium being attained in about 15 minutes at the lower temperatures and within 5 minutes at higher temperatures. This is especially convenient as 5 minutes are required for cooling of the laser ruby between pulses. One operator can measure two samples a day.

DISCUSSION

The effectiveness of radiation heat loss corrections was well demonstrated by the good agreement among values of α for various thicknesses of each sample at a particular temperature. Another correction, the finite pulse-time effect, has already been mentioned. Cape and Lehman⁽⁸⁾ state that when the duration of the energy pulse, τ , is comparable to the characteristic thermal diffusion time, t_c , the rise

in temperature of the sample is expected to be retarded. Taylor et al⁽⁴⁾ further note that t_c should be 50τ for this retardation to be neglected. Our value of τ was approximately 1.5 milliseconds. The values for $t_{1/2}$ (time to half maximum of the thermal pulse) were about 10 msec for .030 inch thicknesses of graphite. When the correction for a square wave pulse as described in (4) is applied to these data, it appears that our values of α are about 10% too low. This calculation is apparently confirmed by the data points on Figure 11 for the .030 inch sample because if the values for α are increased by 10% they will fall in better agreement with the values of α for the .040 and .050 inch samples, at least from 800° to 1200°C. However, the values for all three sample thicknesses agree very well beyond 1200°C, so the correction is apparently not necessary there.

For graphite samples over .040 inches thick, $t_{1/2}$ is sufficiently large so that the finite pulse-time correction as calculated by the method of Taylor et al is less than the random scatter of values due to inaccuracies in the oscilloscope traces. One experimental run was made with a .020 inch sample of TS-699 graphite. The values for $t_{1/2}$ averaged 4 msc. which is similar to the first example in Table 1 of reference (4). According to the authors' calculations, the observed values should be increased by 30%. A cursory inspection of these values of α for the .020 inch sample on Figure 11 indicates that a 30% increase would bring them in line with the values for the .040 and .050 inch samples. This correction is not required over the entire temperature range. Above 1700°C the values of α for the .020 inch sample coincide with the values for the thicker samples.

FUTURE WORK

Very High Temperature Applications

The tantalum tube heater in the vacuum furnace limits the maximum temperature to 2200°C. Attempts to heat the sample over 2200°C caused the tube to sag and block the light path. A graphite heating element and a graphite sample holder are being fabricated and should permit the extension of measurements to 3000°C. No other equipment limitations are apparent at present.

Thermal Conductivity

The thermal conductivity of a solid can be calculated from the formula:

where

$$K = C_p \alpha \rho$$

K = thermal conductivity (cal/sec. cm °C)
 C_p = specific heat (cal/gm °C)
 α = thermal diffusivity (cm²/sec)
 ρ = density (g/cm³)

In order to calculate K , values of C_p and ρ over the same temperature range as the values of α must be known. Specific heats can be determined by pulse heating techniques (9) and the drop calorimeter (10). We propose another method based on equations already developed in the introduction of this paper. If Equation (3) is solved for the no heat loss case ($a = b = 0$), then

$$\theta(l, t) = \frac{Q}{\rho C_p l} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp\left(\frac{-n^2 \pi^2 dt}{l^2}\right) \right] \quad (4)$$

where Q is the heat input from the laser pulse. The maximum temperature, $\theta_{o, m}$ of the thermal pulse in this case will be,

$$\theta_{o, m} = \frac{Q}{\rho C_p l}$$

when we let

$$t \rightarrow \infty \text{ in (4)}$$

The problem is now reduced to finding values for $\theta_{o, m}$ and Q since ρ and l can be easily measured. $\theta_{o, m}$ can be measured by observing the back face of the sample with the photomultiplier tube whose output is displayed on the oscilloscope which has been previously calibrated in volts/°C with an optical pyrometer. Then Q can be found by using a sample of known specific heat and emissivity. Then, assuming the laser output is constant, C_p for an unknown sample may be determined. Heat losses can be corrected by Cowan's techniques (7).

CONCLUSIONS

The flash technique for measuring the thermal diffusivity of tantalum in the 800° to 2200°C range yielded values which compare closely with those obtained by other methods. The thermal diffusivity values of three grades of graphite are presented for the first time. This rapid and precise method requires only small, easily fabricated samples. Corrections for finite pulse-time effects and heat losses can easily be applied. Suggestions are given for application of the method for determining the specific heat of solid materials.

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TABLE 1
THERMAL DIFFUSIVITY OF TANTALUM

No. 1 .030 inches (0.075 cm)		No. 2 .050 inches (0.125 cm)		No. 3 .090 inches (0.225 cm)	
Temperature	α	Temperature	α	Temperature	α
$^{\circ}\text{C}$	cm^2/sec	$^{\circ}\text{C}$	cm^2/sec	$^{\circ}\text{C}$	cm^2/sec
812	0.215	887	0.226	942	0.238
853	.216	962	.207	1012	.231
864	.222	995	.232	1116	.213
1410	.222	1053	.230	1224	.216
1708	.195	1073	.207	1447	.216
1856	.195	1185	.211	1564	.216
2204	.184	1193	.220		
2204	.177	1196	.227		
2204	.175	1290	.214		
2212	.185	1344	.218		
		1366	.227		
		1484	.226		
		1553	.213		
		1625	.214		
		1735	.220		
		1879	.223		
		1961	.225		
		2033	.191		
		2106	.192		
		2148	.187		

TABLE 2

ANALYSIS OF TANTALUM

Density	measured	16.6	gm/cm ³
	theoretical	16.6	
Metallic Impurities			
	Cr	< 1	ppm
	Cu	< 1	"
	Fe	10	"
	Mo	< 10	"
	Ni	2	"
	Si	15	"
	Ti	< 5	"
	W	< 40	"

TABLE 3
THERMAL DIFFUSIVITY OF ATJ GRAPHITE
TRANSVERSE ORIENTATION

No. 1 0.030 in(0.075 cm)		No. 2 0.040 in(0.1 cm)		No. 3 0.050 in(0.125 cm)		No. 4 0.080 in(0.2 cm)	
Temp. °C	α cm ² /sec	Temp. °C	α cm ² /sec	Temp. °C	α cm ² /sec	Temp. °C	α cm ² /sec
856	0.121	891	0.126	923	0.125	810	0.145
987	.124	947	.119	1057	.123	972	.131
1095	.121	1019	.109	1140	.117	1174	.110
1181	.110	1163	.104	1250	.103		
1257	.100	1292	.102	1337	.109		
1341	.104	1427	.103	1416	.101		
1433	.101	1521	.094	1514	.102		
1531	.095	1645	.099	1576	.100		
1660	.091			1688	.099		
1744	.090			1797	.093		
1865	.095			1880	.087		
1952	.090			1945	.088		
				2042	.085		

TABLE 4
THERMAL DIFFUSIVITY OF ATJ GRAPHITE
LONGITUDINAL ORIENTATION

No. 1 0.040 inches (0.1 cm)		No. 2 0.060 inches (0.15 cm)	
Temp. °C	α cm ² /sec	Temp. °C	α cm ² /sec
830	0.166	808	.194
881	.171	929	.178
1021	.152	1018	.175
1130	.151	1129	.163
1226	.146	1242	.155
1283	.163	1463	.141
1370	.159	1555	.143
1475	.150	1651	.144
1576	.147	1739	.140
1656	.127	1863	.128
1754	.139	1949	.111
1816	.117	2028	.104
1904	.102	2116	.106
1975	.105		
2048	.102		
2112	.101		

TABLE 5

THERMAL DIFFUSIVITY OF EP 192 C GRAPHITE

No. 1 0.020 inches(0.05 cm)		No. 2 0.030 inches(0.075 cm)		No. 3 0.050 inches(0.125 cm)	
Temp. °C	α cm ² /sec	Temp. °C	α cm ² /sec	Temp. °C	α cm ² /sec
829	0.079	812	0.081	804	0.086
846	.076	903	.082	842	.087
901	.070	975	.077	866	.084
981	.069	1078	.072	900	.079
1112	.068	1155	.069	954	.079
1223	.064	1255	.064	1039	.074
1312	.065	1363	.064	1137	.067
1342	.065	1483	.062	1205	.065
1418	.064	1601	.060	1313	.067
1450	.061	1706	.060	1456	.064
		1777	.059	1539	.065
		1885	.056	1642	.064
		1969	.055	1748	.056
		2065	.053	1835	.056
		2165	.052	1915	.054
				2030	.053
				2105	.053
				2157	.051

TABLE 6

THERMAL DIFFUSIVITY OF TS-699 GRAPHITE

No. 1 0.020 in(0.05 cm)		No. 2 0.030 in(0.075 cm)		No. 3 0.040 in(0.1 cm)		No. 4 0.050 in(0.125 cm)	
Temp.	α	Temp.	α	Temp.	α	Temp.	α
°C	cm ² /sec	°C	cm ² /sec	°C	cm ² /sec	°C	cm ² /sec
837	0.087	827	0.109	806	0.120	802	0.125
878	.087	865	.096	880	.105	885	.130
988	.082	950	.103	905	.112	895	.128
1009	.094	1111	.102	1011	.110	996	.131
1038	.093	1246	.095	1148	.101	1066	.113
1126	.084	1387	.096	1346	.094	1132	.119
1212	.076	1498	.096	1468	.093	1212	.107
1369	.076	1596	.095	1532	.089	1287	.108
1540	.074	1703	.084	1683	.083	1352	.104
1682	.077	1843	.088	1733	.081	1514	.098
1849	.077	1947	.082	1831	.078	1634	.097
1962	.077	2022	.082	1952	.080	1749	.088
2066	.075	2048	.079	1987	.080	1879	.081
2106	.080	2127	.075	2065	.072	1998	.082
2159	.077	2165	.075	2102	.074	2023	.083
						2093	.080
						2120	.081
						2160	.080

FIGURE 1

GRAPH FOR ASCERTAINING THE VALUE OF w
FROM THE TEMPERATURE-HISTORY CURVE AT
 $R = 1$.

FIGURE 2

SCHEMATIC DIAGRAM OF THERMAL DIFFUSIVITY APPARATUS

Figure 3

I-C-21

Thermal Diffusivity Apparatus

Figure 4

I-C-22

High temperature Furnace

Figure 5

Optical Bench and Phototube Detector

FIGURE 6

THERMAL DIFFUSIVITY OF TANTALUM

- O - SAMPLE #1 - 0.030"
- - SAMPLE #2 - 0.050"
- Δ - SAMPLE #3 - 0.090"
- THIS WORK
- TAYLOR & NAKATA (9)

THERMAL DIFFUSIVITY CM²/SEC

TEMPERATURE - °C

FIGURE 7

TYPICAL OSCILLOSCOPE TRACES OF THE HEAT PULSE
OBSERVED DURING THERMAL DIFFUSIVITY MEASUREMENTS
ON TANTALUM.

TEMPERATURE - 1115 °C
SAMPLE THICKNESS - 0.090"

TEMPERATURE - 1625 °C
SAMPLE THICKNESS - 0.050"

TEMPERATURE - 2205 °C
SAMPLE THICKNESS - 0.030"

FIGURE 8
THERMAL DIFFUSIVITY OF ATL GRAPHITE (TRANSVERSE DIRECTION)

FIGURE 9

THERMAL DIFFUSIVITY OF ATJ GRAPHITE (LONGITUDINAL DIRECTION)

○ - SAMPLE #1 - 0.040"
 ◇ - SAMPLE #2 - 0.060"

THERMAL DIFFUSIVITY - CM²/SEC

TEMPERATURE - °C

FIGURE 10

THERMAL DIFFUSIVITY OF EP192C GRAPHITE

I-C-28

FIGURE 11

THERMAL DIFFUSIVITY OF TS-699 GRAPHITE

I-C-29

9-13-65
JHC