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~~RESTRICTED DATA~~

ATOMIC ENERGY ACT OF 1946

SPECIFIC RESTRICTED DATA CLEARANCE REQUIRED

THERMAL STRESS TESTS

OF

KS GRAPHITE

NEPA 1125-EXR-2

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I.OBJECT

To obtain conditions required to cause thermal stress failure of
KS graphite maintaining typical missile reactor operating temperature
and pressure, and unit power dissipation rates.

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II. INTRODUCTION

One of the properties of a material which is important to know in the design of a nuclear reactor is its resistance to thermal rupture.

Since very little test data concerning this property were available a program was formulated to determine the thermal rupture characteristics of KS graphite under steady state operating conditions simulating the thermal conditions of an uninhabited guided missile reactor.

The first part of the program was directed toward testing tubular shaped specimens with the intent to complement this work with tests to study the effect of fuel element shape on the thermal rupture characteristics. $\frac{1}{3} \angle$

It is planned to continue this test work using fuel elements of different materials as required for different reactors as well as to attempt to establish a "standard material" for comparison purpose.

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III. SUMMARY

Since a thermal rupture was not obtained immediately with the first specimens tested steps were taken to increase the imposed thermal stress by using tubular specimens of greater radius ratio and increasing the power of the electrical supply source. However, the maximum stress conditions that could be obtained with equipment on hand did not cause a thermal rupture.

The following specimens were tested maintaining a maximum surface temperature of 2500° F and 500 psi coolant (Nitrogen) inlet pressure.

<u>Quantity</u>	<u>Dimensions</u>
3	3/4" OD x 3/16" ID
3	3/4" OD x 1/8" ID
2	1" OD x 3/16" ID
2	1" OD x 1/8" ID

The maximum thermal stress calculated using room temperature graphite properties was 30 90 psi.

The maximum net specific power obtained during testing was 5.2 Btu/cu. in. - sec.

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IV. CONCLUSIONS

It has not been possible to obtain a thermal stress failure in KS graphite with equipment presently available although test conditions have greatly exceeded the design operating conditions of the missile reactor. However, the effect of radiation damage has not been considered nor has the effect of element shape.

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V. THEORETICAL CONSIDERATIONS

In this report thermal stresses are considered to be steady state thermal stresses which exist without mechanical loading and which are caused by a steady state non-linear thermal gradient.

Several authors have derived equations from which thermal stresses can be calculated for idealized conditions. However, Timoshenko's derivation (Ref 1) is particularly straightforward and he has worked out the case under consideration, that of a cylinder with a concentric circular hole.

The fundamental derivation is based on the assumption that the material is homogeneous, isotropic and obeys Hooke's law; that is, the proportional limit is not exceeded.

The three components of thermal stress in a long hollow cylinder are in the radial, tangential, and axial directions.

Their equations as given by Timoshenko are:

$$\sigma_r = \frac{\alpha E}{(1-\nu)r^2} \left[\left(\frac{r^2 - a^2}{b^2 - a^2} \right) \int_a^b T_r dr - \int_a^r T_r dr \right] \dots (1)$$

$$\sigma_\theta = \frac{\alpha E}{(1-\nu)r^2} \left[\left(\frac{r^2 + a^2}{b^2 - a^2} \right) \int_a^b T_r dr + \int_a^r T_r dr - T_r r^2 \right] \dots (2)$$

$$\sigma_z = E \epsilon_z - \frac{\alpha E T}{1-\nu} + \frac{2\nu\alpha E}{(1-\nu)(b^2 - a^2)} \int_a^b T_r dr \dots (3)$$

where

E = modulus of elasticity

b = outer radius

α = coefficient of thermal expansion

T_r = temp. at radius r

r = radius

ν = Poisson ratio

a = inner radius

σ = Stress

Duffy (Ref. 2) has simplified these equations for experimental work by replacing the temperature terms with a power term as a function of radius which results from a one dimensional temperature distribution equation (radial heat flow only) and for the case of an internally cooled cylindrical tube. As a result it is found that the maximum thermal stress occurs in tension at the inner radius and the axial stress equals the tangential stress component.

Then by Reference 2:

$$S_{\max} = 1350 \frac{E b}{(1-\sigma)K} W_0 D_1^2 \left[\frac{2 \times 10^4 q_0 X^2 (3X^2 - 1)(X^2 - 1)}{X^2 - 1} \right] \quad (4)$$

Where E = modulus of elasticity - psi

b = coefficient of thermal expansion in/in $^{\circ}\text{F}$

$S_{\max}$ = maximum thermal stress psi

σ = Poisson ratio

K = coefficient of thermal conductivity
Btu/hr ft. $^{\circ}\text{F}$

D_1 = inner diameter - inches

X = outer radius / inner radius

W_0 = Btu/Sec - cu. in.

The radial stress is zero.

Graphite being an anisotropic material possesses different characteristics in the transverse and axial directions. Since the transverse values lead

to higher stresses these values (Ref. 3) are substituted in the above equation.

$$E = 900,000 \text{ psi}$$

$$b = .2 \times 10^{-5} \text{ in/in. } ^\circ\text{F}$$

$$\sigma = .2$$

$$K = 12 \text{ Btu/hr-ft. } ^\circ\text{F}$$

Giving

$$S_{\max} = 253.3 W_0 D_1^2 \left[\frac{2x^4 \log_n x^2 - (3x^2 - 1)(x^2 - 1)}{x^2 - 1} \right] \quad (5)$$

This can be simplified further by substituting $W_0 = \frac{.001205W}{D_1^2(x^2 - 1)}$

Where $W_0 = \text{B.t.u./sec-in.}^3$ $W = \text{watts/linear inch of specimen}$

Then (5) becomes

$$S_{\max} = .30522 W \frac{(2x^4 \log_n x^2 - (3x^2 - 1)(x^2 - 1))}{(x^2 - 1)^2}$$

or

$$S_{\max} = .30522 WF(x)$$

$$\text{where } F(x) = \frac{2x^4 \log_n x^2 - (3x^2 - 1)(x^2 - 1)}{(x^2 - 1)^2}$$

and is plotted on Figure 1, page 34 .

This equation is useful in computing the thermal stress from simple tests provided that a steady state condition is reached, there is only radial inward heat flow, and the material is homogeneous, isotropic and obeys Hooke's Law.

Application to Experiments

From this equation it is apparent that higher thermal stresses can be obtained experimentally by increasing the radius ratio of the tubular specimen and the watts/inch.

If the surface temperature is held constant, then the watts/inch is limited either by the available electric power or the rate at which the

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heat is conducted away by the coolant. Since the coolant itself is determined by other considerations, the maximum rate of heat removal is determined only by choking, which in turn is fixed by the tube diameter, provided, as in this case the inlet pressure is fixed.

The O.D. of the specimen is limited by practical considerations such as space, and preserving a high L/D ratio for low end losses, as well as the power input available. Then the specimen which is subjected to the highest thermal stress is beset by two conflicting requirements which must be optimized:

- (1) The I.D. must be small so that the radius ratio is large.
- (2) The I.D. must be large to allow high coolant flow.

The optimum test condition is reached when choking condition and the maximum available input power point occur simultaneously.

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VI. Method of Test

(1) In order for the experimental setup to correspond to the assumed case upon which the thermal stress equation is derived, there should be no heat flow other than radially inward. However, ideal conditions cannot be completely achieved and there is some axial and radial outward flow.

To compute the thermal stress from the equation given, it is necessary to measure the portion of the power which results in inward radial heat flow. This may be done in either of two ways:

(a) During a thermal stress test, measure the heat developed in the specimen and subtract from it the heat transferred outward through the test rig walls and the heat transferred out the ends of the specimen through the electrodes.

(b) During a thermal stress test, measure the total power consumed by the specimen and subtract from it the power dissipated as non radial inward heat flow which is obtained from a separate test run.

These two methods differ only in the way in which the non-inward radial heat flow is measured and of the two the second is the easiest to perform and probably is more accurate. In this case the test specimen is brought up to the standard test conditions of 2500° F. at 500 p.s.i. nitrogen pressure with no heat removed from the inside wall of the specimen (i.e., no coolant flow). The power required to maintain this condition represents the heat lost outward and axially. Then internal coolant flow is begun maintaining the same temperature and pressure conditions. The difference in power in these two parts of the test represents the power which is dissipated as radial inward heat flow. This method was used in the tests reported herein.

The first method requires a large number of additional measurements and calculations. Thermocouples must be mounted on two sides of the test rig walls in several places in order to compute the heat transfer. Then the results must be summed up over the entire rig, i.e. a heat balance should be obtained.

(2) Of the number of ways in which a test specimen could be heated, the method used, that of self resistance heating, is considered to be best because

- (a) It duplicates the uniform heat generation as caused by homogeneously distributed fissionable material.
- (b) Apparatus was readily available.
- (c) Operation and controlling was relatively simple.

VII. Test Procedure

The following procedure has been established in conducting thermal stress tests:

1. To eliminate air in the system and resulting oxidation of graphite the test rig and adjacent piping is evacuated by a mechanical vacuum pump connected to the nitrogen inlet line at the test rig.
2. The vacuum pump is then shut off and the main inlet valve is opened, allowing nitrogen to flow into the test rig until the pressure reaches 500 p.s.i., as fixed by the pressure regulators.
3. The M-G set is started.
4. All recording instruments are started by a master switch.
5. The field rheostat is gradually advanced, thus increasing the voltage of the M-G set and therefore the power input to the specimen until the maximum temperature of the test specimen reaches 2500° F.
6. The position of the rheostat is then slightly retarded as the test rig heats up until equilibrium is reached, i.e., the rheostat position is such that the surface temperature of the specimen remains constant at 2500° F.
7. This equilibrium condition is maintained for 15 minutes. During this time there is no coolant flow, but nitrogen pressure of 500 p.s.i. exists in the test rig.
8. The back pressure exhaust valve is opened, allowing nitrogen to flow through the rig. Simultaneously the field rheostat is advanced, increasing the power to the specimen. The final state is reached when either the current reaches the maximum available from the M-G set or the coolant flow reaches a maximum (choking). The maximum surface temperature of the specimen is still maintained at 2500° F.

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9. When equilibrium is reached, conditions are maintained for 15 minutes.

10. The rheostat is then returned to zero position and exhaust valve closed, thus halting the nitrogen flow.

Improvements in Test Procedure

Although the operation of the test rig is quite satisfactory, there are several improvements that could be made:

(1) To eliminate the human error in reading the surface temperature of the specimen, a self cycling and recording device is preferable to the optical pyrometer. Either commercial thermopiles or vacuum thermocouples may be satisfactory but these systems have not been completely checked out.

(2) A controller can be incorporated in the recording potentiometer mentioned in the above system to control the M-G set so as to maintain a constant predetermined surface temperature.

(3) A suitable heated radiation shield would eliminate radial outward heat losses thus leaving more M-G set power available for generating thermal stress. As a result of its use the actual radial temperature distribution curve would come much closer to that assumed.

VIII. a. DESCRIPTION - Thermal Stress Test Rig

A cross section of the thermal stress test rig is shown in Figure 4, page 37. A hollow cylinder test specimen (1) is gripped in graphite chucks (2). Electrical bus bars from a M-G set are attached to terminals (9) and (10), furnishing electrical power that allows the test specimen to be heated by its own electrical resistance. Radiation losses are minimized by a radiation shield (3) and Firecrete insulating material (4). In order to allow the test specimen to expand with temperature without imposing mechanical stresses on it, a sliding joint (7) is arranged with the two parts electrically bonded by copper shims.

The temperature along the length of the specimen is determined by an optical pyrometer which is sighted through windows (5). The power dissipated per unit volume of the test specimen is determined by measuring the current through the specimen and the voltage drop at intervals on the specimen using tungsten prods (6).

A thermal stress is set up by establishing a temperature gradient across the walls of the specimen. In the case shown the inside wall is cooled. The nitrogen gas coolant enters at (11), absorbs heat as it passes through the specimen (1), and leaves the test rig at (12). In order to avoid mechanical stresses in the test specimen due to a pressure difference across the walls, holes (8) allow the coolant pressure to be communicated to the outside of the specimen.

Figures 8 and 9, pages 41 and 42, shows the installation of the test rig.

b. DESCRIPTION - Test Specimens

The test specimens were machined from extruded bars of KS graphite $4\frac{1}{2}" \times 4\frac{1}{2}" \times 4$ ft. Tolerances were held $\pm .001$. Each specimen was 12" long, allowing a 1" grip at each end of the specimen. Since all specimens were 12" long, only one orientation is the original block was possible their length being in the direction of extrusion.

Figure 6, page 39, shows one of each of the four different size specimens tested. The table of dimensions follows

<u>Part No.</u>	<u>Length</u>	<u>I.D.</u>	<u>O.D.</u>
190,155	12"	.188	.75
190,535	12"	.125	.75
190,536	12"	.125	1.00
190,546	12"	.188	1.00

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c. DESCRIPTION - Flow Diagram

A schematic flow diagram is shown on Figure 5, page 38, and is believed to be self-explanatory.

The nitrogen, supplied by National Cylinder Gas Company, is guaranteed to have 99.95 percent purity.

The M-G set which was used until February 17th is rated at 3 to 50 volts at 1500 amperes and was manufactured by Hanson-Van Winkle Munning Company.

The M-G set used since then was rated at 3 to 50 volts at 3000 amperes and was manufactured by the Chandeysson Electric Company.

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d. DESCRIPTION - Instrumentation

The instrumentation used in the thermal stress tests is pictured on the right side of Figure 9, page 42. The general information concerning these instruments is tabulated in Table 1, page 24.

In general, recording instruments have been used because they make a continual record which shows at a glance whether the quantities have stabilized, are leveling off, or changing rapidly. Since the charts are started simultaneously and the chart speed is fixed, at any later date all readings can be determined for any particular instant during the test. Their use frees personnel for other duties.

An important exception is the specimen temperature reading, which are taken visually with an optical pyrometer. In the interests of improved accuracy and speed of taking readings, a cycling and recording device is desirable.

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Calibration

Calibration of pressure gages was made with an Ashcroft Model 1300 Dead Weight Gage Tester, accuracy 1/10 percent.

The thermocouple potentiometers were calibrated with an L & N Precision Potentiometer Model 8662, accuracy .05 mv max.

The manufacturer supplied calibration curves for the flowrators and were not separately calibrated. Accuracy is about 1/2 percent.

The 0 to 2 volt multipoint potentiometer was calibrated against a Weston Model 622 voltmeter, accuracy 1/2 percent.

The recording ammeter and voltmeter were furnished with calibration charts but were checked against a Weston 45 50 mv meter and Weston Model 622 voltmeter, accuracy of each 1/2 percent.

The thermocouples themselves were checked in an L & N Model 9003-S Checking Furnace using a B of S calibrated Pt - Pt, Rh, thermocouple.

The optical pyrometer as received from the factory was calibrated for an emissivity of 1.0 (4). A modification of the calibration was required to account for the emissivity of graphite, believed to be .90 at 2500° F. (3) and the transmissibility of the fused quartz windows of .93 (5). A computed calibration curve is shown in Figure 2, page 35.

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Computed Calibration Correction for Optical Pyrometer

As a result of the radiation laws, the general equation for emissivity correction (6) is

$$\frac{1}{T} - \frac{1}{S} = \frac{\lambda \log E_{\lambda}}{C_2 \log e}$$

where T = true temp, °K

S = apparent temp, °K

C₂ = 1.432 cm deg. C

E_λ = emissivity of body viewed

λ = wavelength of light

e = 2.718

or

$$\frac{1}{T} - \frac{1}{S} = C \log e$$

$$\text{where } C = \frac{\lambda}{C_2 \log e}$$

Since the red filter passes primarily light of 6650 Å° in the pyrometer used

$$\begin{aligned} C &= \frac{6650 \times 10^{-8}}{1.432} \\ &= 4643.85 \times 10^{-8} \end{aligned}$$

Since the optical pyrometer is calibrated for black body conditions i.e. and emissivity of 1.0 it must be corrected for the emissivity of graphite believed to be .90 (Ref. 3) and the transmissibility of the quartz window, .93. First correct for emissivity .90.

$$1/T_2 - 1/T_1 = c \log .90$$

Where T₁ = temperature indicated on pyrometer -

T₂ = true temp. of body (°K) having emissivity of .90.

Second, correct for transmissibility of window .93.

$$1/T_3 - 1/T_2 = c \log .93$$

Where T_3 = true temp. of body ($^{\circ}\text{K}$)
viewed through window of
transmissibility = .93

Substituting 1st. equ. in 2nd.

$$\begin{aligned} 1/T_3 - 1/T_1 &= c \log .90 + c \log .93 \\ &= c \log (.90) (.93) \\ &= (4643.85 \times 10^{-8}) \log .837 \\ &= (4643.85 \times 10^{-8}) (-.178) \\ &= -826.60 \times 10^{-8} \end{aligned}$$

$$1/T_3 = \frac{T_1}{1 - 826.6 \times 10^{-8} T_1}$$

This is plotted on Figure 2, page 35.

TABLE I

THERMAL STRESS TEST INSTRUMENTATION

<u>No. Measurements</u>	<u>Measurement</u>	<u>Sensing Device</u>	<u>Type Instrument</u>	<u>Model</u>	<u>Range</u>	<u>Calibrated Accuracy</u>
1	Nitrogen Cylinder Pressure	-	Indicating Gage	Ashcroft Duragage	0 - 5000 p.s.i.	+30 p.s.i. max.
1	Reduced Nitrogen Pres. at flowmeter	-	Indicating Gage	Ashcroft Duragage	0 - 1000 p.s.i.	+3 p.s.i.
1	Nitrogen Temperature at flowmeter	AN5525 Resistance Bulb	Indicating Gage	Edison	-50°F to +120°F	±1°F
1	Nitrogen flow rate		Indicating flow rator	F & P No. J11-2538	20 to 300 PPH	±1.2 pph
			Indicating flowrator	F & P No. J11-2537	100 to 1000 PPH	±4 PPH
1	Nitrogen pressure at rig inlet	Static side of pitot tube	1) Indicating Gage	Ashcroft Duragage	0 - 1000 p.s.i.	-2 p.s.i.
			2) 2 pt. circular chart recorder	Foxboro Recorder	0 - 800 p.s.i.	+5 p.s.i. max.
1	Nitrogen temperature at rig inlet	Iron-constantan thermocouple probe	Multipoint Strip Chart Recorder	Brown Electronik 153X62P16-X-13	0 - 1500° F	±5° F
1	Nitrogen pressure at rig outlet	Static side of pitot tube	1) Indicating Gage	Ashcroft Duragage	0 - 600 p.s.i.	0 p.s.i.
			2) 2 pt. circular chart recorder	Foxboro Recorder	0 - 800 p.s.i.	-2 p.s.i. max.
1	Nitrogen temperature at rig outlet	Chromel-alumel shielded T.C. probe	Circular chart recorder	L & N Micromax	0 - 1500° F	± 10° F.

<u>No. Measurements</u>	<u>Measurement</u>	<u>Sensing Device</u>	<u>Type Instrument</u>	<u>Model</u>	<u>Range</u>	<u>Calibrated Accuracy</u>
2	Upper electrode temperature	iron-constantan thermocouple	Multipoint strip chart recorder	Brown Electronik	0 - 1500° F	± 5° F
2	Lower electrode temperature	Iron-constantan thermocouple	Multipoint strip chart recorder	Brown Electronik	0 - 1500° F	± 5° F
7	Test Specimen Temperature		Optical Pyrometer	L & N 8628	1400 to 5200° F	
6	Voltage drop along test specimen	Tungsten prods	Multipoint strip chart recorder	Brown Electronik	0 - 2 volts P.C.	± .01 volt
1	Specimen current	Calibrated Shunts	Recording Ammeter	E. A. Model AW	0 - 50 MVDC	± .1mV
		0 - 1000 Amp.				
		0 - 2000 Amp.	Indicating Ammeter	Weston 45	0 - 50 MVDC	± .1mV
1	Total voltage		Recording Voltmeter	E. A. Model AW	0 - 50 volts	± .1 volt

IX. TEST RESULTS

A tabulation of test results is shown in Table 2, page 35. It is to be noted that the only data used directly in the thermal stress calculations are the average of the voltage drops measured from one prod to the next and the current in the system, the other data being used to maintain a check on operating conditions.

The missile reactor design conditions (Ref. 7) showed a maximum computed thermal stress of 246 p.s.i. using the same values of material properties as used in this report. The maximum specific power dissipation was 3 Btu/cu.in./sec.

This can be compared to a maximum computed stress of 3090 p.s.i. obtained from tests reported herein and a maximum obtained net power dissipation of 5.2 Btu/cu.in./sec.

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TEST RESULTS

TABLE II

No.	Date of Test	2-9-49	2-15-49	2-17-49	2-7-49	2-14-49	2-17-49	4-19-49	7-20-49	4-21-49	7-19-49
	Specimen Dimensions	3/16"IDx3/4"ODx12"Long			1/8"IDx3/4"ODx12"long			3/16IDx1"ODx12"long		1/8"IDx1"ODx12"long	
	<u>No Flow</u>										
1	Volts/inch, ave	.68	.71	.75	.66	.67	.73	.44	.47	.445	.485
2	Amperes	1020	1160	1221	1012	1080	1234	1340	1530	1454	1620
3	Input power(1)x(2), Watts/inch	694	823	915	668	723	902	590	720	647	787
	<u>Flow</u>										
4	Volts/inch, ave	1.4	1.15	1.15	1.04	1.19	1.18	.96	.85	.87	.88
5	Amperes	1932	1820	1980	1920	1980	1980	2950	2880	2850	2920
6	Input power(4)x(5), Watts/inch	2710	2095	2280	2000	2510	2335	2830	2450	2480	2510
	<u>Stress</u>										
7	Net Power, (6)-(3), Watts/inch	2016	1272	1358	1332	1787	1433	2240	1730	1823	1723
8	F (x)	3.18	3.18	3.18	4.52	4.52	4.52	4.15	4.15	5.54	5.54
9	Stress (7)x(8)x.3050, psi	1960	1235	1320	1830	2460	1980	2830	2190	3090	2920
	<u>Specific Power</u>										
10	Vol. of Specimen/linear inch	.413	.413	.413	.429	.429	.429	.756	.756	.772	.772
11	Total KWatts/cu.in. (6)/(10)	6.6	5.3	5.5	4.7	5.8	5.6	3.8	3.2	3.5	3.3
12	Total Btu/cu.in. $\frac{(11) \times 1.055}{(10)}$	7.0	5.6	5.8	5.0	6.1	5.9	4.0	3.4	3.7	3.4
13	Net KWatts/cu.in. $\frac{(7)-(3)}{(10)}$	4.9	3.1	3.3	3.1	4.2	3.3	3.0	2.3	2.7	2.2
14	Net Btu/cu.in. $\frac{(13) \times 1.055}{(10)}$	5.2	3.3	3.5	3.3	4.4	3.5	3.2	2.4	2.8	2.4
	<u>Miscellaneous</u>										
15	N ₂ Flow Rate P.P.H.	390	290	300	185	280	212	480	420	315	330
16	Resistance of Specimen $\frac{(1) + 12}{(2)}$ ohms	.0080	.0073	.0074	.0078	.0074	.0071	.0039	.0037	.0037	.0036

X. DISCUSSION OF TESTS

1. Calculated Stresses

a) Experimental Errors.

One experimental error lies in setting the power such that the same maximum surface temperature is held for both the heat loss run and the thermal stress run. It has been found from experience however, that near stable conditions at a specimen temperature near 2500° F. a very slight shift in input power has relatively greater effect on the surface temperature. However no quantitative data have been taken.

Because of the outward radial heat flow the temperature distribution curve is not the same as if all the heat flow was radially inward. This is believed to result in a greater temperature difference between the walls and a steeper temperature gradient. The general effect being that slightly greater stresses are induced than indicated by calculations.

An indication of the extent of axial heat flow is shown in the typical curve (Figure 3, page 36) of axial surface temperature distribution on the specimen. This effect is not great because of the large L/D of the specimen.

Refinements in test technique were not believed to be warranted at the time because of lack of success in obtaining a thermal rupture.

b) Material Properties

Probably the greatest error in computing the thermal stress lies in the values of the material properties. When all the necessary KS graphite properties i.e. E, b, k, and σ at high temperature (2500° F) become known then these thermal stress calculations will have to be reworked and checked for correlation.

While it appears that the calculated thermal stresses achieved in these tests are greater than the ultimate tensile strength of graphite, Reference 8 indicates that the ultimate tensile strength of two types of graphite increases greatly with temperature, and it is quite possible that the thermal stress tests reported herein are below the proportional limit.

2. Specimen Flaking and Pitting

In the course of tests it was found that the outer surface as well as the bore of the graphite tube became slightly powdery and the specimens pitted in a stratified manner, as shown in Figure 7, page 40. This pitting was also found on the opposite side, indicating that the variation in properties occurs in layers in the specimen.

The same effect was found after tests without coolant flow passing through the specimen thus eliminating the possibility of being a spalling, or thermal stress effect, or due to erosion.

One test was made, at the suggestion of the Analytical Group of the Chemistry Section, which indicated that the rapid expansion of the entrapped gas during the heating process blew off graphite particles. The test was made as follows:

A small specimen, 1" O.D. x 1/4" I.D. x 1" long of KS graphite was placed in a vacuum coating unit in the Experimental Physics Section. A heating element of platinum wire was placed inside the hole in the specimen. A vacuum was drawn down to 1 micron and held. Immediately the specimen was heated to 2000° F. and held at that temperature for 1/4 hour. At the end of that time the inside of the bell jar was coated with a thin layer of graphite. The test was repeated with an identical specimen except

that a 1 micron vacuum was maintained for 24 hours prior to heating. At the end of the test there was no graphite found on the bell jar.

Graphite is a porous material (nearly 30 percent by volume) and readily absorbs gases, particularly nitrogen. Tests reported in Ref. 9 indicated that gas amounting to 80 percent of the theoretical pore volume was removed by evacuation at room temperature. In the course of 24 hours it is believed that the graphite was sufficiently outgassed so that no high internal gas pressures developed and, as a result, no graphite was blown off the surface.

It is believed that rapid heating of the graphite in the nitrogen atmosphere was responsible for the flaking. To reduce this effect, the heating process prior to a thermal stress test is spread out over a half hour, compared to the original 5 minute period. By comparing test specimens this precaution has been found to be successful.

The pitting is believed to be the result of the same process taking place in areas of relatively greater softness which are formed during the process of fabricating KS graphite.

It would appear that this effect should be more completely investigated if KS graphite is to be coated for reactor use.

3. Electrode Coolant

It was found that during tests the lower or inlet electrode ran hotter than the upper electrode, probably because in the former there is less heat conducting area. The test rig was designed so that the upper electrode could be water cooled but this was not used because the temperature of this electrode was not the limiting factor in operation.

4. Electrode Contact Current Density

As higher powers and therefore higher currents were reached as tests progressed, it was noted that arcing began to take place between the specimen and contact chuck in the lower electrode particularly. This was noted unless a very close, smooth fit was achieved. Reference 10 points out that when very high current densities exist there may be enough heat generated to bring local temperatures up high enough to cause sufficient thermionic emission to maintain an arc. In the case of the 1" dia. specimen operating at a current of 3000 amps., the current density at the contact is nearly 1000 amps/sq.in. According to Ref. 11 and others, the average current density in graphite electrode contacts is 50 amps/sq.in., sometimes reaching 100 amps./sq. in. The arc sensitivity of the test rig contacts is thus understandable. The problem is not easily eliminated because it requires a redesign of the test rig to embody much greater contact area as well as requiring longer specimens. The immediate solution is care in machining and installation and frequent replacement of contact chucks.

5. Limit of Test Rig Operation

It is felt that appreciably greater computed stress cannot be reached with KS graphite in the present rig because

- a) The maximum available current is being used.
- b) Under the above condition the maximum flow (choking) is reached in the specimens
- c) The temperature of the lower electrode is close to the maximum allowable.

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TYPICAL THERMAL STRESS TEST SPECIMEN SURFACE TEMPERATURE DISTRIBUTION

SPECIMEN: PART NO. 190155

DIMENSIONS - $\frac{3}{16}$ " I.D. $\times$ $\frac{3}{4}$ " O.D. $\times$ 12" L

DATE : FEB. 17, 1949

CURVE EX-6

A.R.C.

Fig. 1

① THERMAL STRESS SPECIMEN	⑤ PYROMETER WINDOWS	⑨ LOWER ELECTRODE TERMINAL
② GRAPHITE CHUCKS	⑥ VOLTAGE PRODS	⑩ UPPER ELECTRODE TERMINAL
③ RADIATION SHIELD	⑦ BONDED SLIDING JOINT	⑪ COOLANT INLET
④ INSULATING MATERIAL	⑧ PRESSURE EQUALIZING HOLES	⑫ COOLANT OUTLET

SCHEMATIC FLOW DIAGRAM
THERMAL STRESS TEST

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THERMAL STRESS
TEST SPECIMEN
PART NO. 190535

FIG. 7

405 40

Fig. 8

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