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September 30, 1966

Westinghouse Astronuclear Laboratory

HEATER ELEMENT DESIGN STUDY

FOR

MULTIPLE CLUSTER THERMAL TEST

(Title Unclassified)

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HEATER ELEMENT DESIGN STUDY

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MULTIPLE CLUSTER THERMAL TEST

(Title Unclassified)

by

John R. Ferris
Fluid Flow Laboratory

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by authority of

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ABSTRACT

A design approach is indicated using a central hollow hairpin-type electrical resistance heater element fabricated of graphite to keep the maximum temperature of the graphite in the heater element below 6600°R while accomplishing the heat flux required by Test FFL 1.g. When the heater element is as small as 2 1/8 inches in diameter, a minimum wall thickness of .12 inches is required. It is demonstrated that 6600°R is a reasonable temperature limit to design to without incurring graphite sublimation under furnace pressures of 700 psi. The hairpin heater element is easily fabricated, inherently allows both electrical connections to be at the top cold end and allows free expansion without restraint under changing temperatures. The 2 1/8 inch diameter heater element would have a design-point current and voltage requirement of 1060 amperes and 171 volts. If the heater element diameter is allowed to be larger, the minimum wall thickness can reasonably be quadrupled and the current and voltage schedule can be varied over a wide range: volts down to 70 and amperes up to 2500, all in combinations of producing an input of 181.5 kw.

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DESIGN STUDY

This report has to do with proposed designs of a high temperature heater element fabricated from graphite. A specific heater element design will be applied to the problem of heating the Multiple Cluster Thermal Test, FFL 1.g. This test is described in Reference 5. High temperature designs of this sort are limited by the sublimation temperature of graphite. In an electrical resistance heater in question where the heat release is throughout the graphite section, a maximum temperature in the element is found in the interior of the graphite. The designs in question will permit required and therefore useful levels of heat release and will use maximum surface temperature compatible with interior material temperatures below the sublimation temperature of graphite. The experiment Test FFL 1.g. is heated from the inside surfaces radially outward. Design considerations for the heater elements will be confined to this type of application in this study.

It is important in establishing the limits of this design to conclude in some reasonable fashion what the sublimation temperature of graphite is at the working pressure of 700 psi in an inert gas. An environment of an inert gas such as helium is specified only to avoid the complications of hydrogen corrosion or oxidation. On page 227 of Reference 1, Figure 41 a sublimation temperature of approximately 3950°K (7110°R) at a pressure of 700 psi is indicated. On page 118 of Reference 2, Figure 6.1 at the same 700 psi pressure, the sublimation temperature of graphite is shown to be approximately 3880°K (6980°R). Pertinent to this question, five hitherto unpublished heater element

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tests have been accomplished at the Fluid Flow Laboratory wherein the phenomenon of sublimation has taken place. The results of these tests follow later in this report. First, however, a mathematical analysis of heat transfer in rod-type and cylindrical-type heater elements is presented not only to interpret the results of the five high temperature heater element tests but also to generate design information for describing designs which appear most attractive for Test FFL 1.g.

For purposes of determining radial temperature gradient in the heater element and particularly at the station of maximum temperature, it is reasonable to consider the mathematical model a uniform cylinder without end effects, to omit the influence of axial heat flow due to axial taper of the cross section and to concentrate on heat flow in the radial direction. Previous heater elements have been successfully designed, even with axial taper, making use of analysis based on this simplifying assumption. In the application described in this report, the assumption of no axial heat flow is even more appropriate. For in actuality the tapered heat element is designed with a length of constant cross section on both sides axially of the point of maximum temperature. The length of this constant heat release section can be as long as 6 inches. The maximum temperature at some point within this length is inherently established by a condition of a real minimum of axial heat flow at that axial location. Thus, since the mathematical model is primarily set up to analyze the radial temperature gradient at this maximum temperature axial station, a certain consistency is maintained. The inner and outer surfaces of the cylinder are located at radii r_i and r_s respectively. When r_i is equal to zero, the cylinder becomes

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a solid rod as a limiting case. A differential equation is written which accounts for radial flow in and out of a small incremental volume of the material and for heat generation within this volume, assuming in addition homogeneous material and steady-state conditions,

where $\dot{q}$ is the rate of heat generated per unit volume and where q_{in} and q_{out} are heat flows into and out of the incremental volume. A derivation equivalent to the one that follows is found on pages 188 to 191 of Reference 3.

heat flow in + heat generated = heat flow out

$$-k \Theta r L \left. \frac{dT}{dr} \right|_r + \Theta r \Delta r L \dot{q} = -k \Theta (r + \Delta r) L \left. \frac{dT}{dr} \right|_{r + \Delta r}$$

where T = temperature, k = thermal conductivity, L = axial length, and Θ = central angle.

Rearranging and simplifying

$$k \frac{\left. \frac{dT}{dr} \right|_{r + \Delta r} - \left. \frac{dT}{dr} \right|_r}{\Delta r} + \frac{k}{r} \left. \frac{dT}{dr} \right|_{r + \Delta r} + \dot{q} = 0$$

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Then by the definition of a derivative as Δr approaches zero as a limit

$$\frac{d^2 T}{dr^2} + \frac{1}{r} \frac{dT}{dr} + \frac{\dot{q}}{k} = 0$$

This equation is manipulated and integrated. Constants C_1 and C_2 are given values based on the assumption that at location r_i , $\frac{dT}{dr} = 0$ and by indicating that the temperature at the outside surface is designated, T_s . Thus:

$$\text{Since } \frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) = \frac{d^2 T}{dr^2} + \frac{1}{r} \frac{dT}{dr}$$

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) + \frac{\dot{q}}{k} = 0$$

Rearranging

$$\frac{d}{dr} \left(r \frac{dT}{dr} \right) + r \frac{\dot{q}}{k} = 0$$

Integrating

$$r \frac{dT}{dr} + \frac{r^2 \dot{q}}{2k} = C_1$$

Rearranging

$$dT + \frac{\dot{q} r dr}{2k} = C_1 \frac{dr}{r}$$

Integrating

$$T + \frac{r^2 \dot{q}}{4k} = C_1 \ln r + C_2$$

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Since

$$T(r_s) = T_s \text{ and } \frac{dT}{dr}(r_i) = 0$$

$$C_1 = \frac{r_i^2 \dot{q}}{2k} \text{ and } C_2 = T_s + \frac{\dot{q}}{4k} (r_s^2 - 2 r_i^2 \ln r_s)$$

Substituting

$$T - T_s = \frac{\dot{q}}{4k} (r_s^2 - r^2 - 2 r_i^2 \ln \frac{r_s}{r})$$

The expression shown above is generalized for a temperature difference from some radial position on the inside of the material to that of the surface. But since the maximum temperature in a cylindrical heater element with only radial heat flow occurs at the inner surface, the expression can be specifically designated for this application:

$$T_i - T_s = \frac{\dot{q}}{4k} (r_s^2 - r_i^2 - 2 r_i^2 \ln \frac{r_s}{r_i})$$

Note that the $\dot{q}$ is heat generation per unit volume. A more useful expression is arrived at by dividing by the volume of the material in the heat element when Q is thus established as the total heat generated output.

$$\text{Volume} = \pi (r_s^2 - r_i^2) L$$

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By definition $Q = \dot{q} \pi (r_s^2 - r_i^2) L$

$$\therefore T_i - T_s = \frac{Q \left(r_s^2 - r_i^2 - 2 r_i^2 \ln \frac{r_s}{r_i} \right)}{4 \pi L k (r_s^2 - r_i^2)} \quad \text{or} \quad \frac{Q}{4 \pi k L} \left(1 - \frac{2 r_i^2 \ln \frac{r_s}{r_i}}{r_s^2 - r_i^2} \right)$$

Q can readily be converted to output per unit length of heater element.

When r_i is equal to zero and the model becomes a solid rod, the expression, showing the temperature difference between the center line and outside surfaces, which considers the total generated heat output or that per unit length is seen to be independent of the radius:

$$T_i - T_s = \frac{Q}{4 \pi k L} \quad (\text{solid rod})$$

Interpreted, this means that for a constant total heat generation, the temperature difference from center line to surface remains the same regardless of how large or small the outside radius becomes. No advantage is obtained by going to larger diameters of heater element in seeking lower maximum interior temperatures or vice versa.

The expression for the temperature difference in the cylinder, however, describes a function which decreases sharply, under conditions of constant total heat generation, as the diameter of the heater is increased and as the heater wall thickness is decreased. This function is plotted in Figure 1 and is presented as a multiplying factor

$$f(r) = 1 - \frac{2 r_i^2 \ln \frac{r_s}{r_i}}{r_s^2 - r_i^2} = \frac{T_i - T_s}{\frac{Q}{4 \pi k L}}$$

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to be applied to the same expression which shows the temperature difference in the solid rod, $\frac{Q}{4\pi kL}$. For ease of presentation, each curve of the family represents configurations which have a constant volume of material. Thus, as the diameter moves out, the section thins down. The thinning down requires the heat to travel a shorter distance to the outside surface while the density of heat generation remains the same. Judging a heater element on the basis of maximum interior temperature is much more informative than observing only heat flux at the surface. This latter criterion would show no advantage of a cylinder type heater element over a solid rod type, both of the same outside diameter. Based on maximum temperature difference from inside to outside surface, a cylinder type heater element is markedly superior. Using the same volume of material in both and increasing the diameter of the solid rod by a factor of 2 when transforming to a hollow cylinder, the maximum temperature difference between inside and outside is decreased by a factor of 7. This relationship is independent of the size of the rod being used for the comparison. Practical limits of the minimum thickness of the cylindrical wall section are a purely structural consideration. Two hollow-hairpin-type heater elements, one approximately 18 inches long and the other approximately 66 inches long, both mounted and hanging vertically, free at the bottom and with all electrode connections at the top cold end, have run successfully with minimum wall section thicknesses at .170 and .330 inches respectively. Figure 2 shows the larger of these as it is used in the High Temperature Instrumentation Qualification Furnace. This analysis and the conclusions drawn are independent of the schedule of current and impressed voltage; no particular routing of the current path through the

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cylindrical shell is implied. In practice even with constant thickness from one axial station to another, the resistance of the heater element can be varied over a wide range by slotting this cylinder forming longer and shorter and wider and narrower width of strips that form closed circuits with the electrodes. These strips can be in series and in parallel and so arranged as to not violate the structural integrity of the element. But before going further into design theory or into specific designs that look attractive for FFL l.g, the results of the five high temperature heater element tests are herein presented.

Three different heater element configurations were employed, all fabricated of Graphitite G. One was a solid rod $3/4$ inches in diameter with a working length of 10 inches. The second was a slotted rod with a working length of 10 inches and a slot length of 8 inches. The slot was $1/4$ inch wide; the rod, 1 inch in diameter. The third heater element was the same as the second except that in the axial mid section the outside diameter was turned down to $15/16$ inch for a length of 3 inches. Figure 3 is a photograph showing these heater elements. Pertinent details of these five high temperature heater tests are tabulated in Figure 4. These tests were accomplished during July of 1965 in the A-2 test furnace. Helium atmosphere was used at a pressure of approximately 690 psi. A single view port was employed opposite the center of the test piece. Surface temperature of the test piece was measured by optical pyrometry through a calibrated arrangement of windows and prisms. In each case except the first, with the solid rod, the observed surface temperature exceeded 6000°R . For all tests the calculated maximum interior temperature of the material exceeded 6900°R . For the purpose of making this calculation when the

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amperage, I , is measured the solid rod temperature difference expression was converted to I and resistivity, ρ . Convenient units were arranged and a constant calculated:

$$T_i - T_s = .408 \frac{I^2 \rho}{kr^2}$$

where

T = °R
 I = amperes
 ρ = ohms-cm
 k = $\frac{\text{BTU}}{\text{hr-ft-°R}}$
 r = inches

In all tests, except the first with the solid heater element, moderate to severe graphite sublimation was in evidence. The first test (No. 1694), however, ran for only two minutes above a calculated maximum interior temperature of 6600°R before the heater element was shorted out by the heat shield and the test terminated. The momentary maximum interior temperature of this solid rod heater element was calculated to be 7330°R. The other four tests, however, subjected the heater elements to temperatures above 6600°R for periods of 5, 7-1/2, 17 and 13 minutes respectively. Of these four, the first two (tests 1698 and 1699) were submitted to the highest surface temperatures 6180 and 6240°R respectively and to the highest calculated interior temperatures 7440 and 7590°R, respectively. Of all the tests the severest graphite sublimation took place in these two as evidenced by the photographs, Figures 5 through 8.

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It is apparent that the sublimation initiates at the interior of the material where the temperatures are the highest. The carbon vapor diffuses through the solid material to the outside and condenses in the form of a powder on the cooler surfaces. The structure accordingly progresses to failure.

For the final two tests (Nos. 1700 and 1701) the surface temperatures were slightly less, but because of the step which reduced the diameter the calculated maximum interior temperatures in both cases were less than 7000°R , 6940 and 6980°R respectively. Thus, even though the running time at temperatures above 6600°R were appreciably longer than in the two previous tests, the graphite sublimation had not progressed to the point of structurally destroying the heater element. Condensation of the carbon vapor on the surfaces of the heater elements is apparent as evidenced by Figures 9 through 11. The heater element of the last test, however, was fractured but only during disassembly.

Before concluding from these tests what the effective graphite sublimation temperature is, the limitations and reasonable tolerances applied to the calculation of the interior maximum temperature of the slotted heater element should be pointed out. In the calculation each leg of the slotted rod was considered separately as secondary solid rods with maximum material temperature at a point internal to the material but close to the inside surface of the slot and centered. Even though the choice of the hot point in the material may be chosen accurately, it is inherent that the calculation would underestimate the current density. It would appear that the results if anything are an underestimate of the temperature difference from the surface to the interior. A tolerance of plus and minus 300°R should be applied. It is interesting to note

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that Reference 1 reports the same type of result and pattern of graphite sublimation but at temperatures above 7000°R. Further supported by the sublimation temperature of graphite (6980°R) quoted in Reference 2, the safe and conservative temperature limit up to which one can safely design at pressures of 700 psi can reasonably be set at 6600°R. In further support of this position, a high temperature heater element experiment (Build 4 Test 1) was accomplished more recently in the A-10 test furnace where the measured surface temperature was 5800°R, and the calculated maximum interior temperatures was 5950°R. No graphite sublimation was experienced. Reference 4 describes this test. This test was performed in helium at a pressure of approximately 250 psi. This lower pressure would be expected to lower the sublimation temperature of graphite by 400°R compared with that under the higher pressure condition of Test FFL 1.g.

A representation of a typical cross section of the FFL 1.g experiment is shown in Figure 12 with specific indication of the components and their radial dimensions. With limiting of the maximum interior temperature of the heater element in mind, the designer determines the maximum allowable diameter of the heater element, the heater surface temperature and the radial heat flux. Figure 12 shows that the maximum reasonable diameter of the heater element is 2 1/8 inches, leaving 1/4 inch clearance between it and the core. Figure 13 shows a typical temperature distribution based on the temperature profiles of the hot and cold side of the pyrotilite in the reactor. The maximum heater surface temperature is 6400°R and falls at station 45. Figure 14 shows the heat flux in a radial direction for each axial location on the heater element. Note that the maximum radial heat flux falls at station 40, another possible maximum in-

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terior temperature location. Integration of the curve in Figure 14 results in a total heater element output of 181.5 KW.

The design problem is precisely that of producing the heat required and scheduled on the curve in Figure 14 without incurring a temperature difference from the surface of the heater element, at its hottest axial location or at its point of maximum heat release, to an interior location of more than 200°R. Moreover the heater element has to be structurally sound and readily fabricated. In addition, a reasonable schedule of amperes and volts has to be used.

A properly designed hollow hairpin-type graphite heater element machined from a single log of Graphitite G can more than adequately meet the specified requirements. The Laboratory has had considerable experience with this type of heater element. The latest and largest hollow hairpin heater element, 66 inches long, 3 inches in diameter at its working end and 5 inches in diameter at its upper cold end, has been running for the last 6 months and has proved outstandingly successful. For the FFL l.g. experiment, the outside diameter of the working length of the hairpin heater would be 2 1/8; its working length, 52 inches. The inside diameter would be a maximum of 1.885 inches at station 40 and a minimum of 1.54 at station zero. A 1/4 inch slot would be machined centrally throughout the entire length of the heater element except at the bottom where the two legs of the hairpin are left structurally and electrically connected. The top of the heater element above its working length would taper rapidly to a diameter of 5 inches and would extend some 12 inches in length. This increase in diameter forms a thermal insulating axial plug and gives depth to threaded holes which receive the electrodes. A 1/4-inch thick flat plate of

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aluminum oxide would be cemented in the slot at the very top for maintaining electrical insulation and structural integrity. Copper electrodes would be threaded into the graphite at the top of each side to complete the electric circuit as previously mentioned. The heater element would be supported only from the top and would be free to expand and contract as a function of temperature change. The internal taper of the heater element would be machined by cutting through the graphite at the bottom of the slot and laying the piece open subject to milling. After machining in this fashion, this bottom cut would be rejoined either mechanically or by cementing and graphitizing, thus maintaining this bottom electrical and structural connection. Required electrical current would be 1060 amps at 171 volts.

The temperature rise from the interior surface of the hollow heater to the outside surface at stations 40 and 45 are calculated to be less than 200°R. The material design temperature limit of 6600°R is thus honored, and no graphite sublimation would be expected.

The heater element design is not confined to one set of possibilities. The diameter of the heater element could profitably be increased if more room could be found in the experiment central core. If the minimum wall thickness of the heater element was held at .120 inches, an increase of diameter would substantially increase the required current and lower the volts and would reduce heater element temperatures in general. This decrease of heater element temperatures stems from a decreasing temperature difference across the wall and from a decreasing temperature level of the heater element outside surface. The heater element surface temperature decrease is a result of the lessening of

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the thermal resistance of the core as the core thickness is reduced, with the attendant lowering of the temperature at the inside surface of the core facing the heater element. The design with the 2 1/8 inch diameter heater element suggested in the above paragraphs uses a wall thickness at station 40 which is the maximum permitted by consideration of maximum temperature in this design. With a larger diameter heater, this wall thickness could be increased.

If the inside diameter of the core was enlarged to 3 3/4 inches, and thus in Figure 12 the radius to this surface would show as 1 7/8 inches instead of 1 5/16 inches, a 3 1/4 inch diameter hollow hairpin heater could be installed with the same 1/4-inch radial clearance. Figure 15 indicates the temperature distributions based on the same temperature profiles of the hot and cold sides of the pyrotilite and therefore using the same schedule of heat release as shown in Figure 14. In Figure 15, the lower level of the heater surface temperature, now peaking at 6000°R, is due to the fact as mentioned previously, that with the removal of core thickness its radial thermal resistance has been decreased.

For this larger diameter heater, calculations have been made using minimum wall thicknesses (at station 40) of the heater cylinder from 0.14 inches to 0.50 inches. Over this range of wall thicknesses Figure 16 shows the characteristics of electrical current input and volts required and in addition shows the level of the maximum graphite temperature in the heater element and how it increases with increase of wall thickness. Volts and amperes could be varied over a wide range. Volts could be decreased to approximately 70 with an attendant increase of amperes to approximately 2500 when the minimum heater element wall thickness is 1/2 inch. Over this range of wall thicknesses, the maximum

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graphite temperature in the heater element is found to be at levels from 6100°R to 6450°R, the higher temperatures being associated with the greater thicknesses. This larger diameter design is seen to be less critical in terms of wall thickness and temperature and also in terms of the choice of schedules of amperes and volts for matching to a power supply. The smaller 2 1/8 inch diameter heater element, however, can be designed to operate successfully without qualifications. The advantage of the larger diameter heater element to the designer is that of offering more design variables.

Considering mainly the mass and heat capacity of the graphite core inside the pyrotille, it appears that the FFL l.g. experiment could be brought up to temperature from ambient conditions within an hour using the 2 1/8 inch-diameter, hollow hairpin heater element without exceeding its steady state design power output. When the core of the experiment, however, is below its design temperature, the power output of the heater element could be increased beyond the steady-state design limit without exceeding graphite sublimation temperatures. Minimum time to come up to temperature involves refinements of design of the furnace. It would be advantageous, for instance, to build and code the pressure vessel shell to operate at 1000°F and to provide local cooling for such inherently low temperature items as "O" rings and electrical connections. The pressure vessel could be thermally insulated on the outside and allowed to reach 1000°F as rapidly as possible before gas flow cooling of the experiment outside of the pyrotille thermal barrier was initiated. Schedules of specific power input and coolant flow versus time would be employed to minimize time to reach temperature. Reduction of the mass of the core, if a 3 1/4 inch-diameter heater element was

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used, would substantially reduce the time required to reach temperature. A subsequent report will investigate these subjects further.

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CONCLUSION

In conclusion, a central heater element can be designed to satisfy the requirements of Test FFL 1.g. With careful designing, this heater element can be as small as 2 1/8 inches in diameter; in larger sizes, the designer has more freedom in the choice of variables. The heater elements recommended are hollow cylinders to promote thin graphite cross sections, thus avoiding unnecessarily high internal material temperatures when the sublimation temperature of graphite is approached.

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Figure 1
FFL l.g. Test
Heater Element Design Study Outside Radius Versus $f(r_s)$

Figure 2
High Temperature Instrumentation Qualification
Furnace Showing 66-Inch Heater Element at Left

Figure 3
High Temperature Heater Elements Used in
Tests Numbered 1694, 1698, 1699, 1700, and 1701

High Temperature Heater Element Experiments
Performed in A-2 Furnace July 13, 1965 to July 26, 1965
Details Pertinent to Graphite Sublimation

	Test No. 1694	Test No. 1698	Test No. 1699	Test No. 1700	Test No. 1701
Date	July 13, 1965	July 22, 1965		July 26, 1965	July 26, 1965
Gas	Helium	Helium	Helium	Helium	Helium
Pressure, psi	685	690	690	690	690
Heater Element	Solid Rod	Slotted Rod	Slotted Rod	Slotted, Stepped Rod	Slotted, Stepped Rod
Time of Point From Start of Test Minutes:Seconds	34:30	7:45	11:55	14:00	15:30
Maximum Surface Temp., °R	5850	6180	6240	6090	6161
Time Above 6600°R, Minutes	2	5	7-1/2	17	13
Calc. Max. Inner Temp., °R	7330	7440	7590	6940	6980
Condition of Heater Element	Heat shield shorted out on heater element and ended test prematurely; no sublimation observed.	Heater element failed; severe interior deterioration from sublimation; heavy outside carbon condensation; see Figures 5 and 6.	Same as in 1698. See Figures 7 and 8.	Surface carbon condensation on one side heavier than other. No failure. See Figures 9 and 10.	Same as 1700. Failed only on disassembly. See Figure 11.

Figure 4

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Figure 5
Heater Element After Test No. 1698

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Figure 6
Heater Element Fracture, Test No. 1698

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Figure 7
Heater Element After Test No. 1699

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Figure 8
Heater Element Fracture, Test No. 1699

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Figure 9
Heater Element After Test No. 1700

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Figure 10
Carbon Condensation, Heater Element Test No. 1700

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Figure 11
Heater Element After Test No. 1700
(Fractured During Disassembly)

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FFL l.g. Test Fixture Cross Section

Figure 12
FFL l.g. Test
Heater Element Design Study

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Figure 13
FFL l.g. Test
Heater Element Design Study
Various Material Temperatures Versus Core Axial Station
Core Inside Diameter = 2 5/8 Inches

Figure 14
FFL l.g. Test
Heater Element Design Study
Radial Heat Flow Per Inch of Length Versus Axial Station

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Figure 15
FFL l.g. Test
Heater Element Design Study
Various Material Temperatures Versus Core Axial
Station. Core Inside Diameter = 3 3/4 Inches

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Figure 16
FFL l.g. Test
Heater Element Design Study
Amperes, Volts, Maximum Graphite Temperature
Versus Minimum Heater Element Wall Thickness

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