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Reactor Safety

AI-AEC-12681

HIGH HEAT FLUX HEATER DEVELOPMENT
STATUS REPORT

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION

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Gene Herman
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HIGH HEAT FLUX HEATER DEVELOPMENT
STATUS REPORT

MASTER

By

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ABSTRACT

The development of a high heat flux heater for use in corrosion rate and stress-rupture tests of fuel cladding materials in a sodium environment is described. The heating unit consists of a graphite rod, 1/8-in. in diameter and 2 in. long, in which up to 3.77 kw of electrical energy is dissipated. A boron nitride sleeve is used as the primary electrical insulator for the graphite, and the heater sheath is made of Type 304 stainless steel. Heat fluxes of 1.3×10^6 Btu/hr-ft² have been attained at the heater sheath for periods exceeding 1000 hours. Heater operation and failure modes are discussed, and methods of increasing heater life are described.

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I. INTRODUCTION

A rather extensive fuel and cladding materials development program has been initiated for the Sodium Cooled Fast Breeder Reactor Program. Of particular concern is the desire and the need to perform out-of-pile tests of cladding materials under the high heat fluxes which are expected during reactor operation. At a surface heat flux of 10^6 Btu/ft²-hr, the temperature gradient in a Type 304 Stainless Steel cladding wall is 7°F per mil, which amounts to about 70°F across a typical 0.010-in. wall. This temperature gradient gives rise to appreciably large steady state thermal stresses (~43,000 psi in the heater sheath). If the heating is not continuous, even larger transient temperature gradients and thermal stresses are developed. In addition to investigating the thermal and mechanical behavior of cladding materials, there is also a concern about the chemical and corrosion behavior of materials exposed to hot sodium. Under high heat flux conditions, the clad surface rises several tens of degrees above the temperature of the bulk sodium, and there is a question about the effect on the corrosion rate of this hot surface in nominal 1200°F sodium. To undertake a study of mechanical and chemical properties of clad materials under conditions of high heat flux, it is first necessary to develop a heater capable of delivering a representative heat flux for an extended time. The goal of the present heater development program is therefore to devise a heater capable of delivering 1,000,000 Btu/ft²-hr for 1000 hours of steady state operation.

A heater design developed by Noyes* for a reactor safety program was the starting point for the present development. The goal of Noyes' heaters was to generate 2,000,000 Btu/ft²-hr for a short time for use in burn-out sodium boiling tests. The initial modifications of the Noyes heaters are described by Hayward, et al.† Two versions were made, Model 1 and Model 2. Both designs

*R. C. Noyes, "Boiling Studies for Sodium Reactor Safety, Part I, Experimental Apparatus and Results of Initial Tests and Analysis," NAA-SR-7909, August 1963

†B. R. Hayward, E. L. Babbe, and D. K. Darley, "High Heat Flux Heater Development, Preliminary Performance Tests," NAA-SR-12242, December 1966

involve the use of an ATJ graphite rod, 1/8-in. diameter and 2-in. long, as the heating element. The electrical current (200 to 300 amperes) enters through an insulated molybdenum electrode, passes through the graphite heating element, and then passes through a short stainless steel electrode which is grounded to the heater sheath. The molybdenum and the graphite are separated from the heater sheath by a thin boron nitride (BN) insulating sleeve which is carefully fitted to both the heater sheath and to the graphite. The spaces between the graphite and the BN and between the BN and the heater sheath, are filled with helium at one atm pressure to enhance the heat transfer coupling from the heater to the sheath. In the Model 1 heater, a 60 lb/in. compression spring was used to produce an axial force on the molybdenum electrode to ensure that good electrical contacts were maintained. An O-ring sealed insulating-sliding joint allowed the molybdenum the freedom to move downward against the graphite. These heaters operated for 120 to 150 hours. Their failures were caused by the reaction between the molybdenum and the graphite, by the carburization of the stainless steel electrode, and by the shrinkage of the graphite which allowed the molybdenum electrode to move downward and to short out against the frame. These failings were corrected in the design of the Model 2 heaters by the use of a tungsten diffusion barrier wafer between the molybdenum and the graphite, the use of a platinum wafer between the stainless steel and the graphite, the use of an additional lavite insulator to guide the molybdenum, and the lengthening of the 1/8-in. diameter section of the molybdenum electrode. In addition, the graphite rod was vacuum-fired to 3500°F to drive off the volatile components in the material and to allow the graphite to stabilize in size before the final machining. The remaining differences between the Model 1 and Model 2 heaters was that a dead weight was substituted for the spring and a rubber boot was substituted for the insulating-sliding O-ring joint. The operating lives of the early Model 2 heaters ranged up to 500 hours. The continuation of the heater development studies uses the Model 2 heater as its base, as described in Section II.

II. EXPERIMENTAL

A. DESIGN AND CONSTRUCTION

The basic design of the cladde heater presently in use is much the same as that of the Model 2 heater except that cladding and a NaK bond system have been added. Heat is transferred from the basic heater to the cladding by the NaK bond, which is pressurized with a bellows system to ensure that the NaK does not boil during operation. An extension to the end of the heater was added to provide a fluid flow straightening section length upstream of the heated section. This cladde heater design is called the Model 3. It is also used for stress-rupture tests of cladding specimens by adjusting the pressure of the NaK to provide the desired hoop stress in the cladding specimen. Figure 1 shows a drawing of the Model 3 cladde heater. The functions of the numbered parts are described below.

The basic heating element (6) is a graphite cylinder 0.125-in. in diameter and 2-in. in length. Prior to final machining, the graphite is well outgassed in vacuum at 3500°F, and great care is taken to ensure that the ends are normal to the axis and parallel within 0.001-in., maximum. The heater is polished on its cylindrical surface to be a snug slip fit inside the boron nitride insulator sleeve (5) which extends from the upstream end of the graphite heater along the nominal 0.125-in. diameter length of the molybdenum upper electrode (8) and terminates in the lavite insulator (13). The BN sleeve is fabricated with slightly thicker walls than its final size, and it is hand-shaped and sized to be a slip-fit inside the heater sheath (10). The heater sheath has two sets of four lobes each whose outer diameters are hand-shaped to slip freely (but not loosely) to fit the individual piece of cladding being tested. This is detailed in Sections B-B and D-D. Section C-C shows a mid-length cross section of the heater zone. The section dimensions illustrate the clearances normally obtained.

The upstream end of the Model 3 heater consists of the heater sheath extension (2) which ends in a guide pin. The pin is free to slide in the heater tip. This sliding joint provides thermal expansion relief for the cladding specimen which is welded to the tip. The tip also serves as the means of loading

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 Figure 1. High Heat Flux
 Heater Details
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the pressurizing NaK into the tubing (1). After evacuation through the tip (1), the NaK is introduced and flows along the sheath extension (2), fills the regions (3) and then passes through the broached duct (12) in the heater body into the pressurizing tube (11). It then fills the interior of a stainless steel bellows chamber (17). Pressurization of the NaK is accomplished by the application of gas pressure in the bellows chamber (18), after evacuation of the bellows casing through the tube (21). The bellows is sized to provide room for thermal expansion of the NaK and prevents gas from entering the test loop at cladding failure. The downstream end of the heater extension (2) slips inside the upstream end of the heater sheath (9) and becomes the lower electrode. Section A-A shows the nature of the fit.

A platinum disc (4), whose OD is hand-sized so that it fits snugly inside the end of the BN insulator (5), provides a diffusion barrier between the stainless steel electrode and the graphite heating element (6). The upper end of the heater has a tungsten diffusion barrier (7) between the molybdenum electrode (8) and the graphite. The lower end of the molybdenum electrode (Section D-D) has a 0.1245-in. (+0.0000, -0.0010) diameter over a 2.56-in. length, at which point it expands smoothly into a nominal 0.25-in. diameter stock rod. A lavite insulator (13) is placed in the lower end of the heater body to support the end of the BN insulator and to generally position the molybdenum. The upper end of the molybdenum electrode is brazed into a 1/2-in. copper rod (16) to whose upper end the power lead is attached. The lower end of the copper rod (16) is guided by a lavite insulator (15) and by a ceramic insulator sleeve (24) at the rod's midpoint to guide the movement of the electrode assembly.

The body of the heater has cooling coils (19) brazed to it, as shown in Figure 1, and a tube (20) which is used to evacuate the electrode chamber after assembly. After evacuation, the heater chamber is filled with helium to provide additional heat transfer coupling between the heater (6) and the sheath (10). The lower end of the heater body is fitted with a Conoseal joint fitting (14), at which point it is supported in the sodium loop. The upper end of the heater body supports the Micarta insulator-guide (24) and provides a smooth surface against which the rubber tubular boot (22) is fastened with a hose clamp (23). This boot must provide the needed electrical insulation, the axial flexibility needed to maintain junction contact along the electrical train, and the necessary impermeability to air (oxygen) to maintain an inert atmosphere in the electrode chamber.

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Figure 2. Model 2 Heater, Exploded View

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Figure 3. Model 2 Heater, Assembled

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The upper end of the boot is clamped to a stainless steel attachment (27) which is brazed to the copper electrode (16). The stainless steel part also provides a support for the weight (26) which is sized to provide an adequate pressure on the electrical joints. Because one line of the low voltage ac power for the heater is grounded to the heater body and the sodium loop, a heat-shrinkable plastic cover (25) is used to insulate and cover the weight and minimize the chance that the current will be inadvertently shorted out during operation.

The modifications to this basic design have included: (a) the use of a tantalum diffusion barrier and of a rhenium diffusion barrier in place of the tungsten barrier (7) and (b) the use of stainless steel bellows (with an epoxy insulating seal) in place of the rubber boot (22).

All clad heaters are used with flow-controlling baffles which maintain a 20 ft/sec sodium flow along the length of the cladding specimen.

Figure 2 shows the Model 2 heater in an exploded view. Figure 3 shows an assembled Model 2 heater (with a clear plastic boot to show internal assembly details). Figure 4 is a diagram of a Model 2 heater in place in a leg of the 2-in. sodium loop. Figure 5 shows a Model 3 heater with the flow controlling baffles for the cladding region. The NaK pressurization assembly (Items 17 and 18 in Figure 1) shown in Figure 5 utilizes two small bellows assemblies in parallel; the more recent heaters are built with one larger pressurization assembly. Figure 6 is the fully assembled clad heater used in Test No. 38, and shows the metal bellows replacing the rubber boot, the flow controlling baffles in place over the cladding section, and the large single unit NaK pressurization assembly unit.

B. HEAT TRANSFER ANALYSIS

A steady-state heat transfer analysis was made on the Model 2 and Model 3 heater designs in order to establish the levels of temperatures expected and to identify regions of potential materials interaction problems. A computer code designed for radial and axial conduction was used, and the temperature dependence of the thermal conductivities of the materials was taken into account. The computations were made for 1,000,000, 1,500,000, and 2,000,000 Btu/ft²-hr heat fluxes, measured at the OD of the Type 304 Stainless Steel heater sheath. The

FIGURE 4 AI-AEC-12681

Figure 4. Schematic Diagram of a Heater in Place in the 2-in. Loop

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Figure 5. Model 3 Heater, Assembled

Figure 6. Model 3 Heater, With Bellows and A Single NaK Pressurization Assembly Unit

Figure 7. Calculated Axial Temperature Profiles for Model 2 Heater

inlet coolant sodium temperature was taken at 1200°F, and the flow velocity at 20 ft/sec. Figure 7 shows, for the Model 2 heater, the axial temperature profiles of the various surfaces. The data presented are for a 1,300,000 Btu/ft²-hr heat flux measured at the heater sheath (point C), and were obtained by interpolation of data originally computed for 1,000,000 and 1,500,000 Btu/ft²-hr heat fluxes. Figure 8 shows a similar plot for the Model 3 heater. As expected, the central 75% of the heater length shows rather uniform axial pattern, with a slight increase toward the downstream end (tungsten wafer) caused by the increasing sodium coolant temperature in that direction. At the ends of the heater, a significant amount of heat is conducted axially away from the heater, as is shown by the temperature gradients in the regions of the platinum and tungsten wafers. The added thermal resistance of the NaK-filled annulus and the 0.010-in. thick cladding specimen is shown by the 370°F increase in center-line temperature of the Model 3 heater over the Model 2 heater.

Figure 9 shows the calculated effect of the heat flux on the radial temperature profile at the position of the tungsten wafer of the Model 2 heater, and Figure 10 shows the analogous profiles for the Model 3 heater. Figure 11 shows the analogous profiles for the Model 3 heater. It is of interest to note that the temperature of the inner surface of the stainless steel sheath is calculated to be about 2050°F (1120°C) in the Model 3 heater at a 2,000,000 Btu/ft²-hr heat flux (Figure 12). This poses a very severe operating environment for that material, and suggests that a 2,000,000 Btu/ft²-hr flux is probably the maximum heat flux attainable by the heater. Another serious limitation in the center of the Model 3 heater is the temperature of the BN insulator. At 2,000,000 Btu/ft²-hr, the inner surface temperature of the BN is seen in Figure 12 to be about 4100°F (2260°C). This, too, is a very high service temperature, and may impose a limitation on heat flux. At the nominal 1,300,000 Btu/ft²-hr rate of the present test program, the computed temperature for the inner sheath wall is about 1800°F, and that of the inner BN surface is about 2450°F; these temperatures, though high, are readily tolerated by the materials. However, an examination of Figures 9 to 12 shows the great importance of minimizing the helium gaps in this design. At the 1,300,000 Btu/ft²-hr heat flux, the gaps in the Model 3 heater have 375 and 425°F (calculated) temperature gradients across them in the center of the heater. At the position of the tungsten wafer, the corresponding

Figure 8. Calculated Axial Temperature Profile for Model 3 Heater and Cladding

Figure 9. Calculated Radial Temperature Profiles Across Model 3 Heater at Tungsten Wafer

Figure 10. Calculated Radial Temperature Profiles Across Model 3 Heater at Tungsten Wafer

Figure 11. Calculated Radial Temperature Profiles Across Model 2 Heater at Mid-Length of Graphite

Figure 12. Calculated Radial Temperature Profiles Across Model 3 Heater at Mid-Length of Graphite

calculated temperature gradients are about 60 and 160°F, respectively. It is thus obvious that the nicety of the fit of the graphite, the BN, and the sheath, and of the platinum and tungsten wafers, is an important factor in the performance capability of this heater.

C. Heater Performance Analysis

Three Model 1 heaters were built and tested. The operational data are summarized in Table 1, and were briefly discussed by Hayward et al.* The two problem areas, the graphite-molybdenum interaction, and a too-short tip region on the molybdenum electrode, were corrected in the design of the Model 2 heaters.

Eight Model 2 heaters were built and tested. A summary of their performance is given in Table 2. These heaters showed the greatest operating service times of any. All of them (except for No. 13, which deteriorated during a several-week holding period at temperature) exceeded 400 hours of operation. The failures which occurred by open circuit were caused by the in-leakage of oxygen (air) through the rubber boot. The oxygen reacted with the hot molybdenum electrode to form MoO_3 , which then deposited in the upper regions. In time, the MoO_3 would build up a heavy deposit and cause the electrode to bind in its chamber. Because the graphite shortens during use, it is necessary that the molybdenum electrode be free to move axially downward to maintain the electrical contact. The buildup of MoO_3 would therefore eventually prevent the maintenance of electrical continuity, and the heaters would fail by open circuit.

The short-circuit failures were both at the upper contact, and it is believed that they are caused by the development of a hot spot and the deterioration of the tungsten-graphite interface. If the contact resistance increases, the local temperature rises, and the tendency for reaction increases. If the reaction to form tungsten carbide proceeds, the joint tends to deteriorate and the poor contact makes the process accelerate, so that a hot spot is generated, and failure is imminent.

Two of these tests were designed to investigate the use of tantalum and rhenium as a diffusion barrier in place of the tungsten. The tantalum test, No.13,

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Heater No.	Service Time* (hr)	Mode†	Heat Flux $\times 10^{-6}$ Btu/hr-ft ²		Total "On" Time (hr)	Total Power Developed (Mw-hr)	Cycles	Special Construction Features	Failure Mode	Remarks
			Sheath	Clad						
1	126	S	1.3	None	126	0.47	27	None	Short	Graphite shrank - Mo shorted out at taper
4	370	6	1.3		185	0.69	1854	None	Open	Open circuit at graphite - Mo interface
5	123	S	2.0		123	0.71	36	None	Short	Graphite shrank. Mo shorted out at taper

*Service Time: Time heater was operating on-line. For cyclic operation, this time includes power-off time.
†Mode: 'S' represents steady power, '6' a 6-min 'on', 6-min 'off' sequence (50% duty cycle)

Table 1. Heater Test Summary:
Model 1 Heater

Heater No.	Service Time* (hr)	Mode†	Heat Flux $\times 10^{-6}$ Btu/hr-ft ²		Total "On" Time (hr)	Total Power Developed (Mw-hr)	Cycles	Special Construction Features	Failure Mode	Remarks
			Sheath	Clad						
6	657	S	1.0	None	657	1.77	-		Open	Open circuit; graphite cracked
7	924	6	1.3		462	1.71	4618		Short	Failed at upper contact, arced and ruptured sheath
8	433	S	1.3		433	1.60	-		Open	W-graphite interaction, MoO ₃ on upper Mo electrode surface. Mo electrode showed evidence of buckling; BN degraded in region of W
9	410	S	2.0		410	2.30			Short	Failed at upper contact, arced and ruptured sheath
10	463	S	1.3				22	Re disc between Mo and graphite and Pt cup instead of a Pt wafer	Open	Re showed evidence of compressive deformation. Failure caused by buildup of MoO ₃ or Mo electrode, preventing axial movement
13	0	-	-		0	0	-	Ta disc between Mo and graphite and Pt cup instead of a Pt wafer	Open	Heater in place in the loop at 1200°F for several days before attempt to operate it; heater would not start. It remained in the loop for 589-hr total time and when examined, the Ta was all oxidized and there was a heavy layer of MoO ₃ on the Mo electrode
11A	763	S	1.3		763	2.88	24	MoSi ₂ -coated Mo electrode; metal bellows.	Operable with difficulty at end of test	Rebuilt from Heater No. 11, which was inserted into loop incorrectly. Bellows used proved too stiff and prevented free application of compressive load to heater column. Frequent adjustments of electrode position were required to maintain heater operation. No evidence of MoO ₃ . Some evidence of degradation of BN at W wafer. Graphite heater element shortened about 1/2 in.
12	1117	S	1.3		1117	4.20	26	MoSi ₂ -coated Mo electrode; double thickness rubber boot	Operable at end of test	No evidence of MoO ₃ , but Cu electrode extension was moderately blackened. Graphite shortened 1/8 in. MoSi ₂ on electrode appeared to have interacted with BN, but had not caused any apparent degradation in performance at end of test.

*Service Time: Time heater was operating on-line.
†Mode: S represents steady power, 6 represents a 6-min on, and 6-min off sequence (50% duty cycle).

Table 2. Heater Test Summary:
Model 2 Heater

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was not successful, but the use of tantalum should not be excluded on the basis of this test alone. The tantalum wafer became oxidized before the attempt to operate the heater was made. It was put in place in the loop and the sodium temperature was raised to 1200°F and maintained for several days before the heater was turned on. When the start-up attempt was made, the heater showed an open circuit. Post-test examination of the heater disclosed that the tantalum had completely oxidized. In addition, due to the oxidation of the molybdenum electrode, there was a large amount of MoO_3 in the upper electrode chamber. It seems likely that the boot, or its installation on the heater, was defective.

Heater No. 10 was made with a rhenium wafer in place of the tungsten wafer. It operated well during test and failed due to the heavy build-up of MoO_3 in the upper electrode chamber. As shown in Figure 13, the rhenium deformed during use. However, had the electrode been free to move, it is quite probable that the heater could have continued in operation. The MoO_3 is shown in Figure 14, which is from Heater No. 10, but is also typical of the heavy deposits formed in other heaters using the single rubber boots.

Because of the serious problem with the MoO_3 , an alternate expansion member was sought. Heater 11A was rebuilt from parts originally used on Heater 11, which was installed in the loop but was difficult to start. It was found that Heater 11 had been improperly installed. Heater 11A was the first in which a metal bellows was used in place of the rubber boot. However, the bellows obtained for the unit proved to be too stiff, so that it was difficult to keep the heater in operation. Further, the graphite heating element shortened a full 1/2-in. during its operating life. Typically, the heaters shorten about 1/8-in. during use. It is thought that the light net pressure that was on the heater may have contributed to its excessive shortening because, if an arc developed between the graphite and the tungsten, the graphite could waste away. It is true, however, that such an arc could persist for only a very short time lest the tungsten-graphite interface begin to interact.

The success of the bellows in Heater No. 11A was shown, however, in the fact that there was no evidence of attack of the molybdenum by oxygen. The upper contact did run hot, as shown by the BN reaction at the tungsten wafer interface. This reaction was thought to be due to the combination of a high

Figure 13. Rhenium Wafer, Post-
Test Examination of NaK Heater,
Test No. 10

Figure 14. MoO_3 Deposit
(From Heater Test No. 10)

temperature and the presence of silicon as a MoSi_2 coating on the molybdenum electrode. During the course of development of the heater design, it was thought that if the molybdenum could be protected from any oxygen which might diffuse through the boot, the open circuit stoppage by the MoO_3 deposit might be circumvented. However, in this case the MoSi_2 did appear to react with the BN, so that it is no longer considered as a possible solution to the oxygen influx problem. The bellows test of heater No. 11A clearly demonstrated the superiority of the bellows, which prevents the influx of oxygen, to the MoSi_2 , which can only reduce the rate at which the oxygen attacks the molybdenum.

The longest test period experienced by any heater was that of Heater No. 12. It ran for 1117 hours and was still operable at the end of its test period. A double silicone rubber boot was used to provide axial movement and insulation. A MoSi_2 -coated electrode was used in the heater and showed no evidence of attack by oxygen; there were, however, indications that the MoSi_2 and the BN may have slightly interacted. The only evidence of any oxygen having entered the electrode chamber is that the copper electrode extension was slightly blackened.

Eleven Model 3 heaters were tested, and Table 3 gives a summary of their performances. In all cases, these heaters were prepared for stress rupture tests of cladding or for corrosion tests. The testing procedures were therefore regulated to accommodate the needs of the cladding tests rather than those of the heater. When the cladding tests were completed (i. e., the pressurized cladding had ruptured), the claddings were removed and the bare heaters returned to the loop for testing to failure. As shown in Table 3, the A and B designations indicate the sequential test periods for a given heater structure. The first three heaters tested used the single-layer rubber boot. All had MoO_3 deposits, and Nos. 30-30A and 32-32A-32A' failed because the heavy deposit prevented the electrode from making electrical contact.

The next seven heaters had metal bellows, and no problems were experienced with MoO_3 . Three of them were operable when they were given their post-test examination. The other four failed by the development of a short circuit near the tungsten wafer. In some cases, an arc developed and the heater sheath was damaged.

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Heater No.	Service Time* (hr)	Mode†	Heat Flux x 10 ⁻⁶ Btu/hr-ft ²		Total "On" Time (hr)	Total Power Developed (Mw-hr)	Cycles	Special Construction Features	Failure Mode	Remarks
			Sheath	Clad						
30	223	S	1.3	1.0	223	0.84	32	None	Operable	Test Terminated because of cladding failure
30A	107	S	1.3	-	107	0.40	3	Cladding removed, operating as base heater	Open	Failure caused by buildup of MoO ₃ on Mo electrode, preventing freedom of axial movement
	330C§				330C	1.24C	35C			
32	227	6	1.3	1.0	114	0.43	1140	None	Operable	Test terminated because of cladding failure
32A	72	6	1.3	-	36	0.14	360	Cladding removed, operating as base heater	Operable	Test continued on cyclic duty, but electrical disturbances caused by switching made it very difficult to test other heaters, so test mode was changed, after 72 hr, to steady operation. Nominal failure was caused by buildup of MoO ₃ on Mo electrode
32A	894	S	1.3	-	894	3.36				
	1193C				1044C	3.93C	1500C	Base heater	Open	
36	589	S	1.3	1.0	589	2.22	10	None	Open	Clad failed after 558 hr. Heater operated to failure at 589 hr. Moderate amount of MoO ₃ on Mo electrode W and graphite reacted. Pt wafer appeared to have run hot; much carbon was apparently dissolved in it, and precipitated on cooling
38	198	6	1.3	1.0	99	0.37	990	Metal bellows 0.010-in. wall	Short	W wafer region ran hot; bellows was too stiff to permit adequate freedom of axial movement. No MoO ₃ ; arc developed and ruptured the sheath and clad
40	173	6	1.3	1.0	87	0.33	865	Metal bellows, 0.003-in. wall	Operable	Test terminated because of cladding failure
40A	238	S	1.3	-	238	0.90	1	Cladding removed, operating as base heater	Operable	Test terminated for removal of Heater No. 50
40B	260	S	1.3	-	260	0.43	1	Base heater	Operable	Test terminated following failure of Heater No. 52
	671C				585C	1.66C	867C			
42	134	1	1.3	1.0	67	0.25	4026	Metal bellows, 0.003-in. wall	Operable	Test terminated because of cladding failure
42A	109	1	1.3	-	55	0.21	3282	Cladding removed, operating as base heater	Short	Failure at W wafer. Mo electrode tip bloomed out, punctured BN insulator; some reaction between W and graphite was evident. No MoO ₃ on Mo electrode
	243C				122C	0.46C	7308C			
44	163	1	1.3	1.0	82	0.31	4901	Metal bellows 0.003-in. wall	Operable	Test terminated because of cladding failure
44A	149	S	1.3	-	149	0.56	1	Cladding removed	Short	Failure at W wafer. Molybdenum electrode tip bloomed out, punctured BN insulator. Reaction between W and graphite was slight. No MoO ₃ on Mo electrode
	312C				231C	0.87C	4902C	operating as base heater		
46	385	6	1.3	1.0	193	0.73	1925	Metal bellows, 0.003-in. wall	Operable	Test terminated because of cladding failure. Upon removal of cladding, an 0.004-in. diametral swelling at the level of the W wafer was observed. The heater was dismantled and examined. The W wafer had reacted to form a large button of W-carbide, as discussed in text. No MoO ₃ on Mo electrode
48	393	6	1.3	1.0	197	0.74	1961	Metal bellows, 0.003-in. wall	Operable	Test terminated because of cladding failure
48A	238	6	1.3	-	119	0.45	1195	Cladding removed, operating as base heater	Operable	Test terminated for removal of Heater No. 50
48B	260	6	1.3	-	130	0.21	572	Base heater	Operable	Test terminated following failure of Heater No. 52. No MoO ₃ on Mo electrode
	891C				446C	1.40C	3728C			
50	182	S	1.3	1.0	182	0.69	3	Metal bellows, 0.003-in. wall	Short	Failure at W wafer. Arc developed and punctured the heater sheath. No MoO ₃ on Mo electrode
52	12	S	1.3	1.0	12	0.05	4	Double thickness rubber boot	Short	Failure at W wafer. Arc developed and punctured the heater sheath. No MoO ₃ on Mo electrode

*Service Time: Time heater was operating on-line

†Mode: 'S' represents steady power; '6' represents a 6-min 'on', 6-min 'off' sequence (50% duty cycle) and '1' represents a 1-min 'on', 1-min 'off' sequence (50% duty cycle)

§The C suffix denotes a cumulative value.

Table 3. Heat Test Summary:
Model 3 Heater

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Heater No. 46 completed its stress-rupture test duty as planned, but examination after the cladding was removed disclosed that it had developed an 0.004-in. swelling at the level of the tungsten wafer. Heater Nos. 40, 42, 44, and 48 all showed some tendency for swelling, but in amounts only up to 0.002-in. on the diameter. Because of the greater swelling, Heater No. 46 was retired from the testing and examined. Figure 15 shows the region of the tungsten wafer. A tungsten carbide button had formed and had consumed all of the tungsten in the center of the heater. Further, the molybdenum tip had bloomed outward and nearly cut through the BN insulator on both sides. Apparently the temperature of the joint was such that the radial pressure exerted by the molybdenum was enough to cause the stainless steel wall to creep and to expand 0.004-in. As can be inferred, the development of the carbide button must certainly have caused a localized hot spot to develop, with the further deterioration of the electrical contact. It was estimated that this heater could not have continued in operation for more than another 100 hours. Rather high temperatures were also experienced at the platinum wafer end of Heater No. 46. Figure 16 shows the platinum wafer and the extent to which it had flowed toward the side under the axial pressure loading required to maintain the electrical integrity of the tungsten wafer joint.

Post-test radiographs of Heater Nos. 40, 42, 44, and 48 are shown in Figure 17. The radiograph of Heater No. 40 shows both the platinum and the tungsten to be in very good condition, with rather square interfaces with the graphite, and only a suggestion of blooming on the molybdenum tip.

The radiograph of Heater No. 48 shows the unit to be in fair condition, although the molybdenum can be seen to have begun to distort, and the platinum-graphite interface is no longer straight.

The radiograph of Heater No. 44, which had failed by short circuit, shows the tip of the molybdenum to be deformed and to have breached the BN insulator. The platinum-graphite interface is roughened, but in fair condition.

The radiograph of Heater No. 42 shows a deformed molybdenum tip and the swelling in the sheath. The platinum wafer appears to be in good condition.

The last heater tested, Heater No. 52, had a very short life, and failed by the development of a short circuit at the tungsten wafer. The reason for the

8191-4-3

Figure 15. Tungsten Carbide Formation
in Heater No. 46

8191-2-8

Figure 16. Platinum Wafer, Heater No. 46

7706-4741

Figure 17. Radiographs of Heater No . 40, 42,
44, and 48

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TABLE 4
HEATER PERFORMANCE ANALYSIS

No.	Total Service Life (hr)	Unclad, Steady (hr)	Clad Steady (hr)	Unclad, Cyclic (hr)	Clad, Cyclic (hr)	Heater Heat Flux $\times 10^{-6}$	Failure Mode				
							Open	Short	MoO ₃	Other	Still Operable
12	1117	1117	0	0	0	1.3					yes
32A, A'	1044	898	0	0	150	1.3			X		Barely
11A	763	763	0	0	0	1.3				Stiff Bellows	yes
6	657	0	657	0	0	1.0	X				no
36	589	0	589	0	0	1.3	X		X	W-C Reaction	no
40A, B	585	498	0	0	87	1.3					yes
10	463	0	463	0	0	1.3	X		X	Re-Disc	no
7	462	0	0	0	462	1.3		X			no
48A, B	446	0	0	249	197	1.3					yes
8	433	0	433	0	0	1.3					yes
9	410	0	410	0	0	2.0		X			no
30A	330	107	0	0	223	1.3	X		X		no
44A	231	149	0	0	82*	1.3		X			no
46	193	0	0	0	193	1.3				W-C Reaction	yes
50	182	0	182	0	0	1.3		X			no

*2-min cycle, all others are on a 12-min cycle

very short life of the heater is not known, and could not be inferred from post-test examination because of the amount of localized damage caused by the arcing in the vicinity of the tungsten wafer.

Because the goal of this program is to develop a heater capable of operating for 1000 hours while delivering heat to a cladding specimen at 1,000,000 Btu/ft²-hr, it is of interest to compare the performance of the heaters in this context. The heaters are listed in Table 4 in descending order of their service lives, and in accordance with their service modes. One sees that, in general, the best combination for long life is the "unclad, steady" combination; then the "clad, steady" shows next longest life. The cyclic mode is more severe than the steady mode, as one would expect.

The reason for the longer lives of the unclad heater is readily seen in Figures 7, 8, 9, and 10. The computed ideal temperature difference between the Model 2 and Model 3 heaters for a 1.3×10^6 Btu/ft²-hr heat flux at the heater sheath, is about 125°F. A similar difference is found at the corresponding locations toward the center-line of the heaters. This is a significant difference, but is probably a less important effect than is the consequence of having a poor electrical contact at the tungsten wafer.

III. EVALUATION AND CONCLUSIONS

The Model 3 high heat flux heater design shown in Figure 1 appears to have much promise for the desired service of 1000 hours of steady operation at a cladding surface heat flux of $1,000,000 \text{ Btu/ft}^2\text{-hr.}$ The early troubles with reactions between the graphite and the molybdenum and the stainless steel have been greatly reduced by the use of diffusion barriers of tungsten and platinum. The early difficulty with the diffusion of oxygen (air) through the rubber boot has been resolved in two ways — the double-layer rubber boot, and the bellows using an epoxy seal. There remains, however, the problem of overheating at the tungsten wafer. The solution of this problem will almost certainly give the heaters a major increase in service life.

The question of the best barrier material has not yet been answered. Rhenium should still be considered a prime candidate, tantalum should not be too quickly judged to be a poor barrier material (because of only one poorly-controlled experiment). However, it can be concluded that the leakage (diffusion) of air into the electrode chamber is very severe on tantalum and cannot be tolerated.

The solution to the problem of minimizing the electrical contact resistance is not yet in hand, but it does seem necessary to reduce the number of unbonded interfaces along the electrical path, and particularly to reduce the number of free interfaces in the region of the upper diffusion barrier.