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THE PERFORMANCE OF MOLYBDENUM FILAMENTS IN BWR EMERGENCY COOLING HEAT TRANSFER TESTS

J. D. DUNCAN
R. G. BOCK

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ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC

SAN JOSE, CALIFORNIA

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J. D. Duncan

R. G. Bock

Approved:

F. A. Schraub

Development Engineering

Prepared for Idaho Nuclear Corporation

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TABLE OF CONTENTS

Abstract	1
1. Summary	1
2. Introduction	1
3. Results of Tests Using Heater Bundles with Molybdenum Filaments	2
3.1 Stainless Steel Clad Bundle Tests	2
3.2 Zircaloy Clad Bundle Test	7
4. Analytical Investigation of the Effect of Molybdenum on Heater Power Distribution and Heater Maximum Surface Temperature	29
4.1 Axial Power Distribution	29
4.2 Heater Maximum Surface Temperature	29
5. Conclusions	34
6. Alternatives	34
Nomenclature	35
References	37
Acknowledgements	37

LIST OF ILLUSTRATIONS

Figure	Title	Page
1	Molybdenum Resistance Variation with Temperature (Reference 3)	2
2	Comparison of Axial Power Distributions Resulting from Temperature Dependent Molybdenum Resistance with Design Power Distribution	3
3	Comparison of Molybdenum and Nichrome Heater Axial Temperature Profiles with Design Profile	4
4	Comparison of Molybdenum and Nichrome Filamented Heater Bundle Tests	7
5	Variation of Maximum Axial Peaking Factor with Maximum Surface Temperature for Four Molybdenum Filamented Heater Rods Installed in Bundle SS 3	8
6	Radial Power Shifting in "Inner Rod" and "Outer Rod", Bundle SS 3	9
7	Effect of Molybdenum Power Shifting on Bundle Maximum Temperature (Molybdenum and Nichrome Runs from Figure 3)	10
8	Zircaloy Clad Heater Used in Molybdenum Zircaloy Performance Test	11
9	Molybdenum Zircaloy Performance Test Radial Peaking	12
10	Molybdenum Zircaloy Performance Test Bundle Instrumentation	13
11	Molybdenum Zircaloy Performance Test Heater Bundle Thermocouple Location Plan . . .	14
12	Thermocouple Distribution on Inner Channel, Molybdenum Zircaloy Performance Test . .	15
13	Thermocouple Distribution on Outer Channel, Molybdenum Zircaloy Performance Test . .	15
14	Emergency Cooling Test Facility Used for Molybdenum Zircaloy Performance Test	16
15	Forty-Nine Rod Power Supply Used in Molybdenum Zircaloy Performance Test	17
16	Temperature Response of Rod 23 (6.0 ft Level) to Molybdenum Zircaloy Performance Test Spray Cooling Transient	18
17	Estimated Maximum Temperature of Rod 16 (6.0 ft Level) Molybdenum Zircaloy Performance Test Spray Cooling Transient	20
18	Estimated Maximum Temperature of Rod 48 (6.0 ft Level) Molybdenum Zircaloy Performance Test Spray Cooling Transient	20
19	Estimated Maximum Temperature of Four Central Rods (6.0 ft Level) Molybdenum Zircaloy Performance Test Spray Cooling Transient	21
20	Estimated Maximum Temperature of Three Outer Rods (6.0 ft Level) Molybdenum Zircaloy Performance Test Spray Cooling Transient	21

LIST OF ILLUSTRATIONS—(Continued)

Figure	Title	Page
21	Estimated Maximum Temperature of Various Elevations of Rod 4 Molybdenum Zircaloy Performance Test Spray Cooling Transient	22
22	Outside Rods Radial Power Shift, Molybdenum Zircaloy Performance Test	23
23	Inside Rods Radial Power Shift, Molybdenum Zircaloy Performance Test	24
24	Corner and Central Rods Radial Power Shift, Molybdenum Zircaloy Performance Test	25
25	Molybdenum Zircaloy Performance Test Bundle After Testing	26
26	Molybdenum Zircaloy Performance Test Bundle Distortion	27
27	Photomicrographs (X250) of Rod 25 Cladding After Molybdenum Zircaloy Performance Test	28
28	Heater Rod Dimensions and Conductivities	30
29	Model Used to Study Heat Transfer from a Heater Section	30
30	Sensitivity of Molybdenum and Nichrome — Filamented Heater Maximum Surface Temperature to Center Section Resistance, Coolant Temperature, Film Thermal Resistance and Heater Thermal Resistance	33

LIST OF TABLES

Table No.	Title	Page
1	Results of Bundle SS2 Testing	5
2	Results of Bundle SS3 Testing	6
3	Approximate Initial and Maximum Temperatures, Molybdenum Zircaloy Performance Test Spray Cooling Transient	19

ABSTRACT

The performance of molybdenum filaments as fuel rod simulator heating elements in BWR emergency cooling heat transfer tests has been evaluated. Analysis of test data and a simplified analytical model indicates that molybdenum's high temperature coefficient of electrical resistivity causes a nontypical spatial power distribution in test bundles. Molybdenum is therefore not suitable for use in emergency cooling heat transfer tests intended to demonstrate the thermal performance of BWR fuel rods during a loss-of-coolant accident temperature transient. The high temperature capability of molybdenum can be exploited in tests directed at the determination of Zircaloy cladding performance under high temperature emergency cooling conditions. The results of such tests can not be interpreted as being representative of the thermal performance of BWR fuel bundles undergoing loss-of-coolant accident/emergency cooling transients.

1. SUMMARY

Molybdenum heating elements have been evaluated for use in electrically powered BWR fuel rod simulators during emergency core cooling tests. It is shown that molybdenum heating elements do not provide a representative spatial power distribution due to the power shifting caused by molybdenum's high coefficient of electrical resistivity. Tests conducted with molybdenum elements have attained temperatures considerably higher than those experienced when materials with constant coefficients were tested.

Molybdenum is therefore not suitable for full length emergency cooling heat transfer tests intended to demonstrate the thermal performance of BWR fuel rods during a loss of coolant accident temperature transient.

Molybdenum heating elements should only be used to investigate the material behavior of Zircaloy cladding at temperatures beyond those attainable with any of the known heating elements with constant coefficients of electrical resistivity (e.g., Kanthal or Nichrome).

2. INTRODUCTION

The Full Length Emergency Cooling Heat Transfer (FLECHT) Program (Subcontract S-7044 under contract AT(10-1)-1230 between USAEC and Idaho Nuclear Corporation, described in detail in Reference 1) was planned to examine the various emergency cooling parameters which may affect heat transfer from a boiling water reactor fuel bundle under loss of coolant accident/emergency cooling conditions. It was planned to study the maximum initial cladding temperature* parameter through temperatures ranging to 2400°F and higher if a suitable fuel rod simulator, hereafter called a heater, could be found. A suitable heater required a filament material that could sustain temperatures in excess of 2400°F without melting.

Molybdenum was selected for use as a filament material for two reasons. Molybdenum has the smallest coefficient of electrical resistivity among the candidate materials with high melting temperatures. Further, the demonstrated ruggedness of the molybdenum filament - stainless steel cladding combination was expected to be of value in conducting the extensive FLECHT testing program.

It was recognized that the high temperature coefficient of electrical resistivity of molybdenum, shown in Figure 1, would cause two types of power shifting in an electrically heated fuel rod test bundle. Since the heaters would be connected in parallel, power was expected to shift from the hotter (high resistance) rods to the cooler (low resistance) rods. In addition to this rod to rod (or radial) power shift, an axial shifting of power to the hot (high resistance) section of any single rod in the bundle was expected. Previous testing at low temperatures and low bundle powers had indicated that the combination of axial and radial power shifting did not significantly change the maximum bundle temperature (see, for example, Figure 37 of Reference 2). It was expected that the effects of molybdenum power shifting on later tests could be accounted for by calculation.

The results of testing the first two spray-cooling bundles under the FLECHT program indicated that at higher temperatures and higher bundle powers, the effect of

* Maximum cladding temperature at the start of emergency cooling.

FIGURE 1. MOLYBDENUM RESISTANCE VARIATION WITH TEMPERATURE (REFERENCE 3)

molybdenum's high coefficient of resistivity became much more significant. Temperatures as much as 500°F higher were obtained with molybdenum filaments than with Nichrome filaments.

This report presents an analysis of test data which shows the effects of molybdenum power shifting. In

addition, a simplified analytical model is developed to give an indication of the sensitivity of heater surface temperatures to heater properties and heat transfer phenomenon.

3. RESULTS OF TESTS USING HEATER BUNDLES WITH MOLYBDENUM FILAMENTS

3.1 STAINLESS STEEL CLAD BUNDLE TESTS

Stainless steel clad heater bundles 2 and 3, called SS-2 and SS-3, had molybdenum filaments designed to give a heat flux distribution as shown in Figure 2 with a temperature profile as shown in Figure 3. It must be emphasized that the heater design was based on an *assumed** temperature profile. It will later be shown that this profile rarely (if ever) occurs and thus the power profile will rarely match the design profile. These bundles were tested between July and November 1968 in the low pressure cooling rig at San Jose, California. Tables 1 and 2 summarize the tests conducted with these bundles.

The maximum bundle cladding temperatures attained were 400°F to 500°F higher than those of earlier GE funded tests performed under similar conditions of power,

spray flow rate, and test bundle initial temperature. Maximum bundle temperatures versus time plots for runs from these two test series are shown in Figure 4. The only difference between these bundles was that the earlier test bundle had heaters with Nichrome filaments.

An analysis of the effect of the heater axial temperature distribution on the axial power shape reveals the major cause of the excessive temperatures in the molybdenum tests. Typical axial temperature profiles for Nichrome and molybdenum filamented heaters are compared with the design profile in Figure 3. The

* The assumed temperature profile was based on experimental profiles obtained with Nichrome-filamented heaters in 36 rod bundle tests.

FIGURE 2. COMPARISON OF AXIAL POWER DISTRIBUTIONS RESULTING FROM TEMPERATURE DEPENDENT MOLYBDENUM RESISTANCE WITH DESIGN POWER DISTRIBUTION

FIGURE 3. COMPARISON OF MOLYBDENUM AND NICHROME HEATER AXIAL TEMPERATURE PROFILES WITH DESIGN PROFILE

Table 1

RESULTS OF BUNDLE SS2 TESTING

Steady State Spray, Effect of Subcooling

Run	Date	Peak Power, kW	Inlet Water Temperature °F	Spray Rate GPM	O.C.F.* GPM	T _{max} °F
22	8-6-68	200	100	2.1	0.65	1900
			150	2.1	0.65	1875
			200	2.1	0.65	1875
23	8-7-68	250	100	2.6	0.75	**

Transient Spray, Effect of Initial Temperature

Run	Date	Peak Power, kW	Spray Rate GPM	O.C.F.* GPM	Initial Temperature °F	Maximum Temperature °F
24	9-7-68	120	1.1	0.45	1230	1430
25	8-7-68	120	1.1	0.45	1120	1420
28	8-8-68	120	1.1	0.45	1820	1895
33	8-12-68	120	1.1	0.45	2030	2150
26	8-7-68	240	2.1	0.65	1240	2005
27	8-7-68	240	2.1	0.65	1560	2010
29	8-8-68	240	2.1	0.65	1830	2055
34	8-12-68	240	2.1	0.65	1940	2160
30	8-9-68	300	2.6	0.74	1560	2030
31	8-9-68	300	2.6	0.74	1720	2100
35	8-12-68	300	2.6	0.74	2050	2400
32	8-12-68	390	3.35	0.90	1810	>2500****
36	***					
37	***					
38	8-13-68	390	3.35	0.90	1540	2340

* OCF - Outer Channel Flow

** Lost five rods (8, 9, 10, 15, 16), did not complete test

*** Test not conducted

**** Shutdown test at test equipment limit

molybdenum heater profile is much more sharply peaked at the center than the Nichrome and design profiles. A knowledge of the axial surface temperature distribution, an approximate knowledge of the axial power distribution, and a knowledge of the heater to clad thermal resistance can be used to calculate the heater filament temperature. The actual axial power distribution can then be determined using the filament temperature profile to calculate filament resistance. Details of this procedure are shown in Section IV.

Sample axial power shapes obtained using this technique are compared with the design profile in Figure 2. The peak to average axial power was found to be an approximate linear function of maximum surface temperature. Figure 5 shows the maximum peak to average

power ratio versus maximum surface temperature. Note that at a maximum temperature of 1400°F the maximum axial peaking factors range from 1.40 (rod 17) to 1.76 (rod 25). The rods were designed to have a maximum axial peaking factor of 1.37 with a maximum surface temperature of 1400°F and the design temperature profile shown in Figure 3. Since the molybdenum heater temperatures profiles are more sharply peaked than the design profile (Figure 3) a higher maximum axial peaking factor results. The power shifting caused by molybdenum thus concentrates the bundle power in the axial center of the bundle. This power concentration becomes more severe as the heater temperatures increase (for example at 2000°F, axial peaking ranges from 1.5 to 1.8 for the rods shown in Figure 5). The combination of local power and temperature

Table 2
RESULTS OF BUNDLE SS3 TESTING
Steady State Spray, Effect of Spray Flow

Run	Date	Peak Power, kW	Spray Rate GPM	O.C.F.* GPM	T _{max} °F
39A	9-20-68	200	2.1	0.75	1900
39B	9-20-68	200	1.1	0.46	2200
39C	9-20-68	200	0.85	0.40	2160
39D	9-20-68	200	0.60	0.36	2150

Transient Spray, Effect of Spray Rate

Run	Date	Peak Power, kW	Spray Rate GPM	O.C.F.* GPM	Initial Temperature °F	Maximum Temperature °F
40	9-19-68	120	3.2	0	1315	1455
41A	9-19-68	120	2.1	0	1350	1460
41B	10-24-68	120	2.1	0.65	1355	1615
42	9-19-68	120	1.1	0	1355	1525
43	9-19-68	120	0.9	0	1355	1595
44	9-20-68	120	0.5	0	1275	1585
45	9-20-68	120	0.7	0	1315	1505
46	9-20-68	240	6.2	0-1.35	1345	1845
47A	9-20-68	240	4.35	0-1.0	1245	1915
47B	10-24-68	240	4.35	1.0	1165	1985
47C	10-29-68	240	4.35	1.0	1380	2230
47D	10-29-68	240	4.35	1.0	1380	2260
48A	***					
48B	10-24-68	240	2.1	0.64	1325	2286
48C	11-1-68	240	2.1	0.64	1380	2180
48D	11-1-68	240	2.1	0.64	1340	2170
48E	11-7-68	240	2.0	0.64	1285	2435
48F	11-11-68	240	2.0	0.4	1380	2440
49	9-23-68	240	1.1	0.4	1390	2190
50A	9-23-68	240	0.6	0-0.36	1345	2245
50B	9-23-68	240	0.6	0	1235	>2395****
50C	9-24-68	240	0.6	0	1320	>2380****
50D	9-30-68	240	0.6	0	1265	>2375****
50E	10-24-68	240	0.6	0.36	1235	2385
51	9-23-68	240	0.4	0	1200	>2400****
52	***					
53A	9-24-68	240	2.1	0	1300	2300
53B	10-1-68	240	2.1	0	1270	2360
54	9-30-68	240	2.1	0	1305	2305
55	9-30-68	240	1.1	0	1345	2345
56	9-30-68	240	1.1	0	1315	2405
57A	10-1-68	300	2.6	0	1310	>2410****
57B	10-10-68	300	2.6	0	1315	>2435****
57C	10-23-68	300	2.6	0.74	1450	2240
57D	10-24-68	300	2.6	0	1210	>2350****
57E	11-18-68	300	2.5	0.5	1045	2245
57F	11-22-68	300	2.5	0.34	1010	2200
57G	11-22-68	300	2.5	0.5	1030	2270
57H	11-22-68	300	2.5	0.5	810	2000
65	11-22-68	390	6.5	1.3	900	>2200****

* Outer Channel Flow

*** Test not conducted

**** Shutdown tests at test equipment limit

FIGURE 4. COMPARISON OF MOLYBDENUM AND NICHROME FILAMENTED HEATER BUNDLE TESTS

provide a positive feedback mechanism (increasing temperatures cause increasing local powers which further increase temperatures, etc.) limited only by increased radiation and convection from the heater surfaces. This mechanism (investigated in more detail in Section IV) is not representative of BWR fuel rods.

One test conducted on bundle SS-3 provided a limited amount of information on the radial power shifting which occurs when molybdenum heaters are used. As shown in Figure 6, power shifts to the outer rod (49) in the bundle which becomes relatively cool because of the increased amount of radiation heat transfer to the channel wall. The channel wall wets within one or two minutes after initiation of the spray.

These examples illustrate the two power shifts that occur in molybdenum-filamented bundles. These power shifts do not occur in Nichrome-filamented bundles or in actual fuel bundles. The overall effect of the power shifting on bundle temperature response was investigated using the TIGER V* heat transfer code. An overall bundle heat transfer coefficient was determined for a Nichrome bundle spray-cooling test. This coefficient was then applied to the actual initial conditions of a molybdenum bundle spray-cooling test. The local heater power variation with time, estimated from the above description of molybdenum power shifting experience was input to the code. Considering only the first eight minutes** of the transient,

the TIGER program predicted the actual maximum temperature response to within 100°F of the molybdenum test as shown in Figure 7. It can therefore be concluded that the molybdenum power shifting is a major factor contributing to the excessive temperatures in the molybdenum test bundles.

3.2 ZIRCALOY CLAD BUNDLE TEST

This section presents the results of a 49-rod full length emergency cooling spray test conducted with molybdenum-filamented, Zircaloy clad heater rods. The test was conducted on May 2, 1969 in the low pressure test facility at GE-APED in San Jose, California. The purpose of the test (termed a "Molybdenum-Zircaloy Performance Test") was to determine the effect of the molybdenum radial power shift and the performance of Zircaloy cladding under emergency cooling conditions. A decay power transient peaked at 198 kW was applied to the bundle from an initial maximum temperature of approximately 1790°F. The bundle attained a maximum temperature of approximately 2230°F two minutes after the initiation of spray cooling. A

* TIGER V is a multinode digital computer heat transfer code. Its use as an analytical tool to determine convective heat transfer coefficients is described in Reference 2.

** The film coefficient, h_{Nichrome} , was correct up to eight minutes into the transient.

FIGURE 5. VARIATION OF MAXIMUM AXIAL PEAKING FACTOR WITH MAXIMUM SURFACE TEMPERATURE FOR FOUR MOLYBDENUM FILAMENTED HEATER RODS INSTALLED IN BUNDLE SS 3

FIGURE 6. RADIAL POWER SHIFTING IN "INNER ROD" AND "OUTER ROD", BUNDLE SS-3

FIGURE 7. EFFECT OF MOLYBDENUM POWER SHIFTING ON BUNDLE MAXIMUM TEMPERATURE (MOLYBDENUM AND NICHROME RUNS FROM FIGURE 3)

radial power shift from the center to the outside of the bundle was noted during the transient. The bundle was in excellent condition after the transient was completed.

3.2.1 Test Bundle

The test bundle consisted of 49 molybdenum-filamented, aluminum oxide insulated, Zircaloy clad heater rods. A sketch of the heater rods used is shown in Figure 8. The heaters were designed for an axial peak of 1.37 at 1400°F (see Figures 2 and 3). The radial power distribution was adjusted before the start of the test to approximate the distribution in a reactor bundle at the beginning of life, that is, high peaked (> 1.00) rods on the outside of the 7 × 7 array and low peaked (< 1.00) rods on the inside of the array. The radial peaking and rod numbering system is shown in Figure 9.

The rods were instrumented with thermocouples consisting of single molybdenum wires welded to Zircaloy pads which in turn were welded to the inner surface of the cladding. The Zircaloy cladding provided the second leg of the thermocouple.

3.2.2 Data Acquisition

The bundle instrumentation plan is shown schematically in Figure 10. The following instrumentation was provided:

1. Dymec data acquisition system recording the following signals:
 - a. 72 rod inner clad temperatures (Figure 11, shows the thermocouple arrangement in the bundle).
 - b. 18 inner channel and 4 outer channel temperatures (see Figures 12 and 13).

SPECIFICATIONS

1. MOLYBDENUM HEATING ELEMENT
2. HIGH PURITY Al_2O_3 POWDER (99.5% Al_2O_3), APPROXIMATELY 70% DENSE
3. SINGLE WIRE MOLYBDENUM ZIRCALOY THERMOCOUPLE
4. 0.499 in. i.d. x 0.032 WALL ZIRCALOY-2 TUBE
5. MOLYBDENUM TERMINALS
6. FIBER RESIN SEAL
7. HEATER CAPACITY 7.850 WATTS AT 277 VOLTS A.C. WITH HEAT FLUX DISTRIBUTION AS SHOWN IN FIGURE 2

FIGURE 8. ZIRCALOY CLAD HEATER USED IN MOLYBDENUM ZIRCALOY PERFORMANCE TEST

FIGURE 9. MOLYBDENUM ZIRCALOY PERFORMANCE TEST RADIAL PEAKING

- c. Ten individual rod power signals from wattmeter transducers (rod numbers 1, 2, 3, 4, 9, 10, 11, 17, 18 and 25).
2. Two eight channel Sanborn recorders for continuous monitoring of selected rod temperatures (see Figure 11).
3. 49-rod current ammeters and five transformer terminal voltmeters were mounted in a panel which was photographed (Hasselblad model 500C, single lense reflex camera with 120 panotomic roll film) during the transient to provide individual rod power information.

3.2.3 Test Facility

The bundle was installed in the emergency cooling test facility described in detail in Reference 2 and shown schematically in Figure 14. The heater rods were individually supplied with power from a three-phase diesel generator through a series of transformers (Figure 15). Voltage taps for individual rods were selected to give the radial power distribution shown in Figure 9. The rods were "Y" connected to a grounded common at the top of the test bundle. Bundle and inner channel spray flows were introduced at the top of the facility. Return water flows were monitored at the bottom with rotometers.

3.2.4 Test Conditions and Test Procedure

The following test conditions were established:

1. Peak power: 198 kW (4.7% of 4.2 MW)
2. Bundle spray rate: 2.45 GPM
3. Outer channel spray rate: 0.49 GPM
4. Maximum cladding temperature at spray initiation: 1700°F (desired)
5. Inlet water subcooling: 80°F
6. Pressure: 15 psia

The test was conducted in the following manner (time referenced to zero minutes at the start of the transient):

1. Set spray flow rates.
2. Heated cooling water to 132°F.
3. Started steam generator and purged the bundle until a steady flow of steam issued from the vent.
4. Applied 50 kW and headed the bundle to approximately 550 - 600°F.
5. (-9 minutes) Applied 100 kW heatup power.
6. (-7.5 minutes) Stopped steam generator.
7. (-5 minutes) Applied 200 kW heatup power.
8. (-4 minutes) Turned power off to check overheated transformer connection (problem corrected) and to note thermocouple performance at zero power.
9. (-1 minute) Applied 200 kW heatup power.

FIGURE 10. MOLYBDENUM ZIRCALOY PERFORMANCE TEST BUNDLE INSTRUMENTATION

FIGURE 11. MOLYBDENUM ZIRCALOY PERFORMANCE TEST HEATER BUNDLE THERMOCOUPLE LOCATION PLAN

FIGURE 12. THERMOCOUPLE DISTRIBUTION ON INNER CHANNEL, MOLYBDENUM ZIRCALOY PERFORMANCE TEST

FIGURE 13. THERMOCOUPLE DISTRIBUTION ON OUTER CHANNEL, MOLYBDENUM ZIRCALOY PERFORMANCE TEST

FIGURE 14. EMERGENCY COOLING TEST FACILITY USED FOR MOLYBDENUM ZIRCALOY PERFORMANCE TEST

FIGURE 15. FORTY-NINE ROD POWER SUPPLY USED IN MOLYBDENUM ZIRCALOY PERFORMANCE TEST

10. (0 minutes) Started transient at an initial temperature of 1790°F on rod 4.
 - a. Started spray flows.
 - b. Increased power to 198 kW and followed decay power curve.
11. (+ 15 minutes) Turned power off to check thermocouple performance at zero power.
12. (+ 17 minutes) Returned to decay power curve.
13. (+ 30 minutes) Terminated transient by turning power off and stopping spray flows.

3.2.5 Test Results

3.2.5.1 Temperature Response

The performance of the single wire Molybdenum-Zircaloy cladding thermocouples was poor, (for example see Figure 16), probably due to electrical pickup at high power and temperature. The maximum bundle temperature at the start of the transient is estimated to be 1790°F on rod 4. (The rod numbering system is shown on Figure 9.) The maximum bundle temperature during the transient is estimated to be less than 2230°F (rod 4 at 2.2 minutes). The approximate initial temperatures, maximum temperatures and times of maximum temperature are given in Table 3 for the rods which had thermocouples which did not experience failures.

An example of the quality of temperature data obtained for most rods throughout the transient is shown on Figure 16 for rod 23. The signals from the thermocouples typically became very high with a high level of noise shortly after the start of the transient. A few minutes later the noise had decreased although several still had a large component of noise. Maximum rod temperatures were estimated by sketching an envelope which included most of the data points. An example of this estimation is shown in Figure 16. Post test bundle conditions lend some degree of credence to this procedure.

Figures 17 and 18 show the estimated maximum temperature for two thermocouples at the six foot elevation (center of heated length) of rods 16 and 40.

The transient response of four central rods in the bundle is shown in Figure 19. The rods heated up relatively slowly from initial temperatures of 1400 - 1600°F to maximum temperatures of 1800 - 2100°F in 6 to 9 minutes. Cooldown subsequent to maximum temperatures was also relatively slow, all four rods being above 1200°F 20 minutes after initiation of the spray cooling transient.

Figures 20 and 21 illustrate the effect of the cool outer channel on the temperature response of the outer rods in the bundle. These rods quickly (2.5-4 minutes for the rods shown) attained maximum temperatures and the

FIGURE 16. TEMPERATURE RESPONSE OF ROD 23 (6.0 ft LEVEL) TO MOLYBDENUM ZIRCALOY PERFORMANCE TEST SPRAY COOLING TRANSIENT

Table 3

**APPROXIMATE INITIAL AND MAXIMUM
TEMPERATURES, MOLYBDENUM ZIRCALOY
PERFORMANCE TEST SPRAY COOLING
TRANSIENT**

Rod	Approximate Initial Temperature, °F	Approximate Maximum Temperature, °F	Minutes After Start of Transient Rod Reached T _{max}
1	1400	1490	2.5
2	1350	1630	4.0
3	1450	—	—
4	1790	2230	2.2
8	1450	1680	3.0
11	1600	1630*	0.5
13	900*	1470*	2.2
16	1700	2090	8.5
17	1500	1820	8.5
18	1400	1790	6.0
19	1600	2120	9.0
22	1300	1500	1.7
23	1560	2000	7-11
24	1500	2050	9.0
33	1350*	1650*	—
41	1750	— *	—
48	1550	2160	4.2
49	1350	— *	—

* Questionable thermocouple performance.

six foot elevations cooled to saturation temperatures between 10 and 17 minutes after initiation of the transient.

Figure 21 shows the temperature response of rod 4 throughout the transient for several elevations. The sequential quenching to saturation indicates the advancement of a liquid film down the rod at an approximate velocity of 0.46 feet/second (see insert).

3.2.5.2 Radial Power Shifting

The radial power shifting which occurred throughout the spray cooling transient is shown in Figures 22, 23 and 24.

Outside rods (those nearest the channel but excluding corner rods) are shown in Figure 22. The radial peaking factors for four of these rods (15, 28, 35 and 45) remain relatively constant ($\pm 10\%$) throughout the transient. The general trend for the other outside rods is for the radial peaking factor to remain fairly constant for about 2 or 3 minutes, then increase to maximum values from 16 to 25 minutes after the start of the transient. The most severe increase occurred on rod 2 on which the radial peaking

increased from 1.18 at the start of the transient to 1.67 nineteen minutes later. The corner rods (Figure 24) show a similar trend.

The peaking histories of the inner group of rods (the rods between the nine central rods and the outside rods) is shown in Figure 23. The histories of the nine central rods are shown in Figure 24. The general trend is opposite to that noted in the outside rods. Central rod radial peaking decreased during the transient, reaching minimums about 14 to 20 minutes after the start of the transient. The most severe peaking change occurred on rod 17 which started at 1.00 and decreased to 0.66, 20 minutes later.

3.2.5.3 Axial Power Shift

An additional axial shift occurred during this test which had not been experienced in earlier testing. To preclude excessive Zircaloy-air reaction in the bundle cladding during the heatup to initial conditions, steam was admitted to the bottom of the test facility. With the bundle thus cooled at the lower end during the heatup, the maximum temperatures shifted to an elevation about two

FIGURE 17. ESTIMATED MAXIMUM TEMPERATURE OF ROD 16 (6.0 ft LEVEL) MOLYBDENUM ZIRCALOY PERFORMANCE TEST SPRAY COOLING TRANSIENT

FIGURE 18. ESTIMATED MAXIMUM TEMPERATURE OF ROD 48 (6.0 ft LEVEL) MOLYBDENUM ZIRCALOY PERFORMANCE TEST SPRAY COOLING TRANSIENT

FIGURE 19. ESTIMATED MAXIMUM TEMPERATURE OF FOUR CENTRAL RODS (6.0 ft LEVEL) MOLYBDENUM ZIRCALOY PERFORMANCE TEST SPRAY COOLING TRANSIENT

FIGURE 20. ESTIMATED MAXIMUM TEMPERATURE OF THREE OUTER RODS (6.0 ft LEVEL) MOLYBDENUM ZIRCALOY PERFORMANCE TEST SPRAY COOLING TRANSIENT

FIGURE 21. ESTIMATED MAXIMUM TEMPERATURE OF VARIOUS ELEVATIONS OF ROD 4 MOLYBDENUM ZIRCALOY PERFORMANCE TEST SPRAY COOLING TRANSIENT

feet above the center. Temperatures above the midplane during the transient were not available due to thermocouple failures but post test examination revealed maximum bundle damage (rod bowing) above the midplane. Inner and outer channel maximum temperatures were also above the midplane. These facts suggest that the maximum bundle power and therefore the maximum bundle temperature shifted above the center during this test. This effect is not typical of BWR bundles.

3.2.5.4 Effect of Emergency Cooling Transient on Bundle Condition

The bundle was examined after the transient and found to be in excellent condition (See Figure 25). No rod distortion occurred on the outer rods. Some rod distortion occurred in the central part of the bundle about one to two feet above the bundle center. Rods were displaced about one diameter as shown in Figure 26. The hottest rods in

this area experienced temperatures above 2000°F for one to two minutes and temperatures above 1800°F for 5 to 10 minutes.

Photomicrographs of rod 25 cladding at the 1.2 and 5.0 foot elevations are shown on Figure 27. Zircaloy oxide thicknesses of approximately 0.4 mils at 5 feet and 0.2 mils at 1.2 feet were noted.

3.2.6 Conclusion

The results of the spray cooling transient indicate that:

- 1) Molybdenum causes a radial power shift in test bundles which is not representative of BWR fuel bundle performance. Molybdenum is therefore not a suitable filament material for tests of BWR performance.
- 2) Zircaloy cladding material performance is excellent under emergency cooling conditions at temperatures up to 2200°F.

FIGURE 22. OUTSIDE RODS RADIAL POWER SHIFT, MOLYBDENUM ZIRCALOY PERFORMANCE TEST

FIGURE 23. INSIDE RODS RADIAL POWER SHIFT, MOLYBDENUM ZIRCALOY PERFORMANCE TEST

FIGURE 24. CORNER AND CENTRAL RODS RADIAL POWER SHIFT, MOLYBDENUM ZIRCALOY PERFORMANCE TEST

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TOP OF BUNDLE

BOTTOM OF BUNDLE

FIGURE 25. MOLYBDENUM ZIRCALLOY PERFORMANCE TEST BUNDLE AFTER TESTING

CENTER OF BUNDLE

2 ft ABOVE CENTER

2 ft ABOVE CENTER

MAXIMUM BUNDLE DISTORTION
(MORE RODS REMOVED)

FIGURE 26. MOLYBDENUM ZIRCALOY PERFORMANCE TEST BUNDLE DISTORTION

1.2 FOOT ELEVATION

5.0 FOOT ELEVATION

FIGURE 27. PHOTOMICROGRAPHS (X250) OF ROD 25 CLADDING AFTER MOLYBDENUM ZIRCALOY PERFORMANCE TEST.

4. ANALYTICAL INVESTIGATION OF THE EFFECT OF MOLYBDENUM ON HEATER POWER DISTRIBUTION AND HEATER MAXIMUM SURFACE TEMPERATURE

Experimental evidence of the effect of molybdenum on heater axial power distribution and heater surface temperatures has been presented in the previous section. A procedure for determining axial power distributions and an investigation of the sensitivity of maximum heater surface temperature to various heat transfer parameters is presented here. The axial power distribution is found to be a function of surface temperature distribution. The maximum surface temperature is shown to be very sensitive to heater properties, coolant temperature and the film heat transfer coefficient. Neither effect is representative of a BWR fuel rod.

4.1 AXIAL POWER DISTRIBUTION

With the small axial temperature gradients experienced in spray cooling transients, axial heat conduction can be neglected and the heater axial power distribution may be estimated from a knowledge of the approximate power distribution and measured heater temperatures.

Consider the case of steady state heat transfer from the six inch length of molybdenum-filamented heater shown in cross-section in Figure 28. The coil temperature is given by

$$T_c = T_{TC} + Q \left[\frac{\ln \left(\frac{D4}{D5} \right)}{2\pi kC} + \frac{\ln \left(\frac{D3}{D4} \right)}{2\pi k_1} \right]$$

Inserting the appropriate constants for a stainless steel clad, molybdenum-filamented heater,

$$T_c = T_{TC} + 0.048 Q \quad (1)$$

the sectional power Q can be estimated* from the rod power and the design radial and axial peaking factors.

A time share program was developed to accept the measured temperature profile and compute coil temperature and therefore coil resistance for each of twenty four six-inch rod sections. The coil resistance variation with length provides the axial power distribution.

4.2 HEATER MAXIMUM SURFACE TEMPERATURE

The effect of varying the following parameters:

l/a (coil section length/cross-sectioned area)

T_B (coolant temperature)

r_f (film thermal resistance)

and r_h (heater thermal resistance)

on the maximum heater surface temperature is considered here. Molybdenum-filamented heater temperatures are found to be much more sensitive to changes in these parameters than BWR fuel rod temperatures can be expected to be.

Neglecting axial conduction and combining radiative and convective heat transfer, the steady state heat transfer from a six-inch section at the center of a heater can be represented as shown in Figure 29.

The power generated in the six-inch section is a function of rod current, heater coil dimensions and resistivity:

$$Q = I^2 R$$

$$R = l\rho/a$$

Considering a linear resistivity dependence on temperature (which is an excellent assumption for molybdenum in the temperature range of interest, see Figure 1),

$$\rho = e + f T_c$$

The power generated is:

$$Q = 3.413 \cdot 10^{-6} I^2 \frac{l}{a} (e + f T_c) \frac{\text{Btu}}{\text{hr}} \quad (2)$$

The power generated in the heater coil is transferred through the heater and film resistances:

$$Q = \frac{T_c - T_s}{r_h} \quad \text{or} \quad T_c = r_h Q + T_s \quad (3)$$

and*

$$Q = \frac{T_s - T_B}{r_f} \quad \text{or} \quad T_s = r_f Q + T_B \quad (4)$$

Equations (1), (2) and (3) can be solved for the surface temperature,

$$T_s = \frac{C e r_f + T_B (1 - C f r_h)}{1 - C f (r_h + r_f)} \quad (5)$$

* Radiation thermal resistance has been lumped with convective resistance to give the film resistance, r_f . All heat transfer from the surface is driven by the temperature difference $(T_s - T_B)$ through the resistance, r_f . Radiation follows a fourth power law and has a different sink temperature (the boundary rods). The assumptions inherent in Equation 4 are considered satisfactory for the present purpose. The two heat transfer mechanisms can be separated but the solution of the resulting equation for T_s (Equation 8) is much more tedious.

* Although this estimate may be poor (perhaps 20% off), the error in T_c is small when $T_c \gg 0.048 Q$.

FIGURE 28. HEATER ROD DIMENSIONS AND CONDUCTIVITIES

FIGURE 29. MODEL USED TO STUDY HEAT TRANSFER FROM A HEATER SECTION

where the "power coefficient" C has been defined as $3.413 \times 10^{-6} I^2 (l/a)$.

If the variables in equation (5) are considered to change to new (primed) values and if the coil current reduction resulting from an increase in rod surface temperature to T_s' is represented as*

$$\frac{(I')^2 - I^2}{I^2} = - \frac{1}{12} \frac{T_s' - T_s}{T_s + e/f} \quad (6)$$

the new steady state temperature can be shown to be:

$$T_s' = \frac{mI^2 \left(1 - \frac{1}{12} \frac{T_s' - T_s}{T_s + e/f} \right) K' \text{erf}'_f + T'_B \left[1 - mI^2 \left(1 - \frac{1}{12} \frac{T_s' - T_s}{T_s + e/f} \right) K' f r_h \right]}{1 - mI^2 \left(1 - \frac{1}{12} \frac{T_s' - T_s}{T_s + e/f} \right) K' f (r_h' + r_f')} \quad (7)$$

where $m = 3.413 \times 10^{-6}$ and $(l/a)'$ has been replaced by K' .

This reduces to a quadratic in T_s' :

$$X T_s' + Y (T_s')^2 + Z = 0 \quad (8)$$

with

$$X = 1 - \frac{K' m I^2}{12} \left[f (r_h' + r_f') \left(12 + \frac{T_s}{T_s + e/f} \right) - \frac{\text{erf}'_f}{T_s + e/f} + \frac{T_B' f r_h'}{T_s + e/f} \right]$$

$$Y = \frac{K' m I^2 f (r_h' + r_f')}{12 (T_s + e/f)} \quad \text{and} \quad (9)$$

$$Z = T_B' \left[K' m I^2 f r_h' \left(1 + \frac{T_s}{12 (T_s + e/f)} \right) - 1 \right] - K' m I^2 \text{erf}'_f \left(1 + \frac{T_s}{12 (T_s + e/f)} \right)$$

* If total rod power is considered constant, an increase in center section coil temperature increases the rod resistance and therefore decreases the rod current. At the temperatures of interest, the center section resistance is approximately one

twelfth the rod resistance. If other section resistances are assumed unaffected. Equation (6) represents the resulting current decrease.

Equation (8) gives the new surface temperature after the variables have been changed to their primed values.

The terms in equation (5) are now required. Consider the hottest rod in a typical high power, high temperature run at the time of maximum surface temperature (rod 17 in run 57C at 9.5 minutes, see Figure 4). At this time $T_s = 2230^\circ\text{F}$ and bundle power is 2.6 percent of 5000 kW or 377 Btu/hr per average 6 inch section.

Estimating axial peaking at 1.67 (Figure 5, rod 17 at 2230°F) and radial peaking at 0.88 (Figure 6, rod 17 at 2230°F),

$$Q = (1.67)(0.88)(377) = 554 \text{ Btu/hr}$$

Assume $T_B = 212^\circ\text{F}$. Then from equation (4),

$$r_f = \frac{2230 - 212}{554} = 3.64 \frac{^\circ\text{F hr}}{\text{Btu}}$$

The heater thermal resistance has been previously determined (1),

$$r_h = 0.05 \frac{^\circ\text{F hr}}{\text{Btu}}$$

The resistance of molybdenum may be approximated by (Figure 1)

$$\rho = 0.866 + 0.00634 T_c,$$

which gives e and f .

From equation (3),

$$T_c = 0.05(554) + 2230 = 2258$$

From equation (2),

$$C = 3.413 \times 10^{-6} \frac{l^2 l}{a} = \frac{554}{0.866 + 0.00634(2258)} = 36.6$$

The heater cross section, a , is 0.000804 inch^2 and the coil length, l , in the six inch center section is 50 inches so that

$$I = 13.14 \text{ amps.}$$

All terms in equation (8) have been determined for this "base steady state condition." Returning to the unprimed values (i.e., no change),

$$X = 0.082$$

$$Y = 30.2 \times 10^{-6}$$

$$Z = -337$$

and $T_s = 2250^\circ\text{F} \approx 2230^\circ\text{F}$ (the original steady state surface temperature).

The sensitivity of surface temperature to the various parameters may now be considered. For example, let $K' = 1.05 K$. Recalculation gives

$$X = 0.036$$

$$Y = 31.71 \times 10^{-6}$$

$$Z = -343$$

and $T_s' = 2768^\circ\text{F}$ from equation (8)

so that the surface temperature would be 518°F higher because of a small (5%) error in loading the heater coil into the rod. It should be noted that the neglect of axial conduction and the combination of convective and radiative heat transfer at the rod surface become more suspect at such temperatures.

When the rods are filamented with Nichrome elements, the power generation is nearly independent of temperature and the temperature drop $T_s - T_B$ is directly proportional to power and to the film resistance.

$$T_s' - T_B \propto K' r_f'$$

A 5% error in loading then leads to $T_s' - 212 = 1.05 \times (2250 - 212)$ or $T_s' = 2354$, a 104°F increase in T_s .

Variation of the various parameters results in surface temperature increases as shown in Figure 30. The separate effects are discussed below.

A change in the term K or (l/a) represents an error in fabricating the resistance element to be used in the heater rod, that is, slightly more (or less) resistance is built into a particular heater section than is desired. The possible error in this resistance is on the order of 5%.

The cooling mechanism in effect at the time of maximum temperature is believed to be a combination of radiation to the surrounding cooler rods and natural convection to superheated steam which has been vaporized off the wetted channel surface. A change in the term r_f represents a change in this mechanism (a change in an adjacent rod temperature or in the amount of steam cooling available). A 5 to 10 (or even higher) percent change in this term seems quite reasonable to expect from test to test but the high sensitivity of surface temperature to film resistance is not to be expected in the reactor where power generation is independent of heat removal.

A change in the bulk coolant temperature T_B can be considered to reflect a change in the amount of heat absorbed by the rising steam before it reaches the section under consideration. Bundle exit temperatures as high as 260°F have been recorded in the FLECHT program (run 51) and as high as 425°F in flooding tests (Reference 4). A test to test bulk temperature variation between 260°F and 300°F (for example) at the axially hottest position (resulting in a 260°F to 420°F increase in surface temperature) does not seem unreasonable.

A change in the heater thermal resistance could be caused by a change in the oxide conductivity or the existence of an air gap between the oxide and cladding. The limited high temperature data available appear to indicate a nearly constant oxide conductivity with temperature above

FIGURE 30. SENSITIVITY OF MOLYBDENUM AND NICHROME - FILAMENTED HEATER MAXIMUM SURFACE TEMPERATURE TO CENTER SECTION RESISTANCE, COOLANT TEMPERATURE, FILM THERMAL RESISTANCE AND HEATER THERMAL RESISTANCE

1800°F. Although the gap resistance is not accurately known, (there are some indications that it is at least the same order as the oxide-clad resistance) it is not believed to change drastically from test to test or rod to rod in swaged

stainless steel clad heaters. The effect of expected heater thermal resistance variation on surface temperature is therefore probably small.

5. CONCLUSIONS

Molybdenum-filamented heater rods have been shown to be subject to two different types of spacial power shifting resulting from the high temperature coefficient of resistivity of molybdenum wire. During a spray cooling transient, power shifts axially* toward the center (hotter and therefore high resistance) sections of a rod and power shifts radially from the relatively hot (high resistance) inner rods to the relatively cool (low resistance) outer rods. The axial power shift concentrates the bundle power in the axial center of the bundle. High local power in this region causes higher temperatures which further contribute to increased local powers. The resultant positive feedback mechanism is finally limited by increased heat transfer from the hotter rod surface.

* Other investigators have noted this axial power shift. For example, see page 16 of reference 6.

The surface temperature of molybdenum-filamented heater rods has been shown to be much more sensitive to system heat transfer parameters (which may vary from test to test) and heater properties (which can not be accurately controlled) than would the surface temperature of rods filamented with constant resistance wire.

This power shifting and high sensitivity of surface temperature are not representative of the behavior of actual fuel bundles under emergency cooling conditions.

The use of molybdenum filaments results in maximum temperatures much higher than those obtained with Nichrome filaments or those expected with actual fuel bundles.

The molybdenum-filamented heater is therefore not a satisfactory test vehicle for demonstration of actual fuel bundle performance under loss-of-coolant/emergency cooling conditions.

6. ALTERNATIVES

Kanthal (5.5% Al, 22% Cr, 0.5% Co stainless steel alloy) is recommended as an alternate filament material for heat transfer effectiveness and reactor demonstration tests. Kanthal melts at 2750°F and is reported (Kanthal A-1, Ref. 5) to be operable continuously to 2505°F. The resistance of Kanthal increases by less than 2% from 1300°F to 2500°F. Kanthal-filamented heaters have been successfully tested to surface temperatures of 2200°F under spray cooling conditions.

The high temperature capability of molybdenum can be exploited in tests directed at the determination of Zircaloy cladding performance under high temperature emergency cooling conditions. Action is planned or under consideration to reduce the effects of radial* and axial** molybdenum power shifting but these effects can never be eliminated. Care must be taken to insure that the results of such "Zircaloy cladding performance tests" are not

interpreted as being representative of the performance of BWR fuel bundles under emergency cooling conditions.

The effectiveness of emergency cooling and the material behavior of Zircaloy cladding at temperatures above 2500°F (where the addition of energy from the Zircaloy-water reaction becomes significant) is particularly important. A high temperature heater which does not suffer the disadvantages of molybdenum power shift should be developed.

* A silicon controlled rectifier power supply which will control power to nine rod groups is presently being installed. Radial power shifting within rod groups can be anticipated and may prove significant.

** A heater power profile designed to be correct with a maximum surface temperature of 2400°F is being considered. Conceding the practicality of such a design, the power profile would be correct at only one point in time during a transient.

NOMENCLATURE

		Units
A	Heater heat transfer area in a 6-inch long heater section	ft ²
a	Heater filament cross sectional area	in. ²
C	Power coefficient defined in Section 4	
D1	Heater rod outer diameter (Figure 28)	in.
D2	Inner cladding outer diameter (Figure 28)	in.
D3	Diameter of "TC Circle" (Figure 28)	in.
D4	Cladding inner diameter (Figure 28)	in.
D5	Molybdenum coil outer diameter (Figure 28)	in.
e	Constants describing variation of	microhm-in.
f	Molybdenum resistance with temperature in Section 4	microhm-in. 1 °F
h	Heater surface heat transfer coefficient	Btu/hr ft ² °F
I	Heater current	amperes
k	Ceramic oxide thermal conductivity	Btu/hr in. °F
k ₁	Cladding thermal conductivity	Btu/hr in. °F
K	(1/a), a parameter proportional to rod section cold resistance	1/in.
l	Heater filament length in a 6 inch long section	in.
m	Constant defined in Section 4	
OCF	Outer channel flow	GPM
Q	Power generated in a 6-inch heater section	Btu/hr
R	Resistance of a 6-inch heater section	ohms
r _h	Heater thermal resistance	hr °F/Btu
r _f	Heater film (convection and radiation) thermal resistance	hr °F/Btu
T _B	Coolant temperature	°F
T _c	Heater coil temperature	°F
T _s	Heater surface temperature °F	°F
T _i	Maximum bundle cladding temperature at the beginning of a transient	°F
T _{TC}	Temperature recorded by thermocouple	°F
T _{max}	Maximum bundle temperature	°F
X	Coefficients defined by	
Y	equation (9)	
Z		
ρ	Molybdenum resistivity	microhm-inches

Superscript
prime

representing the value of a variable after a change from a base steady state condition

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DISTRIBUTION

R. W. Griebel 50
 Idaho Nuclear Corporation
 P. O. Box 1845
 Idaho Falls
 Idaho 83401

GEAP-10092 Typographical Errors

Page 5	Table 1	Run 24 date should be 8-7-68 instead of 9-7-68.
Page 16	Figure 16	Steam entering bottom of test bundle was deleted from figure.
Page 23	Figure 22	Label ordinate "Radial Peaking Factor".
Page 27	Figure 26	Center photo should have note "Several rods have been removed".
Page 29	First equation	Second denominator should be $2\pi k_1 C$ not $2\pi k_1$.