ANCR-1038

226
824

2243
UC - 80

EVALUATION OF FILAMENT-TYPE ELECTRIC HEATER RODS
AS EMPLOYED IN SINGLE-LOOP SEMISCALE
TO SIMULATE UO_2 FUEL RODS

D. Ewers and J. R. Larson

MASTER

Aerojet Nuclear Company

NATIONAL REACTOR TESTING STATION

Idaho Falls, Idaho — 83401

May-1972

PREPARED FOR THE

U. S. ATOMIC ENERGY COMMISSION

IDAHO OPERATIONS OFFICE UNDER CONTRACT AT(10-1)-1375

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

**EVALUATION OF FILAMENT-TYPE ELECTRIC HEATER RODS
AS EMPLOYED IN SINGLE-LOOP SEMISCALE TO
SIMULATE UO_2 FUEL RODS**

D. Ewers^[a] and J. R. Larson

Aerojet Nuclear Company
Nuclear Safety Program Division
Idaho Falls, Idaho

[a] Mr. Ewers was an exchange engineer during 1968 and 1969 from AED-TELEFUNKEN, Frankfurt, West Germany.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

AEROJET NUCLEAR COMPANY

Date Published - May 1972

PREPARED FOR THE U. S. ATOMIC ENERGY COMMISSION
IDAHO OPERATIONS OFFICE
UNDER CONTRACT NO. AT(10-1)-1375

ACKNOWLEDGMENTS

Appreciation is extended to H. D. Curet and L. J. Ybarrondo for their help in guiding the task to completion and to T. E. Curry and K. A. Dietz for their help and suggestions in preparation of the final copy.

ABSTRACT

This analysis compares the thermal response, during the blowdown phase of a loss-of-coolant accident, of the electrically heated filament-type heater rods used in the single-loop semiscale system with the thermal response of uranium dioxide fuel rods typically used in a light-water reactor. The analysis was conducted to determine how well the heater rod would simulate a UO_2 fuel rod, to optimize the method of power control to the heaters in the single-loop semiscale test series, and to guide future design of heater rods to be used in later test series. The analysis was accomplished using the HEAT-1 computer code.

The results of this analysis indicate that comparable surface temperatures and surface heat fluxes for the two types of rods are very difficult to obtain, primarily because of the greater amount of heat stored in the uranium dioxide fuel rod. Maintaining the initial steady state power generation rate during the transient appears to be the best method for simulating the UO_2 fuel rod thermal response in the early, transient portion of an LOCA.

SUMMARY

This report describes an analytical comparison of the thermal behavior of electrically heated filament-type heater rods used in the single-loop semiscale system with uranium dioxide (UO₂) fuel rods exposed to conditions expected during the blowdown phase of a postulated loss-of-coolant accident in a light-water reactor. These rods are used primarily to provide a temperature rise in the coolant rather than for obtaining heat transfer information. Filament- or sheath-type electrical heater rods are commonly used in experiments to investigate the thermal response of fuel rods to the postulated accident. The heater rods should yield a surface temperature and heat flux similar to that of the fuel rod in order for the experiment to provide definitive information that can be used to predict the thermal behavior of fuel rod cladding. This study was conducted to determine how well the heater rod would simulate a UO₂ fuel rod, to optimize the method of power control to the heater, and to guide future design of heater rods to be used in later test series.

The analysis was conducted using a computer code to solve the transient, one-dimensional heat conduction equation for models of the heater rod and fuel rod. Input data supplied for the code were: the decay power generation, the cladding surface heat transfer coefficient, and the coolant sink temperature.

The effects of achieving a critical heat flux at different times, heater rod cladding thickness, location of the heater filament, and control of power generation after blowdown initiation on the thermal response of the heater rod were investigated.

The energy stored in the UO₂ fuel rod at the time of initiation of blowdown is several times larger than in the heater rod considered. As a result, the temperature increase of the fuel rod cladding during blowdown is also much higher than in the heater rod if the power supplied to the heater rod is the same as generated in the fuel rod. Variation of parameters did not indicate an obvious way to obtain time-dependent cladding surface temperatures and surface heat fluxes in the heater rod similar to those in the UO₂ fuel rod.

The most promising technique for obtaining better comparative temperature and heat flux histories is to increase the heat generation rate in the heater rod at the time of accident initiation in order to duplicate more nearly the high heat flux in the nuclear fuel rod during blowdown. However, application of this technique is limited because of the melting temperature of the Nichrome filament.

The lack of exact comparison in the UO₂ and heater rod thermal response is not expected to cause significant differences in the hydraulic behavior of the experimental system during the transient.

SYMBOLS AND ABBREVIATIONS

δ (cm)	thickness of annuli
k (cal/sec-cm-°C)	conductivity
l (cm)	length
q''' (cal/sec-cm ³)	power generation per unit volume
R (cm)	radius
s (cm)	thickness
T (°C)	temperature
h (cal/sec-cm ² -°C)	conductance, heat transfer coefficient
ρC_p (cal/cm ³ -°C)	volumetric heat capacity
θ (sec)	time
i	inside
o	outside
CHF	critical heat flux
ρ (g/cm ³)	density
gap	gap between fuel and cladding

CONTENTS

ACKNOWLEDGMENT	ii
ABSTRACT	iii
SUMMARY	iv
SYMBOLS AND ABBREVIATIONS	v
I. INTRODUCTION	1
II. HEATER- AND FUEL-ROD MODELS	3
1. INPUT DATA	3
1.1 Geometry and Materials	3
1.2 Thermal Properties	7
1.3 Heat Generation	8
2. BOUNDARY CONDITIONS	10
2.1 Coolant Sink Temperature	10
2.2 Heat Transfer Coefficient	11
III. RESULTS	13
1. TYPICAL THERMAL TRANSIENT DURING BLOWDOWN	13
2. INFLUENCE OF CHF ON ROD TEMPERATURE	15
3. COMPARISON OF HEATER ROD AND UO ₂ FUEL ROD	17
4. INFLUENCE OF CLADDING THICKNESS OF HEATER ROD	20
5. INFLUENCE OF THE LOCATION OF HEATER ZONES IN HEATER ROD	23
6. INFLUENCE OF VARYING THE POWER GENERATION RATE TO THE HEATER ROD	26
IV. CONCLUSIONS	30
V. REFERENCES	31
APPENDIX A -- FILAMENT FOR THE HEATER ROD	33
APPENDIX B -- DATA FOR FUEL RODS OF LIGHT WATER POWER REACTORS	35
APPENDIX C -- STEADY STATE STUDIES	37

FIGURES

1.	Heater rod model	4
2.	UO ₂ fuel rod model	4
3.	Power (decay heat) during blowdown	9
4.	Coolant temperature during blowdown	10
5.	Heat transfer coefficient during blowdown	12
6.	Radial temperature profiles for heater rod during blowdown -- $\theta_{CHF} = 1$ sec	14
7.	Radial temperature profiles for UO ₂ fuel rod during blowdown -- $\theta_{CHF} = 1$ sec	15
8.	Temperatures of heater rod during blowdown	16
9.	Temperatures of UO ₂ fuel rod during blowdown	17
10.	Comparison of UO ₂ fuel rod and heater rod temperatures during blowdown -- $\theta_{CHF} = 1$ sec	18
11.	Comparison of heat transfer rates in UO ₂ fuel rod and heater rod -- $\theta_{CHF} = 1$ sec	19
12.	Temperature profiles in heater rod and modified heater rod	21
13.	Center-line and cladding-surface temperatures of heater rod and modified heater rod	22
14.	Steady state temperature profiles in the UO ₂ fuel rod and in the modified heater rod with various heater zones	23
15.	Temperatures during blowdown in UO ₂ fuel rod and heater rod with center heater zone	24
16.	Temperatures during blowdown in modified heater rod with various heater zones	25
17.	Power-time curves for heater rod	27
18.	Comparison of cladding surface temperatures in UO ₂ fuel rod and heater rod for various power-time curves during blowdown -- $\theta_{CHF} = 1$ sec	28
19.	Comparison of heat transfer rates in UO ₂ fuel rod and heater rod maintained at 100% power	29
C-1.	Steady state temperature profiles in heater rod	38

C-2. Steady state cladding-surface and center-line temperatures in heater rod as functions of the coefficient of heat transfer at the cladding surface	39
C-3. Steady state temperature profiles in heater rod with various gap conductances	40

TABLES

I. Heater Rod Model	5
II. UO_2 Rod Model	5
III. Modified Heater Rod Model	6
B-1. Typical Fuel Rod Data for Water Reactors	36

EVALUATION OF FILAMENT-TYPE ELECTRIC HEATER RODS AS EMPLOYED IN SINGLE-LOOP SEMISCALE TO SIMULATE UO₂ FUEL RODS

I. INTRODUCTION

Electrically heated rods are commonly used as the heat source simulating uranium dioxide (UO₂) fuel rods typical of those used in light-water reactor cores in experiments designed to provide data for development and evaluation of analytical models that describe the thermodynamic and hydraulic behavior of the reactor coolant and core and mechanical behavior of the structural system during blowdown in a postulated loss-of-coolant accident (LOCA). These experiments are conducted to gain definitive information on the coolant behavior in the primary system, and information on the rate of heat transfer from the heater rod bundle to the coolant.

Since the coolant behavior is affected by the heat source used to simulate the UO₂ fuel rod, the design and operation of the electrical heater rod should be such that the heater rod behaves similarly to the UO₂ fuel rod. The effect of the heater rods on the coolant will be the same as that of the UO₂ fuel rod if the cladding surface temperatures and surface heat fluxes are the same for both rods.

One project designed to investigate thermal-hydraulic phenomena during the LOCA is the Semiscale Blowdown and Emergency Core Cooling (ECC) Project^[1]. The first series of tests in this project was conducted in a single-loop system with a heater rod bundle consisting of 9-in.-long rods with a spiral-wound, electrical resistance filament of Nichrome wire, insulated from the Nickel-200 cladding by boron nitride. The rods used in the semiscale rod bundle were primarily used to maintain a temperature rise in the fluid flowing through the bundle rather than for obtaining heat transfer information. The parametric comparison described in this report was conducted to determine how well the single-loop semiscale heater rod would simulate a UO₂ fuel rod, to optimize the method of power control to the heater, and to guide future design of heater rods to be used in later test series.

The HEAT-1 code^[2] was used to analyze the characteristics of the heater and UO₂ fuel rods. This code provides the numerical solution of the one-dimensional, multiregion heat conduction equation for steady state and transient conditions. The code accepts temperature-dependent thermal properties, time-dependent boundary conditions, and time-and-space-dependent heat sources. The IBM-360/75 computer was used for this analysis.

The next section of this report describes the models of the filament and UO₂ rods and the boundary conditions imposed on the rods typical of an LOCA. The following section describes a typical transient result for a UO₂ fuel rod and compares the UO₂ result with that of a filament heater rod. The effects of critical heat flux, cladding thickness, heater zone location, and power generation control on the heater rod behavior are also presented.

The appendixes contain a description of the modeling procedure for the heater rod filament, typical fuel rod data for water reactors, and a steady state study of the effects of the power generation rate, the cladding surface heat transfer coefficient, and gap conductance on the heater rod radial temperature distribution.

The results indicate that the thermal behavior of the filament heater rod is different from the thermal behavior of the UO_2 fuel rod during the blowdown phase of an LOCA. Maintaining the steady state power generation rate of the heater rod during the transient seems to be the best method for simulating the UO_2 fuel rod.

II. HEATER- AND FUEL-ROD MODELS

The geometry and material property input data of the heater and fuel rods, and of the boundary conditions applied to the conduction equations to obtain solutions are described in the following subsections.

1. INPUT DATA

Input data supplied for the calculations were rod geometry and materials, thermal properties, and heat generation rate.

1.1 Geometry and Materials

In order to evaluate the behavior of the heater rods during blowdown, and especially to compare the heater rods with UO_2 fuel rods, three models were used: a model of the 9-in.-long semiscale heater rod, a model of the UO_2 fuel rod, and a modified model of the semiscale heater rod in which the radial location of the heater filament was varied.

The cross section of the heater rod is illustrated in Figure 1, and the dimensions and materials are given in Table I. The heater zone is a filament coil, the coil being simulated by an annulus as described in Appendix A.

The cross section of the UO_2 fuel rod is illustrated in Figure 2, and the dimensions and materials are given in Table II. The dimensions assumed for the model were representative of those of the typical PWR fuel rod dimensions given in Appendix B.

The dimensions for the modified rod are given in Table III. The modified heater rod model had the same cladding thickness as the UO_2 model and the same materials as the single-loop semiscale heater rod model. The decrease in cladding thickness was compensated for by increasing the insulator radius. In the modified model, the heater zone was nearer the rod center but the volume of the heater zone was maintained constant.

As required by the HEAT-1 code, the models were divided into finite radial increments or mesh spaces (cylindrical annuli with equal thickness, for one material). The calculations were performed at mesh points located at the interface of the radial increments and at the center and exterior surfaces of the model.

Fig. 1 Heater rod model.

Fig. 2 UO_2 fuel rod model.

TABLE I
HEATER ROD MODEL

<u>Region</u>	<u>Material</u>	<u>Number of Mesh Spaces</u>	<u>Thickness of Mesh Spaces, δ (cm)</u>	<u>Outside Radius of Region, R (cm)</u>
Insulator (center)	Boron Nitride	5	0.0380	0.1900
Heat Generation Zone	Nichrome	5	0.0043	0.2115
Insulator	Boron Nitride	10	0.0177	0.3885
Gap	Not Applicable	1	0.0050	0.3935
Cladding	Nickel 200	10	0.0165	0.5585

TABLE II
UO₂ ROD MODEL

<u>Region</u>	<u>Material</u>	<u>Number of Mesh Spaces</u>	<u>Thickness of Mesh Spaces, δ (cm)</u>	<u>Outside Radius of Region, R (cm)</u>
Heat Generation Zone	UO ₂	20	0.0238	0.4760
Gap	Not Applicable	1	0.0165	0.4925
Cladding	Zircaloy	10	0.0066	0.5585

TABLE III

MODIFIED HEATER ROD MODEL

		Modification Number				
		1	2	3	4	5
Number of Mesh Spaces	Insulator (center zone)	5	5	5	5	0
	Heat Generation Zone	5	5	5	5	5
	Insulator	10	10	10	10	15
	Gap	1	1	1	1	1
	Cladding	10	10	10	10	10
Thickness of Mesh Spaces, δ (cm)	Insulator (center zone)	0.0380	0.0290	0.0200	0.0110	0
	Heat Generation Zone	0.0043	0.0054	0.0073	0.0106	0.01856
	Insulator	0.0276	0.03155	0.0351	0.03795	0.0263
	Gap	0.0050	0.0050	0.0050	0.0050	0.0050
	Cladding	0.0066	0.0066	0.0066	0.0066	0.0066
Outside Radius of Region, R (cm)	Insulator (center zone)	0.1900	0.1450	0.1000	0.055	0
	Heat Generation Zone	0.2115	0.1720	0.1365	0.108	0.0928
	Insulator	0.4875	0.4875	0.4875	0.4875	0.4875
	Gap	0.4925	0.4925	0.4925	0.4925	0.4925
	Cladding	0.5585	0.5585	0.5585	0.5585	0.5585

1.2 Thermal Properties

The temperature-dependent thermal properties of the materials were taken into account in the calculations. In most cases simple curves were fit to data selected to represent the property value. Symbols and abbreviations are defined at the front of this report.

1.21 Thermal Conductivity, k (cal/sec-cm- $^{\circ}$ C)

Uranium Dioxide: The following formula was developed by curve-fitting published data^[3]:

$$k = 3.5 \times 10^{-9} T^2 - 1.135 \times 10^{-5} T + 0.01455.$$

Boron Nitride: The following values were selected from data supplied by the heater rod manufacturer

$$\text{for } T \leq 527^{\circ}\text{C} \quad k = 0.0448$$

$$\text{for } T > 527^{\circ}\text{C} \quad k = -2.99 \times 10^{-6} (T - 527) + 0.0448.$$

Nichrome: The following formula was developed from published data^[4]:

$$k = 0.435 \times 10^{-4} T + 0.031.$$

Zircaloy: The following formula was developed from published data for zircaloy-4^[3]:

$$k = 0.219 \times 10^{-4} T + 0.0333.$$

Nickel 200: The following formulas were developed from published data^[4]:

$$\text{for } T \leq 357^{\circ}\text{C} \quad k = -0.326 \times 10^{-3} (T - 357) + 0.105$$

$$\text{for } T > 357^{\circ}\text{C} \quad k = 0.108 \times 10^{-3} (T - 357) + 0.105.$$

Gap: The assumed conductance over the gap for the UO_2 model was $h_{\text{gap}} = 1.356 \times 10^{-3}$ cal/sec-cm 2 $^{\circ}$ C (1000 Btu/hr-ft 2 $^{\circ}$ F).

Since the conductivity of the gap is dependent on gap thickness:

$$k = h_{\text{gap}} \delta_{\text{gap}} \quad \text{or} \quad k = 0.223 \times 10^{-2}.$$

The assumed gap conductance for the heater rod models was:

$$h_{\text{gap}} = 6.781 \times 10^{-3} \text{ cal/sec-cm}^2 \text{ } ^{\circ}\text{C} \text{ (5000 Btu/hr-ft}^2 \text{ } ^{\circ}\text{F),}$$

or

$$k = 0.338 \times 10^{-2}.$$

The effect of the value of the gap conductance on the steady state temperature distribution is shown in Appendix C. The value of the gap conductance is

known to have an important effect on the heat transfer rate in a UO₂ rod during blowdown. The value is not fixed but changes during the transient. The value of the gap conductance assumed for the heater rod was considerably higher than that for the UO₂ rod because close physical contact between the cladding and the insulator was assured by the method of manufacture. Consideration of a change in gap conductance of the heater rod during the transient was beyond the scope of this work.

1.22 Volumetric Heat Capacity, ρC_p (cal/cm³-°C)

UO₂: The following formulas were developed from published data^[3], the assumed density being 10.4 g/cm³:

$$\text{for } T \leq 960^\circ\text{C} \quad \rho C_p = -0.215 \times 10^{-6} T^2 + 0.38 \times 10^{-3} T + 0.633$$

$$\text{for } T > 960^\circ\text{C} \quad \rho C_p = 0.183 \times 10^{-6} T^2 - 0.301 \times 10^{-3} T + 0.92.$$

Boron Nitride: The following formulas were developed from published data^[4], the assumed density being 1.9 g/cm³:

$$\text{for } T \leq 527^\circ\text{C} \quad \rho C_p = -1.0 \times 10^{-6} T^2 + 1.324 \times 10^{-3} T + 0.3195$$

$$\text{for } T > 527^\circ\text{C} \quad \rho C_p = -2.09 \times 10^{-7} T^2 + 0.592 \times 10^{-3} T + 0.486.$$

Nichrome: The following formula was taken from published data^[4]:

$$\rho C_p = 0.299 \times 10^{-3} T + 0.908.$$

Nickel 200: The following formulas were developed on the basis of published data^[4]:

$$\text{for } T \leq 357^\circ\text{C} \quad \rho C_p = 2.15 \times 10^{-3} (T - 357) + 1.53$$

$$\text{for } T > 357^\circ\text{C} \quad \rho C_p = 1.37 \times 10^{-3} (T - 357) + 1.015.$$

Gap: The gap was assumed to have no heat capacity.

1.3 Heat Generation

The maximum steady state design heat flux at the cladding surface of the 9-in. heater rod for the semiscale tests was 44.43 cal/sec-cm² (1200 W/in.²). This value was assumed for both the heater and nuclear rods. For the heater rod, this heat flux corresponds to a source term (q''') generated in the volume of the model simulating the filament of 5810 cal/sec-cm³ for the steady state (full-power) condition. In the UO₂ fuel rod, the corresponding source term was 220 cal/sec-cm³. These sources result in a power generation per length (about 20 kW/ft) that is somewhat higher than that presently used in typical Westinghouse Electric Corporation reactors (Appendix B). The effect of the power generation rate on the steady state profile of the heater rod is shown in Appendix C.

For calculation of the decreasing power transient during blowdown, the decay heat was normalized to the steady state power as shown in Figure 3^[5].

Fig. 3 Power (decay heat) during blowdown.

2. BOUNDARY CONDITIONS

The boundary condition imposed on the surface of the cladding is specified by a coolant sink temperature and a coefficient of heat transfer from the surface to the coolant. In the reactor or experimental situation these boundary conditions are determined by the fluid conditions in the core. These conditions are in turn complex functions of many variables including the heat transfer from the core to the fluid. Consideration of these variables or heat transfer feedback was not practicable; thus, the boundary conditions were fixed for comparison purposes. Any difference in the respective behavior between the heater rod and the UO_2 fuel rod is likely to be increased by differences in boundary conditions that are likely to exist for the two bundles of rods.

2.1 Coolant Sink Temperature

For initial conditions, a constant coolant temperature of 316°C (600°F) was assumed, which corresponds to the outlet temperature of a reactor core. The coolant temperature curve shown in Figure 4 was used during the transient. This curve was obtained from semiscale blowdown tests without a heater rod bundle and is assumed representative of the coolant temperature during blowdown.

Fig. 4 Coolant temperature during blowdown.

2.2 Heat Transfer Coefficient

During the initial steady state condition, a heat transfer coefficient of $2.71 \text{ cal/sec-cm}^2\text{.}^\circ\text{C}$ ($20,000 \text{ Btu/hr-ft}^2\text{.}^\circ\text{F}$), corresponding to nucleate boiling, was usually used. This value was applied until the critical heat flux (CHF) was attained. Other steady state values were also used to determine the effect of heat transfer coefficient on the steady state temperature distribution of the heater rod.

The time until critical heat flux (θ_{CHF}) parameter was varied during the transient; cases evaluated were: $\theta_{\text{CHF}} = 0, 1, 2, \text{ and } 5 \text{ sec}$.

The heat transfer coefficient following CHF is shown in Figure 5[5]. The curve is for the case of $\theta_{\text{CHF}} = 1 \text{ sec}$; the portion of the curve after CHF is reached is always the same in this analysis.

The boundary conditions described are based on a blowdown period of 12 sec, after which the analysis was terminated.

Fig. 5 Heat transfer coefficient during blowdown.

III. RESULTS

The following subsections describe typical calculated results obtained for the thermal response of the heater rod and fuel rod subjected to conditions occurring during a loss-of-coolant accident. The results were obtained for variation of the time to CHF, for variation of the location of the heater zone, for variation of the heater rod cladding thickness, and for variation of the heater rod power generation rate following initiation of the transient.

1. TYPICAL THERMAL TRANSIENT DURING BLOWDOWN

An example of radial temperature profiles in the simulated heater rod during blowdown is given in Figure 6, for which CHF was assumed to occur one second after the start of the transient. The assumed surface-to-coolant heat transfer coefficient was given in Figure 5; the assumed coolant sink temperature was shown in Figure 4; and the decay heat was shown in Figure 3.

An example of radial temperature profiles in the UO₂ fuel rod during blowdown is given in Figure 7. All boundary conditions and input data are standard values as stated in Section II. As can be seen, the cladding surface temperature rapidly increases during the first three seconds. Although the profiles shown are valuable primarily as a pictorial representation of the cooldown process they do show the large effect of the different materials on the energy storage in the rod and the rate at which the energy is removed.

Fig. 6 Radial temperature profiles for heater rod during blowdown -- $\theta_{CHF} = 1$ sec.

Fig. 7 Radial temperature profiles for UO_2 fuel rod during blowdown -- $\theta_{\text{CHF}} = 1$ sec.

2. INFLUENCE OF CHF ON ROD TEMPERATURE

The temperatures in the rod center and at the cladding surface are given in Figure 8 for the heater rod. The time to CHF was 0, 1, 2, and 5 sec. Before CHF is reached, the heat transfer coefficient is constant at $2.71 \text{ cal/sec-cm}^2\text{-}^\circ\text{C}$; other data are standard values as stated in Section II and with boundary conditions applied as for Figure 6.

Fig. 8 Temperatures of heater rod during blowdown.

Fig. 9 Temperatures of UO₂ fuel rod during blowdown.

3. COMPARISON OF HEATER ROD AND UO_2 FUEL ROD

During steady state, full power operation, the center-line temperature of the UO₂ fuel rod is about 2700°C (4900°F), which is much higher than the center-line temperature of the heater rod which is about 850°C (1560°F). Consequently, much more energy is stored in the UO₂ fuel rod than in the heater rod. Figure 10 compares the center-line and cladding-surface temperatures of the UO₂ fuel rod and of the heater rod as functions of time. The time to CHF is one second for the results shown. As can be seen, the cladding temperature increase in the UO₂ fuel rod is much higher than in the heater rod.

Fig. 10 Comparison of UO₂ fuel rod and heater rod temperatures during blowdown -- $\theta_{CHF} = 1$ sec.

The heat transfer rate at the cladding surface of the heater rod and of the UO₂ fuel rod is compared in Figure 11. for this same case. After CHF occurs the heat flux leaving the fuel rod is significantly higher than that of the heater rod.

Fig. 11 Comparison of heat transfer rates in UO₂ fuel rod and heater rod -- $\theta_{CHF} = 1$ sec.

4. INFLUENCE OF CLADDING THICKNESS OF HEATER ROD

The model of the heater rod was changed to reduce the thickness of the cladding to that of the UO₂ model. The materials remained the same and the heater zone was maintained at the same location by increasing the thickness of the insulation between the cladding and heater zone. Figure 12 shows the steady state temperature profiles for the two heater rods at a constant coolant temperature of 316°C.

Figure 13 shows the center-line and cladding-surface temperatures for the two heater rods during blowdown. The center-line temperature under steady state, full power conditions in the rod with decreased cladding thickness is about 60°C higher. The slightly higher temperature was not caused by the change in cladding but was caused by the increased insulator thickness.

Fig. 12 Temperature profiles in heater rod and modified heater rod.

Fig. 13 Center-line and cladding-surface temperatures of heater rod and modified heater rod.

5. INFLUENCE OF THE LOCATION OF HEATER ZONES IN HEATER ROD

In order to study the effect of the location of the heater zone, the zone was moved in toward the rod center; the heater zone volume was maintained constant.

Figure 14 shows the steady state temperature profiles of five cases as the heater zone (HZ) is moved toward the rod center. The figure also shows the profile of a UO_2 fuel rod under the same boundary conditions. The modified heater rod model has the same cladding thickness as the UO_2 model. In Case 5, the heater zone is located directly in the center, the center-line temperature for this case being about 600°C higher than for the original location of the heater zone (HZ1). Note should be taken of the fact that for this case the initial temperature is above the melting point of Nichrome (1400°C). In Case 4, the temperature is near the melting point, but the temperature profile of the outer region of the insulator is not affected. In comparison, the temperature profile of the UO_2 rod is still much higher.

Fig. 14 Steady state temperature profiles in the UO_2 fuel rod and in the modified heater rod with various heater zones.

Figure 15 shows the center-line and cladding-surface temperatures as functions of time during blowdown for the UO_2 model and Case 5 (heater zone directly in the center) of the modified heater model. For the modified heater rod model, the center-line temperature decreases very rapidly but the cladding temperature increase is still not very large.

The center-line and cladding temperatures for all heater zone cases are compared in Figure 16. The effect on the temperature of moving the heater zone toward the rod center is not very large.

Fig. 15 Temperatures during blowdown in UO_2 fuel rod and heater rod with center heater zone.

Fig. 16 Temperatures during blowdown in modified heater rod with various heater zones.

6. INFLUENCE OF VARYING THE POWER GENERATION RATE TO THE HEATER ROD

An attempt was made to simulate the large amount of energy stored in the UO₂ fuel rod by continuing electric power to the heater rod during blowdown. The power curves used are shown in Figure 17. The results are presented in Figure 18 which shows the various cladding temperature-time curves for four cases considered and described as follows:

Case 1 – the power-time curve shown in Figure 17 (Curve 1) was applied to the heater rod

Case 2 – the power-time curve shown in Figure 17 (Curve 2) was applied

Case 3 – the initial steady state power to the heater rod was maintained constant during the transient

Case 4 – the normal decay heat was applied to the heater rod.

Figure 19 shows the surface heat fluxes for the UO₂ rod and the heater rod for Case 3. In all cases the coolant temperature remained constant during blowdown at 316°C and θ_{CHF} was one second. The power to the heater rod was varied in an attempt to obtain the steep initial temperature increase in the heater rod that occurs in the UO₂ fuel rod.

As illustrated by Figure 18, the results for Case 3 show improved agreement with the UO₂ results, although the increase of cladding temperature after CHF is still steeper for the UO₂ rod. In the last few seconds of the blowdown, the temperature is higher for the heater rod than for the fuel rod.

The comparison of the surface heat flux for the 100% constant power case, Case 3, as shown in Figure 19, is also improved over that shown in Figure 11, although the flux is still about half the desired value after the occurrence of CHF.

The results of Case 2 and Case 3 with variable power input indicate that, early in the transient, the cladding temperature-time curve of the heater rod may possibly be made similar to that for the UO₂ fuel rod curve by increasing the power generation at the initiation of blowdown; however, after CHF, the power must be increased temporarily to over 200% of full power.

Fig. 17 Power-time curves for heater rod.

Fig. 18 Comparison of cladding surface temperatures in UO₂ fuel rod and heater rod for various power-time curves during blowdown -- $\theta_{CHF} = 1$ sec.

Fig. 19 Comparison of heat transfer rates in UO₂ fuel rod and heater rod maintained at 100% power. 100% power.

IV. CONCLUSIONS

The temperature and surface-heat-flux responses for the single-loop semiscale heater rod cladding during blowdown are different from the response for the UO_2 fuel rod cladding. The differences are caused by the thermal conductivity of the insulator compared with the conductivity of uranium dioxide, and by the larger amount of stored heat in the UO_2 rod. Use of an insulator material having a thermal conductivity and specific heat similar to those of UO_2 would improve the response of the heaters. The use of thinner cladding, or moving the heater zone into the heater rod center, slightly improves the cladding temperature similarity.

One apparent way to simulate the large amount of stored heat in the UO_2 rod is to use a higher power generation rate in the heater rod. The magnitude and time dependent distribution of the additional power is a function of the coolant temperature and heater rod surface heat transfer coefficient, and would vary with the assumed break location and size. To determine the proper magnitude and distribution would require feedback of the coolant conditions obtained during the experiment into the analysis to change the heat generation rate for the next test.

Since programming of the power to the heater rod above the initial power value would likely cause melting of the heating filament, the results of this analysis indicate that the power to a filament-type heater rod should be maintained constant at the steady state value until the blowdown is essentially complete. At this time the power could be reduced to a level equivalent to decay power.

Since the principal purpose of the semiscale heater rod bundle is to produce a temperature rise in the coolant, the lack of exact comparison between the thermal behavior of the UO_2 fuel rod and the thermal behavior of the heater rod is not expected to significantly affect the hydraulic behavior of the experimental system during blowdown. Thus, semiscale experiments are expected to provide useful information for the development and assessment of thermal-hydraulic analytical models.

V. REFERENCES

- (1) H. W. Heiselmann and J. O. Zane, *Semiscale Blowdown and Emergency Core Cooling (ECC) Project*, IN-1384 (July 1970).
- (2) R. J. Wagner, *HEAT-1, A One Dimensional Time Dependent or Steady State Heat Conduction Code for the IBM-650*, IDO-16867 (April 1963).
- (3) *Thermal and Hydraulic Experimentation Properties Manual*, Westinghouse Electric Corporation, PWR Plant Division (October 2, 1968).
- (4) Y. S. Touloukian, *Thermophysical Properties of High Temperature Solid Materials*, New York: The MacMillin Company (1967).
- (5) S. E. Jensen, *Parametric Studies of Fuel Pin Temperature Response*, IDO-17295 (February 1969).

APPENDIX A

FILAMENT FOR THE HEATER ROD

The dimensions of the semiscale heater coil were determined by comparing X-rays of the rod with the electrical design.

The main dimensions are:

length of rod	$L_R = 9$ in.
windings of coil	$n = 82$
center radius of coil	$R_H = 0.079$ in.
radius of the wire	$r_H = 0.017$ in.

The overall length of the wire is:

$$\ell = \sqrt{(n \cdot 2\pi R_H)^2 + L_R^2}$$

$$\ell = 41.4 \text{ in.}$$

The coil is simulated by an annulus that has the same volume and center radius as the coil; that is,

$$V_C = V_A$$

$$V_C = \ell \cdot \pi r_H^2$$

$$V_A = 2\pi R_H \cdot \ell \cdot s.$$

The thickness of the annuli is

$$S = \ell \cdot \pi r_H^2$$

$$S = 2\pi R_H \cdot \ell$$

$$S = 8.4 \text{ mils}$$

and the outside and inside radii of the heater zone are:

$$R_{Ho} = 0.0832 \text{ in. (0.2115 cm)}$$

$$R_{Hi} = 0.0748 \text{ in. (0.190 cm)}.$$

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX B

DATA FOR FUEL RODS OF LIGHT WATER POWER REACTORS

The data in the following table were taken from safety analysis reports of the four reactor manufacturers in the United States. The outside diameter of the heater rod analyzed in this report was identical with that of the Combustion Engineering, Inc. rod, and the maximum heat flux chosen was similar to the Westinghouse Electric Corporation value.

TABLE B-I

TYPICAL FUEL ROD DATA FOR WATER REACTORS

Item	BWR General Electric Company[a]	PWR Westinghouse Electric Corporation[b]	PWR Babcock & Wilcox Company[c]	PWR Combustion Engineering, Inc.[d]
Average heat flux (Btu/hr-ft ²)	16,450	207,000	167,620	162,000
Maximum heat flux (Btu/hr-ft ²)	427,820	583,000	543,000	501,000
Maximum thermal output (kW/ft)	18.3	19.0	17.5	17.4
Fuel rod outside diameter (in.)	0.562	0.422	0.420	0.440
Diametral gap (in.)	0.005	0.0065	0.006	0.0065
Cladding thickness (in.)	0.032	0.0243	0.026	0.026
Material	zircaloy-2	zircaloy-4	zircaloy-4	zircaloy-4
Fuel pellet outside diameter (in.)	0.488	0.3669	0.362	0.3815
UO ₂ density (%)	~94	94	95	---
Active length (in.)	144	144	144	137

[a] Cooper Nuclear Station, Nebraska Public Power District, Docket No. 50-298 (February 1971).

[b] Diablo Canyon Site, Pacific Gas and Electric Company, Docket No. 50-275 (January 1967).

[c] Oconee Nuclear Station, Duke Power Company, Docket No. 50-269, 270, 287 (June 1969).

[d] Hutchinson Island Plant, Florida Power and Light Company, Docket No. 50-335 (April 1969).

APPENDIX C

STEADY STATE STUDIES

Sensitivity studies were made at steady state conditions to determine the effect of power generation, cladding surface heat transfer coefficient, and gap conductance on the temperature distribution in the heater rod.

Figure C-1 shows the effect of power generation on the steady state temperature profile. Figure C-2 shows the effect of heat transfer coefficient on the cladding surface and center-line temperatures. Figure C-3 shows the effect of gap conductance on the temperature profile.

Fig. C-1 Steady state temperature profiles in heater rod.

Fig. C-2 Steady state cladding-surface and center-line temperatures in heater rod as functions of the coefficient of heat transfer at the cladding surface.

Fig. C-3 Steady state temperature profiles in heater rod with various gap conductances.