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DEVELOPMENT AND RESULTS OF AN ELECTRICALLY
HEATED SEVEN-PIN BUNDLE ASSEMBLY FOR THERMAL HYDRAULICS
TESTING IN LIQUID METALS

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ABSTRACT

This paper presents the development, design and results of an electrically heated seven-pin instrumented bundle assembly for LMFBR thermal hydraulic testing. The test assembly was capable of operating in liquid metals at typical temperatures (800°F) and nominal heat fluxes (500,000 Btu/hr-ft²) of LMFBR's and was typical of LMFBR geometry. Wire wraps were used as spacers.

Heat transfer data was taken over a tenfold range of Peclet number (50 to 500), and the results are presented as local coolant enthalpy rises, local coolant temperatures and local clad temperatures. Even though considerable forced diversion of the coolant by the wire wraps was evident, significant coolant and clad temperatures gradients did exist across pins of the outer row. A severe hot spot did not exist beneath a wire wrap.

INTRODUCTION

In the development of Liquid Metal Fast Reactor Breeder Reactors (LMFBR's), a variety of thermal hydraulic tests in liquid metals are required for design and safety evaluation. These tests will employ electrically heated models of LMFBR fuel assemblies. Actual size modeling of fuel pins and channel geometry will be required for many tests such as for experiments of void initiation and propagation.

The purpose of the tests described herein was to provide preliminary experimental information on fuel clad temperature variations and coolant mixing applicable to the FFTF fuel design.

The developments described herein have resulted in the first successful thermal hydraulic tests in liquid metals with bundle assemblies typical of LMFBR operating conditions and geometry. The specific test assemblies should be considered in the context that they were a major step in an overall program to develop a variety of bundle test assemblies for liquid metals.

The data obtained from these 7-pin assemblies is in general not directly applicable to large fuel bundles (217 pins) but must be considered in the context of an overall thermal hydraulic program⁽¹⁾ which includes data from larger test bundles.

TEST ASSEMBLY

This section summarizes the development and design of an electrically heated 7-pin instrumented bundle assembly for thermal hydraulic tests in sodium. Because of the overall goals of the program, this assembly was designed to function at typical actual operating conditions (500,000 Btu/hr-ft² heat flux in 800°F sodium) and is typical of the fuel design (.23 in. diameter pins, 39 in. long with .056 in. wire wrap spacers). Such a test section required considerable development. This development will be described in four subsections: the heated pins, bundle assembly, electrical heads, and instrumentation.

HEATED PINS

The reliability of pins of the size and capability required had not been established at the beginning of the development. Thus, the development of the basic heater pin was required. Due to experience and facilities at the Pacific Northwest Laboratory and schedule and funding requirements, the development concentrated on double ended electrical resistance metallic heaters.

The final heater pins used in these tests were procured to a specification⁽²⁾ that was especially developed for these heaters. The performance of the pin design was established by single pin tests in sodium at the required operating conditions. The heater pins each had one internal thermocouple.

Figure 1 is a sketch of the instrumented end of a typical heater pin. The pin consists of a center Nichrome V heating rod 1/8 in. in diameter and 42 in. long. This rod was surrounded by powdered boron nitride for electrical resistance and enclosed in a 316 stainless steel sheath of .016 in. wall thickness by 39 in. long. The entire pin assembly was swaged to a .230 in. diameter. To assure thermal uniformity, an extensive quality control program was followed which included nondestructive tests such as X-rays, neutron radiographs and thermal testing.⁽²⁾

BUNDLE ASSEMBLY

Figure 2 shows the overall assembly of the bundle. Two bundles of this basic design have been fabricated and successfully tested. The second bundle will be used for the description as it yielded the most information; any differences between this bundle and the first will be briefly noted. Figure 3 shows the pertinent dimensions and instrumentation details of the second bundle.

The heater pins were wrapped with a .056 in. wire in a clockwise direction with a 12 in. pitch and assembled together into a tight bundle. The resulting pitch-to-diameter ratio (P/D) was 1.25. Figure 4 is a photograph of the bundle of the first assembly. To maintain the pins in a bundle configuration, the pins were separately welded into end plates by an electron beam welding technique. To produce a full penetration weld between the pin and end plates, the electron beam was directed parallel to the pin axis. The sealing ability of this joint was verified by a helium leak test.

The flow housing for the bundle was a hex tube. This hex tube was attached to an expansion bellows to allow for thermal expansion between the pin sheaths and flow housing. In order to balance the weight of electrical heads and other inlet hardware, springs were attached to metal ears on the outside of the flow housing. Figure 5 is a photograph of the overall assembly of the second bundle. The springs are not shown in this photograph.

The second bundle was fabricated with a significance clearance (30 mil total) to determine the effect of manufacturing tolerance accumulation. Magnetic forces of attraction between pins during powered operation tended to maintain the bundle in a tight configuration. In order to maintain the bundle centered within the hex tube, centering pins were placed at each hex corner at the 1/3 and 2/3 axial locations as shown in Figures 3 and 5. The first bundle had a small clearance (10 mil) and did not incorporate these centering pins.

During heat transfer testing, the bundle was installed in a vertical orientation with upward flow. Referring to Figure 2, the flow entered the test assembly through an entrance nozzle, passed down the outside of the flow duct and then turned 180 degrees to enter the bundle. Due to the large length-to-equivalent diameter ratio ($L/D \approx 200$), the flow quickly distributed to a fully developed condition and passed through the bundle. The flow exited from the bundle by a similar path. The major instrumented plane was 4.4 in. from the outlet end of the pins.

The wire wraps contain two thermocouples each. The wire wraps including the thermocouple leads were brought through the outlet end plate by Swagelok[®] fittings.

ELECTRICAL HEADS

The electrical heads provided the electrical connection between the power leads and the heater rods. In addition, they had to provide the following:

- Allow for thermal growth of the heater rod.
- Provide cooling for the heat generated in the heater rod extension as well as within the head itself.
- Allow passage of the pin thermocouple leads.
- Provide a negligible electrical contact resistance between the head and heater rod.

These functions were successfully achieved by the segmented design shown in Figure 2. The sliding contact between the pin segments provided for the thermal expansion of the rod and yet allowed adequate electrical

and thermal contact. Cooling of the heads and heater rod extensions was accomplished by circulating Dowtherm® through drilled channels in the copper heads. This coolant entered and exited the heads through concentric tubes which also served as electrical connectors. The electrical head regions were purged with inert gas throughout testing to prevent oxidation of electrical connections and for safety considerations.

The pin thermocouple leads were electrically insulated in the head region by ceramic beads. In order to permit the thermocouple leads to pass through the electrical head, copper sleeves were placed around the heater rod extensions. These sleeves had holes through which the leads and ceramic beads could pass.

INSTRUMENTATION

The most important aspect of the heat transfer assembly was the temperature instrumentation. This instrumentation consisted of one internal thermocouple per pin, two thermocouples per wire wrap and thermocouples placed on the outside and through the hex tube. Of course, the sodium loop contained RTD's which measured the bulk inlet and outlet temperatures.

The pin instrumentation consisted of one thermocouple in each pin to measure the temperature of the inside surface of the sheath. This thermocouple consisted of one bare Alumel and one bare Chromel wire separately spot welded to the inside surface of the sheath 1/16 in. apart circumferentially. The axial location was 4.4 in. from the end of the sheath. The temperature thus measured was an "average" temperature of the closest Al-SS and Ch-SS junctions. The thermocouple leads were brought out through the boron nitride and through the electrical heads and attached to the circular micarta instrument plate shown in Figure 5.

The wire wrap thermocouples yielded local coolant temperatures and indicated film temperature drops without disturbing the flow. A wire wrap consisted of a 3/4 in. solid wire to which a 10 mil wall .056 in. diameter tube was attached for the instrumentation region. One eighth inch from the junction between the solid wire and tube, the two thermocouples were welded to the inside surface of the tube 180 degrees apart. The thermocouples consisted of 5 mil Alumel and Chromel wires that were

welded together prior to attachment to the tube wall. Powdered MgO was compacted in the tube to insulate the wires.

Thermocouples were placed on the outside surface of the hex tube to measure the local coolant temperature contiguous to the inside surface of the hex tube. The small temperature drop across the hex wall was taken into account by isothermal run calibrations. One 60 mil grounded sheathed thermocouple was inserted through the hex wall to measure the temperature at a location within an outer channel.

The placement of all this instrumentation is shown in Figure 3; the thermocouples are numbered for reference. The pin thermocouples (numbers 1 through 7) were placed in various positions to yield a gross indication of the clad temperature distribution around a pin of the outer row. In addition, comparison of pin thermocouples 3 and 4 permitted evaluation of the temperature beneath a wire wrap.

The axis between the wire wrap thermocouples was positioned parallel and perpendicular to pins to obtain the temperature differences across the wire wrap in these respective directions. In addition, the thermocouple 180 degrees from the pin was considered to measure the local coolant temperature at that point. The wire wrap thermocouples were numbered 8 through 21.

The hex tube thermocouples (numbers 22 through 36) were placed at various locations at the instrumented plane and at a plane one half of a wire wrap pitch upstream (6 inches).

The instrumentation of the first bundle assembly was similar except that the hex wall penetration thermocouple (#30) was not installed.

All thermocouple outputs were calibrated in place to a reference standard during isothermal runs prior and after the powered runs. After applying the resulting calibration, all thermocouples were within $\pm 2^\circ\text{F}$ of the standard during isothermal runs. The hex tube and wire wrap thermocouples at the 180 degrees position were considered to have measured

the local coolant temperatures without further connection. The wire wrap thermocouples readings at a 90 degrees position may have been slightly higher than the local coolant temperature because of a heat flux through the tube wall.

The pin thermocouples measured an "average" inside surface temperature of the sheath. When applying these readings to a reactor fuel pin, an uncertainty may be needed due to any temperature distortions caused by the presence of this thermocouple. This uncertainty is currently being established by an extensive thermocouple verification program. This uncertainty is considered small as evidenced by the excellent agreement between wire wrap thermocouple #9 and pin thermocouple #1, and wire wrap thermocouple #21 and pin thermocouple #7 when considering reasonable values of the heat transfer coefficient and wall temperature drop. Thus, the general conclusion reached from these tests are considered valid.

RESULTS

- The specific purpose of these tests was as follows:
 - To determine the enthalpy distribution within the bundle and the influence of bundle-to-duct spacing in this distribution.
 - To determine the severity of the hot spot beneath a wire wrap.
 - To determine gross clad temperature variations around a pin of the outer row.

The concern for the effect of bundle-to-duct spacing or clearance is a result of possible manufacturing tolerance accumulations at the wall in large bundles. Larger wall clearances cause more coolant to flow in these wall channels which cause them to run cooler. Thus, the temperature difference across the outer row of pins increases stresses within these pins and increases the tendency for pin bowing. To determine the influence of this wall clearance, two bundles have been

tested; the first bundle had a 10 mil total clearance (5 mils each side), and the second bundle had a 30 mil total clearance. Since the second bundle yielded more data, this paper will concentrate on these results.

As described earlier, the bundle was held within the center of the duct by two sets of spacers at the 1/3 and 2/3 positions of the 39 in. bundle. The resistance to flow of these spacers was much less than the resistance and disturbance caused by wire wraps so that they were considered to have had a negligible effect in the hydraulic or enthalpy distribution observed.

In order to assure that the pins remained in a tight configuration and the bundle centered in the duct, radiographs were taken during the data runs at test power (500,000 Btu/hr-ft² heat flux) and coolant temperature (800°F). These radiographs confirmed that the bundle remained tight and nominally centered in the duct. A slight snaking of the bundle occurred with the pitch of the wire wrap; in general, the pin-to-hex flat spacing was greatest wherever the wire wraps faced the duct wall.

The data was correlated with the Peclet number. The Peclet number (Pe) was taken as:

$$Pe = Re Pr = \frac{4w}{\bar{p}\mu} Pr$$

where w was the total flow rate (lbm/hr), $\bar{p}$ was the total wetted perimeter of the pins, wire wraps and flow housing, and μ was the viscosity at the bulk temperature of the instrumented plane. The Prandtl (Pr) was also evaluated at the bulk temperature of the instrumented plane. The flow rate w for power runs was determined from a heat balance as the heat balance was considered more accurate than the flow meter. The flow rate thus determined was considered accurate to $\pm 2\%$.

Enthalpy Variation

The most significant enthalpy rises were plotted versus Pe in Figures 6 and 7. The enthalpies were plotted in a dimensionless form

as the enthalpy rise to the i^{th} thermocouple from inlet conditions (ΔH_i) over the bulk enthalpy rise to the instrumented plane from inlet conditions (ΔH_{ave}). The wire wrap thermocouples and hex tube thermocouple readings were assumed to be the local coolant temperatures.

Figure 6 presents the enthalpy rises to the hottest wire wrap thermocouple (T/C #8) and the coldest hex tube thermocouple (T/C #22). Figure 7 presents the maximum coolant enthalpy difference (T/C #8-T/C #22) measured in the vicinity of a local pin. Figures 6 and 7 also show the corresponding enthalpy rises for a tight bundle (10 mil clearance). Figure 6 shows that the increased clearance caused the enthalpy rise of an outer channel to be reduced and of an inner channel to be increased. Such changes were anticipated as a greater bundle-to-duct clearance allows more coolant flow in the outer channels. Figure 7 indicates that the larger clearance increased the measured maximum coolant enthalpy difference across a pin by as much as 30 to 40%.

Since there existed a significant coolant temperature variation around a pin, the heat flux was not uniform but redistributed toward the cooler channels. The internal thermal properties of the heater pins were such that the internal temperatures of the heater pins were significantly less than the internal temperatures of fuel pins. Thus more heat flux redistribution occurred in the heater pins than will occur in fuel pins (uniform heat flux).

Conduction code calculations indicated that a 5% uncertainty should be considered in applying the enthalpy data of Figure 6 to uniform heat flux bundles--a +5% on the hottest channel and a -5% on the coldest channel. Since Figure 7 presents the difference of these enthalpies, a corresponding uncertainty should be considered when applying the data therein.

"Hot Spot" Beneath a Wire Wrap

Figure 8 indicates that the hot spot beneath a wire wrap was small. Pin thermocouples 3 and 4 face the same inner channel; T/C 4 was beneath a wire wrap and T/C 3 was not. Thus, the difference

between these thermocouple readings was considered a measure of the effect of wire wrap presence on local clad temperatures. Figure 8 presents the difference between T/C 3 and T/C 4 as a function of Pe . The magnitude of this hot spot was small (20 to 25°F). The actual peak may have been slightly higher than this due to the "average" temperature measured by the thermocouple.

Temperature Map

Figure 9 presents a typical temperature map at the major instrumented plane and 6 in. upstream. The temperatures in parentheses are the upstream temperatures. Figure 3 should be referred to for the thermocouple (T/C) numbering sequence. Important features of this map are summarized below:

- The temperatures of wire wrap thermocouples 10 and 12, which were adjacent to the clad of the pins were not high relative to clad temperatures or coolant temperatures in the vicinity of a pin. This further confirms the lack of a severe hot spot beneath a wire wrap.
- The 40°F (approximately) temperature drop across the wire wrap of Pins 2 and 3 was not an excessive film drop. This indicates that coolant flow and mixing around a wire wrap was sufficient to prevent a hot spot beneath a wire wrap. This is further indication of a lack of a severe hot spot beneath a wire wrap.
- The measured clad temperature variation around a pin in the outer row was significantly less than the maximum local coolant temperature variation. The instrumentation in this test was limited to one thermocouple per pin; thus a direct measurement of the temperature variation around a particular pin was not available. However, the thermocouples of the outer pins were in many different orientations. The difference between the maximum and minimum clad temperature of an outer pin at the instrumented plane in Figure 9 was only 76°F (T/C 6-T/C 7) while the maximum coolant variation in the vicinity of a pin was 132°F (T/C 8-T/C 22).

It should be recalled that since a pin thermocouple consisted of two bare wires welded separately (about 30 degrees apart) to the cladding, a pin thermocouple reading was an "average" of the temperature at the closest weld locations. Thus very local temperature peaks or dips may not have been recorded. In addition, a $+12^{\circ}\text{F}$ uncertainty due to heat flux redistribution should be applied to the 76°F variation when applying this data to uniform heat flux pin. It should be noted also that to estimate the maximum possible clad temperature variation around a pin the wire wrap must be considered at the "worst" position.

- The grounded leads of wire wrap T/C's 18 and 19 appear to have been improperly connected, and an average temperature of the entire wire was being measured. T/C's 14 and 15 functioned improperly due to inadvertent grounding of the leads.
- Because of the heat flux redistribution, a 5% uncertainty should be considered for all coolant temperature rises (from inlet) indicated in Figure 9 when applying this data to uniform heat flux bundles.

Wire Wrap Diversion

The effect that wire wraps have on coolant mixing within a bundle have never been adequately determined nor can they be fully deduced from the results of these tests. These tests indicate that the wire wraps cause a significant forced diversion of coolant between channels. This forced diversion or sweeping was evidenced by:

- The large temperature gradients observed within outer channels (the channels around Pin #2).
- The temperature difference that existed between outer channels as shown by the hex tube thermocouples.
- A significant reduction of the bulk temperature difference between inner and outer channels over that predicted without mixing.

To obtain a quantitative presentation of the later evidence, coolant temperature calculations were calibrated using the COBRA-II code⁽³⁾ for the case of a bare bundle (30 mil clearance total) with no coolant mixing. For the conditions shown in Figure 9, the calculations indicated a 170°F bulk temperature difference would exist between inner and outer channels at the instrumented plane without mixing. An inspection of the local coolant temperatures of Figure 9 indicates that about a 90°F bulk temperature difference actually existed. Thus considerable coolant mixing did occur in the wire wrapped bundle to reduce this bulk temperature difference by almost twofold.

The results of this testing suggest a forced diversion or sweeping mechanism for describing the mixing caused by the wire wraps; i.e., mixing caused by a transverse velocity component that is forced by the angle the wire wrap makes with the pin. This component may be particularly strong when the wire wrap is between pins.

CONCLUSIONS

In summary, it should be recalled that the data of these 7-pin tests are generally not directly applicable to reactor design. These tests form a very significant step toward that end and will be integrated with results of instrumentation verification tests and larger bundle tests to supply the results directly applicable to design and safety evaluation. However, some significant conclusions can be made which are applicable to fuel assemblies:

- Increasing the clearance between the bundle and flow duct increased the temperature difference across the outer row of pins.
- A severe hot spot did not exist beneath the wire wrap.
- Sufficient coolant mixing did occur to reduce the bulk temperature difference between inner and outer channel from that predicted without coolant mixing.
- The results indicated that the wire wraps cause a forced diversion of coolant between channels.
- The clad temperature variation around an outer pin was significantly less than the maximum local coolant temperature variation.

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INSTRUMENTED HEATER PIN DESIGN

FIGURE 1

QTY	UNIT	DESCRIPTION	DPN
1	ARRANGEMENT		
1	ASSEMBLY (PRESSURE TUBE)	REF 201	
1		(ELECTRODE CLAMP INLET) 1/4" x 1/2"	
1		(OUTLET) 1/4" x 1/2"	
1		7 PIN TEST ASSY	REF 201
1		6 NICKEL WARE 2 1/2" x 1/2" x 1/2" HOLE TO MATCH 1/4" x 1/2" HOLE 1/4" x 1/2" x 1/2"	
1		7 2 1/2" x 1/2" x 1/2" HOLE 7/8" DIA HOLES 1/4" x 1/2" x 1/2" HOLE TO MATCH PART 7 & 8 ON REF 201	
1		8 REDUCING LUG 1/4" x 1/2" x 1/2" HOLE TO MATCH PART 7 & 8 ON REF 201

GENERAL NOTES
UNLESS OTHERWISE SPECIFIED
ALL MATERIAL TO BE FREE OF WELD SPATTER AND CLEAN
FOR HELIUM LEAK TESTING BY CUSTOMER

FIGURE 2

DESIGNED BY: [] CHECKED BY: [] DATE: []		U S ATOMIC ENERGY COMMISSION RICHLAND OPERATIONS OFFICE PACIFIC NORTHWEST LABORATORY OPERATED BY BATTELLE MEMORIAL INSTITUTE	
TITLE: 7 PIN HEATED TEST SECTION ARRANGEMENT		SK-3-15082	
REFERENCE DRAWING NO: []		DRAWING NO: []	
NEXT USED ON: []		DATE: []

FIGURE 4

FIGURE 5

FIGURE 4

FIGURE 5

ENTHALPY VARIATIONS

FIGURE 6

MAXIMUM ENTHALPY DIFFERENCE ACROSS
A PIN

FIGURE 7

"HOT SPOT" BENEATH A WIRE WRAP

$$\text{Heat Flux} = 530,000 \text{ BTU/hr-ft}^2$$

FIGURE 8

RUN #32.2

$$q = 532,000 \text{ Btu/hr-ft}^2$$

$$Re = 95,300$$

$$Pe = 463$$

$$T_{\text{bulk}} = 788^\circ\text{F}$$

$$T_{\text{inlet}} = 596^\circ\text{F}$$

FIGURE 9

LOOKING DOWNSTREAM
(w/w Clockwise)