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EFFECT OF PARTIAL BLOCKAGES IN SIMULATED LMFBR FUEL ASSEMBLIES*

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CONTENTS

	<u>Page</u>
ABSTRACT	1
INTRODUCTION	1
BACKGROUND	2
Types of Blockages	2
Flow in the Wake Zone Behind Blockages	3
FLOW BLOCKAGE EXPERIMENTS IN THE FUEL FAILURE MOCKUP (FFM)	4
Description of the Facility	4
Effect of 13- and 24-Channel Inlet Blockage FFM Bundle 2B	4
Description of Rod Bundle 2	4
Summary of Results from Inlet Blockage Experiments	6
Comments on Inlet Blockage Experiment	11
Effect of Internal Blockage in FFM Bundle 3A	11
Description of Rod Bundle 3A	11
Summary of Results from Heated-Zone Blockage Experiments ..	13
Comments on Internal Blockage Experiments	16
ANALYSES OF BLOCKAGE EFFECTS	17
Analytical Representation of Flow Downstream from Planar Blockages	17
Temperature Distributions within Blockages	18
CONCLUSIONS	18
REFERENCES	20

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ABSTRACT

Experimental data on the effects of partial blockages in simulated LMFBR rod bundles are reviewed and the results presented. Experiments performed in the ORNL Fuel Failure Mockup (FFM) with 13- and 24-channel inlet blockages in 19-rod sodium-cooled electrically heated rod bundles indicate that excessive temperatures do not occur as a result of the blockages. Similar experiments with 6-channel non-heat-generating blockages in the heated zone of the rod bundle indicate local temperature increases of $\sim 170^{\circ}\text{F}$ at 100% flow and at powers of $\sim 10\text{ kW/ft}$. A simple representation of flow recirculation in the wake of the blockage indicates that a small recirculating flow significantly reduces temperatures in the wake zone. Calculations of temperatures within heat-generating blockages indicate that in order to obtain temperatures above the cladding limit more than one subchannel must be blocked over a length in excess of 0.5 in.

1. INTRODUCTION

Experimental data from the Oak Ridge National Laboratory (ORNL) Liquid-Metal Fast Breeder Reactor (LMFBR) Fuel Failure Mockup facility (FFM) were reviewed to evaluate possible effects of hypothetical partial blockages in Fast Flux Test Facility (FFTF) fuel subassemblies. The FFM is an engineering-scale sodium flow loop in which fuel rod assemblies are simulated with 19-rod bundles of electric cartridge heaters having heat flux and external configuration similar to FFTF fuel. Data were obtained with bundle inlet blockages of 13 and 24 channels and with heated-zone internal blockages of 6 channels.

Various analytical models were used to interpret the data. The ORRIBLE code¹ was used to compute the flow and temperature distributions in the rod bundles downstream of the recirculating wake zone. (ORRIBLE uses a simplified flow formulation and is computationally stable for cases where partial areas of the rod bundle are blocked, but it has no provisions for computing detailed flow distributions within the recirculating wake zone behind a blockage). Temperature distributions in the recirculating wake zone immediately behind the blockage were estimated using simple arbitrary representations of the wake flow with varying levels of recirculation velocity and blockage sizes. Temperatures within the blockage itself were calculated using HEATING,^{2,3} a three-dimensional heat conduction code. Heat conduction computations were made for heat-generating and non-heat-generating blockages with arbitrary shapes and boundary conditions.

This paper is a review of partial results obtained from a continuing program; more definitive conclusions may be drawn after completion of the program.

2. BACKGROUND

2.1 Types of Blockages

Partial blockage of rod bundles may be caused by foreign materials lodging at the inlet to the bundle. Blockages could be caused by single pieces of debris or by buildup of small particulate matter. (A plate about the size of a dime would be required to produce a blockage of about 13 channels). To place this discussion in perspective it should be noted that, since the Fermi accident, inlet flow paths to fuel assemblies have been designed to prevent complete blockage of a subassembly by a single piece of debris. Presently envisioned inlet configurations would not allow entry of foreign material larger than about 0.25 in diameter. The sizes of these entrance flow passages are not likely to be increased in the future because the pressure losses in that region are already small compared with the pressure losses in the fuel rod region.⁴

The smallest flow paths in the system are the fuel subchannels, and buildup of foreign matter in the entrance region of the fuel bundle could conceivably cause excessive blockage. The consequences of such a blockage would depend on whether it is concentrated locally or distributed over the entire frontal surface of the rod bundle. If several contiguous channels were blocked, the temperature of the fuel in the heated zone might be excessive. (Experimental data given later in this report indicate that inlet blockages of less than 24 contiguous subchannels are not likely to cause excessive temperatures in the FFTF fuel). However, properly designed fuel assembly inlets should cause evenly distributed flow to the upstream face of the fuel rods; if the debris follows the flow paths, its buildup would be evenly distributed. In this case flow would probably be reduced in all subchannels uniformly and gradually, possibly allowing the detection of low flow prior to excessive pin damage due to high temperatures, because a uniform reduction in flow would cause a detectable general increase in fuel assembly temperature rather than a hot spot.

Estimates made of the reduction of flow as a consequence of partial subassembly blockages³ show that it is necessary to block about 50% of the total flow area of a subassembly to cause a 5% reduction in flow. This is so because the increased pressure drop due to partial blockages is small compared with the pressure drop due to the rod bundle itself. Therefore, it is not likely that solid blockages covering a small fraction of flow area could be detected prior to fuel failure.

Blockage within the heated zone of the rod bundle could conceivably be caused by 1) lodging of debris within fuel channels; 2) broken wire-wrap spacers; 3) swelling of fuel pins due to defects, weak spots, overenriched pellets, or poor heat transfer (caused perhaps by gas release, debris hangup, or distorted pins and adjacent swelling); 4) fuel debris from failed pins; or 5) widespread pin swelling due to power-flow mismatch during a loss-of-flow incident. All the above items except item 5 are classed as potential accident initiators and are being investigated, particularly with respect to their potential for failure propagation. It should be noted that lodging of debris is not likely in fuel with spiral wire-wrap spacers. Fuel swelling would be minimized by proper oxygen control in the sodium. Also, irradiated cladding is expected to swell only slightly prior to failure due to internal pressure and high temperature, and therefore would not cause extensive blockage of the flow channels. Therefore, in some respects, these blockages are hypothetical because of the phenomena that make their existence in the core unlikely.

2.2 Flow in the Wake Zone Behind Blockages

Considerable information is available on flow separation caused by obstructions such as cylinders,⁶ disks,⁷ steps in a surface of a plate,⁸⁻¹⁰ and walls perpendicular to the flow path.¹¹⁻¹⁴ Investigations have also been made on extensive review of flow separation is given by Chang.¹⁵ Some attempts have been made to apply some of this information to the analysis of flow in rod bundles,^{16,17} and limited experimental work has been done with water.^{18,19}

If a blockage due to an obstruction is such that flow separation does occur, heat transfer in parts of the wake zone may be enhanced. This has been observed in water experiments in rod bundles for four-channel¹⁸ and for six- and for 24-channel planar blockages.¹⁹

Kirsch and Schleisiek²⁰ made the rather startling prediction that flow recirculation in the separated flow zone behind a blockage would safely remove the heat generated behind a blockage extending to more than 40% of the total full-scale SNR Na-2 reactor bundle flow area. They investigated this effect with sodium flowing in an obstructed annulus having one wall shaped to loosely simulate fuel rods. They also conducted experiments in rod bundles with water, using salt injected into the wake zone. They found that the length of the recirculation zone was relatively independent of velocity, as was the mass interchange between the fluid in the recirculation zone and the "free stream" fluid. In a more recent report²¹ Kirsch indicates that, based on water experiments, temperature increases for sodium cooled rod bundles in the SNR reactor were estimated for a blocked area/total flow area ratio of 0.147 and 0.411 for a central blockage and 0.411 for a blockage adjacent to the duct wall. For the 0.147 area ratio central blockage, sodium temperature in the recirculation zone of 232°C (418°F) higher than the coolant temperature immediately ahead of the blockage was predicted. For a central blockage of blocked/total flow area ratio of 0.411 (a blockage radius of ≈ 3.8 cm), the predicted temperature rise was 311°C (560°F). For an edge blockage of 0.411 area ratio, the temperature rise was 411°C (739°F).

Gast²² predicted that void growth and collapse would serve to remove the heat from the region behind a blockage of 55% of the bundle flow area (4.1 cm radius). He stated, "The analytical results lead to preliminary conclusions that, even at superheat as high as 150°C (270°F) individual vapor bubbles recondense within 35 msec, that the fuel cladding within the bubble is not overheated during this time, and that local boiling is unlikely to cause thermal-hydraulic instability in the affected fuel subassembly. Furthermore, it is shown that in case of considerable superheat, the rapid volume change of individual vapor bubbles causes variations of the coolant flow rate at the subassembly outlet, which may be detected by means of an electromagnetic flowmeter." The calculations were performed on the assumption that the fuel rods had no effect on the hydrodynamics. This analysis must be checked experimentally and, if substantiated, should essentially solve the problem of subassembly blockage (particularly if constituted of non-heat-generating material) with respect to gross heat removal from the blocked zone.

Steifel²³ performed experiments in two parallel channels, one of which was blocked. He found that pressure equalized rapidly downstream of the blockage, but differences in flow persisted. This observation might be of value in the development of detection techniques because the coolant in the channels having lower flow should leave the bundle at higher temperatures.

In practice, it is unlikely that a large blockage will occur that is completely impervious. A slight leakage through a blocked zone might significantly diminish temperature in the blocked region.²⁴ However, Basmer, Kirsch, and Schultheiss²⁵ show that slight leakage can destroy the recirculating flow patterns in the wake zone and possibly might hinder heat transfer in this region. The relative importance of these effects is not known at this time but will be investigated in the ORNL LMFBF-FFM program.

3. FLOW BLOCKAGE EXPERIMENTS IN THE FUEL FAILURE MOCKUP (FFM)

3.1 Description of the Facility

The FFM is a large-scale sodium flow facility at ORNL. It has a centrifugal pump with a flow capacity of 600 gpm, which is adequate for testing full-scale 217-rod subassemblies. However, at the present time the power controllers and the heat dump limit the power to 422 kW, which allows 24.5 kW per rod in a 19-rod bundle. Experiments are conducted with rod bundles in which fuel rods are simulated by electrical heaters having the same linear power density (up to 17.5 kW/ft) and external configuration as the FFTF fuel rods. The rods are 0.230 in. in diameter and are spaced by 0.056-in.-diam wires wrapped on a 12-in. pitch. Heater rods are described in reference 26.

The facility has provisions for subdivided control of the individual groups of heaters, so that many combinations of heaters can be operated at any power level up to 24.5 kW/ft each.

Temperatures throughout the rod bundle are measured (without causing flow perturbations) by thermocouples placed within the heater sheath and within the wire-wrap spacers. Descriptions of the instrumentation are given in later sections of this report. Detailed descriptions of the facility are given in refs. 27 and 28.

3.2 Effect of 13- and 24-Channel Inlet Blockage in FFM Bundle 2B

3.2.1 Description of Rod Bundle 2

FFM bundle 2 is a 19-rod bundle in a hexagonal duct. The dimensions and configuration of the rods and spacers are similar to those of the FFTF fuel subassembly except that the heated length is 21 in. rather than 36 in., and there is a 3-in. unheated length between the heated section and the free end of the bundle, rather than 6 in.

Originally, bundle 2 was not intended for inlet blockage investigations; it was designed for baseline thermal hydraulic investigations in unblocked condition. Most of the instrumentation was at the plane 18 in. above the start of the heated zone, which corresponds to the midplane of the FFTF core. The free end of the bundle was the downstream end, thus allowing the use of a thermocouple rake for measuring the exit sodium temperature profile. Results of these experiments are presented in refs. 29 and 30.

After the base line thermal-hydraulic test program was completed, the bundle was inverted in the test section so that the free ends of the heaters faced upstream, thereby allowing testing with inlet blockages. This orientation resulted in a 3-in. unheated entrance length followed by a 21-in. heated length. In this configuration, the heavily instrumented plane is 3 in. above the inlet to the heated zone (6 in. above the inlet face of the rod bundle). Thus most of the instrumentation was well into the heated section but reasonably close (6 in. or less) to the inlet blockage. The orientation of the bundle in the test section for the inlet blockage tests is shown in Fig. 1. The bundle in its original orientation was designated FFM bundle 2A, and the inverted orientation for inlet blockage tests, it was designated FFM bundle 2B.

The four types of temperature instrumentation in this bundle are described below:

1. Thirteen wire-wrap spacers each contain two ungrounded Chromel-Alumel thermocouples spaced 2 or 12 in. apart axially.
2. Six wire-wrap spacers each contain two grounded Chromel-Alumel thermocouples diametrically opposed in the wrap; in bundle 2B three pairs are at the 2-in. level, and three pairs are at the 3-in. level.

3. Alternate Chromel and Alumel bare wires (10 mils in diameter) are installed in the heater in the 0.039-in. clearance between the heating element and the sheath. These wires are separately joined to the sheath to form an intrinsic thermocouple junction on the inner surface of the heater sheath.
4. Chromel-Alumel thermocouples are installed at intervals along the bundle length to measure the inner wall temperatures of the hexagonal duct.

The locations of the heater internal thermocouples, the grounded wire-wrap thermocouples, and the 3-in.-level duct-wall thermocouples for FFM bundle 2B are shown in Fig. 2, along with the rod and channel numbering convention.

The large circles represent the heaters that simulate the fuel rods. These are identified by the central number. The small tangent circles indicate thermocouple junctions at the indicated azimuthal position of the wire-wrap spacers. The junctions are located at an axial level indicated by the numbers in the small circles, which have units of inches from the start of the heated zone. The small circles containing pairs of dots indicate the location of grounded-junction thermocouples. The pair of dots next to the heater surface indicates that a thermocouple junction in the wire wrap is adjacent to the heater, whereas the pairs of dots on the opposite side indicates that the other junction, at the same axial level, measures temperatures near the center of the flow subchannel. The flow subchannels, defined by the lines connecting the centers of the heaters, are identified by the numbers in the triangles so defined. The fuel-rod-simulator heaters have thermal elements attached to the inner surface of the cladding as indicated by the dots labeled A, B, C, etc., in the large circles.

3.2.2 Summary of Results from Inlet Blockage Experiments

Testing was conducted with (1) no inlet blockage, (2) 13 channels blocked (channels 1 to 6 and 13 to 19; see Fig. 2), and (3) 24 channels blocked (channels 1 to 24 - all but the peripheral channels). With the 24-channel inlet blockage plate installed, approximately half of the net flow cross-sectional area was covered.

During this series of tests the flow was varied from 10 gpm (~20% of full flow) to 55 gpm (~100% of full flow) with all 19 rods heated at a uniform heat rate of 2 to 8 kW/ft per rod. Over this flow range the total bundle pressure drop did not increase significantly above the unblocked value with the addition of either inlet blockage plate.

The thermal results of these tests are summarized in Table I and Fig. 3. For comparison, the use of the dimensionless temperature rise $(T - T_{in}) / (T_{out} - T_{in})$ is convenient, where T is the temperature measured by the thermocouple under consideration, T_{in} is the sodium inlet temperature (~600°F), and T_{out} is the bulk sodium outlet temperature. Results from the duct wall thermocouples are not considered in this discussion, since they yielded little information with respect to blockages except that, as flow is diverted to the outer channels by centrally located blockages, relative wall temperatures are slightly depressed.

In these presentations all axial measurements are given in inches downstream from the start of the heated section, which is 3 in. downstream from the inlet blockage.

The dimensionless temperature rises from the wire-wrap thermocouples and from the heater internal thermocouples are given in Tables I and II, respectively, for no blockage, 13-channel inlet blockage, and 24-channel inlet blockage for all 19 rods heated at 4, 5, and 6 kW/ft per rod and a constant flow of 55 gpm. In this range, the effect of power level on the dimensionless temperature rise is small.

The ratios of $[(T - T_{in}) / (T_{out} - T_{in})]$ (blocked) to $[(T - T_{in}) / (T_{out} - T_{in})]$ (unblocked) for a flow of 55 gpm with all 19 rods heated at 5 kW/ft per rod are given in Fig. 3 for the 24-channel inlet blockage. (Space limitation prevents the presentation of the results for the case of 13 channels blocked. The temperature rises due to it are considerably smaller). It may be seen from this figure that, in general, this ratio is greater than one for channels downstream

LMFBF-FFM BUNDLE NO. 2B INSTRUMENTATION

LOCATIONS OF THE GROUNDED
THERMOCOUPLES AND THE
DUCT THERMOCOUPLES

Rod No.	Axial plane (in.)	Channel No.	4 kW/ft ($T_{out} - T_{in} = 61^{\circ}\text{F}$)			5 kW/ft ($T_{out} - T_{in} = 76^{\circ}\text{F}$)			6 kW/ft ($T_{out} - T_{in} = 91^{\circ}\text{F}$)		
			No blockage	13-channel blockage	24-channel blockage	No blockage	13-channel blockage	24-channel blockage	No blockage	13-channel blockage	24-channel blockage
Ungrounded thermocouples											
15	1	38	0.12	0.11	0.10	0.12	0.11	0.11	0.12	0.12	0.10
8	2	8	0.20	0.20	0.21	0.21	0.20	0.22	0.21	0.20	0.22
14	2	36-37	0.19	0.19	0.19	0.19	0.19	0.17	0.19	0.18	0.18
9	3	10	0.34	0.35	0.39	0.35	0.35	0.37	0.35	0.35	0.37
13	3	35	0.30	0.35	0.34	0.31	0.36	0.33	0.31	0.35	0.32
14	4	35	0.27	0.28	0.24	0.28	0.28	0.22	0.28	0.27	0.23
18	4	23	0.40	0.38	0.37	0.40	0.38	0.38	0.40	0.38	0.38
11	5	32	0.26	0.29	0.27	0.26	0.29	0.26	0.26	0.28	0.26
13	5	34	0.24	0.25	0.24	0.24	0.26	0.24	0.25	0.25	0.24
18	6	13	0.46	0.48	0.49	0.46	0.49	0.48	0.46	0.48	0.50
19	7	8-26	0.65	0.64	0.59	0.65	0.66	0.61	0.66	0.66	0.61
4	12	3	0.79	0.78	0.90	0.74	0.78	0.88	0.74	0.77	0.88
5	12	19	0.80	0.79	0.74	0.80	0.79	0.75	0.80	0.78	0.77
10	12	11	0.83	0.85	0.95	0.84	0.86	0.95	0.84	0.86	0.94
12	12	15	0.48	0.53	0.49	0.48	0.53	0.48	0.48	0.52	0.45
16	12	39	0.53	0.53	0.45	0.53	0.52	0.44	0.53	0.52	0.45
15	13	38	0.60	0.56	0.46	0.60	0.56	0.47	0.60	0.56	0.48
8	14	8	1.06	1.04	1.25	1.08	1.07	1.26	1.08	1.09	1.25
9	15	11	1.07	1.10	1.18	1.09	1.11	1.19	1.10	1.10	1.17
11	17	32	0.77	0.77	0.75	0.75	0.80	0.73	0.75	0.78	0.72
Grounded thermocouples											
1	3	4	0.27	0.36	0.46	0.28	0.35	0.45	0.28	0.35	0.45
2	3	1	0.43	0.38	0.56	0.43	0.38	0.57	0.43	0.39	0.57
2	3	6	0.36	0.22	0.43	0.37	0.22	0.42	0.37	0.23	0.42
3	3	2	0.34	0.32	0.50	0.35	0.33	0.51	0.34	0.34	0.51
3	3	13	0.26	0.25	0.34	0.28	0.26	0.34	0.25	0.26	0.33
6	2	(Rod 6)	0.22	0.23	0.24	0.23	0.23	0.22	0.22	0.23	0.23
6	2	20	0.10	0.11	0.11	0.10	0.11	0.11	0.10	0.10	0.11
7	2	(Rod 7)	0.12	0.10	0.20	0.14	0.10	0.22	0.16	0.13	0.20
7	2	22	0.08	0.07	0.14	0.09	0.08	0.17	0.10	0.09	0.16
17	2	(Rod 17)	0.23	0.23	0.19	0.24	0.23	0.20	0.25	0.23	0.20
17	2	40	0.16	0.15	0.11	0.17	0.15	0.13	0.17	0.15	0.14

Rod No.	Axial plane (in.)	Location ^a	4 kW/ft ($T_{out} - T_{in} = 61^{\circ}\text{F}$)			5 kW/ft ($T_{out} - T_{in} = 76^{\circ}\text{F}$)			6 kW/ft ($T_{out} - T_{in} = 91^{\circ}\text{F}$)		
			No blockage	13-channel blockage	24-channel blockage	No blockage	13-channel blockage	24-channel blockage	No blockage	13-channel blockage	24-channel blockage
1	3	AB	1.03	1.01	1.14	1.05	1.01	1.16	1.04	1.03	
1	3	BC	1.13	1.14	1.23	1.14	1.13	1.23	1.13	1.15	1.19
1	3	CD	1.26	1.27	1.37	1.28	1.27	1.37	1.27	1.28	1.31
1	3	DE	1.13	1.14		1.15	1.14		1.15	1.15	
2	3	BC	1.08	1.06		1.09	1.06		1.07	1.09	
2	3	CD	1.07	1.05	1.17	1.07	1.05	1.17	1.06	1.06	1.14
2	3	DE	1.03	0.99	1.10	1.03	1.00	1.10	1.02	1.01	1.08
4	3	AB	1.05	0.99	1.08	1.02	0.99	1.08	1.01	1.00	1.09
4	3	BC	1.05	0.99	1.09	1.02	0.99	1.10	1.02	1.01	1.10
4	3	CD	1.07	1.01	1.14	1.04	1.02	1.15	1.04	1.03	1.15
5	3	AB	1.47	1.50	1.59	1.42	1.50	1.58	1.42	1.50	1.57
5	3	BC	1.14	1.18	<i>b</i>	1.11	1.19	<i>b</i>	1.11	1.20	<i>b</i>
5	3	CD	1.02	1.06	<i>b</i>	1.01	1.08	<i>b</i>	1.02	1.10	<i>b</i>
5	3	DE	1.06	1.03 ^c	<i>b</i>	1.07	1.11	1.15	1.11	1.15	1.16
6	2	AB	1.12	1.14		1.13	1.13		1.11	1.14	
7	2	AB	0.83	0.86	0.95	0.83	0.83	0.93	0.82	0.82	0.92
9	3	BC	1.15	1.12	1.22	1.15	1.11	1.21	1.15	1.12	1.18
10	3	AB	1.65	1.55 ^c	1.55 ^c	1.68	1.68	1.68	1.68	1.70	1.67
11	3	AB	<i>b</i>	1.00	1.06	1.02	1.00	1.07	1.01	1.00	1.06
6	2	AB	1.07 ^c	0.97	0.88 ^c	0.96	0.95	0.94	0.97	0.96	0.95
18	3	BC	1.46	1.38		1.46	1.41		1.45	1.41	

^aSee Fig. 4 for identification.

^bDeleted, standard deviation ≥ 10 .

^cSuspected of being in error.

Fig. 2. Ratio of dimensionless temperature rises above inlet vs axial position for FFM bundle 2B with blockage of 24 channels (1-24) at the inlet. 55 gpm flow, ~600°F inlet temperature. Averages of blockage runs 738-742 and 747 compared with averages of unblocked runs 700-702.

of the inlet blockage and, due to the increased bypass flow, is less than one for the unblocked channels (channels 24 to 42 for the 24-channel inlet blockage). It may be seen that the effect of blockage, as indicated by substantial departures of the ratio from unity, is limited to about 3 in. downstream of the start of the heated section (6 in. from the inlet blockage plate) or about five to six equivalent blockage diameters downstream. No excessively high temperatures were observed. The highest temperature ratio occurred for a 24-channel blockage (55 gpm flow) in channel 22 at an axial position 2 in. downstream from the start of the heated section (5 in. from the inlet blockage). The ratio at that location was ~1.8, indicating an 80% increase in the temperature rise over that of the unblocked case. Since the temperature rise for the unblocked case at that position was ~7°F and the temperature rise in the blocked case was ~13°F, the blockage caused an increase of only ~6°F. The higher dimensionless temperature ratios shown on Fig. 3 for the thermocouples at the start of the heated zone indicate that some flow recirculation behind the blockage was extending to the heated zone. The small amount of backward flow from the heated zone to the position of these thermocouples would heat them greater than would be expected if the flow were not recirculating.

3.2.3 Comments on Inlet Blockage Experiment

It is concluded that centrally located inlet blockages of up to one half of the flow area of 19-rod bundle with a 3-in. unheated entrance length do not result in excessively high temperatures. The temperature increases attributed to the inlet blockages are of the same order as the temperature variations normally observed in unblocked bundles.

Since the unheated entrance length of the fuel pins in an FFTF 217-pin subassembly is 6 in., twice that of the heaters used in the tests reported here, the flow maldistribution caused by the inlet blockage should be further ameliorated prior to reaching the heated zone of the reactor. Therefore, one would expect lower temperature increases in the FFTF subassembly than are indicated by these results. However, there are two other differences between the 19-rod experiment and the FFTF whose effects are difficult to extrapolate to the FFTF configuration. In these experiments the fractions of the frontal flow area covered by the inlet blockage plates were quite large; for example the 24-channel inlet blockage covered 50% of the total flow area. Because of this the fluid velocities around the blockage plate were higher than nominal, and these higher velocities may have aided in correcting the flow maldistributions caused by the blockages. Also, the proximity of the duct wall to the blockage may have had some influence in diverting the flow inward behind the blockages as compared with the relative remoteness of the wall in an FFTF subassembly. These two effects (which probably interact) would cause these tests to underpredict local temperature rises caused by similarly sized inlet blockages in larger bundles. However, it is doubtful that these effects will be sufficient to offset the mitigating effect of the longer unheated entrance length of the full-size fuel assembly. On the basis of the small temperature increases observed in these tests, it is concluded that inlet blockages of as many as 24 contiguous subchannels will not result in excessively high temperatures in the FFTF 217-pin subassembly.

3.3 Effect of Internal Blockage in FFM Bundle 3A

3.3.1 Description of Rod Bundle 3A

Bundle 3A of the FFM program was also of FFTF configuration. Like bundle 2B, bundle 3A had 19 rods of 21 in. heated length. However, instead of a hexagonal duct the duct in bundle 3A was round, with dummy rods having wire wrap spacers inserted in the duct wall to simulate an infinite array. Its central six channels were blocked by a non-heat-generating stainless steel device, 1/4 in. long, brazed to the central rod at the elevation 15 in from the start of the heated zone.

In this series of experiments the bundle was inserted from the bottom of the test section with the free ends of the heaters facing upward. This allowed the use of a thermocouple rake, entering from the opposite end of the test section, for monitoring exit temperatures from selected flow channels.

The bundle instrumentation layout is shown in Fig. 4. The convention for identifying thermocouples, heaters, and subchannels is similar to that of bundle 2B, described previously, except that the positions of the exit rake thermocouples are indicated by circles with crosses in them.

In bundle 3A, the ends of these thermal elements internal to the heaters were grounded to the inner surface of the cladding at 15° azimuthal intervals and at 0.25 in. axial intervals; thus the junction formed by two thermal elements measured an average temperature along the spiral path on the inner surface of cladding between the two junctions. Notice that the thermal elements in heaters 1, 2, and 3 measure temperatures from 15 to 16 in. (from the start of the heated zone) in 1/4-in. increments; those in heater 6 measure from 15.22 to 16.22 in.; and those in heaters 4, 5, and 7 measure from 16 to 17 in.

INCHES FROM
BEGINNING
OF HEATED
ZONE
(360° = 12 in.)

WIRE WRAP POSITION
(UNGROUNDED JCT)

WIRE WRAP POSITION
(GROUNDED JCT)

BUNDLE INTERNAL
BLOCKAGE PLATE
(15-in. LEVEL)

INTERNAL
THERMAL
ELEMENT

FLOW
DIRECTION
UP OUT OF
PAPER

THERMOCOUPLES AT
BUNDLE OUTLET

3.3.2 Summary of Results from Heated-Zone Blockage Experiments

Five sets of experiments have been performed with bundle 3A. These included cases with no power; all rods heated at powers of 5, 7.5, and 10 kW/ft with flows of 54 gpm (100% of full flow) and 11 gpm (20% of full flow); central seven rods heated at 10 kW/ft with a flow of 54 gpm; and three outer rods heated at each "flat" of the hexagon defined by the outer row of rods at a flow of 54 gpm. These latter tests are described in ref. 31. Because of space limitations, this discussion is restricted to the experiments performed at 100% flow and 10 kW/ft. The results are described more fully in references 19 and 32.

Figure 5 shows the central subchannel temperatures, presented as $T - T_{inlet}$, vs distance from the start of the heated zone for run 101 (10 kW/ft, 100% flow). This run is of particular interest because it represents the case of 100% of FFTF specific flow (54 gpm for 19 rods) and a power of 10 kW/ft, which is significantly above the average FFTF linear power density. In these experiments, temperatures were measured by thermocouples inside the central seven heaters and by the wire-wrap thermocouples in the central six subchannels.

The temperatures measured by the thermocouples inside the heaters are shown in Fig. 5 as horizontal lines extending the axial distance between the two thermal elements that make up the particular thermocouple being plotted. This distance is usually 1/4 in., and the indicated temperature may be considered as an average along that length. The number near each line indicates the rod within which that particular thermocouple resides. The outer cladding surface temperature was computed by subtracting a temperature drop across the cladding as calculated for the given heat flux assuming radial heat flux (the latter assumption should be valid everywhere except directly underneath the blockage device). These computed outer cladding surface temperatures are indicated in the figures by the subscript c.

Temperatures measured by thermocouples in the wire-wrap spacers are plotted and labeled so that the first two digits indicate the heater to which the wire-wrap spacer is attached, the second two digits indicate the axial distance of the thermocouple junction downstream from the start of the heated zone, and the last digit indicates the channel in which the spacer resides at that particular axial elevation. For example 04 13 CH 3 indicates that the thermocouple junction is in heater 4, 13 in. from start of heated zone, facing channel 3. Grounded-junction thermocouples in the wire-wrap spacers indicate two temperatures at the same elevation, one near the heater surface and the other near the center of the flow subchannel. These are also plotted.

The 90% (2 σ) confidence limit bands (based on repeated measurements) are not shown because of their small and relatively constant values. Except for internal thermocouples 0115AB, which had a standard deviation, σ , of 3.1°F for the worst case, and 0115DE, for which σ was 3.7°F, all other internal thermocouples had standard deviations of about 0.3 to 1°F. Those of the wire-wrap thermocouples were about 0.5°F.

The abscissa in Fig. 5 starts at 13 in. from the start of the heated zone because all information of interest is downstream of this point. The blockage plate is shown at the 15-in. level. The estimated length of the recirculation zone is shown as 2 in., which is about seven times the radius of the blockage disk; or 12 times the step height of the blockage device above the surface of the central rod. Several investigators have indicated that the recirculation zone for flow over an obstruction is 5.2 to 17 times the radius of a disc or the height of the step.^{17,33} The first value is for flow over a sharp edge disc in a free stream, and the second is for flow over a sharp edge wall on a flat plate. Other configurations have intermediate values.

Figure 5 also shows bulk mixed-mean temperature rises calculated by heat balances. In the region of the blockage the highest measured temperature (rod 7 at 16 to 16.25 in.), adjusted to give the external cladding temperature, is approximately 220°F higher than the mixed-mean temperature at that point. However, it is not appropriate to use the mixed-mean temperature as a base for comparison because temperature peaking would also exist in the center of unblocked rod bundles.

The temperatures for channel 3 of unblocked bundle 2A, run 1109 (54 gpm, 10 kW/ft), as calculated using the ORRIBLE code¹ were compared with some pertinent experimental data points.³⁰ The code parameters used were $C_T = 0.005$, $C_D = 0.6$, and $C_S = 1.0$, where C_T is a parameter related to the turbulent mixing between subchannels, C_D is related to the pressure diversion cross flow, and C_S is related to the sweeping of fluid by the spiral wire-wrap spacers. See ref. 1 for a definition of these parameters. (Calculated temperatures are most sensitive to C_S and are relatively insensitive to the other two coefficients). The good agreement between computed and experimental temperatures in bundle 2A indicated that a computed temperature distribution for bundle 3A, in the unblocked configuration, should serve as a reasonably good reference for comparison of the results from blocked bundle 3A.

The calculated axial temperature distribution of channel 3 (if it were unblocked) is shown on the second line from the top in Fig. 5. The cladding outer surface temperatures appear to be about 80 to $\sim 180^\circ\text{F}$ above the average temperature of the unblocked channel at the 15 to 17-in. level. Figure 5 also shows the temperatures measured by the ungrounded thermocouples in the wire-wrap spacers in the central six subchannels: 04 13 CH 3, 01 15 CH 4, 03 15 CH 2, 01 17 CH 3, 06 19 CH 4, 06 21 CH 5, and 05 21 CH 3. Also plotted are the measurements from the grounded-junction thermocouples, which show the radial temperature difference across the wire-wrap spacers: 02 15 CH 1 and 07 19 CH 6. These indicate that the ΔT s across the wire wraps are about 15°F (02 17 CH 1) to 25°F (07 19 CH 6). Since the ungrounded thermocouple junctions are approximately in the center of the wire-wrap spacers, a rough estimate can be made of the sodium channel temperatures by subtracting half the ΔT obtained from the grounded-junction thermocouples (7 to 12°F) from the readings obtained with the ungrounded-junction thermocouples. Adjusted readings (plotted in Fig. 5) are compared with ORRIBLE predictions for temperatures in channel 3 (which for purposes of presentation, serves as an indicator of the behavior of all six central channels) in the blocked configuration. Apparently, the prediction of temperatures downstream from the blockage is reasonably good for our purposes. Exit temperatures are also plotted and discussed more fully later.

Since ORRIBLE has no provisions for calculating recirculating flow, predictions obtained with it should not be valid in the recirculating zone. If it is assumed that a 10 to 20°F "film drop ΔT " exists between the cladding outer surface and the average channel sodium temperature, the temperatures of the sodium in the recirculating zone could be estimated as being in the range enclosed by the two dashed lines in Fig. 5.

It is interesting to note the factors that could affect some of the measurements plotted in Fig. 5. Referring to Fig. 4, the thermal elements in rod 7 are located from 1 in. upstream from the six o'clock (17 in.) position of the associated wire wrap to 2 in. upstream of the four o'clock position of the wire wrap. At the 16-in. level, the wire wrap on rod 7 creates a dam between rods 6 and 7 and could "trap" hot fluid below this zone, thus possibly accounting for the higher temperatures indicated by rod 7 in Fig. 5.

The spiral formed by the wire-wrap spacer on rod 1 touches rod 5 at a point 0.5 in. below the spiral defined by the rod 5 thermal elements. The closeness of the rod 1 spacer might be affecting the temperatures in rod 5.

The thermal elements in rods 1, 3, 4, and 6 appear to be relatively free of the influence of wire wraps. Those on heater 1 face channel 1, whereas the others face adjacent rods.

The low temperatures in heater 2 are somewhat puzzling. One possible explanation is that the wire wrap, which penetrates the blockage plate at the eight o'clock position, might be leaking sufficient fluid to depress the local temperatures.

All these second-order effects do not significantly affect the main conclusion that can be drawn from these results: a blockage of the shape tested is tolerable at full flow and power.

Space limitations prevent discussion of detailed data from experiments at lower flows. Some high points of the experiment at 10 kW/ft and 60% flow follow. For this case the cladding outer surface temperatures in the vicinity of the blockage ranged from 80 to 220°F higher than the sodium temperature in the central channels (represented by channel 3) expected for the unblocked case. The hottest cladding internal surface temperature was 1327°F, which is about 540°F higher than the inlet temperature of 785°F. It should be noted that the temperature increase caused by the blockage is only slightly affected by flow. These results indicate that a non-heat-generating blockage of the size tested is acceptable even at 60% flow conditions.

The temperatures at the exits of selected subchannels, as indicated by crossed circles in Fig. 4, were measured using the exit thermocouple rake. These indicated temperatures should represent the particular subchannel exit mixed-mean temperature because of the mixing that occurs in the 3 in. of unheated length between the end of the heated zone and the channel exit. Thus, these measurements provide results that can be directly compared with analytical predictions of mixed-mean subchannel temperatures. By comparison with the results from unblocked bundles, the magnitude of the influence of an in-core blockage on the exit temperature profile can be determined. This should help indicate the feasibility of detecting the blockage by thermal devices located in the exit region.

To provide an exit temperature profile from an unblocked case for comparison, a diametral traverse of the normalized temperature distribution $[(T - T_{in}) / (T_{out} - T_{in})]$ measured in unblocked bundle 2A (10 kW/ft; 53 gpm) were compared with ORRIBLE predictions for that case. Bundle 2A was identical to bundle 3A except that it was unblocked and had a hexagonal duct instead of a duct containing wire-wrap dummy rods. The agreement between experimental results and analysis (within ~6°F) indicates that ORRIBLE is a good predictor for that case. The agreement between the calculated and the measured bundle 2A temperature distribution indicates that the calculation for the unblocked bundle 3A may serve as a reference for comparison with the results of the blocked bundle experiments.

Figure 6 shows the calculated temperature distribution across the exit for the unblocked case and the calculated and experimentally determined temperature for the blocked case of 10 kW/ft, 100% flow (54 gpm). The pertinent experimental results for bundle 3A plotted in Fig. 6 show a temperature increase in the channels downstream from the blocked region (over the unblocked case) of ~30°F. The ORRIBLE predictions for the blocked case show a better agreement at channel 6 (within ~16°F) and poorer agreement in the exterior channels. The poorer agreement in the exterior channels may be due to steeper, unequilibrated temperature gradients in that region. The ORRIBLE code calculates average subchannel temperatures, whereas the thermocouples might be in a subchannel temperature gradient. Investigations of this effect are continuing. At any rate, these variations in the edge rows should not have a major effect on the center of the rod bundle.

The FFTF fuel has exit gas plenums of 42 in. Experiments with full-length bundles are planned, and exit temperature distributions obtained from those experiments may indicate the feasibility of blockage detection under more realistic conditions.

3.3.3 Comments on Internal Blockage Experiments

Excessive temperatures are not generated in the heater rods as a consequence of a 0.25-in.-long, non-heat-generating blockage over an area of six subchannels in the 19-pin FFM bundle 3A even at 10 kW/ft and 60% flow. The blockage covers a flow area of only about 10% of the total area. Therefore, one would expect the wall effects on the flow in the vicinity of the blockage to be small. A non-heat-generating blockage of the small size would be expected to behave essentially the same way in a full-size 217-pin FFTF fuel subassembly and therefore would not cause excessive temperatures.

Fig. 17. Measured and calculated exit temperatures, bundle 3A. 100% flow, 10 kW/ft.

4. ANALYSES OF BLOCKAGE EFFECTS

4.1 Analytical Representation of Flow Downstream from Planar Blockages

A model is being developed in which the flow recirculation zone is treated as a cylinder having dimensions similar to those measured for real wakes. The zone is divided into concentric cylindrical subzones with fluid flowing in the direction of the free stream flow in the peripheral flow subzones and in the opposite direction in the central subzones. The cells contain no surfaces or subchannels that correspond to fuel rods; this difference being rationalized by evidence that recirculation zones in blocked bundles may resemble wakes in free stream flow.^{21,25} For large blockages, heat is added as a volume heat generation term. For small blockages (for example, one ring of flow channels) heat generation on the surfaces of the recirculation zone is simulated.

Preliminary comparisons with salt injection experiments in a water mockup of the FFM, and with a six-channel blockage in the sodium cooled FFM, indicate that agreement can be reached by choosing reasonable values for the recirculation velocities (e.g. about one tenth of the free stream velocity, in the peripheral flow zone).

The model indicates that the peak temperatures within the recirculation zone are most sensitive to the blockage diameter and internal recirculation velocity. It also indicates that for blockage in excess of six subchannels, molecular conduction alone (i.e. stagnant fluid) is not adequate to prevent excessive cladding temperatures.

The model is not sufficiently developed to warrant further discussion at this time. It is mentioned because it appears that the study of artificial recirculation cells may be a convenient means for gaining insight to the blockage problems and may serve as an intermediate step toward analyzing blockages until more realistic models become available.

4.2 Temperature Distributions within Blockages

In order to obtain estimates of the temperature distributions in in-core blockages, some simple cases have been analyzed using the HEATING^{2,3} computer code. The cases examined were (1) infinitely long blockages of one, two, and three adjacent subchannels adjoining a single rod; (2) thin planar blockages of infinite radius (0.1 and 0.25 in. thick); and (3) thin planar blockage of a radius equivalent to a six-channel blockage. Blockages composed of both heat-generating material (UO₂) and non-heat-generating material (stainless steel) have been investigated.

Calculations were made for the case of a single channel blocked by a heat-generating material of infinite length. (Lengths greater than 0.5 in. are essentially infinite with respect to heat flow paths). The temperatures are predicted to reach a maximum value of less than 2500°F at the center of the fuel and 1850°F in the center of the blocked channel and therefore are acceptable.

The results calculated for the case of blockage by a heat generating material of two adjoining channels show that temperatures at the center of the blockage region will approach the melting point of UO₂. It appears that the direction of heat flow is into the fuel pins and then out into the unblocked region. This configuration is not acceptable.

Calculations were performed to obtain the temperatures at the center planes of non-heat-generating planar blockages 0.10 and 0.25 in. thick having infinite radius. A thickness of 0.25 in. is near the maximum allowable thickness of a stainless steel blockage whose radius is too large for significant radial heat conduction.

Calculated temperatures in the center plane of a 0.25-in.-thick heat-generating blockage of infinite radius, without radial conduction, will be excessive.

The temperature distribution was calculated for the case of a heat-generating planar blockage ring, 0.25 in. long and 0.20 in. in radius, where the outer surface of the blockage transfers heat to the sodium at 1200°F. For this case the cladding temperature would be about 2500°F. Even if this type of blockage should accumulate in a zone where the temperature is 800°F, the cladding temperature would be above 2100°F and likely would fail. If the heat-generating ring blockage is reduced to 0.125 in. thickness instead of 0.250, its presence would be acceptable.

6. CONCLUSIONS

Blockages at the inlet of the fuel rod bundles caused by a single piece of material small enough to pass through the FFTF inlet flow paths will have little effect on temperatures internal to the fuel subassembly. Experiments were performed with 19-rod bundles in the FFM having identical configuration and heat flux as the FFTF with solid blockages of 13 and 24 channels at the inlet of the heated zones. The effects of 13-channel blockages were barely discernible. The internal temperatures were elevated as a consequence of 24-channel blockages, but they did not exceed the exit temperature for a normal unblocked subassembly. The effects on the 24-channel blockage results of the nearness of the channel walls in the 19-pin experimental assembly and the manner in which it relates to the full-size FFTF 217-pin subassembly are not known. On the other hand, the FFTF has a 6-in. unheated inlet zone, and the longer length would allow more mixing and reestablishment of flow before entering the heated zone. From this standpoint the experimental results are conservative.

If an inlet blockage can be caused by a gradual buildup of many small pieces, it may be possible, but unlikely, to generate a solid blockage of continually greater size. The critical size of the blockage (where the blockage is either intolerable or detectable) will be determined in future investigations.

It has been experimentally established that an internal blockage of six subchannels of non-heat-generating material (stainless steel) 0.25 in. long is tolerable but is not detectable with present FFTF subchannel instrumentation. However, the exit temperature distribution is distorted sufficiently that detection might be possible in future reactors with multiple exit thermocouple correlation techniques.

Calculations indicate that a long (>0.5 in) heat-generating blockage of a single subchannel is tolerable, but a blockage of two adjacent channels is not. Also, a ring blockage of stainless steel 0.25 in. thick and of infinite radius (no radial heat loss) is barely tolerable. A ring blockage of heat-generating material of 0.20 in. radius must be less than 0.125 in. long to be acceptable.

Analysis of simple representations of flow in a recirculation zone indicates that the internal fluid temperatures will depend strongly on blockage size and recirculation velocities.

In the near future, the FFM program will be directed toward determining maximum permissible blockage size (of various shapes and leakages) coupled with the development of detectability techniques. The eventual desired result is that plant safety philosophy be freed from considerations of "credibility" and be based on detection prior to the attainment of some known damage limit. Experimental confirmation of maximum allowable internal blockage size is not yet available. However, present experimental results for all blockages tested indicate that blockages of these sizes will not create excessive temperatures in the bundle assembly.

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FIGURES

Figure 1. Test section orientation for FFM bundle 2B.

Figure 2. LMFBR-FFM bundle No. 2B instrumentation.

Figure 3. Ratio of dimensionless temperature rises above inlet vs axial position for FFM bundle 2B with blockage of 24 channels (1-24) at the inlet 55 gpm flow, $\sim 600^{\circ}\text{F}$ inlet temperature. Averages of blockage runs 738-742 and 747 compared with averages of unblocked runs 700-702.

Figure 4. Spacer wire and internal thermocouple locations for FFM bundle 3A.

Figure 5. Temperatures along the central six channels, bundle 3A, run 101. 100% flow, 10 kW/ft.

Figure 6. Measured and calculated exit temperatures, bundle 3A. 100% flow, 10 kW/ft.

Table I. Comparison of dimensionless temperature rises $[(T - T_{in}) / (T_{out} - T_{in})]$ measured by the wire-wrap thermocouples in FFM bundle 2B with all 19 rods heated, 55 gpm flow, and $T_{in} \sim 600^{\circ}\text{F}$

Table II. Comparison of dimensionless temperature rises $[(T - T_{in}) / (T_{out} - T_{in})]$ measured by the heater internal thermocouples in FFM bundle 2B with all 19 rods heated, 55 gpm flow, and $T_{in} \sim 600^{\circ}\text{F}$