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ANALYSIS OF COOLANT MIXING IN THE FFTF FUEL BUNDLE (a)

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1. INTRODUCTION

The FFTF is a coordinated facility for investigating the behavior of fuels and structural materials subjected to high, fast neutron flux prototypic of fast reactor environments. The principal component of the FFTF is the Fast Test Reactor (FTR), a fast reactor designed to meet the process and handling requirements of multiple closed test loops. The experimental capability of the FTR is highly dependent on the thermal limitations of the reactor core components. Core component temperatures and thermal gradients must be sufficiently well known to predict reactivity coefficients and to assure a design which will meet performance and lifetime requirements.

This paper presents some of the coolant mixing studies in the fuel bundle which were carried out during the conceptual stage in the design of the FTR. The purpose of these studies was to:

- . Determine the temperature and flow distribution in the fuel bundle,
- . Provide a technical basis for instrumentation of the driver subassembly, and
- . Identify thermal-hydraulic problem areas in the design of the driver subassembly.

2. ANALYTICAL METHOD

The studies were carried out using COBRA⁽¹⁾, a digital computer program which analyzes heat transfer and turbulent mixing in rod bundles. Although COBRA was developed specifically for high-pressure water systems and some of its features are less applicable to low-pressure sodium, these features apply mainly to the two-phase portion of the program. Since COBRA is a steady-

state analysis, it has not been possible to consider boiling problems with sodium because of the unstable characteristics of its two-phase flow. Extensive modifications to COBRA are in progress to make it more useful in analyzing fast reactor problems.

The thermal mixing between adjacent coolant subchannels is divided into two types. The first type is due to the net convective transport caused by flow distribution resulting from equalizing pressures. This type is calculated from the momentum and energy equations. The second mechanism for thermal mixing is a fluctuating cross flow due to turbulent interchange (no net imbalance of flow when averaged over a short period of time). This fluctuating cross flow is assumed to be proportional to the rod spacing and the average mass flow rate:

$$w_{ij} = \beta s_{ij} \frac{G_i + G_j}{2} \quad (1)$$

The proportionality factor β is called the turbulent mixing parameter. The heat transferred per unit length is given by:

$$\frac{Q}{L} = w_{ij} c_p (T_i - T_j) \quad (2)$$

Another way of expressing the heat transfer is:

$$q = \epsilon_H \rho c_p \frac{\partial T}{\partial y} \sim \epsilon_H \rho c_p \frac{T_i - T_j}{\Delta y} \quad (3)$$

The effective distance between the adjacent subchannels, Δy , may be less than the centroidal distance, especially for tightly-packed rod bundles. Comparing Equations (1), (2), and (3) gives:

$$\beta = \frac{\epsilon_H \rho}{\Delta y} \frac{2}{G_i + G_j} \quad (4)$$

Thus, the turbulent mixing parameter can be related to the eddy diffusivity if the effective distance between subchannels is known.

Experiments with water using an electrically-heated test section⁽²⁾ have yielded the following correlation for the turbulent mixing parameter:

$$S = 0.0062 \frac{D}{s} (N_{Re})^{-0.1} \quad (5)$$

A consequence of Equation (5) is that the effective distance between subchannels is proportional to the rod spacing. A plausible argument for this is that the scale of turbulence is governed by the channel dimensions. However, Equation (5) should be applied to rod bundles with geometric dimensions comparable to those of the experiment (pitch-to-diameter ratios between 1.04 and 1.15).

3. TEMPERATURE AND FLOW DISTRIBUTION

3.1 Fuel Bundle Geometry and Parameters

Figure 1 is a diagram of the FTR Driver Fuel Subassembly during the conceptual design stage which was used as the basis for the analysis. The duct is hexagonal in shape in the active core region and becomes circular in the fission gas plenum region in order to reduce the pressure drop across the fuel bundle. The core location was that of the hottest subassembly in the outer fuel zone of a two-zone core. Table I gives the fuel bundle parameters used in the analysis.

3.2 Analytical Model of Fuel Bundle

Since the radial power profile is not symmetrical, the smallest portion which would be required for complete accuracy is one-half of the fuel bundle. It was felt that such a comprehensive model was not warranted and that simpler models would be adequate to obtain the desired results.

Figure 2 shows the two models used to obtain the coolant temperature and flow distribution in the fuel bundle along with the assumed radial power profile for the hottest subassembly in the outer fuel zone. The 30-degree seg-

ment model would be expected to give more accurate flow distribution results, especially when the duct shape changes from hexagonal to circular. Although two 30-degree segments could be used for each half of the fuel bundle, there would be a discontinuity in the center. Therefore, the narrow width approximation to the 30-degree segment was extended across the entire fuel bundle so that a continuous radial temperature profile could be obtained.

3.3 Coolant Temperature Distribution

Figure 3 shows the effect of turbulent mixing on the radial coolant temperature profile at the end of the active fuel length and at the end of the pin bundle. The temperature profile is significantly flatter at the end of the pin bundle than at the core outlet mainly because of the flow redistribution caused by the change in duct shape. A turbulent mixing parameter at zero corresponds to no coolant mixing by turbulent interchange although mixing by the flow redistribution due to equalizing pressures has been taken into account. The values of 0.01 and 0.04 for the turbulent mixing parameter are intended to bracket the actual solution.

In Figure 3, it was assumed that the duct shape changes abruptly from hexagonal to circular at 14 inches above the core. According to the diagram of the fuel subassembly (Figure 1), the transition is completed at this location. Therefore, this assumption underestimates the amount of flow redistribution and results in higher pressure drops. The effect of varying the point of transition from hexagonal to circular duct shape is shown in Figure 4. The effect of making the transition at the top of the core does not appreciably alter the profile at the end of the pin bundle. On the other hand, a constant hexagonal duct shape along the entire fuel bundle results in little change in the temperature profile in the center.

The temperature difference across the subassembly flats is shown in Figure 5. This temperature differential is important in assessing the potential for thermal bowing.

3.4 Coolant Flow Distribution

Figure 6 shows the difference in flow distribution across the fuel bundle for a constant hexagonal duct shape and for a change from hexagonal to circular duct shape at 14 inches above the core. Although the results using the 30-degree segment model are discontinuous in the center of the fuel bundle, it is felt they are more accurate because the actual geometry is more accurately modeled. At the end of the fuel bundle, the portion of the total flow streaming along the outer periphery of the bundle is 61 percent. If the transition is made at the top of the core, then this portion is increased to 70 percent.

Figure 7 shows the change in pressure drop for the different transition points. For the transition at 14 inches above the core, the pressure drop in the remaining 16 inches of fission gas plenum is reduced by 74 percent. For the transition at the top of the core, the pressure drop in the upper axial reflector and fission gas plenum is reduced by 78 percent because of the greater flow redistribution.

4. FLOW BLOCKAGE

4.1 Analytical Model and Parameters

Figure 8 shows the model used for the analysis of coolant subchannel blockages. Since this part of the analysis was carried out prior to the previous section, slightly different fuel bundle parameters were used corresponding to an earlier stage in the conceptual design. The fuel bundle parameters which are different from Table I are:

Active fuel length, in.	36
Fission gas plenum length, in.	36
Pin average heating rate, KW/ft.	13.6
Mass velocity, $\text{lb}_m/\text{hr-ft}^2$	7.62×10^6

A uniform radial power distribution was assumed.

A single-subchannel blockage corresponds to zero flow rate in the coolant subchannel at the 60-degree apex of the triangle and a six-subchannel blockage corresponds to zero flow at the 30-degree apex. In all of the cases studied, the triangle was found to be sufficiently large to avoid edge effects; that is, a disturbance at one apex of the triangle did not affect coolant temperatures and flow rates at the other apexes.

Two types of flow blockages were considered: Blockages along the entire length of the fuel bundle and blockages at mid-core. Although blockages along the entire length of the fuel bundle are unrealistic, they are an extreme case which can be compared with previous analyses and with the results of this study for local blockages. Local blockages would most probably occur at the bottom of the fuel bundle where there is a sudden reduction in coolant flow area. However, local blockages at mid-core represent an upper limit in severity because of the much higher power generation. Therefore, only the local blockages at mid-core are presented here although analyses were also carried out blockages at the bottom of the fuel bundle.

4.2 Single-Subchannel Blockage

For a single-subchannel blockage along the entire length of the pin bundle, the heat which would normally flow radially into the blocked channel must flow radially and circumferentially through the fuel, cladding, and blockage material into the adjacent subchannels. Figure 9 shows the axial tempera-

ture profile in the adjacent subchannel for no turbulent mixing and for optimistic (0.04) and conservative (0.01) values of the turbulent mixing parameter (β). At the end of the fission gas plenum the coolant temperature in the subchannels adjacent to the blocked channel is 149°F higher than normal for no turbulent mixing, 26°F above normal for low turbulent mixing (β of 0.01), and 8°F above normal for good turbulent mixing (β of 0.04).

The single-subchannel blockage at mid-core was effected by restarting the no blockage case at mid-core with zero flow in the blocked channel. Thus the blockage was assumed to be infinitely thin. As shown in Figure 10, this type of blockage is virtually undetectable. At the end of the fission gas plenum, the coolant temperature in the blocked channel is 5°F and 1°F for turbulent mixing parameters of 0.01 and 0.04 respectively.

It is desirable to know the effect of local blockages on cladding and fuel temperatures. Figure 11 shows the model used for determining the temperature distribution inside the fuel pin for a single-subchannel blockage. A heating rate of 15.1 KW/ft was used corresponding to the hot-channel fuel pin at mid-core. It was assumed that the thermal conductivity of the blockage material was zero since this condition produces the maximum fuel and cladding temperatures. Figure 12 shows the maximum fuel (node 1) and cladding (node 102) temperatures as a function of time. The maximum fuel temperature rises by only 156°F but the maximum cladding temperature increases over 900°F above the normal level. Although the cladding does not reach its melting point, the lower strength at the high temperatures could result in rupture of the cladding.

4.3 Six-Subchannel Blockage

For a six-subchannel blockage along the entire length of the fuel bundle, the coolant temperatures in the adjacent subchannels at the end of the fission gas plenum are substantially higher than for the single-subchannel

blockage, as shown in Figure 13. The temperatures above normal are 102°F and 36°F for turbulent mixing parameters of 0.01 and 0.04 respectively.

Unlike the single-subchannel blockage at mid-core, a blockage of six subchannels at the same location produces a sharp coolant temperature peak in the immediate vicinity of the blockage. In Figure 14, it is seen that this peaking is substantially reduced for higher values of the turbulent mixing parameter. These temperature peaks would probably be much less severe if conduction within the coolant could have been taken into account.

The temperature peak is virtually eliminated by allowing a small amount of flow through the blockage, as shown in Figure 15. For the 99 percent blockage, which corresponds to allowing 1 percent of the normal flow at the inlet of the blocked channel, the coolant temperature peak is reduced from 368°F to 47°F above the normal level.

The coolant temperatures in the six blocked subchannels at the end of the fission gas plenum are somewhat higher than for the single-subchannel blockage at mid-core, as shown in Figure 16. The temperatures are 32°F and 8°F for turbulent mixing parameters of 0.01 and 0.04 respectively.

Since the above flow blockage studies were carried out for a limited size geometry and assuming a uniform radial power profile, it was decided to study the six-subchannel blockage using the 30-degree segment model shown in Figure 2 along with the fuel bundle parameters of Table I. Figure 17 shows the results for complete blockage of six adjacent subchannels in the center of the fuel bundle both at the inlet and at mid-core. It is seen that the coolant temperatures in the center of the fuel bundle at the end are approximately the same regardless of whether the blockage is at the inlet or at mid-

core and regardless of whether there is a change in subassembly duct shape. A temperature of at least 31°F above normal would be expected.

Cladding and fuel temperatures have not been determined for the six-subchannel blockage. The consequences would be expected to be much more severe than for the single-subchannel blockage. If the same degree of conservatism is desired by requiring that the thermal conductivity of the blockage material be zero, then the heat generated within the fuel pin must escape axially and an axial length for the blockage must be assumed.

5. DISCUSSION OF RESULTS

5.1 Previous Flow Blockage Studies

Bentley⁽³⁾ considered the blockage of one coolant subchannel along its entire length. Assuming that there was negligible turbulent mixing, he used an equation for conduction in a homogeneous medium and found that a blip in the coolant outlet temperature of 10°C (18°F) over a circular area of diameter one inch was produced.

On the other hand, this study considered the effect of turbulent mixing but not conduction. The effect of conduction here would be appreciably less (for no change in coolant flow area along the fuel bundle) since the flow velocity is approximately twice that used by Bentley. However, this study shows that the disturbance in the coolant temperature profile at the end of the fuel bundle is five to eight times lower for local blockages than for blockages along the entire length of the fuel bundle.

Brook⁽⁴⁾ determined the fuel and cladding temperatures for blockages of one, two, four, and six adjacent subchannels. He assumed various thermal conductivities and heat generation rates for the blockage material corresponding to stagnant sodium, sodium-fuel mixtures, inert (non-fissile) mixture, and

dry oxide. He concluded that blockage of two or more adjacent subchannels with a fuel-coolant mixture could lead to coolant boiling and melting of fuel. However, he found that the presence of small flows, especially through short blockages, was very effective in reducing the temperatures to safe levels. This type of comprehensive parametric study for the FTR fuel bundle has not yet been undertaken.

5.2 Uncertainty in Turbulent Mixing Parameter

The values of 0.01 and 0.04 for the turbulent mixing parameter were intended to bracket the actual solution. Using Equation 5 for the conditions of the FTR fuel bundle gives 0.017. However, there are several considerations which could revise this estimate upwards or downwards.

The amount of mixing for the wire-wrapped bundle would be expected to be several times larger than for the clean (no spacers) bundle. The results of Bishop, et al.,⁽⁵⁾ for the 19-rod hexagonal fuel bundle of the CVTR show that spiral wire wrap spacers increase the amount of mixing approximately three times over the bare pins. Although the increased mixing due to spiral wire wrap spacers can be accounted for in COBRA by assuming a higher value for the turbulent mixing parameter, the actual mechanism of thermal mixing is not correctly simulated. The spiral wire wrap spacers cause a net diversion of flow from one coolant subchannel to another whereas an increased turbulent mixing parameter allows for more fluctuating cross flow between the two subchannels.

Bishop used a lithium ion tracer technique which gives about three times the level of mixing found by Rowe⁽²⁾ who used an electrically-heated test section. Rowe postulates two reasons why the amount of turbulent mixing obtained by Bishop could actually be less than indicated by the experimental data. Therefore, the uncertainties in the experimental technique can greatly affect the mixing results.

Another consideration is the use of the experimentally-determined mixing parameters in analytical methods such as COBRA. The use of dyes and conductivity probes in experiments with water determine the eddy diffusivity for momentum transfer rather than the eddy diffusivity for heat transfer. If the reactor coolant is water, then the assumption that the two eddy diffusivities are equal is reasonably good. However, this assumption for liquid metals may be seriously in error. According to Dwyer⁽⁶⁾, the ratio of the two eddy diffusivities can be estimated by:

$$\frac{\epsilon_H}{\epsilon_M} = 1 - \frac{(0.2/Pr) - 2}{(c_M/v)^{0.9}} \quad (6)$$

Using the geometry of a circular tube and assuming the Nikuradse velocity profile for turbulent flow, it can be shown⁽⁷⁾ that:

$$\left(\frac{\epsilon_M}{v}\right)_{\max} = \frac{N_{Re}}{20} \sqrt{\frac{f}{8}} \quad (7)$$

Using the fuel bundle parameters in Table I and Equations 6 and 7 gives values of ϵ_H/ϵ_M between 0.57 and 0.68.

The experimental technique of Rowe⁽²⁾ would circumvent the above difficulty by using electrically-heated test sections.

6. CONCLUSIONS

1. Flow streaming at the periphery of the fuel bundle produces severe temperature gradients across the outer row of pins and provides a mechanism for thermal bowing of the entire subassembly. It may be possible to alleviate this problem by inserting rods or wedges into the outer coolant subchannels, by roughening the duct wall, by having a small wire wrap spacer pitch for the outer row of pins, or by wrapping the entire fuel bundle.⁽⁸⁾

2. Single-subchannel blockages in the core probably will not be able to be detected. It is possible that cladding temperatures for those blockages will be substantially increased over their normal operating levels as to result in cladding failure.
3. It may be possible to detect six-subchannel blockages in the core with an array of coolant temperature sensors located sufficiently close to the top of the fuel bundle. Further analytical work to determine the number and location of these sensors for maximum protection of the sub-assembly will be required.
4. A flow mixing device above the fuel bundle may be required to obtain an accurate coolant temperature rise across the core due to the large temperature gradient across the fuel bundle.

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NOMENCLATURE

c_p	Heat capacity at constant pressure, BTU/lb _m -°F
D	Rod diameter, A
f	Moody friction factor
G	Mass flow rate, lb _m /hr-ft ²
L	Length, ft
N_{Re}	Reynolds number
q	Heat flux, BTU/hr-ft ²
Q	Heat transferred, BTU/hr
s	Rod spacing, ft
T	Temperature, °F
w	Turbulent fluctuating cross flow, lb _m /hr-ft
y	Distance, ft

Greek Symbols

β	Turbulent mixing parameter
ϵ_H	Eddy diffusivity for heat transfer, ft ² /hr
ϵ_M	Eddy diffusivity for momentum transfer, ft ² /hr
ρ	Density, lb _m /ft ³
ν	Kinematic viscosity, ft ² /hr

Subscripts

i	Subchannel i
j	Subchannel j

TABLE I.. FUEL BUNDLE PARAMETERS

Number of Pins	217
Pin OD, in.	0.250
Wire Wrap Spacer Size, in.	0.030
Spacer Pitch, in.	12
Active Fuel Length, in.	32
Upper Axial Reflector Length, in.	6
Fission Gas Plenum Length, in.	24
Pin Average Heating Rate, KW/ft	9.7
Axial Power Peaking Factor	1.24
Radial Power Peaking Factor across Fuel Bundle	1.17
Coolant Temperature Rise across Fuel Bundle, °F.	398
Mass Velocity, lb _m /hr-ft ²	5.25 x 10 ⁶

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FIGURE 2 Models for Analysis of Coolant Flow and Temperature Distribution in 217 Pin Bundle

FIGURE 3 Effect of Turbulent Mixing on Coolant Temperature Distribution

FIGURE 4 Effect of Transition Point from Hexagonal to Circular Duct Shape on Coolant Temperature Distribution at End of Pin Bundle

FIGURE 5 Temperature Difference Across Subassembly Flats

FIGURE 6

Effect of Transition from Hexagonal to Circular Duct Shape on Flow Distribution at End of Pin Bundle

FIGURE 7

Effect of Transition Point from Hexagonal to Circular Duct Shape on Pressure Drop

Single-Subchannel Blockage

Six-Subchannel Blockage

FIGURE 8 *Model for Analysis of Coolant Subchannel Blockages*

FIGURE 9 Effect of Turbulent Mixing on Coolant Temperatures for Single Subchannel Blocked Along Entire Length of Pin Bundle

FIGURE 10 . Effect of Turbulent Mixing on Coolant Temperatures in Single Subchannel Completely Blocked at Mid-Core

FIGURE 11 Model for Analyzing Fuel and Cladding Temperatures for Single Coolant Subchannel Blockage

FIGURE 12 Maximum Fuel and Cladding Temperatures
for Single Coolant Subchannel Blockage

FIGURE 13 Effect of Turbulent Mixing on Coolant Temperatures for Six Subchannels Blocked Along Entire Length of Pin Bundle

FIGURE 14 *Effect of Turbulent Mixing on Coolant Temperatures in Six Subchannels Completely Blocked at Mid-Core—Detail in the Region of the Blockage*

FIGURE 15

Effect of Degree of Blockage on Coolant Temperatures in Six Subchannels Blocked at Mid-Core

FIGURE 16 Effect of Turbulent Mixing on Coolant Temperatures in Six Subchannels Blocked at Mid-Core

FIGURE 17

Effect of Local Blockage on Temperature Distribution at End of 217 Pin Bundle