PARTIAL FLOW BLOCKAGE EFFECTS
WITHIN A (LIQUID METAL COOLED FAST REACTOR)
LMFBR FUEL ASSEMBLY

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A lumped thermal-hydraulic model was used to calculate the increase in the sodium and cladding temperatures in the wake behind a non-porous partial flow blockage within a typical LMFBR fuel rod assembly. The model predicts that over 25% of the cross sectional flow area may be blocked before the wake fluid temperature reaches boiling; the actual size depends on the blockage axial location and radial location. Agreement with the limited sodium flow rod bundle blockage data is achieved by the model if the wide variation observed in the experimental cladding temperatures within the wake region is attributed to variations in local heat transfer coefficients. The dimensionless fluid residence time, which is an important parameter of the model, is a function of blockage geometry, blockage location, fuel rod geometry, and is characteristically the same whether or not rods are present in the blockage wake.
A. INTRODUCTION

An analysis of fuel rod assembly partial blockage for a liquid metal cooled fast breeder reactor (LMFBR) involves philosophy in addition to approach. In the approach used currently, various sizes, geometries, and locations of partial blockages, solid and porous, within a fuel rod assembly are analyzed to determine the wake fluid and cladding temperatures disregarding the mechanistic route causing blockage. (It is recognized that a partial blockage is extremely unlikely because of engineering design features, inspection and operation techniques.) The temperatures determined are then used to ascertain whether boiling might occur and if the local higher coolant temperature caused by the blockage and/or boiling might be detected. In an alternate approach, emphasis would be placed on devising a mechanistic chain of events which leads to blockage (such a chain has not been identified). Thus the second method involves a probability analysis of blockage and results in a determination of the size, location and blockage material which are credible. Even if the second approach is employed initially, the type of thermal-hydraulic analysis currently used might be required to determine the characteristics of a credible size blockage.
Operation of existing fast breeder reactors, as well as water reactors has not demonstrated any traceable history of fuel assembly damage caused by blockages cited below. There is an extensive blockage prevention program executed during design, manufacture, inspection and operation. Emphasis has been placed in LMFBR development on analyzing a solid non-porous or porous blockage which completely restricts normal flow over a given axial distance in one or more sub-channels. The reason considerable attention is given to the "solid" blockage is not because it has been identified by a mechanistic group of events but because it is considered to represent the ultimate worst case for four types of blockages caused by foreign particles in the primary coolant, wire wrap failure, excessive fuel rod bowing, and excessive fuel rod cladding swelling.

In this paper, the effect of a local blockage within a fuel assembly is discussed and calculated with reference to the hydrodynamics, local coolant temperature and local cladding temperature in the blockage region of a typical wire wrapped LMFBR fuel rod assembly. A lumped model is employed. The results of the model are compared with experimental data obtained using sodium flowing through an electrically heated wire wrapped 19 fuel rod assembly. Published results are cited for water flowing through a gridded 169 fuel rod assembly.
effects of porous blockages, small fuel rod pitch-to-diameter ratios, blockage location and blockage size are also discussed.

B. HYDRODYNAMICS IN THE NEAR WAKE BLOCKAGE REGION

Wake flow past a bluff body (such as a sharp edged blockage) occurs at a sufficiently high Reynolds number. The dividing streamlines first separate from the body to form free shear layers, enveloping a recirculating flow region, the near-wake. (1)(2) This region is characterized by a nearly constant wake base pressure \( P_B \) which is less than the free stream pressure \( P_{\infty} \). Reattachment of the mean streamline, marks the closure of the near-wake; closure can create a Karman vortex sheet. The flow after wake closure is called the far-wake. The essential interaction between the blockage and the separated flow occurs in the near-wake region. However, the near-wake flow pattern is in turn related to the state of motion in the far-wake.

The mass flow rate at which turbulence can entrain fluid from an adjoining undisturbed flow is established by the scale and intensity of its energy-containing eddies. (2) The scale of these energy-containing eddies is related to the integral scale length \( L_x \) thus

\[
\dot{m} = \left( \rho, \mu, L_x, (u^2)^{0.5} \right) \quad (1)
\]
in turbulent flow the base pressure difference $P_B - P$ is expressed by

$$P_B - P_{\infty} = F(p, \mu, U, d_B, m)$$  \hspace{1cm} (3)

so that

$$\left( C_p \right)_B = \frac{P_B - P_{\infty}}{\frac{1}{2} \rho U_2^2} = f \left( \frac{\rho U_2 d_B}{\mu} \right) \frac{m}{\rho U_2^2 d_B^2}$$  \hspace{1cm} (4)

however, the base pressure coefficient $(C_p)_B$, as is the drag coefficient $C_D$, independent of the Reynolds number over a large range.

Therefore

$$F \left( \frac{LX^2}{d_B^2} \left( \frac{\bar{u}^2}{U} \right)^{0.5} \right) = F \left( \frac{m}{d_B^2 U^2} \right)$$  \hspace{1cm} (5)
Our interpretation of experimental data obtained for flat plate blockages shows in Figure 1 that

\[ (C_P)_B = C_1 \left( \frac{m}{\rho U_d^2} \right)^C \]  

(6)

Although the above method for calculating the wake entrainment flow rate using measured base pressure coefficients appears to be attractive for fuel rod bundles, virtually no applications of it are known to us. Whether the Karlsruhe workers followed up on their initial base pressure data shown in Figure 2 has not been published. The method commonly used to deduce wake entrainment flow rates in fuel rod bundles behind a blockage is to measure the decay of a dye tracer, salt conductivity or temperature spike in the near wake region \( (4) \) \( (6) \) \( (7) \) \( (27) \). The experimental data from this diffusion model is then used to calculate the average residence time, \( \tau \), of the fluid in the wake.

\[ \frac{C}{C_0} = \exp \left( -\frac{At}{\tau} \right) \]  

(7)

The parameter \( \Lambda \) is related to the dimensionless group \( LS/V_{WF} \) where \( L \) is proportional to the diffusional length for mass transfer, \( S \) equals the surface area and \( V_{WF} \) equals the volume.
of the near wake bubble. Only if $A$ is unity should the residence time $\tau$ equal the time constant for the diffusion process.

Moreover, some experimental data indicate $\tau$ is a function of the position in the wake region which then requires an averaging process for use in the subsequent analysis. The value of $\tau$ obtained is used to generate a dimensionless residence time

$$t_R = \frac{\tau U}{d_B} \quad (8)$$

and an entrainment mass flow rate

$$\dot{m} = \frac{\rho V_{WF}^2}{\tau} \quad (9)$$

Observe that if $V_{WF} = C_1 d_B^3$, equation (9) and (5) can be used to show that

$$\frac{\dot{m}}{\rho U d_B^2} = \frac{C_1 d_B^2}{2U} = \frac{C_1}{t_R} \quad (10)$$
Wake hydrodynamic characteristics behind a blockage without rods have been found to be valid where rods exist, at least for P/D as small as to 1.23 \( \times \) \( \frac{d_B}{L} \). Data obtained both by ORNL \( ^{6} \) and Karlsruhe \( ^{6} \) suggest that the near wake length-to-blockage diameter ratio \( L/d_B \) increases with increasing blockage Reynolds number. As the Reynolds number increases from 4.0 \( \times \) \( 10^4 \) to 2.0 \( \times \) \( 10^5 \), \( L/d_B \) increased from 1.6 to 2.5 for central blockages and from 2.6 to 4 for edge blockage. \( ^{8} \) Conversely, limited Karlsruhe data has \( B/d_B \) the maximum wake diameter to blockage diameter decreasing as the Reynolds number increases, which is in agreement with theory. Because the drag coefficient is relatively independent of Reynolds number, the wake volume might still remain relatively constant even though its length increases and its diameter decreases.

Experimental data obtained for wake characteristics in rod bundles and for blockages in otherwise unobstructed streams show that \( t_R \) is proportional to the blockage ratio and is independent of Reynolds number based on the characteristic blockage dimension \( d_B \). The dimensionless time ratio \( t_R \) also depends on the lateral location of the blockage; \( ^{6} \)(\( ^{8} \))(\( ^{28} \)) it is different for center and edge blockages, as discussed in Reference \( ^{11} \). However, to qualify as a true edge blockage, the blockage must be entirely two-dimensional (i.e., flow past
one edge only). All blockages, if they exist, can range from three-dimensional center blockages to complete edge two-dimensional obstructions. It should be noted that true edge blockage are even less probable than center or off-center blockages because they span the entire edge or corner of an assembly. Figure 3 and Table 1 are the authors' summary of existing experimental dimensionless residence time data for fuel rod bundles as a function of \( \beta \), the fraction of the flow area blocked.

Although a wake will generally form upstream as well as downstream of a local blockage, the upstream wake is considerably smaller and therefore, is not the limiting temperature region.

C. FUEL ROOD PITCH-TO-DIAMETER EFFECT ON THE DIMENSIONLESS RESIDENCE TIME

As shown in Figure 3 and tabulated in Table 1, the slope of \( t_R \) versus \( \beta \) appears to be constant for the three geometries tested. Although the SNR has a larger pitch-to-diameter ratio than the ORNL test bundle, the parameter \( t_R \) is somewhat larger. Thus, in addition to P/D, other factors are involved in determining \( t_R \). The possible effect of wire wrap versus grids (SNR) cannot be discounted. However, the apparent constant slope in Figure 3, negates somewhat effects of spacers on wake flow characteristics. More data are required to resolve spacer, laminar flow and low P/D effects. The SNR test bundle has
approximately 11 rods per square inch of cross section whereas
the ORNL test bundle has 1.42 rods per square inch of cross
section. In the SNR test bundle, there is a more tortuous
path for fluid circulating in the wake. As expected, \( t_R \) for
the flat plate has the lowest value of \( t_R \) because there is no
obstruction to circulating fluid in the wake region. But the
data for the ORNL 1.23 P/D bundle\(^8\) are very close to those
for the Winterfield\(^4\) disc test data. Using this inference,

\[
\frac{t_d}{\lambda} = \frac{cD}{\lambda} = f\left(\frac{p}{D}, R_A, \beta\right)
\]

(11)

The relation obtained is:

\[
t_R = C_3 \left(\frac{R_A}{p}\right)^{0.5} \frac{1}{\beta^{0.8}}
\]

(12)

Although this empirical relation for \( t_R \), which must be substantiated by experiment, does not go to infinity as \( P/D \to 1.0 \),
such a limit may not be required in the P/D range examined.

Galbraith and Knudsen\(^{29}\) reported data showing that fluid
mixing characteristics for bare rods were similar for \( P/D \) as
small as 1.028; at \( P/D \) equal to 1.011 a significant change in
the fluid mixing characteristics occurred. Even though a
typical radial blanket assembly has a P/D = 1.08 the number of rods per square inch is relatively small and because of the large size rod, the absolute space between rods is ~0.040" which is comparable to 0.056" in the core. A value of \( t_R = 17 \) was calculated for a radial blanket assembly at a blockage fraction \( \beta = 0.1 \), however, the larger value \( t_R = 22.5 \) calculated for a typical core used the analysis.

D. TEMPERATURE OF THE NEAR WAKE FLUID

Existing engineering models to predict the heat transfer variation and temperature distribution within the near wake region and between the near wake region and solid boundaries (i.e. fuel rods) have not been perfected. (10) (9) (6) (7) However, a simple lumped engineering model has been proposed (6) to calculate the average temperature in the wake. Assumptions in the model are assessed to result in a conservative value of the average fluid temperature; however, comparisons with sodium data in fuel rod bundles are extremely limited.

\[
T_B - T_L = \frac{\dot{Q}}{\dot{m} C_P} = \frac{\dot{Q} \gamma}{\rho V_{W_0} C_P} \\
\dot{m} = \frac{\rho V_{W_0}}{T_0}
\]  

(13)
The need to know the actual near wake volume $V_{WF}$ is eliminated by requiring the specific power input into the wake fluid $Q_{WF}/V_{WF}$ be equal to the unobstructed local specific power into the coolant.

The local cladding temperature in the wake is determined by the heat transfer coefficient, heat flux and local wake temperature. Experimental data obtained by Kirsch [6] in a water loop indicates that the maximum coolant temperature in the wake is not much higher ($\approx 20\%$) than the average wake temperature. Molecular conduction effects in sodium would reduce the maximum-to-average wake fluid temperature. The axial variation in film heat transfer coefficient between cladding and wake fluid is shown in Figure 4 by ORNL data obtained in a water loop. For water, the ratio of $h_{B}/h_{w}$ decreases with increasing Reynolds number because the turbulence intensity and possibly the scale of turbulence also, decreases with increasing Reynolds number in the wake region. [12][13][14]

Directly similar heat transfer coefficient data are not available from a sodium system. [15] Although the axial heat transfer coefficient might be approximately similar, molecular conduction would be expected to play an important role in sodium especially near a solid boundary. In sodium the axial variation is not expected to be as drastic nor is the
of $h_B/h_\infty$ in the region of the blockage expected to be as low. \cite{15}

Few theoretical models have been published for use in calculating heat transfer coefficients in separated flow regions. \cite{14,16} This deficiency is particularly true for the region directly behind a blockage where the heat transfer coefficient is considered to be a minimum as shown in Figure 4. Only one code has been reported which appears to be directly applicable. \cite{17}

Data obtained to date have used blockage plates with rectangular edges. This might not be conservative because the drag coefficient and hence the entrainment rate $\dot{n}$ would be expected to decrease as the blockage edge is rounded.

E. **Comparison of Fluid Near Wake and Cladding Temperature Calculations with Experimental Data**

To our knowledge, the only published fuel rod bundle sodium data which show temperatures in the wake region are the results of seven tests reported by ORNL. \cite{7,8} Table 4 summarizes data for all seven tests along with our calculated results using the lumped model. One set of data obtained in a "simulated rod bundle" were partially reported by Kirsch and Schlesisick. \cite{5}

Whether the observed wide variation of inside cladding temperatures in the wake region shown in Figure 5 was caused by a wide difference in heat transfer coefficients, local wake
fluid temperature variation, or to other factors is not known. The near wake appears to have a length of approximately 1.75 inches and an $L/d_B$ equal to three which is within the expected range. The fluid temperatures at the beginning and end of the wake region were associated with the grounded junction thermocouple measurements shown. The fluid temperature adjacent to the heaters in the wake region can only be estimated by making an assumption concerning the magnitude of the heat transfer coefficients. In Table 4 and Figure 5 the cladding temperatures are referenced to $T_L$, the calculated temperature in Channel 3 which was normally higher than the average fluid temperature outside the wake region because of boundary conditions.

Table 1 shows experimentally determined values of the dimensionless residence time $t_R = \tau U/d_B$ obtained by ORNL, Winterfield and Karlsruhe. We calculated the values for the Karlsruhe tests based on their data. All the hydraulic data shown were obtained in water systems.

Kirsch and Schleisiek obtained limited residence time data for both water and sodium; temperature measurements were used. They concluded, (1) that molecular heat conduction does not measurably influence energy transport in the recirculation zone (wake), (2) the only factor determining the temperature distribution is the turbulent recirculating flow, (3) experimental results for the temperature level and temperature
distribution in the wake obtained from water measurement can be extrapolated to sodium.

Using the dimensionless residence time, $\tau U/d_B$, for the ORNL data from Table 1 calculations were made by the authors to determine $T_{B} - T_{L}$, the fluid temperature increase caused by the blockage. The $d_B$ values of the characteristic blockage dimension obtained in the triple scale water model were reduced by a factor of three when applied to the sodium data obtained in the full scale 19 rod bundle. The need for a scale geometry factor should also be assessed in applying the $t_R$ obtained in one geometry to that of another geometry even when the $P/D$ is identical. The heat input used was that into the fluid within a unit channel. Our calculated results are shown in the column "as calculated" $T_{P} - T_{L}$ in Table 4. The agreement is fair only if it is assumed that the variation in cladding temperatures in Figure 5 is caused by variations in heat transfer coefficients and not large variations in wake fluid temperatures. This assumption suggests that the lower dotted line in Figure 5 represents approximately the true wake temperature which corresponds to the entry $T_{B} - T_{L}$ estimated in the Table. Even when this assumption is made the as calculated temperatures $T_{B} - T_{L}$ must be multiplied by a factor of 1.15 to 1.42 to get agreement. (Kirsch suggested that the as calculated values of $T_{B} - T_{L}$...
should give high values of the average wake fluid temperature.)

In Tests 6 and 7 the as calculated value overpredicts the "wake temperature" where blockage leakage was suspected, Test 6, and where known leakage was built into Test 7. In Test 5 it is not felt justifiable to make a conclusion because the $T_{BC} - T_L$ value was only estimated by us from earlier test data. It does appear however, that leakage significantly reduces the wake fluid temperature. Our conclusion is that the simple model used to predict wake fluid temperatures is not completely adequate. However, the approach used in the previous discussion was used to obtain wake and cladding temperatures for a typical LMFBR fuel rod assembly in the next section.

Kirsch and Schleisiek (5) used their hydraulic data obtained for $t_R = \frac{v}{d_B}$ to calculate blockage conditions in the SNR reactor. The calculations showed that over 40% of the center part of a core assembly could be blocked without boiling occurring based on the average fluid temperature in the wake. Their calculations, to our knowledge, were not compared with actual sodium rod bundle data. Their calculational model is similar to that used in this analysis.

Other water data reported by Kirsch indicated that the maximum temperature in the wake exceeded the average temperature only by approximately a factor of 1.2. In these tests
the maximum wake temperature was near the outer edge of the wake.

F. CALCULATED WAKE AND FUEL ROD CLADDING TEMPERATURES FOR TYPICAL LMFBR FUEL ROD ASSEMBLY

The increase in the wake temperature behind a blockage depends on the axial location, radial location and the blockage size. Flow rate and heat flux are also important parameters. Two basic types of blockages have been identified: (11) a three-dimensional center or off-center blockage, and a two-dimensional edge blockage. For otherwise equal conditions, a two-dimensional blockage is worse because the wake is larger and the residence time, \( \tau \), is larger. This factor has been verified experimentally. (6)(8)

Calculations were made using equation 13 and data from Figure 3 to determine the average and maximum fluid temperatures in the wake region behind a central six channel blockage in a typical LMFBR fuel assembly. Cladding temperatures were also calculated. The results are shown in the following table. Heat transfer coefficients were obtained from the sodium flow blockage data. (7)(8)

<table>
<thead>
<tr>
<th></th>
<th>Midplane</th>
<th>Exit-Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Wake Temperature (°F)</td>
<td>1104</td>
<td>1197</td>
</tr>
<tr>
<td>Maximum Wake Temperature (°F)</td>
<td>1261</td>
<td>1244</td>
</tr>
<tr>
<td>Midwall Cladding Temp (°F)</td>
<td>1396</td>
<td>1312</td>
</tr>
</tbody>
</table>
It can be seen that at either the midplane or the core exit plane, the postulated six channel center blockage would cause temperatures which are considerably lower than the temperature corresponding to prompt cladding failure.

If the six channel blockage occurred on the edge of the fuel assembly, the hydraulics would still be quasi-three dimensional. Although the dimensionless residence time \( t_R \) would be larger, the colder edge fluid flowing by the small blockage could partially compensate for the higher \( t_R \). Only if the six-channel blockage occurred in a corner, would there truly be a two-dimensional effect, possibly producing higher wake and cladding temperatures than shown in the previous table. Because of uncertainties in existing edge blockage data and prediction models, two-dimensional definitive blockage calculations for edge channels were not made. An approximate evaluation indicates however, that even a true two-dimensional corner blockage of six subchannel does not cause excessive mid-wall cladding temperatures.
G. POSTULATED LOCAL BOILING EFFECTS; CORE FUEL ROD ASSEMBLY

There is no basic difference in the method used to calculate the blockage size which might cause local boiling and the method used to calculate the effects of smaller size blockages. The following Table shows the calculated sizes of central blockages, fraction area blocked and the boiling temperatures assumed at the midplane and exit plane of the core.

<table>
<thead>
<tr>
<th>Boiling Temperature °F</th>
<th>d_B (inches)</th>
<th>( \beta ) (approx.)</th>
<th>( t_R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midplane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1850</td>
<td>2.35</td>
<td>0.25</td>
<td>22.5</td>
</tr>
<tr>
<td>1800</td>
<td>2.23</td>
<td>0.22</td>
<td>22.5</td>
</tr>
<tr>
<td>1750</td>
<td>2.11</td>
<td>0.20</td>
<td>22.5</td>
</tr>
<tr>
<td>Exit-Plane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1770</td>
<td>3.55</td>
<td>0.56</td>
<td>22.5</td>
</tr>
<tr>
<td>1720</td>
<td>3.29</td>
<td>0.48</td>
<td>22.5</td>
</tr>
<tr>
<td>1700</td>
<td>3.02</td>
<td>0.40</td>
<td>22.5</td>
</tr>
</tbody>
</table>

(1) For non-porous blockages.

The previous Table illustrates the significant difference between blockage at the exit and mid-plane. A factor
equal to 1.3 \((T_B - T_L)_{avg}\) was used in the calculations. The results published in Reference (5) reflect similar blockage sizes required for boiling; however, this should not be considered an independent check because the same calculational model was used. True edge blockages might be more severe. However, there are not sufficient data to calculate the boiling blockage area with any degree of confidence.

H. EFFECT OF POROUS BLOCKAGES

Leakage flow through a blockage increases the static base pressure immediately down stream of the blockage. The result is a decrease in the drag coefficient across the blockage and a decrease in the volume of the near-wake region. Increased leakage flow moves the wake downstream and decreases its volume and the circulation intensity within the wake.

Kirsch reported experimental data for rod bundles showing that the wake region essentially disappears when the ratio of the flow rate through the blockage to the steady state flow rate is approximately 0.15. For a two-dimensional blockage, Castro's data indicates that the wake region is very weak when \(\beta_L \) is approximately 0.3. Bearman's data and the wake code calculations give similar results. Kirsch reported that for a leakage area \(\beta_L \) of the order of 0.05 and a central blockage area-ratio \(r\) equal to 0.411, leakage reduced the wake
temperature 100°F for the SNR fast breeder reactor thermal conditions. The basic data reported by Kirsch were obtained using a full scale fuel rod assembly in a water loop. Table 4 shows recent blockage data obtained in flowing sodium where 14 edge channels were blocked. For the three tests run, there was no leakage through the blockage, suspected leakage and known leakage. For the later two cases the parameter, cladding minus unblocked fluid temperature is significantly lower than for the non-porous blockage run. The leakage was through a sharp edge passage between the rods and the blockage plate.

Leakage flow through sharp edged passages is very effective in reducing the wake temperature and in particular the cladding temperature because the leakage flow acts most effectively where it is needed—directly behind the blockage. As the leakage leaves the blockage, the expanding small jets create considerable turbulence.

Both Kirsch and ORNL used a direct leakage path through the blockage, i.e. drilled holes, an off-set blockage plate. The hydraulic resistance of such a passage is considerably lower than for the tortuous path through a blockage consisting of small particles. The result is that the coolant velocity through
a direct leakage path, for the same porosity is much greater than for the type porous blockage envisioned in a reactor. \(21(22)\)

Thus, porous blockages, even with relatively high porosity, are assessed to be more similar to non-porous blockage. Calculations reported in Reference (28) indicate that uniformly porous blockages produce higher wake region temperatures than non-porous blockages. In contrast, porosity represented by sharp edged discrete orifices reduced the wake temperature below the reference non-porous blockage case.

1. **EFFECTS OF HEAT-GENERATING BLOCKAGE**

   There are no experimental data describing the effects of heat-generating blockage on fuel rod performance. Such information has not been obtained from in-pile or out-of-pile studies. If the heat generating blockage caused a wake to form downstream of the blockage, much of the hydraulic wake discussion of the effects of non-heat-generating blockage would be expected to be valid. The additional factor and complication is local heat-transfer and temperature distribution within the blockage itself.

   A thermal-hydraulic model was devised for a local heat generating blockage; the model was one-dimensional. \(23\) The purpose was to determine the heat transfer performance of sodium flowing through a porous medium having internal heat generation.
The porous heat thickness which caused coolant boiling was determined as a function of the average effective particle diameter for various bed positions. Over a range of fuel-debris sizes of 100 to 1000 μm and bed porosity of 0.25 to 0.50 it was concluded that for an average particle size of 500 to 600 μm and a bed porosity equal to 0.35 to 0.45, a quantity of 2 to 5 grams of fuel per flow channel would be required to produce boiling and that steady state temperatures within the porous medium would be obtained shortly after blockage was initiated. The axial location was midplane of the highest power fuel assembly. The actual blockage height was, therefore, approximately 0.4 to 0.8 inches, a height larger than a fuel pellet. This can be considered to be a substantial amount of fuel. Experimental data are required to substantiate this analysis. It is possible that a three-dimensional analytical model supported by experimental data, would indicate even larger amounts of heat generating debris would be required to cause boiling.

J. LOCAL BOILING STABILITY AND DRY-OUT EFFECTS

Theoretical analysis (24) of local boiling in the wake behind a blockage large enough to be detected indicates that boiling will not lead to rapid dry-out, fuel pin failure and ejection of molten fuel, flow instability, bulk-coolant boiling and gross melting of cladding. Even when the hot spot in the
wake fluid reaches the local boiling temperature the average wake temperature is considerably lower. An important basis of this one-dimensional analysis is that because of the short lifetime of bubbles, local dry-out is unlikely to occur during the lifetime of a bubble because a thin liquid layer remains on the fuel rod surface. Moreover, where little or no superheat is required for local boiling, the wake subcooling prevents the steady state vapor velocity from exceeding the liquid film destruction velocity (flooding).

Schleisiek (25)(26) conducted tests in which 12 subchannels were blocked. This geometry represented a two-dimensional cut out of a 61-rod bundle with a central blockage of 37 rods. Local boiling conditions were achieved in the wake behind the blockage. In the absence of superheat, boiling started with the formation of small, hardly detectable bubbles. The temperature in the boiling area did not exceed significantly the saturation temperature (1450-1700°F)*. Nearly all the bubbles collapsed completely and the succeeding bubble was formed without delay. Dry out of the test section wall was observed only when very high superheat caused instability of the total sodium flow. High sodium boiling superheats are not expected under reactor conditions.

* low pressure tests
CONCLUSIONS

1. Lumped hydrodynamics of a wake region downstream of a partial blockage can be characterized by the same dimensionless time parameter \( t_R = \tau U / d \) whether or not rods are present.

2. The dimensionless time parameter \( t_R \) is a function of the fraction of flow area blocked, the fuel rod pitch-to-diameter ratio, the number of fuel rods per unit area and the blockage radial location.

3. The lumped thermal-hydraulic model currently used to predict wake fluid temperatures provides reasonable agreement with the limited sodium flow rod bundle blockage data only if the wide variation in experimental cladding temperatures observed in the blockage region is attributed to variations in local heat transfer coefficients.

4. The model predicts that over 25% of a fuel assembly planar flow area in a typical LMFBR can be totally blocked before the wake fluid temperature reaches boiling. The actual size depends on the blockage axial and radial location.

5. Measurement of the blockage base pressure and drag coefficients might be used to check independently the value of the dimensionless time parameter.

6. A porous blockage which provides low hydraulic resistance flow paths significantly lowers the wake fluid temperatures.

7. The influence on the dimensionless time parameter of laminar flow, small pitch-to-diameter ratios, blockage height and edge geometry, spacer geometry and blockage porosity requires additional analysis and experimental verification.
REFERENCES


NOMENCLATURE

$\dot{M}$  wake entrainment flow rate
$\rho$  fluid density
$\mu$  viscosity
$L_X$  turbulence scale length
$(\tilde{U})^{0.5}$  turbulent velocity
$P_B$  base static pressure along downstream side of blockage plate
$P_\infty$  free stream static pressure
$(C_{PB})$  base pressure coefficient
$U$  free stream velocity
$d_B$  blockage characteristic linear dimension
$V_{WF}$  volume of fluid in the near-wake region
$\tau$  average residence time of fluid in the near-wake region
$t_R$  dimensionless residence time $\frac{\tau U}{d_B}$
$T_L$  average local fluid temperature without blockage
$Q_{WF}$  heat input rate into wake fluid
$C_P$  heat capacity of fluid in the wake region
$L/D$  length-to-diameter ratio
$P$  fuel rod pitch
$D$  fuel rod diameter
$R_A$  number of fuel rods/unit area
$\beta$  blockage fraction
$Q$  linear heat rate
$A_{WF}$  coolant area per unit subchannel
$T_{BC}$  cladding temperature, outside
$\dot{m}$  mass flow rate entrained in blockage near wake
$C$  concentration
$C_0$  initial concentration
$h_B$  local heat transfer coefficient
$h_\infty$  fully developed heat transfer coefficient
Table 1: Dimensionless Residence Time, $\frac{\tau U}{d_B}$: Blockage Test Data

<table>
<thead>
<tr>
<th></th>
<th>Number of Rods</th>
<th>Blockage Fraction ($)</th>
<th>Number Blocked Channels</th>
<th>Bundle Scale</th>
<th>$d_B$ inches</th>
<th>$\frac{\tau U}{d_B}$</th>
<th>$\frac{P}{D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winterfield</td>
<td>-</td>
<td>0.13</td>
<td>-</td>
<td>-</td>
<td>1.97</td>
<td>9</td>
<td>$\infty$</td>
</tr>
<tr>
<td>ORNL - Center</td>
<td>19</td>
<td>0.13</td>
<td>6</td>
<td>Triple</td>
<td>1.49</td>
<td>12</td>
<td>1.23</td>
</tr>
<tr>
<td>ORNL - Center</td>
<td>19</td>
<td>0.62</td>
<td>24</td>
<td>Triple</td>
<td>3.13</td>
<td>8</td>
<td>1.23</td>
</tr>
<tr>
<td>ORNL - Edge</td>
<td>19</td>
<td>0.13</td>
<td>5</td>
<td>Triple</td>
<td>1.22</td>
<td>28</td>
<td>1.23</td>
</tr>
<tr>
<td>ORNL - Edge</td>
<td>19</td>
<td>0.60</td>
<td>24</td>
<td>Triple</td>
<td>3.21</td>
<td>19</td>
<td>1.23</td>
</tr>
<tr>
<td>Karlsruhe (Center)</td>
<td>169</td>
<td>0.147</td>
<td>54</td>
<td>Full Size</td>
<td>1.71</td>
<td>18**</td>
<td>1.317</td>
</tr>
<tr>
<td>Karlsruhe (Center)</td>
<td>169</td>
<td>0.411</td>
<td>150</td>
<td>Full Size</td>
<td>2.88</td>
<td>13**</td>
<td>1.317</td>
</tr>
</tbody>
</table>

* not a function of Reynolds Number

** calculated by the authors from Karlsruhe data
### Table 4: Comparison of Experimental and Calculated Effect of Blockage on Local Wake Fluid Temperature

<table>
<thead>
<tr>
<th>Estimated Film</th>
<th>Power (kw/ft)</th>
<th>Approx. Velocity (ft/sec)</th>
<th>Temperature Difference (°F)</th>
<th>Estimated (°F)</th>
<th>As Calculated (°F)</th>
<th>Test No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-115</td>
<td>10</td>
<td>34</td>
<td>80-180</td>
<td>50</td>
<td>44</td>
<td>1</td>
</tr>
<tr>
<td>35-140</td>
<td>10</td>
<td>27.2</td>
<td>100-207</td>
<td>75</td>
<td>55</td>
<td>2</td>
</tr>
<tr>
<td>35-120</td>
<td>10</td>
<td>20.4</td>
<td>140-223</td>
<td>105</td>
<td>72</td>
<td>3</td>
</tr>
<tr>
<td>20-80</td>
<td>7.5</td>
<td>34</td>
<td>60-120</td>
<td>40</td>
<td>33</td>
<td>4</td>
</tr>
</tbody>
</table>

**ORU-L - 19 Rods - 6 Center Channels Blocked (0.250" Thick Plate, P/D = 1.23) Sodium**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Power (kw/ft)</th>
<th>Approx. Velocity (ft/sec)</th>
<th>Temperature Difference (°F)</th>
<th>Estimated (°F)</th>
<th>As Calculated (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>25.8</td>
<td>121**</td>
<td>-</td>
<td>97</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>25.8</td>
<td>69</td>
<td>-</td>
<td>97</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>25.8</td>
<td>76</td>
<td>-</td>
<td>97</td>
</tr>
</tbody>
</table>

**ORU-L - 19 Rods - 14 Edge Channels Blocked (0.125" Thick Plate, P/D = 1.23) Sodium**

**This temperature estimated from early Test No. 5 data**

\[ T_B - T_L = \text{Wake Fluid Temperature} - \text{Adjacent Unblocked Fluid Temperature} \] (calculated)

(i) These temperatures are based on peak measured cladding temperatures.
Figure 1. Correlation of Turbulence Parameter vs. Drag Coefficient and Base Pressure Coefficient in the Near Wake Region. (From Reference 2)
Figure 2. Dimensionless Pressure Profiles Behind a Blockage in a Rod Bundle, $\beta = 0.147$  (From Reference 6)
Winterfield, circular disc, no rods
Δ ORNL, 19-rod, central blockage (P/D = 1.23)
Ο ORNL, no rods, edge blockage
Ο Karlsruhe, 19-rod, central blockage (P/D = 1.317)
▽ ORNL, 19-rod, edge blockage (P/D = 1.23)

Fraction of Flow Area Blocked, $\beta$

Figure 3. Dimensionless Residence Time vs. Fraction of Flow Area Blocked.
**Figure 4. Axial Variation of Plane-Average Heat Transfer Coefficient for Triple-Scale FFM Water Mockup with 24-Subchannel Symmetrical Internal Blockage Plate. (From Reference 8)**
54 GPM, 10 KW/ft, 826 °F, $T_{\text{inlet}}$

$T_{\text{out}} - T_{\text{in}}$ (Mixed Mean) = 161 °F

- $x$: Temperature measured on inside surface of heater clad
- $x_c$: Temperature of outside surface of heater clad using calculated $\Delta T$ drop across clad thickness

$C_i$: Indicates temperature next to heater and next to the central channel for grounded-junction thermocouples.
Figure 5. Temperatures Along the Central Six Blocked Channels, 19 Rod Bundle, Full Scale. (From Reference 8)