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MIXING MODEL FOR WIRE WRAP FUEL ASSEMBLIES

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1. INTRODUCTION

A mixing model, used to determine temperature distributions in a wire wrap fuel assembly, has been embodied into a digital computer code named COTEC. Four phenomena are included in the model which effect heat and mass transfer between subchannels. Two of these phenomena, pumping and sweeping, are dependent upon the wire-angle relative to a gap between pins and account for wire spiraling around the pin. This results in a net interchange of mass and thermal energy between adjacent subchannels. Two other phenomena, which only interchange thermal energy between adjacent subchannels, are turbulent mixing and thermal conduction. These effects are discussed briefly as follows:

- Pumping - Due to the spiral of the wire wrap around the fuel pin, the flow area and equivalent diameter of a subchannel are not equal at different axial locations. As these parameters change, flow is "pumped" from the channel that had no wire wrap positioned in it at an upstream position but does at this axial location. The amount of flow pumped is based upon equal axial pressure drop in each subchannel.

- Sweeping - As the wire located in a particular subchannel approaches the gap between pins, a certain fraction of fluid under that projection of the wire is "swept" into an adjacent subchannel. This is fluid that essentially is following the angle of the wire.

- Turbulent Mixing - In the turbulent flow region, a certain amount of heat is transferred between adjacent subchannels due to the eddy diffusivity of the fluid. COTEC uses the β parameter, analagous to that used in the COBRA codes(1,2), to model mixing.

- Thermal Conduction - In a liquid metal, the amount of heat transferred by thermal conduction must also be included. The heat transferred is related to the gap width and the equivalent conduction length, which is not the distance between centroids of the adjacent subchannels(3).

The COTEC code was developed using the above four mechanisms which transfer heat between subchannels. This code has been checked against 19 pin sodium h transfer data obtained in the FFM loop at ORNL(4). Reasonable agreement has been obtained between the experimental sodium heat transfer results and the COTEC code predictions, using two different models to predict swirl in the outer edge subchannels. However, these swirl flow models give dramatically different results when they are applied to the FFTF 217 pin bundle.

2. MODELS

The four different mechanisms of heat and mass transfer that are employed in the COTEC code are discussed in this section of the report. Two of the mechanisms only exchange energy while the remainder exchange both mass as well as energy.

2.1 Pumping

Pumping of fluid is caused by the wire wrap spiraling around each fuel pin and changing dimensions of subchannels at different axial locations. Different models are used for the central and the side subchannels. Across any particular gap between pins in a central subchannel, the fluid will flow into or leave the subchannel of interest, depending upon the wire wrap position. However, across a gap connecting one edge subchannel to another edge channel, the fluid only flows in one direction, always leaving or entering the subchannel of interest.

Figure 1 schematically illustrates pumping that occurs in all central subchannels. The upper portion of this figure illustrates the subchannel (enclosed by the dotted lines and surface of the pins), that does not have a wire located within its boundaries. As the fluid progresses axially downstream from this position, the wire rotates to within the boundaries of this subchannel. This causes a reduction in the flow area, A, and hydraulic or equivalent diameter, De, which in turn causes a net outflow of mass from this channel, ΔM. The quantity of mass which leaves the subchannel is based on pressure drop calculations assuming equal axial pressure losses; transverse momentum effects are neglected. The direction of the mass transfer is also shown on this figure, and is based on electrolytic concentration measurements made by HEDL in a water mixing experiment(5).

Figure 2 illustrates the effect of pumping in the channels between the outer row of pins and the duct wall. The "dashed" wire represents the upstream position while the solid wire is the position at the axial location of interest. As the wire moves into a set of edge channels, a quantity of flow, Δm, is pumped from the channel formed by the wall and rods 1 and 2 to that associated with rods 2 and 3. The amount of flow

FIGURE 1

PUMPING

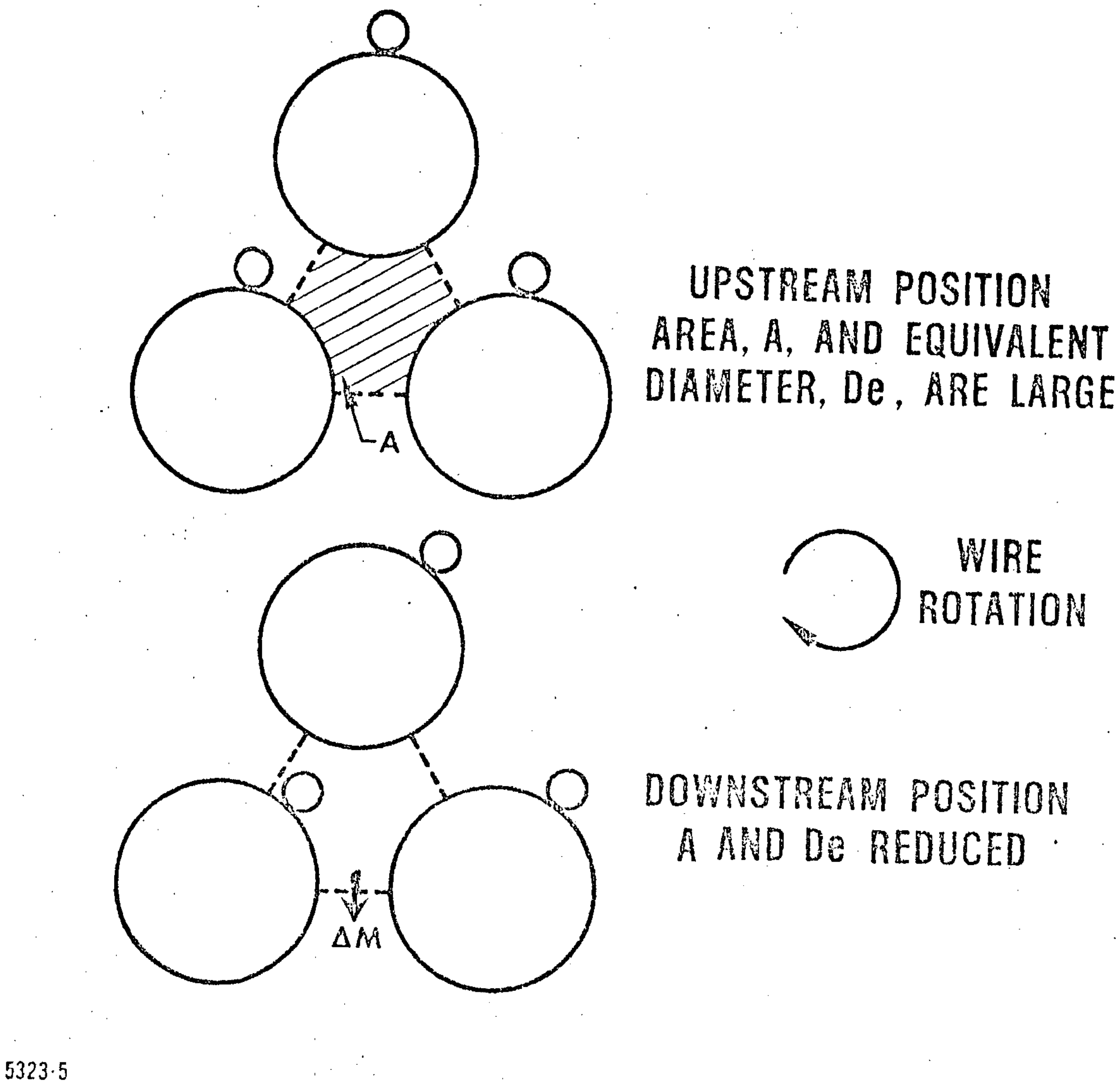
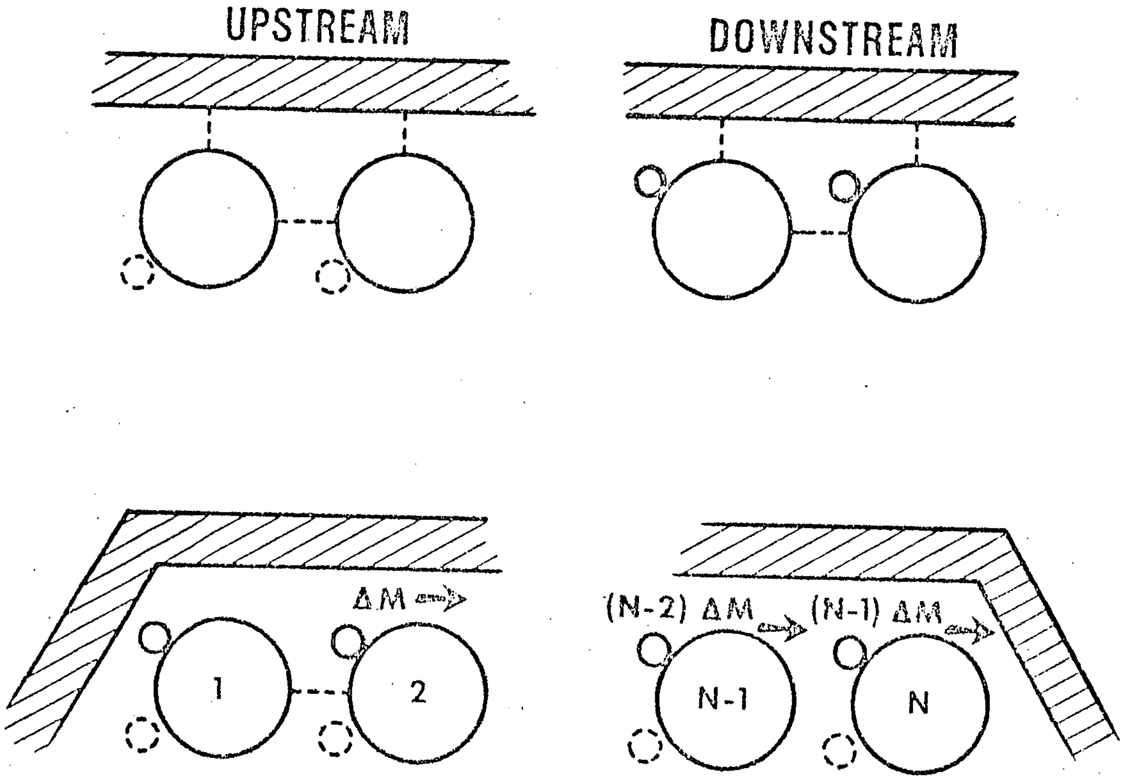


FIGURE 2

EDGE ROW MIXING MODEL



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is calculated using the reduced flow area and equivalent diameter. The flow leaving the channel formed with rods 2 and 3 is the same Δm associated with the reduction in area plus the flow entering the channel for a total of 2 Δm. The flow in the edge channel, which has had its area and equivalent diameter reduced due wire rotation passing the nth rod is (n-1) Δm. This increase is due to the fact that equal axial pressure gradients are assumed. The implications of this increasing flow will be discussed later in this report.

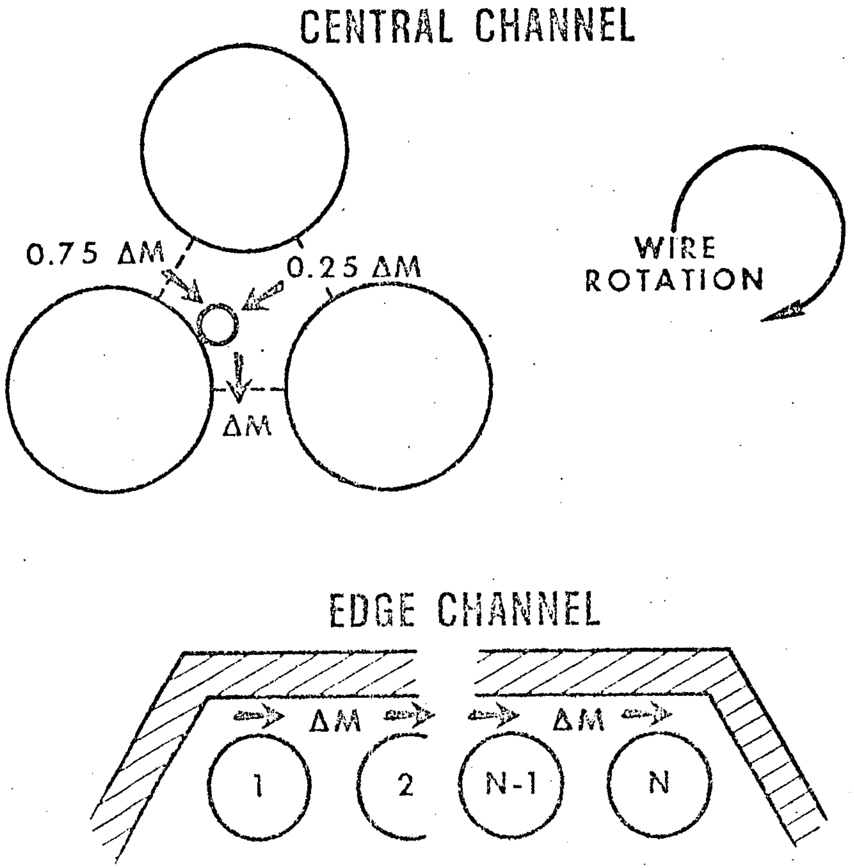
2.2 Sweeping

Sweeping assumes that a certain fraction of the fluid under the "projection" of the wire wrap is moved or swept from one channel to another. This fluid is essentially following the angle at which the wire is rotating at relative to the pin. Figure 3 illustrates the sweeping in both central and side channels. For the central channels, the sweeping occurs only if the angle, θ, between the wire and the next boundary it will cross is less than 60°. If this occurs, Δm is swept from this channel; in order to preserve continuity and equal axial pressure drop, Δm must also enter this channel through the remaining two gaps. The division of 75% and 25% was assumed but calculations indicated that the temperature distribution calculation in fuel assemblies were insensitive to the division of entering flow.

The lower portion of this figure illustrates sweeping in the edge channel. Again, this sweeping has only one direction, compared with sweeping in the central channels which can have two directions across a given gap. The sweeping in the edge channel follows the directions of the wire, is constant circumferentially around the duct at a given axial position, and does not necessarily have the same value as the sweeping in the central subchannels.

FIGURE 3

SWEEPING



2.3 Conduction

Heat, without mass interchange, is exchanged between adjacent subchannels in a liquid metal cooled reactor due to thermal conduction.

$$Q = KA\frac{\Delta T}{\Delta X}$$

where

$$Q = KA\frac{\Delta T}{\Delta X}$$

K = Thermal Conductivity

A = Area = (Gap Width) x (Length)

ΔT = Temperature Difference

ΔX = Effective Conduction Length = Centroid Distance Between Adjacent Subchannels

The effective conduction length, ΔX, is not equal to the distance between centroids since the geometry for heat flow through the sodium is constantly changing between the centroids. The geometry changes due to the curved surface of the rods. ORNL$^{(6)}$ studied this phenomenon and found, using electrical analog techniques, that the effective conduction length is:

$$\Delta X = \frac{\Delta X\ \text{Centroid}}{\frac{1.38}{\sqrt{3}}\left(\frac{\text{Gap}}{\text{Dia}}\right)^{.674}\left(\frac{\text{Pitch}}{\text{Gap}}\right)}$$

Using FFTF dimensions, the effective conduction length is found related to the distance between centroids by the following relationship.

$$\Delta X = \frac{\Delta X_{\text{centroid}}}{1.7}$$

2.4 Turbulent Mixing

In the turbulent flow regime, a certain quantity of heat is transferred between adjacent subchannels due to the turbulence or eddy diffusivity of the flowing fluid. COTEC uses the parameter, β, to model this interchange. It is basically the same parameter that has been used in the COBRA$^{(1,2)}$ computer codes and is defined as

$$\beta = \frac{V'}{\overline{V}} = \frac{\text{Turbulent Interchange Velocity}}{\text{Subchannel Avg. Velocity}}$$

$\overline{V}$ is the average velocity of the two adjacent subchannels under consideration.

The quantity of heat transferred between adjacent subchannels due to turbulence is proportional to their temperature difference, ΔT.

$$Q = \rho \times \beta \times C_p \times \text{Gap} \times \text{Length} \times \Delta T$$

3. COTEC CODE DESCRIPTION

The COTEC code was developed in order to do rapid computer analyses of wire-wrapped assemblies. It can handle any number of fuel pins, located on a triangular pitch within a hexagonal can, up to a maximum of 271 pins. The nodal layout is generated automatically so that the user does not have to do the laborious job of specifying all channel connections. The code solves the energy and continuity equations, simultaneously, as well as a "pseudo" momentum equation which assumes equal frictional pressure loss in all channels and neglects transverse momentum. Since the code was written for highly turbulent flow, as will occur in normal FFTF fuel assembly operation, buoyancy effects were neglected.

The calculational procedure used in COTEC is:

1. Calculate cross flows for selected calculational step.

   The continuity equation is satisfied.

2. If cross flows are too large, reduce calculational increment.
3. Calculate temperatures at end of axial position using cross-flow as well as flow and temperature conditions at beginning of increment.
4. Update new flows and temperatures.
5. Repeat steps 1 - 4 until calculation proceeds to end of axial length being analyzed.

This procedure calculates fuel assembly coolant temperatures rapdily. In fact, using the CDC-7600, the calculation time required to analyze the full 217 pin FFTF fuel assembly, including the unheated plenum, is only about 30 seconds.

4. COMPARISON WITH DATA

Figure 4 illustrates the comparison of COTEC analytical predictions with experimental data obtained in the FFM. The center of this figure illustrates the channel numbering scheme used for FFM as well as the channels in which exit thermocouples were located. These thermocouples were located about three inches downstream from the end of the heated pin region.

The curve at the left of Figure 4 illustrates the comparison of analytical predictions (solid or dashed lines) with experimental data taken in many runs. All pins were uniformly heated axially and radially. Two cross-flow mixing models were used and both gave reasonable agreement with the data and each other. One model assumed just sweeping, with no pumping, which in turn caused the circumferential swirl in the side channels. The other model assumed that pumping, in the side channels, caused by wire wrap rotation, was the only mechanism that caused swirl flow. Even though both models give reasonable agreement for 19 pins, these models yield dramatically different results for a 217 heated pin assembly.

The graph located on the right side illustrates measured dimensionless temperature and predicted temperatures when only the three rods (shown in the center of this figure) are heated. Again, both pumping and sweeping swirl models are in reasonable agreement and predict the data. These data also conclusively indicate that swirl flow does exist. Although both channels 27 and 36 are equidistant from the heated pins, channel 36 is much warmer than Channel 27. This would infer a counterclockwise swirl, which is the same direction as the wire rotating around the pin.

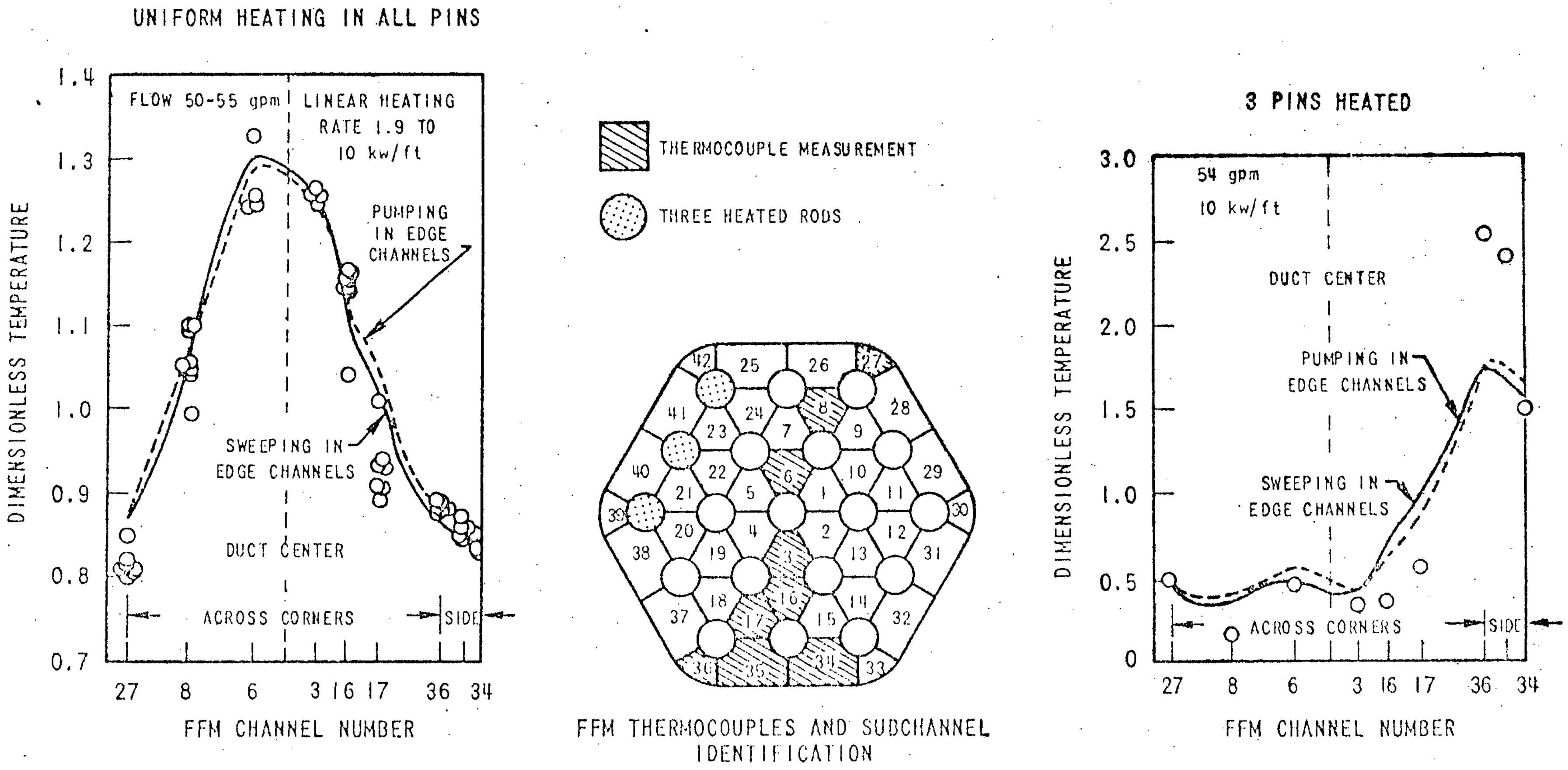


Figure 4. Comparison of Calculated and Experimental Results

5. 217 PIN CALCULATION

The previous section discussed the capability of COTEC for accurately calculating 19 pin sodium heat transfer data. Two analytical models were shown to be in good agreement; the only difference in these models is the treatment of edge swirl flow models. When these two models are used to predict temperature in a 217 pin bundle, dramatic differences in edge temperature distributions occur. When only sweeping is considered, the swirl flow in the side subchannels of both the 19 pin and 217 pin bundles are approximately the same. However, when pumping is considered, the swirl flow is increased compared to that which exists with 19 pins. The reason for this increase is the larger number of pins along the side of the assembly. Figure 2 illustrates that the amount of swirl is related to the number of edge pins.

The effect these two models have on temperature gradients (the difference between maximum and minimum temperatures) in the edge channels is shown in Table 1. When uniform power is produced in all 217 pins, the gradients are not very large. This table indicates that the small gradients obtained with uniform power are slightly higher with the pumping model than those computed with swirl. This is attributable to wire wrap rotation and different analytical treatment of the edge channel in the two models. The opposite is true for a power gradient condition. When a power skew exists across an assembly, such as in the outer edge row of the reactor, then a temperature gradient occurs. If swirl is the same as in the 19 pin bundle, then a gradient of about 75°F will occur downstream from the end of the active core (36" elevation). However, if pumping is the dominant mechanism, the increased swirl will cause a reduction in this gradient to 45°F at the end of the active core. Further downstream, the gradient is reduced even further due to swirl, pumping and conduction and convective heat transfer.

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TABLE 1

COMPARISON OF CALCULATED TRANSVERSE DUCT TEMPERATURE GRADIENTS

AXIAL LOCATION FROM START OF CORE (IN.)	EDGE ROW PUMPING (°F)	EDGE ROW SWIRL (°F)	RATIO MAX. TO AVERAGE POWER
18	18	11	1.0
36	19	11	
54	7	4	
72	5	2	
18	29	47	1.2
36	45	75	
54	18	73	
72	15	73	

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