DEVELOPMENT OF STABILITY CRITERIA AND
AN INTERASSEMBLY CONDUCTION MODEL FOR
THE THERMAL-HYDRAULICS CODE SUPERENERGY

by

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TABLE OF CONTENTS

	<u>Page No.</u>
Title Page	i
Table of Contents	ii
List of Figures	iii
List of Tables	iv
1. INTRODUCTION	1
2. STABILITY CRITERIA	2
2.1 Derivation of SUPERENERGY Temperature Expressions	2
2.1.1 Interior Subchannel Energy Balance	3
2.1.2 Edge Subchannel Energy Balance	4
2.1.3 Corner Subchannel Energy Balance	5
2.1.4 Gap Edge Subchannel Energy Balance	6
2.1.5 Gap Corner Subchannel Energy Balance	7
2.1.6 Duct Wall Subchannels	8
2.2 Derivation of the Stability Criteria	9
2.2.1 Interior Subchannel Criteria	9
2.2.2 Edge Subchannel Criteria	10
2.2.3 Corner Subchannel Criteria	11
2.2.4 Gap Edge Subchannel Criteria	11
2.2.5 Gap Corner Subchannel Criteria	12
2.3 Discussion of the Stability Criteria	13
3. INTERASSEMBLY CONDUCTION SOLUTION	14
3.1 Derivation of Governing Equations	14
3.1.1 Edge Subchannel Solution	15
3.1.2 Corner Subchannel Solution	16
3.2 Approximation of Error Induced by the Conduction Solution	18
4. CONDUCTION SOLUTION EXAMPLES	21
4.1 Example 1 - EBR-II	21
4.2 Example 2 - Investigation of Maximum Error	24
5. CONCLUSIONS	27
Nomenclature	29
List of References	33
Figures	34
Tables	38
Appendix A	40

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LIST OF FIGURES

<u>Fig. No.</u>		<u>Page No.</u>
1	Subchannels in an Assembly	34
2	Interior Subchannel Configuration	35
3	Edge Subchannel Configuration	35
4	Corner Subchannel Configuration	35
5	Gap Edge Subchannel Configuration	36
6	Gap Corner Subchannel Configuration	36
7	Edge Subchannel Configuration - Conduction Solution	37
8	Corner Subchannel Configuration - Conduction Solution	37

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
4-1	EBR-II Parameters for Example 1	38
4-2	EBR-II Parameters for Example 2	39

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1. INTRODUCTION

The SUPERENERGY⁽¹⁾ code is a forced convection regime multiassembly fast reactor subchannel code developed from the ENERGY^(2,3) model. The model represents the transfer of heat from one subchannel to another due to wire wrap sweeping and swirl effects by two constants which are obtained from correlation of available wire wrapped bundle data. These constants are an enhanced eddy diffusivity ϵ^* and a swirl to average axial velocity ratio C_1 which have been correlated by Khan^(2,4). The forced convection part of this model, i.e., that part used in SUPERENERGY, does not include buoyancy effects, which for many cases of interest are negligible when compared to the wire wrap sweeping effects, thus eliminating the need for simultaneous solution of the energy and momentum equations. This allows a simple explicit marching procedure solution technique for the governing energy equation.

As is the case of all explicit solution schemes, SUPERENERGY does become unstable and the solution begins to oscillate when too few axial steps are used. Until recently this problem was of little concern for all geometry and forced convection flow combinations investigated because SUPERENERGY's fast computation times allowed the usage of 500 axial steps — far more than the apparent

stability limit. This, however, is not the case with the EBR-II type bundles because of their small interassembly gaps and corresponding low mass flow rates through that gap. When modeled by SUPERENERGY the resulting temperature fields became unstable. The following report is an investigation and recommended solution of these SUPERENERGY instability problems.

2. STABILITY CRITERIA

2.1 Derivation of SUPERENERGY Temperature Expressions

Before a stability criteria for SUPERENERGY can be developed it is necessary to derive the temperature expressions used in the code. This is done by performing a nodal energy balance on each subchannel arrangement in the wire wrapped bundle using an explicit formulation.

The ENERGY model used (Fig. 1) breaks the assembly into two regions, Region I the bundle interior, where the inter-subchannel heat transfer is modeled by an enhanced eddy diffusivity ϵ^* , and Region II, the bundle periphery, where the swirl effects caused by the wire wrap are most important. In SUPERENERGY these regions are broken up into subchannels in the conventional manner. The velocities in these channels are now being determined at MIT by experiment. At the present, however, Novenstern's flow split method is used. The volumetric heat sources are determined using a weighted average of the radial power/

factors of fuel pins surrounding each subchannel along with the average heat flux and axial power profile. Using this information it is possible to perform a nodal energy balance on each subchannel configuration in the following manner:

Nodal Energy Balance

$$\left[\begin{array}{c} \text{Change in} \\ \text{subchannel} \\ \text{energy} \end{array} \right] = \left[\begin{array}{c} \text{Total input} \\ \text{from heat} \\ \text{source} \end{array} \right] + \left[\begin{array}{c} \text{Total input due to} \\ \text{heat flow from} \\ \text{surrounding subchannels} \end{array} \right]$$

2.1.1 Interior Subchannel Energy Balance (Fig. 2)

$$\begin{aligned} \rho C_p V_1 A_1 (T_o^{J+1} - T_o^J) &= Q_o A_1 \Delta Z \\ &+ (P-D) \Delta Z \left[\frac{T_1^J - T_o^J}{H_1} + \frac{T_2^J - T_o^J}{H_2} + \frac{T_3^J - T_o^J}{H_3} \right] \end{aligned} \quad (2-1)$$

where all the variables are defined in the accompanying nomenclature listing. The quantities H_1 , H_2 and H_3 may be expanded to the following

$$H_1 = H_2 = \frac{\eta_1}{k + \rho C_p \epsilon_{H_1}}$$

$$H_3 = \frac{\eta_A}{k + \rho C_p \epsilon_{H_A}}$$

where the subscript

A = 1 if node 3 is an interior subchannel

A = 2 if node 3 is an edge subchannel

Substituting these expressions and rearranging (2-1) yields:

$$\begin{aligned}
T_o^{J+1} = T_o^J + \frac{Q_o \Delta Z}{\rho C_p V_1} + \frac{(P-D) \Delta Z}{A_1 \rho C_p V_1} (k + \rho C_p \epsilon_{H_1}) \left[\frac{T_1^J + T_2^J - 2T_o^J}{\eta_1} \right] \\
+ \frac{(P-D) \Delta Z}{A_1 \rho C_p V_1} (k + \rho C_p \epsilon_{H_A}) \left[\frac{T_3^J - T_o^J}{\eta_A} \right] \quad (2-2)
\end{aligned}$$

This is the SUPERENERGY expression for temperature in an interior subchannel. Notice that T_o^{J+1} is found explicitly, thus lending itself to a simple marching solution scheme.

2.1.2 Edge Subchannel Energy Balance (Fig. 3)

$$\begin{aligned}
\rho C_p V_2 A_2 (T_o^{J+1} - T_o^J) = Q_o A_2 \Delta Z + (P-D) \Delta Z \left[\frac{T_1^J - T_o^J}{H_1} \right] \\
+ g \Delta Z \left[\frac{T_2^J - T_o^J}{H_2} \right] + g \Delta Z \left[\frac{T_3^J - T_o^J}{H_3} \right] \\
+ P \Delta Z \left[\frac{T_4^J - T_o^J}{H_4} \right] + \rho C_p V_\theta g \Delta Z \left[T_2^J - T_o^J \right] \quad (2-3)
\end{aligned}$$

where

$$\begin{aligned}
H_1 &= \frac{\eta_2}{k + \rho C_p \epsilon_{H_2}} & H_2 &= \frac{\eta_A}{k + \rho C_p \epsilon_{H_A}} \\
H_3 &= \frac{\eta_B}{k + \rho C_p \epsilon_{H_B}} & H_4 &= R_2 = \frac{1}{h_2} + \frac{S_1}{2k_w}
\end{aligned}$$

and the subscripts

A = 3 if node 2 is an edge subchannel

A = 4 if node 2 is a corner subchannel

B = 3 if node 3 is an edge subchannel

B = 4 if node 3 is a corner subchannel

replacing these expressions and rearranging (2-3) yields

$$\begin{aligned}
 T_o^{J+1} = & \frac{Q_o \Delta Z}{\rho C_p V_2} + \frac{(P-D) \Delta Z}{\rho C_p V_2 A_2} (k + \rho C_p \epsilon_{H_2}) \left[\frac{T_1^J - T_o^J}{\eta_2} \right] + T_o^J \\
 & + \frac{g \Delta Z}{\rho C_p V_2 A_2} \left[\frac{(T_2^J - T_o^J)}{\eta_A} (k + \rho C_p \epsilon_{H_A}) + \frac{(T_3^J - T_o^J)}{\eta_B} (k + \rho C_p \epsilon_{H_B}) \right] \\
 & + \frac{P \Delta Z}{\rho C_p V_2 A_2} \left[\frac{T_4^J - T_o^J}{R_2} \right] + \frac{V_\theta}{V_2} \frac{g \Delta Z}{A_2} [T_2^J - T_o^J] \quad (2-4)
 \end{aligned}$$

2.1.3 Corner Subchannel Energy Balance (Fig. 4)

$$\begin{aligned}
 \rho C_p V_3 A_3 (T_o^{J+1} - T_o^J) = & Q_o \Delta Z A_3 + g \Delta Z \left[\frac{T_1^J - T_o^J}{H_1} \frac{T_2^J - T_o^J}{H_2} \right] \\
 & + X_1 \Delta Z \left[\frac{T_3^J - T_o^J}{H_3} \right] + \rho C_p V_\theta g \Delta Z [T_1^J - T_o^J] \quad (2-5)
 \end{aligned}$$

where

$$H_1 = H_2 = \frac{\eta_4}{k + \rho C_p \epsilon_{H_4}} \quad H_3 = R_3 = \frac{1}{h_3} + \frac{S_1}{\sqrt{3} k_w}$$

replacing these expressions and rearranging (2-5) yields

$$\begin{aligned}
 T_o^{J+1} = T_o^J &+ \frac{Q_o \Delta Z}{\rho C_p V_3} + \frac{g \Delta Z}{\rho C_p V_3 A_3} (k + \rho C_p \epsilon_{H_4}) \left[\frac{T_1^J + T_2^J - 2T_o^J}{\eta_4} \right] \\
 &+ \frac{X_1 \Delta Z}{\rho C_p V_3 A_3} \left[\frac{T_3^J - T_o^J}{R_3} \right] + \frac{V_\theta}{V_3} \frac{g \Delta Z}{A_3} [T_1^J - T_o^J] \quad (2-6)
 \end{aligned}$$

This is the SUPERENERGY expression for temperature in a corner subchannel.

2.1.4 Gap Edge Subchannel Energy Balance (Fig. 5)

$$\begin{aligned}
 \rho C_p V_6 A_6 (T_o^{J+1} - T_o^J) &= P \Delta Z \left[\frac{T_1^J - T_o^J}{H_1} + \frac{T_4^J - T_o^J}{H_4} \right] \\
 &+ \frac{S_2 \Delta Z}{2} \left[\frac{T_2^J - T_o^J}{H_2} + \frac{T_3^J - T_o^J}{H_3} \right] \quad (2-7)
 \end{aligned}$$

where

$$H_1 = R_6 = \frac{1}{h_6} + \frac{S_1}{2kw}$$

$$H_2 = \frac{\eta_A}{k}$$

$$H_3 = \frac{\eta_B}{k}$$

$$H_4 = \frac{S_2}{2k}$$

and the subscripts

A = 3 if node 2 is a gap edge subchannel

A = 6 if node 2 is a gap corner subchannel

B = 3 if node 3 is a gap edge subchannel

B = 6 if node 3 is a gap corner subchannel

replacing these expressions and rearranging (2-7) yields

$$\begin{aligned}
 T_o^{J+1} = T_o^J + \frac{P\Delta Z}{\rho C_p V_6 A_6} \left[\frac{T_1^J - T_o^J}{R_6} + 2k \frac{(T_4^J - T_o^J)}{S_2} \right] \\
 + \frac{S_2 k \Delta Z}{\rho C_p V_6 A_6} \left[\frac{T_2^J - T_o^J}{\eta_A} + \frac{T_3^J - T_o^J}{\eta_B} \right]
 \end{aligned} \quad (2-8)$$

This is the SUPERENERGY expression for temperature in the interassembly gap edge subchannel

2.1.5 Gap Corner Subchannel Energy Balance (Fig. 6)

$$\begin{aligned}
 \rho C_p V_7 A_7 (T_o^{J+1} - T_o^J) = X_2 \Delta Z \left[\frac{T_1^J - T_o^J}{H_1} \right] + X_3 \Delta Z \left[\frac{T_4^J - T_o^J}{H_4} \right] \\
 + \frac{S_2}{2} \Delta Z \left[\frac{T_2^J - T_o^J}{H_2} + \frac{T_3^J - T_o^J}{H_3} \right]
 \end{aligned} \quad (2-9)$$

where

$$H_1 = R_7 = \frac{1}{h_7} + \frac{S_1}{\sqrt{3} kw}$$

$$H_2 = H_3 = \frac{\eta_6}{k}$$

$$H_4 = \frac{S_2}{2k}$$

replacing these expressions and rearranging (2-9) yields.

$$\begin{aligned} T_o^{J+1} = T_o^J + \frac{X_2 \Delta Z}{\rho C_p V_7 A_7} \left[\frac{T_1^J - T_o^J}{R_7} \right] + \frac{2X_3 \Delta Z k}{\rho C_p V_7 A_7} \left[\frac{T_4^J - T_o^J}{S_2} \right] \\ + \frac{S_2 k \Delta Z}{\rho C_p V_7 A_7} \left[\frac{T_2^J + T_3^J - 2T_o^J}{\eta_6} \right] \end{aligned} \quad (2-10)$$

This is the SUPERENERGY expression for temperature in the interassembly gap corner subchannel.

2.1.6 Duct Wall Subchannels

The ENERGY model assumes that azimuthal conduction effects in the duct wall are small and therefore can be neglected. This assumption is based on two criteria; first, the small ΔT across the thin duct wall and second, the high conductivity of the liquid sodium on either side of the duct wall which tends to equalize the azimuthal temperature profile.

The duct wall temperature at any axial level is found by simple resistance averaging of the temperatures in the bordering bundle and interassembly gap subchannels at the same axial level. Again, this simplifies the solution technique by allowing a simple marching procedure.

For the duct wall edge type channels:

$$T_o^{J+1} = \frac{R_6 T_1^{J+1} + R_2 T_4^{J+1}}{R_6 + R_2} \quad (2-11)$$

For the duct wall corner type channels

$$T_o^{J+1} = \frac{R_7 X_1 T_1^{J+1} + R_3 X_2 T_4^{J+1}}{R_7 X_1 + R_3 X_2} \quad (2-12)$$

2.2 Derivation of the Stability Criteria

2.2.1 Interior Subchannel Criteria

For no oscillation of the temperature solution T_o^{J+1} in the interior subchannels it is necessary for the right hand side of equation (2-2) to remain positive in the most limiting case. The most limiting case occurs when the heat generation term is zero and when the temperatures T_1^J , T_2^J and T_3^J are very small compared to T_o^J . Then for the right hand side to remain positive the sum of coefficients of the mixing terms must be less than one.

$$1 - \frac{(P-D)\Delta Z}{A_1 \rho C_p V_1} \frac{(k + \rho C_p \epsilon_{H_1})}{\eta_1} - \frac{(P-D)\Delta Z}{A_1 \rho C_p V_1} \frac{(k + \rho C_p \epsilon_{H_2})}{\eta_2} \geq 0 \quad (2-13)$$

By rearranging (2-13)

$$\Delta Z_A \leq \frac{A_1 \rho C_p V_1}{(P-D) \left[\frac{2(k + \rho C_p \epsilon_{H_1})}{\eta_1} + \frac{(k + \rho C_p \epsilon_{H_2})}{\eta_2} \right]} \quad (2-14)$$

where as in Section 2.1.1 the subscript

A = 1 if node 3 is an interior subchannel

A = 2 if node 3 is an edge subchannel

2.2.2 Edge Subchannel Criteria

As in the interior subchannel case, for no oscillation of the temperature solution T_o^{J+1} in edge subchannel it is necessary for the right hand side of equation (2-4) to remain positive. This occurs when

$$1 - \frac{(P-D)\Delta Z}{\rho C_p V_2 A_2} \frac{(k + \rho C_p \epsilon_{H_2})}{\eta_2} - \frac{g\Delta Z}{\rho C_p V_2 A_2} \left[\frac{(k + \rho C_p \epsilon_{H_A})}{\eta_A} + \frac{(k + \rho C_p \epsilon_{H_B})}{\eta_B} \right] - \frac{P\Delta Z}{\rho C_p V_2 A_2} \frac{1}{R_2} - \frac{V_\theta}{V_2} \frac{g\Delta Z}{A_2} \geq 0 \quad (2-15)$$

By rearranging (2-15)

$$\Delta Z_B \leq \frac{\rho C_p A_2 V_2}{\left[\frac{(P-D)}{\eta_2} (k + \rho C_p \epsilon_{H_2}) + \frac{g}{\eta_A} (k + \rho C_p \epsilon_{H_A}) + \frac{g}{\eta_B} (k + \rho C_p \epsilon_{H_B}) + \frac{P}{R_2} + \rho C_p g V_\theta \right]} \quad (2-16)$$

where

A = 4 if node 2 is a corner subchannel

A = 3 if node 2 is an edge subchannel

B = 4 if node 3 is a corner subchannel

B = 3 if node 3 is an edge subchannel

2.2.3 Corner Subchannel Criteria

In a similar manner using Eq. (2-6)

$$1 - \frac{2g\Delta Z}{\rho C_p V_3 A_3} \frac{(k + \rho C_p \epsilon_{H_4})}{\eta_4} - \frac{X_1 \Delta Z}{\rho C_p V_3 A_3} - \frac{V_\theta}{V_3} \frac{g\Delta Z}{A_3} \geq 0 \quad (2-17)$$

by rearranging (2-17)

$$\Delta Z_5 \leq \frac{\rho C_p A_3 V_3}{\left[\frac{2g}{\eta_4} (k + \rho C_p \epsilon_{H_4}) + \frac{X_1}{R_3} + \rho C_p V_\theta g \right]} \quad (2-18)$$

2.2.4 Gap Edge Subchannel Criteria

In a similar manner using Eq. (2-8)

$$1 - \frac{P\Delta Z}{\rho C_p V_6 A_6} \left[\frac{1}{R_6} + \frac{2k}{S_2} \right] - \frac{S_2 k \Delta Z}{\rho C_p V_6 A_6} \left[\frac{1}{\eta_A} + \frac{1}{\eta_B} \right] \geq 0 \quad (2-19)$$

By rearranging (2-19)

$$\Delta Z_c \leq \frac{\rho C_p V_6 A_6}{\left[\frac{P}{R_6} + \frac{2kP}{S_2} + \frac{S_2 k}{\eta_A} + \frac{S_2 k}{\eta_B} \right]} \quad (2-20)$$

where the subscripts

A = 3 if node 2 is a gap edge subchannel

A = 6 if node 2 is a gap corner subchannel

B = 3 if node 3 is a gap edge subchannel

B = 6 if node 3 is a gap corner subchannel

C = 6 if node 2 is a gap edge subchannel

C = 7 if node 2 is a gap corner subchannel

2.2.5 Gap Corner Subchannel Criteria

Using (2-10)

$$1 - \frac{X_2 \Delta Z}{\rho C_p V_7 A_7} \frac{1}{R_7} - \frac{2X_3 \Delta Z k}{\rho C_p V_7 A_7 S_2} - \frac{2S_2 k \Delta Z}{\rho C_p V_7 A_7 \eta_6} \geq 0 \quad (2-21)$$

by rearranging (2-21)

$$\Delta Z_8 \leq \frac{\rho C_p V_7 A_7}{\left[\frac{X_2}{R_7} + \frac{2X_3 k}{S_2} + \frac{2S_2 k}{\eta_6} \right]} \quad (2-22)$$

2.3 Discussion of the Stability Criteria

The maximum axial step size possible for stability is obtainable by examining the results of Section 2.2. Represented there are the eight maximum axial step sizes possible for each subchannel geometry present in the wire wrapped bundle. The smallest of these is the governing step size for the assembly. The minimum number of axial steps necessary for a stable solution is then

$$N = \frac{L}{\Delta Z_{\min}} \quad (2-23)$$

where

L = the bundle axial length.

$\Delta Z_{\min}$ = the minimum constraining maximum axial step size

This prediction of the minimum necessary number of axial steps was checked for different bundles by raising the axial step size in SUPERENERGY until the solution became unstable. In all cases tested, the criteria proved to be quite accurate or at most slightly conservative in its predictions.

By using the equations from Section 2.2, it is possible to determine the necessary number of axial steps for a multi-assembly run of coupled EBR-II type 91 pin bundles with low flowrates (the flowrates are not, however, in the mixed convection regime as predicted by the Gr_c^* criteria in Ref. 2). For example, for a gap flowrate of 100 lbm/hr,

which is not uncommon since the interassembly gap thickness is 0.027", the minimum number of axial steps as predicted by the governing step size ΔZ_6 (Eq. 2-20) is 4903 axial steps. Use of this number of axial steps is not economically feasible for multiassembly solutions.

This simple example implies that for small inter-assembly gap sizes and flowrates, stability requirements may dictate non-economic solutions. One way around this stability constraint is to suppress the interassembly gap flow and impose a conduction solution across the gap. This solution may be slightly less accurate but may be justified as a good approximation in light of the relatively small volumetric flowrate through the gap and the costs in computer time for an accurate solution. Section 3 examines this type of solution.

3. INTERASSEMBLY CONDUCTION SOLUTION

3.1 Derivation of Governing Equations

A conduction solution can be developed with relative ease as will be seen below by using the thermal resistance method. The sodium in the interassembly gap is assumed to be a stagnant liquid pool. The contact resistance between the bulk sodium and the duct wall is calculated by finding the heat transfer coefficient at the actual velocity of the interassembly gap flow. Azimuthal conduction effects are ignored.

3.1.1 Edge Subchannel Solution (Fig. 7)

By performing an energy balance on the edge subchannel

$$\begin{aligned}
 \rho C_p V_2 A_2 (T_o^{J+1} - T_o^J) &= Q_o A_2 \Delta Z + (P-D) \Delta Z \left[\frac{T_1^J - T_o^J}{H_1} \right] \\
 &+ g \Delta Z \left[\frac{T_2^J - T_o^J}{H_2} \right] + g \Delta Z \left[\frac{T_3^J - T_o^J}{H_3} \right] + P \Delta Z \left[\frac{T_4^J - T_o^J}{H_4} \right] \\
 &+ \rho C_p V_\theta g \Delta Z [T_2^J - T_o^J]
 \end{aligned} \tag{3-1}$$

where

$$H_1 = \frac{\eta_2}{(k + \rho C_p \epsilon_{H_2})}$$

$$H_2 = \frac{\eta_A}{(k + \rho C_p \epsilon_{H_A})}$$

$$H_3 = \frac{\eta_B}{(k + \rho C_p \epsilon_{H_B})}$$

$$H_4 \equiv R_4 = \frac{S_1^L}{k_w} + \frac{S_1^M}{k_w} + \frac{1}{h_2^L} + \frac{1}{h_2^M} + \frac{1}{h_6^L} + \frac{1}{h_6^M} = R_2^L + R_2^M + R_6^L + R_6^M$$

and the subscripts

A = 3 if node 2 is an edge subchannel

A = 4 if node 2 is a corner subchannel

B = 3 if node 3 is an edge subchannel

B = 4 if node 3 is a corner subchannel

Note that the only difference between the above equation (3-1) and equation (2-3) is the values of T_4^J and H_4 . By rearranging (3-1) the final expression becomes

$$\begin{aligned}
 T_o^{J+1} = & \frac{Q_o \Delta Z}{\rho C_p V_2} + \frac{(P-D) \Delta Z}{\rho C_p V_2 A_2} (k + \rho C_p \epsilon_{H_2}) \left[\frac{T_1^J - T_o^J}{\eta_2} \right] \\
 & + \frac{g \Delta Z}{\rho C_p V_2 A_2} \left[\frac{(T_2^J - T_o^J)}{\eta_A} (k + \rho C_p \epsilon_{H_A}) + \frac{(T_3^J - T_o^J)}{\eta_B} (k + \rho C_p \epsilon_{H_B}) \right] \\
 & + \frac{P \Delta Z}{\rho C_p V_2 A_2} \left[\frac{(T_4^J - T_o^J)}{R_4} \right] + \frac{V_\theta}{V_2} \frac{g \Delta Z}{A_2} [T_2^J - T_o^J] \quad (3-2)
 \end{aligned}$$

The stability criteria for this equation is exactly the same as (2-16) except R_2 is now R_4 .

3.1.2 Corner Subchannel Solution (Fig. 8)

By using Kirchoffs current law on node 3 the following expression results

$$\frac{T_4^J - T_3^J}{F_4} + \frac{T_5^J - T_3^J}{F_5} + \frac{T_o^J - T_3^J}{F_3} = 0 \quad (3-3)$$

where

$$F_4 = \frac{R_3^M}{X_1^M} + \frac{R_7^M}{X_2^M} \quad F_5 = \frac{R_3^K}{X_1^K} + \frac{R_7^K}{X_2^K} \quad F_3 = \frac{R_3^L}{X_1^L} + \frac{R_7^L}{X_2^L}$$

by rearranging (3-3)

$$T_3^J = \frac{\left[\frac{T_4^J}{F_4} + \frac{T_5^J}{F_5} + \frac{T_0^J}{F_3} \right]}{\frac{1}{F_3} + \frac{1}{F_4} + \frac{1}{F_5}} \quad (3-4)$$

This represents an expression for the temperature at node 3 in terms of the other known quantities at axial level J.

Then by performing an energy balance at node 0, the following expression results.

$$\begin{aligned} \rho C_p V_3 A_3 (T_0^{J+1} - T_0^J) = Q_0 \Delta Z A_3 + g \Delta Z \left[\frac{T_1^J - T_0^J}{H_1} + \frac{T_2^J - T_0^J}{H_2} \right] \\ + X_1 \Delta Z \left[\frac{T_3^J - T_0^J}{H_3} \right] + \rho C_p V_\theta g \Delta Z [T_1^J - T_0^J] \end{aligned} \quad (3-5)$$

where

$$H_1 = H_2 = \frac{\eta_4}{k + \rho C_p \epsilon_{H_4}}$$

$$H_3 \equiv R_5 = \left[\frac{R_3^L}{X_1^L} + \frac{R_7^L}{X_3^L} \right] X_1^L = R_3^L + \frac{R_7^L X_1^L}{X_3^L}$$

Note the similarity between Eqs. (3-5) and (2-5).

The only differences are in T_3^J and H_3 . By rearranging Eq. (3-5) the final expression becomes.

$$\begin{aligned}
T_o^{J+1} = T_o^J &+ \frac{Q_o \Delta Z}{\rho C_p V_3} + \frac{g \Delta Z}{\rho C_p V_3 A_3} (k + \rho C_p \epsilon_{H_4}) \left[\frac{T_1^J - T_2^J - 2T_o^J}{\eta_4} \right] \\
&+ \frac{X_1 \Delta Z}{\rho C_p V_3 A_3} \left[\frac{T_3^J - T_o^J}{R_5} \right] + \frac{V_\theta}{V_3} \frac{g \Delta Z}{A_3} [T_1^J - T_o^J]
\end{aligned} \quad (3-6)$$

The stability criteria in this case is more complicated because of the T_o^J term in Eq. (3-4). If the T_o^J effect in Eq. (3-4) is neglected for the purpose of getting a simple relatively accurate stability expression, the following form results

$$\Delta Z_5 \leq \frac{\rho C_p A_3 V_3}{\left[\frac{2g}{\eta_4} (k + \rho C_p \epsilon_{H_4}) + \frac{X_1}{R_5} + \rho C_p V_\theta g \right]} \quad (3-7)$$

Notice that this is Eq. (2-18) with R_3 replaced by R_5 .

3.2 Approximation of Error Induced by the Conduction Solution

While the conduction solution does conserve energy, it introduces slightly higher temperatures in the bundle due to the fact that energy is no longer removed by way of the interassembly gap. It is possible to get an estimation of the excess energy added to the bundle by using the stability criteria developed in Section 2. For a bundle similar to the EBR II 91 pin type with a small interassembly gap and low mass flow rate the governing equation for maximum step

size to yield a stable solution usually is (2-20)

$$\Delta Z \leq \frac{\rho C_p V_6 A_6}{\left[\frac{P}{R_6} + \frac{2kP}{S_2} + \frac{2S_2 k}{\eta_3} \right]} \quad (2-20)$$

The acceptable maximum axial step size necessary for stability and thereby the limiting geometry and operating conditions can then be determined by comparing this expression to the number of economically feasible axial steps as determined by the user.

$$\Delta Z = \frac{L}{N_e} \leq \frac{\rho C_p V_6 A_6}{\left[\frac{P}{R_6} + \frac{2kP}{S_2} + \frac{2S_2 k}{\eta_3} \right]} \quad (3-8)$$

where

L = bundle length

N_e = number of economically feasible axial steps before the conduction solution has to be used.

Since S_2 is small compared to η_3 and P

$$\frac{2kP}{S_2} \gg \frac{2S_2 k}{\eta_3} \quad (3-9)$$

At low flow conditions

$$Nu = \frac{hD}{k} \approx 7$$

replacing this in the expression for R_6 and using typical numbers for the EBR II gives

$$R_6 = \frac{1}{h_6} + \frac{S_1}{2k_w} = \frac{D}{7k} + \frac{S_1}{2k_w} = \frac{(0.027)}{(24)(7)(40)} + \frac{(0.04)}{(24)(14)}$$

which implies

$$\frac{S_1}{2k_w} \gg \frac{1}{h_6}$$

and

$$R_6 \approx \frac{S_1}{2k_w} \quad (3-10)$$

applying (3-9) and (3-10) to (3-8) the expression becomes.

$$\frac{L}{N_e} \leq \frac{\rho C_p V_6 A_6}{\left[\frac{2Pk_w}{S_1} + \frac{2Pk}{S_2} \right]} \quad (3-11)$$

rearranging

$$V_6 \leq \frac{2LP}{N_e} \frac{(k_w S_2 + k S_1)}{\rho C_p A_6 S_1 S_2} \quad (3-12)$$

Thus, the minimum velocity in the gap that can be treated without the aid of the conduction solution has been fixed as a function of the economic number of axial steps N_e and the geometry. The total energy that would be removed from the interassembly gap at this velocity is then approximately

$$Q_g = \dot{m}_g C_p \Delta T \approx \rho A_g V_6 C_p \Delta T_g \approx \frac{2LP A_g (k_w S_2 + k S_1)}{N_e A_6 S_1 S_2} \Delta T_g \quad (3-13)$$

where

A_g = total area of the interassembly gap associated with the bundle

$\dot{m}_g$ = total interassembly gap flowrate

ΔT_g = axial temperature rise in interassembly gap.

Approximating ΔT_g by the bundle temperature rise then

$$\Delta T_g \approx \Delta T = \frac{Q_{TOT}}{\dot{m}_T C_p} \quad (3-14)$$

using this expression and the definition $A_6 = PS_2/2$, (3-13)

becomes

$$\frac{Q_g}{Q_{TOT}} \approx \frac{4 L A_g (k_w S_2 + k S_1)}{N_e S_1 S_2^2 \dot{m}_T C_p} \times 100 \quad (3-15)$$

This expression is only a very rough approximation of the percent increase in energy that the bundle will see due to the conduction solution. As expected the more steps economically feasible before the conduction solution has to be used, the lower the interassembly gap velocity possible for a given geometry. This translates into a total energy error inversely dependent on the number of steps.

4. CONDUCTION SOLUTION EXAMPLES

4.1 Example - EBR II

As a typical example to verify the derivations of Section 3 for the bundle of interest, the EBR II 91 pin

fuel bundle, two runs were made at the conditions listed in Table 4-1. These are the set of conditions mentioned earlier in Section 2.3

Run one was made using the regular SUPERENERGY inter-assembly gap flow solution technique at the minimum number of axial steps for stability as predicted by the criteria in Section 2. The results were as follows at the bundle outlet:

$$\begin{aligned} Q_{TOT} &= \text{total heat added to the bundle} &= 268.7 \text{ kw} \\ Q_g &= \text{total heat removed by convection} \\ &\quad \text{in the interassembly gap} &= 0.7 \text{ kw} \\ Q_B &= \text{total heat removed through convection} \\ &\quad \text{inside the bundle} &= 268.0 \text{ kw} \end{aligned}$$

yielding an expected energy increase of

$$\left. \frac{Q_g}{Q_{TOT}} \right\}_{\text{expected}} = \frac{0.7}{268.7} \times 100 = 0.261\%$$

when the conduction solution is used with the same bundle geometry and operating conditions. This can be compared with the predicted value derived in Section 3.

$$\begin{aligned} \left. \frac{Q_g}{Q_{TOT}} \right\}_{\text{predicted}} &= \frac{4 L A_g (k_w S_2 + k S_1)}{N_e S_1 S_2^2 \dot{m}_T C_p} \times 100 & (3.15) \\ &= \frac{4(60)(1.276)(3)[(12.1)(0.027) + (41.4)(0.040)](100)}{4900(0.040)(0.027)(12)(35000)(0.3063)} \\ &= 0.263\% \end{aligned}$$

This is extremely excellent agreement considering the crude approximations made in the derivation of Eq. (3-15).

In order to check the expected value and the predicted value of the energy change due to the use of the conduction solution a second run was made with the same conditions listed on Table 4-1, only this time with the SUPERENERGY conduction solution. Note that 4900 axial steps were also used in this case so that the actual solution error could be viewed as closely as possible without introducing other errors dependent on step size. The total heat added to the bundle Q_{TOT} , should be the same as the regular SUPER-ENERGY result. The result, however, was

Q_{TOT} = total heat added to the bundle = 269.3 kw
yielding an actual energy difference of

$$\left. \frac{Q_{g_{eg}}}{Q_{TOT}} \right|_{\text{actual}} = \frac{269.3 - 268.0}{268.7} \times 100 = 0.484\%$$

or almost double that expected. This can probably be attributed to slight differences in the solution schemes compounded over 4900 steps. Even so, errors of a half a percent are trivial when compared with model uncertainties and in particular uncertainties in the bundle geometry.

By examining and comparing the two output temperature maps it is possible to find the maximum local energy change due to the conduction solution. The maximum deviation in temperature is a $+1^{\circ}\text{F}$ difference between the conduction solution and the gap flow solution which occurs in the edge

subchannels. The total temperature rise in these subchannels is 80°. Then

$$\left. \frac{Q_g}{Q_{TOT}} \right|_{\text{local}} = \frac{m_T C_p (1^\circ)}{m_T C_p T} \times 100 = \frac{100}{80} = 1.25\%$$

Thus the local error ranges from a minimum value of 0% in the interior subchannels to a maximum value of 1.25% in the edge subchannels with an average error of 0.484% for this, a typical case of the EBR II 91 pin fuel assembly

4.2 Investigation of Maximum Error - Example

To examine the maximum energy error induced by the conduction solution it is necessary to analyze a set of bundle geometry and flow conditions which combine to give a minimum limit on the number of axial steps for a stable solution far below that which would be normally imposed by economic constraints. This is because, as discussed in Section 3, the error is inversely proportional to the minimum number of axial steps as defined by the stability criteria in Section 2. For this purpose the set of conditions listed in Table 4-2 were chosen. Note the stable minimum limit on the number of axial steps as imposed by Eq. (2-20) (the governing equation in this EBR II example) is 490. This is a very low economic constraint. With SUPERENERGY axial step numbers of 2000 or higher are easily affordable. Thus the example chosen would normally use the regular SUPERENERGY solution technique only.

The first run was made with the regular SUPERENERGY interassembly gap solution method. The results were as follows:

$$Q_{TOT} = 272.4 \text{ kw}$$

$$Q_g = 6.2 \text{ kw}$$

$$Q_B = 266.2 \text{ kw}$$

Thus as in Section 4.1, the expected energy increase is

$$\left. \frac{Q_g}{Q_{TOT}} \right)_{\text{expected}} = \frac{6.2}{272.4} \times 100 = 2.28\%$$

when the conduction solution is used. This can be compared with the predicted value derived in Section 3.

$$\begin{aligned} \left. \frac{Q_g}{Q_{TOT}} \right)_{\text{predicted}} &= \frac{4 L A_g (k_w S_2 + k S_1)}{N_e S_1 S_2^2 m_T C_p} & (3-15) \\ &= \frac{4(60)(1.276)(3)[(12.1)(0.027) + (41.4)(0.040)](100)}{(490)(0.040)(0.027)(12)(35000)(0.3063)} \\ &= 2.63\% \end{aligned}$$

To check the predicted and expected values against the actual case the conduction solution was run at the same operating conditions yielding a value of Q_{TOT} equal to that of the regular SUPERENERGY solution:

$$Q_{TOT} = 272.4 \text{ kw}$$

then

$$\left. \frac{Q_g}{Q_{TOT}} \right)_{\text{actual}} = \left. \frac{Q_g}{Q_{TOT}} \right)_{\text{expected}} = 2.28\%$$

Thus for the low economic step limit of 490 the average energy increase error inside the bundle duct wall is about 2.28%. The local error can be examined in this example by examining the temperature maps. The maximum deviation between the two solutions was 4° out of 75°, again in the edge subchannels. This yields a local difference of

$$\left. \frac{Q_g}{Q_{TOT}} \right|_{\text{local}} = \frac{m_T C_p^{(4)} \Delta T}{m_T C_p \Delta T} \times 100 = \frac{400}{75} = 5.33\%$$

To further examine this local effect two runs were made changing only the enhanced eddy diffusivities from 0.02 to 0.001, thus in effect decoupling Region II from Region I. This resulted in the same average energy increase error but in a more pronounced local effect. The maximum temperature deviation between the solutions was now 6° out of 61°. Then

$$\left. \frac{Q_g}{Q_{TOT}} \right|_{\text{local}} = \frac{m_T C_p^{(6)} \Delta T}{m_T C_p \Delta T} \times \frac{600}{61} = 9.84\%$$

The above numbers presented in this subsection seem to be characteristic of the maximum local error to be expected since in realistic examples (Section 4.1) (1) the subchannels are not decoupled by such a low eddy diffusivity and (2) a case with such a high interassembly gap velocity (and thereby a high energy error in the conduction solution) would be run with the normal SUPERENERGY

mode of operation. The cases where the conduction solution should produce the most error under normal circumstances are high power skew coupled multiassembly calculations. If it is found that the stability limits derived in Section 2 are applicable and constraining in a situation of this type, implying that a conduction solution is indicated, sample calculations similar to those presented in this section should be performed for the specific geometry and operating conditions to assess the error.

5. CONCLUSIONS

This report has presented a look into the derivation of the governing temperature field equations for SUPERENERGY, a stability criteria for use with these equations, and an alternate solution technique for use when these criteria are not specifically met. The stability criteria in Section 2 are valid for all cases tested to date, and indeed show for most geometries that the stability limit is well within the range of economic acceptability. The conduction solution presented in Section 3 does not exactly model the normal solution but approaches it as the critical interassembly gap flowrate, i.e., the minimum flowrate at which the normal solution is stable for a given number of axial steps, approaches zero. Section 4 analyzes the energy increase error within the bundle duct wall associated with the loss of the interassembly gap convection in the conduction solution. Results are presented for a typical case and a maximized case.

Both the stability criteria and the conduction solution have been incorporated into the next revision of SUPERENERGY which will be released in the Spring 1977.

NOMENCLATURE

- A_1 = axial flow area of an interior subchannel
 A_2 = axial flow area of an edge subchannel
 A_3 = axial flow area of a corner subchannel
 A_6 = axial flow area of an interassembly gap edge subchannel
 A_7 = axial flow area of an interassembly gap corner subchannel
 A_9 = total flow area of the interassembly gap
 C_1 = ratio of swirl flow to average bundle axial velocity
 C_p = average specific heat of sodium
 D = pin diameter
 F_3 = thermal resistance from node 0 to node 3 in corner conduction solution
 F_4 = thermal resistance from node 4 to node 3 in corner conduction solution
 F_5 = thermal resistance from node 5 to node 3 in corner conduction solution
 g = distance between an outer fuel pin and the inside duct wall
 h_2 = heat transfer coefficient between edge subchannel bulk fluid and inside duct wall
 h_3 = heat transfer coefficient between corner subchannel bulk fluid and inside duct wall
 h_6 = heat transfer coefficient between gap edge subchannel bulk fluid and outside duct wall
 h_7 = heat transfer coefficient between gap corner subchannel bulk fluid and outside duct wall
 H_1 = inverse equivalent heat transfer coefficient between subchannel 1 and subchannel 0
 H_2 = inverse equivalent heat transfer coefficient between subchannel 2 and subchannel 0

H_3 = inverse equivalent heat transfer coefficient between subchannel 3 and subchannel 0

H_4 = inverse equivalent heat transfer coefficient between subchannel 4 and subchannel 0

k = average conductivity of liquid sodium

k_w = conductivity of the duct wall

L = bundle axial length

$\dot{m}_g$ = total interassembly gap mass flow rate

$\dot{m}_T$ = total bundle mass flowrate

N = number of axial steps

N_e = number of axial steps determined economically feasible

P = pin pitch

Q_B = total heat removed by convection inside the bundle

Q_g = total heat removed by interassembly gap convective flow

Q_{geg} = apparent heat removed by interassembly gap convective flow

Q_o = volumetric heat generation rate for subchannel 0

Q_T = total bundle heat added by the fuel pins

R_2 = inverse equivalent heat transfer coefficient between the duct wall center and the edge subchannel bulk fluid

R_3 = inverse equivalent heat transfer coefficient between the duct wall center and the corner subchannel bulk fluid

R_4 = inverse equivalent heat transfer coefficient between the bulk fluids of two edge subchannels of neighboring bundles (conduction solution)

R_5 = inverse equivalent heat transfer coefficient between the bulk fluid of three neighboring bundle corner subchannels (conduction solution)

R_6 = inverse equivalent heat transfer coefficient between the duct wall center and the gap edge subchannel bulk fluid

R_7 = inverse equivalent heat transfer coefficient between the duct wall center and the gap corner subchannel bulk fluid

S_1 = duct wall thickness

S_2 = interassembly gap thickness

T_0 = temperature of subchannel 0

T_1 = temperature of subchannel 1

T_2 = temperature of subchannel 2

T_3 = temperature of subchannel 3

T_4 = temperature of subchannel 4

T_5 = temperature of subchannel 5

ΔT = average axial temperature rise in the bundle

ΔT_g = average axial temperature rise in the interassembly gap

V_1 = axial velocity in the interior subchannel

V_2 = axial velocity in the edge subchannel

V_3 = axial velocity in the corner subchannel

V_6 = axial velocity in the gap edge subchannel

V_7 = axial velocity in the gap corner subchannel

V_θ = swirl velocity in Region II

x_1 = inside duct wall distance along corner subchannel

x_2 = outside duct wall distance along gap corner subchannel

x_3 = distance along centerline of interassembly gap along gap corner subchannel

$\left. \begin{array}{l} \Delta Z_1 \\ \Delta Z_2 \\ \Delta Z_3 \\ \Delta Z_4 \\ \Delta Z_5 \\ \Delta Z_6 \\ \Delta Z_7 \\ \Delta Z_8 \end{array} \right\} =$ maximum axial step size associated with a particular geometry type as predicted by the stability criteria

$\Delta Z_{\min}$ = minimum constraining maximum axial step size

Greek letters

ρ = average sodium density

η_1 = distance between interior nodes

η_2 = distance between interior and edge nodes

η_3 = distance between edge nodes

η_4 = distance between edge and corner nodes

η_6 = distance between gap edge and gap corner nodes

ϵ_{H_1} = enhanced eddy diffusivity between interior nodes

ϵ_{H_2} = enhanced eddy diffusivity between interior and edge nodes

ϵ_{H_3} = enhanced eddy diffusivity between edge nodes

ϵ_{H_4} = enhanced eddy diffusivity between edge and corner nodes

ϵ^* = non dimensionalized enhanced eddy diffusivity

Superscripts

J = axial level

J+1 = next highest axial level

$\left. \begin{array}{l} K \\ L \\ M \end{array} \right\} = \text{bundle reference letters}$

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SUBCHANNELS IN AN ASSEMBLY

1. Interior subchannel	5. Duct corner subchannel
2. Edge subchannel	6. Gap edge subchannel
3. Corner subchannel	7. Gap corner subchannel
4. Duct edge subchannel	

Figure 1

INTERIOR SUBCHANNELS

Figure 2

EDGE SUBCHANNELS

Figure 3

CORNER SUBCHANNELS

Figure 4

GAP EDGE SUBCHANNELS

Figure 5

GAP CORNER SUBCHANNELS

Figure 6

EDGE SUBCHANNELS - CONDUCTION

Figure 7

CORNER SUBCHANNELS - CONDUCTION

Figure 8

TABLE 4-1

Geometry-EBR II Fuel Assembly

Bundle Height	60.0 inches
Rod Diameter	0.174 inches
Wire Wrap Diameter	0.049 inches
Wire Wrap Pitch	6.00 inches
Pin Pitch	0.224 inches
Duct Thickness	0.040 inches
Interassembly Gap Thickness	0.027 inches
Duct Wall Inside Length per Side	1.276 inches

Operating Conditions

Average Heat	45000 Btu/hr-ft ²
Bundle Flow Rate	35000 lbm/hr
Interassembly Gap Flow Rate	100 lbm/hr
Radial Power Profile	flat
Axial Power Profile	flat

Code Input

Number of axial steps (minimum number for stability)	4900
Effective Eddy Diffusivities, ϵ^*	0.020
Swirl Flow Ratio, C_1	0.080
Boundary Conditions	isolated assembly

TABLE 4-2

Geometry-EBR II Fuel Assembly

Bundle Height	60.0 inches
Rod Diameter	0.1740 inches
Wire Wrap Diameter	0.0490 inches
Wire Wrap Lead	6.00 inches
Pin Pitch	0.2240 inches
Duct Thickness	0.040 inches
Interassembly Gap Thickness	0.0270 inches
Duct Wall Inside Length	1.276 inches

Operating Conditions

Average Heat Flux	45000 But/hr-ft ²
Bundle Flow Rate	35000 lbm/hr
Interassembly Gap Flow Rate	1000 lbm/hr
Radial Power Profile	flat
Axial Power Profile	flat

Code Input

Number of Axial Steps (minimum number for stability)	490
Effective Eddy Diffusivities, ϵ^*	0.020
Swirl Velocity Ratio, C_1	0.080
Boundary Conditions	isolated assembly

APPENDIX A

CONDUCTION SOLUTION IMPLEMENTATION IN
SUPERENERGY

INPUT INSTRUCTIONS FOR SUPERENERGY-INTERIM VERSION 1

CARD 1 Format (I5)

JXQ = Number of cases to be run

CARD GROUP 1 - Multiassembly Data Pack

CARD 1 Format (2F10.1)

TIN = Coolant inlet temperature

TOUT = Approximate average coolant outlet temperature

CARD 2 Format (5I5)

NOASSM = Total number of assemblies for this case.
Maximum number of 2 with enclosed listing.
Maximum can be changed by enlarging all
02 dimensions in DIMENSION statements.

NOINCR = Total number of axial steps to be used with
this case

ISOLAT = Boundary condition to be used with this case.
= 0 coupled assemblies boundary condition
= 1 isolated assembly boundary condition -
adiabatic at the interassembly gap center
= 2 isolated wall boundary condition -
adiabatic at the duct wall

KOND = Interassembly gap conduction model option
= 1 for option

CARD 3-J Format (8F10.1)

PRNT(I) = Desired axial printout heights in inches,
Repeat card until all NOPRNT printouts are
listed

CARD GROUP 2 Assembly Data Pack

Repeat this card group for each assembly in the case in
numerical order (i.e., L=1, NOASSM)

CARD 1 Format (I5)

ITYPE(L) = Assembly type
= 1 fuel assembly
= 2 blanket assembly

As long as all the assemblies in the case
are of the same type either number may be
used. For coupled assemblies of different
types (i.e., different number of pins)
only a 217 pin fuel assembly (ITYPE=1) and
a 91 pin blanket assembly (ITYPE=2) are
properly coupled.

CARD 2 Format (8F10.5)

DR(K) = Rod diameter in inches
 DW(K) = Wire wrap diameter in inches
 LEAD(K) = Wire wrap lead in inches
 P(K) = Rod pitch in inches
 DFLAT(K) = Duct flat to flat distance in inches
 LENGTH(K) = Assembly length in inches
 S1(K) = Thickness of the duct wall in inches
 S2(K) = Width of the interassembly gap in inches

CARD 3 Format (3F10.1)

QAVG(L) = Average linear heat generation rate for
 assembly L in BTU/hr-ft²
 FLOW(L) = Total flowrate in assembly in lbm/hr
 FLOWGP(L) = Interassembly gap flowrate in lbm/hr

CARD 4 Format (5F10.5)

EHSTA1 = Effective enhanced eddy diffusivity between
 interior channels
 EHSTA2 = Effective enhanced eddy diffusivity between
 edge and interior channels
 EHSTA3 = Effective enhanced eddy diffusivity between
 edge channels
 EHSTA4 = Effective enhanced eddy diffusivity between
 edge channels
 C1 = Ratio of swirl flow velocity to bundle average
 axial velocity

Khan's correlations (Ref. 2 and 4) can be used within their limits but must be corrected by lateral and axial porosities for this subchannel type code as suggested in appendices of same references.

CARD 5 Format (2I5)

NOOFAX(L) = Number of points to specify the axial flux shape
 NROD(K) = Number of rods in assembly

CARD 6 to X Format (8F10.5)

AXIAL(I,L) = Relative axial distance associated with
 flux point
 FAX(I,L) = Normalized axial flux point - the flux should
 be normalized to one over the entire assembly
 length.

Repeat the input procedure in the above groups of two until NOOFAX(L) points have been read in. The first point group must be at 0.0 and the last at 1.00 on the relative height scale.

CARD X+1 to Y Format (8F10.5)

POWER(I) = Relative radial power distribution for the assembly. Read in NROD(K) points. See code manual for numbering scheme

CARD GROUP 3 Format(6I5)

NA(L,I) = Neighboring assembly numbers as a function of face. Read in I=6 faces on L cards where L=NOASSM. The assemblies are numbered in the order they were input in card group 2. See manual for face numbering scheme.

Repeat card groups 2 and 3 for each case.

C ***** SUPERENERGY INTERM VERSION 1 *****
C MAIN PROGRAM ONLY

C ADDITIONS TO SUPERENERGY --- EASY TO RECOGNIZE IN GENERAL BY MISSING
C OR MISPLACED IDENTIFICATION NUMBERS AT RIGHT

C THIS VERSION IS MEANT ONLY TO INSTRUCT HOW TO IMPLIMENT THE CONDUCTION
C SOLUTION -- A BETTER CODED FINAL VERSION OF THE CODE WILL BE RELEASED
C IN MID-1977 ANY QUESTUONS SHOULD BE REFERED TO THE AUTHORS OF THIS
C DOCUMENT

C COMMENT CARDS INCLUDED TO HELP IN FOLLOWING LOGIC

C REAL LEAD,LENGTH 00000020
C INTEGER T 00000030
C COMMON/PROP]/P40,CP,COND,CONDW,ALPHA 00000040
C COMMON/GE0 /DR(3),DW(3),LEAD(3),P(3),DFLAT(3),POD(3),GAP(3),A1(3), 00000050
C 1A2(3),A3(3),A4(3),A5(3),A6(3),A7(3),ATOTAL(3),ATOTLG(3),DF1(3), 00000060
C 2DE2(3),DE3(3),DE6(3),DE7(3),HP1(3),HP2(3),HP3(3),HPTOTL(3), 00000070
C 3ETA1(3),ETA2(3),ETA3(3),ETA4(3),ETA6(3),ETAB(3),X1(3),X2(3),X3(3), 00000080
C 4S1(3),S2(3),LFGTH(3),V1R(3),V2R(3),V3R(3),V6R(3),V7R(3) 00000090
C COMMON/NUM /VROD(3),NPIN3(3),NCHANL(3),N1(3),N2(3),N3(3),N4(3),
C 1N5(3),N6(3),N7(3),N8(3),LC(3,550,4),VROD(3,440,3)
C COMMON/TEMP/T(550)
C COMMON FACTOR(3,3) 00000130
C DIMENSION FLOW(02),FLOWGP(02),G(02),GGAP(02),VAVG(02),VAVGG(02), 00000140
C 1V1(02),V2(02),V3(02),V6(02),V7(02),VSWIRL(02)
C DIMENSION ITYPE(02),NOOFAX(02),AXIAL(50,02),FAX(50,02),NA(02,6) 00000160
C DIMENSION EH1(02),EH2(02),EH3(02),EH4(02)
C DIMENSION PE2(02),PE3(02),PE6(02),PE7(02),NU2(02),NU3(02),NU6(02), 00000180
C 1NU7(02),RES2(02),RES3(02),RES6(02),RES7(02)
C DIMENSION OTOTAL(02),DIFFH(02),DIFFH3(02),QSA(02),QSB(02),QSC(02) 00000200
C DIMENSION QTPRIM(550,02),QTP(550,02),SUMM(440,02),POWER(20) 00000 10
C DIMENSION T1(550,02),T2(550,02),T3(550,02),QAVG(02),TAVG(02) 00000220
C DIMENSION PRNT(20)
C READ(5,10) JXQ
C JXQ=NO. OF SEPARATE CASES TO BE RUN
C THIS LOOP IS REPEATED FOR JXQ CASES
C DO 7776 JXS=1,JXQ
C FACTOR(1,1)=1. 00000270
C FACTOR(1,2)=0.5 00000280
C FACTOR(2,1)=2. 00000290
C FACTOR(2,2)=1. 00000300
C CONTINUE 00000310
C READ(5,50) TIN,TOUT 00000320
C TIN=INLET TEMPERATURE ,TOUT=OUTLET TEMPERATURE- USED IN PROP CORRELATIONS
C CALCULATE AVERAGE TEMPERATURE TT AND PROPERTIES BASED ON TT
C WRITE(6,1) TIN,TOUT 00000330
C 1 FORMAT(1X,18HINLET TEMPERATURE=,F10.1,10X,24HAVG. OUTLET TEMPERATU 00000340
C 1RE=,F10.1/ 00000350
C TT=0.5*(TIN+TOUT) 00000360
C CALL PROP(TT)
C READ(5,10) NOASSM,NOPRNT,NOINCR,ISOLAT,KOND
C NOASSM=NO. OF ASSEMBLIES IN THIS CASE. NOPRNT=NO. OF AXIAL PRINTOUTS
C DESIRED PER ASSEMBLY. NOINCR=NO. OF TOTAL AXIAL STEPS TO BE USED WITH
C THIS CASE. ISOLAT=BOUNDARY CONDITIONS-SEE SUPERENERGY MANUAL, KOND=1
C FOR INTERASSEMBLY CONDUCTION MODEL OR 0 OTHERWISE
C VARIABLE PRINTOUT ROUTINE ADDED- INPUT DESIRED PRINTOUT HEIGHTS IN
C INCHES
C READ(5,50) (PRNT(I),I=1,NOPRNT)

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WRITE(6,51)
51 FORMAT(1X,'PRINTOUTS AT THE FOLLOWING AXIAL HEIGHTS')
WRITE(6,52) (PRNT(I),I=1,NOPRNT)
52 FORMAT(AF10.3)
IF(KOND.EQ.1) WRITE(6,20)
20 FORMAT(1X,'CONDUCTION SOLUTION SELECTED')
WRITE(6,11) NOASSM,NOPRNT,NOINCR,ISOLAT 00000390
10 FORMAT(6I5) 00000400
11 FORMAT(1X,14HNO. OF ASSEMBLIES=,I5,5X,14HNO. OF PRINTS=,I5/,32HNO. 00000410
10F INCREMENTS BETWEEN PRINTS=,I5,5X,28HTYPE OF BOUNDARY CONDITIONS 00000420
2=,I5) 00000430
C DATA INPUT FOR EACH ASSEMBLY IN THE CASE- UNCHANGED FROM ORIGINAL CODE
C L=ASSEMBLY NUMBER 00000440
DO 30 L=1,NOASSM 00000450
WRITE(6,19) L 00000460
19 FORMAT(1X,22HDATA PACK FOR ASSEMBLY,I5)
C ITYPE(L)=ASSEMBLY TYPE- SEE MANUAL
C ITYPE=1 FOR FUEL ASSEMBLY. ITYPE=2 FOR BLANKET ASSEMBLY 00000470
READ(5,10) ITYPE(L) 00000480
WRITE(6,12) ITYPE(L)
12 FORMAT(1X,17HTYPE OF ASSEMBLY=,I5) 00000500
K=ITYPE(L) 00000510
WRITE(6,16) 00000520
16 FORMAT(1X,40HROD DIA. WIRE DIA. LEAD PITCH FLATS LEN 00000530
16TH DUCT TH. GAP TH. )
C INPUT IN ORDER, DIMENSIONS IN INCHES-- ROD DIAMETER, WIRE WRAP DIAMETER
C WIRE WRAP LEAD, ROD PITCH, FLAT TO FLAT DISTANCE, ASSEMBLY LENGTH,
C DUCT WALL THICKNESS, INTERASSEMBLY GAP THICKNESS
READ(5,40) DR(K),DW(K),LEAD(K),P(K),DFLAT(K),LENGTH(K),S1(K),S2(K) 00000540
WRITE(6,40) DR(K),DW(K),LEAD(K),P(K),DFLAT(K),LENGTH(K),S1(K),S2(K) 00000550
WRITE(6,17) 00000560
17 FORMAT(1X,52HAVG HEAT FLUX, FLOW RATES IN THE ASSEMBLY AND THE GAP) 00000570
C INPUT-- AVERAGE HEAT FLUX, FLOW RATES IN ASSEMBLY AND INTERASSEMBLY
C GAP-- SEE MANUAL FOR DIMENSIONS
READ(5,50) QAVG(L),FLOW(L),FLOWGP(L) 00000580
WRITE(6,50) QAVG(L),FLOW(L),FLOWGP(L) 00000590
50 FORMAT(AF10.1) 00000600
WRITE(6,18) 00000610
18 FORMAT(1X,60HFOUR EFFECTIVE EDDY DIFFUSIVITIES AND SWIRL VELOCITY 00000620
1Y RATIO) 00000630
C READ 4 EFFECTIVE EDDY DIFFUSIVITIES AND SWIRL FLOW RATIO---KHAN'S
C CORRELATION (COO-2245-16TR, COO-2245-17TR) CAN BE USED BUT MUST BE
C CORRECTED BY LATERAL AND AXIAL POROSITIES SINCE THIS CODE IS A SUBCHAN-
C NEL CODE SEE APPENDICES OF SAME DOCUMENTS
READ(5,40) EHSTA1,EHSTA2,EHSTA3,EHSTA4,C1 00000640
WRITE(6,40) EHSTA1,EHSTA2,EHSTA3,EHSTA4,C1 00000650
C NOOFAX(L)= NO. OF AXIAL FLUX SHAPE POINTS, NROD(K)=NO. OF RODS
READ(5,10) NOOFAX(L),NROD(K) 00000660
WRITE(6,13) NOOFAX(L),NROD(K) 00000670
13 FORMAT(1X,12HNO. OF FLUX=,I5,5X,12HNO. OF RODS=,I5) 00000680
NOOFA=NOOFAX(L) 00000690
WRITE(6,14) 00000700
14 FORMAT(1X,35HAXIAL DISTANCE VS FLUX DISTRIBUTION) 00000710
C AXIAL FLUX DISTRIBUTION AS A FUNCTION OF AXIAL HEIGHT
READ(5,40) (AXIAL(I,L),FAX(I,L), I=1,NOOFA) 00000720
WRITE(6,40) (AXIAL(I,L),FAX(I,L), I=1,NOOFA) 00000730
40 FORMAT(AF10.5) 00000740
NRO=NROD(K) 00000750
WRITE(6,15) 00000760
15 FORMAT(1X,34HRADIAL POWER DISTRIBUTION OF FUEL RODS) 00000770

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CONTINUE                                00000780
C RADIAL RELATIVE POWER DISTRIBUTION AS A FUNCTION OF ROD NUMBER- SEE
C MANUAL
  READ(5,40) (POWER(I),I=1,NRO)          00000790
  WRITE(6,40) (POWER(I),I=1,NRO)         00000800
C NUMB= AUTOMATIC NUMBERING SCHEME FOR CHANNELS AND RODS
  CALL NUMB(K)                            00000810
C GEOM= CALCULATES CHANNEL SIZES, AND NOVENSTERN'S FLOW SPLIT - NEW
C FLOWSPLIT INFORMATION WILL EVENTUALLY REPLACE THIS
  CALL GEOM(K)                            00000820
  M2=N2(K)                                00000830
  M3=N3(K)                                00000840
  M4=N4(K)                                00000850
  M8=N8(K)                                00000860
  MK2=M2+1                                00000870
  MK3=M3+1                                00000880
  IOVER=NROD(K)+1                         00000890
  POWER(IOVER)=0                          00000900
  DO 60 I=1,M4                            00000910
  PROD=0                                  00000920
C CALCULATE AVERAGE POWER FACTOR FOR CHANNEL I BASED ON SURROUNDING
C ROD POWER FACTORS
  DO 70 J=1,3                              00000930
  M=MROD(K,I,J)                            00000940
  PROD=PROD+POWER(M)                       00000950
70 CONTINUE                               00000960
  SUMM(I,L)=PROD                          00000970
60 CONTINUE                               00000980
C AVERAGE VOLUMETRIC HEAT GENERATION RATE CALCULATION
  QTPAVG=(QAVG(L)*HPTOTL(K)/ATOTAL(K))*12 00000990
C CALCULATION OF VOLUMETRIC HEAT GENERATION RATE FOR SUBCHANNEL I
  DO 80 I=1,M2
  QTPRIM(I,L)=QTPAVG*(ATOTAL(K)/A1(K))*(HP1(K)/HPTOTL(K))*SUMM(I,L)
  1/3.0
80 CONTINUE
  DO 90 I=MK2,M3
  QTPRIM(I,L)=QTPAVG*(ATOTAL(K)/A2(K))*(HP2(K)/HPTOTL(K))*SUMM(I,L)
  1/2.0
90 CONTINUE
  DO 100 I=MK3,M4
  QTPRIM(I,L)=QTPAVG*(ATOTAL(K)/A3(K))*(HP3(K)/HPTOTL(K))*SUMM(I,L)
100 CONTINUE
  IF (FLOWGP(L).LE.50.0) FLOWGP(L)=50.0
  G(L)=(FLOW(L)/ATOTAL(K))*144.0
  GGAP(L)=(FLOWGP(L)/ATOTLG(K))*144.0
C CALCULATION OF AVERAGE VELOCITY
  VAVG(L)=G(L)/RHO
  VAVGG(L)=GGAP(L)/RHO
C CALCULATION OF VELOCITY FOR EACH SUBCHANNEL TYPE
  V1(L)=VAVG(L)*V1R(K)
  V2(L)=VAVG(L)*V2R(K)
  V3(L)=VAVG(L)*V3R(K)
  V6(L)=VAVGG(L)*V6R(K)
  V7(L)=VAVGG(L)*V7R(K)
C
C *** THIS CONVERSION FACTOR HAS BEEN CHANGED IN ORDER THAT THE EDDY
C DIFFUSIVITIES IN THIS CODE ARE CONSISTANT WITH KHAN'S DEFINITION OF
C USING THE INTERIOR SUBCHANNEL EQUIVALENT DIAMETER FOR NONDIMENSIONAL-
C IZATION RATHER THAN THE ROD DIAMETER USED FORMERLY BY THIS CODE
  CONVER=VAVG(L)*DE1(K)/12.0

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C DIMENSIONALIZED EDDY DIFFUSIVITIES
EH1(L)=EHSTA1*CONVER
EH2(L)=EHSTA2*CONVER
EH3(L)=EHSTA3*CONVER
EH4(L)=EHSTA4*CONVER
VSWIRL(L)=C1*VAVG(L)
PE2(L)=DE2(K)*V2(L)/(ALPHA*12.)
PE3(L)=DE3(K)*V3(L)/(ALPHA*12.)
PE6(L)=DE6(K)*V6(L)/(ALPHA*12.)
PE7(L)=DE7(K)*V7(L)/(ALPHA*12.)
NU2(L)=7.0+0.025*PE2(L)**0.8
NU3(L)=7.0+0.025*PE3(L)**0.8
NU6(L)=7.0+0.025*PE6(L)**0.8
NU7(L)=7.0+0.025*PE7(L)**0.8
C CALCULATION OF THERMAL RESISTANCES
RES2(L)=(1/NU2(L)+(S1(K)/DE2(K))*COND/CONDW/2)*DE2(K)/COND/12
RES3(L)=(1/NU3(L)+(S1(K)/DE3(K))*COND/CONDW/1.732)*DE3(K)/COND/12
RES6(L)=(1/NU6(L)+(S1(K)/DE6(K))*COND/CONDW/2)*DE6(K)/COND/12
RES7(L)=(1/NU7(L)+(S1(K)/DE7(K))*COND/CONDW/1.732)*DE7(K)/COND/12
30 CONTINUE
WRITE(6,31)
31 FORMAT(1X,24HNEIGHBORS FOR ASSEMBLIES)
C READ IN NEIGHBORING ASSEMBLIES SEE MANUAL
DO 32 L=1,NOASSM
READ(5,10) (NA(L,I),I=1,5)
WRITE(6,10) (NA(L,I),I=1,6)
32 CONTINUE
CONTINUE
II=ITYPE(1)
IPRINT=1
PRINT=PRNT(IPRINT)
C DETERMINE STEP SIZE DZ AND AXIAL HEIGHT Z
DZ=LENGTH(II)/NOINCR
Z=DZ/2.
DO 115 L=1,NOASSM
QSA(L)=0
QSB(L)=0
QSC(L)=0
K=ITYPE(L)
M4=N4(K)
C INITIALIZE TEMPERATURES OF SUBCHANNELS
DO 110 I=1,M4
T2(I,L)=TIN
110 CONTINUE
IF(KOND.NE.1) GO TO 115
MK2=N2(K)+1
M4=N4(K)
C INITIALIZE TEMPERATURE FOR CONDUCTION SOLUTION NEIGHBORING SUBCHANNEL
DO 111 I=MK2,M4
T1(I,L)=TIN
111 CONTINUE
115 CONTINUE
C MAIN LOOP STARTS HERE
1000 CONTINUE
ZOL=Z/LENGTH(II)
DO 120 L=1,NOASSM
C FIND AXIAL MULTIPLICATION FACTOR BASED ON RELATIVE HEIGHT ZOL
CALL CURVE(FAXL,ZOL,FAX,AXIAL,NOOFAX,L)
K=ITYPE(L)
M4=N4(K)

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DO 130 I=1,M4                                00001680
C  AXIALLY CORRECTED VOLUMETRIC HEAT GENERATION RATE FOR CHANNEL I
  QTP(I,L)=QTPRIM(I,L)*FAXL                    00001690
130 CONTINUE                                    00001700
120 CONTINUE                                    00001710
C  BEGINNING OF INNER LOOP --- REPEATED FOR EACH ASSEMBLY AT THIS AXIAL
C  HEIGHT
  DO 140 L=1,N0ASSM                            00001720
  K=ITYPE(L)                                    00001730
C  M1, M2, M3, ETC. NUMBER OF CERTAIN CHANNEL TYPE FROM SUBROUTINE NUMB(K)
  M1=N1(K)                                       00001740
  M2=N2(K)                                       00001750
  M3=N3(K)                                       00001760
  M4=N4(K)                                       00001770
  M5=N5(K)                                       00001780
  M6=N6(K)                                       00001790
  M7=N7(K)                                       00001800
  M8=N8(K)                                       00001810
  MK1=N1(K)+1                                   00001820
  MK2=N2(K)+1                                   00001830
  MK3=N3(K)+1                                   00001840
  MK4=N4(K)+1                                   00001850
  MK5=N5(K)+1                                   00001860
  MK6=N6(K)+1                                   00001870
  MK7=N7(K)+1                                   00001880
C  INTERIOR SUBCHANNEL TEMPERATURE CALCULATION
C  ETA1,ETA2,ETA3,ETA4,ETC. NUCLAL DISTANCES FOR DIFFERENT GEOMETRIES
  DO 150 I=1,M1                                00001890
C  MM1,MM2,MM3 NEIGHBORING SUBCHANNEL NUMBERS-
  MM1=LC(K,I,1)                                00001900
  MM2=LC(K,I,2)                                00001910
  MM3=LC(K,I,3)                                00001920
C  INTERIOR SUBCHANNEL GOVERNING EQUATION
  T3(I,L)=T2(I,L)+QTP(I,L)*DZ/12/(V1(L)*RHO*CP)+((P(K)-DP(K))*DZ/
  1A1(K))*((ALPHA+EH1(L))/V1(L))*(T2(MM1,L)+T2(MM2,L)+T2(MM3,L)-
  23*T2(I,L))/ETA1(K)*12                        00001930
  00001940
  00001950
C  QSA(L)= TOTAL HEAT ADDED TO THIS SUBCHANNEL TYPE FROM QTP(I,L) TO
C  THIS AXIAL HEIGHT -- QSR(L) AND QSC(L) SIMILAR
  QSA(L)=QSA(L)+QTP(I,L)                        00001960
150 CONTINUE                                    00001970
C  LAST RING OF INTERIOR SUBCHANNELS TEMPERATURE CALCULATION
  DO 160 I=M<1,M2                              00001980
  MM1=LC(K,I,1)                                00001990
  MM2=LC(K,I,2)                                00002000
  MM3=LC(K,I,3)                                00002010
  R=(I-1)/6.                                    00002020
  N=SQRT(R)+1.0001
C  IQ=FACE NUMBER, IR RELATIVE POSITION ONFACE
  IQ=(I-6*(N-1)*(N-1)-1)/(2*N-1)+0.0001        00002040
  IR=I-6*(N-1)*(N-1)-IQ*(2*N-1)+0.0001          00002050
  J=IR/2                                          00002060
  IF (IR.EQ.2*J) GO TO 1160                     00002070
  EHA=EH1(L)                                    00002080
  EHB=EH2(L)                                    00002090
  ETAA=ETA1(K)                                  00002100
  ETAB=ETA2(K)                                  00002110
  GO TO 2160                                     00002120
1160 CONTINUE                                    00002130
  EHA=EH1(L)                                    00002140
  EHB=EH1(L)                                    00002150

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      ETAA=ETA1(K)                                00002160
      ETAB=ETA1(K)                                00002170
2160 CONTINUE                                     00002180
C   LAST INTERIOR RING GOVERNING EQUATION
      T3(I,L)=T2(I,L)+QTP(I,L)*DZ/12/(V1(L)*RHO*CP)+((P(K)-DR(K))*D7)/ 00002190
      1(A1(K)*V1(L))*((ALPHA+EHA)*(T2(MM1,L)+T2(MM2,L)-2*T2(I,L))/ETAA+ 00002200
      2(ALPHA+EHB)*(T2(MM3,L)-T2(I,L))/ETAB)*12 00002210
      QSA(L)=QSA(L)+QTP(I,L)                      00002220
160 CONTINUE                                     00002230
C   EDGE SUBCHANNELS TEMPERATURE CALCULATION
      DO 170 I=M*2,M3                             00002240
      MM1=LC(K,I,1)                                00002250
      MM2=LC(K,I,2)                                00002260
      MM3=LC(K,I,3)                                00002270
      IF(MM2.GT.M3) GO TO 1170                     00002290
      ETAA=ETA3(K)                                  00002300
      EHA=EH3(L)                                    00002310
      GO TO 2170                                    00002320
1170 CONTINUE                                     00002330
      ETAA=ETA4(K)                                  00002340
      EHA=EH4(L)                                    00002350
2170 CONTINUE                                     00002360
      IF(MM3.GT.M3) GO TO 3170                     00002370
      ETAB=ETA3(K)                                  00002380
      EHB=EH3(L)                                    00002390
      GO TO 4170                                    00002400
3170 CONTINUE                                     00002410
      ETAB=ETA4(K)                                  00002420
      EHB=EH4(L)                                    00002430
4170 CONTINUE                                     00002440
      IF(KOND.EQ.1) GO TO 4175
      MM4=LC(K,I,4)
      RES1=RES2(L)
      TTT=T2(MM4,L)
      GO TO 3175
4175 CONTINUE
      IQ=(I-M2-1)/NRING(K)+1.0001
      LP=NA(L,IQ)
C   RES1= THERMAL INVERSE EQUIV. HEAT TRANSFER COEF. TO NEIGHBORING CHANNEL
      RES1=RES2(L)+RES2(LP)+RES6(L)+RES6(LP)
C   T1(I,L) TEMPERATURE OF SUBCHANNEL IN NEIGHBORING BUNDLE THAT IS DIRECTLY
C   OPPOSITE OF I
      TTT=T1(I,L)
3175 CONTINUE
C   EDGE SUBCHANNEL GOVERNING EQUATION
      T3(I,L)=T2(I,L)+QTP(I,L)*DZ/12/(V2(L)*RHO*CP)+(GAP(K)*DZ/A2(K))* 00002450
      1(VSWIRL(L)/V2(L))*(T2(MM2,L)-T2(I,L))+12*(P(K)-DR(K))*D7/A2(K)* 00002460
      2((ALPHA+EHA*(L))/V2(L))*(T2(MM1,L)-T2(I,L))/ETA2(K)+12*(GAP(K)*D7/ 00002470
      3(V2(L)*A2(K))*((ALPHA+EHA)*(T2(MM2,L)-T2(I,L))/ETAA+(ALPHA+EHB)* 00002480
      4(T2(MM3,L)-T2(I,L))/ETAB)+(P(K)*D7/A2(K))*(TTT-T2(I,L))/(V2(L)*RHO
      5*CP*RES1)
      QSB(L)=QSB(L)+QTP(I,L)                      00002510
170 CONTINUE                                     00002520
C   CALCULATION OF CORNER SUBCHANNEL TEMPERATURES
      DO 180 I=M*3,M4                             00002530
      MM1=LC(K,I,1)                                00002540
      MM2=LC(K,I,2)                                00002550
      IF(KOND.EQ.1) GO TO 5300
      MM3=LC(K,I,3)
      TTT=T2(MM3,L)

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      RESI=RES3(L)
      GO TO 5310
5300 CONTINUE
C   RESI= THERMAL INVERSE EQUIV. HEAT TRANSFER COEF. TO NEIGHBORING CHANNEL
      RESI=RES3(L)+RES7(L)*X1(K)/X2(K)
C   IN THIS CASE T1(I,L) IS THE TEMPERATURE AT THE INTERASSEMBLY GAP CENTER
      TTT=T1(I,L)
5310 CONTINUE
C   GOVERNING EQUATION FOR CORNER SURCHANNELS
      T3(I,L)=T2(I,L)+QTP(I,L)*DZ/12/(V3(L)*RHO*CP)+(GAP(K)*DZ/A3(K))* 00002570
      1(VSWIRL(L)/V3(L))*(T2(MM1,L)-T2(I,L))+ (GAP(K)*DZ/A3(K))*12* 00002580
      2((ALPHA+EH4(L))/V3(L))*(T2(MM1,L)+T2(MM2,L)-2*T2(I,L))/ETA4(K)+ 00002590
      3 (X1(K)*DZ/A3(K))*(TTT-T2(I,L))/(V3(L)*RHO*CP*RESI)
      OSC(L)=OSC(L)+QTP(I,L) 00002610
180 CONTINUE 00002620
C   AT THIS POINT ALL TEMPERATURES INSIDE THE DUCT WALL HAVE BEEN CALCULATED
C   AND ARE IN ARRAY T2(I,L) FOR ASSEMBLY L
C   CONDUCTION SOLUTION GOES TO 140 AT THIS POINT
      IF(KOND.EQ.1) GO TO 140
      DO 210 I=M*6,M8 00002630
      MM1=LC(K,I,1) 00002640
      MM2=LC(K,I,2) 00002650
      MM3=LC(K,I,3) 00002660
      IF(I.GT.M7) GO TO 7210 00002670
C   INTERASSEMBLY GAP EDGE SURCHANNEL TEMPERATURE CALCULATION
      A=A6(K) 00002680
      V=V6(L) 00002690
      RES=RES6(L) 00002700
      X=P(K) 00002710
      TTT=T2(I,L) 00002720
      IQ=(I-M6-1)/NRING(K)+1.0001 00002730
      IR=I-M6-(IQ-1)*NRING(K)+0.0001 00002740
      J=IR/2 00002750
      JJ=IR-2*J 00002760
      LP=NA(L,IQ) 00002770
      I1=ITYPE(L) 00002780
      I2=ITYPE(LP) 00002790
      FAC=FACTOR(I1,I2) 00002800
      IF(ISOLAT.EQ.1) GO TO 2217 00002810
      IF(LP.EQ.L) GO TO 1215 00002820
      IF(IQ.GT.3) GO TO 1210 00002830
C   MM4 IS THE NEIGHBORING ASSEMBLY CHANNEL NUMBER
      MM4=N6(I2)+(IQ+2)*NRING(I2)+(NRING(K)-IR)*FAC+1 00002840
      GO TO 2210 00002850
1210 CONTINUE 00002860
      MM4=N6(I2)+(IQ-4)*NRING(I2)+(NRING(K)-IR)*FAC+1 00002870
      GO TO 2210 00002880
1215 CONTINUE 00002890
      TTT=T2(I,L) 00002900
      GO TO 2217 00002910
C   CODE GOES THROUGH AVERAGING TECHNIQUE TO FIND EQUIVALENT TEMPERATURE
C   IN ADJACENT CHANNEL OF NEIGHBORING BUNDLE --- FOR LIKE ASSEMBLIES
C   WITH THE SAME NUMBER OF RODS. THE CODE SIMPLY FINDS THE ADJACENT CHANNEL
C   NUMBER -- FOR UNLIKE ASSEMBLIES ONLY 91 PIN BLANKET BUNDLES (DESIGNATED
C   ITYPE(L)=2) AND 217 FUEL BUNDLES (ITYPE(L)=1) CAN BE HANDLED PROPERLY
C   BY THE CODE AT PRESENT
C   ALL COMBINATIONS OF BOUNDARY CONDITIONS ARE ALSO CONSIDERED
C   TTT IS THE EQUIVALENT TEMPERATURE FOR THE ADJACENT CHANNEL IN THE
C   NEIGHBORING ASSEMBLY
2210 CONTINUE 00002920

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IF(FAC.EQ.1) GO TO 2215
IF(FAC.GT.1) GO TO 2213
IF(IR.GF.(NRING(K)-1)) GO TO 2211
TTT=T2(MM4,LP)-(T2(MM4,LP)-T2(MM4-1,LP))/4.+JJ*(T2(MM4,LP)-
1T2(MM4-1,LP))/2.0
GO TO 2217
2211 TTT=T2(MM4,LP)-(T2(MM4+1,LP)-T2(MM4,LP))/4.0+JJ*(T2(MM4+1,LP)-
1T2(MM4,LP))/2.0
GO TO 2217
2213 TTT=(T2(MM4,LP)+T2(MM4+1,LP))/2.0
GO TO 2217
2215 CONTINUE
TTT=T2(MM4,LP)
2217 CONTINUE
IF(MM2.GT.M7) GO TO 3210
ETAA=ETA3(K)
GO TO 4210
3210 CONTINUE
ETAA=ETA8(K)
4210 CONTINUE
IF(MM3.GT.M7) GO TO 5210
ETAB=ETA3(K)
GO TO 6210
5210 CONTINUE
ETAB=ETA8(K)
6210 CONTINUE
GO TO 7210
7210 CONTINUE
C INTERASSEMBLY GAP CORNER SUBCHANNEL TEMPERATURE CALCULATION
TTT=T2(I,L)
A=A7(K)
V=V7(L)
RES=RES7(L)
X=X2(K)
ETAA=ETA8(K)
ETAB=ETA8(K)
220 CONTINUE
CONTINUE
C GOVERNING TEMPERATURE FOR BOTH THE CORNER AND EDGE INTERASSEMBLY GAP
C SUBCHANNELS -- NORMAL CODE SOLUTION ONLY
T3(I,L)=T2(I,L)+X*DZ/(RHO*CP*V*A)*((T2(MM1,L)-T2(I,L))/RES+(TTT-
1T2(I,L))*COND*24/S2(K))+COND*DZ*S2(K)/(2*RHO*CP*V*A)*((T2(MM2,L)-
2T2(I,L))/ETAA+(T2(MM3,L)-T2(I,L))/ETAB)*12
IJ=I-12*(NRING(K)+1)
IF(ISOLAT.EQ.2) T3(I,L)=T3(IJ,L)
210 CONTINUE
C DUCT WALL TEMPERATURE DETERMINED BY RESISTANCE AVERAGING
DO 190 I=MM4,M6
MM1=LC(K,I,1)
MM4=LC(K,I,4)
IF(I.GT.M5) GO TO 1190
C EDGE DUCT WALL SUBCHANNEL EQUATION
T3(I,L)=(RES6(L)*T3(MM1,L)+RES2(L)*T3(MM4,L))/(RES6(L)+RES2(L))
GO TO 190
1190 CONTINUE
C CORNER DUCT WALL SUBCHANNEL EQUATION
T3(I,L)=(RES7(L)*X1(K)*T3(MM1,L)+RES3(L)*X2(K)*T3(MM4,L))/
1(RES7(L)*X1(K)+RES3(L)*X2(K))
190 CONTINUE
C END OF ASSEMBLY INNER LOOP-AT THIS POINT ALLOF THE TEMPERATURES FOR

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C THE NON-CONDUCTION SOLUTION CASE HAVE BEEN CALCULATED AND ARE IN
C T2(I,L) FOR ASSEMBLY L -- REPEAT FOR EACH ASSEMBLY
140 CONTINUE
C BEGINNING OF SECOND INNER LOOP-REPEATED FOR EACH ASSEMBLY
DO 230 L=1,NOASSM
K=ITYPE(L)
M8=N8(K)
C INTERASSEMBLY GAP FLOW SOLUTION GOES TO 270 AT THIS POINT
IF(KOND.NE.1) GO TO 270
M3=N3(K)
M4=N4(K)
MK2=N2(K)+1
MK3=M3+1
DO 5400 I=MK2,M3
C EDGE SUBCHANNELS
C CONDUCTION SOLUTION--- FINDS THE TEMPERATURE IN SUBCHANNEL DIRECTLY
C OPPOSITE SUCHANNEL I IN SAME MANNER AS DO210 LOOP ABOVE
C THIS TEMPERATURE T1(I,L) IS USED IN THE NEXT AXIAL STEP
C IQ=FACE DESIGNATION NUMBER
IQ=(I-M2-1)/NRING(K)+1.0001
C IR=RELATIVE LOCATION OF SUBCHANNEL ON FACE IQ
IR=I-M2-(IQ-1)*NRING(K)+0.0001
C LP=NEIGHBORING ASSEMBLY REFERENCE NUMBER
LP=NA(L,IQ)
I2=ITYPE(LP)
FAC=FACTOR(K,I2)
J=IR/2
JJ=IR-2*J
MM5=LC(K,I,4)
MM6=LC(K,MM5,4)
IF(ISOLAT.GT.0) GO TO 4180
IF(LP.NE.L) GO TO 4185
4180 CONTINUE
T1(I,L)=T3(I,L)
T3(MM5,L)=T3(I,L)
T3(MM6,L)=T3(I,L)
GO TO 5400
4185 CONTINUE
IF(IQ.GT.3) GO TO 4190
MM4=N2(I2)+(IQ+2)*NRING(I2)+(NRING(K)-IR)*FAC+1
GO TO 4195
4190 CONTINUE
MM4=N2(I2)+(IQ-4)*NRING(I2)+(NRING(K)-IR)*FAC+1
4195 CONTINUE
IF(FAC.EQ.1) GO TO 4010
IF(FAC.GT.1) GO TO 4020
IF(IR.GE.(NRING(K)-1)) GO TO 4030
T1(I,L)=T3(MM4,LP)-(T3(MM4,LP)-T3(MM4-1,LP))/4.+JJ*(T3(MM4,LP)-
1T3(MM4-1,LP))/2.0
GO TO 4200
4010 CONTINUE
T1(I,L)=T3(MM4,LP)
GO TO 4200
4020 CONTINUE
T1(I,L)=(T3(MM4,LP)+T3(MM4+1,LP))/2.0
GO TO 4200
4030 CONTINUE
T1(I,L)=T3(MM4,LP)-(T3(MM4+1,LP)-T3(MM4,LP))/4.0+JJ*(T3(MM4+1,LP)-
1T3(MM4,LP))/2.0
4200 CONTINUE

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C   HERE TEMPERATURES FOR THE DUCT WALL AND INTERASSEMBLY GAP ARE FOUND
C   BY RESISTANCE AVERAGING NEIGHBORING BUNDLE TEMPERATURES
      RL=RES2(L)+RES6(L)
      RLP=RES2(LP)+RES6(LP)
      T3(MM6,L)=(T3(I,L)*RLP+T1(I,L)*RL)/(RL+RLP)
      T3(MM5,L)=(T3(I,L)*(RLP+RES6(L))+T1(I,L)*RES2(L))/(RL+RLP)
5400 CONTINUE
      DO 5500 I=MM3,MM4
C   CORNER SUBCHANNELS
C   CONDUCTION SOLUTION--- FINDS THE TEMPERATURE IN SUBCHANNEL DIRECTLY
C   OPPOSITE SUBCHANNEL I IN SAME MANNER AS DO210 LOOP ABOVE
C   THIS TEMPERATURE T1(I,L) IS USED IN THE NEXT AXIAL STEP
C   IQ=FACE DESIGNATION NUMBER
      IQ=I-M3
      IS=IQ-1
      IF(IQ.EQ.1) IS=6
C   LP=NEIGHBORING ASSEMBLY REFERENCE NUMBER
      LP=NA(L,IQ)
      LR=NA(L,IS)
      I1=IYPE(LP)
      I2=IYPE(LR)
      MM3=LC(K,I,3)
      MM6=LC(K,MM3,4)
      IF(ISOIAT.EQ.0) GO TO 5401
      T1(I,L)=T3(I,L)
      T3(MM6,L)=T3(I,L)
      T3(MM3,L)=T3(I,L)
      GO TO 5500
5401 IF(IQ.LT.3) GO TO 5405
      MM5=N3(I1)+IQ-2
      GO TO 5410
5405 CONTINUE
      MM5=N3(I1)+IQ+4
5410 CONTINUE
      IF(IS.LT.4) GO TO 5415
      MM4=N3(I2)+IS-3
      GO TO 5420
5415 CONTINUE
      MM4=N3(I2)+IS+3
5420 CONTINUE
      UX4=RES3(LR)/X1(I2)+RES7(LR)/X2(I2)
      UX5=RES3(LP)/X1(I1)+RES7(LP)/X2(I1)
      UX1=RES3(L)/X1(K)+RES7(L)/X2(K)
      T1(I,L)=(T2(MM4,L)/UX4+T2(MM5,L)/UX5+T2(I,L)/UX1)/(1.0/UX4+1.0/
      1UX5+1.0/UX1)
C   HERE TEMPERATURES FOR THE DUCT WALL AND INTERASSEMBLY GAP ARE FOUND
C   BY RESISTANCE AVERAGING NEIGHBORING BUNDLE TEMPERATURES
      T3(MM6,L)=T1(I,L)
      T3(MM3,L)=(RES7(L)*X1(K)*T3(I,L)+RES3(L)*X2(K)*T3(MM6,L))/(RES7(L)
      1*X1(K)+RES3(L)*X2(K))
5500 CONTINUE
270 CONTINUE
      DO 240 I=1,MB
      T2(I,L)=T3(I,L)
240 CONTINUE
C   END OF SECOND INNER LOOP
230 CONTINUE
      Z=Z+DZ
C   INCREMENT AXIAL DISTANCE AND REENTER MAIN LOOP AT 1000 IF NO PRINTOUT
C   IS CALLED FOR

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00003500

00003510

00003520

00003530

00003540


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IF(IPRINT.GT.NOPRNT) GO TO 245
PRINT=PRNT(IPRINT)
GO TO 255
245 PRINT=LENGTH(II)+10.0
255 CONTINUE
C STOP IF THIS IS THE LAST PRINTOUT -- IF NOT REENTER LOOP AT 1000
  IF(PRINT.GT.LENGTH(II)) GO TO 2000
  GO TO 1000
2000 CONTINUE
3000 CONTINUE
7776 CONTINUE
STOP
END
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00004080
00004090
00004100
00004110

00004120
00004130