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Revision 1

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TURBULENT SWEEPING FLOW MIXING MODEL FOR
WIRE WRAPPED LMFBR ASSEMBLIES

by

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REVISION RECORD

Revision 1

1. Page 15. Constants for sweeping flow between interior and subchannels have been recalibrated to better fit the data of low $\frac{P}{D}$ and $\frac{H}{D}$ ratios. The results of recalibration shows $\frac{n}{2} = -0.5$ and $C' = 0.562$, in place of $\frac{n}{2} = -0.35$ and $C' = 0.716$ reported in the original version.
2. Page 21. The formula for ϵ_{1L}^* (Equation 5-3) has been rewritten according to the modifications made for the constants $\frac{n}{2}$ and C' .
3. Page 23, 24 and 25. Section 5.2 is completely deleted because it is believe by the authors and COBRA code developers that the input parameter δ in COBRA code can not be transformed directly from ϵ_{1L}^* or C_{1L} . This is because ϵ_{1L}^* is the parameter which takes into account both sweeping flow and diversion crossflow and δ is the parameter only taking care of sweeping flow. Until it can be shown that the magnitude of the sweeping flow is much larger than that of the diversion crossflow, the derivation made in section 5.2 is invalid.
4. Page 37. Figure 4-2 is replotted because of the updates of the constants C' and $\frac{n}{2}$ for sweeping flow between interior subchannels.

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B. Topical Reports, Continued

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ABSTRACT

A physical model is proposed to derive the sweeping flow for LMFBR triangular array wire-wrapped assemblies under the turbulent flow condition. Two correlations are suggested for the sweeping flow through two different types of gaps between subchannels, the gap between the interior subchannels and the gap between the wall subchannels. These two sweeping flow correlations are evolved by calibrating the constants in the proposed model against the available experimental data. Agreement between the correlations and all the experimental data of $\pm 35\%$ is obtained over the assembly design range of $1.315 > P/D > 1.067$ and $52 > H/D > 4$.

Based on these correlations, flow sweeping input parameters for two popular computer codes, i.e., COBRA and SUPERENERGY, are recommended.

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NOMENCLATURE

A_1	Subchannel area for subchannel 1, $m^2(ft^2)$
A_r	Projected area of the wire in Subchannel, $m^2(ft^2)$
A_s	Subchannel area, $m^2(ft^2)$
A_{s1}	Interior subchannel area, $m^2(ft^2)$
A_{s2}	Edge subchannel area, $m^2(ft^2)$
C	Constant in Eq. (2-13)
C_1	Swirl flow parameter; defined by Eq. (8-2) as $V_{swirl}/\bar{V}$
C_{1L}	Local swirl flow parameter, defined by Eq. (5-2) as C_1/x_2
C'	Constant in Eq. (2-15)
C_D	Drag coefficient
D	Fuel pin diameter, $m(ft)$
D_e	Bundle equivalent hydraulic diameter, $m(ft)$
D_{el}	Interior subchannel equivalent diameter, $m(ft)$
D_{ij}	Characteristic hydraulic diameter of the gap between subchannels i and j, $m(ft)$
D_w	Wire diameter, $m(ft)$
f_s	Smooth tube friction factor
F_r	Drag force on wire, Newton (lbf)
Gap	Gap between subchannels, $m(ft)$
h	Enthalpy, Joule/kg (BTU/lbm)
H	Wire wrap lead length, $m(ft)$
i	Subscript for subchannels
j	Subscript for subchannels surrounding subchannel 1
K_{ij}	Crossflow resistance parameter
L_{ij}	Characteristic length through which ΔP_r is characterized in Eq. (2-8), $m(ft)$

m_1	Subchannel flow rate for subchannel 1 kg/sec (lbm/hr)
m_1	Subchannel flow rate for interior subchannels, kg/sec (lbm/hr)
m_2	Subchannel flow rate for edge subchannels, kg/sec (lbm/hr)
n	Exponent in Eq. (2-9)
N	Number of fuel pins in the assembly
P	Fuel pin pitch length, $(D+D_w)$, m(ft)
q'_1	Linear heat generating rate Joule/sec-m (BTU/hr-ft)
T	Coolant temperature, C° (F°)
V_1	Average axial velocity, for subchannel 1, m/sec (ft/hr)
V_p	Perpendicular axial velocity component to the axis of the wire, m/sec (ft/hr)
V_T	Sweeping velocity crossing the gap between subchannels 1 and j, m/sec (ft/hr)
V_{swirl}	Swirl flow velocity defined in Reg. (22), m/sec (ft/hr)
V_1	Axial average velocity for interior subchannels, m/sec (ft/hr)
V_2	Axial average velocity for edge subchannels, m/sec (ft/hr)
$\bar{V}$	Bundle average velocity
$\bar{W}_{1j}$	Sweeping flow from subchannel 1 to subchannel j averaged over one lead length kg/sec-m (lbm/hr-ft)
x	Subchannel length, m(ft)
x_1	Flow split parameter for interior subchannels; defined as the ratio of interior subchannel average velocity to the bundle average velocity
x_2	Flow split parameter for edge subchannels; defined as the ratio of edge subchannel average velocity to the bundle average velocity
ΔP_r	Pressure drop due to roughness element, i.e., the wire, Newton/m ² (lbf/ft ²)

ϵ	Enhanced eddy diffusivity defined in Ref. (21), sec/m ² (hr/ft ²)
ϵ_1^*	Effective enhanced eddy diffusivity; defined by Eq. (B-1) as $\epsilon_H/V D_{e1}$
ϵ_{1L}^*	Local effective enhanced eddy diffusivity; defined by Eq. (5-2) as ϵ_1^*/x_1
ρ	Fluid density; kg/m ³ (lbm/ft ³)
η	Centroid-to-centroid distance between subchannels, m(ft)
θ	Angle between axial flow direction and the wire wrap (illustrated in Fig. 3)

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CHAPTER 1

INTRODUCTION

The intersubchannel mixing in an IMFBR assembly is mainly due to the flow sweeping effect (Ref. 1). The sweeping flow is a diversion of flow by the wires wrapped onto the fuel rods which transport the coolant energy from one subchannel to its adjacent subchannels. Various methods (Refs. 2, 3, 4) of correlating flow sweeping results have been suggested or developed. A review of these suggested methods has been made by Rogers and Todreas (Ref. 1). All these correlations calibrate their constants against those of either Canadian bundles or bundles with many closely-approaching, opposing fins. A common drawback for these methods is that they do not take into account the effect of the static pressure disturbance around the wire in the determination of the sweeping flow. More recent work by Sha (Ref. 5) and Basehore and Todreas (Ref. 6) has presented functions for flow sweeping based on experimental data for the edge subchannel only. However these functions were not developed together with a physical model which would provide a reliable basis for adapting these functions to the geometrics of varying $\frac{H}{D}$ and $\frac{P}{D}$ ratios. Experimental data, first in Ref. (7), and later in Ref. (8), have proven that there is a strong static pressure disturbance (static pressure dip) directly downstream of the wire as might be expected. Fig. (1-1) illustrates this

feature based on the experimental data obtained by Lafey and reported in Ref. (7).

The object of this report is to correlate the sweeping flow as a function of the bundle geometric parameters under the turbulent flow condition in a triangular array wire-wrapped bundle with single wires at same start angle wrapped in phase as currently used for LMFBR assemblies. This correlation is based on a model which considers the major driving force for the sweeping flow to be the local static pressure disturbance caused by the wire wraps. The sweeping flow is considered to be different in the gaps between the edge and edge subchannels than in the gaps between the interior and interior subchannels because of the considerably different geometric characteristics of these two types of gaps. Consequently, the sweeping flow is correlated by two correlations: one for interior-to-interior subchannel sweeping flow and the other for edge-to-edge subchannel sweeping flow. The sweeping flows between the interior and edge subchannels is derived by extending the correlation for the sweeping flow between two interior subchannels.

CHAPTER 2

PROPOSED MODEL

Consider a wire wrapped fuel rod separating subchannels i and j (as shown in Fig. (2-1)). The coolant flow in these two subchannels is forced upward. Because of the existence of the wire, the static pressure field around the wire will be disturbed. More specifically, the static pressure in front of the wire (upstream) will be higher than that in the free stream region because the velocity is stagnated in front of the wire. The static pressure behind the wire will be lower than that in the free stream region due to the flow separation effect.

In fully turbulent flow, the magnitude of the pressure rise from flow stagnation is only about $1/3$ of the magnitude of the pressure dip from separation. Additionally, in an in-phase wire wrapped bundle, the high pressure zone of a particular rod is always adjacent to the low pressure zone of an adjacent rod (note that this low pressure zone is not that associated with the wire which created the high pressure zone and is relatively far from the gap crossing point of that wire for both interior and edge subchannels). (Refer to Fig. (2-2) for illustration.) This low pressure zone with a weakly disturbed static pressure (because it is not located right behind the associated wire), tends to divert the subchannel flow in an opposite direction with respect to the sweeping flow diverted by the high pressure zone. Therefore the net driving force upstream of the

gap crossing point to divert the subchannel flow is not significant since the magnitude of the adjacent high and low pressure disturbances are equal, it should be noted that this is not the case for the low pressure zone directly downstream from the wire where the static pressure of the adjacent rod is not disturbed, since this undisturbed zone is sufficiently far away from the wire to be unaffected by its existence. The low pressure zone directly downstream from the wire can thus induce a rather strong sweeping flow because it is not canceled by two strongly unequal pressure differences. For the above reasons, the sweeping flow is modeled as if the only driving force were due to the flow wake effect behind the wire.

We can derive the static pressure behind the wire by assuming that the axis of the wire is located perpendicular to the free stream flow direction. In this case, the difference between the static pressure behind the wire and the static pressure in the free stream is mainly due to the form drag of the wire. The form drag force is usually expressed in terms of the projected area of the body and a dimensionless drag coefficient. The drag coefficient is basically equivalent to a friction factor, but depends mainly on the shape and size of the wake behind the body. Thus, $F_r = \frac{\rho}{2g_c} v_w^2 A_r C_D$ (2-1)

Where F_r = drag force on the wire

v_w = wall velocity

A_r = projected area of the wire in subchannel

C_D = drag coefficient

ρ = density of fluid.

The axial pressure drop between subchannel planes of

area A_r located upstream and downstream from the wire is:

$$\Delta P_r = \frac{\frac{\rho}{2g_c} v_w^2 A_r C_D}{A_s} \quad (2-2)$$

The above equation can be rearranged as:

$$\Delta P_r = \left(\frac{A_r}{A_s}\right) \frac{\rho}{2g_c} \left(\frac{v_w}{V_p}\right)^2 C_D V_p^2$$

where C_D is assumed to be a constant

V_p = subchannel average velocity which is perpendicular to the wire location (as shown in Figs. (2-3) and (2-4)),

The ratio of the wall velocity to the channel average velocity can be derived by assuming the subchannel velocity profile before the wire and knowing the boundary layer thickness. Morris (Ref. 8) has found this ratio for the open channel flow to be equal to:

$$\left(\frac{v_w}{V_p}\right)^2 = 16.8 f_s \quad (2-3)$$

where f_s = friction factor for smooth tube.

However, since the turbulent velocity profile close to the wall is the same for both the open channel and closed subchannel flow, it is reasonable to assume Eq. (2-3) also holds for the subchannel flow. Inserting Eq. (2-3) into Eq. (2-2) we obtain:

$$\Delta P_r = 16.8 f_s \left(\frac{A_r}{A_s}\right) C_D \frac{\rho}{2g_c} V_p^2 \quad (2-4)$$

where C_D is assumed to be a constant.

This equation gives the form pressure drop across a wire located perpendicular to the stream flow direction. In reality,

the wire is located at an angle less than 90° from the direction of the flow. The form pressure loss thus should be caused by the component of the stream flow which is perpendicular to the wire. This component can be derived (as Fig. (2-4) shows):

$$V_p = V \sin \theta \quad (2-5)$$

where the $\sin \theta$ is equal to:

$$\sin \theta = \frac{\pi(D + D_w)}{\sqrt{\pi^2(D + D_w)^2 + H^2}} \quad (2-6)$$

Inserting the last two equations into Eq. (2-4), we obtain:

$$\Delta P_r = 16.8 f_s \left(\frac{A_r}{A_s} \right) C_D \frac{\rho}{2g_c} \left[\frac{\pi(D + D_w)}{\sqrt{\pi^2(D + D_w)^2 + H^2}} \right]^2 V^2 \quad (2-7)$$

The above equation gives the difference between the average planar subchannel static pressure just downstream of the gap crossing point right behind the wire and that sufficiently in front of the wire to be unaffected by its existence. This pressure difference is considered in this proposed model to be the driving force of the sweeping flow which is, governed by the following equation:

$$\Delta P_r = K_{1j} \frac{L_{1j}}{D_{1j}} \frac{\rho V_T^2}{2g_c} \quad (2-8)$$

where K_{1j} = crossflow resistance factor

L_{1j} = characteristic length through which the ΔP_r occurs due to the viscous effect of V_T

V_T = transverse velocity which is equal to
the sweep velocity across the gap between
subchannels 1 and j

D_{1j} = characteristic hydraulic diameter of gap
between subchannels

If we assume that

$$\frac{L_{1j}}{D_{1j}} = \left(\frac{\eta}{Gap}\right)^n \quad (2-9)$$

where η = centroid to centroid distance between sub-
channels 1 and j

Gap = gap width between subchannels

n = constant, depends on the subchannel geometry,

Eq. (2-8) becomes

$$\Delta P_r \approx K_{1j} \left(\frac{\eta}{Gap}\right)^n \frac{\rho V_T^2}{2g_c} \quad (2-10)$$

Equating Eqs. (2-10) and (2-7), we obtain:

$$16.8 f_s \left(\frac{A_r}{A_s}\right) C_D \frac{\rho}{2} \left[\frac{\pi(D + Dw)}{\sqrt{\pi^2(D + Dw)^2 + H^2}} \right] \frac{V^2}{g_c} = K_{1j} \left(\frac{\eta}{Gap}\right)^n \frac{\rho V_T^2}{2g_c} \quad (2-11)$$

Rearranging the above equation, we obtain:

$$\left(\frac{V_T}{V}\right) = \sqrt{\frac{16.8 f_s \left(\frac{A_r}{A_s}\right) C_D \left[\frac{\pi(D + Dw)}{\sqrt{\pi^2(D + Dw)^2 + H^2}} \right]^2}{K_{1j} \left(\frac{\eta}{Gap}\right)^n}}$$

$$\left(\frac{V_T}{V}\right) = \left(\frac{16.8 f_s C_D}{K_{1j}}\right)^{\frac{1}{2}} \left(\frac{A_r}{A_s}\right)^{\frac{1}{2}} \left(\frac{Gap}{\eta}\right)^{\frac{n}{2}} \frac{\pi(D + Dw)}{\sqrt{\pi^2(D + Dw)^2 + H^2}} \quad (2-12)$$

Since both f_s and K_{1j} are friction factors, the nature of the dependence on the Reynolds number for these two parameters is assumed to be the same. This characteristic leads to the first term on the right hand side of Eq. (2-12) being a constant, C . Thus Eq. (2-12) becomes:

$$\left(\frac{V_T}{V}\right) = C \left(\frac{A_r}{A_s}\right)^{\frac{1}{2}} \left(\frac{Gap}{\eta}\right)^{\frac{n}{2}} \frac{\pi(D + Dw)}{\sqrt{\pi^2(D + Dw)^2 + H^2}} \quad (2-13)$$

We now define two parameters:

$\overline{W}_{1j}$ = diversion crossflow (sweeping flow) averaged over one lead length from subchannel 1 to subchannel j .
(Refer to Chapter 2 in Ref. (10) for derivation.)

m_1 = subchannel flow rate

We know from a mass balance on transverse flow that

$$\rho V_T Gap H = \overline{W}_{1j} H \quad (2-14a)$$

and

$$m_1 = \rho A_s V. \quad (2-14b)$$

Thus, the parameter $\frac{\overline{W}_{1j} H}{m_1}$ can be evaluated from Eq. (2-13) such that:

$$\frac{\overline{W_{1j}} H}{m_1} = C' \left(\frac{A_r}{A_s}\right)^{\frac{1}{2}} \left(\frac{Gap}{\eta}\right)^{\frac{n}{2}} \frac{H}{\sqrt{\pi^2 (D + Dw)^2 + H^2}} \frac{GAP (D + Dw)}{A_s}$$

(2-15)

where constant C' is introduced from Eqs. (2-14a) and (2-13).

The physical meaning of the parameter $\frac{\overline{W_{1j}} H}{m_1}$ is the ratio of the total sweeping flow swept from subchannel 1 to subchannel j (integrating W_{1j} over one lead length) to the total subchannel flow.

The model proposed above predicts the following characteristics for the sweeping flow:

- 1) The sweeping flow should be more dominant behind the wire (downstream) than in front of the wire (upstream).
- 2) The parameter $\frac{\overline{W_{1j}} H}{m_1}$ should be independent of Re in the turbulent flow regime.
- 3) The parameter $\frac{\overline{W_{1j}} H}{m_1}$ should be independent of the wire lead length provided the length is more than three times as large as πD . This characteristic stems from

$$\frac{H}{\sqrt{\pi^2 (D + Dw)^2 + H^2}} \approx 1 \quad \text{for } H > 3\pi D \text{ or approximately } \frac{D}{H} < 0.1.$$

In addition, $\frac{W}{m_1} H$ should weakly depend on the wire lead length even when the wire lead length is very close to πD ($H \geq \pi D$).

4) The parameter $\frac{W_{1j}}{m_1} H$ should increase as the $\frac{P}{D}$ ratio increases. This is because all the parameters (A_p/A_s), (Gap/η) and ($\text{Gap}(D + D_w)/A_s$) in Eq. (2-15) increase as the $\frac{P}{D}$ ratio increases. This characteristic of these parameters is illustrated in Figs. (2-5), (2-6), and (2-7) for the interior and edge subchannel geometries.

CHAPTER 3

EXPERIMENTAL RESULTS

Several experiments have been performed to study the coolant mixing behavior in a triangular array, wire wrapped bundle. These experiments, along with their methodologies, are summarized in Table (3-1). The mixing parameters ϵ_1^* (effective enhanced eddy diffusivity) and C_1 (swirl flow parameter) were reduced from these experiments by E. Khan (Ref. 21) by calibrating the ENERGY code against the data. These two mixing parameters can in turn be converted into the parameter $\frac{W_{1j}}{m_1} H$ for the two different types of gaps: the gap between the interior subchannels and the gap between the edge subchannels. The conversion factors for the parameter $\frac{W_{1j}}{m_1} H$ and the mixing parameters are derived in Appendix A.

Since the mixing parameter ϵ_1^* reduced from Skok's (Cadarache's) 7-pin experiment does not fully represent the sweeping flow mixing for a "true" interior subchannel, the results of this experiment are not used to reduce the parameter $\frac{W_{1j}}{m_1} H$ (or ϵ_1^*) for the gaps between the interior subchannels. The "true" interior subchannel denotes the interior subchannel for which the hydraulic properties are not influenced by those of the edge subchannels. It is obvious that for a 7-pin bundle all the interior subchannels are adjacent to the edge subchannels and thus that the sweeping

flow properties for the interior subchannels are not independent from the hydraulic properties of the edge subchannels. However, for a bundle having more than 7 pins, the sweeping flow properties for the center interior subchannels should be effectively decoupled from the hydraulic characteristics of the edge subchannels.

It should be noted that the swirl flow parameter C_1 (or $\frac{\overline{W}_{1j}}{m_1} H$ for the gap between the wall subchannels) can be reduced from the 7-pin experimental results. This is mainly because the swirl flow in the wall subchannels is always affected by the hydraulic characteristics of the interior subchannels, no matter what the number of fuel pins is.

The data of the Japanese 19-pin blanket experiment (Ref. 12) is not used in this study because it presents questionable results, discussed in Ref. (10), and limited data on subchannel salt concentrations. Concentration data from only three interior subchannels were used to reduce the interior subchannel mixing parameter $\frac{\overline{W}_{1j}}{m_1} H$.

The parameters $\frac{\overline{W}_{1j}}{m_1} H$ derived from the mixing parameters α_1^* and C_1 determined by Khan for all the data except Chin and Hanson for the two types of gaps (between interior-to-interior and edge-to-edge subchannels) are shown in Figs. (3-1) and (3-2) respectively. This parameter is plotted against the bundle design parameters $\frac{H}{D}$ and $\frac{P}{D}$.

Figure (3-1) illustrates the following two characteristics of the parameter $\frac{\overline{W}_{1j}}{m_1} H$ which have been predicted by the model proposed in this report:

1) Within experimental error, the parameter $\frac{\overline{W}_{1j} H}{m_1}$ is independent of the lead length as shown by Baumann and Hoffman's ($\frac{P}{D} = 1.315$) (Ref. 20) and Chiu's ($\frac{P}{D} = 1.067$) (Ref. 10) experimental data.

2) The parameter $\frac{\overline{W}_{1j} H}{m_1}$ increases as the $\frac{P}{D}$ ratio increases.

The other two characteristics pertaining to the parameter $\frac{\overline{W}_{1j} H}{m_1}$ predicted by the model are experimentally observed in Refs. (10), (12) and (22). In Ref. (22), the 11:1 experimental data show that the sweeping flow is more dominant behind the wire than in front of the wire. In Refs. (10) and (12), experimental data indicate that the parameter $\frac{\overline{W}_{1j} H}{m_1}$ is independent of the Reynolds number in the high turbulent flow regime.

The scattering of the experimental data is mainly due to the error involved in the data reduction method and the uncertainty in the determination of the rod alignment mode. In general, large uncertainty will be involved in the data reduction process, i.e., calibrating ϵ_1^* or C_1 against the data, if the experimental data are obtained from a heated bundle. This is because uncertainties in the determination of the subchannel flow rate in the process of data reduction will induce large uncertainties in the determination of the mixing parameters (Ref. 10). This may explain why the $\frac{\overline{W}_{1j} H}{m_1}$ for the ORNL experiment differs from that for the HEDL experiment. Both experiments employ identical bundles but the ORNL experiment uses the heated rod technique, and the HEDL experiment

uses the salt injection technique. However this logic alone would indicate the HEDL data should have less error whereas Fig. 3-2 shows it deviates more from the other data of $P/D = 1.25$ than the ORNL result. At the same time, the distribution of the bundle flat-to-flat tolerance can greatly affect the actual rod alignment mode, for instance, whether all the tolerance is accumulated in the edge subchannels or is all accumulated in the interior subchannels, and thus in turn can affect the actual rod alignment mode is hard to determine for a certain test section, the consequent uncertainty inherent in the sub-channel flow rates may then affect the determination of the mixing parameters. Additionally, the type of experimental technique employed to obtain the mixing information also has great bearing on the determination of the mixing parameter. For instance, the mixing parameter $\frac{W_{1j}H}{m_2}$ in Fig. (3-2) for the 61-pin M.I.T. mockup ($\frac{P}{D} = 1.25$) differs greatly for the two different types of experimental techniques, i.e., the salt injection technique and the laser technique.

In Fig. (3-2), which deals with the edge subchannel sweeping flow, the characteristics of the independent of $\frac{W_{1j}H}{m_2}$ from the $\frac{H}{D}$ ratio can be observed from Skok's (Cadarache) data and from Chiu's (M.I.T.) data. The characteristic of $\frac{W_{1j}H}{m_2}$ increasing as the $\frac{P}{D}$ ratio increases can also be observed from Fig. (3-2). Thus, we can conclude that the model proposed here can predict the correct characteristics of the sweeping flow parameter $\frac{W_{1j}H}{m_1}$

CHAPTER 4

RECOMMENDED CORRELATIONS FOR SWEEPING FLOW

Two unknown constants, n and C' , in Eq. (2-15) need to be calibrated to fit the data presented in Chapter 3. Both of these constants are considered dependent on the type of gap and surrounding subchannel through or in which the sweeping flow flows. For this reason, there are two correlations recommended for the parameter $\frac{\overline{W}_{1j} H}{m_1}$. One is for the sweeping flow diverted from one interior subchannel to another. The other correlation is for the sweeping flow diverted from one wall subchannel to another. The calibration of the constants n and C' is performed to fit all the data within $\pm 35\%$ presented in Chapter 3. The results show that for the interior subchannel gap, $\frac{n}{2}$ equals -0.5 and C' equals 0.562 , and that for the edge subchannel gap, $\frac{n}{2}$ equals 0.35 and C' equals 10.5 . Thus, we obtain:

Interior-to-interior sweeping flow:

$$\frac{\overline{W}_{1j} H}{m_1} = 0.562 \left(\frac{P-D}{P'} \right)^{-0.5} \left(\frac{A_r}{A_s} \right)^{0.5} \frac{H}{\sqrt{2(D-D_W)^2 + H^2}} \frac{(P-D)(D+D_W)}{A_s} \quad (4-1)$$

where

$$A_s = \frac{\sqrt{3}}{4} P^2 - \frac{\pi D^2}{8} \quad (4-1a)$$

$$A_r = \frac{\pi(P - \frac{D}{2})^2 - \frac{\pi D^2}{4}}{6} \quad (4-1b)$$

and $P' = P$ (it should be noted that $n = P/3$, and 3 is accommodated by the constant 0.716). (4-1c)

Edge-to-edge sweeping flow:

$$\frac{W_{14}}{m_2} H = 10.5 \left(\frac{P-D}{P'} \right)^{0.35} \left(\frac{A_r}{A_s} \right)^{0.5} \frac{H}{\sqrt{\pi^2 (D + D_w)^2 + H^2}} \frac{(P-D)(D + D_w)}{A_s} \quad (4-2)$$

where

$$A_r = \frac{(\frac{D}{2} + D_w)^2 \pi - \frac{\pi D^2}{4}}{4} \quad (4-2a)$$

$$A_s = P(\frac{D}{2} + D_w) - \frac{\pi D^2}{8} \quad (4-2b)$$

$$P' = P$$

$$D_w = P - D \quad (4-2c)$$

if the donor edge subchannel is not located next to the corner fuel pin. For the donor edge subchannel located next to the corner fuel pin (as shown in Fig. (4-1) and hereafter called corner edge subchannel), the parameters P' , A_r and A_s become:

$$A_s = P(P - \frac{D}{2}) - \frac{\pi D^2}{8} + (\frac{1}{2}(P - \frac{D}{2})^2 \tan 30^\circ - \frac{\pi D^2}{48}) \quad (4-3a)$$

$$A_r = ((\frac{D}{2} + D_w)^2 \pi - \frac{D^2 \pi}{4}) \times \frac{1}{3} \quad (4-3b)$$

$$P' = ((\frac{D}{2} + \frac{D_w}{2}) \tan 30^\circ + \frac{P}{2}) \times 2 \quad (4-3c)$$

(Note that m_2 is the corner edge subchannel flow rate.) where A_s and A_p are the subchannel area and wire projected area for the corner edge subchannels next to the corner pin and P' is the centroid-to-centroid distance between two corner edge subchannels.

It should be noted that the parameter $\frac{\overline{W}_{1j} H}{m_2}$ is lower for the corner edge subchannel than for the regular edge subchannel by about 10%. At the same time, the flow rate m_2 in the corner edge subchannel is higher than that in the regular edge subchannel by about 10%, provided the average subchannel velocities for these two kinds of subchannels are the same. This implies that the total sweeping flow $\overline{W}_{1j} H$ is the same for both kinds of gaps, i.e., for those between two regular edge subchannels and for those between two corner edge subchannels, as might be expected from the swirl flow balance. Therefore, we can assume:

$$\overline{W}_{1j} H \text{ corner gap} = \overline{W}_{1j} H \text{ gap between two edge subchannels.}$$

The above formula will not involve any difference larger than 2% from Eq. (4-2) in the determination of the sweeping flow through the corner gap. Thus, for simplicity, equation (4-3d) formula is recommended to evaluate the sweeping flow through the corner gap for a bundle having more than 19 fuel pins. For a bundle having 7 or 19 fuel pins (all the edge subchannels are located next to the corner fuel pins), the total sweeping flow over a lead length $\overline{W}_{1j} H$ through all the wall gaps is

recommended to be evaluated by Eq. (4-2) with the parameters P' , A_s and A_r defined by Eq. (4-3c), (4-3b) and (4-3a) respectively.

Even though there is no experimental data for the sweeping flows through the gaps between the interior and edge subchannels, the sweeping flows through these kinds of gaps can be derived from Eq. (4-1) with the following assumptions:

- 1) The sweeping flow from the interior subchannel to the edge subchannel has the same characteristics as those for the sweeping flow between two interior subchannels.
- 2) The sweeping flow from the interior subchannel to the edge subchannel is equal to that from the edge subchannel to the interior subchannel.

From the first assumption, the sweeping flow $\bar{W}_{1j}$ from the interior subchannel to the edge subchannel can be evaluated by Eq. (4-1) where the subchannel centroid-to-centroid distance parameter P' in the term $(P - D/2)^{-0.35}$ should be equal to:

$$P' = \frac{\sqrt{3}}{3.46} P + \frac{\sqrt{3}}{2} (P - \frac{D}{2}) \quad (4-4)$$

which is equal to the centroid-to-centroid distance between the interior and edge subchannels divided by $\sqrt{3}$.

From the second assumption, the total sweeping flow $\bar{W}_{1j}$ from the edge subchannel to the interior subchannel should be equal to the sweeping flow evaluated above.

Agreement of $\pm 35\%$ between most of the experimental data and the correlations is obtained. This fact can be illustrated

by plotting the ratio of the parameter $\overline{W}_{1j} H/m_1$ predicted by the correlations to the parameter $\overline{W}_{1j} H/m_1$ obtained from the experimental data. The results are illustrated in Figs. (4-2) and (4-3) for the sweeping flow between interior subchannels and wall subchannels respectively. As can be observed in the above two figures, all the predictions for the sweeping flow between interior subchannels fall into the $\pm 35\%$ range of the experimental data and almost all the predictions for the sweeping flow between wall subchannels fall into the $\pm 25\%$ range of the experimental data except for the prediction for the HEDL experimental data. The reason for this discrepancy of the HEDL data is not known.

CHAPTER 5
RECOMMENDED INPUT PARAMETERS
FOR COBRA AND SUPERENERGY

The conversion factors between ϵ_{1L}^* as well as C_{1L} and the parameter $\frac{W_{1j}H}{m_1}$ derived in Appendix A are used here to translate the sweeping flow correlations for $\frac{W_{1j}H}{m_1}$ (as stated in Eqs. (4-1) and (4-2)) to the correlations for ϵ_{1L}^* and C_{1L} , which are the input parameters to the latest version of SUPERENERGY (Ref. 23) code. At the same time, we can employ the conversion factors between the effective pitch length (which is the input parameter for the COBRA code (Ref. 24)) and the mixing parameters ϵ_{1L}^* and C_{1L} to obtain the sweeping flow correlations for the COBRA input parameter. These conversion factors between the effective pitch length and ϵ_{1L}^* and C_{1L} are derived in Ref. (10).

5.1 Recommended Input Parameter for SUPERENERGY

The original input parameters to the original version of SUPERENERGY (COO-2245-20TR Revision1) are C_1 and ϵ_1^* . However, since C_1 and ϵ_1^* are found to be a function of the number of the fuel pins in the bundle (refer to Appendix B for details), these input parameters are changed to ϵ_{1L}^* and C_{1L} , which depend only on the local fluid characteristics for the latest version of SUPERENERGY (23). The definitions of ϵ_{1L}^* and C_{1L} are stated as follows:

$$\epsilon_{1L}^* = \frac{H}{V_1 De_1} = \frac{\epsilon_1^*}{x_1} \quad (5-1)$$

and

$$C_{1L} = \frac{V_{swirl}}{V_2} = \frac{C_1}{x_2} \quad (5-2)$$

(The discussion on the parameters ϵ_1^* and C_1 for their dependence on the fuel pin number is given in Appendix B.) From Appendix A, we know that:

$$\frac{\overline{W_{1j}} H}{m_1} = \epsilon_{1L}^* \frac{(4.4 (1 - \frac{D}{P})) H}{P} \quad (A-9)$$

for the sweeping flow between interior subchannels, and that

$$\frac{\overline{W_{1j}} H}{m_2} = \frac{(P - D) H}{A_{s2}} C_{1L} \quad (A-15)$$

for the sweeping flow between wall subchannels, i.e., edge subchannels. By using the above two formulas, we can obtain the correlations for ϵ_{1L}^* and C_{1L} from Eqs. (4-1) and (4-2):

Interior-to-interior subchannels

$$\epsilon_{1L}^* = 0.128 \left(\frac{P-D}{P}\right)^{-0.5} \left(\frac{A_r}{A_s}\right)^{0.5} \frac{(D + Dw) P^2}{\sqrt{\pi^2 (D + Dw)^2 + H^2}} \left(\frac{1}{A_s}\right) \quad (5-3)$$

where A_r and A_s are defined by Eqs. (4-1a) and (4-1b) respectively, and P' equals P .

(For the sweeping flow between interior and edge subchannels, P' is defined by Eq. (4-4).)

Edge-to-edge subchannels (donor edge subchannel is not next to corner pin)

$$C_{1L} = 10.5 \left(\frac{P-D}{P'} \right)^{0.35} \left(\frac{A_r}{A_s} \right)^{0.5} \frac{(D + D_w)}{\sqrt{\pi^2 (D + D_w)^2 + H^2}} \quad (5-4)$$

(If the donor edge subchannel is not located next to the corner pin, the parameters P' , A_r and A_s are defined by Eqs. (4-2a), (4-2b) and (4-2c). Otherwise, the parameters P' , A_r and A_s are defined by Eqs. (4-3c), (4-3b) and (4-3a), which make the above formula applicable for the 7 or 19 pin bundle.

It should be noted that there exist two correlations for ϵ_1^* and C_1 proposed by E. Khan (Ref. 25). His correlations are based purely on the experimental results, most of which pertain to large $\frac{P}{D}$ ratio bundles ($\frac{P}{D} > 1.20$). He concludes that ϵ_1^* increases as the $\frac{P}{D}$ ratio increases and that C_1 is not a function of the $\frac{P}{D}$ ratio. However, the recommended correlations for ϵ_{1L}^* and C_{1L} (which are numerically very close to ϵ_1^* and C_1) suggest that both parameters are functions of the $\frac{P}{D}$ ratio and that ϵ_{1L}^* decreases as the $\frac{P}{D}$ ratio increases. The discrepancy between Khan's and our correlations of the $\frac{P}{D}$ ratio effect on the parameter ϵ_{1L}^* (or ϵ_1^*) is mainly due to the fact that the low $\frac{P}{D}$ ratio data (M.I.T. $\frac{P}{D} = 1.067$) were not previously available. Therefore, Khan included Skok's (Cadache's) 7-pin experimental data ($\frac{P}{D} = 1.14$) in the ϵ_1^* correlation to make his correlation valid for $\frac{P}{D} \geq 1.14$. Since the sweeping flow of the interior subchannels in a 7-pin bundle does not represent the sweeping flow in a "true" interior subchannel (as discussed in Chapter 2), the trend that he concludes exists for the

mixing parameter ϵ_{1L}^* may thus not be correct even though his correlation predicts all the interior subchannel mixing data for bundles of $1.14 \leq \frac{P}{D} < 1.32$ within $\pm 35\%$. Comparisons between Khan's and our correlations for ϵ_{1L}^* and C_{1L} are illustrated in Figs. (5-1) and (5-2), respectively.

5.2 Recommended Input Parameters for COBRA

From Appendix A in Ref. (10), we know that the effective pitch length δ (input parameter to the COBRA code), is related to ϵ_{1L}^* and C_{1L} by the following two formulas:

$$\delta = \epsilon_{1L}^* \left(\frac{De_1}{P} \right) \sqrt{3} \quad (5-5a)$$

$$\delta = C_{1L} \quad (5-5b)$$

where De_1 = equivalent hydraulic diameter for the interior subchannel

$$\text{and } De_1 = \frac{4A_s}{\frac{\pi P}{2}} \text{ since wetted perimeter} = \frac{\pi D}{2} + \frac{\pi Dw}{2}$$

Therefore, the effective pitch length can be derived by inserting Eqs. (5-5a) and (5-5b) into Eqs. (5-3) and (5-4) as follows:

Interior-to-interior subchannels

$$\delta = 0.716 \left(\frac{P-D}{P'} \right)^{-0.35} \left(\frac{A_r}{A_s} \right)^{0.5} \frac{(D + Dw)}{\sqrt{\pi^2 (D + Dw)^2 + H^2}} \quad (5-6)$$

where the parameters P' , A_r and A_s are again defined by Eqs. (4-1c), (4-1b) and (4-1a) respectively. For the sweeping flow from the interior to edge subchannels, the parameter P' is defined by Eq. (4-4) to obtain the

corresponding effective pitch length δ_1 . However, the effective pitch length for the sweeping flow from the edge to interior subchannels should not be equal to that for the sweeping flow from the interior to the edge subchannels, otherwise the net sweeping flow over one lead length in these gaps would not be equal to zero and thus might result in continuous flow diversion out of one of these two connecting subchannels. The definition of δ in COBRA with respect to the total diversion crossflow is presented as follows:

$$\overline{W}_{1j} H = \pi(D + Dw) \frac{P-D}{A_s} (m)(\delta_1) \quad (5-6a)$$

By letting the total sweeping flow $\overline{W}_{1j} H$ from the interior to the edge subchannels equal that from the edge to the interior subchannels, we can derive the effective pitch length for the sweeping flow from edge to interior subchannels δ_2 , from eqn. (5-6a) as

$$\delta_2 = \delta_1 \frac{A_{s2}}{A_{s1}} \frac{m_1}{m_2} \quad (5-7)$$

For the case of uniform velocity across the bundle, i.e., $x_1 = x_2 = 1.0$, the δ_2 will be equal to δ_1 .

Edge-to-edge subchannels

$$\delta = 0.128 \left(\frac{P-D}{P'} \right)^{-0.5} \left(\frac{A_r}{A_s} \right)^{0.5} \frac{(D + Dw)}{\sqrt{\pi^2 (D + Dw)^2 + H^2}} \quad (5-8)$$

For the sweeping flow diverted from an edge subchannel not next to the corner pin, the parameters P' , A_r and A_s are

defined by Eqs. (4-1c), (4-1b) and (4-1a) respectively. Otherwise, the parameters P' , A_r and A_s are defined by Eqs. (4-3c), (4-3b) and (4-3a).

FIGURE 1-1 Axial Static Pressure in a Peripheral Edge Subchannel

Top View of the Fuel Rod

FIGURE 2-1 Proposed Model for Sweeping Flow

FIGURE 2-2 Local Static Pressure in Multirod Subchannels

FIGURE 2-3 Wire Location in the Subchannel Flow Field

$$\tan \theta = \frac{\pi D}{H}, \quad D = \text{Fuel Pin Diameter}$$

$$V_p = \sin \theta V, \quad H = \text{Wire Wrap Lead Length}$$

FIGURE 2-4 Relationship Between V_p and V

FIGURE 2-5 Parameter A_r/A_s versus P/D Ratio

FIGURE 2-6 Parameter $(P-D)/P$ versus P/D Ratio

FIGURE 2-7 Parameters $\frac{\text{Gap}(D+D_w)}{A_s}$ versus P/D Ratio

FIGURE 3-1 Experimental Results of $\frac{W_{1j}H}{m_1}$ for Gaps Between Interior Subchannels

FIGURE 3-2 Experimental Results of $\frac{W_{1j} H}{m_2}$ for Gaps Between Wall Subchannels

FIGURE 4-1 Configuration of Edge Subchannels Next to the Corner Fuel Pin

FIGURE 4-2 Comparison Between the Predicted and the Experimental Sweeping Flow Parameters for Gaps Between Interior Subchannels

FIGURE 4-3 Comparison Between the Predicted and the Experimental Sweeping Flow Parameters for Gaps Between Wall Subchannels

Figure 5-1 Comparison between Khan's and Proposed Correlations for ϵ_{1L}^*

Figure b-2 Comparison between Khan's and Proposed Correlations
 C_{1L} ($N_R > 19$)

TABLE 3-1
Data used in Analysis

Experimentalist	P/D	N	H/D	Type of Experiment
Chiu et al (MIT) ^{(10)*}	1.067	61	8,4	Salt injection
Skok (Cadarache) ⁽¹¹⁾	1.14	7	14,21,29	Hot water injection
Okamoto et al. (Japanese) ⁽¹²⁾	1.20	91	43	Salt injection
Collingham et al. (HEDL) ⁽¹³⁾	1.24	217	52	Salt injection
Pedersen et al. (ANL-RAS) ⁽¹⁴⁾	1.24	91	48	Hot water injection
Lorentz et al. (ANL-CT) ⁽¹⁵⁾	1.24	91	48	Salt injection
Fontana et al. (ORNL) ⁽¹⁶⁾	1.24	19	52	Heated rods
Chen et al. (MIT) ⁽¹⁷⁾	1.25	61	24,48	Laser
Hanson et al. (MIT) ^{(8)*}	1.25	61	24,48	Salt injection
Wheeler et al. (BNWL) ⁽¹⁸⁾	1.25	7	48	Laser
Hines et al. (GE) ⁽¹⁹⁾	1.28	127	24	Hot water injection
Baumann et al. (Karlsruhe) ⁽²⁰⁾	1.315	61	17,33,50	Heated rod

*Data are reduced by the Experimenters

APPENDIX A
CONVERSION FACTORS BETWEEN $\frac{\overline{W}_{1j} H}{m_1}$ AND

$$\epsilon_{1L}^* \text{ AND } C_{1L}$$

For the interior subchannels, the energy transport equation employing parameter $\overline{W}_{1j}$ can be written as:

$$m_1 \frac{\partial h_1}{\partial x} = q_1' + \sum_j \overline{W}_{1j} (h_j - h_1) \quad (A-1)$$

(Refer to Chapter 2 in Ref. (10) for derivation.)

where

$$\overline{W}_{1j} = \frac{\int_0^H |W_{1j}| dx}{2H}, \text{ which physically represents}$$

the average sweeping flow from subchannel 1
to subchannel j (over a lead length). (A-2)

At the same time, the energy equation used in the SUPERENERGY code is as follows:

$$\frac{\partial T_1}{\partial x} = q_1' + \sum_j \frac{(P-D)}{A_s} \frac{\epsilon_H}{V_1 n} (T_j - T_1) \quad (A-3)$$

where ϵ_H is defined in Ref. (23).

$$\text{Since } \epsilon_{1L}^* = \frac{\epsilon_1^*}{De_1 x_1} = \frac{\epsilon_H}{De_1 V_1}, \quad (A-4a)$$

$$\text{and } m_1 = \rho A_s V_1, \quad (A-4b)$$

Utilizing Eqns. A-4a and A-4b, Eq. (A-3) can be reformed as:

$$m_1 \frac{\partial h_1}{\partial x} = q_1' + \sum_j \frac{(P-D) \rho \epsilon_{1L}^* V_1 De_1}{n} (h_j - h_1) \quad (A-5)$$

Comparing Eq. (A-5) to Eq. (A-1), we obtain:

$$\overline{W_{1j}} = \frac{(P-D)\rho\epsilon_{1L}^* V_1 De_1}{\eta} \quad (A-6)$$

where

$$De_1 = \frac{4A_{s1}}{\pi(D + Dw)/2} \quad (A-7)$$

where A_{s1} = area for interior subchannels

and η = centroid to centroid distance in
interior subchannels, i.e.,

$$\eta = \frac{P}{\sqrt{3}} . \quad (A-8)$$

Inserting the last two equations into Eq. (A-6), we obtain:

$$\overline{W_{1j}} = \frac{(P-D)\epsilon_{1L}^* \rho V_1 8A_{s1}\sqrt{3}}{\pi(D + Dw)P} .$$

Noting that $\rho V_1 A_{s1} = m_1$ and $D + Dw = P$, the above equation can be simplified to:

$$\frac{\overline{W_{1j}}}{m_1} = \frac{4.41 \epsilon_{1L}^* (\frac{P-D}{P})}{P} \quad (A-9)$$

By multiplying both sides of the above equation by H , we obtain:

$$\frac{\overline{W_{1j}}}{m_1} H = 4.41 (1 - \frac{D}{P}) (\frac{H}{P}) \epsilon_{1L}^* \quad (A-10)$$

From this equation, we can derive the sweeping flow parameter $\frac{\overline{W}_{1j} H}{m_1}$ from the local effective enhanced eddy diffusivity ϵ_{1L}^* . It should be noted that ϵ_1^* is used in the calibration against the experimental data by E. Khan instead of ϵ_{1L}^* . However, by knowing the flow split parameter x_1 predicted by the code ENERGY, which is used in the calibration, we can obtain ϵ_{1L}^* by the following formula:

$$\epsilon_{1L}^* = \frac{\epsilon_1^*}{x_1} \quad (5-1)$$

Therefore,

$$\frac{\overline{W}_{1j} H}{m_1} = 4.41(1 - \frac{D}{P})(\frac{H}{P}) \frac{\epsilon_1^*}{x_1} \quad (A-11)$$

To derive the conversion factor between $\frac{\overline{W}_{1j} H}{m_1}$ and C_1 (or C_{1L}), we start with the following equation, derived in Appendix A (Ref. 10):

$$\rho \text{Gap} V_{\text{swirl}} = \overline{W}_{1j} \quad (A-12)$$

where V_{swirl} is defined in Ref. (22).

By knowing that

$$C_{1L} = \frac{V_{\text{swirl}}}{V_2} = \frac{C_1}{\overline{W}x_2} \quad (A-13)$$

$$\text{and } m_1 = \rho A_s V_2, \quad (A-14)$$

we can derive the parameter $\frac{\overline{W}_{1j} H}{m_1}$ as a function of C_{1L} . The result is:

$$\frac{\overline{W}_{1j} H}{m_1} = \frac{\rho \text{Gap} V_{\text{swirl}} H}{\rho A_s V_2} = \frac{\text{Gap}}{A_s} \frac{H}{V_2} C_{1L}. \quad (A-15)$$

By knowing that

$$C_{1L} = \frac{C_1}{x_2} \quad (5-2)$$

we can conclude that

$$\frac{\overline{W_{1j}} H}{m_1} = \frac{Gap}{A_s x_2} H C_1 \quad (A-16)$$

When using values of C_1 , as determined by Khan with Eqn. A-16 to predict $\frac{\overline{W_{1j}} H}{m_1}$ the edge subchannel flow split parameter x_2 should be predicted by Novendstern's method (Ref. 26), which is employed in the ENERGY code. This is because this code is originally used to calibrate the swirl flow parameter C_1 against the experimental data.

APPENDIX B
DEPENDENCE OF ϵ_1^* AND C_1
ON THE NUMBER OF PINS IN A FUEL BUNDLE

The mixing parameters ϵ_1^* and C_1 used in the ENERGY code are defined as

$$\epsilon_1^* = \frac{\epsilon_H}{VDe_1} \quad (B-1)$$

and

$$C_1 = \frac{V_{swirl}}{\bar{V}} \quad (B-2)$$

From Appendix A, we know that:

$$\frac{\overline{W_{1j}} H}{m_1} = 4.41 \left(1 - \frac{D}{F}\right) \left(\frac{H}{F}\right) \frac{\epsilon_1^*}{x_1} \quad (A-11)$$

and

$$\frac{\overline{W_{1j}} H}{m_2} = \frac{Gap H}{A_s x_2} \quad (A-16)$$

The parameter $\frac{\overline{W_{1j}} H}{m_1}$ is the ratio of the total diversion cross-flow (or sweeping flow) swept over a lead length from subchannel 1 to subchannel j to the mass flow in subchannel 1. This parameter depends only on the local fluid characteristics. Thus, it does not depend on the number of fuel pins in the bundle. For any interior subchannels having identical $\frac{P}{D}$ and $\frac{H}{D}$ ratios, no matter how many fuel pins in their bundle, the parameter $\frac{\overline{W_{1j}} H}{m_1}$ will be the same.

However, the flow split parameters x_1 and x_2 are functions of the number of pins in the bundle if the constant pressure loss condition is employed to derive these two parameters (such as the prediction proposed by Novendstern (Ref. 26)). This characteristic will lead to the dependence of the mixing parameters ϵ_1^* and C_1 on the bundle size. This is because all the other parameters, i.e., $(1 - \frac{D}{P})$, $(\frac{H}{P})$, $\frac{Gap}{A_s} \frac{H}{P}$ and $\frac{\overline{W_{1j}}}{m_1} \frac{H}{P}$, in Eqs. (A-11) and (A-16), which are fundamental definitions of ϵ_1^* and C_1 , are not functions of the bundle fuel pin numbers, since these parameters only represent local geometric and fluid characteristics. Thus the parameters ϵ_1^* and C_1 must depend on the number of fuel pins in such a way as to make ϵ_1^*/x_1 and C_1/x_2 independent of the number of fuel pins. It should be noted that since the flow split parameters x_1 and x_2 are weakly dependent on the number of pins in the bundle, the dependence of ϵ_1^* and C_1 on the bundle fuel pin number is thus weak.

To alleviate the dependence of ϵ_1^* and C_1 on the bundle size, it is suggested that ϵ_{1L}^* and C_{1L} , which are defined as the local effective enhanced eddy diffusivity and the local swirl flow parameter, be employed. (Definitions of these two parameters are stated in Eqs. (5-1) and (5-2).) By employing these two parameters, Eqs. (A-11) and (A-16) become:

$$\frac{\overline{W_{1j}}}{m_1} \frac{H}{P} = 4.41 (1 - \frac{D}{P}) (\frac{H}{P}) \epsilon_{1L}^* \quad (A-10)$$

$$\frac{\overline{W_{1j}}}{m_1} H = \frac{Gap}{A_s} H C_{1L} \quad (A-15)$$

From the above argument for the bundle fuel-pin number dependence, we can conclude that these two local mixing parameters are not functions of the number of fuel pins comprising the bundle.

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