ENCLOSURE III

CEN-160-(S)-P (CTOP-D)
Errata pages

CHANGE PAGES FOR CETOP-D ON
SONGS (CEN-160(S) NP).

A FORMAL SUBMITTAL WILL FOLLOW.

$$m_i \frac{\partial h_i}{\partial x} = q'_i - (h_i - h_j)\, w'_{ij} + (h_i - h^*) w_{ij} \qquad (1.5)$$

Considering all adjacent flow channels, the energy equation becomes:

$$\frac{\partial h_i}{\partial x} = \frac{q'_i}{m_i} - \sum_{j=1}^{N} (h_i - h_j) \frac{w'_{ij}}{m_i} + \sum_{j=1}^{N} (h_i - h^*) \frac{w_{ij}}{m_i} \qquad (1.6)$$

1.2.1.3 Axial Momentum Equation

Referring to Figure 1.3b, the axial momentum equation for channel i, considering only one adjacent channel j, has the form:

$$-F_i dx + p_i dA_i - gA_i\, \rho_i\, dx + p_i A_i - (p_i A_i + \frac{\partial}{\partial x} p_i A_i dx) =$$

$$-m_i u_i + (m_i u_i + \frac{\partial}{\partial x} m_i u_i dx) - w'_{ji} u_j dx + w'_{ij} u_i dx + w_{ij} u^* dx \qquad (1.7)$$

where $u^* = 1/2\ (u_i + u_j)$.

By using the assumption $w'_{ij} = w'_{ji}$, one has:

$$-F_i - gA_i \rho_i - A_i \frac{\partial p_i}{\partial x} = \frac{\partial}{\partial x}\, m_i u_i + (u_i - u_j) w'_{ij} + u^* w_{ij} \qquad (1.8)$$

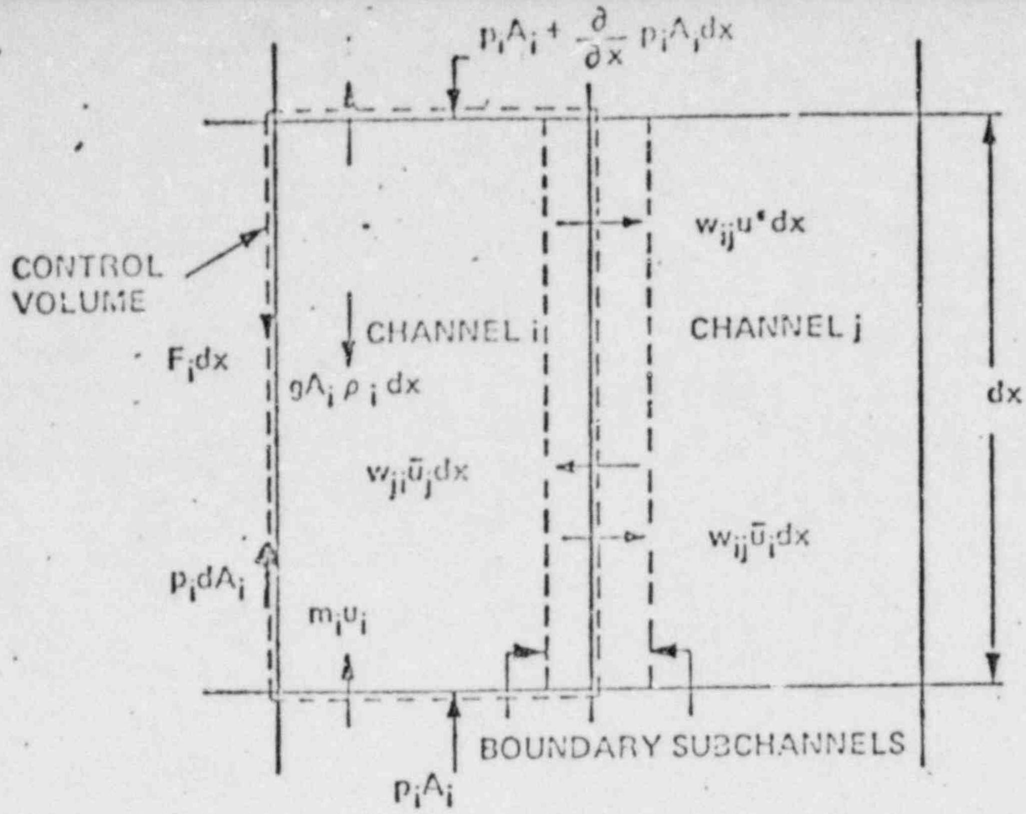
Substituting the following definitions:

$$u_i \equiv \frac{m_i v_{p_i}}{A_i}\ ;\ F_i \equiv \left(\frac{A_i v_i f_i \phi_i}{2De_i} + \frac{A_i K_{G_i} v_i}{2\Delta x} \right) \left(\frac{m_i}{A_i}\right)^2 \qquad (1.9)$$

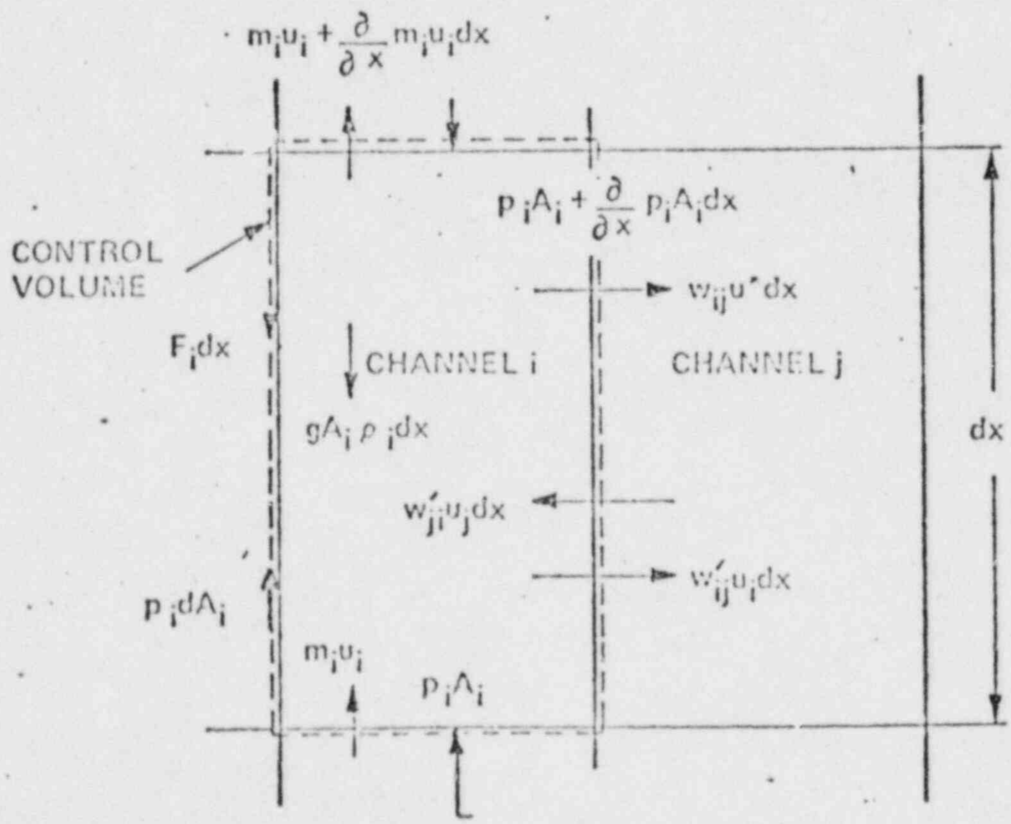
and Eq. (1.2) into Eq. (1.8), one obtains:

$$A_i \frac{\partial p_i}{\partial x} = -A_i \left(\frac{m_i}{A_i}\right)^2 \left[\frac{v_i f_i \phi_i}{2De_i} + \frac{K_{G_i} v_i}{2\Delta x} + A_i \frac{\partial}{\partial x} \left(\frac{v_{p_i}}{A_i}\right)\right] - gA_i \rho_i \qquad (1.10)$$

$$- (u_i - u_j)\, w'_{ij} + (2u_i - u^*) w_{ij}$$



(A) CONTROL VOLUME FOR LUMPED CHANNEL



(B) CONTROL VOLUME FOR AVERAGED CHANNEL

Figure 1.3

CONTROL VOLUMES FOR AXIAL MOMENTUM EQUATION

2.0 EMPIRICAL CORRELATIONS

CETOP-D retains the empirical correlations which fit current C-E reactors and the ASME steam table routines which are included in the TORC code.

In CETOP-D, the following correlations are used:

2.1 Fluid Properties

Fluid properties are determined with a series of subroutines that use a set of curve-fitted equations developed in References 7 and 8 for describing the fluid properties in the ASME steam tables. In CETOP-D, these equations cover the subcooled and saturated regimes.

2.2 Heat Transfer Coefficient Correlations

The film temperature drop across the thermal boundary layer adjacent to the surface of the fuel cladding is dependent on the local heat flux, the temperature of the local coolant, and the effective surface heat transfer coefficient:

$$DTF = T_{wall} - T_{cool} = \frac{q''}{h} \tag{2.1}$$

For the forced convection, non-boiling regime, the surface heat transfer coefficient h is given by the Dittus-Boelter correlation, Reference 9:

$$h = \frac{0.023k}{De} (Re)^{0.8} (Pr)^{0.4} \tag{2.2}$$

For the nucleate boiling regime, the film temperature drop is determined from the Jens-Lottes correlation, Reference 10:

$$DTJL = (T_{sat} - T_{cool}) + \frac{60(q''/10^6)^{0.25}}{e^{P/900}} \tag{2.3}$$

The initiation of nucleate boiling is determined by calculating the film temperature drop on the bases of forced convection and nucleate boiling.

Fyle (Reference 13) to account for mass velocity and pressure level dependencies.

2.5 Void Fraction Correlations

The modified Martinelli-Nelson correlation is used for calculating void fraction in the following ways:

1) For pressures below 1850 psia, the void fraction is given by the Martinelli-Nelson model from Reference 12:

$$\alpha = B_0 + B_1 X + B_2 X^2 + B_3 X^3 \tag{2.6}$$

where the coefficients B_n are defined in Reference 10 as follows:

For the quality range $0 \leq X < 0.01$:

$B_0 = B_1 = B_2 = B_3 = 0$; the homogeneous model is used for calculating void fraction:

$$\alpha = 0 \qquad \text{For } X \leq 0$$
$$\alpha = \frac{X \nu_g}{(1-X)\nu_f + X\nu_g} \qquad \text{For } X > 0 \tag{2.7}$$

For the quality range $0.01 \leq X < 0.10$:

$$\begin{aligned}
B_0 &= 0.5973 - 1.275\times10^{-3}p + 9.010\times10^{-7}p^2 - 2.065\times10^{-10}p^3 \\
B_1 &= 4.746 + 4.156\times10^{-2}p - 4.011\times10^{-5}p^2 + 9.867\times10^{-9}p^3 \\
B_2 &= -31.27 - 0.5599p + 5.580\times10^{-4}p^2 - 1.378\times10^{-7}p^3 \\
B_3 &= 89.07 + 2.408p - 2.367\times10^{-3}p^2 + 5.694\times10^{-7}p^3
\end{aligned} \tag{2.8}$$

For the quality range $0.10 \leq X < 0.90$:

$$\begin{aligned}
B_0 &= 0.7847 - 3.900\times10^{-4}p + 1.145\times10^{-7}p^2 - 2.711\times10^{-11}p^3 \\
B_1 &= 0.7707 + 9.619\times10^{-4}p - 2.010\times10^{-7}p^2 + 2.012\times10^{-11}p^3 \\
B_2 &= -1.060 - 1.194\times10^{-3}p + 2.618\times10^{-7}p^2 - 6.893\times10^{-12}p^3
\end{aligned} \tag{2.9}$$

where: q''_{CHF} = critical heat flux, BTU/hr-ft^2
p = pressure, psia
d = heated equivalent diameter of the subchannel, inches
d_m = heated equivalent diameter of a matrix subchannel with the same rod diameter and pitch, inches
G = local mass velocity at CHF location, lb/hr-ft^2
X = local coolant quality at CHF location, decimal fraction
h_{fg} = latent heat of vaporization, BTU/lb

and b_1 = 2.8922×10^{-3}
b_2 = -0.50749
b_3 = 405.32
b_4 = -9.9290×10^{-2}
b_5 = -0.67757
b_6 = 6.8235×10^{-4}
b_7 = 3.1240×10^{-4}
b_8 = -8.3245×10^{-2}

The above parameters were defined from source data obtained under following conditions:

pressure (psia)	1785 to 2415
local coolant quality	-0.16 to 0.20
local mass velocity(lb/hr-ft^2)	0.87×10^6 to 3.2×10^6
inlet temperature (°F)	382 to 644
subchannel wetted equivalent diameter (inches)	0.3588 to 0.5447
subchannel heated equivalent diameter (inches)	0.4713 to 0.7837
heated length (inches)	84,150

To account for a non-uniform axial heat flux distribution, a correction factor FS is used. The FS factor is defined as:

$$FS = \frac{q''_{CHF,\ Equivalent\ Uniform}}{q''_{CHF,\ Non\text{-}uniform}}$$

$$FS(J) = \frac{C(J)}{q''(J)\left(1-e^{-C(J)\,X(J)}\right)} \int_0^{X(J)} q''(x)\,e^{-C(J)\,(X(J)-x)}\,dx$$

Table 2.2

Functional Relationships in the Two-Phase Friction Factor Multiplier (References 11,12,13)

For local boiling:

$$f_1 = C_1 \left(1 + 0.76 \left(\frac{3500-P}{1500}\right) \left(\frac{10^6}{G}\right)^{2/3} \omega\right)$$

where $C_1 = (1.05)(1-0.0025\theta^*)$

θ^* = The smaller of DTJL and DTF

$\omega = 1 - \theta^*/\mathrm{DTF}$

For bulk boiling:

$$\mathrm{FAM} = 1 + \frac{7X^{0.75}}{(G/10^6)^{1+X}}$$

$$\mathrm{FMN1} = \frac{X^{(0.9326 - (0.2263\times10^{-3})P)}}{1.65\times10^{-3} + (2.988\times10^{-5})P - (2.528\times10^{-9})P^2 + (1.14\times10^{-11})P^3}$$

$$\mathrm{FMN2} = \frac{X^{(1.0205 - (0.2053\times10^{-3})P)}}{7.876\times10^{-4} + (3.177\times10^{-5})P - (8.728\times10^{-9})P^2 + (1.073\times10^{-11})P^3}$$

$$\mathrm{FMN3} = 1 + (-0.0103166X + 0.005333X^2)(P - 3206)$$

$$f_2 = 1.26 - 0.0004P + 0.119\left(\frac{10^6}{G}\right) + 0.00028P\left(\frac{10^6}{G}\right)$$

$$f_3 = 1.36 + 0.0005P + 0.1\left(\frac{G}{10^6}\right) - 0.000714P\left(\frac{G}{10^6}\right)$$

$$f_4 = 1 + 0.93\left(0.7 - \frac{G}{10^6}\right)$$

$$- 2u_i w_{ij} + \left(\frac{u_i + u_j}{2} + \frac{(u_i - u_j)n}{2N_U} \right) w_{ij} \Bigg\}_J \qquad (3.3)$$

(4) Lateral Momentum Equation

$$\frac{p_i(J-1) - p_j(J-1)}{N_p} = K_{ij} \frac{w_{ij}(J)\, w_{ij}(J)}{2gs^2\rho^*}$$

$$+ \frac{\ell}{s} \frac{u^*(J) w_{ij}(J) - u^*(J-1) w_{ij}(J-1)}{\Delta x} \qquad (3.4)$$

Where J is the axial elevation indicator and Δx is the axial nodal length.

3.2 Prediction - Correction Method

In CETOP-D a non-iterative numerical scheme is used to solve the conservation equations. This prediction-correction method provides a fast yet accurate scheme for the solution of m_i, h_i, w_{ij} and p_i at each axial level. The steps used in the CETOP-D solution are as follows:

The channel flows, m_i, enthalpies h_i, pressures p_i and fluid properties are calculated at the node interfaces. The linear heat rates q_i', crossflows, w_{ij}, and turbulent mixing, w_{ij}', are calculated at mid-node. The solution method starts at the bottom of the core and marches upward using the core inlet flows as one boundary condition and equal core exit pressures as another.

each flow channel, thus, for a channel containing n rods, the idea of effective radial power factor is used:

$$\hat{f}_R(i) = \frac{\sum_{j=1}^{n} \zeta_j \, f_R(i,j)}{\sum_{j=1}^{n} \zeta_j} \qquad (4.11)$$

where ζ_j is the fraction of the rod j enclosed in channel i.

4.3.2 Axial Power Distributions

The fuel rod axial power distribution is characterized by the axial shape index (ASI), defined as:

$$ASI = \frac{\int_0^{L/2} F_Z(k)dZ - \int_{L/2}^{L} F_Z(k)dZ}{\int_0^{L} F_Z(k)dZ} \qquad (4.12)$$

where the axial power factor at elevation k, $F_Z(k)$, satisfies the normalization condition:

$$\int_0^{L} F_Z(k)dZ = 1 \qquad (4.13)$$

and L, dZ are total fuel length and axial length increment respectively.

The total heat flux supplied to channel i at elevation k is:

$$\phi_i = (\text{core average heat flux}) \, (\hat{f}_R(i)) \, (F_Z(k)) \qquad (4.14)$$

4.3.3 Effective Rod Diameter

For a flow channel containing n rods of identical diameter d, the effective rod diameter defined by:

$$\hat{D}(i) = \sum_{j=1}^{n} \zeta_j d \qquad (4.15)$$

is used to give effective heated perimeter in channel i. The following expression, derived from Eq's. (4.5) and (4.9), implies that equivalent energy is being received by channel i: