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COBRA-III:
A DIGITAL COMPUTER PROGRAM
FOR STEADY STATE AND
TRANSIENT THERMAL-HYDRAULIC
ANALYSIS OF ROD BUNDLE
NUCLEAR FUEL ELEMENTS

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INTERIM REPORT

COBRA-III: A DIGITAL COMPUTER PROGRAM
FOR STEADY STATE AND TRANSIENT THERMAL-
HYDRAULIC ANALYSIS OF
ROD BUNDLE NUCLEAR FUEL ELEMENTS

By

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INTRODUCTION

This interim report presents the progress on the development of the COBRA-III computer program for both steady state and transient subchannel analysis of rod bundle nuclear fuel elements. Development of this transient program is motivated by the need for improved methods of reactor safety analyses.

Much of the safety analysis for licensing and safe operation of nuclear reactors is related to the transient response of the reactor core and fuel following normal operating transients and potential accident situations. The analysis must show, for example, that critical heat flux limits are not exceeded during an overpower situation or that core integrity can be maintained following a major piping rupture. The analysis of these transients is difficult to perform with present analyses methods. More sophisticated analysis techniques are definitely required.

With the acceptance of the subchannel analysis approach by much of the nuclear industry, there has been considerable interest in a similar analysis for transients because this analysis philosophy could then be extended to include transients.

The version of COBRA presented in this report represents an interim stage of developing a transient subchannel computer program. The COBRA program is still a highly developmental program that will undergo considerable revision as its development continues. When appropriate stages of development are reached, additional versions of the program will be released. These may be designated as COBRA-IIIB, IIIC, etc. Since COBRA is being developed under USAEC sponsorship for use by the nuclear industry, comments from the users of COBRA-III are encouraged to help guide future developments in the program.

SUMMARY

The COBRA-III computer program computes the flow and enthalpy in rod-bundle nuclear fuel element subchannels during both steady state and transient conditions. It uses a mathematical model that considers both turbulent and diversion crossflow mixing between adjacent subchannels. Each subchannel is assumed to contain one-dimensional, two-phase slip-flow. The two-phase flow structure is assumed to be fine enough for local void fraction to be a function of enthalpy, flow rate, heat flux, pressure position and time. At the present time, steady-state two-phase flow correlations are assumed to apply to transients. The mathematical model neglects sonic velocity propagation; therefore, it is limited to transients where the transient times are greater than the time for a sonic wave to pass through the channel. A simplified transverse momentum equation is also used to simplify the numerical solutions. This simplification neglects the transverse temporal and spatial acceleration and therefore gives instantaneous response of the diversion crossflow to changes in subchannel pressure gradient. The equations of the mathematical model are solved by using a semi-explicit finite difference scheme. The scheme is stable for all time and space steps; however, reasonably small steps are required to obtain accurate solutions. This scheme also gives a boundary-value flow solution for both steady state and transients where the boundary conditions are the inlet enthalpy, inlet mass velocity, and exit pressure.

The features of COBRA-III can be summarized as follows:

- It contains all the analysis capability of the COBRA-II program.
- It can consider transients of fast-to-intermediate speed--no sonic velocity propagation effects are considered.
- The numerical scheme performs a boundary value solution to more properly include the effects of crossflow resistance.
- The numerical solution has no stability limitation on space or time steps.

Development of COBRA-III is continuing to improve its capability. Presently, major emphasis is being directed toward developing a more complete transverse momentum equation that includes both the temporal and spatial components of transverse acceleration. This is required to allow a more realistic analysis of subchannel flow in a fuel bundle containing blockages. A

method of including forced diversion crossflow is also being developed to allow analysis of wire wrapped fuel bundles.

Future plans call for development of reverse flow analysis capability to eliminate the present restriction of flow moving in only one direction. This will be followed by the inclusion of a pressure drop boundary condition to eliminate the present a priori knowledge of the inlet flow rate. A fuel heat transfer model will also be developed to account for the thermal response of the fuel.

DESCRIPTION OF MATHEMATICAL MODEL

Two-phase flow in rod bundle nuclear fuel elements is a complicated process which is not completely understood at the present time. One of the major difficulties is the inability to predict the transport processes of the liquid and vapor phases within the bundle. Reasonable descriptions of these processes have been made for selected regimes of two-phase flow in simple channels; but these descriptions cannot be easily applied to the complex geometry of rod bundles. This is because the added degrees of lateral freedom in rod bundles allows additional modes of liquid and vapor exchange which tend to invalidate the descriptions of transport processes in simple channels. This exchange, however, has a very significant influence on the flow and enthalpy in various regions of the bundle.

To develop a method for predicting the flow and enthalpy in selected regions of a rod bundle, a mathematical model is used that considers the important lateral transport processes. The approach used is similar to the original COBRA program⁽¹⁾ where the cross section of the rod bundle is divided into discrete flow subchannels as shown in Figure 1. By making suitable assumptions concerning the flow and crossflow in these subchannels, the equations of continuity, energy and momentum can be derived for each subchannel. This set of equations can then be solved numerically by using a digital computer.

BASIC ASSUMPTIONS

- One-dimensional, two-phase slip flow exists in each subchannel during boiling.
- The two-phase flow structure is fine enough to allow specification of local void fraction as a function of enthalpy, pressure, flow rate, axial position and time.

FIGURE 1. Method of Subchannel Selection

- A turbulent crossflow exists between adjacent subchannels that causes no net flow redistribution.
- The turbulent crossflow may be superimposed upon a diversion crossflow between subchannels that results from flow redistribution. This may occur artificially from devices that force diversion crossflow.
- Transverse spatial and temporal acceleration is neglected.
- Sonic velocity propagation effects are ignored.

The last two assumptions greatly simplify the mathematical model and the numerical solution. Neglecting temporal acceleration can be justified for slow or moderate speed transients since the acceleration of fluid in the gaps between subchannels would be small. For high speed transients, this assumption may not be acceptable. The result of this assumption is that the diversion crossflow has instantaneous response to changes in the pressure gradient. Neglecting sonic velocity propagation is also justified for moderate speed transients. Meyer⁽¹⁵⁾ justifies this assumption for transients with times that are longer than the sonic propagation time through the channel.

GENERALIZED EQUATIONS

The equations of continuity, energy, and momentum may be derived by using these basic assumption as shown in Appendix A. This derivation gives a set of $3N$ first order, partial, differential equations plus K algebraic equations where N is the number of subchannels and K is the

number of connections between subchannels. If the equations for flow, enthalpy and pressure are represented as N component column vectors, and if the two crossflows are represented by K component column vectors, the transport equations may be written in the following matrix notation as shown in Appendix B.

Continuity

$$\left\{ A \frac{\partial \rho}{\partial t} \right\} + \left\{ \frac{\partial m}{\partial x} \right\} = -[S^T]\{w\} \quad (1)$$

Energy

$$\begin{aligned} \left\{ \frac{1}{u} \frac{\partial h}{\partial t} \right\} + \left\{ \frac{\partial h}{\partial x} \right\} &= \{Q\} - \left[\frac{1}{m} \right] [S^T] [\Delta h] \{w\} \\ &+ \left[\frac{1}{m} \right] [S^T] [\Delta T] \{c\} + \left[\frac{1}{m} \right] [S^T] [\Delta h^*] \{w\} \end{aligned} \quad (2)$$

Axial Momentum

$$\left\{ \frac{1}{A} \frac{\partial m}{\partial t} \right\} - \left\{ 2u \frac{\partial \rho}{\partial t} \right\} + \left\{ \frac{\partial p}{\partial x} \right\} = -\{a\} - \left[\frac{1}{A} \right] [S^T] [\Delta u] \{f, w\} + \left[\frac{1}{A} \right] [S^T] [\Delta u^*] \{w\} \quad (3)$$

Transverse Momentum

$$\{Cw\} = [S]\{p\} \quad (4)$$

The above shorthand notation gives a simple form that shows the basic phenomena included in the mathematical model. Consider the various terms in the above equations.

The right side of Equation (1) states that the rate of flow change in a subchannel is a linear combination of the diversion crossflows. The matrix transformation $[S^T]$ is used to order only those crossflows permitted by the problem set up. The turbulent crossflow term does not appear in Equation (1) because, on a time average, it does not cause a net flow change. The time derivative of density gives the component of

flow change caused by the fluid expansion or contraction.

In the Energy Equation (2), the terms on the right illustrate four mechanisms of steady state thermal energy transport to a subchannel in a rod bundle fuel element. The first term $\{Q\}$ is the power-to-flow ratio of a subchannel and gives the rate of enthalpy change if no thermal mixing occurs. The second term $[1/m] [S^T] [\Delta h] \{w'\}$ accounts for the turbulent enthalpy transport between all interconnected subchannels. This is analogous to eddy diffusion as discussed in Reference 1. The diagonal matrix $[\Delta h]$ contains the subchannel enthalpy differences for each pair of interconnected subchannels. The turbulent thermal mixing $\{w'\}$ is defined through empirical correlations. The third term $[1/m] [S^T] [\Delta T] \{c\}$ accounts for thermal conduction between adjacent subchannels. During boiling, the temperatures contained in $[\Delta T]$ are limited to saturation temperature; therefore, the conduction term vanishes when all channels are boiling. The thermal conduction coefficient is defined in terms of geometric and fluid parameters. The fourth term $[1/m] [S^T] [\Delta h^*] \{w\}$ accounts for thermal energy carried by the diversion crossflow. This is a convective term that requires a selection of the enthalpy to be carried by the diversion crossflow. This selection of the enthalpy is denoted by the matrix $[\Delta h^*]$ which is set up the same way as $[\Delta h]$. The matrix $[\Delta h^*]$, however, permits selection of an effective enthalpy that is carried by the diversion crossflow. This may be used, for example, to account for the nonuniform enthalpy distribution in a subchannel by selecting the effective enthalpy transported from known information about the liquid-and vapor-phase distribution. The first term on the left side of Equation (2) gives the transient contribution to the spatial rate of enthalpy change. Equation (2) can be classified as a system of hyperbolic partial differential equations with a characteristic velocity of u'' . All energy transport during transients are related to this velocity. In the present version of COBRA-III, u'' is calculated from the homogenous flow model for transients. Note that sonic velocity propagation effects are ignored by the absence of a $\partial p / \partial t$ term.

The right side of the Axial Momentum Equation (3) shows three contributions to the steady state pressure gradient. The first term $\{a\}$ represents the pressure gradient without any crossflow between subchannels. It includes the friction, spatial acceleration and elevation components of pressure

gradient. This term gives the pressure gradient in an equivalent simple channel with the same thermal hydraulic characteristics as the rod bundle subchannel. It is in this term where the important empirical correlations are contained that govern the subchannel flow solution. The second term $[1/A] [S^T] [\Delta u] \{f_T w'\}$ accounts for the turbulent momentum transport between subchannels and is analogous to a Reynolds stress as discussed in Reference 1. The matrix $[\Delta u]$ contains the subchannel velocities and is set up the same way as $[\Delta h]$. Since the analogy between thermal and momentum turbulent transport processes may not be the same, the factor f_T is included to modify the turbulent crossflow which is selected to satisfy the energy equation. The remaining term $[1/A] [S^T] [\Delta u^*] \{w\}$ of Equation (3) is the axial momentum contribution of the diversion crossflow. This is a convective term that is analogous to the convective energy term. The matrix $[\Delta u^*]$ contains the axial velocities that are carried through the gap by the diversion crossflow. The first two terms on the left side of Equation (3) give the transient components of the pressure gradient. The first is due to the time rate of flow change (temporal acceleration) and the second is due to the rate of change fluid mass.

The Transverse Momentum Equation (4) is a linearized friction model where the pressure drop between subchannels is proportional to the diversion crossflow rate. The linear approximation is justified because of the weak influence of crossflow resistance on many problems. Nonlinear crossflow resistance can be included by letting C be a variable. This simplified equation neglects temporal and spatial acceleration of the diversion crossflow; therefore, it gives instantaneous response of the crossflow to changes in subchannel pressure. The resistance coefficient C is evaluated in terms of an empirical function which depends on the geometric and flow parameters. Although this equation has rather weak influence when C is small, it still plays an important role in the numerical solutions.

METHOD OF SOLUTION

The steady flow in rod bundle subchannels is governed by the boundary conditions imposed at the ends of the bundle; therefore, the flow solution requires a boundary-value solution. Since this solution is difficult to set up and difficult to solve, it has been common practice to use a simpler

initial-value solution as an approximate solution. Various types of initial-value solutions are used in the HAMBO,⁽²⁾ SASS,⁽³⁾ THINC-II,⁽⁴⁾ MIXER⁽⁵⁾ and COBRA-II⁽⁶⁾ subchannel analyses programs for steady state analysis. The use of an initial-value solution is justified⁽⁷⁾ as an approximation to the boundary-value solution if a stability criterion can be satisfied. This criterion gives the minimum allowable calculation increment (Δx) in terms of the crossflow resistance. The calculation increment must be larger than this to permit adequate flow redistribution. If the increment is smaller than this, the flow redistribution must occur over additional calculation increments, and a boundary-value solution is required. While this criterion does justify the use of an initial-value solution, it imposes a numerical stability limitation that restricts solutions to a limited class of problems.

In developing COBRA-III, considerable time was devoted to develop a transient solution that could include the boundary conditions at the ends of bundle and also be reasonably efficient, accurate and fast. The selected method represents a compromise between these desirable features. The following paragraphs discuss the formulation of the problem, numerical methods, and the stability of the numerical solution.

FORMULATING THE PROBLEM

It is most convenient to work with equations for enthalpy, flow and diversion crossflow. Pressure can be easily eliminated by differentiating Equation (4) and substituting Equation (3) which gives

$$\left\{ \frac{\partial C w}{\partial x} \right\} = -[S]\{a'\} + [S]\left[\frac{1}{A}\right][S^T][\Delta u^*]\{w\} - [S]\left\{\frac{1}{A} \frac{\partial m}{\partial t}\right\} + [S]\left\{2u \frac{\partial p}{\partial t}\right\} \quad (5)$$

where

$$\{a'\} = \{a\} + \left[\frac{1}{A}\right][S^T][\Delta u]\{f, w\}.$$

This eliminates pressure explicitly but it is still contained implicitly to evaluate fluid properties. Equations (1) (2) and (5) are the equations used in the solution. Note that $\partial p / \partial t$ is calculated from

$\partial h / \partial t$ through the equation of state

$$\rho = \rho(h, p^*, m, x, t) \quad (6)$$

This leaves two time derivatives and three spatial derivatives. The initial and boundary conditions must be specified for these derivatives. Note that there is no time derivative for the diversion crossflow; therefore, it is determined from the boundary conditions. The boundary conditions selected for the spatial derivatives are the inlet enthalpy $\{h(o,t)\}$, inlet flow rate $\{m(o,t)\}$ and exit diversion crossflow $\{w(L,t)\}$. It is presently assumed that $\{w(L,t)\} = 0$ which implies uniform bundle exit pressure. The steady solution using these boundary conditions at $t = 0$ gives the initial conditions of $\{h(x,0)\}$ and $\{m(x,0)\}$ that correspond to the two time derivatives of the problem.

Note that the inlet pressure is not used as a boundary condition since this would "over-specify" the problem. The inlet pressure can be obtained from a "back-calculation" once the solution for $\{m(x,t)\}$, $\{h(x,t)\}$ and $\{w(x,t)\}$ is obtained.

The inlet boundary conditions on enthalpy and flow rate can also be used as transient forcing functions. In addition to these, transients can also be performed by changing the exit pressure, heat flux, geometric parameters or flow parameters.

Numerical Solution

First order finite difference equations are used to approximate Equations (1), (2) and (5). These difference equations are presented in the order they are used in the computer computation to show the numerical procedures. The combined Momentum Equation (5) is approximated with a finite difference equation that treats the time derivative as backward difference and the space derivative as staggered forward difference. The staggered difference equation uses values of crossflow at $(x,t+\Delta t)$ and at $(x+\Delta x,t)$ as shown in the sketch of the space time grid plane.

The resulting finite difference equation is

$$\begin{aligned}
 & \left\{ \frac{C(x+\Delta x, t) w(x+\Delta x, t) - C(x, t) w(x, t+\Delta t)}{\Delta x} \right\} = -[S] \{ a'(x, t+\Delta t) \} \\
 & + [S] \left[\frac{1}{A(x)} \right] [S^T] [\Delta u^*(x, t+\Delta t)] \{ w(x, t+\Delta t) \} - [S] \left\{ \frac{m(x, t+\Delta t) - m(x, t)}{A(x) \Delta t} \right\} \\
 & + [S] \left\{ 2u(x, t+\Delta t) \frac{p(x, t+\Delta t) - p(x, t)}{\Delta t} \right\}. \quad (7)
 \end{aligned}$$

All quantities in this equation are known except $\{w(x, t+\Delta t)\}$. This can be solved for $\{w(x, t+\Delta t)\}$ by rearranging the above equation into a set of simultaneous equations of the form

$$[M]\{w(x, t+\Delta t)\} = \{b\} \quad (8)$$

where

$$[M] = -[S]\left[\frac{1}{A(x)}\right][S^T][\Delta u^q(x, t+\Delta t)] - \left[\frac{C(x, t)}{\Delta x}\right]; \quad (9)$$

$$\begin{aligned} \{b\} = & -[S]\{a'(x, t+\Delta t)\} - [S]\left\{\frac{m(x, t+\Delta t) - m(x, t)}{A(x) \Delta t}\right\} \\ & + [S]\left\{2u(x, t+\Delta t) + \frac{p(x, t+\Delta t) - p(x, t)}{\Delta t}\right\} \\ & - \left\{\frac{C(x+\Delta x, t) w(x+\Delta x, t)}{\Delta x}\right\}. \end{aligned} \quad (10)$$

This difference scheme could be considered semi-explicit because only those crossflows at x are calculated at one time. A completely implicit difference scheme would use $\{C\}$ and $\{w(x+\Delta x, t+\Delta t)\}$ and thus require simultaneous solution of all crossflows at one time. This would be a time-consuming and difficult numerical calculation. Notice that this semi-explicit difference scheme does give a boundary-value crossflow solution through dependence of upstream crossflows on the downstream values of crossflow and the crossflow resistance. The accuracy of this numerical scheme can be related to the time step and the crossflow resistance. For very low values of crossflow resistance $\{C(x+\Delta x, t) w(x+\Delta x, t)/\Delta x\}$ has very little influence on $\{w(x, t+\Delta t)\}$; therefore, large time steps could be used without introducing much error. For large values of crossflow resistance, a small time step should be used to limit the crossflow change to a small amount per time step.

For large values of Δt , Equation (7) reduces to the difference equation used for steady state calculations. In this case, however, the downstream values of $\{C\}$ and $\{w(x+\Delta x)\}$ are included by iteration. The iteration procedure is equivalent to using large time steps because the values of $\{C(x)/\Delta x\}$ and $\{C w(x+\Delta x)/\Delta x\}$ are taken from the previous iteration. To eliminate the problem of crossflow changing too rapidly in some problems, the newly calculated value of crossflow can be modified by

$$\{w(x)\} = \delta \{w(x)\}_{new} + (1-\delta) \{w(x)\}_{old}. \quad (11)$$

For many problems $\delta = 1$ is satisfactory. This is only used for the steady state calculations.

For both the steady state and transient analysis, the calculation of the diversion crossflow requires solving a set of K simultaneous equations and K unknowns. A solution is possible if $[M]$ is not singular. It should be noted that $[M]$ is the matrix - $[S] [1/A] [S^T] [\Delta u^*]$ but with its diagonal elements modified by adding the diagonal matrix - $[C/\Delta x]$. For any rod bundle problem that has one or more flow paths around a fuel rod (or any transverse flow loop), the matrix - $[S] [1/A] [S^T] [\Delta u^*]$ is singular and only by adding - $[C/\Delta x]$ does it become nonsingular. Physically, the addition of this term means that the summation of pressure drops around any transverse flow loop must be zero. The problem is that these added diagonal elements can be small as compared to the nonzero elements of $[S] [1/A] [S^T] [\Delta u^*]$; therefore, $[M]$ can be close to singular for some problems. Fortunately, there is control over this by selecting a sufficiently small step size for a given crossflow resistance coefficient.

The continuity Equation (1) is approximated by a difference equation given by

$$\left\{ A(x) \frac{p(x, t+\Delta t) - p(x, t)}{\Delta t} \right\} + \left\{ \frac{m(x, \Delta x, t+\Delta t) - m(x, t+\Delta t)}{\Delta x} \right\} = -[S^T] \{w(x, t+\Delta t)\} \quad (12)$$

This equation uses a backward difference for the time derivative and a forward difference for the space derivative. All quantities are known

in this equation except for $\{M(x+\Delta x, t+\Delta t)\}$. For large Δt time dependence is lost and Equation (12) becomes the forward difference equation used for steady state calculations.

The Energy Equation (2) is approximated by the finite difference equation

$$\begin{aligned}
 & \left\{ \frac{h(x+\Delta x, t+\Delta t) - h(x+\Delta x, t)}{u(x, t+\Delta t) \Delta t} \right\} + \left\{ \frac{h(x+\Delta x, t+\Delta t) - h(x, t+\Delta t)}{\Delta x} \right\} = \\
 & \{ Q(x, t+\Delta t) \} - \left[\frac{1}{m(x, t+\Delta t)} \right] [S^T] [\Delta h(x, t+\Delta t)] \{ w(x, t+\Delta t) \} \\
 & - \left[\frac{1}{m(x, t+\Delta t)} \right] [S^T] [\Delta T(x, t+\Delta t)] \{ c(x, t+\Delta t) \} \\
 & + \left[\frac{1}{m(x, t+\Delta t)} \right] [S^T] \Delta h^*(x, t+\Delta t) \{ w(x, t+\Delta t) \}. \quad (13)
 \end{aligned}$$

The time and space derivatives are approximated with a backward finite difference. All quantities are known or specified in this equation except for $\{h(x+\Delta x, t+\Delta t)\}$, which can be solved by simply rearranging the difference equation. The following sketch shows the quantities required for this calculation in the finite difference grid plane.

All quantities at the solid points are known or calculated prior to calculating $\{h(x+\Delta x, t+\Delta t)\}$. For the velocity u'' positive, the characteristic path through $(x+\Delta x, t+\Delta t)$ will pass between the solid grid points. As long as this condition is satisfied, this difference scheme for the energy equation is stable. The scheme is therefore stable for any $\Delta t > 0$ and unstable for negative velocity (flow reversals). If data at the grid point (x, t) is exchanged with either the point $(x, t+\Delta t)$ or $(x+\Delta x, t)$ then stability limitations are encountered that relate to the time required for fluid to travel the distance Δx . For very large Δt , the above finite difference

equation reduces to the equation used for the steady state solutions.

The above equations do not require detailed pressure information since pressure is eliminated explicitly in the combined momentum equation. The calculation of pressure is, therefore, only a back calculation. It is calculated from a difference equation which is compatible with the combined momentum equation. The difference approximation to Equation (3) is

$$\begin{aligned} & \left\{ \frac{m(x, t+\Delta t) - m(x, t)}{A(x) \Delta t} \right\} - \left\{ 2 u(x, t+\Delta t) \frac{p(x, t+\Delta t) - p(x, t)}{\Delta t} \right\} \\ & + \left\{ \frac{p(x+\Delta x, t+\Delta t) - p(x, t+\Delta t)}{\Delta x} \right\} = - \left\{ a'(x, t+\Delta t) \right\} \\ & + \left[\frac{1}{A(x)} \right] \left[S^T \right] \left[\Delta u^*(x, t+\Delta t) \right] \left\{ w(x, t+\Delta t) \right\} \end{aligned} \quad (14)$$

With the exit boundary condition of $p(L, t+\Delta t)$ given this equation can be solved directly for $p(L-\Delta x, t+\Delta t)$ because all data are known for the calculation. The calculation moves backward until the inlet pressure $\{p(0, t+\Delta t)\}$ is calculated. Since this is just a back calculation which only adds the subchannel pressure drop to the exit pressure, computing time can be saved by calculating the pressure drop in the forward direction as the required functions are computed for the flow diversion solution. When the exit is reached, the pressures are corrected to agree with the exit pressure boundary condition.

In summary, the numerical solution for both steady state and transients are performed in the following way. At the beginning of each node, $\{w(x, t+\Delta t)\}$ is calculated from prior data specified by initial conditions, previous time or previous iteration. Next, the calculation moves forward to $x+\Delta x$ by calculating $\{h(x+\Delta x, t+\Delta t)\}$, $\{m(x+\Delta x, t+\Delta t)\}$ and $\{p(x+\Delta x, t+\Delta t)\}$. This continues until the exit is reached. Then all $\{p(x)\}$ at $t+\Delta t$ are corrected to the exit pressure boundary condition. The calculation sweeps through the channel for another iteration in the steady state calculation or moves to the next time step in the transient solution. The steady state iteration continues until convergence is achieved as defined by

$$|w(x) - w(x)_{old}| < w_{error} \quad (15)$$

for all crossflows $w(x)$.

COMPUTER PROGRAM DESCRIPTION

COBRA-III should be thought of as an automated solution to the basic set of differential equations of the mathematical model. To actually perform this solution, the user must provide input. This input not only includes the geometric parameters and operating conditions, but also the various required empirical or semiempirical correlations. Any set of correlations can give a solution, but some correlations will give better solutions. At the present time, guidelines have not been established for complete selection of these correlations; therefore, the COBRA-III program does not contain a pre-selected set of input correlations. Several correlations are provided for examples, but the final selection must be made by the user. Considerable work is required to define correlations applicable to rod bundle transients.

The following sections present the general features of the COBRA-III program, an illustrated description of the program organization and a description of the program's subroutines.

GENERAL FEATURES

The significant features of COBRA-III include the following:

- It considers both steady state and transient flow in rod bundle fuel elements.
- It performs a boundary-value flow solution that permits the influence of downstream flow disturbances to be felt upstream.
- It can consider both single- and two-phase flow.
- It considers the effects of turbulent and thermal conduction mixing throughout the bundle by using empirically determined mixing coefficients.
- It includes mixing which results from the convective transport of enthalpy by diversion crossflow.
- It includes the momentum transport between adjacent subchannels which results from both turbulent and diversion crossflow.
- It includes the effect of transverse resistance to diversion crossflow in the boundary-value flow solution.
- It can consider an arbitrary layout of fuel rods and flow subchannels for analysis of most any rod bundle configuration. A single subchannel may interact with up to four adjacent subchannels,

and a fuel rod may transfer heat to a maximum of six adjacent subchannels.

- It can include arbitrary heat flux distribution by specifying the axial flux distribution, relative rod power, and the fraction of rod power to each of the six adjacent subchannels. (The latter feature allows variation in circumferential rod heat flux.)
- It can consider variable subchannel area and gap spacing.
- It can consider nonuniform hydraulic behavior by assigning different single-phase friction factors to selected subchannels.
- Its subroutines are designed to allow the user to set up empirical correlations of his choice and then select these correlations through input options.
- It includes options to select arbitrary subchannel inlet flow and enthalpy.

PROGRAM ORGANIZATION

The organization of the COBRA-III program is similar to that of the COBRA-II program; however, the subroutines have been reorganized to permit the expanded program capability and the calculational procedures have been revised to use the previously described numerical solutions for both steady state and transient conditions.

The organization of the program can best be described by following the flow chart of Figure 3. The first function of the program is to read in the input data. This is accomplished by successively reading in the 12 groups of input data that are required for the calculations. Some of these groups are optional and are not needed for certain problems. New cases, after the first, require input of only the card groups that will change the input of the previous case. The new input data for each case may be printed out prior to starting the calculations. The user can also omit this or can print out the entire set of input for each case.

Boundary conditions are now established for the steady state solution by recalling previously stored values of inlet flow rate and enthalpy established from the input data. Subroutine SPLIT is used to calculate

subchannel flows to give equal subchannel pressure gradients if it is requested by an input option. All crossflows are set equal to zero to establish the exit boundary condition and to provide an initial estimate of the crossflows.

An iteration loop is now entered which sweeps through the bundle until the crossflow solution converges. Within this loop is a calculational loop that carries the solution through the bundle at steps of Δx .

At the beginning of each space step, all geometric and flow parameters are calculated by using Subroutines CURVE, AREA, FORCE, PROP, VOID and MIX. These are evaluated at x by using $\{m(x,0)\}$, $\{h(x,0)\}$ and the reference pressure. The diversion crossflow $\{w(x,0)\}$ is calculated from DIVERT which sets up Equation (8) for steady state conditions and calls the simultaneous equation solving routines DECOMP and SOLVE. DIFFER(3,J) calculates the pressure gradient functions required for the equation set up performed in divert. The newly calculated $\{w(x,0)\}$ is compared with the previous value of $\{w(x,0)\}$ to determine if it has converged. A signal is set up to indicate if convergence has not occurred. Once $\{w(x,0)\}$ is calculated, $\{m(x+\Delta x,0)\}$, $\{h(x+\Delta x,0)\}$ and $\{p(x+\Delta x,0)\}$ can be calculated using steady state forms of the difference Equations (7), (12) and (13). This procedure is repeated for each x until the end of the bundle is reached. The convergence is checked and, if the solution has not converged, another iteration is performed. When convergence occurs, the subchannel pressures are adjusted to correspond with the exit pressure boundary condition. The desired results are then printed as specified by input options. If just a steady state solution is being performed, the calculation moves on to a new case; otherwise, the transient calculation is started.

The transient calculation is performed in much the same way as the steady state solution. Instead of an iteration loop, a time loop is entered that carries the solution through successive time steps of Δt . At the beginning of each time step, the channel boundary conditions and forcing functions are set at $t+\Delta t$.

Another loop is now entered that takes the calculation through the bundle at time $t+\Delta t$ in steps of Δx . The calculations are identical to the steady state calculations except that transient Equations (7), (12), (13), and (14) are used to calculate $\{w(x,t+\Delta t)\}$, $\{m(x+\Delta x,t+\Delta t)\}$, $\{h(x+\Delta x,t+\Delta t)\}$

FIGURE 2. Computer Flow Diagram for COBRA-III

FIGURE 2. (contd)

and $\{p(x+\Delta x, t+\Delta t)\}$, respectively. When the end of the bundle is reached, the subchannel pressures are adjusted to correspond with the exit pressure boundary condition. The desired results are then printed as specified by input options.

This calculation procedure repeats for each time step until the end of the transient is reached. The calculation then moves on to a new case if there is one.

SUBROUTINES

The organization of the COBRA-III program puts most of the calculational effort into subroutines. The more important ones are discussed here to describe their use.

Function S(K,I)

This function subprogram calculates the elements of $[S]$ according to the subchannel connection logic described in Appendix B. This calculation first assumes that

$$S(K,I) = 0$$

and then checks to see if I corresponds to either of the subchannel pair that defines K . If I corresponds to Subchannel i of the pair ij where $i < j$ then

$$S(K,I) = 1.$$

If I corresponds to subchannel j of the pair ij then

$$S(K,I) = -1.$$

Subroutine DIFFER(IPART, J)

This subroutine is used to calculate the steady state spatial derivatives of mass velocity, enthalpy and pressure. It is divided into four parts as indicated by the variable $IPART$. The notation and procedures used in DIFFER correspond directly to the notation used in the previously presented matrix equations. As an example of how the computations are performed, the calculation of dm/dx for steady state can be written as

$$\frac{dm_i}{dx} = - \sum_{k=1}^K S_{ki} w_k \quad (16)$$

where the S_{ki} are elements of $[S]$ and are calculated by function $S(K,I)$. Similar computations are performed for the energy and momentum equations.

Subroutine DIVERT

This subroutine sets up Equation (8)

$$[M] w(x, t + \Delta t) = \{b\} \quad (8)$$

and solves for $\{w(x, t + \Delta t)\}$. The setup is done by using the function $S(K, I)$ to calculate the elements of $[S]$. This setup uses $\{a'\}$ which is calculated in DIFFER(3). The elements of $[M]$ are calculated from

$$M_{kl} = - \sum_{i=1}^N S_{ki} 1/A_i \Delta u_l^* S_{li} \quad (17)$$

for off-diagonal elements. For diagonal elements ($k=l$), the same equation is used but $-C_k/\Delta x$ is added. The value of Δu_l^* is calculated from

$$\Delta u_l^* = 2 u_{i(l)} - u^* \quad (18)$$

where

$$u^* = \frac{1}{2} (u_{i(l)} + u_{j(l)}) \quad (19)$$

This assumes that the axial velocity of the crossflow is the average of the two subchannels. This has a stabilizing effect on the solutions and is as reasonable as assuming u^* is the axial velocity of the donor subchannel.

The elements of $\{b\}$ are calculated using the function $S(K, I)$ in the same manner as described above. The variable IPART is used in DIVERT to distinguish between steady state and transient calculations required for $\{b\}$.

If forced flow diversion between subchannels is specified by FORCE, Equation (14) is modified to account for this. After the modification is complete, Equation (8) is solved for $\{w(x, t + \Delta t)\}$.

Subroutine MIX

Subroutine MIX calculates the thermal mixing parameters that are vital to subchannel analysis. This includes both the turbulent and thermal conduction mixing coefficient. Since completely acceptable correlations for mixing have not been developed for single and two-phase mixing, this subroutine is set up so that improved correlation functions can be included when they become available. The approach used for now is to separate the

mixing into boiling and nonboiling regions. For nonboiling conditions, several correlation forms are included as shown in Appendix C. For two-phase flow, the single-phase correlations may be assumed to apply or the mixing rate may be specified as a function of quality.

The thermal conduction coefficient is assumed to be a function of the subchannel geometry and the average fluid thermal conductivity as shown in Appendix C.

Subroutine PROP(IPART)

This subroutine consists of two parts. The first part calculates the saturated fluid properties as a function of the system reference pressure. The second part calculates all the liquid fluid properties as a function of temperature and limits these to saturated values during boiling. The second part also calculates the convection heat transfer coefficient and the single-phase friction factor with a wall viscosity correction.

Subroutine VOID

Subroutine VOID calculates the two-phase flow parameters which include subcooled void fraction, bulk void fraction, density, effective specific volume for momentum and two-phase friction gradient multiplier. Several correlations are included in this subroutine that the user can select by option. These are provided as an example with the thought that the user will set up correlations that are most applicable to their particular problems.

Subroutine AREA

This subroutine calculates subchannel area and gap spacings by using the tabular list of area and gap variations supplied as input. A linear interpolation is used to select values from these tables.

Subroutine FORCE

Subroutine FORCE is provided to specify forced diversion crossflow at selected gaps and at selected axial positions. If a forced crossflow is specified, the logical variable FDIV = .TRUE.; otherwise, FDIV = .FALSE. Subroutine FORCE is only a dummy in this version of COBRA-III because all aspects of forced flow diversion have not been debugged with the new difference scheme.

Other Subroutines

Several other subroutines are required for operation of the COBRA-II program. Subroutine CURVE performs a linear interpolation of tabulated data. Subroutine DECOMP and SOLVE perform the solution to the simultaneous equations. Subroutine SPLIT divides the subchannel flow rates at the inlet of the bundle to give equal pressure gradients by assuming that there is no spatial acceleration component of pressure drop.

USE OF COBRA

This section presents some general comments on the use of COBRA and then illustrates its capabilities by showing the results of some sample calculations.

GENERAL COMMENTS

The COBRA-III program is written for the UNIVAC-1108. Except for the round-off problems that are encountered on computers with a short word length, there should be no difficulty in setting up and operating this program for other computers capable of compiling FORTRAN IV or V. Adjustable dimensions are included so that the program can be easily contracted or expanded to accommodate the users' computer or problem size. The storage capacity of COBRA-III is presently about 15K as compared to about 32K for the same dimensions in COBRA-II. This storage savings is mostly a result of using the function S(K,I), more efficient use of BLOCK COMMON, and less storage of output data for printing.

Complete input instructions are included in the program listing. The input is set up with options by which the user may select correlations for input to a problem. This has been done to make it clear that the user should treat these correlations as input since none of these correlations have universal validity. By forcing the user to make this selection, the correlations are given the status of input. In particular, the user must select or provide for:

- Friction factor correlation
- Subcooled void fraction correlation
- Two-phase friction multiplier correlation

- Two-phase void fraction correlation
- Single-phase mixing correlation
- Two-phase mixing correlation
- Pressure loss coefficients for spacers
- Flow diversion from spacing devices
- Diversion crossflow resistance factor

This interim version of COBRA-III uses steady state correlations for transients. This approximation must be thoroughly evaluated for any transient analysis.

SAMPLE PROBLEMS

To illustrate the features of the transient and boundary-value flow solution, the results of several sample calculations are presented. These include results for both a 49-rod bundle and a 19-rod bundle.

49-Rod Bundle

A 1/8 section of symmetry is used for this bundle. The bundle's size is typical of boiling water reactor geometry as shown in Figure 3. The results of four transient calculations are shown in Figures 4 through 7. Each of them represents a perturbation on the operating conditions. The data is presented for only subchannel 8, which is the hottest. In all calculations, smooth tube friction factors and homogeneous two-phase flow correlations are used. Crossflow resistance for this bundle is small. All calculations took about one minute of computer time when using $\Delta x = 3$ inches and $\Delta t = 0.05$ sec.

Figure 4 shows the results of a 50 percent step in heat flux. The duration of the transient is approximately 0.6 sec, which is the approximate transit time through the bundle. This transit time is directly related to the characteristic velocity in the Energy Equation (2). During the initial part of the transient, the flow rate is seen to increase toward the exit of the bundle. This is caused by expulsion of fluid as the channel average void fraction increases. At the end of the transient, the point of boiling moves to a point farther upstream to correspond to the higher power. The inlet flow does not change because it is a fixed boundary condition.

Figure 5 shows the effect of a step reduction of inlet enthalpy by 50 Btu/lb. The results are rather interesting since they show a significant

ROD DIAMETER 0.562"
 ROD-ROD SPACING 0.177"
 ROD-WALL SPACING 0.140"

LENGTH 90"

UNIFORM AXIAL POWER DISTRIBUTION

ROD POWER PEAKING AS SHOWN

NOMINAL OPERATING CONDITIONS:

1000 PSIA	SYSTEM PRESSURE
500 BTU/LB	INLET ENTHALPY
1.5×10^6 LB/HR/FT ²	AVERAGE MASS VELOCITY
0.5×10^6 BTU/HR/FT ²	HEAT FLUX

FIGURE 3. 7 x 7 Rod Bundle Simulation for Input to COBRA-III

FIGURE 4. 50% Step in Heat Flux

FIGURE 5. Step Reduction in Inlet Enthalpy

DEPRESSURIZATION TO 750 PSIA IN 0.1 SEC.

SUBCHANNEL 8

FIGURE 6. Depressurization to 750 psia in 0.1 sec

FIGURE 7. Reduction to 1/2 Flow in 0.1 sec

decrease in exit flow rate which is caused by the collapse of voids in the bundle. Note that the transient is still not complete at 1 second because the transit time through the bundle has been increased due to lower average coolant velocity.

Figure 6 shows the effect of a depressurization from 1000 psia to 750 psia in 0.1 sec. The reduced pressure causes a void growth which increases the channel flow and therefore decreases the enthalpy for a short time. Once the transient is over the starting and final conditions are nearly the same except for moving the point of boiling toward the inlet.

Figure 7 shows the effect of reducing to 1/2 flow in 0.1 sec. The results show that exit flow tends to remain high for a short time following the inlet reduction. This is caused by the void growth which causes expulsion out the exit of the bundle. This transient is nearly finished in 0.6 sec even though the inlet velocity is reduced to one-half. The transit time through the bundle is not reduced this much because the average void fraction is increasing which helps maintain the original average velocity.

19-Rod Bundle

A 1/12 section of symmetry is used for this bundle as shown in Figure 8. The same assumptions for correlations apply here as in the case of the 49-rod bundle. Because of the fewer number of subchannels, these calculations are about 3 times faster.

The calculations also used fictitiously high values of crossflow resistance to show how the boundary-value flow solution can cause downstream disturbances to be propagated upstream.

Figure 9 shows the results for subchannel 1 when the heat flux is stepped from zero to 0.4×10^6 Btu/hr ft². Prior to about 0.4 sec, fluid is just being heated; however, the decrease in liquid density is seen to cause an increase in velocity toward the exit of the bundle. At this time boiling occurs over the downstream portion of the bundle and causes increased exit flow. There is also significant flow diversion into adjacent subchannels that have not started to boil. As the enthalpy continues to increase in the downstream, the exit flow remains fairly high until nearly steady conditions are reached at 1.0 sec. Note that, after the start of boiling, the start of flow diversion moves about one foot upstream from the location of boiling.

19-ROD BUNDLE SIMULATION FOR COBRA III

ROD DIAMETER 0.563"

ROD-ROD SPACING 0.080"

ROD-WALL SPACING 0.080"

LENGTH 5'-0"

UNIFORM RADIAL & AXIAL POWER DISTRIBUTION

NOMINAL OPERATING CONDITIONS:-

PRESSURE 1000 PSIA

INLET ENTHALPY 400 BTU/LB

INLET MASS VELOCITY 1.0 x 10⁶ LB/HR/FT²

HEAT FLUX STEP TO 0.4 x 10⁶ BTU/HR/FT²

FIGURE 8. 19-Rod Bundle Simulation for COBRA-III

FIGURE 9. Step to High Heat Flux

This is caused by high crossflow resistance used for this calculation. When the crossflow resistance is high, downstream disturbances, such as boiling in this case, cause flow diversion to occur over some upstream distance. The disturbance effectively "dams" up the channel and the high crossflow resistance retards the flow from redistributing to get around it. Similar behavior occurs for local subchannel blockages.

Figure 10 shows a comparison with a calculation using low crossflow resistance. This shows how high crossflow resistance can affect the flow solution. It is interesting to note the similarity of the enthalpy distribution. The mild variation of enthalpy results from an integration of the flow distribution.

FUTURE DEVELOPMENT

The version of COBRA described in this report is not complete. Further development is continuing in several areas to remove deficiencies in its capability to analyze reactor fuel bundle transients.

Presently, major emphasis is being directed toward developing a more complete transverse momentum equation that includes both the temporal and spatial components of transverse acceleration. This is required to allow a more realistic analysis of subchannel flow in a fuel bundle containing blockages. A method of including forced diversion crossflow is also being developed to allow analysis of wire wrapped fuel bundles.

The present program is only capable of considering flow in one direction. The ability to consider flow reversals is required for analysis of many problems; therefore, significant effort is being directed to develop this capability in COBRA-III.

For the analysis of many problems, the inlet flow boundary condition is not very convenient because it is not known except through some other analysis. A more convenient boundary condition is the reactor pressure drop. This boundary condition permits the inlet flow to respond as changes occur within the bundle or in the connecting piping. The complete success of using this type of boundary condition will depend, in part, on the ability to consider flow reversals.

FIGURE 10. Effect of Crossflow Resistance

Since the heat flux is not normally known during a transient, a fuel temperature model is being developed to relate surface heat flux to internal power generation, coolant temperature heat transfer coefficient and thermal properties of the fuel rod. The presently used input function for heat flux will be changed to one for internal power density in a later version of COBRA-III.

In addition to further development of the analytical techniques, much experimental work is needed to verify the mathematical model and to develop transient correlations for two-phase flow and heat transfer.

REFERENCES

1. D. S. Rowe, Crossflow Mixing Between Parallel Flow Channels During Boiling, Part 1. COBRA--Computer Program for Coolant Boiling in Rod Arrays, BNWL-371, Pt 1. Pacific Northwest Laboratory, Richland, Washington (March 1967).
2. R. W. Bowring. HAMBO, A Computer Programme for the Subchannel Analysis of the Hydraulic and Burnout Characteristics of Rod Clusters, Part 1. General Description, AEEW-R524. Atomic Energy Establishment, Winfrith, Great Britain (1967).
3. C. C. St. Pierre. SASS Code 1, Subchannel Analysis for the Steady State, AECL-APPE-41. Atomic Energy of Canada, Ltd., Chalk River, Ontario, Canada (1966).
4. Proprietary Computer Program of Westinghouse Electric Co., Pittsburgh, Pennsylvania.
5. Proprietary Computer Program of General Electric Co., San Jose, California.
6. D. S. Rowe, COBRA-II: A Digital Computer Program for Thermal Hydraulic Subchannel Analysis of Rod Bundle Nuclear Fuel Elements, BNWL-1229. Pacific Northwest Laboratory, Richland, Washington (February, 1970)
7. D. S. Rowe, "Initial-and Boundary-Value Flow Solutions During Boiling in Two Interconnected Parallel Channels," American Nuclear Society Transactions, vol. 12, No. 2 pp 834-835 (November 1969).
8. J. P. Waggener. "Friction Factors for Pressure Drop Calculations," Nucleonics, vol. 19, p. 145 (1961).
9. L. S. Tong. "Pressure Drop Performance of a Rod Bundle," Heat Transfer in Rod Bundles, ASME, pp. 57-69 (1968).
10. A. A. Armand. "The Resistance During the Movement of a Two-Phase System in Horizontal Pipes," Translated by V. Beak, AERE Trans. 828. Izvestiya Vsesojuznogo Teploekhnicheskogo Instituta (1), pp. 16-23 (1946).
11. W. A. Massena. Steam-Water Pressure Drop and Critical Discharge Flow - A Digital Computer Program, HW-65706. Hanford Atomic Products Operation, Richland, Washington (June 17, 1960).
12. S. Levy. Forced Convection Subcooled Boiling--Prediction of Vapor Volumetric Fraction, GEAP-5157. General Electric Co., Atomic Power Equipment Dept., San Jose, California (April 1966).

13. J. T. Rogers and N. E. Todreas. "Coolant Mixing in Reactor Fuel Rod Bundles--Single-Phase Coolants," Heat Transfer in Rod Bundles, ASME, pp. 1-56 (1968).
14. D. S. Rowe and C. W. Angle. Crossflow Mixing Between Parallel Flow Channels During Boiling, Part III, Effect of Spacers on Mixing Between Two Channels, BNWL-371, Pt. 3. Pacific Northwest Laboratory, Richland, Washington (January 1969).
15. J. E. Meyer. Conservation Laws in One-Dimensional Hydrodynamics, WAPD-BT-20, pp. 61-72. Westinghouse Electric Corporation, Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania (September 1960).

NOMENCLATURE*

<u>Equations</u>	<u>Computer Program</u>	
a	DPDX	Single channel pressure gradient
a'	DPDX	Pressure gradient without crossflow in Equation (8), (F/L^3)
A	A	Cross-sectional area, (L^2)
[b]	B	Column vector defined by Equation (10)
c	COND	Thermal conduction coefficient $(H/T\theta)$
C	CFR	Loss coefficient for transverse crossflow in Equation (4)
C_p	CP	Specific heat $(H/M\theta)$
dh/dx	DHDX	Enthalpy derivative, (H/L)
dm/dx	DFDX	Flow rate derivative, (M/TL)
dp/dx	DPDX	Pressure gradient, (F/L^3)
D	DHYD	Hydraulic diameter, $4A/P_w$, (L)
D_r	D	Rod Diameter (L)
f	FSP	Friction factor based on all-liquid flow, (Dimensionless)
f_A	AXIAL	Local-to-average axial power distribution
f_c	PWRF	Fraction of rod power transferred to an adjacent subchannel (Dimensionless)
f_R	RADIAL	Relative rod power distribution (Dimensionless)
f_T	FTM	Turbulent momentum factor (Dimensionless)
F		Force (ML/T^2)
g_c	GC	Gravitational constant, (ML/FT^2)
G		Mass velocity, (M/TL^2)
h	HFILM	Heat transfer coefficient, $(H/TL^2\theta)$
h	H	Enthalpy, $Xh_g + (1-X)h_f$, (H/M)
h^*	HSTAR	Enthalpy carried by diversion crossflow, (H/M)
h_g, h_f	HG, HF	Saturated vapor and liquid enthalpy (H/M)
$[\Delta h], [\Delta h^*]$		Enthalpy matrices defined by Equations (B-8) and (B-10), (HT/M^2)
k	CON	Thermal conductivity, $(H/TL\theta)$
K	NK	Number of connections between adjacent subchannels, (Dimensionless)
K	CDRAG, CD	Spacer loss coefficient

*Dimensions are denoted by:

L = length, T = time, M = mass, θ = temperature, $F = ML/T^2$ = force
and $H = ML^2/T^2$ = energy

Equations Computer Program

K_g	GK	Geometry factor for conduction (Dimensionless)
K	KIJ	Crossflow resistance coefficient
L	Z	Channel length, (L)
$[M]$	AAA	Matrix of coefficients defined by Equation (9)
m	F	Flow rate (M/T)
N	NCHANL	Number of subchannels (Dimensionless)
p	PEXIT, PREF	Pressure (F/L^2)
P_H	HPERIM	Heated perimeter, (L)
P_w	PERIM	Wetted perimeter, (L)
P_r	PR	Prandtl number (Dimensionless)
q'	QPRIM	Heat addition per unit length, (H/L)
$\bar{q}''$	AFLUX	Average heat flux, (H/TL^2)
Q		Specific power-to-flow ratio, q'_i/m_i , (H/ML)
Q	Q	Parameter given by Equation (C-17)
Re	RE	Reynolds number, (Dimensionless)
s	GAP	Rod spacing (L)
$[S]$	S	Matrix transformation defining adjacent subchannels, (Dimensionless)
t		Time (t)
$[\Delta T]$		Temperature matrix defined by Equation (B-9), (θ)
T	T	Temperature (θ)
u		Internal energy (H/M)
u	U	Effective momentum velocity (L/T)
u''	UH	Effective enthalpy transport velocity (L/T)
u^*	USTAR	Effective velocity carried by diversion crossflow (L/T)
$[\Delta u]$		Velocity matrix defined by Equation (B-14), (T/L^2)
$[\Delta u^*]$		Velocity matrix defined by Equation (B-15), (T/L^2)
v	V	Liquid specific volume, $1/\rho$, (L^3/M)
v'	VP	Effective specific volume for momentum, $(1-X)^2/\rho_f(1-\alpha) + X^2/\rho_g\alpha$, (L^3/M)
w	W	Diversion crossflow between adjacent subchannels (M/TL)
w'	WP	Turbulent (fluctuating) crossflow between adjacent subchannels, (M/TL)
x	X	Distance (L)

<u>Equations</u>	<u>Computer Program</u>	
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X	QUAL	Quality, $m_g/(m_g+m_f)$, (Dimensionless)
X_d	XD	Parameter given by Equation (D-19)
z_{ij}	LENGTH	Effective centroid distance (L)
α	ALPHA	Void fraction, A_g/A_g+A_f , (Dimensionless)
β		Turbulent mixing parameter, (Dimensionless)
γ	AV(1)	Slip ratio, u_g/u_f , (Dimensionless)
θ	THETA	Orientation of channel with respect to vertical, (Radians)
ρ	RHO	Density, $\rho_g\alpha + \rho_f(1-\alpha)$, (M/L ³)
ρ_g, ρ_f	RHOG, RHOF	Saturated vapor and liquid density, (M/L ³)
σ	SIGMA	Surface tension, (F/L)
τ_w	TAUW	Wall shear stress (F/L ²)
ϕ	PHI, FMULT	Two-phase friction multiplier, (Dimensionless)
μ	VISC	Viscosity, (F/LT)
μ_w	VISCW	Wall viscosity, (F/LT)

Subscripts

f, g		Saturated conditions for liquid and vapor, respectively
i, j	I, J	Subchannel identification number
ij, ji		Double subscripts imply subchannel connection i to j and j to i, respectively
$i(k), j(k)$	IK, JK	Subchannel pair for connection number (k)
k	K, L	Subchannel connection number

APPENDIX A

DERIVATION OF EQUATIONS

The equations of continuity, energy and momentum for each Subchannel are derived by applying the conservation equations to a control volume that consists of a segment of Subchannel (i) connected to an arbitrary Subchannel (j). The primary assumptions given in the description of the mathematical model are used together with a few additional assumptions that are required to formulate complete equations.

Continuity Equation

Apply the continuity equation for a control volume to Subchannel (i) which is adjacent to Subchannel (j).

$$\frac{\partial}{\partial t} \rho_i A_i dx - m_i + m_i + \frac{\partial m_i}{\partial x} dx - w_{ji} dx + w_{ij} dx + w_{ij} dx = 0. \quad (\text{A-1})$$

By assuming $w_{ij} = w_{ji}$ and $\partial A / \partial t = 0$

$$A_i \frac{\partial \rho_i}{\partial t} + \frac{\partial m_i}{\partial x} = -w_{ij} \quad (\text{A-2})$$

By considering all adjacent subchannels and taking w_{ij} to be positive for flow from i to j , Equation (A-2) can be written as

$$A_i \frac{\partial \rho_i}{\partial t} + \frac{\partial m_i}{\partial x} = - \sum_{j=1}^N w_{ij} \quad ; \quad i=1,2,3,\dots,N. \quad (A-3)$$

Energy Equation

Apply the energy equation for a control volume to Subchannel (i) which is adjacent to Subchannel (j).

$$\begin{aligned} \frac{\partial}{\partial t} \rho_i'' u_i A_i dx - m_i h_i + m_i h_i + \frac{\partial}{\partial x} m_i h_i dx - \bar{q}_i' dx \\ - w_{ji}' h_j dx + w_{ij}' h_i dx + w_{ij} h^* dx = 0 \end{aligned} \quad (A-4)$$

The internal energy is defined by the relationship

$$\rho_i'' u_i = \rho_i'' h_i - p_i \quad (A-5)$$

By assuming $\partial A / \partial t = 0$ and using Equation (A-5), this reduces to

$$\begin{aligned} A_i \frac{\partial}{\partial t} \rho_i'' h_i + \frac{\partial}{\partial x} m_i h_i = \bar{q}_i' + (h_j - h_i) w_{ij}' \\ - w_{ij} h^* + A_i \frac{\partial p_i}{\partial t} \end{aligned} \quad (A-6)$$

where h^* is the enthalpy carried by the diversion crossflow and ρ_i'' is the effective density for heat capacity.⁽¹⁵⁾ By using Equation (A-2) and neglecting $\partial \rho_i / \partial t$ this may be reduced to

$$A_i \left[\rho_i + h_i \left(\frac{\partial \rho''}{\partial h} - \frac{\partial \rho}{\partial h} \right) \right] \frac{\partial h_i}{\partial t} + m_i \frac{\partial h_i}{\partial x} = \bar{q}_i' - (h_i - h_j) w_{ij}' + (h_i - h^*) w_{ij} \quad (A-7)$$

By neglecting $\partial \rho_i / \partial t$, sonic velocity propagation is omitted from this mathematical model.

The heat transfer term $\bar{q}_i$ may be divided into two terms. The first is the heat transfer rate from the fuel surface q_i' . For steady state this term can be specified quite easily; however, for transients it depends upon the fluid temperature, fuel surface temperature and surface heat transfer coefficient. At the present time the transient heat transfer effect on the fuel is ignored in this interim description of COBRA-III. As an alternate, the value of q_i' is specified as a function of time. The second term of $\bar{q}_i$ is the thermal conduction between adjacent subchannels. It is assumed to be proportional to the subchannel temperature difference and constant of proportionality is assumed to depend upon the subchannel geometry and fluid thermal conductivity.

By considering the thermal conduction term and all the adjacent subchannels, the energy equation can be written as

$$\frac{1}{u_i''} \frac{\partial h_i}{\partial t} + \frac{\partial h_i}{\partial x} = q_i' - \sum_{j=1}^N (T_i - T_j) \frac{C_{ij}}{m_i} - \sum_{j=1}^N (h_i - h_j) \frac{w_{ij}'}{m_i} + \sum_{j=1}^N (h_i - h^*) \frac{w_{ij}}{m_i} \quad (A-8)$$

where an effective enthalpy transport velocity may be defined as

$$\frac{1}{u_i''} = \frac{A_i \rho_i}{m_i} \left[\frac{\rho_i''}{\rho_i} + \frac{h_i}{\rho_i} \frac{\partial (\rho'' - \rho)}{\partial h} \right] \quad (A-9)$$

For homogeneous two-phase flow or for single-phase flow, the quantity in brackets reduces to 1 and $u_j'' = u_j$. In the present writing of COBRA-III $u_j'' = u_j$ for transients regardless of the two-phase flow correlations selected.

Axial Momentum Equation

Apply the momentum equation for a control volume to Subchannel (i) which is adjacent to Subchannel (j).

$$\begin{aligned}
 & -F_i dx + p_i A_i - g A_i \rho_i \cos \theta dx + p_i A_i - p_i A_i - \frac{\partial}{\partial x} p_i A_i dx = \\
 & \frac{\partial}{\partial t} m_i dx - m_i u_i + m_i u_i + \frac{\partial}{\partial x} m_i u_i dx \\
 & - w_{ji}' u_j dx + w_{ij}' u_i dx + w_{ij} u_i^* dx.
 \end{aligned}
 \tag{A-10}$$

Since $w_{ij}' = w_{ji}'$, this reduces to

$$\begin{aligned}
 & -F_i - g A_i \rho_i \cos \theta - A_i \frac{\partial p_i}{\partial x} = \frac{\partial m_i}{\partial t} + \frac{\partial}{\partial x} m_i u_i \\
 & + (u_i - u_j) w_{ij}' + u_i^* w_{ij}.
 \end{aligned}
 \tag{A-11}$$

By using the equations

$$u_i = \frac{m_i v_i'}{A_i} ; \quad F_i = \left[\frac{A_i v_i' f_i \phi_i}{2 D_i} + \frac{A_i K_i v_i'}{2} \right] \left(\frac{m_i}{A_i} \right)^2 \quad (\text{A-12,13})$$

and Equation (A-2); Equation (A-11) may be written as

$$\begin{aligned} \frac{\partial m_i}{\partial t} - 2 u_i \frac{\partial \rho_i}{\partial t} A_i + A_i \frac{\partial \rho_i}{\partial x} &= -A_i \left(\frac{m_i}{A_i} \right)^2 \left[\frac{v_i' f_i \phi_i}{2 D_i} + \frac{K_i v_i'}{2} + \frac{\partial}{\partial x} \left(\frac{v_i'}{A_i} \right) \right] \\ &\quad - g A_i \rho_i \cos \theta - (u_i - u_j) w_{ij}' \\ &\quad + (2 u_i - u^*) w_{ij} \end{aligned} \quad (\text{A-14})$$

By considering all adjacent subchannels and assuming $\partial A / \partial t = 0$, this can be written as

$$\begin{aligned} \frac{1}{A_i} \frac{\partial m_i}{\partial t} - 2 u_i \frac{\partial \rho_i}{\partial t} + \frac{\partial \rho_i}{\partial x} &= - \left(\frac{m_i}{A_i} \right)^2 \left[\frac{v_i' f_i \phi_i}{2 D_i} + \frac{K_i v_i'}{2} + \frac{\partial}{\partial x} \left(\frac{v_i'}{A_i} \right) \right] \\ &\quad - g \rho_i \cos \theta - f_T \sum_{j=1}^N (u_i - u_j) \frac{w_{ij}'}{A_i} \\ &\quad + \sum_{j=1}^N (2 u_i - u^*) \frac{w_{ij}}{A_i} . \end{aligned} \quad (\text{A-15})$$

The factor f_T is included to help account for the imperfect analogy between the eddy diffusivity of heat and momentum.

Transverse Momentum Equation

Since spatial and temporal acceleration are neglected, the pressure difference between subchannels is given by the linearized form

$$C_{ij} w_{ij} = p_i - p_j \quad (\text{A-16})$$

where C_{ij} is the linearized crossflow resistance. If an orifice type loss coefficient is defined as

$$K_{ij} = \frac{(p_i - p_j)}{\rho v_{ij}^2 / 2 g_c} \quad (\text{A-17})$$

then the crossflow resistance can be written as

$$C_{ij} = \frac{K_{ij} |w_{ij}|}{2g\rho^* s_{ij}^2} \quad (A-18)$$

where ρ^* is the density of the diversion crossflow. Presently ρ^* is assumed to be the density of the donor subchannel defined by

$$\rho^* = \begin{cases} \rho_i & ; w_{ij} > 0 \\ \rho_j & ; w_{ij} < 0 \end{cases} \quad (A-19)$$

The loss coefficient K_{ij} consists of both the friction and the form loss components of the transverse pressure drop. The K_{ij} replaces the factor fl in the earlier versions of COBRA. The relationship between them is given by

$$K_{ij} = \frac{fl}{2s_{ij}} \quad (A-20)$$

In the present version of COBRA-III the quantity $K_{ij} |w_{ij}|$ is input as the constant crossflow resistance factor K . Other forms can be used by changing the function subprogram CFR.

APPENDIX B

GENERALIZED FORM OF THE EQUATIONS

This appendix presents a matrix representation of the mathematical model's equations. The matrix notation presented here is similar in form but simpler than the notation used in the description of the COBRA-II program. The generalized form of the equations will follow directly from the matrix notation.

Matrix Notation

For an arbitrary layout of subchannels numbered in sequence, a number may be assigned to each gap connection between a pair of adjacent subchannels. The gap connection numbers are assigned in ascending order by considering Subchannel (i) and then assigning connection numbers for each successive connected Subchannel (j) where j is greater than i. Each pair of connected subchannels are given a unique connection number by this procedure. The subchannel order is recorded by using two column vectors I and J with elements $i(k)$ and $j(k)$, respectively. These vectors identify the channels i and j corresponding to each k. The following example illustrates this subchannel connection logic.

Gap Connection
Number

Subchannel Pair Corresponding to
Connection Number

<u>k</u>	<u>i(k)</u>	<u>j(k)</u>
1	1	2
2	2	3
3	2	4
4	3	5
5	4	5
6	5	6

The above notation allows the crossflows to be written as

$$w_{ij} = w_k$$

with the sign convention that for $w_k > 0$ the crossflow is from Subchannel (i) to Subchannel (j) where i is less than j.

For purposes of notation, let [] denote a rectangular matrix that is not necessarily square and let { } denote a column vector.

Generalized Equations

Using the previous subchannel connection logic, it is possible to construct a matrix transformation that properly orders all crossflows in the conservation equations. To illustrate this, consider the Transverse Momentum Equation (4). For the previous example, the six transverse momentum equations can be written compactly as

$$\{Cw\} = [S]\{P\} \quad (4)$$

where [S] is given by the transformation

$$[S] = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix} \quad (B-1)$$

This matrix consists only of ± 1 or zero and its elements can be

calculated very easily by using the vectors I and J. Note that each element of $\{C w\}$ is calculated from

$$C_A w_A = \sum_{i=1}^N S_{ki} P_i \quad (B-2)$$

where S_{ki} are the elements of the k the row of $[S]$. S_{ki} is seen to be zero except for two values that are either +1 or -1. If $i = i(k)$, then $S_{ki} = +1$. If $l = j(k)$ then $S_{ki} = -1$. This very simple logic is used in FUNCTION S(K,I) to construct the elements of $[S]$ as needed in the computations. The actual matrix $[S]$ is not stored in the program.

Now consider the Continuity Equation (A-3) which can be written as

$$\left\{ A \frac{\partial \rho}{\partial t} \right\} + \left\{ \frac{\partial m}{\partial x} \right\} = -[R]\{w\} \quad (B-3)$$

where $[R]$ is matrix transformation to order the crossflows. For the previous example, $[R]$ is given by

$$[R] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix} \quad (B-4)$$

A comparison with Equation (B-1) shows that $[R]$ is the transpose of $[S]$. This can be proved in general; thus,

$$[R] = [S^T] \quad (B-5)$$

Equation (B-3) can therefore be written as

$$\left\{ A \frac{\partial \rho}{\partial t} \right\} + \left\{ \frac{\partial m}{\partial x} \right\} = -[S^T]\{w\}. \quad (B-6)$$

Following this logic and notation, the Energy Equation (A-8) can be written as

$$\begin{aligned} \left\{ \frac{1}{u} \frac{\partial h}{\partial t} \right\} + \left\{ \frac{\partial h}{\partial x} \right\} &= \{Q\} - \left[\frac{1}{m} \right] [S^T] [\Delta T] \{C\} \\ &\quad - \left[\frac{1}{m} \right] [S^T] [\Delta h] \{w'\} + \left[\frac{1}{m} \right] [S^T] [\Delta h^*] \{w\} \end{aligned} \quad (B-7)$$

where

$$\Delta h_k = h_{i(k)} - h_{j(k)} \quad (B-8)$$

$$\Delta T_k = T_{i(k)} - T_{j(k)} \quad (B-9)$$

$$\Delta h_k^* = h_{i(k)} - h_k^* \quad (B-10)$$

At the present time h^* is assumed to be the enthalpy of the donor subchannel; therefore,

$$h_k^* = \begin{cases} h_{i(k)} & ; w_k > 0 \\ h_{j(k)} & ; w_k < 0 \end{cases} \quad (B-11)$$

Similarly the axial momentum equation can be written as

$$\left\{ \frac{1}{A} \frac{\partial m}{\partial t} \right\} - \left\{ 2u \frac{\partial p}{\partial x} \right\} + \left\{ \frac{\partial p}{\partial x} \right\} = -\{a\} - \left[\frac{1}{A} \right] [S^T] [\Delta u] \{f, w'\} \\ + \left[\frac{1}{A} \right] [S^T] [\Delta u^*] \{w\} \quad (B-12)$$

where

$$\{a\} = \left\{ \left(\frac{m}{A} \right)^2 \left(\frac{v f \phi}{2D} + \frac{K v'}{2} + A \frac{\partial}{\partial x} \frac{v'}{A} \right) - g \rho \cos \theta \right\} \quad (B-13)$$

$$\Delta u_k = u_{i(k)} - u_{j(k)} \quad (B-14)$$

$$\Delta u_k^* = 2 u_{i(k)} - u_k^* \quad (B-15)$$

In previous versions of COBRA, u^* was assumed to be the axial velocity of the donor subchannel. Computational experience has shown that solutions are not very sensitive to the choice of u^* and that the average of the subchannel velocities gives more stable solutions.

In COBRA-III, u^* is presently assumed to be

$$u_k^* = \frac{1}{2} (u_{i(k)} + u_{j(k)}) \quad (B-16)$$

therefore

$$\Delta u_k^* = \frac{3}{2} u_{i(k)} - \frac{1}{2} u_{j(k)} \quad (B-17)$$

regardless of the crossflow direction. This choice eliminates the discontinuity when the diversion crossflow changes direction.

APPENDIX C

COMPUTER PROGRAM CORRELATIONS

To carry out a solution, empirical and semiempirical correlations must be selected for input to the computer program..

Friction Factor

The friction factor correlation is assumed to be of the form⁽⁸⁾

$$f_i = a(R_{e_i})^b + c \quad (C-1)$$

where a, b, and c are specified constants that depend upon the subchannel roughness and geometry. Since these constants can be influenced by different subchannel roughnesses and the pitch-to-diameter ratio,⁽⁹⁾ the program can accept up to four sets of constants that correspond to four subchannel types which may be assigned to the subchannels of the bundle. For example, subchannels next to a flow housing may be given a different friction factor from those subchannels within the bundle.

The friction factor is also corrected for wall viscosity by using the relationship⁽⁹⁾

$$\frac{f}{f_{iso}} = \left(\frac{\mu_{wall}}{\mu_{bulk}} \right)^{0.6} \quad (C-2)$$

where μ_{wall} is evaluated at the wall temperature which is calculated from

$$t_{wall} = t_{bulk} + \frac{q'}{P_h h}. \quad (C-3)$$

The heat transfer coefficient is calculated from

$$\frac{hD}{k} = 0.023 \left(\frac{GD}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4} \quad (C-4)$$

where bulk fluid properties are used.

Two-Phase Friction Multiplier

Several correlations are available for the two-phase friction multiplier. Three are presently included in the program.

Homogeneous Model

$$\begin{aligned}\phi &= 1.0 & X < 0. \\ \phi &= \frac{\rho_f}{\rho} & X > 0.\end{aligned}\tag{C-5}$$

Armand⁽¹⁰⁾

$$\begin{aligned}\phi &= 1.0 & \alpha \leq 0 \\ \phi &= \frac{(1-X)}{(1-\alpha)^{1.42}} & 0.39 < (1-\alpha) \leq 1.0 \\ \phi &= 0.478 \frac{(1-X)^2}{(1-\alpha)^{2.2}} & 0.1 < (1-\alpha) \leq 0.39 \\ \phi &= 1.730 \frac{(1-X)^2}{(1-\alpha)^{1.64}} & 0. < (1-\alpha) \leq 0.1\end{aligned}\tag{C-6}$$

Polynomial Function

$$\begin{aligned}\phi &= 1.0 & X < 0 \\ \phi &= a_0 + a_1X + a_2X^2 + \dots a_nX^n & X > 0\end{aligned}\tag{C-7}$$

where the coefficients are supplied as input.

Spacer Loss Coefficient

The pressure drop from spacers is lumped into an effective loss coefficient which may be defined⁽⁹⁾ in terms of all liquid flow as

$$\Delta P = \frac{K}{2\rho} \left(\frac{m}{A} \right)^2\tag{C-8}$$

For two-phase flow, the same coefficient is used but it is modified by the two-phase specific volume for momentum. This pressure drop loss coefficient is converted to a pressure gradient loss coefficient at the location of the spacer by dividing by the calculation increment Δx ; therefore,

$$K_i = \frac{K}{\Delta x}\tag{C-9}$$

This is the coefficient used in Equation (A-12).

Void Fraction

Four ways of specifying void fraction are presently included in the program:

Homogeneous Model

$$\begin{aligned}\alpha &= 0. & X &\leq 0. \\ \alpha &= \frac{Xv_g}{(1-X)v_f + Xv_g} & X &> 0.\end{aligned}\tag{C-10}$$

Slip Model

$$\begin{aligned}\alpha &= 0. & X &\leq 0. \\ \alpha &= \frac{Xv_g}{(1-X)v_f\gamma + Xv_g} & X &> 0.\end{aligned}\tag{C-11}$$

where γ is a specified slip ratio.

Modified Armand⁽¹¹⁾

$$\begin{aligned}\alpha &= 0. & X &\leq 0. \\ \alpha &= \frac{(0.833+0.167X)Xv_g}{(1-X)v_f + Xv_g} & X &> 0.\end{aligned}\tag{C-12}$$

Polynomial Function

$$\begin{aligned}\alpha &= 0. & X &< 0. \\ \alpha &= a_0 + a_1X + a_2X^2 + \dots a_nX^n & X &> 0.\end{aligned}\tag{C-13}$$

Subcooled Void Fraction

Two options are presently included. Subcooled void formation may be ignored or it may be included by using Levy's subcooled void model.⁽¹²⁾ Levy's model calculates the true quality in terms of the equilibrium quality and the quality at which bubble departure starts. It is given by

$$\begin{aligned}X &= 0. & X_e &< X_d \\ X &= X_e = X_d \exp\left(\frac{X_e}{X_d} - 1\right) & X_e/X_d &< 1\end{aligned}\tag{C-14}$$

where X_e is the equilibrium quality and

$$X_d = -\frac{C_p \Delta T}{h_{fg}} \quad (C-15)$$

$$\Delta T = \frac{q'}{P_h h} - Q P_r Y_B \quad 0 < Y_B \leq 5$$

$$\Delta T = \frac{q'}{P_h h} - 5Q(P_r + \log(1 + P_r(2Y_B - 1))) \quad 5 < Y_B \leq 30$$

$$\Delta T = \frac{q'}{P_h h} = 5Q(P_r + \log(1 + 5P_r) + \frac{1}{2} \log(\frac{Y_B}{30})) \quad 30 < Y_B \quad (C-16)$$

$$Q = \frac{q'}{P_h v} C_p \sqrt{\tau_w v} \quad (C-17)$$

$$\tau_w = \frac{fv}{8} \left(\frac{m}{A}\right)^2 \quad (C-18)$$

$$Y_B = \frac{0.015}{\mu} \sqrt{\frac{\sigma D}{v}} \quad (C-19)$$

The heat transfer coefficient h is calculated from Equation (C-4).

Single-Phase Turbulent Mixing

Several forms of equations for specifying the turbulent crossflow are included. The presently available forms in COBRA-III for calculating w' include:

$$w'_k = \beta s_k \bar{G} \quad (C-20)$$

$$w'_k = a Re^b s_k \bar{G} \quad (C-21)$$

$$w'_k = a Re^b \bar{D} \bar{G} \quad (C-22)$$

$$w'_k = a Re^b \frac{s_k}{z_R} \bar{D} \bar{G} \quad (C-23)$$

$$\text{where } Re = \frac{\bar{G} \bar{D}}{\mu} \quad (C-24)$$

$$\bar{D} = 4 (A_{i(k)} + A_{j(k)}) / (Pw_{i(k)} + Pw_{j(k)}) \quad (C-25)$$

$$\bar{G} = (m_{i(k)} + m_{j(k)}) / (A_{i(k)} + A_{j(k)}) \quad (C-26)$$

$$\bar{\mu} = \frac{1}{2} (\mu_{i(k)} + \mu_{j(k)}) \quad (C-27)$$

and a and b are input constants. Since a definitive mixing correlation does not exist and other forms are available,⁽¹³⁾ the user should set up correlations of his choice.

Also included in the subcooled mixing is the thermal conduction. When it is included, the conduction coefficient is given by

$$c_k = \left(\frac{k_{i(k)} + k_{j(k)}}{2} \right) \frac{s_k}{z_k} K_g \quad (C-28)$$

where K_g is a geometric correction factor. Note that the distance z_k is used in both Equations (C-23) and (C-28). This is the centroid-to-centroid distance between subchannels. Care should be taken to select this value for its intended use. For example, z_k could be selected as the effective mixing distance as identified by Todreas and Rogers.⁽¹³⁾

Two-Phase Turbulent Mixing

Complete information concerning mixing during boiling is not available. It is known, however, that mixing is strongly dependent on quality; therefore, COBRA-III is set up to accept β as tabular function of quality. When the quality of two adjacent subchannels is different, the calculations use a quality calculated from the mean mixed enthalpy of the two subchannels.

Transient Correlations

In the present version of COBRA-III, steady state correlations are assumed to apply to transients. This assumption must be thoroughly evaluated from transient experimental data.

APPENDIX D SAMPLE PROBLEM

INPUT FOR CASE 1 7x7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

FLUID PROPERTY TABLE

P	T	VF	VG	HF	HG	VISC.	KF	SIGMA
50.0	281.00	.01727	8.51400	250.20	1174.10	.49100	.39590	.00301
100.0	327.80	.01774	4.43100	298.50	1187.20	.41000	.39360	.00261
150.0	358.40	.01809	3.01390	330.60	1194.10	.36900	.38930	.00235
200.0	381.80	.01839	2.28730	355.50	1198.30	.34500	.38520	.00209
250.0	401.00	.01865	1.84320	376.10	1201.10	.32600	.38060	.00193
300.0	417.40	.01889	1.54270	394.00	1202.90	.31300	.37600	.00180
350.0	431.70	.01912	1.32550	409.80	1204.00	.30100	.37180	.00168
400.0	444.60	.01934	1.16100	424.20	1204.60	.29000	.36820	.00158
440.0	454.00	.01950	1.05540	434.80	1204.80	.28300	.36580	.00150
480.0	462.80	.01967	.96680	444.70	1204.80	.27800	.36310	.00144
520.0	471.10	.01982	.89137	454.20	1204.50	.27300	.36040	.00138
560.0	478.80	.01988	.82637	463.10	1204.20	.26900	.35800	.00132
600.0	486.20	.02013	.76975	471.70	1203.70	.26400	.35500	.00127
640.0	493.20	.02028	.71995	479.90	1203.00	.26000	.35520	.00122
680.0	499.90	.02043	.67581	487.70	1202.30	.25500	.34940	.00117
720.0	506.20	.02058	.63630	495.40	1201.40	.25200	.34620	.00113
760.0	512.30	.02072	.60037	502.70	1200.40	.24800	.34350	.00108
800.0	518.20	.02087	.56896	509.80	1199.40	.24500	.34050	.00104
840.0	523.90	.02101	.53988	516.70	1198.20	.24200	.33770	.00100
880.0	529.30	.02116	.51333	523.40	1197.00	.24000	.33500	.00096
920.0	534.60	.02130	.48901	530.00	1195.70	.23700	.33250	.00092
960.0	539.70	.02145	.46662	536.30	1194.40	.23400	.32990	.00089
1000.0	544.60	.02159	.44596	542.40	1192.90	.23200	.32750	.00086
1040.0	549.40	.02174	.42681	548.60	1191.40	.22900	.32430	.00082
1080.0	554.00	.02188	.40902	554.60	1189.90	.22700	.32240	.00079
1120.0	558.50	.02203	.39244	560.50	1188.20	.22500	.31980	.00076
1160.0	562.90	.02217	.37695	566.20	1186.60	.22300	.31740	.00073
1200.0	567.20	.02232	.36245	571.90	1184.80	.22100	.31400	.00070
1240.0	571.40	.02247	.34884	577.40	1183.00	.21900	.31130	.00068
1280.0	575.40	.02262	.33603	582.90	1181.20	.21700	.30860	.00065

FRICITION FACTOR CORRELATION

CHANNEL TYPE 1 FRIC = .1E6*RE**(-.200) + -.0000

TWO-PHASE FLOW CORRELATIONS

NO SUBCOOLED VOID CORRELATION

HOMOGENEOUS BULK VOID MODEL

HOMOGENEOUS MODEL FRICTION MULTIPLIER

HEAT FLUX DISTRIBUTION

X/L RELATIVE FLUX

.000 1.000

1.000 1.000

SUBCHANNEL INPUT DATA

CHANNEL NO.	TYPE	AREA (SQ-IN)	WETTED PERIM. (IN)	HEATED PERIM. (IN)	HYDRAULIC DIAMETER (IN)	(ADJACENT CHANNEL NO., SPACING, CENTROID DISTANCE)							
1	1	.148900	.882300	.882300	.675054	(2, .177,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
2	1	.299700	1.765000	1.765000	.679207	(3, .177,-.000)	(5, .177,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
3	1	.299700	1.765000	1.765000	.679207	(4, .177,-.000)	(6, .177,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
4	1	.187600	1.622000	.882300	.462639	(7, .140,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
5	1	.148900	.882300	.882300	.675054	(6, .177,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
6	1	.299700	1.765000	1.765000	.679207	(7, .177,-.000)	(8, .177,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
7	1	.187600	1.622000	.882300	.462639	(9, .140,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
8	1	.148900	.882300	.882300	.675054	(9, .177,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)
9	1	.220900	2.169000	1.103000	.420009	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)	(-0,-.000,-.000)

ROD INPUT DATA

ROD NO.	DIAMETER (IN)	RADIAL POWER FACTOR	FRACTION OF POWER TO ADJACENT CHANNELS (ADJ. CHANNEL NO.)										
1	.5620	.8000	.1250(1)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
2	.5620	.9000	.2500(1)	.2500(2)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
3	.5620	1.0000	.2500(2)	.2500(3)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
4	.5620	1.0000	.2500(3)	.2500(4)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
5	.5620	.9000	.1250(1)	.2500(2)	.1250(5)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
6	.5620	1.0000	.2500(2)	.2500(3)	.2500(5)	.2500(6)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
7	.5620	1.1000	.2500(3)	.2500(4)	.2500(6)	.2500(7)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
8	.5620	1.0000	.1250(5)	.2500(6)	.1250(8)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
9	.5620	1.1000	.2500(6)	.2500(7)	.2500(8)	.2500(9)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)
10	.5620	1.2000	.1250(8)	.3750(9)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)	-.0000(-0)

CALCULATION PARAMETERS

CROSSFLOW RESISTANCE .100+01
 MOMENTUM TURBULENT FACTOR .0000
 CHANNEL LENGTH 90.00 INCHES
 CHANNEL ORIENTATION .0 DEGREES
 NUMBER OF AXIAL NODES 30
 NODE LENGTH 3.000 INCHES
 NUMBER OF TIME STEPS 20
 TIME STEP .050 SECONDS

MIXING CORRELATIONS

SUBCOOLED MIXING, BETA = .0020
 BOILING MIXING, BETA IS ASSUMED SAME AS SUBCOOLED

OPERATING CONDITIONS

SYSTEM PRESSURE = 1000.0 PSIA
 INLET ENTHALPY = 500.0 BTU/LB
 AVG. MASS VELOCITY = 1.500 MILLION LB/(HR-SQFT)
 INLET TEMPERATURE = 510.0 DEGREES F
 AVG. HEAT FLUX = .500 MILLION BTU/(HR-SQFT)
 FORCING FUNCTION FOR HEAT FLUX
 TIME HEAT FLUX
 (SEC) FACTOR
 .0000 1.5000
 10.0000 1.5000

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .00000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	950.00	500.00	48.38	.43084
.250	933.59	506.52	48.08	.43361
.500	916.61	512.98	47.77	.43574
.750	899.65	519.38	47.46	.43771
1.000	882.77	525.75	47.15	.43943
1.250	865.89	532.07	46.84	.44108
1.500	849.09	538.37	46.52	.44252
1.750	832.36	544.65	46.20	.44360
2.000	815.22	550.94	45.88	.442170
2.250	798.04	557.56	45.56	.439647
2.500	780.73	564.55	45.24	.440195
2.750	763.44	571.44	44.92	.440321
3.000	746.21	578.32	44.60	.440455
3.250	728.89	585.17	44.28	.440551
3.500	711.38	592.00	43.96	.440629
3.750	693.58	598.80	43.64	.440696
4.000	675.43	605.58	43.32	.440756
4.250	657.87	612.33	43.00	.440812
4.500	639.86	619.06	42.68	.440865
4.750	621.37	625.78	42.36	.440915
5.000	602.36	632.47	42.04	.440963
5.250	583.81	639.15	41.72	.441009
5.500	564.70	645.81	41.40	.441054
5.750	545.02	652.45	41.08	.441097
6.000	525.74	659.09	40.76	.441138
6.250	506.85	665.71	40.44	.441179
6.500	487.35	672.31	40.12	.441218
6.750	468.23	678.91	39.80	.441256
7.000	448.46	685.49	39.48	.441294
7.250	429.06	692.07	39.16	.441330
7.500	409.00	698.63	38.84	.441366

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .10000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1737.84	500.00	48.38	.43084
.250	1721.43	509.34	47.94	.43360
.500	1704.11	518.05	47.53	.43571
.750	1686.84	526.19	47.13	.43782
1.000	1669.56	533.86	46.75	.44016
1.250	1652.36	541.16	46.38	.44224
1.500	1635.20	548.17	39.44	.44447
1.750	1609.59	555.28	33.34	.39240
2.000	1559.81	563.10	28.50	.43413
2.250	1501.68	570.62	25.00	.44424
2.500	1442.88	578.03	22.30	.46508
2.750	1383.60	585.31	20.17	.47684
3.000	1323.28	592.48	18.43	.48788
3.250	1261.89	599.58	16.98	.49728
3.500	1199.27	606.59	15.76	.50560
3.750	1135.34	613.54	14.71	.51306
4.000	1070.04	620.42	13.79	.51978
4.250	1003.33	627.26	13.00	.52588
4.500	935.18	634.05	12.29	.53144
4.750	865.55	640.79	11.66	.53652
5.000	794.44	647.51	11.09	.54120
5.250	721.83	654.19	10.58	.54552
5.500	647.72	660.84	10.12	.54951
5.750	572.09	667.47	9.69	.55322
6.000	494.94	674.08	9.30	.55667
6.250	416.27	680.66	8.95	.55989
6.500	336.08	687.23	8.62	.56291
6.750	254.35	693.78	8.31	.56574
7.000	171.10	700.31	8.03	.56840
7.250	86.32	706.83	7.76	.57090
7.500	.00	713.34	.00	.57326

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX.

TIME = .20000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1596.21	500.00	48.38	.43084
.250	1579.80	509.72	47.92	.43360
.500	1562.51	519.20	47.47	.43557
.750	1545.29	528.39	47.02	.43739
1.000	1528.07	537.26	46.57	.43924
1.250	1511.00	545.77	46.04	.44049
1.500	1491.69	554.09	34.23	.40434
1.750	1452.58	563.01	28.54	.40147
2.000	1402.18	571.94	24.47	.41838
2.250	1352.52	580.57	21.51	.42656
2.500	1301.99	588.99	19.24	.43558
2.750	1250.44	597.25	17.43	.44352
3.000	1197.82	605.33	15.96	.45066
3.250	1143.94	613.28	14.74	.45732
3.500	1088.73	621.10	13.71	.46346
3.750	1032.12	628.80	12.83	.46921
4.000	974.08	636.41	12.06	.47461
4.250	914.56	643.92	11.39	.47969
4.500	853.54	651.35	10.79	.48450
4.750	791.00	658.70	10.26	.48906
5.000	726.93	665.98	9.78	.49340
5.250	661.30	673.20	9.35	.49753
5.500	594.12	680.36	8.96	.50148
5.750	525.37	687.46	8.60	.50524
6.000	455.05	694.52	8.28	.50884
6.250	383.16	701.52	7.97	.51229
6.500	309.69	708.49	7.70	.51559
6.750	234.64	715.41	7.44	.51876
7.000	158.01	722.30	7.20	.52181
7.250	79.80	729.15	6.97	.52473
7.500	.00	735.97	.00	.52754

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .30000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1471.42	500.00	48.38	.43084
.250	1455.02	509.77	47.92	.43360
.500	1437.74	519.42	47.46	.43555
.750	1420.53	528.94	47.00	.43731
1.000	1403.34	538.29	46.52	.43903
1.250	1386.33	547.46	40.17	.43996
1.500	1365.54	556.56	32.44	.39964
1.750	1324.68	566.46	26.82	.39926
2.000	1278.32	576.29	22.88	.40619
2.250	1232.41	585.93	20.00	.40982
2.500	1185.68	595.40	17.80	.41415
2.750	1138.22	604.71	16.07	.41805
3.000	1089.80	613.87	14.66	.42187
3.250	1040.34	622.89	13.50	.42562
3.500	989.76	631.77	12.52	.42928
3.750	937.99	640.53	11.68	.43284
4.000	884.99	649.17	10.96	.43631
4.250	830.71	657.71	10.33	.43969
4.500	775.14	666.14	9.77	.44298
4.750	718.23	674.48	9.28	.44618
5.000	659.97	682.74	8.84	.44930
5.250	600.34	690.91	8.44	.45233
5.500	539.32	699.01	8.08	.45529
5.750	476.91	707.03	7.75	.45817
6.000	413.08	714.98	7.45	.46098
6.250	347.84	722.87	7.18	.46371
6.500	281.16	730.69	6.92	.46638
6.750	213.04	738.46	6.69	.46898
7.000	143.48	746.17	6.47	.47152
7.250	72.47	753.83	6.27	.47400
7.500	.00	761.44	.00	.47641

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .40000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1403.39	500.00	48.38	.43084
.250	1380.98	509.78	47.92	.43360
.500	1369.71	519.46	47.46	.43555
.750	1352.50	529.05	46.99	.43730
1.000	1335.31	538.56	46.51	.43899
1.250	1319.33	547.97	39.65	.43981
1.500	1297.11	557.37	31.89	.39811
1.750	1256.39	567.70	26.25	.39701
2.000	1211.16	577.98	22.32	.40119
2.250	1166.39	588.14	19.44	.40273
2.500	1121.00	598.20	17.24	.40476
2.750	1075.03	608.15	15.51	.40662
3.000	1028.27	618.00	14.10	.40855
3.250	980.65	627.75	12.94	.41048
3.500	932.10	637.39	11.97	.41243
3.750	882.54	646.95	11.14	.41438
4.000	831.94	656.41	10.42	.41632
4.250	780.25	665.79	9.80	.41825
4.500	727.45	675.08	9.25	.42017
4.750	673.51	684.30	8.76	.42207
5.000	618.40	693.44	8.32	.42396
5.250	562.11	702.51	7.93	.42582
5.500	504.62	711.50	7.58	.42766
5.750	445.91	720.44	7.26	.42948
6.000	385.98	729.30	6.97	.43127
6.250	324.80	738.11	6.70	.43304
6.500	262.38	746.85	6.45	.43479
6.750	198.70	755.54	6.23	.43651
7.000	133.74	764.18	6.01	.43820
7.250	67.51	772.76	5.82	.43987
7.500	.00	781.29	.00	.44152

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .50000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1371.45	500.00	48.38	.43084
.250	1355.04	509.78	47.92	.43360
.500	1337.76	519.46	47.46	.43555
.750	1320.55	529.07	46.99	.43730
1.000	1303.37	538.62	46.50	.43898
1.250	1286.39	548.10	39.51	.43979
1.500	1268.20	557.60	31.74	.39739
1.750	1224.58	568.08	26.08	.39607
2.000	1179.71	578.54	22.14	.39931
2.250	1135.35	588.91	19.26	.40004
2.500	1090.45	599.22	17.05	.40123
2.750	1045.04	609.46	15.31	.40229
3.000	998.93	619.62	13.90	.40339
3.250	952.05	629.72	12.73	.40451
3.500	904.31	639.74	11.75	.40564
3.750	855.68	649.71	10.92	.40678
4.000	806.10	659.61	10.20	.40792
4.250	755.53	669.45	9.57	.40907
4.500	703.96	679.23	9.02	.41022
4.750	651.35	688.96	8.53	.41136
5.000	597.68	698.63	8.10	.41250
5.250	542.95	708.25	7.70	.41363
5.500	487.12	717.82	7.35	.41475
5.750	430.19	727.34	7.03	.41586
6.000	372.15	736.81	6.74	.41697
6.250	312.98	746.24	6.47	.41806
6.500	252.68	755.62	6.22	.41914
6.750	191.24	764.96	6.00	.42021
7.000	128.65	774.26	5.79	.42127
7.250	64.91	783.52	5.59	.42232
7.500	.00	792.74	.00	.42336

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .60000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	H-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1358.62	500.00	48.38	.43084
.250	1342.22	509.78	47.92	.43360
.500	1324.94	519.47	47.46	.43555
.750	1307.73	529.08	46.99	.43730
1.000	1290.55	538.63	46.50	.43898
1.250	1273.57	548.13	39.48	.43978
1.500	1252.39	557.66	31.70	.39723
1.750	1211.80	568.19	26.03	.39581
2.000	1167.04	578.70	22.09	.39876
2.250	1122.81	589.14	19.20	.39922
2.500	1078.06	599.54	16.99	.40012
2.750	1032.83	609.88	15.24	.40088
3.000	986.94	620.16	13.93	.40167
3.250	940.31	630.40	12.66	.40246
3.500	892.87	640.58	11.68	.40326
3.750	844.57	650.71	10.84	.40407
4.000	795.36	660.80	10.12	.40487
4.250	745.22	670.84	9.49	.40567
4.500	694.11	680.84	8.94	.40647
4.750	642.02	690.79	8.45	.40727
5.000	588.92	700.71	8.01	.40805
5.250	534.80	710.59	7.62	.40883
5.500	479.65	720.44	7.26	.40960
5.750	423.45	730.25	6.94	.41036
6.000	366.19	740.02	6.64	.41112
6.250	307.86	749.76	6.37	.41186
6.500	248.47	759.47	6.13	.41259
6.750	187.99	769.15	5.90	.41332
7.000	126.42	778.80	5.69	.41403
7.250	63.76	788.42	5.49	.41474
7.500	.00	798.02	.00	.41543

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .70000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1354.02	500.00	48.38	.43084
.250	1337.61	509.78	47.92	.43360
.500	1320.33	519.47	47.46	.43555
.750	1303.12	529.08	46.99	.43730
1.000	1285.94	538.63	46.50	.43898
1.250	1268.96	548.14	39.47	.43978
1.500	1247.79	557.67	31.69	.39719
1.750	1207.20	568.21	26.02	.39574
2.000	1162.47	578.74	22.68	.39861
2.250	1118.27	589.20	19.18	.39900
2.500	1073.57	599.63	16.97	.39981
2.750	1028.40	610.00	15.22	.40047
3.000	982.57	620.32	13.81	.40115
3.250	936.02	630.60	12.64	.40184
3.500	888.68	640.84	11.65	.40252
3.750	840.49	651.03	10.82	.40320
4.000	791.41	661.18	10.09	.40388
4.250	741.41	671.30	9.46	.40456
4.500	690.46	681.38	8.91	.40522
4.750	638.55	691.42	8.42	.40588
5.000	585.65	701.43	7.98	.40653
5.250	531.75	711.42	7.58	.40716
5.500	476.83	721.37	7.23	.40779
5.750	420.89	731.29	6.91	.40840
6.000	363.92	741.19	6.61	.40901
6.250	305.91	751.07	6.34	.40960
6.500	246.85	760.91	6.09	.41018
6.750	186.73	770.74	5.86	.41075
7.000	125.56	780.54	5.65	.41131
7.250	63.31	790.32	5.45	.41186
7.500	.00	800.08	.00	.41240

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .80000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
0.000	1352.51	500.00	48.38	.43084
.250	1338.11	509.78	47.92	.43360
.500	1318.83	519.47	47.46	.43555
.750	1301.62	529.08	46.99	.43730
1.000	1284.44	538.63	46.50	.43898
1.250	1267.46	548.14	39.47	.43978
1.500	1246.29	557.67	31.69	.39718
1.750	1205.71	563.22	26.02	.39572
2.000	1160.98	578.75	22.07	.39858
2.250	1116.79	589.22	19.18	.39894
2.500	1072.10	599.65	16.97	.39973
2.750	1026.94	610.03	15.22	.40036
3.000	981.14	620.37	13.80	.40101
3.250	934.61	630.66	12.63	.40166
3.500	887.30	640.91	11.65	.40231
3.750	839.14	651.12	10.81	.40296
4.000	790.09	661.29	10.09	.40359
4.250	740.14	671.43	9.45	.40422
4.500	689.24	681.54	8.90	.40484
4.750	637.38	691.61	8.41	.40545
5.000	584.54	701.66	7.97	.40605
5.250	530.71	711.67	7.57	.40664
5.500	475.88	721.66	7.22	.40721
5.750	420.03	731.63	6.89	.40777
6.000	363.15	741.57	6.60	.40832
6.250	305.24	751.49	6.33	.40886
6.500	246.30	761.39	6.08	.40939
6.750	186.30	771.27	5.85	.40990
7.000	125.26	781.12	5.64	.41040
7.250	63.16	790.96	5.44	.41089
7.500	.00	800.79	.00	.41137

CHANNEL RESULTS

CASE 1 7x7 BOL BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = .90000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1352.07	500.00	48.38	.43084
.250	1335.66	509.78	47.92	.43360
.500	1318.38	519.47	47.46	.43555
.750	1301.17	529.08	46.99	.43730
1.000	1283.99	538.63	46.50	.43898
1.250	1267.01	548.14	39.47	.43978
1.500	1245.84	557.67	31.69	.39718
1.750	1205.26	568.22	26.02	.39572
2.000	1160.53	578.75	22.07	.39857
2.250	1116.35	589.22	18.18	.39893
2.500	1071.66	599.66	16.97	.39971
2.750	1026.51	610.04	15.22	.40033
3.000	980.71	620.38	13.90	.40098
3.250	934.19	630.67	12.63	.40162
3.500	886.88	640.93	11.65	.40226
3.750	838.73	651.14	10.81	.40289
4.000	789.69	661.32	10.08	.40352
4.250	739.75	671.47	9.45	.40413
4.500	688.87	681.58	8.90	.40474
4.750	637.02	691.66	8.41	.40534
5.000	584.21	701.72	7.97	.40592
5.250	530.40	711.75	7.57	.40649
5.500	475.59	721.75	7.22	.40705
5.750	419.76	731.73	6.89	.40759
6.000	362.91	741.68	6.60	.40812
6.250	305.04	751.62	6.33	.40864
6.500	246.12	761.53	6.08	.40915
6.750	186.17	771.43	5.85	.40964
7.000	125.16	781.30	5.64	.41012
7.250	63.11	791.16	5.44	.41059
7.500	.00	801.00	.00	.41105

CHANNEL RESULTS

CASE 1 7X7 ROD BUNDLE, 50 PERCENT STEP CHANGE IN HEAT FLUX

TIME = 1.00000 SECONDS DATA FOR CHANNEL 8

DISTANCE (FEET)	P-PEXIT (PSF)	ENTHALPY (BTU/LB)	DENSITY (LB/CU-FT)	FLOW (LB/SEC)
-0.000	1351.94	500.00	48.38	.43084
.250	1335.54	509.78	47.92	.43360
.500	1318.26	519.47	47.46	.43555
.750	1301.05	529.08	46.99	.43730
1.000	1283.87	538.63	46.50	.43898
1.250	1266.89	548.14	46.02	.43978
1.500	1245.71	557.67	45.54	.43978
1.750	1205.14	568.22	45.07	.43972
2.000	1160.41	578.75	44.60	.43957
2.250	1116.23	589.22	44.13	.43992
2.500	1071.54	599.66	43.66	.43971
2.750	1026.38	610.04	43.20	.44033
3.000	980.59	620.38	42.73	.44097
3.250	934.07	630.68	42.26	.44161
3.500	886.76	640.93	41.79	.44224
3.750	838.61	651.15	41.32	.44287
4.000	789.58	661.33	40.85	.44350
4.250	739.64	671.48	40.38	.44411
4.500	688.76	681.59	39.91	.44471
4.750	636.92	691.68	39.44	.44530
5.000	584.11	701.74	38.97	.44588
5.250	530.31	711.77	38.50	.44645
5.500	475.50	721.77	38.03	.44700
5.750	419.68	731.75	37.56	.44754
6.000	362.84	741.71	37.09	.44807
6.250	304.98	751.65	36.62	.44858
6.500	246.07	761.57	36.15	.44908
6.750	186.13	771.47	35.68	.44957
7.000	125.14	781.35	35.21	.45004
7.250	63.10	791.22	34.74	.45050
7.500	.00	801.07	34.27	.45096

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