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COBRA-II: A DIGITAL COMPUTER PROGRAM FOR THERMAL-HYDRAULIC SUBCHANNEL ANALYSIS OF ROD BUNDLE NUCLEAR FUEL ELEMENTS

D. S. Rowe

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COBRA-11: A DIGITAL COMPUTER PROGRAM FOR THERMAL-HYDRAULIC SUBCHANNEL ANALYSIS OF ROD BUNDLE NUCLEAR FUEL ELEMENTS

By

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February 1970

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D. S. Rowe

ABSTRACT

The **COBRA-HI** program calculates the steady-state flow and enthalpy in the subchannels **of** rod bundle nuclear fuel elements during both **boiling** and nonboiling conditions. The program uses a mathematical model that includes the effects sf turbulent and diversion crossflow mixing between the subchannels. Turbulent crossflow mixing is cawed by lateral flow fluctuations between subchannels and diversion crossflow mixing is caused by flow redistribution resulting from changes in the axial pressure gradient or from forced crossflow. The equations or the mathematical model are solved as **an** initial-value problem by using finite differences. The solution of the equations for flow, enthalpy, pressure and diversion crossflow must rely on input correlations to specify the turbulent crossflow **and** subchannel pressure gradient. The program is designed to allow the user to **select** these correlations to best fit his particular application. Besides having a faster and a more accurate numerical solution than in the original version of COBRA, COBRA-II has new features to improve its versatility. It can include the effect of subcooled voids. Subchannels may be typed so that nonuniform hydraulic behavior can be considered. Distorted bundles may be analyzed by selecting variable subchannel areas and gap spacings along the length. Spacer pressure loss and forced diversion crossflow can be con-**sidered,** Turbulent mixing without boiling may be specified by several different correlation forms. During boiling, the mixing correlation **for** nonboiling can be used **or** turbulent mixing may be given as **a** function of steam quality. Adjustable dimensions are included in COBRA-II to allow the user to expand or contract the size of the program to accomodate his computer storage capability. The program has performed successfully with **36** subchannels, 25 fuel rods and **GO** subchannel connections.

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INTRODUCTION

The purpose of this report is .$~&scribethe digital computer program, COBRA-II, This program is a refinement and extension of the earlier program COBRA[1] which was written to aid in calculating the flow and enthalpy in the subchannels of rod bundle nuclear fuel elements, COBRA-I1 contains many new features that make it a more flexible and useful tool for rod bundle subchannel analysis,

Subchannel analysis has become an important tool to help establish the thermal performance of rod bundle nuclear fuel elements because it considers the distribution of coolant flow and enthalpy in the bundle, This is a significant improvement over the bundle average analysis approach because the arrangement of fuel rods in present bundle design causes the local flow and enthalpy to be very different from the average, Subchannel analysis also allows better interpretation of laboratory data that give the thermal-hydraulic performance parameters such as critical heat flux and two-phase pressure drop, By using a subchannel analysis approach, the fuel designer can apply laboratory data to the reactor's operating conditions with a greater degree of confidence,

SUMMARY AND CONCLUSIONS

The digital computer program COBRA-11 computes the flow and enthalpy in the subchannels of rod bundle nuclear fuel during both boiling and nonboiling conditions. It uses a mathematical model that considers two types of cross-flow mixing, The first type is a net diversion crossflow caused by flow redistribution, and the second is a turbulent (fluctuating) crossflow caused by the random travel of coolant between adjacent subchannels. Each subchannel

is assumed to contain one dimensional, two-phase, slip-flow and is assumed to have a fine enough two-phase flow structure to permit specification of local void fraction as a function of enthalpy, flow, pressure and position, The equations sf the mathematical model are solved as an initial-problem by using finite differences. The numerical procedures are a significant improvement over the procedures used in the original COBRA program,

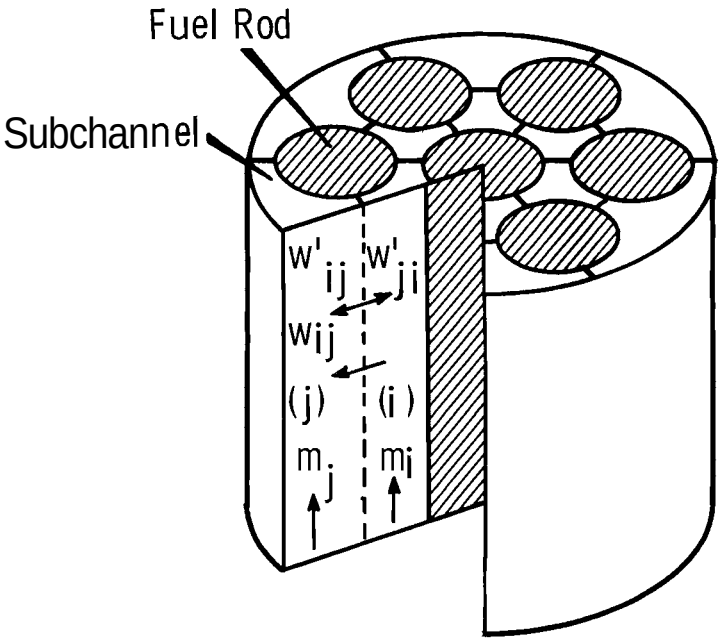
The COBRA-II program contains new features that permit analysis of many different rod bundle problems. Its significant features include the following:

- It has the ability to consider both single-and two-phase flow,
- It accounts fen. intersubchannel thermal mixing that results from thermal conduction, turbulent crossfPow and diversion crossflow.
- It considers the momentum interchanges that result from both turbulent and diversion crossflow between adjacent subchannels,
- It includes the effect of transverse resistance to diversion crossflow.
- It can consider an arbitrary layout of fuel rods and flow subchannels and thus allows analysis of most any rod bundle configuration
- It can include arbitrary heat flux distribution by specifying the axial flux distribution, relative rod power, and the fraction of rod power to each adjacent subchannel.
- It can consider variable subchannel area and gap spacings,
- It can include the effect of subcooled void.
- It can include the effect of forced diversion crossflow produced by flow diverting devices.
- It can include the pressure losses caused by spacing devices,
- It permits nonuniform hydraulic behavior by selecting different subchannel hydraulic characteristics.
- Input options are provided to allow the user to select various empiricab correlations required fon the calculations,

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 essentially the same as in the original COBRA program where the cross section of the rod bundle is divided into discrete flow subchannels as shown in Figure 1.



1. Method of Subchannel Selection

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

Steady, one-dimensional, two-phase ~Pipflow 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 and axial position
- a A turbulent crossflow exists between adjacent subchannels that causes no net flow redistribution
- a The turbulent crossflow may be superimposed upon a diversion crossflow between subchannels that results from flow redistribution This may occur naturally by pressure gradients trying to equalize or may occur artificially from devices that force diversion crossflow
- Transverse spatial acceleration is neglected

GENERALILED EQUATIONS

The equations of continuity, energy, and momentum may be derived by using the basic assumptions as shown in Appendix 4 This derivation gives a set of 3N first order, ordinary, 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

$$\left\{\frac{dm}{dx}\right\} = -[R]\{w\} \tag{1}$$

Energy

$$\left\{\frac{dh}{dx}\right\} = \{Q\} - [R][H]\{w'\} - [R][T]\{c\} + [R][H^*]\{w\} \tag{2}$$

Axial Momentum

$$\left\{\frac{dp}{dx}\right\} = -\{a\} - [R][U]\{f_T w'\} + [R][U^*]\{w\} \tag{3}$$

Transverse Momentum

$$\{C|w|w\} = [S]\{p\} \tag{4}$$

The shorthand notation used in these equations gives a simple form that shows the basic phenomena included in the mathematical model, Now, consider the various terms in the above equations.

Equation (1) states that the rate of flow change in a subchannel is a linear combination of the diversion crossflows, The matrix transformation [R] 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.

In the Energy Equation (2), the terms on the right illustrate four mechanisms of thermal energy transport between the subchannels 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 [R][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 [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 $[R][T]c$ accounts for thermal conduction between adjacent subchannels. During boiling, the temperatures contained in [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 $[R][H^*]\{w\}$ 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 [H*] which is set up the same way as [H]. The matrix [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 transported enthalpy from known information about the liquid-and vapor-phase distribution.

The right side of the Axial Momentum Equation (3) illustrates the mechanism of momentum transport. The first term (a) represents the pressure gradient without any crossflow between subchannels, It includes the friction, spatial acceleration and elevation components of pressure drop, 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 $[R][U]'f_T w'$ accounts for the turbulent momentum transport and is analogous to a Reynolds stress as discussed in Reference 1. The matrix [U] contains the subchannel velocities and is set up the same way as [H]. Since the analogy between thermal and momentum turbulent transport processes may nor 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 $[R][U^*]\{w\}$ of Equation 43) is the momentum contribution sf the diversion crossflow. This is a convective term that is analogous to the convective energy term, The matrix [U*] contains the axial velocities that are carried through the gap by the diversion crossflow.

The Transverse Momentum Equation (4) is a simple friction model where the pressure drop between subchannels is proportional to the diversion crossflow rate squared, The resistance coefficient C is evaluated in terms of an empirical function which depends on the geometric and flow parameters. This equation has rather weak influence for a few problems, but it plays an important role in the numerical stability of some solutions.

NUMERICAL SOLUTION

The 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, a simpler initial-value solution is commonly accepted as an approximate solution. Various types of initial-value solutions are used in the HAMBO[2], SASS[3], THINC-II[4] and MIXER[5] subchannel analyses programs.

The use of an initial-value solution can be justified from the results presented in Reference 6 where an initial-value solution is shown to adequately approximate the boundary-value solution if a stability criterion is satisfied, This criterion gives the minimum allowable calculation increment in terms of the crossflow resistance, The actual calculation increment must be larger than this to permit proper flow redistribution, If the increment is smaller than this, the flow redistribution occurs over additional calculation increments, and a boundary-value solution is required.

The numerical procedure in COBRA-II uses an initial-value solution that is patterned after the one discussed in Reference 6. By applying this procedure to many subchannels, a similar set of numerical equations and a similar stability criterion is obtained.

Initial-Value Numerical Solution

Equations (1) through (4) are solved as an initial-value problem by using finite differences, It is assumed that the values of {m}, {h}, {w} and {p} are available to start the solution, Both forward and backward

finite differences are used for the solution, The Energy Equation (2) is solved by using the forward difference equation

$$\left\{\frac{h(x+\Delta x)-h(x)}{\Delta x}\right\} = \{Q(x)\} - [R][T(x)]\{C(x)\} - [R][H(x)]\{w'(x)\} + [R][H^*(x)]\{w(x)\} \quad (5)$$

This equation can be easily solved for $\{h(x+\Delta x)\}$ because all other quantities are known. A backward finite difference is used to solve the Continuity and Momentum Equations * FOP the Continuity Equation (1) the difference equation is

$$\left\{\frac{m(x+\Delta x)-m(x)}{\Delta x}\right\} = -[R]\{w(x+\Delta x)\}. \quad (6)$$

The values of $\{w(x+\Delta x)\}$ must be obtained before this equation can be solved for $\{m(x+\Delta x)\}$. An equation for $\{w\}$ can be obtained by eliminating pressure from Equations (3) and (4). The result** is

$$\frac{d(C|w|w)}{dx} = -[S]\{a^0\} + [S][R][U^*]\{w\} \quad (7)$$

where $$\{a^0\} = \{a\} + [R][U]\{f_T w^0\} \quad (8)$$

The backward difference approximation is used in this equation which gives

$$\left\{\frac{C(x+\Delta x)|w(x+\Delta x)|w(x+\Delta x) - C(x)|w(x)|w(x)}{\Delta x}\right\} =$$

$$[S]\{a^0(x+\Delta x)\} + [S][R][U^*(x+\Delta x)]\{w(x+\Delta x)\}. \quad (9)$$

---

*The use of the backward difference eliminates the confusing crossflow sign inconsistency in the original COBRA program.[1]

**Notice that Equation (7) could be differentiated again and after substituting Equation (1) would give a system of second order equations that could be solved as a boundary–value problem for $\{w\}$.

By substituting Equation (4) and rearranging, this may be written as

$$\left[\frac{C(x+\Delta x)|w(x+\Delta x)|}{\Delta x} - [S][R][U^*(x+\Delta x)]\right]\{w(x+\Delta x)\} = [S]\{a'(x+\Delta x)\} + \frac{1}{\Delta x}[S]\{p(x)\} \tag{10}$$

Equation (10) is a set of K simultaneous, nonlinear equations and K unknowns. This can be solved as a linear system by iteration where, for each iteration, the previous iterate is used for $\{C(x+\Delta x)|w(x+\Delta x)|/\Delta x\}$, $[U^*(x+\Delta x)]$ and $\{a'(x+\Delta x)\}$. Once the iterative solution for $\{w(x+\Delta x)\}$ converges to within an acceptable tolerance, $\{m(x+\Delta x)\}$ can be calculated from Equation (6) and $\{p(x+\Delta x)\}$ can he calculated from

$$\left\{\frac{p(x+\Delta x) - p(x)}{\Delta x}\right\} = -\{a'(x+\Delta x)\} + [R][U^*(x+\Delta x)]\{w(x+\Delta x)\} \tag{11}$$

which is a backward difference approximation to Equation (3).

The procedure used to solve these equations is patterned after the iterative solution contained in Reference 6, and it is illustrated in Figure 2. Initial values of $\{h(x)\}$, $\{m(x)\}$, $\{w(x)\}$ and $\{p(x)\}$ are first established. Equation (5) is used to calculate $\{h(x+\Delta x)\}$. The values of $\{m(x)\}$, $\{w(x)\}$ and $\{p(x)\}$ are assumed to apply at $x+\Delta x$ for the purpose of evaluating fluid properties, With this information, the liquid and two-phase properties can be evaluated at $x+\Delta x$. In the present writing of COBRA, these properties are assumed* to remain constant for the iteration loop that follows.

The iteration loop starts by using the fluid properties to evaluate $\{C(x+\Delta x)|w(x+\Delta x)|/\Delta x\}$, $\{a'(x+\Delta x)\}$ and $[U^*(x+\Delta x)]$; then, $\{w(x+\Delta x)\}$ is calculated by using Equation (10). The new $\{w(x+\Delta x)\}$ is compared with the old one to determine if all of the crossflows have converged to within an

*Fluid property evaluation could be included in the iteration loop, but it can cause instabilities near the point of boiling when void correlations are used that depend on flow rate.

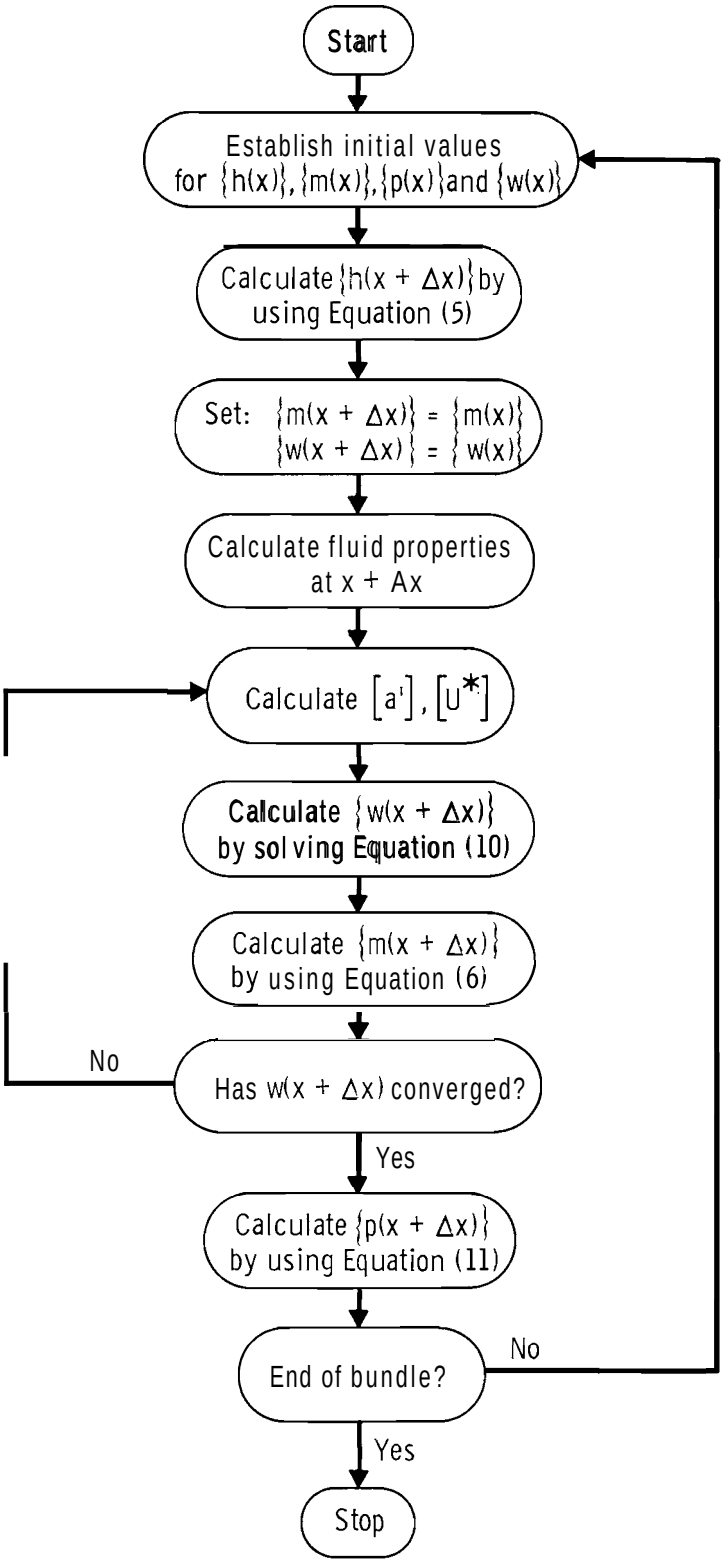


FIGURE 2. **Initial-Value Solution**

acceptable tolerance. If convergence does not occur, a signal is set up to remain in the loop for another iteration, Since the new solution for $\{w(x+\Delta x)\}$ is quite sensitive to the old one, $\{w(x+\Delta x)\}$ is modified by

$$\{w(x+\Delta x)\} = \frac{1}{2}\{w(x+\Delta x)\}_{calc} + \frac{1}{2}\{w(x+\Delta x)\}_{old} \tag{12}$$

This value fs then used in Equation *(6)* to calculate $\{m(x+\Delta x)\}$ which is used in the next iteration if convergence did not occur, If convergence did occur, $\{p(x+\Delta x)\}$ is calculated from Equation (11) and the calculation moves to the next increment,

Stability of the Initial—Value Flow Solution

The backward difference is used in Equation (7) because of severe stability limitations that are required with a forward difference, If Equation (7) is pre-multiplied by a matrix $[C^{-1}]$ with only diagonal elements of $1/C$, the following equation is obtained

$$\left\{\frac{d|w|w}{dx}\right\} = -[C^{-1}][S]\{a'\} + [C^{-1}][S][R][U^*]\{w\} \tag{13}$$

The elements of [S], [R] and [U*] are of the order unity, but the elements of $[C^{-1}]$ can be many orders higher, Therefore, the eigenvalues of the characteristic matrix of Equation (13) are *very* large, As shown in Appendix C, a stable solution for such a set of equations is not possible with a forward difference, By using a backward difference approximation for the flow solution, stable solutions can be obtained if two requirements are satisfied, The first requires that there be a sufficiently large crossflow resistance to prevent transverse flow loops, and the second requires a sfgnificantly large Δx for a given crossflow resistance. These two requirements will now be discussed,

Equation (10) may be written more compactly as

$$[A]\{w(x+\Delta x)\} = \{B\}. \tag{14}$$

This is a set of K simultaneous equations and K unknowns, A solution is possible if [A] is not singular. It should be noted that [A] is the matrix -[S][R][U*] but with its diagonal elements modified by adding the diagonal matrix [C|w|/Δx]. For any rod bundle problem that has one or more flow paths around a fuel rod (or any transverse flow loop) the matrix -[S][R][U*] is singular and only by adding [C|w|/Δx] 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 are small as compared to the nonzero elements of [S][R][U*]; therefore, [A] 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, provided the value of |w| is not zero, To eliminate the problem of |w| going to zero, the crossflow resistance is linearized for small values of crossflow in the present writing of COBRA This is done by putting a lower limit on |w|; thus, for $w \quad w_L$, $|w| = w_L$ and for $|w| \; w_L$, $|w| = |w|$.

In addition to requiring that [A] be nonsingular, the second requirement is that the absolute value of the largest eigenvalue of $[A]^{-1}$ must be lass than one an Equation (14). This criterion puts a Power limit on the calculation increment for a given crossflow resistance. Its physical basis, which is discussed in Appendix C and Reference (6), requires that the diversion crossflow occur within the increment Δx and still satisfy the momentum equations, If this condition is not satisfied, errors grow in the flow solution and flow reversals may occur in an attempt to satisfy the momentum equations, Fortunately, the minimum Δx is much smaflier than the Δx desired for most rod bundle calculations.

The previous discussion helps to clarify the role of the crossflow resistance in the COBRA-II program, Notice that in Equations (7) and (10) the crossflow resistance terms are very small, thus, the crossflows are driven by dafferences in the axial pressure gradient, The crossflow resistance should be interpreted as a mechanism that directs the diversion

crossflow through the path of least resistance and gives zero pressure drop around transverse flow loops, The crossflow resistance only has importance when these loops exist, For problem where there are no loops, the crossflow resistance has little importance because the stability criterion requires dominance of $[S][R][U^*]$ over $[C|w|/\Delta x]$.

COMPUTER PROGRAM DESCRIPTION

The COBRA-I1 program is a revised version of the original COBRA program, This revision has been guided by users' comments and through experience which has identified the need for improvements and expanded capability, This has resulted in a rather general program that can be used by the nuclear industry for analysis of many rod bundle thermal-hydraulics problems,

COBRA-I1 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-I1 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,

The following sections present the general features of the COBRA-I1 program, an illustrated description of the program organization and a description of the program's subroutines,

GENERAL FEATURES

The significant features of COBRA-I1 include the following:

- It has the ability to consider both single- and two-phase flow,
- It can consider 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,
- 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 sf 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 forced diversion crossflow by specifying the local diversion crossflow in terms of geometric and flow parameters.
- 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 the inlet flow and enthalpy conditions,

PROGRAM ORGANIZATION

The organization of the COBRA II program is similar to that of the original COBRA program; however, the input procedures and subroutines have been reorganized to permit the expanded program capability, The calculational procedures have also been revised to use the previously described numerical solution.

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,

Following the input, the initial conditions are established, Previously stored values of initial conditions of inlet flow, enthalpy and pressure are recalled or the initial conditions are established from new input data, Subroutine SPLIT is used here to calculate subchannel flows to give equal subchannel pressure gradients if it is requested by an input option,

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,

A loop is now entered which takes the calculation stepwise through the bundle at preselected steps of Δx. At the beginning of selected steps, the answers are saved for later printing. When the end of the bundle is reached, these answers are printed as specified by options,,

At the beginning of each space step, the rate of enthalpy rise $\{dh/dx\}$ is calculated in Subroutine DIFFER(1) and this is used to calculate $\{h(x+\Delta x)\}$. Properties are evaluated at $x+\Delta x$ by using $\{m(x)\}$, $\{w(x)\}$ and the reference pressure. All geometries and flow parameters are now calculated at $x+\Delta x$ by using Subroutines AREA, FORCE, PROP(2), VOID and MIX,

An iteration loop is now started to refine the previous estimates of $\{m(x+\Delta x)\}$ and $\{w(x+\Delta x)\}$. In this iteration, the previously estimated flow properties are assumed to be sufficiently accurate that the iteration may proceed without their continual re-evaluation, For problems where this assumption is not valid, the property evaluation could be easily included for each iteration, The values of $\{a'(x+\Delta x)\}$ and $[S][R][U^*(x+\Delta x)]$ are

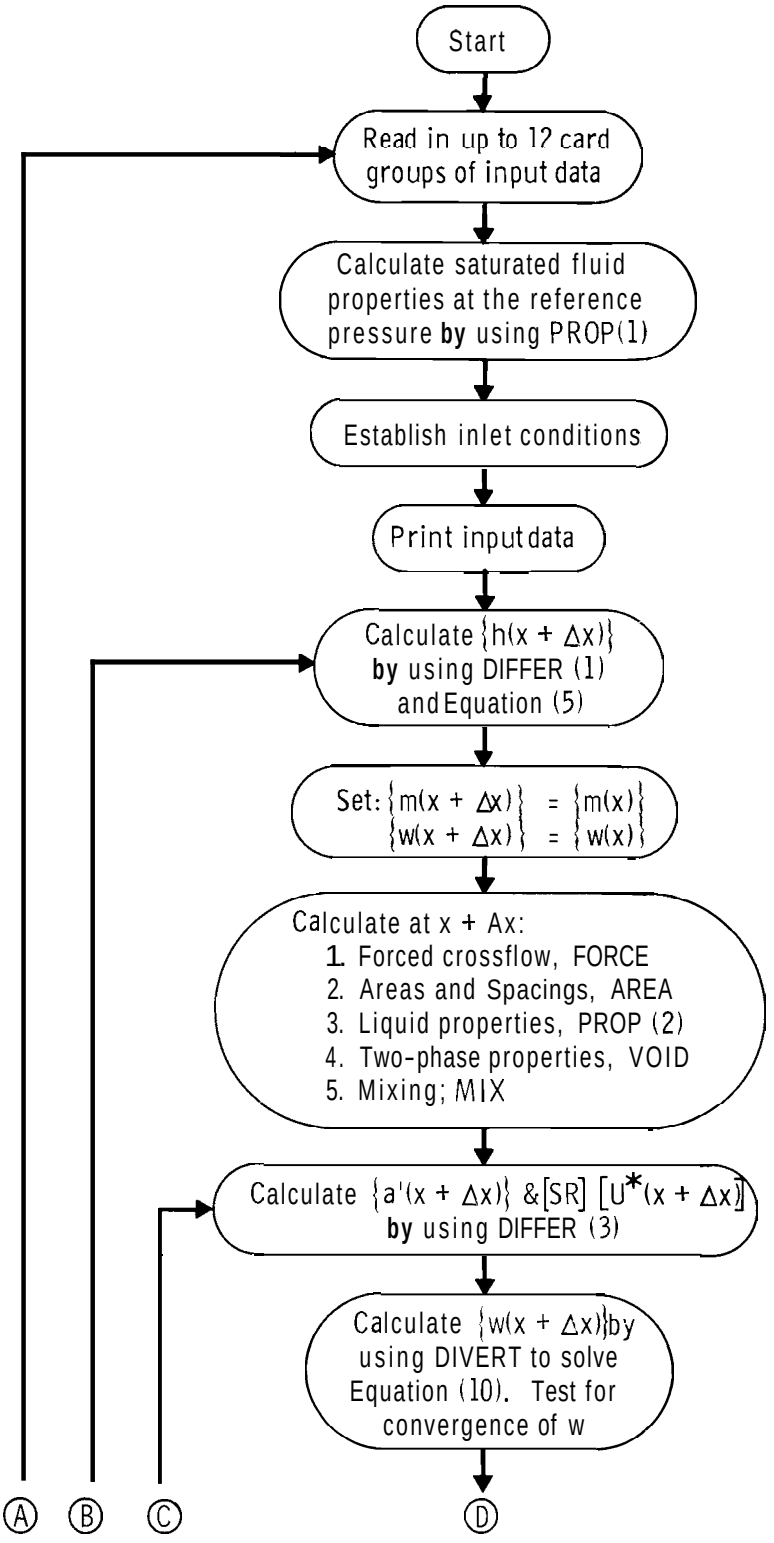


FIGURE 3. COBRA-II Flow Diagram

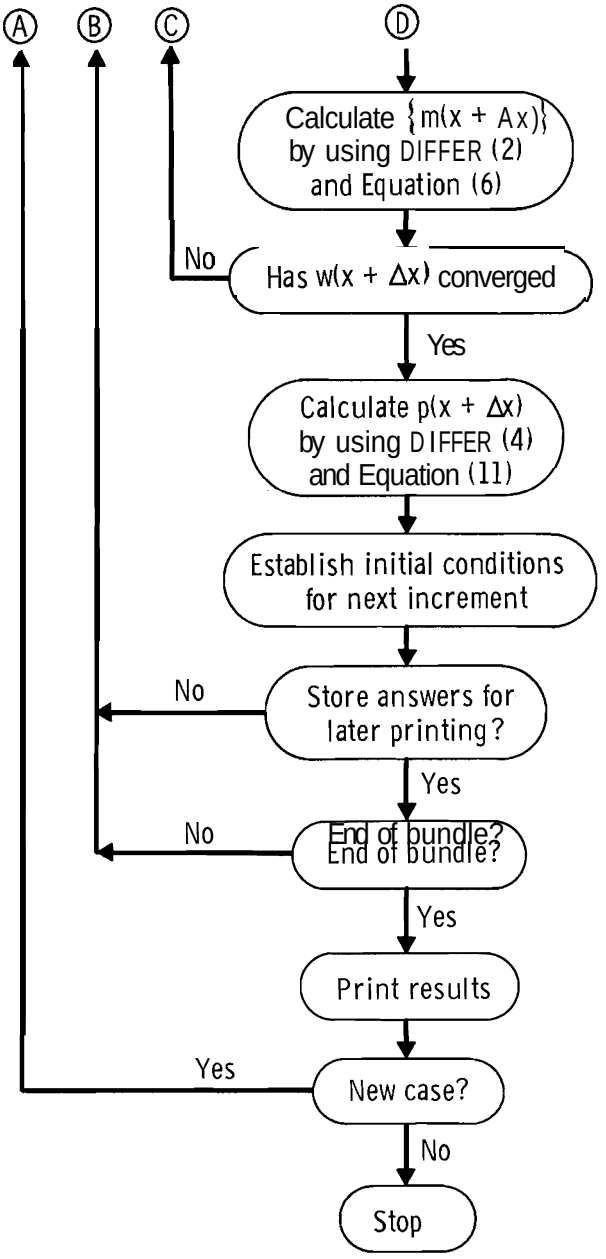


FIGURE 3. COBRA-II Flow Diagram (Contd.)

evaluated by using Subroutine DIFFER(3) for each iteration because they are flow dependent, With these quantities defined, Equation (14) can be solved for {w(x+Δx)} by using DIVERT Now, by using Subroutine DIFFER(2), {dm/dx} is calculated and then m(x+Δx) is calculated by using Equatfon (6). When {w(x+Δx)} converges to within an acceptable tolerance, the iteration is stopped and a calculation of {dp/dx} is made using Subroutine DIFFER(4), and this is used to calculate {p(x+Δx)} by using Equation (11). The initial conditions are now established for the next increment?

SUBROUTINES

The organization of the COBRA-II program puts most of the calculational effort into subroutines. The more important ones will now be discussed to describe their function and to identify the required input correlations,

Subroutine DIEEER(IPART)

This subroutine is used to calculate the spatial derivatives of flow, enthalpy and pressure, It is divided into four parts as indicated by the variable IPART. 'She notation and procedures used in DIFFER do not correspond directly to the notation used in the previously presented matrix equations, There are actually no rectangular matrices [R], [S], [U*], etc. There are, however, the column vectors corresponding to {w'}, {C}, {w}, {m}, {h}, {p} and {a'} which. are defined in the Nomenclature, The method of performing the previously indicated matrix transformations is actually done by using the index notation of Appendix A and the subchannel connection scheme presented in Appendix B. As an example of how this is done, the calculation performed in the second part of Subroutine DIFFER will be explained in detail,

In this calculation, the elements of {dm/dx} are calculated by using Equation (A-3) whaeh as

$$\frac{dm_i}{dx} = \sum_{j=1}^{N} w_{ij} \qquad i = 1, 2 \ldots N. \qquad \text{(A-3)}$$

By using the subchannel conneetion notation of Appendix B, each pair (ij) gives a subchannel connection number k that is identified by the array KCHAN (I,J), If there is no connection KCHAN(I,J) is zero, The values of dm_i/dx are calculated by selecting a subchannel number (i) and then, by considering all other subchannels (j), accumulate those values of w_k that have nonzero values of k. To account for the direction of the diversion crossflow the sign of w_k is positive if i<j and is negative if i>j. This procedure is equivalent to performing the transformation -[R]{w}.

The calculation of the other spatial derivatives is done in much the same way, Some explanation is required, however, to show how [U*] and [H*] are treated, These quantities include the axial velocity and enthalpy that are transported through the gap by the diversion erossflow, Since they are both handled the same way, consider [H*]. From Appendices A and 13, the elements of [R][H*]{w} are

$$\sum_{j=1}^{N} (h_i - h^*)\frac{w_{ij}}{m_i} \qquad i = 1, 2...N$$

where h* is presently defined in COBRA-I1 as

$$h^* = \begin{cases} h_i; \text{ if } w_{ij} \geq 0 \\ h_j; \text{ if } w_{ij} < 0 \end{cases}; \tag{15}$$

therefore, the enthalpy being carried through the gap by the diversion crossflow is the enthalpy from the donor subchannel. Similarly

$$u^* = \begin{cases} u_i; \text{ if } w_{ij} \geq 0 \\ u_j; \text{ if } w_{ij} < 0 \end{cases}. \tag{16}$$

Both Equations (15) and (16) imply that the enthalpy and velocity are uniform in each subchannel. In reality, this is an approximation, As additional information is obtained concerning two-phase transport processes in bundles h* and u* can be formulated more correctly,

Subroutine DIVERT

This subroutine sets up Equation (14)

$$[A]\{w(x+\Delta x)\} = \{B\} \qquad (14)$$

and solves for $\{w(x+\Delta x)\}$. The setup is done by using index notation and not actually by using the matrices [S], [R] and [U*] . This setup uses $\{a'\}$ and the coefficients of $\{w\}$ which are calculated in DIFFER(3). The elements of [A] are filled by successively selecting rows from which the pair of adjacent subchannels can be defined by the arrays IK and JK. Each element of the row is then filled to correspond to the subchannel connection logic.

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

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 D. 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 D.

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 users 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 FORGE 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, An example of how forced crossflow is treated is included in the present writing of COBRA, In this example, flow diverters may be assigned to spacers which divert a fraction of the flow out a subchannel into another one, This flow fraction is converted into a diversion crossflow per unit length by dividing the diverted flow by Δx.

Other Subroutines

Several other subroutines are required for operation of the COBRA-I1 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

The COBRA-II program is written for the WIVAC-1108, Except for the round-off problem 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 accomodate the users computer or problem size,

Complete input instructions are included in the program listing, A sample problem that illustrates the input and use of the new features of COBRA-II is given in APPENDIX E. 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

Many of these correlations already exist from studies of flow in simple channels; however, there is not yet enough information to indicate which correlations are best for most rod bundle problems. An evaluation of available correlations will have to be made to determine which correlations are suitable for rod bundle subchannel analysis,

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NOMENCLATURE*

Equations	Computer Program	
a	DP	Single channel pressure gradient
a'	DP	Pressure gradient without crossflow in Equation (3), (F/L^3)
A	A	Cross-sectional area, (L^2)
[A]	AAA	Matrix of coefficients in Equation (14)
{B}	B	Column vector in Equation (14)
c	COND	Thermal conduction coefficient'.(H/Tθ)
C	C	Loss coefficient for transverse crossflow in Equation (4)
C_p	CP	Specific heat (H/Mθ)
dh/dx	DH	Enthalpy derivative, (H/L)
dm/dx	DF	Flow derivative, (M/TL)
dp/dx	DP	Pressure derivative (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 (Dimensionless)
f_c	PWRF	Fraction of rod power transferred to an adjacent subchannel (Dimensionless)
fℓ	FL	Uivcrsion crossflow resistance parameter (L)
f_R	RADIAL	Relative roil power distribution (Dimensionless)
f_T	FTM	Turbulent momentum factor (Dimensionless)

*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	
F		Force (ML/T^2)
g_c	G	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)
[H], [H*]		Enthalpy matrices defined by Equations (B-6) and (B-7), (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
K_g	GK	Geometry factor for conduction (Dimensionless)
ℓ		Length, (L)
L	Z	Channel length, (L)
m	F	Mass flow rate, $Au_f[\rho g\alpha\gamma+\rho_f(1-\alpha)]$, (M/T)
N	NCHANL	Number of subchannels [Dimensionless)
p		Pressure (F/L^2)
P_H	HPERIM	Heated perimeter, (L)
P_w	PERIM	Wetted perimeter, (L)
P_r	PRANTL	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 (D-17)
[R]		Matrix to order crossflows (Dimensionless)
Re	RE	Reynolds number, (Dimensionless)

Equations	Computer Program	
s	GAP	Rod spacing (L)
[S]		Matrix transformation defining adjacent subchannels, (Dimensionless)
t	T	Temperature (θ)
u	U	Channel effective momentum velocity
u*	USTAR	Effective velocity carried by diversion crossflow (L/T)
[U]		Velocity matrix defined by Equation (B-11), (T/L^2)
[U*]	DD	Velocity matrix defined by Equation (B-12), (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 erossflow between adjacent subchannels (M/TL)
w'	WP	Turbulent (fluctuating) crossflow between adjacent subchannels, (M/TL)
x	X	Distance (L)
X	QUAL	Quality, $m_g/(m_g+m_f)$, (Dimensionless)
X_d	XD	Parameter given by Equation (D-15)
Y_B	YB	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	BETA	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, $\rho_g\alpha + \rho_f(1-\alpha)$, ($M/L^3$)

Equations	Computer Program	
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-?base friction multiplier, (Dimensionless)
μ	VISC	Viscosity, (F/LT)

Subscripts

f, g		Saturated conditions for liquid and vapor, respectively
i, j	I, J	Channel identification number
ij, ji		Double subscripts imply i to j and j to i, respectively
k(i,j)	KCHAN	Number identifying each subchannel connection; each k implies a pair ij or ji
r		Rod identification number
ri		Refers to connection from r to subchannel i

APPENDIX A

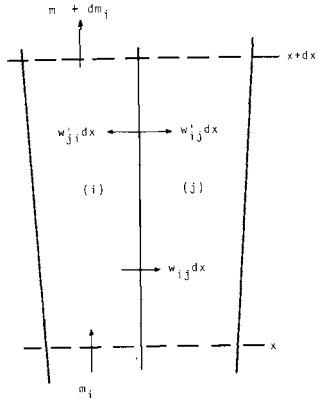
DERIVATION OF EQUATIONS

APPENDIX A

DERIVATION OF EQUATIONS

The equations of continuity, energy and momentum are derived here by applying the conservation equations to a segment of Subchannel (i) whish is connected to another Subchannel (j) .

Continuity Equation



A mass balance on Subchannel (i) gives

$$m_i + w'_{ji}dx = m_i + dm_i + w_{ij}dx + w'_{ij}dx \qquad \text{(A-1)}$$

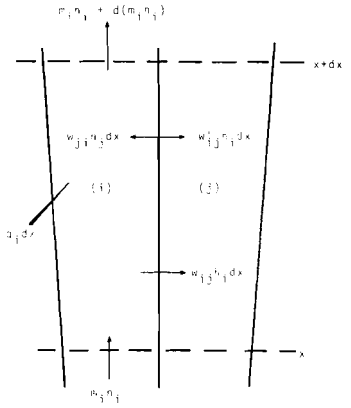
Since by assumption, the turbulent crossflow causes no net flow change ($w'_{ji} = w'_{ij}$), the continuity equation reduces to

$$\frac{dm_i}{dx} = -w_{ij}. \qquad \text{(A-2)}$$

If the diversion crossflow from (i) to (j) is chosen to be positive, then, by considering all such adjacent subchannels, the continuity equation becomes

$$\frac{dm_i}{dx} = -\sum_{j=1}^{N} w_{ij} \qquad i = 1,2, \ldots N. \qquad \text{(A-3)}$$

Energy Equation



An energy balance on Subchannel (i) gives

$$m_i h_i + w'_{ji} h_j dx + \bar{q}'_i dx = w_{ij} h_i dx + w'_{ij} h_i dx + m_i h_i + d(m_i h_i). \qquad \text{(A-4)}$$

Since, by assumption, $w'_{ij} = w'_{ji}$, this reduces to

$$m_i \frac{dh_i}{dx} + h_i \frac{dm_i}{dx} = \bar{q}_i + w'_{ij}(h_j - h_i) - w_{ij} h_i. \qquad \text{(A-5)}$$

This equation applies when the diversion crossflow is from i to j. To account for the uncertainty of the enthalpy which is carried through the gap, this equation may be written as

$$m_i \frac{dh_i}{dx} + h_i \frac{dm_i}{dx} = \bar{q}'_i + w'_{ij}(h_j - h_i) - w_{ij} h^* \qquad \text{(A-6)}$$

where h* is the effective enthalpy that is carried through the gap by the diversion crossflow. If the subchannel enthalpy is uniform, h* is defined as

$$h^* = \begin{cases} h_i; \text{ if } w_{ij} > 0 \\ h_j; \text{ if } w_{ij} < 0 \end{cases}. \qquad \text{(A-7)}$$

The heat transfer term $\overline{q_i'}$ may be divided into two terms, The first is the heat transfer rate from the fuel surface q_i', and the second is heat conduction between adjacent subchannels. The heat conduction is assumed to be proportional to the subchannel temperature difference and the constant of proportionality as assumed to be a function of the subchannel geometry and fluid properties.

By considering the heat conduction term and all such adjacent subchannels, the energy equation may be written as

$$m_i \frac{dh_i}{dx} = q_i' - \sum_{j=1}^{N} (h_i - h_j) w_{ij}' - \sum_{j=1}^{N} (t_i - t_j) c_{ij} + \sum_{j=1}^{N} (h_i - h^*) w_{ij} \qquad (A-8)$$

where t is limited to the saturation temperature during boiling,

Axial Momentum Equation

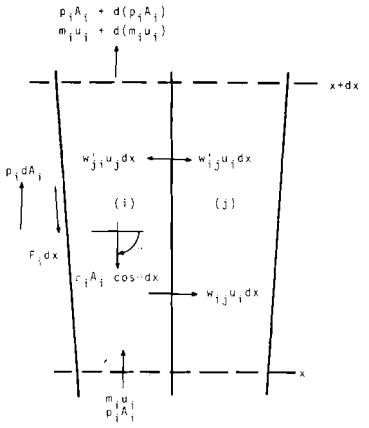
The derivation of the momentum equation is a little more complex than the continuity and energy equations; however, the sane technique applies, For a one-dimensional analysis, the momentum in a two-phase flow stream can be defined as

$$\frac{AG^2 v'}{g_c} = \frac{m^2}{A} \frac{Av'}{g_c} - \frac{mu}{g_c} \qquad (A-9)$$

where the momentum velocity is

$$u = \frac{mv'}{A} . \qquad (A-10)$$

The effective specific volume term is that used by Meyer[7] in his development of two-phase flow equations,



By equating forces acting on Subchannel (i) in the x direction to the change in momentum, the axial momentum equation is

$$g_c(A_i p_i - F_i dx - A_i p_i - d(A_i p_i) + p_i dA_i - A_i \rho_i \cos\theta dx) =$$

$$+ w_{ij} u_i dx + w'_{ij} u_i dx + m_i u_i + d(m_i u_i) - m_i u_i - w'_{ji} u_j dx \qquad \text{(A-11)}$$

By using Equation (A-3) and $w'_{ij} = w'_{ji}$, this reduces to

$$\frac{dp_i}{dx} = -\frac{F_i}{A_i} - \rho_i \cos\theta - \frac{w'_{ij}}{A_i g_c}(u_i - u_j)$$

$$- \frac{2u_i}{A_i g_c}\frac{dm_i}{dx} - \frac{u_i w_{ij}}{A_i g_c} - \left(\frac{m_i}{A_i}\right)^2 \frac{A_i}{g_c}\frac{d(v'_i/A_i)}{dx}. \qquad \text{(A-12)}$$

As in the derivation of the energy equation, this applies when the diversion crossflow is from i to j, To account for the uncertainty of the axial velocity which is carried through the gap, this equation may be written as

$$\frac{dp_i}{dx} = -\frac{F_i}{A_i} - \rho_i \cos\theta - f_T \frac{w'_{ij}}{A_i g_c}(u_i - u_j) - \frac{2u_i}{A_i g_c}\frac{dm_i}{dx} - \frac{u^* w_{ij}}{A_i g_c} - \left(\frac{m_i}{A_i}\right)^2 \frac{A_i}{g_c}\frac{d(v'_i/A_i)}{dx} \tag{A-13}$$

where u^* is the effective axial velocity that is carried through the gap by the diversion crossflow, The factor f_T is used to account for an imperfect analogy between the turbulent transport of enthalpy and momentum. If the velocity is uniform in the subchannels, u^* is defined by

$$u^* = \begin{cases} u_i; \text{ if } w_{ij} \geq 0 \\ u_j; \text{ if } w_{ij} < 0 \end{cases}. \tag{A-14}$$

The flow resistance force in a subchannel is assumed to consist of a wall friction term plus an additional drag term which may account for spacing devices or other types of flow blockage, This is given by the equation

$$\frac{F_i}{A_i} = \frac{1}{g_c}\left(\frac{m_i}{A_i}\right)^2 \left[\frac{v_i f_i \phi_i}{2D_i} + \frac{K_i v'_i}{2}\right] \tag{A-15}$$

where K_i is the drag coefficient[8] defined in terms of the unperturbed subchannel velocity,

By substituting Equation (A-15) into Equation (A-13) and by considering all subchannels adjacent to Subchannel (i), the axial momentum equation becomes

$$\frac{dp_i}{dx} = -\frac{1}{g_c}\left(\frac{m_i}{A_i}\right)^2 \left[\frac{v_i f_i \phi_i}{2D_i} + \frac{K_i v'_i}{2} + A_i \frac{d(v_i/A_i)}{dx}\right] - \rho_i \cos\theta - \frac{1}{g_c A_i}\sum_{j=1}^{N}(u_i - u_j) f_T w'_{ij} + \frac{1}{g_c A_i}\sum_{j=1}^{N}(2u_i - u^*) w_{ij} \tag{A-16}$$

$$i = 1, 2, \ldots N.$$

erse Momentum Equation

By neglecting the transverse spatial acceleration, the transverse momentum equation may be written as

$$C_{ij}|w_{ij}|w_{ij} = p_i - p_j \qquad \text{(A-17)}$$

where C_{ij} is the transverse crossflow resistance factor.

APPENDIX B

GENERALIZED FORM OF THE EQUATIONS

APPENDIX B

GENERALIZED FORM OF THE EQUATIONS

This Appendix presents a matrix representation of the mathematical model's equations. To set up this notation, it is necessary to introduce some notation to show how the subchannel connections are ordered, The generalized form of the equations will follow directly from the matrix notation,

Matrix Notation

The connections between adjacent subchannels are identified by a matrix K whose elements are k(i,j); where k(i,j) = 0 if there is no connection and k(i,j) is assigned a value for each valid connection, The nonzero values of k(i,j) 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. Therefore, each pair of Subchannels (i) and (j) have a unique connection number, Likewise, each connection number identifies a unique pair of subchannels. Let these subchannels be denoted by two column vectors I and J with elements i(k) and j(k) , respectively,

The identification procedure allows the crossflows to be written as a column vector with elements

$$w_{k(i,j)} = w_{ij} \tag{B-1}$$

and with a sign convention that for $w_k > 0$ the flow 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

Let [K] be a (N X K) matrix that performs the summation in Equation (A-3); then, Equation (A-3) has the form

$$\left\{\frac{dm}{dx}\right\} = -[R]\{w\}. \tag{B-2}$$

Similarly, the Energy Equation (A-8) may be written as

$$\begin{aligned}\left\{m\frac{dh}{dx}\right\} = \{q'\} &- [R][[h_I]-[h_J]]\{w'\} \\ &- [R][[t_I]-[t_J]]\{e\} \\ &+ [R][[h_I]-[h^*]]\{w\}\end{aligned} \tag{B-3}$$

where the elements of the (K X K) diagonal matrices $[h_I]$ and $[h_J]$ are given by $h_{i(k)}$ and $h_{j(k)}$, respectively. The temperature matrixes are defined similarly. The element of the (K X K) diagonal matrix [h*] are selected from $[h_I]$ or $[h_J]$ depending upon the sign of the diversion crossflow.

Equation (B-3) can be reduced to the more compact form

$$\left\{\frac{dh}{dx}\right\} = \{Q\} - [R][H]\{w'\} - [R][T]\{c\} + [R][H^*]\{w\} \tag{B-4}$$

where

$$\{Q\} = \left\{\frac{q'}{m}\right\} \tag{B-5}$$

$$[H] = [m_I]^{-1}[[h_I]-[h_J]] \tag{B-6}$$

$$[I^*] = [m_I]^{-1}[[h_I]-[h^*] \tag{B-7}$$

$$[T] = [m_I]^{-1}[[t_I]-[t_J]] \tag{B-8}$$

In a similar way the Axial Momentum Equation (A-16) may be written in the compact form

$$\left\{\frac{dp}{dx}\right\} = a \quad - [R][U]\{f_T w'\} + [R][U^*]\{w\} \tag{B-9}$$

where

$$\{a\} = \frac{1}{g_c}\left\{\left(\frac{m}{A}\right)^2\left[\frac{vf\phi}{2D} + \frac{Kv'}{2} + A\frac{d(v/A)}{dx}\right]\right\} + \left\{\rho\cos\theta\right\} \quad \text{(B-10)}$$

$$[U] = \frac{1}{g_c}[A_I]^{-1}[[u_I]-[u_J]] \quad \text{(B-11)}$$

$$[U^*] = \frac{1}{g_c}[A_I]^{-1}[[2u_I]-[u^*]] \quad \text{(B-12)}$$

The remaining equation is the Transverse Momentum Equation (A-17) which may be written as

$$\{C|w|w\} = [S]\{p\} \quad \text{(B-13)}$$

where [S] is a (K X N) matrix that orders the pressure into proper pairs for determining the crossflow for each subchannel connection.

APPENDIX C

NUMERICAL STABILITY

APPENDIX C

NUMERICAL STABILITY

Numerical stability is concerned with the propagation of errors by the numerical technique as the solution progresses with a finite step size; therefore, a stability analysis is concerned with the possible growth of errors, In other words, will an error at one step tend to increase or decrease as the solution progresses,

The stability of the numerical schemes used in COBRA-II can be investigated by examining the vector equation

$$\frac{dy}{dx} = A\,y + b \qquad \text{(C-1)}$$

where A is a square matrix of coefficients and b is a column vector of coefficients. Since both forward and backward difference approximations are used in COBRA-II, these two approximations to Equation (C-1) will be considered separately,

Forward Difference

By using a forward difference, Equation (C-1) may be written as

$$y(x+\Delta x) = (I+\Delta x A)\,y(x) + b \qquad \text{(C-2)}$$

where I is the identity matrix, If the solution actually obtained is $Y(x+\Delta x)$ and it contains an error $\varepsilon(x+\Delta x)$, it may be written as

$$Y(x+\Delta x) = (I+\Delta x A)\,Y(x) + b + \varepsilon(x+\Delta x) \qquad \text{(C-3)}$$

If A and b are assumed constant and the error is bounded by $|\varepsilon(x+\Delta x)|<\delta$, an equation for determining an upper bound on the propagation of this error is

$$w(x+\Delta x) = (I+\Delta x A)\, w(x) + \delta \qquad (C-4)$$

where $w = Y-y$. The solution of this equation may be examined by assuming a solution of the form $w(x) = C\lambda^n$ where $n = x/\Delta x$. This gives

$$C\lambda^{n+1} = (I+\Delta x A)C\lambda^n + \delta \qquad (C-5)$$

or, for the homogeneous equation,

$$(I+\Delta x A - \lambda)C\lambda^n = 0. \qquad (C-6)$$

Thus the roots of the determinant

$$|I+\Delta x A - \lambda| = 0 \qquad (C-7)$$

give the values of λ which are the eigenvalues of $I+\Delta x A$. The eigenvector C can be evaluated in terms of the error bound δ. The eigenvalues of $(I+\Delta x A)$ must all be less than one to prevent the growth of $C\lambda^n$ and insure stability, If the eigenvalues of $(I+\Delta x A)$ are of mixed sign, then the largest in absolute value controls the growth of errors, An estimate of the maximum eigenvalue can be obtained by taking norms of Equation (C-6). The result is

$$|\lambda|_{max} < 1+\Delta x \|A\|. \qquad (C-8)$$

This bound does not indicate when stability occurs, but it does indicate how bad instability can be, If $\Delta x\|A\|$ is small as compared to unity, then the error growth can not be very fast,

The forward difference approximation is only used for the energy equation in **COBRA-11**, For this equation, the value of $\|A\|$ is rather small,

This can be seen by using the infinity norm (maximum-row-sum)

$$\|A\|_\infty = \max_i \sum_j |a_{ij}| \qquad (C\text{-}9)$$

where a_{ij} are multiples of $|(w_{ij}-w^{\ell}_{ij})/m_I|$, For most cases, these are significantly less than one, Also, since there are only a few such quantities for even large problems and $\Delta x \ll 1, |\lambda|_{max}$ is only a little greater than one, It could actually be less than one, Thus the error growth in the solution of the Energy Equation should not be excessive,

The reason a forward difference is not suitable for the Momentum Equation is easily seen in the above criterion, Note that for a forward difference in Equation (7), $(I+\Delta xA)$ is equivalent to $(I+\Delta x(C|w|)^{-1}SRU^*)$ which has very large eigenvalues. Since the value of C^{-1} is very large as compared to any reasonable Δx, the forward difference is not suitable for solving the momentum equations,

Backward Difference

By using a backward difference, Equation (C-1) may be approximated by

$$y(x+\Delta w) = (I-\Delta xA)^{-1}y(x) + (I-\Delta xA)^{-1}b \qquad (C\text{-}10)$$

and the error equation may be written as

$$w(x+\Delta x) = (I-\Delta xA)^{-1}w(x) + \delta \qquad (C\text{-}11)$$

as in the case of the forward difference a stable solution is obtained if the eigenvalues of $(I-\Delta xA)^{-1}$ are less than unity, To satisfy this, it is necessary that the eigenvalues of $(I-\Delta xA)$ be greater than unity, Furthermore, since the condition number is given by Cond $(I-\Delta xA) = \|(I-\Delta xA)\| \|(I-\Delta xA)^{-1}\| > 1$, it is necessary that $\|(I-\Delta xA)\| \blacksquare$ Cond $(I-\Delta xA)$, Since the condition number can be quite large for a linear system, the eigenvalues of $(I-\Delta xA)$ may have

to be quite large to insure a stable solution, This can be achieved by selecting a sufficiently large Δx. Unfortunately, there is no easy way to select the minimum allowable Δx because the condition number is not readily available during computation,

A backward difference is used to solve Equation (7). In this case the matrix $(I - \Delta x A)$ is equivalent to $(I - \Delta x(C|w|)^{-1} SRU^*)$. For most rod bundles, C^{-1} is large; therefore, if Δx is large enough, stable solutions can be obtained,

As an example of what is required to insure stability, consider the case of two subchannels In this ease, the eigenvalue of the inverse is simply

$$\lambda = \frac{1}{1 - \frac{\Delta x SRU^*}{C|w|}} . \qquad (C-12)$$

For $\Delta x \blacksquare 2\ C|w|/SRU^*)$ the solution is stable, As Δx approaches $C|w|/(SRU^*)$ the errors grow and when $\Delta x = C|w|/(SRU^*)$, the solution blows up, For $\Delta x < C|w|/(SKU^*)$ errors grow from flow reversals which are not physically possible,

COBRA-I1 contains two rather simple checks that test for numerical instability. As in Equation (C-12) the diagonal elements of $I - \Delta x(C|w|)^{-1} SRU^*$ are cheeked for sign, If the diagonal elements are positive, the flow solutions will blow tap, The second test checks to determine if

$$\left\| I - \Delta x(C|w|)^{-1} SRU^* \right\|_\infty < K$$

where K is a positive constant, If this test is true then the solution is unstable, Since the constant K is not known, it is set equal to its lower bound $K = 1.0$ in the present writing of COBRA-11, It should be realized that this test only checks for instability, If the constant K is not large enough, instability could also occur outside this bound, To check for this possibility,

it is suggested that the user of COBRA-I1 run several calculations at different values of AX, If errors grow for decreasing Δx then Δx is not large enough, If the errors decrease, then Δx is large enough to insure stability. This type of check is not required for all problems, but it is suggested that a sample problem be examined from a set of similar problems, It should also be noted that an error may grow locally and then diminish, This can be caused by the changing value of $(C|w|)^{-1}$. Present experience with COBRA-I1 indicates that Δx on the order of one inch easily satisfies the stability criteria for most rod bundles, This is usually small enough to get good numerical solutions,

APPENDIX D

COMPUTER PROGRAM CORRELATIONS

APPENDIX D

COMPUTER PROGRAM CORRELATIONS

To carry out a solution, empirical and semiempirical correlations must be selected for input to the computer program, The following correlations are an example of what is available,

Friction Factor

The friction factor correlation is assumed to be of the form[8]

$$f_i = a(R_{e_i})^b + c \qquad (D\text{-}1)$$

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]

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

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

$$t_{wall} = t_{bulk} + \frac{q''}{P_h h}. \qquad (D\text{-}3)$$

The heat transfer coefficient is calculated from

$$\frac{hD}{\Pi} = 0.023\left(\frac{GD}{\mu}\right)^{0.8}\left(\frac{C_p \mu}{k}\right)^{0.4} \qquad (D\text{-}4)$$

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

$$\phi = 1.0 \qquad X \leq 0.$$

$$\phi = \frac{\rho_f}{\bar{\rho}} \qquad X > 0. \tag{D-5}$$

Armand[10]

$$\phi = 1.0 \qquad \alpha \leq 0$$

$$\phi = \frac{(1-X)^2}{(1-\alpha)^{1.42}} \qquad 0.39 < (1-\alpha) \leq 1.0$$

$$\phi = 0.478\,\frac{(1-X)^2}{(1-\alpha)^{2.2}} \qquad 0.1 < (1-\alpha) \leq 0.39$$

$$\phi = 1.730\,\frac{(1-X)^2}{(1-\alpha)^{1.64}} \qquad 0. < (1-\alpha) \leq 0.1 \tag{D-6}$$

Polynomial Function

$$\phi = 1.0 \qquad X \leq 0$$

$$\phi = a_o + a_1 X + a_2 X^2 + \ldots a_n X^n \qquad X > 0 \tag{D-7}$$

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

$$\Delta P = \frac{K}{2g_c}\left(\frac{m}{A}\right)^2 \qquad (D\text{-}8)$$

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,

$$K_i = \frac{K}{\Delta x} . \qquad (D\text{-}9)$$

This is the coefficient used in Equation (A-15).

Void Fraction

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

Homogeneous Model

$$\begin{aligned} \alpha &= 0. && X \le 0. \\ \alpha &= \frac{Xv_g}{(1-X)v_f + Xv_g} && X > 0. \end{aligned} \qquad (D\text{-}10)$$

Slip Model

$$\begin{aligned} \alpha &= 0. && X \le 0. \\ \alpha &= \frac{Xv_g}{(1-X)v_f\gamma + Xv_g} && X > 0. \end{aligned} \qquad (D\text{-}11)$$

where γ is a specified slip ratio.

Modified Armand[11]

$$\begin{aligned} \alpha &= 0. && X \le 0. \\ \alpha &= \frac{(0.833+0.167X)Xv_g}{(1-X)v_f + Xv_g} && X > 0. \end{aligned} \qquad (D\text{-}12)$$

Polynomial Function

$$\alpha = 0. \qquad X < 0.$$
$$\alpha = a_o + a_1X + a_2X^2 + \ldots a_nX_n \qquad X > 0. \tag{D-13}$$

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. Levy's model calculates the true quality in terms of the equilibrium quality in terms of the quality at which bubble departure starts. It is given by

$$X = 0. \qquad X_e < X_d$$
$$X = X_e - X_d \exp\left(\frac{X_e}{X_d} - 1\right) \qquad X_e/X_d < 1 \tag{D-14}$$

where X_e is the equilibrium quality and

$$X_d = -\frac{C_p \Delta t}{h_{fg}} \tag{D-15}$$

$$\Delta t = \frac{q'}{P_h h} - QP_rY_B \qquad 0 < Y_B \leq 5$$
$$\Delta t = \frac{q'}{P_h h} - 5Q(P_r + \log(1+P_r(2Y_B-1))) \qquad 5 < Y_B \leq 30$$
$$\Delta t = \frac{q'}{P_h h} - 5Q(P_r + \log(1+5P_r) + \frac{1}{2}\log\left(\frac{Y_B}{30}\right)) \qquad 30 < Y_B \tag{D-16}$$

$$Q = \frac{q'}{P_h v C_p}\sqrt{\tau_w g_c v} \tag{D-17}$$

$$\tau_w = \frac{fv}{8g_c}\left(\frac{m}{A}\right)^2 \tag{D-18}$$

$$Y_B = \frac{0.015}{\mu}\sqrt{\frac{\sigma g_c D}{v}} \tag{D-19}$$

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

Single-Phase Turbulent Mixing

Several forms of equations for specifying the turbulent crossflow are included. Although they specify the turbulent mixing parameter β, the final result is the turbulent crossflow rate given by

$$w'_{ij} = \beta_{ij} s_{ij} \frac{m_i + m_j}{A_i + A_j} \tag{D-20}$$

The presently available forms in COBRA-I1 for calculating β include:

$$\beta_{ij} = a \tag{D-21}$$

$$\beta_{ij} = a\, Re^b \tag{D-22}$$

$$\beta_{ij} = \frac{4}{s_{ij}} \frac{A_i + A_j}{P_{w_i} + P_{w_i}}\, a\, Re^b \tag{D-23}$$

$$\beta_{ij} = \frac{4}{z_{ij}} \frac{A_i + A''_j}{P_{w_i} + P_{w_j}}\, a\, Re^b \tag{D-24}$$

where $Re = \dfrac{8(m_i+m_j)}{(P_{w_i}+P_{w_j})(\mu_i+\mu_j)}$ (D-25)

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

$$c_{ij} = \left(\frac{k_i + k_j}{2}\right) \frac{s_{ij}}{z_{ij}} K_g \qquad \text{(D-26)}$$

where K_g is a geometric correction factor. Note that the distance z_{ij} is used in both Equations (D-24) and (D-26). This is the centroid-to-centroid distance between subchannels, Care should be taken to select this value for its intended use, For example, z_{ij} could be selected as the effective mixing 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-II 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,

Iransverse Crossflow Resistance

To obtain an estimate of the transverse crossflow resistance, a simple friction model, is used, If the gap is assumed to be a slot of spacing s and a wide, the resistance coefficient is

$$C_{ij} = \frac{f\ell}{4g_c s^3_{ij} \rho_i} \qquad \text{(D-27)}$$

where f is a selected friction factor, The product $f\ell$ is an arbitrary constant that is input to the problem. The density ρ_i is taken in lieu of a two-phase friction multiplier for the transverse two-phase flow,

Power Distribution

The heat input per unit length of channel is the sum of all such inputs from fuel rods adjacent to the subchannel. The heat transfer (q'_{ri}) from a rod (r) to a subchannel (i) is given by

$$q'_{ri} = \bar{q}'' D_r f_c f_R f_A(x/L) \tag{D-28}$$

where $$\int_0^1 f_A(x/L)\,d(x/L) \equiv 1. \tag{D-29}$$

The sum of the heat inputs from rods adjacent to Subchannel (i) is the total heat input per unit length (q_i).

APPENDIX E

SAMPLE PROBLEM

APPENDIX E

DIGITAL COMPUTER PROGRAM SAMPLE PROBLEM

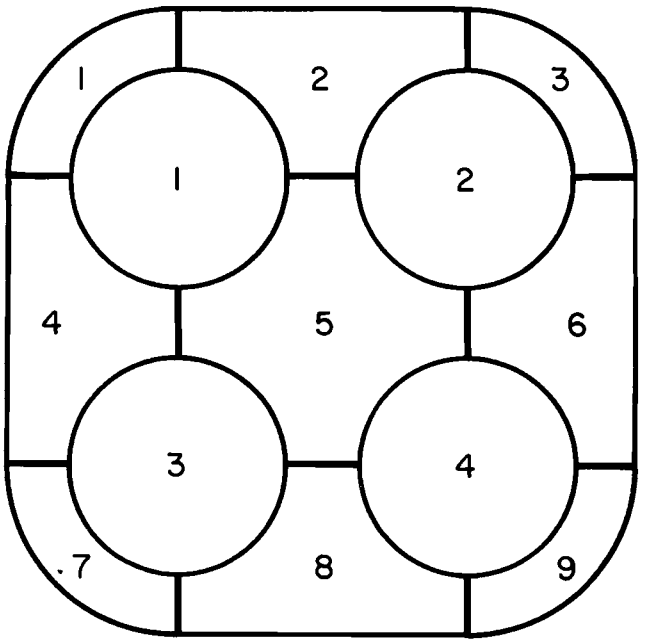
A 4-rod bundle is used for the sample problem to show the input for COBRA-11, The subchannel and fuel rod numbering scheme is shown in the sketch and the nominal dimensions of the three types of subchannels are given in the table, The axial power distribution is assumed to be uniform. The radial power distribution is skewed with relative powers of 1.2, 1.0, 1.0 and 0.8 in Rods 1,2,3 and 4, respectively, The operating conditions are: 1000 psia, 0.4 x 10^6 Btu/hr ft^2 heat flux, 1.0 x 10^6 lb/hr-ft^2 mass velocity and 500 Btu/lb inlet enthalpy,

Several of the new features of COBRA are illustrated by the input, The outer wall subchannels are designated as Type 1 and are given a higher friction factor than the interior subchannel designed as Type 2, A blockage is assumed to occur in Subchannel 1 that reduces the flow area and gap spacing at x/L = 0.2. Two types of spacers are considered, Type 1 simulates the inlet and exit pressure losses and Type 2 simulates losses of 3 grid spacers, These spacers have flow diverters that divert flow into Subchannel 5 from Subchannels 2 and 8, The loss coefficients of the diverters are also assumed to be greater, The mixing parameter β is assumed to be constant for single-phase flow and a function of quality for two-phase flow, Output options are selected to print the exit summary, crossflows and complete answers for Subchannels 1,4 and 5,

SUBCHANNEL DIMENSIONS(a)

Subchannels	Area (in,^{2})	Wetted Perimeter (in,)	Heater Perimeter (in.)
1,3,7,9	0.0783	1.116	0.4476
2,4,6,8	0.1824	1.633	0.8954
5	0.2894	1.791	1.791

(a) Rod-to-rod spacing 0,168 in,; Rod-to-wall spacing 0,135 in, Rod diameter 0,570 in,; Length 72.0 in,



Page E-3 contains a complete listing of the input data for the sample problem. Pages E-4 through E-8 contain the computer input for the sample problem.

```
1
    1   30SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.
  50.281.0  0.017274     8.5140      250.2     1174.1      0.491     0.3959  0.003012
 100.327.8  0.017740     4.4310      298.5     1187.2      0.410     0.3936  0.002606
 150.358.4  0.01809      3.0139      330.6     1194.1      0.369     0.3893  0.002350
 200.381.8  0.01839      2.2873      355.5     1198.3      0.345     0.3852  0.00209
 250.401.0  0.01865      1.8432      376.1     1201.1      0.326     0.3806  0.00193
 300.417.4  0.01889      1.5427      394.0     1202.9      0.313     0.3760  0.00180
 350.431.7  0.01912      1.3255      409.8     1204.0      0.301     0.3718  0.00168
 400.444.6  0.01934      1.1610      424.2     1204.6      0.290     0.3682  0.00158
 440.454.0  0.01950      1.0554      434.8     1204.8      0.283     0.3658  0.00150
 480.462.8  0.01967      0.9668      444.7     1204.8      0.278     0.3631  0.00144
 520.471.1  0.01982     0.89137      454.2     1204.5      0.273     0.3604  0.00138
 560.478.8  0.01988     0.82637      463.1     1204.2      0.269     0.3580  0.00132
 600.486.2  0.02013     0.76975      471.7     1203.7      0.264     0.3550  0.00127
 640.493.2  0.02028     0.71995      479.9     1203.0      0.260     0.3552  0.00122
 680.499.9  0.02043     0.67581      487.7     1202.3      0.255     0.3494  0.00117
 720.506.2  0.02058     0.63639      495.4     1201.4      0.252     0.3462  0.00113
 760.512.3  0.02072     0.60097      502.7     1200.4      0.248     0.3435  0.00108
 800.518.2  0.02087     0.56896      509.8     1199.4      0.245     0.3405  0.00104
 840.523.9  0.02101     0.53988      516.7     1198.2      0.242     0.3377  0.00100
 880.529.3  0.02116     0.51333      523.4     1197.0      0.240     0.3350  0.00096
 920.534.6  0.02130     0.48901      530.0     1195.7      0.237     0.3325  0.00092
 960.539.7  0.02145     0.46662      536.3     1194.4      0.234     0.3299  0.00089
1000.544.6  0.02159     0.44596      542.4     1192.9      0.232     0.3275  0.00086
1040.549.4  0.02174     0.42681      548.6     1191.4      0.229     0.3243  0.00082
1080.554.0  0.02188     0.40902      554.6     1189.9      0.227     0.3224  0.00079
1120.558.5  0.02203     0.39244      560.5     1188.2      0.225     0.3198  0.00076
1160.562.9  0.02217     0.37695      566.2     1186.6      0.223     0.3174  0.00073
1200.567.2  0.02232     0.36245      571.9     1184.8      0.221     0.3140  0.00070
1240.571.4  0.02247     0.34884      577.4     1183.0      0.219     0.3113  0.00068
1280.575.4  0.02262     0.33603      582.9     1181.2      0.217     0.3086  0.00065
    2    1     0    0
 .316 -.25    0. .400 -.25   0.
    3    2
   0.   1.    1.   1.
    4    9    9
2   1.07831.116.4476     2 .135          4 .135
2   2.18241.633.8954     3 .135          5 .168
2   3.07831.116.4476     6 .135
2   4.18241.633.8954     5 .168          7 .135
1   5.28941.7911.791     6 .168          8 .168
2   6.18241.633.8954     9 .135
2   7.07831.116.4476     8 .135
2   8.18241.633.8954     9 .135
2   9.07831.116.4476
    5    1    5
   0.   .1   .2   .3   1.
    1
   1.   1.   .5   1.   1.
    6    2    5
   0.   .1   .2   .3   1.
    1    2
   1.   1.   .5   1.   1.
    1    4
   1.   1.   .5   1.   1.
    7    2    5    2
.0001    1  .25    2  .5    2  .75    2   1.    1
    1  .3   0.    0
    2  .3   0.    0
    3  .3   0.    0
    4  .3   0.    0
    5  .3   0.    0
    6  .3   0.    0
    7  .3   0.    0
    8  .3   0.    0
    9  .3   0.    0
    1  .2   0.    0
    2  .4   .3    5
    3  .2   0.    0
    4  .2   0.    0
    5  .2   0.    0
    6  .2   0.    0
    7  .2   0.    0
    8  .4   .3    5
    9  .2   0.    0
    8    4    4
    1 .570  1.2    1  .25    2  .25    4  .25    5  .25
    2 .570  1.0    2  .25    3  .25    5  .25    6  .25
    3 .570  1.0    4  .25    5  .25    7  .25    8  .25
    4 .570   .8    5  .25    6  .25    8  .25    9  .25
    9
 .001   1.  72.   0.   25    6
   10    0    5    0
 .01
   0.  .01  .05  .06   .1  .06  .25  .02   .6  .01
   11    0    0
     1000.      500.        1.        .4
   12    1    3
1 4 5
    0
    0
```

INPUT FOR CASE 1 SAMPLE PROBLEM FOR COBRA TC ILLUSTRATE INPUT.

FLUID PROPERTY TABLE

P	T	VF	VG	HF	HG	VISC.	KF	SIGMA
20.0	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	356.40	.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	1.16160	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	.96080	444.70	1204.80	.27800	.36310	.00144
520.0	471.10	.01982	.89157	454.20	1204.50	.27300	.36040	.00138
560.0	478.80	.01998	.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	.67561	487.70	1202.30	.25500	.34940	.00117
720.0	506.20	.02056	.63639	495.40	1201.40	.25200	.34620	.00113
760.0	512.30	.02072	.60097	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

FRICTION FACTOR CORRELATION
CHANNEL TYPE 1 FRICT = .316*RE**(-.250) + .0000
CHANNEL TYPE 2 FRICT = .400*RE**(-.250) + .0000

TWO-PHASE FLOW CORRELATIONS
LEVY 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. 1 (IN)	HEATED PERIM. (IN)	HYDRAULIC DIAMETER (IN)	(ADJACENT CHANNEL NO., SPACING, CENTROID DISTANCE)
1	2	.078300	1.116000	.447600	.280645	(2, .135,-.000)(4, .135,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
2	2	.182400	1.633000	.895400	.446785	(3, .135,-.000)(5, .168,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
3	2	.078300	1.116000	.447600	.280645	(6, .135,-.000)(-0,-.000,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
4	2	.182400	1.633000	.895400	.446785	(5, .168,-.000)(7, .135,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
5	1	.289400	1.791000	1.791000	.646543	(6, .168,-.000)(8, .168,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
6	2	.182400	1.633000	.895400	.446785	(9, .135,-.000)(-0,-.000,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
7	2	.078300	1.116000	.447600	.280645	(8, .135,-.000)(-0,-.000,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
8	2	.182400	1.633000	.895400	.446785	(9, .135,-.000)(-0,-.000,-.000)(-0,-.000,-.000)(-0,-.000,-.000)
9	2	.078300	1.116000	.447600	.280645	(-0,-.000,-.000)(-0,-.000,-.000)(-0,-.000,-.000)(-0,-.000,-.000)

X/L AREA VARIATION FACTORS FOR SUBCHANNEL (I)

	(1)
.000	1.000
.100	1.000
.200	.500
.300	1.000
1.000	1.000

X/L GAP SPACING VARIATION FACTORS FOR ADJACENT SUBCHANNELS (I,J)

	(1, 2)	(1, 4)
.000	1.000	1.000
.100	1.000	1.000
.200	.500	.500
.300	1.000	1.000
1.000	1.000	1.000

SPACER DATA
SPACER TYPE NO. 1 2 2 2 1
LOCATION (X/L) .000 .250 .500 .750 1.000

SPACER TYPE 1

CHANNEL NO.	DRAG COEFF.	FRACTION OF FLOW DIVERTED	CHANNEL DIVERTED TO
1	.3000	.0000	0
2	.3000	.0000	0
3	.3000	.0000	0
4	.3000	.0000	0
5	.3000	.0000	0
6	.3000	.0000	0
7	.3000	.0000	0
8	.3000	.0000	0
9	.3000	.0000	0

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   SPACER TYPE 2
      CHANNEL    DRAG     FRACTION OF      CHANNEL
        NO.     COEFF.  FLOW DIVERTED  DIVERTED TO
         1      .2000       .0000           0
         2      .4000       .3000           5
         5      .2000       .0000           0
         4      .2000       .0000           0
         5      .2000       .0000           0
         6      .2000       .0000           0
         7      .2000       .0000           0
         8      .4000       .3000           5
         3      .2000       .0000           0

ROD INPUT DATA
  ROD  DIAMETER   RADIAL POWER     FRACTION OF POWER TO ADJACENT CHANNELS (ADJ. CHANNEL NO.)
  NO.    (IN)       FACTOR
   1    .5700       1.2000      .2500( 1)   .2500( 2)   .2500( 4)   .2500( 5)   -.0000(-0)   -.0000(-0)
   2    .5700       1.0000      .2500( 2)   .2500( 3)   .2500( 5)   .2500( 6)   -.0000(-0)   -.0000(-0)
   3    .5700       1.0000      .2500( 4)   .2500( 5)   .2500( 7)   .2500( 8)   -.0000(-0)   -.0000(-0)
   4    .5700        .8000      .2500( 5)   .2500( 6)   .2500( 8)   .2500( 9)   -.0000(-0)   -.0000(-0)

CALCULATION PARAMETERS
  TRANSV. FRICTION (FT.)       .0010
  MOMENTUM TURBULENT FACTOR   1.0000
  CHANNEL LENGTH              72.00 INCHES
  CHANNEL ORIENTATION           .0 DEGREES
  DIVISION FOR PRINT-OUT       25
  CALCULATION SUBDIVISION       6
  CALCULATION INCREMENT         .500 INCHES

MIXING CORRELATIONS
   SUBCOOLED MIXING,   BETA =  .0100
   CONDUCTION MIXING,  GEOMETRY FACTOR =  .0000
   BOILING MIXING, BETA IS A FUNCTION OF STEAM QUALITY
        X        BETA(X)
      .000       .010000
      .050       .060000
      .100       .080000
      .250       .020000
      .600       .010000

OPERATING CONDITIONS
  SYSTEM PRESSURE     =    1000.0 PSIA
  INLET ENTHALPY      =     500.0 BTU/LM
  AVG. MASS VELOCITY  =     1.000 MILLION LB/(HR-SQFT)
  INLET TEMPERATURE   =     510.0 DEGREES F
  AVG. HEAT FLUX      =      .400 MILLION BTU/(HR-SQFT)

INITIAL CHANNEL CONDITIONS
   UNIFORM INLET ENTHALPY SPECIFIED
   UNIFORM MASS VELOCITY


BUNDLE AVERAGED RESULTS

CASE    1     SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.


DISTANCE  DELTA-P   ENTHALPY    TEMP.    QUALITY   MASS VEL  AVG FLUX  MAX FLUX
  (IN.)    (PSI)   (BTU/LB)  (DEG-F)             (M-LB/HR-FT2)    (M-BTU/HR-FT2)
  3.00     -.177     506.45    515.42    .0057     1.0000     .4000     .4800
  6.00     -.301     512.90    520.76    .0093     1.0000     .4000     .4800
  9.00     -.428     519.36    526.04    .0137     1.0074     .4000     .4800
 12.00     -.557     525.80    531.23    .0184     1.0200     .4000     .4800
 15.00     -.687     532.27    536.44    .0233     1.0277     .4000     .4800
 18.00     -.820     538.72    541.65    .0287     1.0149     .4000     .4800
 21.00    -1.024     545.17    544.60    .0342     1.0025     .4000     .4800
 24.00    -1.159     551.62    544.60    .0407     1.0000     .4000     .4800
 27.00    -1.295     558.07    544.60    .0478     1.0000     .4000     .4800
 30.00    -1.443     564.52    544.60    .0552     1.0000     .4000     .4800
 33.00    -1.589     570.97    544.60    .0629     1.0000     .4000     .4800
 36.00    -1.739     577.42    544.60    .0709     1.0000     .4000     .4800
 39.00    -2.001     583.86    544.60    .0789     1.0000     .4000     .4800
 42.00    -2.159     590.33    544.60    .0874     1.0000     .4000     .4800
 45.00    -2.320     596.78    544.60    .0960     1.0000     .4000     .4800
 48.00    -2.484     603.23    544.60    .1047     1.0000     .4000     .4800
 51.00    -2.652     609.68    544.60    .1135     1.0000     .4000     .4800
 54.00    -2.824     616.14    544.60    .1225     1.0000     .4000     .4800
 57.00    -3.155     622.59    544.60    .1314     1.0000     .4000     .4800
 60.00    -3.335     629.04    544.60    .1406     1.0000     .4000     .4800
 63.00    -3.519     635.49    544.60    .1498     1.0000     .4000     .4800
 66.00    -3.707     641.94    544.60    .1591     1.0000     .4000     .4800
 69.00    -3.899     648.40    544.60    .1684     1.0000     .4000     .4800
 72.00    -4.095     654.85    544.60    .1778     1.0000     .4000     .4800

CHANNEL RESULTS

CASE    1     SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.
SUMMARY OF RESULTS, EXIT CONDITIONS

 CHANNEL  DELTA-P   ENTHALPY  DELTA-H    TEMP.    DELTA-T   QUALITY   MASS VEL     FLOW
           (PSI)   (BTU/LB)  (BTU/LB)  (DEG-F)   (DEG-F)             (M-LB/HR-FT2) (LB/HR)
    1    -4.095     603.45    103.45    544.60     34.56     .1861      .9062     492.76
    2    -4.096     658.35    158.35    544.60     34.56     .1870      .9706    1229.46
    3    -4.095     655.81    155.81    544.60     34.56     .1783      .9278     504.50
    4    -4.095     656.18    156.18    544.60     34.56     .1869      .9746    1234.50
    5    -4.095     655.56    155.56    544.60     34.56     .1764     1.0813    2173.16
    6    -4.095     646.92    149.92    544.60     34.56     .1695     1.0267    1300.54
    7    -4.096     656.21    156.21    544.60     34.56     .1807      .9217     501.17
    8    -4.096     650.31    150.31    544.60     34.56     .1717     1.0170    1288.21
    9    -4.095     648.85    148.85    544.60     34.56     .1655      .9694     527.09
  AVG    -4.095     654.85    154.85    544.60     34.56     .1778     1.0000    9251.39
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CHANNEL RESULTS

CASE 1 SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.
CHANNEL 1

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMP. (DEG-F)	QUALITY	MASS VEL (M-LB/HR-FT2)	FLOW (LB/HR)	FLUX (M-BTU/HR-FT2)
.00	.000	500.00	510.04	.0061	1.0000	543.75	.4801
3.00	-.177	508.40	517.04	.0125	.9178	999.07	.4801
6.00	-.301	516.97	524.12	.0204	.8665	471.17	.4801
9.00	-.428	525.19	530.74	.0235	.9875	469.82	.4801
12.00	-.557	533.34	537.31	.0241	1.1812	428.17	.4801
15.00	-.686	542.74	544.60	.0238	1.2047	354.82	.4801
18.00	-.820	550.39	544.60	.0172	.9893	403.44	.4801
21.00	-1.024	553.31	544.60	.0187	.9863	513.98	.4801
24.00	-1.160	559.17	544.60	.0275	1.0065	547.30	.4801
27.00	-1.299	565.16	544.60	.0366	1.0114	555.39	.4801
30.00	-1.443	571.34	544.60	.0455	1.0188	553.96	.4801
33.00	-1.589	577.69	544.60	.0548	1.0086	548.41	.4801
36.00	-1.739	584.15	544.60	.0643	.9960	541.59	.4801
39.00	-2.001	589.65	544.60	.0729	1.0104	549.41	.4801
42.00	-2.159	596.28	544.60	.0829	.9859	536.11	.4801
45.00	-2.320	602.93	544.60	.0931	.9712	528.08	.4801
48.00	-2.484	609.61	544.60	.1033	.9597	521.83	.4801
51.00	-2.652	616.32	544.60	.1136	.9500	516.58	.4801
54.00	-2.824	623.05	544.60	.1240	.9417	512.03	.4801
57.00	-3.154	628.62	544.60	.1325	.9601	512.05	.4801
60.00	-3.335	635.58	544.60	.1432	.9404	511.35	.4801
63.00	-3.519	642.54	544.60	.1539	.9287	504.98	.4801
66.00	-3.707	649.56	544.60	.1646	.9200	500.26	.4801
69.00	-3.899	656.46	544.60	.1753	.9128	496.32	.4801
72.00	-4.095	663.45	544.60	.1861	.9062	492.76	.4801

CHANNEL RESULTS

CASE 1 SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.
CHANNEL 4

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMP. (DEG-F)	QUALITY	MASS VEL (M-LB/HR-FT2)	FLOW (LB/HR)	FLUX (M-BTU/HR-FT2)
.00	.000	500.00	510.04	.0059	1.0000	1266.67	.4400
3.00	-.177	506.61	515.55	.0099	.9808	1242.36	.4400
6.00	-.301	513.45	521.22	.0148	.9707	1229.51	.4400
9.00	-.426	520.48	526.94	.0209	.9579	1213.36	.4400
12.00	-.557	527.66	532.67	.0268	.9648	1222.11	.4400
15.00	-.687	534.76	538.45	.0327	.9768	1237.27	.4400
18.00	-.820	541.72	544.05	.0403	.9507	1204.28	.4400
21.00	-1.024	547.94	544.60	.0459	.9457	1197.85	.4400
24.00	-1.159	554.83	544.60	.0522	.9338	1182.87	.4400
27.00	-1.299	561.58	544.60	.0592	.9301	1178.13	.4400
30.00	-1.443	568.16	544.60	.0666	.9309	1179.16	.4400
33.00	-1.589	574.65	544.60	.0744	.9337	1182.66	.4400
36.00	-1.739	581.10	544.60	.0823	.9372	1187.14	.4400
39.00	-2.001	586.67	544.60	.0902	.9550	1209.68	.4400
42.00	-2.159	593.28	544.60	.0984	.9539	1208.31	.4400
45.00	-2.320	599.82	544.60	.1067	.9541	1208.53	.4400
48.00	-2.484	606.34	544.60	.1152	.9556	1210.38	.4400
51.00	-2.652	612.80	544.60	.1239	.9576	1212.98	.4400
54.00	-2.824	619.36	544.60	.1327	.9599	1215.87	.4400
57.00	-3.155	625.10	544.60	.1413	.9792	1240.32	.4400
60.00	-3.335	631.70	544.60	.1501	.9764	1236.72	.4400
63.00	-3.519	638.32	544.60	.1591	.9746	1234.54	.4400
66.00	-3.707	644.94	544.60	.1683	.9740	1233.73	.4400
69.00	-3.899	651.56	544.60	.1775	.9741	1233.84	.4400
72.00	-4.095	658.18	544.60	.1869	.9746	1234.50	.4400

CHANNEL RESULTS

CASE 1 SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.
CHANNEL 5

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMP. (DEG-F)	QUALITY	MASS VEL (M-LB/HR-FT2)	FLOW (LB/HR)	FLUX (M-BTU/HR-FT2)
.00	.000	500.00	510.04	.0007	1.0000	2009.72	.3999
3.00	-.177	507.19	516.03	.0025	1.0513	2112.87	.3999
6.00	-.301	515.97	521.65	.0054	1.0835	2177.58	.3999
9.00	-.428	520.55	526.98	.0095	1.0980	2206.68	.3999
12.00	-.557	526.9~	532.13	.0141	1.1111	2232.94	.3999
15.00	-.687	533.24	537.22	.0191	1.1215	2253.84	.3999
18.00	-.820	539.50	542.27	.0251	1.1199	2250.63	.3999
21.00	-1.024	545.36	544.60	.0310	1.1029	2216.54	.3999
24.00	-1.155	551.96	544.60	.0375	1.0986	2207.81	.3999
27.00	-1.299	538.51	544.60	.0445	1.0941	2198.90	.3999
30.00	-1.443	565.01	544.60	.0518	1.0900	2190.69	.3999
33.00	-1.589	571.48	544.60	.0594	1.0870	2184.61	.3999
36.00	-1.739	577.96	544.60	.0674	1.0846	2179.77	.3999
39.00	-2.001	584.26	544.60	.0752	1.0774	2165.36	.3999
42.00	-2.159	590.85	544.60	.0839	1.0773	2165.03	.3999
45.00	-2.320	597.36	544.60	.0927	1.0770	2164.51	.3999
48.00	-2.484	603.84	544.60	.1015	1.0766	2163.60	.3999
51.00	-2.652	610.31	544.60	.1106	1.0763	2163.13	.3999
54.00	-2.824	616.77	544.60	.1197	1.0763	2163.10	.3999
57.00	-3.155	623.02	544.60	.1284	1.0696	2149.62	.3999
60.00	-3.335	bLY.65	544.60	.1381	1.0721	2154.68	.3999
63.00	-3.519	636.16	544.60	.1476	1.0746	2159.69	.3999
66.00	-3.707	642.65	544.60	.1572	1.0769	2164.27	.3999
69.00	-3.899	649.12	544.60	.1668	1.0791	2168.67	.3999
72.00	-4.095	655.56	544.60	.1764	1.0813	2173.16	.3999

DIVERSION(W) AND TURBULENT(WP) CROSSFLOW BETWEEN ADJACENT SUBCHANNELS (I,J)

CASE 1 SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.

DISTANCE	W(1, 2)	WP(1, 2)	W(1, 4)	WP(1, 4)	W(2, 3)	WP(2, 3)	W(2, 5)	WP(2, 5)	W(3, 6)	WP(3, 6)
.00	.0	179.6	.0	179.6	.0	166.6	.0	177.6	.0	134.8
3.00	77.5	224.8	77.5	224.8	-6.7	205.5	132.9	218.3	87.2	161.0
6.00	42.6	279.0	42.6	279.0	-4.1	254.0	87.5	272.8	41.7	196.0
9.00	.4	300.9	.4	300.9	-4.2	314.2	39.7	344.1	21.8	239.3
12.00	138.0	275.7	138.0	275.7	24.9	377.1	61.3	421.6	16.6	291.6
15.00	-125.6	252.0	-125.6	252.0	-14.9	444.9	-32.2	506.5	-9.5	348.1
18.00	-159.4	360.2	-159.4	360.2	1.9	513.6	-5.7	597.5	-1.5	409.7
21.00	-67.6	465.2	-112.4	492.1	-92.2	539.3	-133.6	656.3	-28.3	484.0
24.00	-29.4	568.8	-40.1	584.7	-18.8	609.8	-22.1	752.6	3.4	547.2
27.00	-3.1	640.3	-9.2	646.2	-8.8	624.4	-18.9	854.1	-3.2	619.4
30.00	10.0	642.8	5.8	646.3	-3.8	626.7	-13.6	861.7	-5.2	680.4
33.00	13.9	643.4	11.9	645.6	-2.8	629.3	-10.0	861.9	-3.8	679.4
36.00	14.2	643.3	13.4	644.7	-2.3	631.8	-8.2	862.3	-3.4	678.9
39.00	44.2	640.2	18.9	657.0	-27.6	629.1	-20.1	853.9	6.6	685.5
42.00	26.1	642.0	15.3	651.1	-12.0	633.8	-11.3	858.6	-1.1	682.1
45.00	17.2	636.2	10.5	640.5	-7.0	627.3	-8.8	861.3	-2.9	679.9
48.00	13.3	610.3	9.9	612.7	-4.9	605.1	-6.7	838.5	-2.8	678.2
51.00	10.6	584.0	9.1	585.4	-4.5	582.0	-4.9	805.6	-1.6	651.2
54.00	9.0	557.5	8.3	558.2	-4.3	558.1	-3.6	771.9	-.9	624.1
57.00	48.2	530.5	19.4	545.2	-36.0	531.2	-19.8	731.0	12.2	602.1
60.00	23.9	504.4	9.5	513.0	-17.0	507.4	-7.5	699.5	2.4	572.2
63.00	15.4	477.0	7.0	482.8	-10.7	482.4	-3.7	666.1	1.0	543.2
66.00	11.0	450.2	6.2	453.5	-7.6	456.7	-1.2	631.7	.9	514.5
69.00	8.9	422.5	6.1	424.7	-6.1	430.4	.5	596.6	1.4	486.1
72.00	7.8	394.6	6.1	396.0	-5.4	403.7	1.8	561.0	1.9	457.8

DIVERSION(W) AND TURBULENT(WP) CROSSFLOW BETWEEN ADJACENT SUBCHANNELS (I,J)

CASE 1 SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.

DISTANCE	W(4, 5)	WP(4, 5)	W(4, 7)	WP(4, 7)	W(5, 6)	WP(5, 6)	W(5, 8)	WP(5, 8)	W(6, 9)	WP(6, 9)
.00	.0	177.6	.0	166.6	.0	155.7	.0	155.7	.0	127.4
3.00	132.9	218.3	-6.7	205.5	-42.1	187.7	-42.1	187.7	-15.6	146.9
6.00	87.5	272.8	-4.1	254.0	-23.9	232.9	-23.9	232.9	-12.4	175.1
9.00	39.7	344.1	-4.2	314.2	-9.4	292.6	-9.4	292.6	-7.3	211.0
12.00	61.3	421.6	24.9	377.1	19.9	362.8	19.9	362.8	5.9	258.8
15.00	-32.2	506.5	-14.9	444.9	-18.0	439.9	-18.0	439.9	-.7	311.3
18.00	-5.7	597.5	1.9	513.6	7.2	526.0	7.2	526.0	9.7	369.1
21.00	-16.9	675.3	-36.4	577.2	-70.0	618.3	-1.7	610.0	-23.4	450.2
24.00	2.1	763.5	.6	629.0	-9.4	709.5	24.0	709.1	5.6	514.3
27.00	-5.2	860.8	1.9	626.0	-5.1	808.5	16.4	813.4	6.3	587.7
30.00	-6.2	864.2	2.3	626.2	-4.0	898.7	11.9	888.6	5.2	668.1
33.00	-6.4	863.4	2.0	627.7	-3.0	896.3	8.4	887.9	1.1	696.3
36.00	-6.8	863.2	1.5	629.6	-2.9	894.6	5.7	887.3	-1.0	695.2
39.00	24.8	865.4	4.2	641.0	-22.0	892.7	27.0	876.0	-3.9	699.5
42.00	11.9	864.9	5.1	639.4	-14.9	891.8	15.4	880.1	.3	695.7
45.00	3.7	864.8	2.9	625.5	-10.7	890.7	8.5	882.1	-.1	693.6
48.00	-.2	840.2	1.2	602.0	-8.4	888.8	4.4	877.6	-.9	690.9
51.00	-1.8	806.5	-.2	578.3	-7.2	853.2	1.8	843.5	-2.3	674.0
54.00	-2.3	772.4	-1.1	554.1	-6.6	817.3	.1	808.9	-3.0	645.8
57.00	34.4	741.1	.1	538.6	-31.2	779.8	28.8	763.9	-8.4	620.0
60.00	19.8	705.3	2.1	510.7	-21.5	744.1	11.5	732.0	-1.3	590.1
63.00	12.2	669.7	.7	483.5	-15.8	707.9	5.0	698.4	-1.1	560.8
66.00	8.0	634.0	-.4	456.5	-12.1	671.5	1.2	663.7	-1.7	531.9
69.00	5.9	598.1	-1.4	429.5	-10.1	634.9	-1.0	628.4	-2.3	503.2
72.00	5.0	562.0	-2.1	402.4	-9.0	598.2	-2.6	592.7	-2.9	474.6

DIVERSION(W) AND TURBULENT(WP) CROSSFLOW BETWEEN ADJACENT SUBCHANNELS (I,J)

CASE 1 SAMPLE PROBLEM FOR COBRA TO ILLUSTRATE INPUT.

DISTANCE	W(7, 8)	WP(7, 8)	W(8, 9)	WP(8, 9)
.00	.0	134.8	.0	127.4
3.00	87.2	161.0	-15.6	146.9
6.00	41.7	196.0	-12.4	175.1
9.00	21.8	239.3	-7.3	211.0
12.00	16.6	291.6	5.9	258.8
15.00	-9.5	348.1	-.7	311.3
18.00	-1.5	409.7	9.7	369.1
21.00	27.8	482.4	-62.4	438.2
24.00	11.8	555.4	-13.1	513.7
27.00	3.3	634.3	-5.4	594.8
30.00	.3	661.7	-3.4	679.7
33.00	-1.3	663.3	-5.3	684.0
36.00	-2.2	664.7	-5.8	684.5
39.00	22.0	656.4	-30.9	675.2
42.00	8.6	661.5	-16.3	678.7
45.00	3.1	664.4	-10.6	680.4
48.00	.8	656.4	-7.9	681.2
51.00	.2	632.1	-7.2	660.0
54.00	.0	607.2	-6.6	633.5
57.00	32.6	571.7	-40.9	596.9
60.00	14.2	549.5	-19.0	572.6
63.00	8.3	525.2	-12.2	547.0
66.00	5.3	499.7	-8.8	520.6
69.00	4.0	473.6	-7.1	493.7
72.00	3.5	447.0	-6.2	466.5

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