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REPORT

**CROSS-FLOW MIXING BETWEEN PARALLEL
FLOW CHANNELS DURING BOILING
PART I
COBRA - COMPUTER PROGRAM
FOR COOLANT BOILING IN ROD ARRAYS**

D. S. ROWE

MARCH 1967

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By

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Reactor Engineering Section
Engineering Development Department

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ABSTRACT

This report presents a mathematical model and digital computer program for computing coolant flow and enthalpy in the subchannels of rod bundle fuel elements. One dimensional, two-phase, slip flow in the subchannels provides the basis for the mathematical model. The model also includes the effect of mixing that occurs through the gap between adjacent subchannels by using a turbulent (fluctuating) cross-flow and a diversion cross-flow that results from flow redistribution.

The digital computer program COBRA solves the mathematical equations by using numerical procedures similar to the modified Euler method, but with an additional feature to control diversion cross-flow and insure a stable solution. COBRA considers both single and two-phase flow in rod bundles of arbitrary geometry and can consider up to 36 subchannels and 25 fuel rods. Arbitrary heat flux distributions are specified by the axial flux distribution, relative rod power and fraction of rod power to each adjacent subchannel.

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CROSS-FLOW MIXING BETWEEN PARALLEL FLOW CHANNELS DURING BOILING
PART I

COBRA - COMPUTER PROGRAM FOR COOLANT BOILING IN ROD ARRAYS

D. S. Rowe

INTRODUCTION

This report presents COBRA, a digital computer program that computes flow and enthalpy in the subchannels of rod bundle nuclear fuel elements during boiling. The development of the analytical methods used in COBRA represent the first portion of a two-part study of two-phase flow and mixing in rod bundle fuel elements under the sponsorship of a cooperative program between the United States and Canada for the development of heavy water moderated power reactors. The second part of the study, to be published later, consists of laboratory experiments to verify the analytical work and supply key information that can only be obtained from experiments. The results of the total study will be a significant step toward a more accurate method for predicting the coolant conditions leading to the occurrence of boiling burnout in rod bundle nuclear fuel elements.

Accurate prediction of boiling burnout in rod bundle elements has not been possible except by using the results of laboratory tests that closely simulate the bundle geometry, power distribution, and flow conditions. One of the primary reasons for this is the difficulty in calculating the local coolant flow and enthalpy throughout the bundle. Calculating these local coolant conditions is a problem in rod bundle fuel elements for two reasons:

- First, the different sized flow channels, formed by the arrangement of fuel rods in most rod bundle designs, are such that the ratio of heat transfer surface area to flow

area is not equal for all channels; thus, causing the coolant enthalpy rise in some flow channels to be much greater than in others. This imbalance in coolant enthalpy affects the channel flow distribution, especially during boiling conditions where the pressure drop for two-phase mixtures is much greater than for liquid flow. Since the pressure drop is nearly the same in each flow channel of the rod bundle, there is an interchange of flow between channels when the gain in coolant enthalpy is not equal. This same effect can also result from nonuniform power distribution in the bundle.

- Second, local flow and enthalpy is affected by the random travel of the coolant through the gap between adjacent flow channels. This mixing effect is caused by the natural turbulent fluctuations of the coolant flow plus those fluctuations induced by mechanical devices such as rod spacers and reduces the enthalpy difference between adjacent flow channels.

The influence of the mixing phenomena is an important factor affecting flow and enthalpy in rod bundles. Knudsen⁽¹⁾ illustrated this by applying the effect of mixing to much of the world's boiling burnout data. His simplified analysis showed that the apparent differences between much of the data could be reduced significantly by including the effect of mixing to get a better estimate of the coolant enthalpy at the burnout location.

No analyses are now available to accurately predict local flow and enthalpy in rod bundle subchannels during boiling. Numerous analytical⁽²⁻⁸⁾ and experimental⁽⁹⁻¹²⁾ studies of flow and heat transfer in rod bundles have been done, but they are only concerned with single-phase flow. Several computer programs⁽¹³⁻¹⁷⁾ for multidimensional two-phase flow

have been developed and they have occasionally been applied to rod bundles;⁽¹⁸⁻¹⁹⁾ however, they have only been partly successful because they do not include sufficient detail to fully analyze the problem. The primary shortcomings of these computer programs, when applied to rod bundles, are that they do not allow turbulent, thermal mixing between adjacent subchannels or do not properly identify the enthalpy transport that occurs during bulk flow redistribution, or both. The latter point also restricts these analyses to certain types of problems.

SUMMARY AND CONCLUSIONS

COBRA, a digital computer program, uses an improved mathematical model to compute coolant flow and enthalpy in the subchannels of rod bundle fuel elements during boiling. The most significant feature of the model, developed for COBRA, is its ability to include mixing from two types of cross flow. The first type is diversion cross flow caused by flow redistribution when pressures try to equalize as the coolant flows through the bundle. The second is turbulent cross flow caused by the random travel of the coolant between adjacent subchannels. A complete description of the energy and momentum transported by these cross flows is extremely difficult for two-phase flow; therefore, as an approximation, several assumptions are made to develop the model:

- Steady, one-dimensional, two-phase slip flow exists in each subchannel during boiling.
- Turbulent cross flow exists between adjacent subchannels.
- The turbulent cross flow may be superimposed upon the diversion cross flow.
- The two-phase flow structure is fine enough to allow specification of local void fraction as a function of enthalpy and pressure.

The conservation equations derived from these basic assumptions are coupled to each other by the cross flows in several ways. Turbulent cross flow transports thermal energy and momentum between adjacent subchannels, and are analogous to thermal diffusion and turbulent shear stress, respectively. Presently, no way exists to calculate the turbulent cross flow that occurs during boiling. As an approximation, the turbulent cross flow per unit length is assumed to be proportional to the rod spacing times the average mass velocity of the adjacent channels.

The diversion cross flow transports thermal energy from one subchannel to another and affects pressure drop because of changes in the axial and transverse components of momentum. A transverse momentum equation is used to relate pressure drop between adjacent subchannels to the square of the diversion cross flow.

This mathematical model and its numerical solution provide the basis for the digital computer program COBRA. Although this computer program is written principally for rod bundles, it is also general enough for the solution of many multidimensional two-phase flow problems if the model's assumptions are reasonably satisfied. For problems where the validity of the assumptions is questionable, solutions may still provide considerable insight to the problem.

The significant features of COBRA are:

- It has the ability to consider both single- and two-phase flow.
- It accounts for thermal mixing between interconnected parallel flow channels which results from both the transport of energy by turbulent cross flow and diversion cross flow.

- It considers the momentum interchanges between adjacent subchannels which result from both turbulent and diversion cross flow.
- It includes the effect of transverse resistance to diversion cross flow.
- It considers an arbitrary layout of fuel rods and flow subchannels and thus allows analysis of most any rod bundle configuration. Up to 36 subchannels, 25 fuel rods, and 60 subchannel connections may be considered.
- It includes 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.

A parametric study, using COBRA to evaluate the importance of several terms in the model, shows that turbulent shear stress, transverse component of axial momentum, and frictional resistance to diversion cross flow are weak parameters for most multirod designs. The turbulent thermal mixing is the most significant parameter. Mixing from diversion cross flow is only significant if the diversion cross flow is of the same magnitude as the turbulent cross flow.

DESCRIPTION OF ANALYTICAL MODEL

DEVELOPMENT OF EQUATIONS

The analytical model developed for COBRA is based upon a nodal representation of the flow cross section. In a multi-rod bundle, this representation is very convenient because the arrangement of fuel rods forms discrete flow subchannels defined by the subchannel walls and the narrow gap between rods. Figure 1 illustrates the subchannels of a 19 rod bundle and also shows (in the segment removed from the bundle) the representation

FIGURE 1. Subchannel Cross-Flow Representation for Mathematical Model

of the assumed turbulent cross flow and net transverse diversion cross-flow between three adjacent subchannels.

The diversion cross flow is caused by actual flow redistribution resulting from pressures trying to equalize as the coolant passes through the bundle. Such flow redistribution can also be caused by "forced"* diversion from mechanical devices such as wire wraps. The turbulent cross flow is the random travel of the coolant across the gap between adjacent subchannels. Therefore, it causes no net flow diversion when averaged over a short period of time. Because both types of cross flow couple adjacent subchannels through the transfer of mass, energy, and momentum, a description of coolant conditions in a particular subchannel must include the transport effects between all adjacent subchannels.

Phase and velocity distribution makes complete description of these transport processes for two-phase flow conditions extremely difficult. Not knowing how much of the vapor and liquid phases is transported between adjacent subchannels and at what velocities is the largest problem. As an approximation to the actual conditions, several assumptions were made to allow a reasonable description of interchannel mixing:

- Steady, one-dimensional, two-phase slip flow exists in each subchannel during boiling.
- A turbulent (fluctuating) cross flow exists between adjacent subchannels.
- The turbulent cross flow may be superimposed upon any net diversion cross flow that may be occurring.
- The two-phase flow structure is fine enough to allow specification of local void fraction as a function of enthalpy and pressure.

* The present writing of COBRA does not include the effects of forced diversion; only natural diversion from pressure differences is considered.

While these assumptions appear to be very restrictive, they permit development of equations that retain the features of actual mixing processes. By use of basic assumptions, the equations of continuity, energy, and momentum are derived in Appendix A;

Continuity

$$\frac{dm_i}{dx} = - \sum_{j=1}^N w_{ij} \quad i = 1, 2, \dots, N \quad (1)$$

Energy

$$m_i \frac{dh_i}{dx} = q'_i + \sum_{j=1}^N w'_{ij} (h_j - h_i) - \sum_{j=1}^N \left[\begin{array}{ll} 0 & ; \text{ if } w_{ij} \geq 0 \\ w_{ij} (h_j - h_i) & ; \text{ if } w_{ij} < 0 \end{array} \right] \quad i = 1, 2, \dots, N \quad (2)$$

Axial Momentum

$$\begin{aligned} - \left[1 + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \frac{\partial v'_i}{\partial p} \right] \frac{dp_i}{dx} &= \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \left(\frac{f_i \phi_i}{2 \rho_f D_i} + \frac{\partial v'}{\partial h} \frac{dh_i}{dx} \right) \\ &+ \rho_i \cos \theta + \frac{1}{g_c A_i} \sum_{j=1}^N f_T w'_{ij} (u_i - u_j) \\ &+ \frac{1}{g_c A_i} \sum_{j=1}^N \left[\begin{array}{ll} w_{ij} u_i (f_D - 2) & ; \text{ if } w_{ij} \geq 0 \\ w_{ij} (f_D u_j - 2u_i) & ; \text{ if } w_{ij} < 0 \end{array} \right] \quad i = 1, 2, \dots, N \quad (3) \end{aligned}$$

Transverse Momentum

$$p_i - p_j = C_{ij} w_{ij} |w_{ij}| \quad (4)$$

Turbulent Cross Flow

$$w'_{ij} = \frac{1}{2} \beta s_{ij} \left(\frac{m_i}{A_i} + \frac{m_j}{A_j} \right) \quad (5)$$

The above equations are written for a Subchannel (i) which is one of N (total) subchannels. A Subchannel (i) is only coupled to another Subchannel (j) if either turbulent or diversion cross-flow exists between them.

The statement of Equation (1) is simply that the rate of flow change in the subchannel is equal to the net diversion* to and from the subchannel. The turbulent cross-flow term does not appear in Equation (1) because, on a time average, it does not cause a net flow change ($w'_{ij} = w'_{ji}$).

In the energy Equation (2), each of the terms on the right illustrate the mechanism of thermal mixing or energy transport in a bundle fuel element. The first term is the contribution of heat input to the subchannel and gives the rate of enthalpy change if no interchannel mixing occurs. The second term includes the effects of turbulent enthalpy transport between all interconnected subchannels, and the third accounts for energy transported into a Subchannel (i) from flow diversion. A term for energy diverted out of the subchannel is absent because the enthalpy change in a Subchannel (i) is dependent upon where the cross-flow has been, rather than where it is going.

* The diversion cross-flow w_{ij} is taken to be a positive value if flow is from subchannel i to j.

The terms in the momentum Equation (3) also show some interesting effects. The first two terms in the brackets on the right side (Equation 3) represent the friction and acceleration pressure drop, respectively. The third term represents the elevation component of the pressure drop; the fourth term is the contribution of turbulent cross-flow, if uniform velocity is assumed in each subchannel. This is analogous to Reynolds' stresses in turbulent flow fields. Since the subchannel velocity distributions are not uniform in a real multi-rod bundle, the turbulent cross-flow effect is actually less than shown in Equation (3). Modification of this term, based on experimental data, will probably be required, but, presently, the quantity* f_T is being used to specify the importance of this term. The fifth term accounts for the effect of flow being diverted out of or into a particular channel. Some modification may also be required for this term because of the nonuniform velocity distribution in the subchannels. The quantity* f_D is presently being used to specify the importance of the transverse component of axial momentum included in this term.

Equation (4) is a statement of pressure loss between two adjacent channels resulting from diversion cross-flow. Other transverse momentum effects exist but are difficult to include because the direction of the momentum must also be included. The overall effect of this transverse momentum is considered small because of the rather low cross-flow velocities at the center of a subchannel. These effects can also be approximated by appropriate choice of C_{ij} because the transverse momentum is proportional to the square of the cross-flow.

* A value of f_T or $f_D = 1.0$ implies an importance of these terms as derived from the one-dimensional assumption for subchannel conditions.

Equation (5) assumes that the turbulent cross flow per unit length is proportional to the rod spacing times the average flow rate per unit area of the two adjacent channels. The proportionality factor β is, presently, assumed constant and must be obtained experimentally.

ANALOGY TO TURBULENT FLOW ANALYSIS

The analytical model, based upon the transport processes between adjacent subchannels, is somewhat different from a diffusion model used for many single-phase turbulent flow and mixing studies. However, the differences are small and with proper definition of quantities, analogous relationships can be derived.

The heat flow in a turbulent flow field is often written as

$$q_t = -\epsilon_q \rho C_p \frac{dt}{dy} \quad (6)$$

where ϵ_q is the eddy diffusivity. In difference notation,

$$q_t = -\epsilon_q \rho C_p \left(\frac{t_i - t_j}{l} \right). \quad (7)$$

If the specific heat is combined with the temperature, we can write

$$q_t = -\epsilon_q \rho \left(\frac{h_i - h_j}{l} \right). \quad (8)$$

In Equation (8), we used enthalpy instead of temperature as the transported quantity. For single-phase flow, Equations (7) and (8) are equivalent; for two-phase flow, only Equation (8) can apply because no temperature gradients for heat flow exist in a two-phase flow stream, although energy exchange can only occur if there is a transport of enthalpy.* Comparison of Equation (8) with the second term of the energy Equation (2)

* This is more correctly a mass transport of either, or both, phases and implies an enthalpy exchange.

reveals a similarity - they are both proportional to a difference in enthalpy. The turbulent cross-flow of Equation (5) can also be related to the eddy diffusivity; therefore, by proper choice of the proportionality factor β , the analogy between the transport and diffusion models can be realized.

Since specific values of the proportionality factor (β) for the turbulent cross flow used in this analysis are not presently available, only approximations can be made at this time. For the present analysis, we assume a value for β will have to await the results of experiments to determine the amount of turbulent cross-flow. The turbulent cross flow will probably be significantly affected by subchannel velocity and phase distributions, and mechanical devices such as rod spacers.

For single-phase turbulent flow, the momentum exchange within the flow field is described by using a turbulent shear stress (Reynolds stress) given as

$$\tau_t = \frac{\rho \epsilon_m}{g_c} \frac{\partial u}{\partial y} \quad (9)$$

If the partial derivative term is approximated by difference notation, we get

$$\tau_t = \frac{\rho \epsilon_m}{g_c} \left(\frac{u_i - u_j}{\ell} \right) \quad (10)$$

where u_i and u_j are two velocities at some ℓ distance apart. The term ϵ_m is the turbulent diffusivity for momentum and is usually a function of the axial flow rate. Equation (10) is interpreted as the apparent stress created by a fluctuating transverse flow traveling between two velocities at some distance apart. This equation may be directly related to the momentum equation's fourth term which is the pressure drop contribution of the interfacial shear stress between adjacent subchannels. The one-dimensional treatment used for this

analysis may not rigorously account for the interfacial shear stress, but the form should be satisfactory; i.e., the interfacial shear stress between adjacent channels is proportional to the difference of the average subchannel velocities.

It is questionable whether the turbulent cross flows used for energy transport can also be used for momentum transport. For momentum, a reduced value can be expected since most momentum exchange occurs very near the gap where the velocity difference between the adjacent subchannels is reduced. The factor f_T accounts for the importance of the turbulent momentum exchange in this analysis.

PARAMETRIC STUDY

Values of the four parameters (β , f_T , f_D , and f_l) included in the mathematical model have different influences on the solution of the equations. To determine the importance of each parameter, a comparison is made with a nominal case. The nominal case is a two-subchannel approximation (Figure 2) of Subchannels 1 and 2 of the 19 rod bundle sample problem given in Appendix D. Comparison of Figures 3 and 4 shows that the two subchannels reasonably approximate the corresponding two subchannels of the 19 rod bundle.

Effect of Interfacial Turbulent Shear

The influence of interfacial shear can be determined by varying the parameter f_T . Figure 5 compares the effects of $f_T = 0$ and $f_T = 1.0$ for the nominal operating conditions, and, obviously, the overall influence of f_T is small. This small effect during boiling is caused by the frictional and acceleration components of the pressure drop becoming

FIGURE 2. Two-Subchannel Representation of Sample Problem

FIGURE 3. Two-Channel Representation of 19-Rod Bundle Sub-channel Enthalpy and Mass Velocity for Nominal Case

FIGURE 4. 19-Rod Bundle Subchannel Enthalpy and Mass Velocity for Nominal Case

FIGURE 5. Effect of Interfacial Shear on Enthalpy and Mass Velocity

dominant when boiling starts. Therefore, the influence of interfacial turbulent shear is small, especially during boiling conditions.

Effect of Flow Diversion Momentum

Diversion cross-flow momentum effects can be investigated by varying the parameter f_D , which gives the importance of the momentum being transported out of, or into, a subchannel from diversion cross-flow. Calculations for $f_D = 0$ and $f_D = 1.0$ give very little difference in the subchannel enthalpy. Some small variations in the subchannel mass velocity are noted near the point of maximum flow diversion as shown in Table I. This calculation shows that the transverse momentum term is not a strong parameter affecting the subchannel conditions.

TABLE I. *Effect of the Parameter f_D on the Subchannel Mass Velocity*

Distance Along Channel, X/L	Subchannel 1 (10^6 lb/hr-ft ²)		Subchannel 2 (10^6 lb/hr-ft ²)	
	$f_D = 1.0$	$f_D = 0$	$f_D = 1.0$	$f_D = 0$
0.00	0.906	0.906	1.031	1.031
0.10	0.906	0.906	1.031	1.031
0.20	0.908	0.907	1.030	1.030
0.30	0.911	0.909	1.029	1.030
0.40	0.913	0.911	1.028	1.029
0.45	0.760	0.826	1.078	1.057
0.50	0.655	0.751	1.112	1.081
0.55	0.757	0.775	1.079	1.073
0.60	0.804	0.796	1.064	1.066
0.65	0.818	0.806	1.059	1.063
0.70	0.822	0.811	1.058	1.062
0.80	0.811	0.808	1.062	1.062
0.90	0.807	0.806	1.063	1.063
1.00	0.809	0.808	1.062	1.063

Effect of Transverse Cross-Flow Resistance

Transverse cross-flow resistance can be varied by changing the friction constant (f_l). Calculations for f_l , ranging from 0.0 to 0.01, give nearly identical results when compared to the nominal case. Although, the transverse cross-flow resistance appears to be a weak parameter, it could become more significant for very closely spaced rods.

The fact that f_l is a weak parameter affecting the solution does not justify the ignoring of the transverse momentum equation or the setting of f_l equal to zero for all computations. For some problems, such as in square rod arrays, transverse flow resistance is required for stable computer solutions (Appendix B).

Effect of Turbulent Mixing Parameter

The effects of a single, uniform turbulent mixing parameter (β) (Figure 6) can cause very significant changes in the sub-channel enthalpy rises. This parameter (β) ranges from about 0.02 to 0.06 in multirod fuel bundles for single-phase flow conditions and with a variety of rod spacing devices. No experimental data have been reported for two-phase conditions; however, if a range as indicated above exists, determination of β would be very important.

The subchannel mass velocity is significantly influenced by β as seen in Table II. The lower mass velocities in Subchannel 1 for $\beta = 0$ can be attributed to larger acceleration pressure drop caused by larger enthalpy rises in Subchannel 1. The effect of interfacial shear on the mass velocity would only be significant prior to boiling (Figure 5).

FIGURE 6. Effect of Mixing Parameter (β) on Subchannel Enthalpy Rise

TABLE II. *Effect of the Parameter β on the Subchannel Mass Velocity*

Distance Along Channel, X/L	Subchannel 1 (10^6 lb/hr-ft ²)		Subchannel 2 (10^6 lb/hr-ft ²)	
	$\beta = 0$	$\beta = 0.06$	$\beta = 0$	$\beta = 0.06$
0	0.800	0.921	1.065	1.026
0.10	0.803	0.926	1.064	1.025
0.20	0.815	0.925	1.060	1.024
0.30	0.785	0.927	1.070	1.024
0.35	0.606	0.927	1.128	1.024
0.40	0.536	0.928	1.151	1.023
0.45	0.495	0.828	1.164	1.056
0.50	0.455	0.699	1.177	1.098
0.55	0.414	0.794	1.191	1.067
0.60	0.502	0.836	1.162	1.053
0.65	0.533	0.852	1.152	1.048
0.70	0.528	0.858	1.153	1.046
0.80	0.499	0.854	1.163	1.048
0.90	0.468	0.853	1.173	1.048
1.00	0.466	0.856	1.174	1.047

DIGITAL COMPUTER PROGRAM DEVELOPMENT

GENERAL FEATURES AND OPERATION

The digital computer program, COBRA is written to carry out the numerical solution of the mixing equations. If the assumptions of the model are reasonably satisfied, two-phase flow in multirod fuel elements as well as other heat transfer and fluid flow problems can be analyzed. Other problems could include geometric systems, such as rectangular channels or eccentric annuli.

The significant features of COBRA are:

- It has the ability to consider both single- and two-phase flow.

- It accounts for thermal mixing between interconnected parallel flow channels which results from both the transport of energy by turbulent cross-flow and diversion cross-flow when flow redistribution occurs.
- It considers the momentum interchanges between adjacent subchannels which results from both turbulent and diversion cross flow. (Parameters are included that allow the importance of these quantities to be specified.)
- It includes the effect of transverse resistance to diversion cross-flow.
- It considers an arbitrary layout of fuel rods and flow subchannels to allow analysis of most any rod bundle configuration up to 36 subchannels, 25 fuel rods, and 60 subchannel connections. 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 includes 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 and includes the variations in circumferential rod heat flux.)

General operation* of COBRA is explained by a flow diagram (Figure 7). The program is started by reading in a fluid property table and friction correlation constants that will be used for all succeeding cases. A control card is then read specifying what input is to be read in for the case under consideration. For the first case, all data are read; for all succeeding cases, quantities not read in are the same as the previous case. Once data are read in, the geometry information is generated and stored for future use. Most of the initial conditions are specified by the input data. If individual subchannel flow rates

* Specific details are given in the program listing and sample problem in Appendices D and E.

FIGURE 7. Simplified Flow Diagram for COBRA

are not specified, the program distributes the total flow among the individual subchannels to give equal pressure gradients. Once this has been established, the first derivatives of flow, enthalpy, and pressure are computed for initial conditions. Actual integration of the equations then begins by extrapolating to the end of the first increment. This extrapolation is updated and checked by successively solving for diversion cross-flow until convergence is achieved. If the iteration fails after a specified number of iterations, output data available to that point are written out, and the computation moves on to the next case. For a successful iteration, values at the end of the increment are computed and stored for output. These values provide the basis for new initial conditions at the start of the next increment where the entire procedure is repeated. When the end of the problem is reached, output data previously stored are written out, and the program moves on to the next case by reaching a new control card. A blank control card signals the program to stop.

Several checks are provided in COBRA to stop the calculation if trouble results. For all these stops, an error message and other potentially helpful data are written out. Also retained in the program is the option to write out intermediate data during the calculations.

COBRA was written in Fortran IV language for a UNIVAC 1107 computer. Except for memory storage, no problem should be encountered on other machines capable of compiling, assembling, and operating with a punched Fortran IV source deck and input cards. The UNIVAC 1107 at Hanford has two memory banks available for program storage, and COBRA uses 6400 and 31077, respectively, for a total storage requirement of 37477. Other machines may use more, or less, storage depending upon the storage assignment during compilation. Although no auxiliary

scratch tapes are used, their use could reduce the memory storage requirements. Input and output are on Tape Units 5 and 6, respectively, but these can easily be changed by redefining the unit assignment variables I5 and I6 and recompiling the main program. Running time is difficult to estimate because it depends upon the size of the problem and how many times the simultaneous equations are solved. As an example of running time, the sample problem in Appendix D is 17 sec on the UNIVAC 1107.

DIGITAL COMPUTER PROGRAM COMPARISONS

Several computer programs^(13,17) have been written to analyze multidimensional two-phase flow in reactor channels and, in some cases, these programs have been used to predict^(18,19) local subchannel conditions in multirod fuel elements. Other programs^(7,8) have been written to analyze subchannel conditions but are limited to single-phase analyses only. Other work is also continuing on development of two-phase subchannel analyses in the United States and in foreign countries; however, only limited information is available concerning the capabilities of these analyses. A general comparison of these digital computer programs is given in Table III.

THINC⁽¹⁷⁾ has been developed by Westinghouse to predict flow and enthalpy in a semiopen or closed channel core during boiling. It is a general program for analyzing multirod bundles; however, as written, it has no provision for including turbulent thermal mixing. The analytical treatment in THINC is quite similar to this analysis but has a more simplified treatment of transverse momentum effects. An improved version of THINC, called THINC-II, has been written but is company proprietary.

TABLE III. *Comparisons of Features in Some Digital Computer Programs That Have Been Used for Rod Bundle Sub-channel Analyses*

Computer Programs	Program Capabilities								
	Single-Phase Analysis	Two-Phase Analysis	Arbitrary Geometry	Transverse Turbulent Momentum	Transverse Diversion Momentum	Turbulent Thermal Mixing	Diversion Enthalpy Transport	Arbitrary Power Distribution	Transverse Flow Resistance
COBRA	X	X	X	X	X	X	X	X	X
THINC ⁽¹⁷⁾	X	X	X	-	X	-	X	X	X
HAMBO ⁽²⁰⁾	(a)	(a)	(b)	(b)	(b)	(a)	(b)	(a)	(b)
General Electric Company - APED ⁽²¹⁾	X	X	X	(b)	(a)	X	(a)	X	a
HECTIC-II ⁽⁷⁾	X	-	X	X	-	X	-	X	-
U-3 ⁽⁸⁾	X	-	X	-	-	X	-	X	-
Atomics International ⁽¹⁵⁾	X	X	(c)	-	X	-	(c)	X	-
TITE ⁽¹³⁾ XITE ⁽¹⁴⁾	X	X	(c)	-	X	-	X	X	-

(a) Apparently included, but no specific details are available (not published).

(b) No details are available (not published).

(c) Somewhat restrictive for rod bundle subchannel analysis.

HAMBO is a program being developed by the British. Very little information is available but it is reported⁽²⁰⁾ to be a rather complete program for multirod subchannel analysis.

General Electric Company, APED,⁽²¹⁾ is developing a subchannel analysis program using a model similar to the one presented here. Specific details of the program are not yet available, but it will probably have many of the features of COBRA.

HECTIC-II⁽⁷⁾ has been developed for the Army Gas-Cooled Reactor Systems Program. It is a rather complete analysis of heat transfer and fluid flow for gas-cooled reactor channels and is applicable to many other mixing problems involving a single-phase coolant. The model used is similar to that of COBRA but is limited to single-phase conditions.

U-3,⁽⁸⁾ limited to single-phase coolants, is a modified version of a program originally written in Canada for heat transfer analysis of multirod elements. Modifications to the program have been made for heat transfer analyses of heavy-water-moderated organic-cooled reactors.

Atomics International developed a program⁽¹⁵⁾ that has been used for two-phase rod bundle subchannel analysis. However, because it does not account for turbulent energy interchange between subchannels, this program is limited to problems where the coolant enthalpy is nearly uniform across the bundle. Enthalpy transport from diversion cross-flow is also limited because the flow diversion can only be in one direction, i.e., out from the center of the bundle.

TITE⁽¹³⁾ and XITE⁽¹⁴⁾ are steady state and transient programs, respectively, that have limitations similar to those for the Atomics International program when applied to rod

bundle subchannels. These programs, developed for two-phase flow in rectangular coolant channels, are set up to provide an adjacent subchannel on either side of a subchannel.

NUMERICAL METHODS USED TO DEVELOP COBRA

The equations of continuity, energy, and momentum are very complex nonlinear equations. Only for very simple cases, such as two parallel subchannels and single-phase flow, can a closed form analytical solution⁽²⁾ be obtained. Generally, a numerical solution is required.

The numerical solution is treated as an initial value problem* by integrating the equations in a stepwise manner starting at the inlet of the fuel bundle. Initial values of enthalpy, pressure, and flow rate are assumed to be known at the inlet to start the solution, and pressure drops are computed as positive values to give the proper direction of flow diversion.

Actual numerical solution of the equations proved to be a rather difficult task. The more simple integration techniques (Euler and Runge-Kutta) for solution of the differential equations were not satisfactory during the initial development of COBRA.

Modified Euler Method

The modified Euler method was the first technique attempted. This method computes the first derivative, based upon the initial conditions, and uses this first derivative to predict quantities at the end of the first increment. The calculation is repeated at the end of the first increment to get the average first derivative for the increment. Another prediction of the values at the end of the first increment is made and, if agreement with

* *The physical problem is more truly a boundary value problem; however, because of the nearly equal pressures between rod bundle subchannels, treatment as an initial value problem is justified.*

the previous value is within an allowable tolerance, the calculation proceeds to the next increment. If agreement is not achieved, iteration continues until agreement is achieved.

The problem with the Euler method is that a small error in the predicted pressure at the end of the first increment can cause a large diversion cross-flow to occur [as computed from Equation (4)]. When this diversion cross-flow was used in the next calculation to predict pressure at the end of the increment, the difference in pressure between the channels was larger and opposite in direction than for the first calculation. This effect grew very rapidly with the next few iterations and led to a divergent solution. The source of the problem was traced to the momentum equations's last term which can be large with moderate values of flow diversion. Apparently, a method more accurately predicting the pressure at the end of the increment was needed.

Runge-Kutta Method

The Runge-Kutta formulas are generally considered stable and capable of predicting accurately ahead; therefore, the method of solution was shifted to those formulas. Difficulties similar to those found in the modified Euler technique were encountered but only for certain conditions. Stable solutions could be obtained if the increment were small and if the transverse resistance were large. For opposite conditions, unstable behavior was encountered except where continual flow diversions from boiling could be established.

This unstable behavior of the solution can be explained mathematically by looking at a partial derivative of Equation (4); in particular, the last term which is of the form $u_i w_{ij}$. If this is combined with Equation (4), we find the form

$$\frac{\partial}{\partial p_i} \left[u_i \sqrt{\frac{p_i - p_j}{C_{ij}}} \right] = \frac{u_i}{\sqrt{C_{ij}}} = \frac{1}{\sqrt{p_i - p_j}} \quad (11)$$

A valid solution requires that such a partial derivative be bounded; however, it is not bounded if p_i equals p_j or if C_{ij} equals zero.

These were the conditions that tended to give unstable solutions; i.e., p_i close to p_j and C_{ij} small. If the flow diversion condition could be established causing p_i to not equal p_j , or C_{ij} taken large, then the partial derivative was finite and a solution was obtained. It was apparent from this difficulty that some other numerical technique was required.

Iterative Solution

In the two previous methods, failure of the numerical integration had been caused by the inability to control the amount of diversion cross-flow as the solution moved forward. To correct this problem, a procedure, similar to the modified Euler method, has been developed that uses a special iterative scheme to control the diversion cross-flow. This procedure was designed to satisfy both the axial and transverse momentum equations.

The equations used are:

$$m_{i,x+\Delta x} = m_{i,x} + \frac{\Delta x}{2} \left(\frac{dm_{i,x}}{dx} + \frac{dm_{i,x+\Delta x}}{dx} \right) \quad (12)$$

$$h_{i,x+\Delta x} = h_{i,x} + \frac{\Delta x}{2} \left(\frac{dh_{i,x}}{dx} + \frac{dh_{i,x+\Delta x}}{dx} \right) \quad (13)$$

$$p_{i,x+\Delta x} = p_{i,x} - \frac{\Delta x}{2} \left(\frac{dp_{i,x}}{dx} + \frac{dp_{i,x+\Delta x}}{dx} \right) \quad (14)$$

The minus sign is used in Equation (14) to properly account for the direction of flow diversion as influenced by pressure differences between subchannels.

The first derivatives in Equations (12), (13), and (14) are known from the initial conditions at the start of the solution and then at the beginning of every step as the integration proceeds. If the step size is small enough to give rather small changes in the flow, reasonable estimates of the first derivatives at $x+\Delta x$ in Equations (12) and (13) can be made. The same is not true in Equation (14) because the pressure gradient at $x+\Delta x$ is greatly influenced by the amount of diversion cross flow (w_{ij}) which could be large and yet give a small change in axial flow for a small Δx . The pressure at $x+\Delta x$ can be determined by substituting Equation⁽³⁾ into Equation⁽¹⁴⁾ where we find that the pressure at $x+\Delta x$ is a linear function of the diversion cross-flows into or out of the subchannel. We can illustrate this effect and show how it is used to determine the cross-flow at $x+\Delta x$ by considering two subchannels. (Detailed in Appendix B.)

For the two-channel case, consider Subchannel 1 as boiling and diverting flow into Subchannel 2. If we plot the pressure at $x+\Delta x$ as a function of w_{12} , we get two linear curves (Figure 8). If we form the difference, p_1-p_2 , as in Equation (B-12), we obtain another linear curve. We also have the transverse momentum Equation (B-15) which will intersect the linear curve of p_1-p_2 versus w_{12} . The point of intersection of Equation (B-12) represents the solution of Equation (B-15). In this simple case, it is the solution of a quadratic equation; for the general case, a nonlinear set of simultaneous equations results instead of the quadratic equation. The solution of this set of equations provides diversion cross-flows for a new evaluation of conditions at $x+\Delta x$ from which the entire procedure may be repeated. The iteration is stopped when the diversion cross-flows between successive iterations converge to an acceptable value.

FIGURE 8. *Illustration of Method Used to Solve for Diversion Crossflow*

FUTURE DEVELOPMENT

The development of COBRA has relied primarily upon analytical considerations and has utilized several empirical correlations for its development. Future refinements to the model and program will be possible from some existing and future experimental data. Several areas of improvement, based upon experimental data, include:

- More accurate prediction of two-phase pressure drop, if needed.
- More accurate void correlation, if needed.
- Subcooled void fraction.
- Prediction of the local turbulent mixing parameter (β) based on a correlation with local subchannel coolant conditions and mechanical design of the bundle. Additional turbulence, caused by rod spacer design (wire wraps, warts, grids, etc.), is expected to have a strong influence on β .
- Effect of rod spacer design for computing pressure drop.
- Correlation of the transverse diversion cross-flow resistance* to bundle geometry and coolant conditions.
- Correlation of the momentum factors* f_T and f_D to bundle geometry and coolant conditions.

Possible future work to improve the general nature of the program includes:

- Variable channel area and gap spacing along length of channel to allow studies of rod bowing or misalignment within the bundle.
- "Forced"*** cross-flow diversion resulting from mechanical devices such as wire wraps.

* *These are weak parameters, but a more accurate determination of their values and what factors influence them would be useful.*

** *"Forced" diversion cross flow is not included in COBRA. The diversion cross-flows computed by COBRA could be considered "natural" because they result from pressures trying to equalize.*

NOMENCLATURE

Dimensions are denoted by:

- L = length, T = time, M = mass, θ = temperature,
 $F = ML/T^2$ = force and $H = ML^2/T^2$ = energy.
- A = cross-sectional area, (L^2)
 C = loss function for transverse momentum, Equation (4)
 C_p = specific heat ($H/M\theta$)
 D = hydraulic diameter, (L)
 D_r = rod diameter (L)
 F = force (ML/T^2)
 K = number of connections between adjacent subchannels, (Dimensionless)
 L = channel length, (L)
 N = number of subchannels, (Dimensionless)
 Re = Reynolds number, (Dimensionless)
 X = quality, $m_g/(m_g + m_f)$, (Dimensionless)
 f = friction factor based on all-liquid flow, (Dimensionless)
 f_A = local to average axial power distribution (Dimensionless)
 f_c = fraction of rod power transferred to an adjacent subchannel, (Dimensionless)
 f_l = diversion cross-flow resistance parameter, (L)
 f_R = relative rod power distribution, (Dimensionless)
- f_T, f_D = correction terms for turbulent and diversion momentum, respectively, (Dimensionless)
 g_c = gravitational constant, (ML/FT^2)
 h = enthalpy, $Xh_g + (1-X)h_f$, (H/M)
 h_g, h_f = saturated vapor and liquid enthalpy, (H/M)
 ℓ = length (L)
 m = mass flow rate, $Au_f [\rho_g \alpha \gamma + \rho_f (1-\alpha)]$, (M/T)
 p = pressure (F/L^2)
 q' = heat addition per unit length, (H/L)
 $\bar{q}''$ = average heat flux, (H/TL^2)
- s = rod spacing, (L)
 u = channel effective momentum velocity, mv'/A , (L/T)
 v = specific volume, $1/\rho$, (L^3/M)
 v' = effective specific volume for momentum considerations, $(1-X)^2/\rho_f(1-\alpha) + X^2/\rho_g\alpha$, (L^3/M)
 w = diversion cross-flow between adjacent subchannels, (M/TL)
 w' = turbulent (fluctuating) cross-flow between adjacent subchannels, (M/TL)
 x = space variable, (L)
 α = void fraction, $A_g/(A_g + A_f)$, (Dimensionless)
 β = turbulent mixing parameter, (Dimensionless)
 γ = slip ratio, u_g/u_f , (Dimensionless)
 ϵ_q = eddy diffusivity, (L^2/T)
 ϵ_t = turbulent diffusivity for momentum, (L^2/T)
 θ = orientation of channel with respect to vertical, (Radians)
 ρ = density, $\rho_g\alpha + \rho_f(1-\alpha)$, (M/L^3)
 ρ_g, ρ_f = saturated vapor and liquid density, (M/L^3)
 τ_t = turbulent shear stress, (F/L^2)
 ϕ = two-phase friction multiplier, (Dimensionless)
- Subscripts
- f, g = saturated conditions for liquid and vapor, respectively
 i, j = channel identification number
 ij, ji = double subscripts imply i to j and j to i , respectively
 k, ℓ = number identifying each subchannel connection; each k or ℓ implies a pair ij or ji
 r = rod identification number
 ri = refers to conditions from rod r to subchannel i

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APPENDIX A

APPENDIX ADERIVATION OF MIXING EQUATIONS

Consider a section of Flow Channel (i) with two types of adjacent subchannels. Adjacent subchannels of type (j) are diverting flow into (i), and adjacent subchannels of type (k) are receiving flow from (i). Assume that one-dimensional, separated, two-phase, slip flow exists in each subchannel. A further assumption is that, in addition to the diversion of flow between channels, a turbulent cross-flow simultaneously exists and causes no net flow imbalance when averaged over a short period of time. With these basic assumptions, we can now derive the basic equations of continuity, energy, and momentum along Flow Channel (i).

Continuity Equation

From a mass balance on Subchannel (i),

$$\begin{aligned} m_i + w_{ji}dx + w'_{ji}dx + dx + w'_{ki}dx \\ = m_i + dm_i + w_{ik}dx + w'_{ik}dx + w'_{ij}dx. \end{aligned}$$

Our definition of the turbulent cross flow gives

$$w'_{ji} = w'_{ij} \quad (A-1)$$

and

$$w'_{ij} = w'_{ki} \quad ; \quad (A-2)$$

therefore, the continuity equation reduces to

$$\frac{dm_i}{dx} = w_{ji} - w_{ij} \quad (A-3)$$

or, if we consider all possible Adjacent Subchannels (n) and take w_{ik} as diversion cross-flow from (i) to (k) as positive, we find

$$\frac{dm_i}{dx} = - \sum_{j=1}^N w_{ij} \quad i = 1, 2, \dots, N \quad (A-4)$$

Energy Equation

An energy balance on Subchannel (i) gives

$$\begin{aligned}
 m_i h_i + w_{ji} h_j dx + w'_{ji} h_j dx + w'_{ki} h_k dx + q'_i dx \\
 = w_{ik} h_i dx + w'_{ik} h_i dx + w'_{ij} h_i dx + m_i h_i + d(m_i h_i).
 \end{aligned}$$

Inserting Equations (A-1) and (A-2) and combining with Equation (A-3) gives

$$\frac{dh_i}{dx} = \frac{q'_i}{m_i} + \frac{w_{ji}}{m_i} (h_j - h_i) + w'_{ik} (h_k - h_i) \quad . \quad (A-5)$$

There is not a term for w_{ik} because, on an enthalpy basis, the system enthalpy change is dependent upon where fluid is coming from, not where it is going. If we adopt the same sign convention for diversion cross flow as in the continuity equation and consider all possible Subchannels (N), we find

$$\begin{aligned}
 m_i \frac{dh_i}{dx} = q'_i + \sum_{j=1}^N w_{ij} (h_j - h_i) \\
 - \sum_{j=1}^N \left\{ \begin{array}{ll} 0 & ; \text{ if } w_{ij} \geq 0 \\ w_{ij} (h_j - h_i) & ; \text{ if } w_{ij} < 0 \end{array} \right\} \\
 i = 1, 2, \dots, N \quad (A-6)
 \end{aligned}$$

Axial Momentum Equation

Derivation of the momentum equation is a little more complex than the continuity and energy equations; however, the same technique applies. The primary difference is that an effective specific volume for momentum transport is used. The momentum in a two-phase flow stream is

$$\frac{AG^2 v'}{g_c} = \left(\frac{m}{A}\right)^2 \frac{Av'}{g_c} = \frac{mu}{g_c}$$

where we now have a momentum velocity,

$$u = \frac{mv'}{A}.$$

The effective specific volume term is that used by Meyer⁽²³⁾ in his development of two-phase flow equations.

Equating forces acting upon Subchannel (i) in the x direction to the change in momentum, gives

$$\begin{aligned} g_c (A_i p_i - F_i dx - A_i p_i - A_i dp_i - A_i \rho_i \cos \theta dx) = \\ + [f_D w_{ik} u_i dx + f_T w'_{ik} u_i dx + f_T w'_{ij} u_i dx + m_i u_i \\ + d(m_i u_i)] - (m_i u_i + f_D w_{ji} u_j dx + f_T w'_{ki} u_k dx \\ + f_T w'_{ji} u_j dx) \end{aligned} \quad (A-7)$$

where the terms f_T and f_D are arbitrarily included to help account for nonuniform velocity and phase distributions in each subchannel for the turbulent and diversion momentum terms, respectively. These are used because the momentum interchange from the cross-flows occur primarily near the gap where reduced velocities exist and phase distribution is unknown.

If Equations (A-1), (A-2), and (A-3) are combined with the above equation, we find

$$\begin{aligned}
 - \frac{dp_i}{dx} = & \frac{F_i}{A_i} + \rho_i \cos \theta + \frac{f_T w'_{ik}}{g_c A_i} (u_i - u_k) + \frac{f_T w'_{ij}}{g_c A_i} (u_i - u_j) \\
 & + \frac{w_{ji}}{g_c A_i} (2u_i - f_D u_j) + \frac{w_{ik}}{g_c A_i} u_i (f_D - 2) \\
 & + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \frac{dv'_i}{dx} \quad .
 \end{aligned} \tag{A-8}$$

The frictional force along the subchannel wall is evaluated by using

$$\frac{F_i}{A_i} = \frac{f_i \phi_i}{2 g_c \rho_f D_i} \left(\frac{m_i}{A_i} \right)^2 , \quad \theta_i \tag{A-9}$$

where ϕ_i is a two-phase friction multiplier based on all-liquid flow. The pressure drop component, due to density change, is evaluated from the equation of state that relates void fraction to enthalpy and pressure

$$\alpha = \alpha(h, p) \quad . \tag{A-10}$$

With v' evaluated as

$$v' = \frac{(1 - x)^2}{(1 - \alpha) \rho_f} + \frac{x^2}{\alpha \rho_g} , \tag{A-11}$$

we may write

$$\frac{dv_i}{dx} = \frac{\partial v'_i}{\partial p} \frac{dp_i}{dx} + \frac{\partial v'_i}{\partial h} \frac{dh_i}{dx} \quad (A-12)$$

By inserting Equations (A-9) and (A-12) into Equation (A-8) gives

$$\begin{aligned} - \left[1 + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \left(\frac{\partial v'_i}{\partial p} \right) \right] \frac{dp_i}{dx} &= \frac{f_i \phi_i}{2 g_c \rho f^D_i} \left(\frac{m_i}{A_i} \right)^2 + \rho_i \cos \theta \\ &+ \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \left(\frac{\partial v'_i}{\partial h} \right) \frac{dh_i}{dx} + \frac{f_T w'_{ik}}{g_c A_i} (u_i - u_k) \\ &+ \frac{f_T w'_{ij}}{g_c A_i} (u_i - u_j) + \frac{w_{ji}}{g_c A_i} (2u_i - f_D u_j) \\ &+ \frac{w_{ik}}{g_c A_i} u_i (f_D - 2) \quad (A-13) \end{aligned}$$

If we consider all possible subchannels connected to (i) and use the same sign convention for cross-flow as in the continuity and momentum equations, Equation (A-13) reduces to

$$\begin{aligned} - \left[1 + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \frac{\partial v'_i}{\partial p} \right] \frac{dp_i}{dx} &= \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \left[\frac{f \phi_i}{2 \rho f^D_i} + \frac{\partial v_i}{\partial h} \frac{dh_i}{dx} \right] \\ &+ \rho_i \cos \theta + \frac{1}{g_c A_i} \sum_{j=1}^N f_T w'_{ij} (u_i - u_j) \\ &+ \frac{1}{g_c A_i} \sum_{j=1}^N \begin{bmatrix} w_{ij} u_i (f_D - 2) & ; & \text{if } w_{ij} \geq 0 \\ w_{ij} (f_D u_i - 2u_i) & ; & \text{if } w_{ij} < 0 \end{bmatrix} \quad (A-14) \\ & \quad \quad \quad i = 1, 2, \dots, N \end{aligned}$$

Transverse Momentum

If we assume that significant cross-flow velocity only occurs in the gap between adjacent subchannels and that any cross-flow occurring in a subchannel has a small velocity compared to the axial velocity, then a transverse momentum equation may be written as

$$p_i - p_j = C_{ij} w_{ij} |w_{ij}| \quad (A-15)$$

The factor C_{ij} is a loss function, which accounts for the transverse resistance to flow plus any other unrecoverable losses occurring.

APPENDIX B

APPENDIX BNUMERICAL SOLUTION TO MIXING EQUATIONS

Consider the continuity, energy, and momentum equations where Δx is sufficiently small validate the approximations:

Continuity

From Equation (12) write

$$m_{i,x+\Delta x} = m_{i,x+\Delta x/2} + \frac{\Delta x}{2} \frac{dm_{i,x+\Delta x}}{dx} \quad (B-1)$$

where we have from initial conditions at x

$$m_{i,x+\Delta x/2} = m_{i,x} + \frac{\Delta x}{2} \frac{dm_{i,x}}{dx} \quad (B-2)$$

The last term of Equation (B-1) is evaluated as updated values are obtained during iteration.

Energy

From Equation (13) write

$$h_{i,x+\Delta x} = h_{i,x+\Delta x/2} + \frac{\Delta x}{2} \frac{dh_{i,x+\Delta x}}{dx} \quad (B-3)$$

where we have from initial conditions at x ,

$$h_{i,x+\Delta x/2} = h_{i,x} + \frac{\Delta x}{2} \frac{dh_{i,x}}{dx} \quad (B-4)$$

The last term in Equation (B-3) is evaluated by using updated values of $m_{i,x+\Delta x}$ as they are obtained during iteration.

Momentum

From Equation (14) write

$$p_{i,x+\Delta x} = p_{i,x+\Delta x/2} - \frac{\Delta x}{2} \frac{dp_{i,x+\Delta x}}{dx} \quad (B-5)$$

where

$$P_{i,x+\Delta x/2} = P_{i,x} - \frac{\Delta x}{2} \frac{dp_{i,x}}{dx} \quad (B-6)$$

For each pair of Adjacent Channels (i,j), we can select a number (k) to identify it. If we select (k) to identify the connection (i) to (j), where (i) is smaller than (j), we can write the linear set of equations for pressure at $x+\Delta x$ by performing the substitution of Equation (A-14) into (B-5). The equations are:

$$P_{i,x+\Delta x} = Q_i + \sum_{k=1}^K R_{ik} w_k \quad i = 1, 2, \dots, N \quad (B-7)$$

where

$w_k = w_{ij}$, for k defined as the identification

number of the connection from i to j.

$$Q_i = P_{i,x} - \frac{\Delta x}{2} \frac{dp_{i,x}}{dx} + \frac{\Delta x}{2} \left\{ \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \left[\frac{f_i \phi_i}{2D_i \rho_f} + \frac{\partial v'_i}{\partial h} \frac{dh_i}{dx} \right] \right. \\ \left. + \rho_i \cos \theta + \frac{1}{g_c A_i} \sum_{j=1}^N f_T w'_{ij} (u_i - u_j) \right\} \\ \left\{ 1 + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \frac{\partial v'_i}{\partial p} \right\}^{-1} \quad (B-8)$$

$$R_{ik} = \frac{\Delta x}{2} \left[\frac{1}{g_c A_i} u_i (f_D - 2) \right] \left[1 + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \frac{\partial v'_i}{\partial p} \right]^{-1}; \\ w_k \geq 0 \quad (B-9)$$

or

$$R_{ik} = \frac{\Delta x}{2} \left[\frac{1}{g_c A_i} (f_D u_j - 2u_i) \right] \left[1 + \frac{1}{g_c} \left(\frac{m_i}{A_i} \right)^2 \frac{\partial v'_i}{\partial p} \right]^{-1}; \text{ if } w_k < 0 \quad (\text{B-10})$$

In the above equations for Q_i and R_{ik} , the quantities are evaluated at $x + \Delta x$ as updated values become available after each iteration.

By selecting a Subchannel (i) and another Subchannel (j) in the manner chosen to define (k), we now can generate a new set of equations by subtraction,

$$(p_i - p_j)_{x+\Delta x} = Q_\ell + \sum_{k=1}^K R_{\ell k} w_k \quad \ell = 1, 2, \dots, K \quad (\text{B-11})$$

where

$$Q_\ell = Q_i - Q_j \quad (\text{B-12})$$

$$R_{\ell k} = R_{ik} - R_{ij}, \quad (\text{B-13})$$

and (ℓ) is the subchannel connection number with the same definition as (k). From Equation (4), we may also write

$$(p_i - p_j)_{x+\Delta x} = C_\ell w_\ell |w_\ell|. \quad \ell = 1, 2, \dots, K \quad (\text{B-14})$$

Combining Equations (B-11) and (B-14) for each value of (ℓ) gives

$$\sum_{k=1}^K R_{\ell k} w_k - C_\ell w_\ell |w_\ell| + Q_\ell = 0. \quad \ell = 1, 2, \dots, K \quad (\text{B-15})$$

This is a nonlinear set of simultaneous equations with (K) equations and (K) unknowns—the diversion cross-flows. An

iterative solution to these equations is made by solving a set of linear equations with the method of Crout.⁽²⁴⁾ The linear set consists of

$$\sum_{k=1}^{\ell-1} R_{\ell k} w_k + (R_{\ell \ell} - C_{\ell} |w_{\ell}|) w_{\ell} + \sum_{k=\ell+1}^K R_{\ell k} w_k + Q_{\ell} = 0 \quad \ell=1, 2, \dots, K \quad (B-16)$$

The term $C_{\ell} |w_{\ell}|$ is evaluated by using the presently known value of w_{ℓ} . Solution of the set of Equations (B-16) gives an updated value for w_{ℓ} which is used in the next iteration to correct a previous estimate of $C_{\ell} |w_{\ell}|$. Iteration is continued until all the new and old values of w_{ℓ} have converged to suitable values.

Solutions to the set of equations (B-16) were found to be very sensitive to the coefficients. Matrix inversion was initially used to solve the equations but was found unsuitable because of large errors. The Crout⁽²⁴⁾ method was found to be satisfactory if the number of significant figures required to balance the set of Equations (B-16) was not excessive. Accuracy to a few figures (presently 4) was found to be sufficient since additional significant figures did not cause significant improvement in the accuracy of the solution.

The problem with the solution of the Equations (B-16) is that they are "ill-conditional" for certain types of problems. For example, in a square rod array with zero cross-flow resistance ($C_{\ell} = 0$) and all subchannel conditions equal, the equations are homogeneous and any value of division cross-flow satisfies them. This produces uncontrolled transverse flow loops around fuel rods. Including cross-flow resistance helps considerably by modifying the term $(R_{\ell \ell} - C_{\ell} |w_{\ell}|)$ in Equation (B-16) and thus reducing the "ill-condition." This permits realistic solutions that do not allow transverse flow loops.

Initial calculations were carried out by using the new value of diversion cross-flow for the updating quantities for the next iteration. This gave a slowly converging oscillating solution for the cross flows. To improve the convergence, a reduced value of the updated cross-flow was used.

$$w_k = 0.6(w_k)_{\text{New}} + 0.4(w_k)_{\text{old}} \quad . \quad (B-17)$$

Equation (B-17) reduces the new cross flow if it changes very much from the old value.

APPENDIX C

APPENDIX CDIGITAL COMPUTER PROGRAM CORRELATIONS

To carry out a solution, several correlations have been assumed in the computer program. Although others could have been used, these appear to be satisfactory for the present time.

Friction Factor

The friction factor correlation is based upon that of Koos⁽²⁵⁾ and is of the form

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

where a, b, and c are specified constants.

Two-Phase Friction Multiplier

Increases in the friction pressure gradient from two-phase flow are accounted for by using the Armand⁽²⁶⁾ friction multiplier (ϕ) which is the ratio of the pressure gradient for two-phase flow to that for all-liquid flow.

$$\phi = 1.0 \quad h \leq h_f \quad (C-2)$$

$$\phi = \frac{(1 - X)^2}{(1 - \alpha)^{1.42}} \quad 0.39 < (1 - \alpha) \leq 1.0 \quad (C-3)$$

$$\phi = 0.478 \frac{(1 - X)^2}{(1 - \alpha)^{2.2}} \quad 0.1 < (1 - \alpha) \leq 0.39 \quad (C-4)$$

$$\phi = 1.730 \frac{(1 - X)^2}{(1 - \alpha)^{1.64}} \quad 0. < (1 - \alpha) \leq 0.1 \quad (C-5)$$

Void Fraction

The relationship between void fraction and enthalpy and pressure represents the equation state. The program uses the Armand⁽²⁶⁾ void correlation as modified by Massena.⁽²⁷⁾

$$\alpha = 1.0 \quad h \leq h_f \quad (C-6)$$

$$\alpha = \frac{(0.833 + 0.167X)Xv_g}{(1 - X)v_f + Xv_g} \quad h > h_f \quad (C-7)$$

Turbulent Cross-Flow

The turbulent cross-flow for two-phase flow is assumed to have a form similar to that for single-phase flow; i.e., the turbulent cross-flow per unit area is some fraction of the axial flow rate per unit area. Since an adjacent channel may be flowing at a different mass velocity, the average is assumed to be the turbulent cross-flow between the two channels.

$$w'_{ij} = \frac{1}{2} \beta S_{ij} \left(\frac{m_i}{A_i} + \frac{m_j}{A_j} \right) \quad (C-8)$$

Loss Function for Transverse Momentum

For purposes of obtaining an estimate on the transverse flow resistance, a simple friction model is used. If we assume the gap is a slot of spacing S and ℓ wide, the loss function is

$$C_{ij} = \frac{f\ell}{4g_c S^3_{ij} \rho_i} \quad (C-9)$$

The product $f\ell$ is an arbitrary friction 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

$$q'_{ri} = \bar{q}'' \pi D_r f_c f_R f_A(x/L) \quad (C-10)$$

where

$$\int_0^1 f_A(x/L) d(x/L) \equiv 1 \quad (C-11)$$

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

Fluid Properties

Fluid properties are obtained from a linear interpolation of the table of input properties. The terms $\partial v'_i / \partial p$ and $\partial v'_i / \partial h$ are evaluated

as

$$\frac{\partial v'_i}{\partial p} = \left(\frac{v'_{i,p+\Delta p} - v'_{i,p}}{\Delta p} \right)_h, \quad (C-12)$$

and

$$\frac{\partial v'_i}{\partial h} = \left(\frac{v'_{i,h+\Delta h} - v'_{i,h}}{\Delta h} \right)_p \quad (C-13)$$

where

v'_i is evaluated from equation (A-11).

APPENDIX D

APPENDIX DDIGITAL COMPUTER PROGRAM SAMPLE PROBLEM

A section of symmetry from a 19 rod bundle will be used for a sample problem to illustrate how it is set up and input to the computer program. The section of symmetry from a 19 rod bundle consisting of three fuel rods and five sub-channels will be used for the problem (Figure 2). Dimensions and power distribution are shown in the tabulations. For the calculations, we will assume that the quantities f_T and f_D are equal to 1.0. The cross-flow resistance constant is assumed to be 0.001, and the mixing parameter β is assumed to be 0.04.

Operating Conditions for the sample problem are:

Average heat flux	= 0.4×10^6 Btu/hr-ft ²
Average mass velocity	= 1.0×10^6 lb/hr-ft ²
System pressure	= 1000 psia
Inlet enthalpy	= 400 Btu/lb
Channel length	= 60 in.

Channel Geometry^(a)

<u>Channel</u>	<u>Area, in.²</u>	<u>Wetted Perimeter, in.</u>	<u>Heated Perimeter, in.</u>
1	0.027	0.442	0.442
2	0.083	0.884	0.884
3	0.027	0.442	0.442
4	0.064	0.935	0.516
5	0.064	0.935	0.516

(a) Rod diameter = 0.563 in.;
 Rod spacing = 0.080 in.;
 Rod-to-Wall spacing = 0.080 in.

Rod Flux Distribution^(b)

Rod	Relative Power	Fraction of Power to Channels				
		1	2	3	4	5
1	1.0	0.0833	-	-	-	-
2	1.0	0.1667	0.2500	0.0833	-	-
3	1.0	-	0.2500	0.1667	0.2916	0.2916

^(b)Uniform axial flux distribution.

INPUT LISTING FOR SAMPLE PROBLEM

```

30
  50.  281.01  .0173  8.5150  250.1  1174.1  .491
 100.  327.81  .0177  4.4320  298.4  1187.2  .410
 150.  358.42  .0181  3.0150  330.5  1194.1  .369
 200.  381.79  .0184  2.2880  355.4  1198.4  .345
 250.  400.95  .0187  1.8438  376.0  1201.1  .326
 300.  417.33  .0189  1.5433  393.8  1202.8  .313
 350.  431.72  .0191  1.3260  409.7  1203.9  .301
 400.  444.59  .0193  1.1613  424.0  1204.5  .290
 440.  454.02  .0195  1.0556  434.6  1204.6  .283
 480.  462.82  .0197  .9670  444.6  1204.5  .278
 520.  471.07  .0198  .8915  454.1  1204.2  .273
 560.  478.85  .0200  .8265  463.0  1203.8  .269
 600.  486.21  .0201  .7698  471.6  1203.6  .264
 640.  493.21  .0203  .7198  479.8  1202.5  .260
 680.  499.88  .0204  .6757  487.7  1201.7  .255
 720.  506.25  .0206  .6362  495.3  1200.7  .252
 760.  512.36  .0207  .6007  502.6  1199.7  .248
 800.  518.23  .0209  .5687  509.7  1198.6  .245
 840.  523.88  .0210  .5396  516.6  1197.4  .242
 880.  529.33  .0212  .5130  523.3  1196.1  .240
 920.  534.59  .0213  .4886  529.8  1194.7  .237
 960.  539.68  .0214  .4663  536.2  1193.3  .234
1000.  544.61  .0216  .4456  542.4  1191.8  .232
1050.  550.57  .0218  .4216  550.0  1189.9  .229
1100.  556.31  .0220  .4001  557.4  1187.8  .226
1150.  561.86  .0221  .3802  564.6  1185.6  .223
1200.  567.22  .0223  .3619  571.7  1183.4  .221
1250.  572.42  .0225  .3450  578.6  1181.0  .219
1300.  577.46  .0227  .3293  585.4  1178.6  .217
1350.  582.35  .0229  .3148  592.1  1176.1  .215
.5 -.32.0056
11111111SAMPLE PROBLEM
2
0.  1.  1.  1.
5
1 -2  0  0  0
2 -1  3 -5  0
3  2 -4  0  0
4 -3  5  0  0
5 -2  4  0  0
1 .027 .442 .442 .08  0  0  0
2 .083 .884 .884 .08 .08 .08  0
3 .027 .442 .442 .08 .08  0  0
4 .064 .935 .516 .08 .08  0  0
5 .064 .935 .516 .08 .08  0  0
3
1  1  0  0  0  0  0
2  1  2  3  0  0  0
3  2  3  4  5  0  0
1 .563 1..0833 0  0  0  0  0
2 .563 1..1667.2500.0833 0  0  0
3 .563 1..2500.1667.2916.2916 0  0
.04 .001 1.  1.  21  3
1000. 400.  2.  .4  60.

```

FLUID PROPERTY TABLE

P	T	VF	VG	HF	HG	VISC
50.0	281.01	.0173	8.5150	250.1	1174.1	.4910
100.0	327.81	.0177	4.4320	298.4	1187.2	.4100
150.0	358.42	.0181	3.0150	330.5	1194.1	.3690
200.0	381.79	.0184	2.2880	355.4	1198.4	.3450
250.0	400.95	.0187	1.8438	376.0	1201.1	.3260
300.0	417.33	.0189	1.5433	393.8	1202.8	.3130
350.0	431.72	.0191	1.3260	409.7	1203.9	.3010
400.0	444.59	.0193	1.1613	424.0	1204.5	.2900
440.0	454.02	.0195	1.0556	434.6	1204.6	.2830
480.0	462.82	.0197	.9670	444.6	1204.5	.2780
520.0	471.07	.0198	.8915	454.1	1204.2	.2730
560.0	478.85	.0200	.8265	463.0	1203.8	.2690
600.0	486.21	.0201	.7698	471.6	1203.6	.2640
640.0	493.21	.0203	.7198	479.8	1202.5	.2600
680.0	499.88	.0204	.6757	487.7	1201.7	.2550
720.0	506.25	.0206	.6362	495.3	1200.7	.2520
760.0	512.36	.0207	.6007	502.6	1199.7	.2480
800.0	518.23	.0209	.5687	509.7	1198.6	.2450
840.0	523.88	.0210	.5396	516.6	1197.4	.2420
880.0	529.33	.0212	.5130	523.3	1196.1	.2400
920.0	534.59	.0213	.4886	529.8	1194.7	.2370
960.0	539.68	.0214	.4663	536.2	1193.3	.2340
1000.0	544.61	.0216	.4456	542.4	1191.8	.2320
1050.0	550.57	.0218	.4218	550.0	1189.9	.2290
1100.0	556.31	.0220	.4001	557.4	1187.8	.2260
1150.0	561.86	.0221	.3802	564.6	1185.6	.2230
1200.0	567.22	.0223	.3619	571.7	1183.4	.2210
1250.0	572.42	.0225	.3450	578.6	1181.0	.2190
1300.0	577.46	.0227	.3293	585.4	1178.6	.2170
1350.0	582.35	.0229	.3148	592.1	1176.1	.2150

FRICITION FACTOR CORRELATION $FRICT = .500*RE^{**}(-.32) + .0056$

INPUT LISTING FOR CASE 1 SAMPLE PROBLEM

HEAT FLUX DISTRIBUTION

X/L RELATIVE FLUX

.000 1.000
1.000 1.000

CHANNEL INPUT DATA

CHANNEL NO.	AREA (SQ-IN)	HEATED PERIM. (IN)	HYDRAULIC DIAMETER (IN)	ROD SPACING BETWEEN ADJACENT CHANNELS (IN)	ADJ. CHANNEL NO.
1	.0270	.4420	.2443	.0800(-2)	.0000(0)
2	.0850	.8840	.3756	.0800(-1)	.0800(-5)
3	.0270	.4420	.2443	.0800(2)	.0000(0)
4	.0640	.9350	.2738	.0800(-3)	.0000(0)
5	.0640	.9350	.2738	.0800(-2)	.0000(0)

ROD INPUT DATA

ROD NO.	DIAMETER (IN)	RADIAL POWER FACTOR	FRACTION OF POWER TO ADJACENT CHANNELS (ADJ. CHANNEL NO.)
1	.5630	1.0000	.0833(1)
2	.5630	1.0000	.1667(1)
3	.5630	1.0000	.2500(2)

CALCULATION PARAMETERS

TURBULENT INTENSITY = .0400
 TRANSV. FRICTION (FT.) = .0010
 MOMENTUM DIVERSION FACTOR = 1.0000
 DIVISION FOR PRINT-OUT = 21
 CALCULATION SUBDIVISION = 3

CHANNEL OPERATING CONDITIONS

SYSTEM PRESSURE = 1000.0 PSIA
 INLET ENTHALPY = 400.0 BTU/LB
 AVG. MASS VELOCITY = 1.000 MILLION LB/(HR-SQFT)
 AVG. HEAT FLUX = .400 MILLION BTU/(HR-SQFT)
 CHANNEL LENGTH = 60.00 INCHES
 CHANNEL ORIENTATION = .0 DEGREES
 CALC INCREMENT = 1.00 INCHES
 AVG. EXIT ENTHALPY = 653.6 BTU/LB

CASE 1 SAMPLE PROBLEM

DISTANCE	CHANNEL 1					CHANNEL 2						
	PRESSURE	ENTHALPY	X	MASS VEL	FLOW	FLUX	PRESSURE	ENTHALPY	X	MASS VEL	FLOW	FLUX
0.00	.000	400.00	.000	.950	179.3	.400	.000	400.00	.000	1.061	611.7	.400
3.00	.126	419.80	.000	.958	179.6	.400	.126	412.56	.000	1.061	611.6	.400
6.00	.251	438.36	.000	.960	180.1	.400	.251	425.72	.000	1.061	611.7	.400
9.00	.375	455.97	.000	.963	180.6	.400	.375	439.14	.000	1.062	612.0	.400
12.00	.498	472.83	.000	.966	181.1	.400	.498	452.66	.000	1.062	612.0	.400
15.00	.619	489.08	.000	.968	181.5	.400	.619	466.19	.000	1.062	612.2	.400
18.00	.740	504.81	.000	.970	181.9	.400	.740	479.68	.000	1.062	612.3	.400
21.00	.859	520.12	.000	.973	182.3	.400	.859	493.12	.000	1.063	612.5	.400
24.00	.977	535.09	.000	.974	182.7	.400	.977	506.50	.000	1.063	612.6	.400
27.00	1.099	550.50	.012	.647	158.8	.400	1.099	520.84	.000	1.075	619.6	.400
30.00	1.222	569.55	.042	.691	129.5	.400	1.222	534.95	.000	1.093	630.1	.400
33.00	1.367	589.54	.072	.663	124.4	.400	1.367	548.18	.009	1.034	590.1	.400
36.00	1.521	609.57	.103	.657	123.1	.400	1.521	562.71	.031	.915	527.2	.400
39.00	1.698	626.23	.129	.687	128.9	.400	1.698	577.33	.054	.906	522.5	.400
42.00	1.904	640.83	.151	.729	136.7	.400	1.904	590.81	.075	.945	544.5	.400
45.00	2.112	656.13	.175	.743	139.4	.400	2.112	604.28	.095	.967	557.2	.400
48.00	2.324	671.53	.199	.745	139.7	.400	2.323	617.72	.116	.980	565.0	.400
51.00	2.542	686.64	.222	.744	139.6	.400	2.541	631.22	.137	.987	568.6	.400
54.00	2.769	701.45	.245	.743	139.2	.400	2.769	644.73	.158	.989	569.9	.400
57.00	3.006	716.06	.267	.741	139.0	.400	3.006	658.21	.178	.988	569.5	.400
60.00	3.255	730.41	.290	.742	139.1	.400	3.255	671.60	.199	.987	569.2	.400

COMPUTATION RESULTS FOR EACH CHANNEL

CASE 1 SAMPLE PROBLEM

DISTANCE	CHANNEL 3					CHANNEL 4						
	PRESSURE	ENTHALPY	X	MASS VEL	FLOW	FLUX	PRESSURE	ENTHALPY	X	MASS VEL	FLOW	FLUX
.00	.000	400.00	.000	.984	184.5	.400	.000	400.00	.000	.968	430.2	.400
3.00	.126	418.00	.000	.984	184.6	.400	.126	410.30	.000	.968	430.0	.400
6.00	.251	433.56	.000	.984	184.6	.400	.251	421.01	.000	.967	429.8	.400
9.00	.375	447.86	.000	.984	184.5	.400	.375	431.96	.000	.966	429.5	.400
12.00	.498	461.49	.000	.984	184.6	.400	.498	443.09	.000	.966	429.1	.400
15.00	.619	474.77	.000	.984	184.6	.400	.619	454.36	.000	.965	428.8	.400
18.00	.740	487.85	.000	.985	184.6	.400	.740	465.76	.000	.964	428.5	.400
21.00	.859	500.82	.000	.985	184.6	.400	.859	477.27	.000	.963	428.2	.400
24.00	.977	513.73	.000	.985	184.7	.400	.977	488.90	.000	.963	427.9	.400
27.00	1.099	526.37	.000	1.002	187.9	.400	1.099	500.93	.000	.978	434.6	.400
30.00	1.222	539.22	.000	1.020	191.2	.400	1.222	512.86	.000	.995	442.2	.400
33.00	1.367	552.82	.016	.892	167.2	.400	1.366	526.02	.000	1.071	476.2	.400
36.00	1.521	567.63	.039	.817	153.1	.400	1.521	538.39	.000	1.160	515.4	.400
39.00	1.698	580.23	.058	.830	155.6	.400	1.698	549.17	.010	1.157	514.0	.400
42.00	1.904	592.31	.077	.871	163.4	.400	1.904	559.63	.026	1.115	495.6	.400
45.00	2.112	605.51	.097	.889	166.7	.400	2.112	570.54	.043	1.094	486.3	.400
48.00	2.323	618.67	.118	.900	168.7	.400	2.324	581.79	.061	1.082	481.1	.400
51.00	2.542	632.34	.139	.904	169.5	.400	2.542	593.29	.078	1.078	478.9	.400
54.00	2.769	645.74	.159	.905	169.6	.400	2.769	604.97	.096	1.076	478.3	.400
57.00	3.006	659.03	.180	.904	169.5	.400	3.005	616.81	.115	1.077	478.7	.400
60.00	3.255	672.14	.200	.904	169.5	.400	3.256	628.71	.133	1.077	478.8	.400

COMPUTATION RESULTS FOR EACH CHANNEL

CASE 1 SAMPLE PROBLEM

DISTANCE	PRESSURE	ENTHALPY	CHANNEL 5		FLOW	FLUX
			X	MASS VEL		
.00	.000	400.00	.000	.976	434.6	.400
3.00	.126	410.00	.000	.976	434.5	.400
6.00	.251	420.28	.000	.977	434.1	.400
9.00	.375	430.86	.000	.976	433.8	.400
12.00	.498	441.72	.000	.975	433.5	.400
15.00	.619	452.81	.000	.975	433.2	.400
18.00	.740	464.11	.000	.974	432.9	.400
21.00	.859	475.59	.000	.973	432.6	.400
24.00	.977	487.23	.000	.973	432.4	.400
27.00	1.099	499.33	.000	.989	439.5	.400
30.00	1.222	511.43	.000	1.006	447.3	.400
33.00	1.366	524.61	.000	1.085	482.4	.400
36.00	1.521	537.03	.000	1.173	521.5	.400
39.00	1.698	547.94	.008	1.168	519.3	.400
42.00	1.904	558.65	.025	1.125	500.1	.400
45.00	2.112	569.79	.042	1.104	490.7	.400
48.00	2.324	581.21	.060	1.093	485.7	.400
51.00	2.542	592.83	.078	1.086	483.6	.400
54.00	2.769	604.60	.096	1.087	483.1	.400
57.00	3.005	616.51	.114	1.086	483.6	.400
60.00	3.256	628.49	.133	1.088	483.7	.400

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

CASE 1 SAMPLE PROBLEM

DISTANCE	W(1, 2)	WP(1, 2)	W(2, 3)	WP(2, 3)	W(2, 5)	WP(2, 5)	W(3, 4)	WP(3, 4)	W(4, 5)	WP(4, 5)
.00	.0	269.0	.0	272.6	.0	271.9	.0	260.2	.0	259.5
3.00	-3.6	269.2	-1.6	272.7	-2.3	271.8	-2.1	260.3	.1	259.4
6.00	-4.0	269.6	-1.6	272.8	-2.8	271.7	-2.3	260.2	-.1	259.2
9.00	-3.9	270.0	-1.2	272.8	-2.8	271.7	-2.5	260.0	.1	259.0
12.00	-3.2	270.3	-1.1	272.8	-2.1	271.6	-1.9	260.0	.0	258.8
15.00	-3.6	270.7	-1.0	272.9	-2.7	271.6	-2.5	259.9	.2	258.6
18.00	-3.4	271.0	-.6	272.9	-2.4	271.5	-2.4	259.8	.2	258.4
21.00	-3.1	271.4	-.8	273.0	-2.3	271.5	-2.2	259.7	.2	258.3
24.00	-2.7	271.6	-.8	273.0	-1.9	271.4	-1.7	259.7	.1	258.1
27.00	333.6	256.3	63.5	276.9	107.4	275.2	86.5	263.9	-4.4	262.2
30.00	152.9	237.9	22.0	281.7	36.6	279.9	29.3	268.6	-1.8	266.8
33.00	-1.3	225.0	126.6	255.4	416.1	281.2	378.7	261.7	-9.9	287.6
36.00	17.4	209.5	69.1	230.9	256.3	278.4	238.6	263.5	-3.6	311.0
39.00	-98.4	212.5	-53.4	231.5	-228.3	276.7	-215.4	264.8	.3	310.0
42.00	-34.9	223.2	-30.3	242.1	-99.1	276.0	-91.3	264.8	1.5	298.7
45.00	-9.5	228.0	-15.9	247.4	-58.7	276.1	-55.3	264.4	.9	293.1
48.00	.8	230.0	-7.9	250.6	-25.1	276.4	-23.3	264.3	.8	290.1
51.00	.8	230.8	-1.2	252.1	-5.7	276.7	-5.6	264.2	.1	288.7
54.00	1.6	230.9	.5	252.5	3.9	276.8	3.8	264.1	.1	288.4
57.00	1.4	230.5	1.4	252.2	3.9	276.8	3.7	264.1	.1	288.7
60.00	-3.2	230.6	-.6	252.2	-2.7	276.8	-2.6	264.2	-.1	288.8

APPENDIX E

APPENDIX EFORTRAN IV LISTING OF COBRA

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C  COBRA - A DIGITAL PROGRAM FOR ANALYSIS OF COOLANT BOILING IN ROD ARRAYS
C
C  REFERENCE DOCUMENT BNWL-371
C
C  THIS PROGRAM COMPUTES THE LOCAL FLOW AND ENTHALPY CONDITIONS IN
C  MULTIROD ARRAY NUCLEAR FUEL BUNDLES.
C
C  INPUT INSTRUCTIONS
C
C  CARD GROUP 1, SATURATED FLUID PROPERTY TABLE
C    FIRST CARD - NUMBER OF CARDS IN TABLE(MAXIMUM OF 30). (FORMAT I5)
C    EACH CARD OF TABLE - PRESSURE(PSIA), TEMPERATURE(F), LIQUID SPECIFIC
C      VOLUME(CU-FT/LB), VAPOR SPECIFIC VOLUME(CU-FT/LB), LIQUID ENTHALPY
C      (BTU/LB), VAPOR ENTHALPY(BTU/LB), LIQUID VISCOSITY(LB/FT HR). CARDS
C      MUST BE IN ORDER OF INCREASING PRESSURE (FORMAT 7F10.0)
C
C  CARD GROUP 2, FRICTION FACTOR CONSTANTS
C    ONE CARD - LEADING COEFFICIENT, EXPONENT OF REYNOLDS NO., CONSTANT TERM.
C      (FORMAT 3F5.0)
C
C  CARD GROUP 3, CONTROL CARD FOR CASE TO BE RUN.
C    ONE CARD - CASE NUMBER(GREATER THAN ZERO), HEAT FLUX DISTRIBUTION,
C      CHANNEL LAYOUT, CHANNEL AND GAP DIMENSIONS, ROD LAYOUT, ROD DIAMETERS
C      AND POWER DISTRIBUTION, CALCULATION VARIABLES, OPERATING CONDITIONS,
C      OPTIONAL DESCRIPTION OF RUN. (FORMAT I3,7I1,11A6). FOR COLUMNS 4-10,
C      BLANK OR ZERO MEANS DATA WILL NOT BE READ IN FOR THIS CASE - ANY
C      POSITIVE NUMBER REQUIRES DATA TO BE READ IN - ALL DATA MUST BE READ IN
C      FOR THE FIRST CASE OF A SERIES OF RUNS.
C
C  CARD GROUP 4, HEAT FLUX DISTRIBUTION TABLE
C    FIRST CARD - NUMBER OF VALUES IN TABLE(MAXIMUM 30), (FORMAT I5)
C    EACH CARD FOLLOWING - RELATIVE DISTANCE FROM INLET(X/L), RELATIVE POWER
C      (LOCAL/AVG), UP TO 7 PAIRS OF VALUES ON EACH CARD, MONOTONIC FROM INLET
C      (FORMAT 14F5.3)
C
C  CARD GROUP 5, CHANNEL LAYOUT TABLE
C    FIRST CARD - NUMBER OF CHANNELS(MAXIMUM 36), (FORMAT I5)
C    EACH CARD OF TABLE - CHANNEL NUMBER, NUMBER OF AN ADJACENT CHANNEL IN
C      ACCENDING ORDER(NEGATIVE IF A NODE LINE SPLITS A SUBCHANNEL - THIS
C      TELLS THE PROGRAM TO USE HALF THE FULL GAP CROSSFLOW).
C      UP TO 4 ADJACENT CHANNELS MAY BE CONSIDERED. (FORMAT 5I5)
C
C  CARD GROUP 6, CHANNEL DIMENSIONS TABLE
```

C EACH CARD OF TABLE - CHANNEL NUMBER, CHANNEL AREA(SQ-IN.), WETTED
C PERIMETER(IN.), HEATED PERIMETER(IN.), ROD GAP BETWEEN ADJACENT
C CHANNELS AS SPECIFIED IN CARD GROUP 5(IN.). (FORMAT 15,7F5.3)
C
C CARD GROUP 7, ROD-CHANNEL LAYOUT TABLE
C FIRST CARD - NUMBER OF RODS(MAXIMUM 25), (FORMAT 15)
C EACH CARD OF TABLE - ROD NUMBER, NUMBER OF AN ADJACENT SUBCHANNEL IN
C ACCENDING ORDER. UP TO 6 ADJACENT CHANNELS MAY BE CONSIDERED.
C (FORMAT 7I5)
C
C CARD GROUP 8, ROD DIAMETER AND POWER DISTRIBUTION TABLE
C EACH CARD OF TABLE - ROD NUMBER, DIAMETER(IN.), RELATIVE ROD POWER(LOCAL/
C AVG), FRACTION OF ROD POWER TO THE ADJACENT SUBCHANNELS AS SPECIFIED
C IN CARD GROUP 7. (FORMAT I3,8F5.3)
C
C CARD GROUP 9, CALCULATION VARIABLES
C ONE CARD - TURBULENT INTENSITY, FRICTION FACTOR FOR DIVERSION CROSSFLOW
C (FT.), DIVERSION MOMENTUM FACTOR, TURBULENT MOMENTUM FACTOR, NUMBER
C OF AXIAL LOCATIONS FOR PRINT OUT, NUMBER OF AXIAL SUBDIVISIONS IN PRINT
C OUT INCREMENT USED FOR CALCULATIONS, DEBUG CONSTANT(IF ZERO OR BLANK,
C NOTHING - IF 1 PRINT OUT DEBUG INFORMATION AT EACH ITERATION(THIS CAN
C GENERATE A LOT OF PAPER)), ALLOWABLE ERROR IN DIVERSION CROSSFLOW(IF
C BLANK, A VALUE OF 10. IS USED), MAXIMUM NUMBER OF ITERATIONS(IF BLANK,
C 25 IS USED). (FORMAT 4F5.3,3I5,F5.2,I5)
C
C CARD GROUP 10, OPERATING CONDITIONS
C ONE CARD - SYSTEM PRESSURE(Psia), INLET ENTHALPY(BTU/LB), AVERAGE MASS
C VELOCITY(MILLION LB/HR SQ-FT), AVERAGE HEAT FLUX(MILLION BTU/HR SQ-FT),
C CHANNEL LENGTH(IN.), CHANNEL ORIENTATION FROM HORIZONTAL(DEGREES),
C (FORMAT 6F10.0)
C ANY ADDITIONAL CARDS ARE FOR INDIVIDUAL SUBCHANNEL CONDITIONS --
C IF THE INLET ENTHALPY IS NEGATIVE, EACH SUBCHANNEL INLET ENTHALPY
C IS READ IN ORDER OF INCREASING SUBCHANNEL NUMBER(FORMAT 12F5.0).
C IF THE INLET MASS VELOCITY IS NEGATIVE, EACH SUBCHANNEL FLOW RATE
C (LB/HR) IS READ IN ORDER OF INCREASING SUBCHANNEL NUMBER(FORMAT 6F10.0)
C
C CARD GROUPS 1 AND 2 ARE READ IN ONLY ONCE AT THE START OF THE CALCULATIONS
C CARD GROUPS 3-10 MUST BE SPECIFIED INITIALLY. ANY GROUPS NOT CHANGED BY
C SUCCEEDING CASES WILL REMAIN THE SAME AS THE PREVIOUS CASE. A BLANK CARD
C AFTER CARD GROUP 10 STOPS THE CALCULATIONS.
C
C REQUIRED SUBROUTINES - PROP, MIX, DIFFER, DIVERT, CROUT5, ARMAND, CURVE
C
C UNITS OF OUTPUT -
C DISTANCE(INCHES), PRESSURE DROP(PSI), ENTHALPY(BTU/LB),
C QUALITY,X(DIMENSIONLESS), MASS VELOCITY(MILLION-LB/HR-SQFT),
C SUBCHANNEL AVERAGE HEAT FLUX(MILLION-BTU/HR-SQFT),
C CROSSFLOW(LB/HR-FT)
C


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    DIMENSION TEXT(11),DHYDE(36),KKOD(36,25),LC(36,4),LR(25,6),
    IS(36,4),PHI(25,6),PWRF(36,25),RADIAL(25),D(25),PERIM(36),
    IHPERIM(36),AC(36),PW(36),PH(36),DR(25),DC(36),WOLD(60)
    DIMENSION PV(36,31),HV(36,31),FV(36,31),QV(36,31),XV(31),
    IFLOW(36,31),QUALTY(36,31),HEAD(4,60),WV(60,31),WPV(60,31)
    COMMON /BTBL/ PP(30),TT(30),VVF(30),VVG(30),HHF(30),HHG(30),
    IUUF(30),HH(26),DVPDPP(25),NPROP,LPROP
    COMMON /BPROP/ RHU(36),V(36),VP(36),DVPDP(36),DVPDH(36),VISC(36),
    IPREF,GUAL(36),ALPHA(36),VF,VG,T(36)
    COMMON /BEQN/ AAA(60,61),W(60)
    COMMON /BMIX/ WP(60),U(36),P(36,2),H(36,2),F(36,2),A(36),GAP(60),
    IX(2),BETA,XMIX,FDIV,FMIX,C(60),DF(36),DH(36),DP(36),DX,DHYD(36),
    IQPRIM(36),AFLUX,Z,KCHAN(36,36),AXIAL(30),Y(30),AQPRIM(36),AA,
    IBB,CC,THETA,NAX,FACTOR(60),IK(60),JK(60),PI,G
    COMMON /BCOM/ I3,NCHANL,NK,IERROR,KDEBUG,N
    DATA (HEAD(1,I),I=1,60)/60*6H W(/,(HEAD(2,I),I=1,60)/60*1H,/,
    1(HEAD(3,I),I=1,60)/60*5H) WP(/,(HEAD(4,I),I=1,60)/60*1H)/

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C

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1 FORMAT ( I5 / (7F10.5) )
2 FORMAT ( I3,7I1,11A6 )
3 FORMAT (23H1INPUT LISTING FOR CASE I6,5X 11A6 )
5 FORMAT ( I5 / (14F5.3) )
6 FORMAT (23H0HEAT FLUX DISTRIBUTION //23H X/L RELATIVE FLUX//
1(F7.3,F12.3))
7 FORMAT ( I5 / (7I5) )
8 FORMAT ( I5 / (5I5) )
9 FORMAT (6F10.0)
10 FORMAT(12F5.0)
11 FORMAT (I5,7F5.3)
12 FORMAT(19H0CHANNEL INPUT DATA //
1108H CHANNEL AREA WETTED HEATED HYDRAULIC ROD SPACIN
16 BETWEEN ADJACENT CHANNELS (ADJ. CHANNEL NO.) /
1 76H NO. (SQ-IN) PERIM. PERIM. DIAMETER
1 (IN)
1/46H (IN) (IN) (IN) / (I5,4F10.4,
1F14.4,1H(I2,1H)F10.4,1H(I2,1H)F10.4,1H(I2,1H)F10.4,1H(I2,1H))
13 FORMAT (22H1FLUID PROPERTY TABLE //
168H P T VF VG HF HG
2VISC // ( F8.1,F10.2,2F10.4,2F10.1,F9.4) )
14 FORMAT (I5,8F5.3)
15 FORMAT(15H0ROD INPUT DATA // 96H ROD DIAMETER RADIAL POWER
1 FRACTION OF POWER TO ADJACENT CHANNELS (ADJ. CHANNEL NO.) /
1 30H NO. (IN) FACTOR / (I5,F9.4,F13.4,F11.4,1H(I2,
11H)F9.4,1H(I2,1H)F9.4,1H(I2,1H)F9.4,1H(I2,1H)F9.4,1H(I2,1H)F9.4,
11H(I2,1H))
17 FORMAT ( 4F5.3,3I5,F5.2,I5)
18 FORMAT (23H0CALCULATION PARAMETERS //
1 28H TURBULENT INTENSITY F8.4 /
2 28H TRANSV. FRICTION (FT.) F8.4 /

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3 28H   MOMENTUM DIVERSION FACTOR F8.4 /
4 28H   MOMENTUM TURBULENT FACTOR F8.4 /
5 28H   DIVISION FOR PRINT-OUT   IS /
6 28H   CALCULATION SUBDIVISION IS )

20 FORMAT (7F10.0)
21 FORMAT (29H0CHANNEL OPERATING CONDITIONS //
1 25H   SYSTEM PRESSURE      = ,F8.1,5H PSIA /
2 25H   INLET ENTHALPY      = ,F8.1,7H BTU/LB /
3 25H   AVG. MASS VELOCITY = ,F8.3,21H MILLION LB/(HR-SQFT) /
4 25H   AVG. HEAT FLUX      = ,F8.3,22H MILLION BTU/(HR-SQFT) /
5 25H   CHANNEL LENGTH      = ,F8.2,7H INCHES /
5 25H   CHANNEL ORIENTATION = ,F8.1,8H DEGREES /
6 25H   CALC INCREMENT      = ,F8.2,7H INCHES /
7 25H   AVG. EXIT ENTHALPY = ,F8.1,7H BTU/LB )

22 FORMAT (23H0FAILURE INTEGRATION IN,I4,17H ITERATIONS AT X=
1F8.4,2I10)
24 FORMAT (49H0NEGATIVE FLOW NOT ALLOWED, CALCULATION STOPPED /
1( ,I5,3E12.6))
25 FORMAT ( ,38H1COMPUTATION RESULTS FOR EACH CHANNEL //
15H CASE I5,5X11A6///
130X7HCHANNEL I3,40X7HCHANNEL I3 //
1 11H DISTANCE
2 53H PRESSURE ENTHALPY X MASS VEL FLOW FLUX
3 53H PRESSURE ENTHALPY X MASS VEL FLOW FLUX //
4(F7.2,F12.3,F10.2,F6.3,F8.3,F10.1,F7.3
5 ,F12.3,F10.2,F6.3,F8.3,F10.1,F7.3))
26 FORMAT ( ,38H1COMPUTATION RESULTS FOR EACH CHANNEL //
15H CASE I5,5X11A6///
130X7HCHANNEL I3 //
1 11H DISTANCE
2 53H PRESSURE ENTHALPY X MASS VEL FLOW FLUX //
4(F7.2,F12.3,F10.2,F6.3,F8.3,F10.1,F7.3))
27 FORMAT (32H FAILURE OF INITIAL FLOW SPLIT ,I5/(I5,2F12.4))
28 FORMAT(1H0/40H FRICTION FACTOR CORRELATION FRIC = F5.3,6H*RE**
1(F5.2,4H) + F6.4 )
29 FORMAT(1H1)
30 FORMAT (F7.2,2X,5(F12.1,F10.1))
31 FORMAT (76H1DIVERSION(W) AND TURBULENT(WP) CROSSFLOW BETWEEN ADJAC
1ENT SUBCHANNELS (I,J) // 5H CASE I5,5X11A6///
210H DISTANCE 5(A6,I2,A1,I2,A5,I2,A1,I2,A1)/ )
50 FORMAT(20I5)
51 FORMAT (8E12.3)
52 FORMAT (I5,6E12.6)
53 FORMAT (I5,3E12.6)
54 FORMAT (28H *** ITERATION COMPLETED *** /)

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C
C INITIALIZE
I2=5
I3=6

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      PI=3.1416
      G = 0.417E+09
      READ (I2,1)  NPROP,(PP(I),TT(I),VVF(I),VVG(I),HHF(I),HHG(I),
1UUF(I),          I=1,NPROP )
      WRITE (I3,13) (PP(I),TT(I),VVF(I),VVG(I),HHF(I),HHG(I),
1UUF(I),          I=1,NPROP )
      READ (I2,10) AA,BB,CC
      WRITE(I3,28) AA,BB,CC
200 READ (I2,2)    KASE,J1,J2,J3,J4,J5,J6,J7,TEXT
C  CHECK FOR CONTINUATION OF CALCULATION
      IF(KASE.LT.1) STOP
      IERROR = 1
210 WRITE (I3,3)   KASE,TEXT
      NLINE = 1
C  CHECK FOR NEW AXIAL HEAT FLUX DISTRIBUTION
      IF(J1)220,220,212
212 READ (I2,5)    NAX  ,(Y(I), AXIAL(I) ,I=1,NAX)
C  CHECK FOR NEW CHANNEL LAYOUT
220 IF(J2)2230,2230,221
C  READ IN ADJACENT CHANNEL NUMBERS(IN ACCENDING ORDER)
221 DO1222 I=1,36
      DO1222 J=1,36
222 KCHAN(I,J) = 0
      READ (I2,8) NCHANL,(I,(LC(I,L),L=1,4),J=1,NCHANL)
C  CHECK FOR NEW CHANNEL VARIABLES
2230 IF(J3)230,230,232
232 READ (I2,11) (I,A(I),PERIM(I),HPERIM(I),(S(I,L),L=1,4),J=1,NCHANL)
C  COMPUTE CHANNEL LAYOUT FACTORS
      PHTOT = 0.
      ATOTAL =0.
      K=0
      DO 234 I=1,NCHANL
      DO 223 L=1,4
      IF(LC(I,L))2220,223,222
222 J=LC(I,L)
      IF(J.LE.I) GO TO 223
      K=K+1
      FACTOR(K) = 1.
      GO TO 2221
2220 J =-LC(I,L)
      IF(J.LE.I) GO TO 223
      K=K+1
      FACTOR(K) = .5
2221 JK(K) = J
      IK(K) = I
      KCHAN(I,J) = K
      KCHAN(J,I) = K
      GAP(K) = S(I,L)/12.
223 CONTINUE

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    PW(I) = PERIM(I)
    PERIM(I) = PERIM(I)/12.
    PH(I) = HPERIM(I)
    HPERIM(I)=HPERIM(I)/12.
    AC(I) = A(I)
    A(I)= A(I)/144.
    DHYD(I) = 4.*A(I)/PERIM(I)
    DC(I) = DHYD(I)*12.
    PHTOT = PHTOT + HPERIM(I)
234 ATOTAL = ATOTAL + A(I)
    NK=K
230 IF(J4)235,235,224
224 DO1225 I=1,36
    DO1225 J=1,25
    PWRF(I,J) = 0.
1225 KROD(I,J) = 0
    READ (I2,7) NROD, (NR, (LR(NR,L),L=1,6), J=1,NROD)
235 IF(J5) 250,250,236
236 READ (I2,14) (I,D(I),RADIAL(I), (PHI(I,L),L=1,6),J=1,NROD)
C  COMPUTE ROD LAYOUT FACTORS
    DO 238 NR=1,NKOD
    DO 226 L=1,6
    IF(LR(NR,L))226,226,225
225 K = LR(NR,L)
    KROD(K,NR) = 1
    PWRF(K,NR) = PHI(NR,L)
226 CONTINUE
    DR(NR) = D(NR)
238 D(NR)=D(NR)/12.
C  CHECK FOR NEW CALCULATION TOLERANCES, ETC.
250 IF(J6)260,260,252
252 READ(I2,17) BETA,XMIX,FDIV,FMIX,NPRINT,NX,KDEBUG,WERROR,ITERAT
    IF(NX.LT.1) NX=1
    IF(WERROR.LT.1.0E-10) WERROR = 10.
    IF(ITERAT.LT.1) ITERAT = 25
C  CHECK FOR NEW OPERATING CONDITIONS
260 IF(J7)290,290,262
262 READ (I2,20) POUT,HIN,GIN,AFLUX,Z, THETA
    IF(HIN)254,254,255
254 READ(I2,10) (H(J,1),J=1,NCHANL)
255 IF(GIN)256,256,257
256 READ(I2,9) (F(J,1),J=1,NCHANL)
257 PREF = POUT
    ZZ = Z
    Z = Z/12.
290 DX = Z/FLOAT((NPRINT-1)*NX)
    DXX = DX*12.
    HOUT = HIN + AFLUX*PHTOT*Z/(GIN*ATOTAL)
    PIN = 0.

```

```

      FLO = GIN * ATOTAL *1.0E+06
      LPROP = 1
      CALL PROP
      IF(IEERROR.GT.1) GO TO 540
      LPROP = 2
      NCHANL = NCHANL
      DO 263 I=1,NCHANL
263  AQPRIM(I)=0.
      NCHANL = NCHANL
      DO 265 I=1,NCHANL
      NROD = NROD
      DO 265 NR=1,NROD
      IF(KROD(I,NR)) 265,265,264
264  AQPRIM(I) = AQPRIM(I) + PI*D(NR)*AFLUX*RADIAL(NR)*PWRF(I,NR)
      1*1.0E+06
265  CONTINUE
      WRITE (I3,6)      (Y(I),AXIAL(I),I=1,NAX)
      NLINE = NLINE + NAX + 5
      IF(NLINE + NCHANL + 6 - 48) 2650,2650,2651
2650 NLINE = NLINE+NCHANL+6
      GO TO 2652
2651 NLINE = 0
      WRITE (I3,29)
2652 WRITE (I3,12) (I,AC(I),PW(I),PH(I), DC(I),(S(I,L),LC(I,L),L=1,4)
      1,I=1,NCHANL)
      IF(NLINE+NROD+5-48) 2653,2653,2654
2653 NLINE = NLINE+NROD+5
      GO TO 2655
2654 NLINE = 0
      WRITE (I3,29)
2655 WRITE(I3,15)(I,DR(I),RADIAL(I), (PHI(I,L),LR(I,L),L=1,6),I=1,NROD)
      IF(NLINE+9-48) 2656,2656,2657
2656 NLINE = NLINE+9
      GO TO 2658
2657 NLINE = 0
      WRITE (I3,29)
2658 WRITE(I3,18) BETA,XMIX,FDIV,FMIX,NPRINT,NX
      IF(NLINE+11-48) 2660,2660,2659
2659 WRITE( I3,29)
2660 WRITE(I3,21) POUT,HIN,GIN,AFLUX,ZZ,THETA,DXX,HOUT
      IEERROR=1
      IF(KDEBUG) 267,267,266
266 WRITE (I3,50) ((LC(I,L),I=1,NCHANL),L=1,4)
      WRITE (I3,50) ((KCHAN(I,J),J=1,NCHANL),I=1,NCHANL)
      WRITE (I3,50) ((K(K),JK(K),K=1,NK)
      WRITE (I3,51) (FACTOR(K),K=1,NK)
      WRITE (I3,50) ((LR(NR,L),NR=1,NROD),L=1,6)
      WRITE (I3,50) ((KROD(I,NR),NR=1,NROD ),I=1,NCHANL)
      WRITE (I3,51) ((PWRF(I,NR),NR=1,NROD ),I=1,NCHANL)

```

```

WRITE (I3,51) (D(NR),NR=1,NROD),(RADIAL(NR),NR=1,NROD)
WRITE (I3,51) (AQPRIM(I),I=1,NCHANL),(HPRIM(I),I=1,NCHANL)
267 NCHANL = NCHANL
DO 291 I=1,NCHANL
291 DHYDE(I) = DHYD(I)**0.3
DO 302 J=1,NCHANL
DEN = 0.
DO 301 I=1,NCHANL
301 DEN = DEN + A(I)*DHYDE(I)/(A(J)*DHYDE(J))
P(J,1) = PIN
IF(HIN)3011,3011,3010
3010 H(J,1) = HIN
3011 IF(GIN)302,302,3012
3012 F(J,1) = FLO /DEN
F(J,2) = F(J,1)
302 CONTINUE
N = 1
CALL PROP
C FLOW SPLITTING ROUTINE
E = .005
DO 3030 K=1,NK
3030 W(K) = 0.
IF(GIN)311,311,303
303 DO 309 L=1,200
ISPLIT = 1
CALL MIX
CALL DIFFER (1)
IF(IERROR.GT.1) GO TO 3090
IF(KDEBUG.LT.1) GO TO 304
WRITE (I3,52) (I,DP(I),DH(I),DF(I),
1P(I,N),H(I,N),F(I,N),I=1,NCHANL)
304 FTOT = 0.
PAVG = 0.
DO 305 I=1,NCHANL
IF(DP(I)) 3090,3090,305
305 PAVG = PAVG + DP(I)*A(I)
PAVG = PAVG/ATOTAL
DO 306 I=1,NCHANL
CORR = (PAVG/DP(I))**(0.4-0.3*FMIX)
IF(CORR.LT.1.05.AND.CORR.GT..95) GO TO 3050
IF(CORR.GT.1.04) CORR=1.05
IF(CORR.LT..96) CORR=.95
3050 F(I,1) = F(I,1)*CORR
IF((PAVG/DP(I)).GT.1.-E.AND.(PAVG/DP(I)).LT.1.+E ) GO TO 306
ISPLIT = 2
306 FTOT = FTOT + F(I,1)
FTOT = FLO /FTOT
DO 307 I=1,NCHANL
F(I,1) = F(I,1) * FTOT

```

```

307 F(I,2) = F(I,1)
   IF(FTOT.GT.1.-E.AND.FTOT.LT.1.+E ) GO TO 308
   ISPLIT = 3
308 GO TO (310,309,309),ISPLIT
309 CONTINUE
3090 WRITE (I3,27 ) ISPLIT,(J,F(J,1),DP(J),J=1,NCHANL)
   IERROR = 2
   GO TO 540
311 CALL MIX
   CALL DIFFER(1)
   K=1
   IF(IERROR.GT.1) GO TO 520
310 X(1) = 0.
C
C  START OF CHANNEL INTEGRATION
C
   DO 500 K=1,NPRINT
   XV(K)=X(1)*12.
   NCHANL = NCHANL
   DO 401 J=1,NCHANL
   PV(J,K)= P(J,1)
   HV(J,K)= H(J,1)
   QUALTY(J,K)=QUAL(J)
   FLOW(J,K) = F(J,1)
   FV(J,K)= F(J,1)*1.0E-06/A(J)
401 QV (J,K) = QPRIM(J) *1.0E-06/HPERIM(J)
   DO 402 L=1,NK
   WV(L,K) = W(L)
402 WPV(L,K) = WP(L)
   IF(K.EQ.NPRINT) GO TO 521
   DO 500 NSEG=1,NX
   N = 1
C**  SET UP EXTRAPOLATION TO NEXT INCREMENT
   X(N+1)=X(N)+DX
   DO 410 I=1,NCHANL
   F(I,N ) = F(I,N) + 0.5*DF(I)
   H(I,N ) = H(I,N) + 0.5*DH(I)
   F(I,N+1) = F(I,N) + 0.5*DF(I)
   H(I,N+1) = H(I,N) + 0.5*DH(I)
410 P(I,N ) = P(I,N) + 0.5*DP(I)
   N = 2
   CALL PROP
   CALL MIX
   CALL DIFFER(1)
   IF(IERROR.GT.1) GO TO 520
C**  BEGIN ITERATION
411 DO 450 M=1,ITERAT
   N=2
   CALL MIX

```

```

      CALL DIFFER(IPART)
C** PRESSURE AT X+DX WITHOUT NATURAL DIVERSION CROSSFLOW
      DO 420 I=1,NCHANL
420 P(I,2) = P(I,1) + 0.5*DP(I)
C** COMPUTE NATURAL DIVERSION CROSSFLOW AT X+DX
      CALL DIVERT
      IF(IEERROR.GT.1) GO TO 520
      IPART = 2
      DO 430 L=1,NK
      IF(ABS(W(L)-WOLD(L)).GT.WERROR) IPART=1
      IF(C(L).GT.1.E-30) W(L) = .6*W(L) + .4*WOLD(L)
430 WOLD(L)=W(L)
C** COMPUTE VALUES FOR NEXT ITERATION OR NEXT INCREMENT
      CALL DIFFER(IPART)
      IF(IEERROR.GT.1) GO TO 520
      N=1
      DO 440 I=1,NCHANL
      F(I,N+1) = F(I,N) + 0.5*DF(I)
      H(I,N+1) = H(I,N) + 0.5*DH(I)
440 P(I,N+1) = P(I,N) + 0.5*DP(I)
      IF(KDEBUG.LT.1) GO TO 425
      WRITE(I3,52) (I,DP(I),DH(I),DF(I),P(I,N+1),H(I,N+1),F(I,N+1),
1 I=1,NCHANL)
425 GO TO (450,480),IPART
450 CONTINUE
      WRITE (I3,22) ITERAT,X(N+1),K,NSEG
      GO TO 520
480 IF(KDEBUG) 482,482,481
481 WRITE (I3,54)
482 DO 445 I=1,NCHANL
      P(I,N) = P(I,N+1)
      F(I,N) = F(I,N+1)
445 H(I,N) = H(I,N+1)
      X(N) = X(N+1)
      DO 500 J=1,NCHANL
      IF(F(J,1).LT.0.) GO TO 505
500 CONTINUE
      GO TO 521
505 WRITE (I3,24) (J,P(J,1),H(J,1),F(J,1),J=1,NCHANL)
      IEERROR = 2
520 N=1
      WRITE (I3,53) (I,DP(I),DH(I),DF(I),I=1,NCHANL)
      WRITE (I3,52) (I,P(I,N+1),H(I,N+1),F(I,N+1),P(I,N),H(I,N),F(I,N),
1 I=1,NCHANL)
      WRITE (I3,53) (I,RHO(I),U(I),QUAL(I),I=1,NCHANL)
      WRITE (I3,53) (L,W(L),WOLD(L),WP(L),L=1,NK)
521 ND = K
      DO 535 M=1,NCHANL,2
      MM=M+1

```



```
      IF(NCHANL.GE.MM) GO TO 531
      IF(NCHANL.GE.MM-1) GO TO 532
      GO TO 535
531  WRITE (I3,25) KASE,TEXT,(J,J=M,MM),(XV(N),(PV(J,N),HV(J,N),
      1QUALTY(J,N),FV(J,N), FLOW(J,N),QV(J,N),J=M,MM),N=1,ND)
      GO TO 535
532  MM=MM-1
      WRITE (I3,26) KASE,TEXT,(J,J=M,MM),(XV(N),(PV(J,N),HV(J,N),
      1QUALTY(J,N),FV(J,N), FLOW(J,N),QV(J,N),J=M,MM),N=1,ND)
535  CONTINUE
      DO 539 M=1,NK,5
      MM=M+4
      IF(NK.LE.MM) MM=NK
      WRITE (I3,31) KASE,TEXT,(HEAD(1,K),IK(K),HEAD(2,K),JK(K),
      1HEAD(3,K),IK(K),HEAD(2,K),JK(K),HEAD(4,K),K=M,MM)
      DO 536 N=1,ND
536  WRITE (I3,30) XV(N),(WV(K,N),WPV(K,N),K=M,MM)
539  CONTINUE
540  GO TO 200
      END
```

```

SUBROUTINE PROP
  DIMENSION B(36)
  COMMON /BTBL/ PP(30),TT(30),VVF(30),VVG(30),HHF(30),HHG(30),
  1UUF(30),HH(26),DVPDPP(25),NPROP,LPROP
  COMMON /BPROP/ RHO(36),V(36),VP(36),DVPDP(36),DVPDH(36),VISC(36),
  1PREF,QUAL(36),ALPHA(36),VF,VG,T(36)
  COMMON /BMIX/ WP(60),U(36),P(36,2),H(36,2),F(36,2),A(36),GAP(60),
  1X(2),BETA,XMIX,FDIV,FMIX,C(60),DF(36),DH(36),DP(36),DX,DHYD(36),
  1QPRIM(36),AFLUX,Z,KCHAN(36,36),AXIAL(30),YY(30),AQPRIM(36),AA,
  1BB,CX,THETA,NAX,FACTOR(60),IK(60),JK(60),PI,G
  COMMON /BCOM/ I3,NCHANL,NK,IERROR,KDEBUG,N
  JJ=1
  GO TO (100,200),LPROP
C  COMPUTE SATURATED PROPERTIES
  100 DO 115 I=1,NPROP
C  SEARCH FOR PRESSURE
    IF(PREF.LT.PP(I))GO TO 120
  115 CONTINUE
    JJ=3
    GO TO 400
  120 IF(I.GT.1) GO TO 140
    JJ=2
    GO TO 400
  140 CC=(PREF-PP(I-1)) / (PP(I)-PP(I-1))
    HF = HHF(I-1) +CC*(HHF(I)-HHF(I-1))
    HG = HHG(I-1) +CC*(HHG(I)-HHG(I-1))
    VF = VVF(I-1) +CC*(VVF(I)-VVF(I-1))
    VG = VVG(I-1) +CC*(VVG(I)-VVG(I-1))
    UF = UUF(I-1) +CC*(UUF(I)-UUF(I-1))
    TF = TT(I-1) +CC*(TT(I)-TT(I-1))
    HFG = HG-HF
    RHOF = 1./VF
    RHOG = 1./VG
C  COMPUTE TABLE OF DVPDP VS H
    CC=(PREF+10.-PP(I-1)) / (PP(I)-PP(I-1))
    VFP= VVF(I-1) +CC*(VVF(I)-VVF(I-1))
    VGP= VVG(I-1) +CC*(VVG(I)-VVG(I-1))
    HFP= HHF(I-1) +CC*(HHF(I)-HHF(I-1))
    HGP= HHG(I-1) +CC*(HHG(I)-HHG(I-1))
    DH = HFG*0.04
    HFGP = HGP-HFP
    HH(1) = HF
    HH(2)=HF+DH
    DVPDPP(1)=0.

```

```

DO 190 J=2,25
  Y = (HH(J)-HF)/HFG
  CALL ARMAND (ALPH,PHI,Y,VG,VF)
  VP1= VF*(1.-Y)**2/(1.-ALPH ) + VG*Y**2/ALPH
  Y = (HH(J)-HFP)/HFGP
  IF(Y.GT.0.)GO TO 145
  Y = 0.
145 IF(Y.LT.1.)GO TO 155
  Y = 1.
155 CALL ARMAND (ALPH,PHI,Y,VGP,VFP)
  VPP= VFP*(1.-Y)**2/(1.-ALPH ) + VGP*Y**2/ALPH
  DVPDPP(J) = (VPP - VP1)*.1
190 HH(J+1)=HH(J)+DH
  GO TO 400
200 DO 399 J=1,NCHANL
  IF(H(J,N).GT.HF) GO TO 300
C COMPUTE SUBCOOLED PROPERTIES
  DO 215 I=1,NPROP
C SEARCH ON H TO GET PROPERTIES
  IF(H(J,N).LT.HHF(I)) GO TO 220
215 CONTINUE
  JJ=5
  GO TO 400
220 IF(I.GT.1) GO TO 240
  JJ= 4
  GO TO 400
240 B(J)=(H(J,N)- HHF(I-1)) / (HHF(I) -HHF(I-1))
  V(J) = VVF(I-1) + B(J)*(VVF(I) - VVF(I-1))
  T(J) = TT(I-1) + B(J)*( TT(I) - TT(I-1))
  VISC(J)=UUF(I-1)+ B(J)*(UUF(I) - UUF(I-1))
  VP(J)= V(J)
  DVPDP(J) = 0.
  DVPDH(J) = 0.
  RHO(J)= 1./V(J)
  ALPHA(J) = 0.
  QUAL(J) = 0.
  GO TO 399
C COMPUTE TWO-PHASE PROPERTIES
300 IF(H(J,N).LT.HG) GO TO 301
  QUAL(J) = 1.0
  WRITE ( 6,2) J
  2 FORMAT (36H SUPERHEATED VAPOR FOUND IN CHANNEL ,I2,20H CALCULATIO
  IN STOPPED )
  IERROR = 3
  GO TO 302
301 QUAL(J) = (H(J,N)-HF)/HFG
302 CALL ARMAND (ALPHA(J),PHI,QUAL(J),VG,VF)
  RHO(J)= RHOG*ALPHA(J)+RHOF*(1.-ALPHA(J))
  V(J) = 1./RHO(J)

```

```
VP(J) = VF*(1.-QUAL(J))**2/(1.-ALPHA(J))+VG*QUAL(J)**2/ALPHA(J)
CALL CURVE (DVPDP(J),H(J,N),DVPDPP,HH,25,K)
XP = QUAL(J)+10./HFG
IF(XP.LT.1.) GO TO 305
XP = 1.
305 CALL ARMAND (ALPHAP,PHI,XP,VG,VF)
VPP =VF *(1.-XP)**2/(1.-ALPHAP) +VG *XP**2/ALPHAP
DVPDH(J) = (VPP - VP(J))*1
VISC(J) = UF
399 CONTINUE
400 IF(JJ.EQ.1)GO TO 500
WRITE (I3,1) JJ
1 FORMAT (60H FAILURE OF PROPERTY SUBROUTINE, CALCULATION STOPPED,
1JJ = I5 )
IERROR = 2
500 RETURN
END
```

```

      SUBROUTINE ARMAND (ALPHA,PHI,X,VG,VF)
      IF(X) 20,20,10
C  VOID FRACTION, ALPHA
10  ALPHA = (0.833+0.167*X)*X*VG/((1.0-X)*VF+X*VG)
C
C  FRICTION MULTIPLIER, PHI
      PHI = 1.0
      IF((1.-ALPHA).GT..39.AND.(1.-ALPHA).LT.1.0001) GO TO 12
      IF((1.-ALPHA).GT..10.AND.(1.-ALPHA).LT..391) GO TO 14
      IF((1.-ALPHA).GT.(-.0001).AND.(1.-ALPHA).LT..1001) GO TO 16
12  PHI = (1.-X)**2/(1.-ALPHA)**1.42
      GO TO 30
14  PHI = 0.478*(1.-X)**2/(1.-ALPHA)**2.2
      GO TO 30
16  PHI = 1.730*(1.-X)**2/(1.-ALPHA)**1.64
      GO TO 30
20  ALPHA = 0.
      PHI = 1.
30  RETURN
      END

```

```

      SUBROUTINE CURVE (FX,X,F,Y,N,J)
C
C  DIMENSION F(35),Y(35)
C
      J=1
      DO 50 I=1,N
      IF(X-Y(I))10,40,20
10  IF(I-1)30,30,15
15  FX=F(I-1) + (F(I)-F(I-1))*(X-Y(I-1))/(Y(I)-Y(I-1))
      GO TO 60
20  IF(N-I)30,30,50
30  J=2
      GO TO 60
40  FX=F(I)
      GO TO 60
50  CONTINUE
60  RETURN
      END

```

```

SUBROUTINE MIX
COMMON /BPROP/ RHO(36),V(36),VP(36),DVPDP(36),DVPDH(36),VISC(36),
1PREF,QUAL(36),ALPHA(36),VF,VG,T(36)
COMMON /BMIX/ WP(60),U(36),P(36,2),H(36,2),F(36,2),A(36),GAP(60),
1X(2),BETA,XMIX,FDIV,FMIX,C(60),DF(36),DH(36),DP(36),DX,DHYD(36),
1QPRIM(36),AFLUX,Z,KCHAN(36,36),AXIAL(30),Y(30),AQPRIM(36),AA,
1BB,CC,THETA,NAX,FACTOR(60),IK(60),JK(60),PI,G
COMMON /BEQN/ AAA(60,61),W(60)
COMMON /BCOM/ I3,NCHANL,NK,IERROR,KDEBUG,N
NK=NK
DO 20 K=1,NK
  WP(K)=0.
20 C(K)=0.
  NCHANL=NCHANL
  DO 100 I=1,NCHANL
    DO 100 J=I,NCHANL
      K=KCHAN(I,J)
      IF(K) 100,100,30
C** COMPUTATION OF TURBULENT CROSSFLOW WP(K)
  30 WP(K) = GAP(K)*BETA*0.5*(F(I,N)/A(I) + F(J,N)/A(J))
C** COMPUTE NATURAL DIVERSION CROSSFLOW COEFFICIENT C(K)
  IF(W(K)) 40,40,50
  40 C(K) = XMIX*V(J)/(576.*G*GAP(K)**3)
    GO TO 100
  50 C(K) = XMIX*V(I)/(576.*G*GAP(K)**3)
100 CONTINUE
  RETURN
  END

```

```

SUBROUTINE DIFFER (IPART)
COMMON /BPROP/ RHO(36),V(36),VP(36),DVPDP(36),DVPDH(36),VISC(36),
1PREF,QUAL(36),ALPHA(36),VF,VG,T(36)
COMMON /BEQN/ AAA(60,61),W(60)
COMMON /BMIX/ WP(60),U(36),P(36,2),H(36,2),F(36,2),A(36),GAP(60),
1X(2),BETA,XMIX,FDIV,FMIX,C(60),DF(36),DH(36),DP(36),DX,DHYD(36),
1QPRIM(36),AFLUX,Z,KCHAN(36,36),AXIAL(30),Y(30),AQPRIM(36),AA,
1BB,CC,THETA,NAX,FACTOR(60),IK(60),JK(60),PI,G
COMMON /BCOM/ I3,NCHANL,NK,IERROR,KDEBUG,N
C COMPUTE AXIAL FLUX FACTOR
CALL CURVE (QAX,X(N)/Z,AXIAL,Y,NAX,JA)
NCHANL = NCHANL
DO 10 I=1,NCHANL
10 U(I) = F(I,N) * VP(I) / A(I)
NCHANL=NCHANL
DO 90 I=1,NCHANL
C COMPUTE INITIAL VALUES BEFORE ANY MIXING
DF(I) = 0.
CALL ARMAND(ALPHA(I),PHI,QUAL(I),VG,VF)
RE = F(I,N) / A(I) * DHYD(I) / VISC(I)
IF(KDEBUG) 16,16,15
15 WRITE(I3,101) I,F(I,N),DHYD(I),VISC(I),QUAL(I),ALPHA(I),PHI,
1DVPDH(I),DVPDP(I),RHO(I),DH(I),U(I)
101 FORMAT (I5,11E10.3)
16 FSP = AA*RE**BB+ CC
DP(I) = (F(I,N)/A(I))**2/G*(0.5*FSP*VF*PHI/DHYD(I)+DVPDH(I)
1*DH(I)/DX + RHO(I)*COS(0.017453*THETA)
QPRIM(I) = AQPRIM(I)*QAX
DH(I) = QPRIM(I)
DO 70 J=1,NCHANL
K=KCHAN(I,J)
IF(K) 70,70,20
20 DH(I) = DH(I) + WP(K)*(H(J,N)-H(I,N))*FACTOR(K)
DP(I) = DP(I) + WP(K)*(U(I)-U(J))*FMIX*FACTOR(K)/G/A(I)
IF(I-J) 21,21,40
21 DF(I) = DF(I) - W(K)*FACTOR(K)
IF(W(K)) 22,30,30
22 DH(I) = DH(I) - W(K)*(H(J,N)-H(I,N))*FACTOR(K)
IF(IPART,EQ.2)
1DP(I) = DP(I) + W(K)*U(I)*(FDIV*U(J)/U(I)-2.)*FACTOR(K)/G/A(I)
GO TO 70
30 IF(IPART,EQ.2)
1DP(I) = DP(I) + W(K)*U(I)*(FDIV-2.)*FACTOR(K)/G/A(I)
GO TO 70

```

```
40 DF(I) = DF(I) + W(K)*FACTOR(K)
   IF(W(K)) 50,50,60
50 IF(IPART.EQ.2)
   1DP(I) = DP(I) - W(K)*U(I)*(FDIV-2.)*FACTOR(K)/G/A(I)
   GO TO 70
60 DH(I) = DH(I) + W(K)*(H(J,N)-H(I,N))*FACTOR(K)
   IF(IPART.EQ.2)
   1DP(I) = DP(I) - W(K)*U(I)*(FDIV*U(J)/U(I)-2.)*FACTOR(K)/G/A(I)
70 CONTINUE
   DF(I) = DF(I)*DX
   DH(I) = DH(I)*DX/F(I,N)
   DP(I) = DP(I)*DX/(144.+(F(I,N)/A(I))**2*DVPDP(I)/G)
90 CONTINUE
   RETURN
   END
```



```

SUBROUTINE DIVERT
DIMENSION DD(36,60)
COMMON /BEQN/ AAA(60,61),W(60)
COMMON /BPROP/ RHO(36),V(36),VP(36),DVPDP(36),DVPDH(36),VISC(36),
1PREF,QUAL(36),ALPHA(36),VF,VG,T(36)
COMMON /BMIX/ WP(60),U(36),P(36,2),H(36,2),F(36,2),A(36),GAP(60),
1X(2),BETA,XMIX,FDIV,FMIX,C(60),DF(36),DH(36),DP(36),DX,DHYD(36),
1QPRIM(36),AFLUX,Z,KCHAN(36,36),AXIAL(30),Y(30),AQPRIM(36),AA,
1BB,CC,THETA,NAX,FACTOR(60),IK(60),JK(60),PI,G
COMMON /BCOM/ I3,NCHANL,NK,IERROR,KDEBUG,N
C** COMPUTE COEFFICIENTS OF CROSSFLOW TERMS
NCHANL=NCHANL
DO 5 I=1,NCHANL
NK=NK
DO 5 K=1,NK
5 DD(I,K) = 0.
DO 50 I=1,NCHANL
Q = 0.5*DX*U(I)/G/A(I)/(144.+(F(I,N)/A(I))**2*DVPDP(I)/G)
DO 50 J=1,NCHANL
K=KCHAN(I,J)
IF(K) 50,50,10
10 IF(I=J) 12,12,30
12 IF(W(K)) 22,20,20
20 DD(I,K) = Q*(FDIV-2.)*FACTOR(K)
GO TO 50
22 DD(I,K) = Q*(FDIV*U(J)/U(I)-2.)*FACTOR(K)
GO TO 50
30 IF(W(K)) 31,31,32
31 DD(I,K) = -Q*(FDIV-2.)*FACTOR(K)
GO TO 50
32 DD(I,K) = -Q*(FDIV*U(J)/U(I)-2.)*FACTOR(K)
50 CONTINUE
C** COMPUTE MATRIX ELEMENTS A(L,K) AND B(L) BY SUBTRACTING THE
C COEFFICIENTS FROM EQUATIONS FOR ADJACENT CHANNELS
NK = NK
DO 100 L=1,NK
II = IK(L)
JJ = JK(L)
AAA(L,NK+1) = P(JJ,N ) - P(II,N )
DO 100 K=1,NK
AAA(L,K) = DD(II,K) - DD(JJ,K)
IF(K.EQ.L) AAA(K,K) = AAA(K,K) - C(K)*ABS(W(K))
100 CONTINUE
IF(KDEBUG) 101,101,102

```

```
102 NKP = NK+1
    DO 103 L=1,NK
103 WRITE (I3,2) L,(AAA(L,K),K=1,NKP)
    2 FORMAT (I3,10E12.6,/(3X,10E12.6))
    WRITE (I3,1) (C(L),L=1,NK)
    1 FORMAT(10E12.6 )
101 NK=NK
    CALL CROUT5 (AAA,w,NK,7*NK,4,IERROR)
    NK=NK
    IF(IERROR.GT.1) GO TO 180
    IF(KDEBUG) 200,200,111
111 WRITE(I3,1) (w(K),K=1,NK),(WP(K),K=1,NK)
180 NKP = NK+1
    DO 190 L=1,NK
190 WRITE (I3,2) L,(AAA(L,K),K=1,NKP)
200 RETURN
    END
```

```

SUBROUTINE CROUT5(AA,C,INPUTN,NC,NF,IERROR)
C SOLVES A SYSTEM OF N LINEAR ALGEBRAIC EQUATIONS IN N UNKNOWN BY
C THE CROUT METHOD
C REF- AIEE TRANS 1941 VOL 60 P1235-1240
C
C A IS N,N+1 MATRIX OF INPUT COEFFICIENTS
C C IS N,1 COLUMN MATRIX OF UNKNOWN AS OUTPUT
C NC IS MAX NUMBER OF ITERATIONS TO BE PERMITTED
C NF IS NUMBER OF SIGNIFICANT FIGURES OF ACCURACY REQUIRED IN
C BALANCE OF TWO SIDES OF EACH EQUATION (NOT TO EXCEED 6)
C
C (REVISION FOR SPECIFIC APPLICATIONS - A CHANGE IN THE DIMENSION
C STATEMENT DOES NOT REQUIRE ANY ADDITIONAL PROGRAM CHANGES)
C
DIMENSION A(60,61),B(60,61),D(60),AL(61)
COMMON /BEQN/ AA(60,61),C(60)
100 FORMAT (84H0ACCURACY OF SIMULTANEOUS EQUATION SOLUTION HAS NOT REA
1CHED THE REQUIRED VALUE AFTER I3,13H CORRECTIONS./59H MAXIMUM ERROR
2 IN BALANCE OF TWO SIDES OF EACH EQUATION IS 1PE10.3,8H IN THE I1,
322HTH SIGNIFICANT FIGURE.)
101 FORMAT (119H0SUBROUTINE CROUT5 REQUIRES THAT AT LEAST ONE INPUT EQ
1UATION HAVE A NON-ZERO FIRST COEFFICIENT. NO SOLUTION IS POSSIBLE)
102 FORMAT (119H0SUBROUTINE CROUT5 IS UNABLE TO FORM AN AUXILIARY MATR
1IX WITHOUT A ZERO ON THE DIAGONAL. NO VALID SOLUTION IS POSSIBLE.)
104 FORMAT (101H0NO SOLUTION IS POSSIBLE FROM CROUT5 BECAUSE OF AN INS
1UFFICIENT NUMBER OF EQUATIONS IN THE INPUT SET./4H ROW I3,28H IS A
2N EXACT MULTIPLE OF ROW I3,1H.)
105 FORMAT(7H0COLUMN I5,21H IS IDENTICALLY ZERO.)
106 FORMAT(7H0 ROW I5,21H IS IDENTICALLY ZERO.)
107 FORMAT(7H0COLUMN I5,31H IS AN EXACT MULTIPLE OF COMUMNI5,1H.)
I3=6
N=INPUTN
ZFAC=10.** (NF-1)
KOUNT = 0
NIL=1
NP=N+1
NM=N-1
DO 201 I=1,N
DO 201 J=1,NP
201 A(I,J)=AA(I,J)
C TESTS FOR INVALID INPUT DATA
DO 401 J=1,N

```

```

      IF(FACTOR) 311,1211,311
1211 P=ABS(A(I,J))
      Q=ABS(A(I,K))
      IF(BOOL(AND(OR(P,Q),OR(COMPL(P),COMPL(Q))))511,211,511
211 CONTINUE
      GO TO 511
311 IF(KKI=N) 1311,1311,511
1311 DO 411 I=KKI,N
      IF(ABS((FACTOR-A(I,J)/A(I,K))/FACTOR)-.5E-7) 411,411,511
411 CONTINUE
      GO TO 85
511 CONTINUE
C   CONSTRUCTION OF INTERMEDIATE MATRIX
12 DO 13 I=1,N
      D(I)=0.0
      AL(I)=A(I,NP)
13 B(I,1)=A(I,1)
14 DO 15 I=1,N
15 B(1,I+1)=A(1,I+1)/A(1,1)
      DO 17 L=2,N
      DO 17 I=L,N
          SM=0.
          SP=0.
          TM=0.
          TP=0.
          DO 16 J=2,L
              S=B(I,J-1)*B(J-1,L)
              T=B(L,J-1)*B(J-1,I+1)
              IF(S) 215,415,315
215 SM=SM+S
              GO TO 415
315 SP=SP+S
415 IF(T) 515,16,615
515 TM=TM+T
              GO TO 16
615 TP=TP+T
16 CONTINUE
          S=SP+SM
          T=TP+TM
          B(I,L)=A(I,L)-S
17 B(L,I+1)=(A(L,I+1)-T)/B(L,L)
C   TEST FOR ZERO DIAGONAL IN AUXILIARY MATRIX
      DO 23 I=1,N
          IF (B(I,I)) 23,202,23
23 CONTINUE
C   CALCULATION OF MATRIX OF VARIABLES (BACK SUBSTITUTION)
31 KOUNT=KOUNT+1
      C(N)=B(N,NP)
      DO 33 I=2,N

```

```

      AJ=0.
      DO 301 I=1,N
301  AJ=AMAX1(AJ,ABS(A(I,J)))
      IF(AJ) 83,83,401
401  CONTINUE
      DO 601 I=1,N
      AJ=0.
      DO 501 J=1,N
501  AJ=AMAX1(AJ,ABS(A(I,J)))
      IF(AJ) 84,84,601
601  CONTINUE
      IZ=2
      1 IF (A(1,1)) 6,2,6
202  DO 302 J=1,N
302  A(J,NP)=AL(J)
      NIL=3
      2 IF (IZ=N) 3,3,5
      3 DO 4 JZ=1,NP
      AL(JZ)=A(1,JZ)
      A(1,JZ)=A(IZ,JZ)
      4 A(IZ,JZ)=AL(JZ)
      IZ=IZ+1
      GO TO 1
      5 GO TO (71,71,72), NIL
      6 GO TO (7,7,12), NIL
      7 DO 11 I=1,NM
      IP=I+1
      DO 11 K=IP,N
      DO 209 J=1,NP
      KKI=J+1
      FACTOR = A(I,J)/A(K,J)
      IF(FACTOR) 309,1209,309
1209 P=ABS(A(I,J))
      Q=ABS(A(K,J))
      IF(BOOL(AND(OR(P,Q),OR(COMPL(P),COMPL(Q)))))11,209,11
209  CONTINUE
      GO TO 11
309  IF(KKI=NP) 409,409,11
409  DO 10 J=KKI,NP
      IF(ABS((FACTOR-A(I,J)/A(K,J))/FACTOR) -.5E-7) 10,10,11
      10 CONTINUE
      GO TO 74
      11 CONTINUE
      DO 511 J=1,NM
      JP=J+1
      DO 511 K=JP,N
      DO 211 I=1,N
      KKI=I+1
      FACTOR=A(I,J)/A(I,K)

```

```

      K=NP-I
      KM1=K-1
      SM=0.
      SP=0.
      DO 32 L=2,I
      KL=KM1+L
      S=C(KL)*B(K,KL)
      IF(S) 231,32,331
231  SM=SM+S
      GO TO 32
331  SP=SP+S
      32 CONTINUE
      S=SP+SM
      33 C(K)=B(K,NP)-S
C    CORRECTION OF ELEMENTS OF VARIABLES MATRIX
      DO 41 I=1,N
      41 C(I)=C(I)+D(I)
C    CALCULATION OF NEXT CORRECTION
      DO 52 I=1,N
      SM=0.
      SP=0.
      DO 51 J=1,N
      S=A(I,J)*C(J)
      IF(S) 50,51,250
      50 SM=SM+S
      GO TO 51
250  SP=SP+S
      51 CONTINUE
      A(I,NP)=AL(I)-(SP+SM)
      52 D(I)=C(I)
C    CHECK FOR ACCURACY
      NIL=1
      ZOUNDS=0.0
      DO 69 I=1,N
      ZZ=0.
      DO 61 J=1,N
      61 ZZ=ZZ+C(J)*A(I,J)
      ZZ=ABS(AL(I)-ZZ)
      Z=ABS(AL(I))
      IF (ZZ/Z-0.5E-7) 69,69,62
      62 IF (1.0-Z) 65,66,63
      63 Z=10.0*Z
      ZZ=10.0*ZZ
      GO TO 62
      64 IF (1.0-Z) 65,66,66
      65 Z=0.1*Z
      ZZ=0.1*ZZ
      GO TO 64
      66 ZZ=ZZ*ZFAC

```

```
      IF (1.0-ZZ) 67,67,69
67  IF (KOUNT - NC) 70,70,68
68  NIL=2
      ZOUNDS=AMAX1(ZOUNDS,ZZ)
69  CONTINUE
      GO TO (81,77,81), NIL
C   MAKE CORRECTIONS
70  B(1,NP)=A(1,NP)/B(1,1)
      DO 870 I=2,N
          IM=I-1
          IF(A(I,NP)) 270,370,370
270  TM=A(I,NP)
          TP=0.
          GO TO 470
370  TM=0.
          TP=A(I,NP)
470  DO 770 K=1,IM
          T=B(I,K)*B(K,NP)
          IF(T) 570,770,670
570  TP=TP-T
          GO TO 770
670  TM=TM-T
770  CONTINUE
870  B(I,NP)=(TP+TM)/B(I,I)
      GO TO 31
C   MESSAGES FOR DUBIOUS SOLUTION OR INVALID INPUT
71  WRITE (I3,101)
      GO TO 75
72  WRITE (I3,102)
      GO TO 75
74  WRITE (I3,104)K,I
75  DO 76 I=1,N
76  C(I)=0.0
      IERROR=3
      GO TO 81
77  WRITE (I3,100)NC,ZOUNDS,NF
      IERROR=3
C   PREPARATION FOR RETURN
81  RETURN
83  WRITE (I3,105)J
      GO TO 75
84  WRITE (I3,106)I
      GO TO 75
85  WRITE (I3,107)K,I
      GO TO 75
      END
```


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