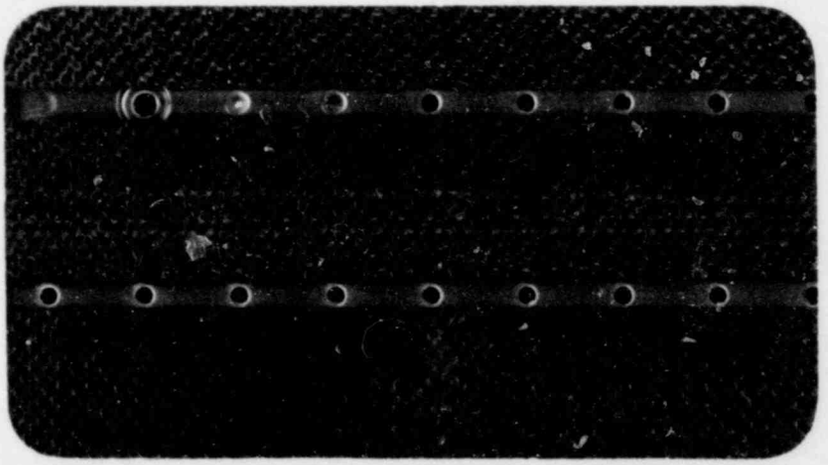

WCAP 10077

WESTINGHOUSE NON-PROPRIETARY CLASS 3

NOTRUMP

A NODAL TRANSIENT GENERAL NETWORK CODE

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ABSTRACT

NOTRUMP is a computer code for the simulation of general thermal hydraulic network transients. This report describes the governing equations and their numerical solution. It also describes the extensive modeling capabilities of the code. Detailed input and output descriptions are given. Comparisons of NOTRUMP results with experimental data are included to provide qualification.

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1.0 INTRODUCTION

NOTRUMP is a computer code for the simulation of general thermal hydraulic networks transients.

The following list of requirements were felt to be the minimum subset of important phenomena which should be reasonably represented:

1. A momentum balance suitable for predicting time-dependent flows.

2. A suitable slip flow model for the thermal hydraulic conditions involved.

3. Natural and mechanical phase separation models, including counter-current flow modeling capabilities.

4. The capability of incorporating time and spatial changes in operating conditions due to changes in boundary conditions or control systems.

5. Sufficient detail to represent the different physical and behavioral regions of steam generators.

6. Running times suitable for making a relatively large number of survey type runs.

The NOTRUMP computer code has been developed to fulfill these objectives. The name NOTRUMP is an acronym for NOdal TRansient U, M and P. (U, M and P are the important nodal paramaters: total mass, total internal energy and pressure, respectively.)

NOTRUMP addresses each of the requirements listed above. It is a general one-dimensional network code. The spatial detail of a problem is modeled by elemental control volumes, (nodes), appropriately interconnected by paths, (links). The spatial-temporal solution is then governed by the integral forms of the conservation equations in the nodes and links.

Flexible noding capabilities, i.e., the general interconnecting of nodes by links, make NOTRUMP a powerful analytical tool. This, together with the large number of allowable nodes and links, allows for sufficient modeling detail to represent many problems. Important applications of NOTRUMP are anticipated for problems requiring general one-dimensional thermal hydraulic network analyses.

The numerical integration procedure for the network conservation equations is a generalization of the implicit method [1]* used in FLASH-4[2], WFLASH [3] and TRANFLO[4].

NOTRUMP has a detailed momentum balance. Gravitational terms in NOTRUMP account for the elevations of fluid nodes and flow links and for the effects of phase distribution in stratified fluid nodes. The NOTRUMP treatment of gravitational terms allows for detailed modeling regions where these terms are important.

Frictional terms in the NOTRUMP momentum balance include the effects of friction and form losses. Friction and form factors can be supplied externally or calculated internally in the code and can also be included in the NOTRUMP momentum balance.

The drift flux and bubble rise models in NOTRUMP permit modeling of vertical slip flow, including counter-current flow. The treatment of phase separation (both natural and mechanical) and water level behavior is greatly facilitated by these models.

Even with the phase separation capabilities in NOTRUMP, some special models are needed for treating steam separator equipment. The TRANFLO models are used for the swirl vane and Peerless chevron separators.

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* Symbols in brackets apply to references in Section 13.

It is anticipated that, as better correlations and models are developed, they may be included in NOTRUMP.

Differential equations representing controllers are included in NOTRUMP. The controllers are the feedwater valve controller, the throttle valve controller and the primary water heater controller (for simulating model boilers). Modeling of the control systems gives greater capabilities for modeling certain transients.

"Boundary" nodes and "critical" links (critical links allow mass or heat flows to be specified) in NOTRUMP permit a convenient way of imposing boundary conditions. These may be used instead of controllers for the modeling of certain transients.

NOTRUMP has mixed implicit-explicit solution capabilities. The implicit (backward time differencing) technique is an extension of the implicit method to include implicitly the effect of metal nodes. Longer time steps are generally possible for this technique than for the explicit (forward time differencing) approach. However, where the use of explicit equations is adequate, NOTRUMP takes advantage of the reduced calculational effort associated with it. For example, metal nodes modeling the steam generator tubes can usually be treated explicitly.

The following material includes a general code description and detailed descriptions of modeling capabilities. Mathematical details, including solution techniques, are discussed. Information is given on code use, including input preparation and output interpretation. Code qualification is also discussed.

2.0 GENERAL CODE DESCRIPTION

This section contains a general description of the NOTRUMP code structure. NOTRUMP is a network code. The components which make up the network are defined and the conservation equations associated with these components are presented. An implicit (backward time differencing) technique is introduced. The vector differential equation representing the set of conservation equations is converted by the time differencing to a matrix equation. Finally the calculation procedure is described briefly.

The code components are: fluid nodes, metal nodes, flow links, heat links, and controller equations. These components themselves may be of several types, as will be described later in this section. Physical problems are modeled by using the components to form a network of multiple fluid and metal nodes, appropriately interconnected by flow and heat links. The nodes provide for mass and energy storage; the links provide for mass and energy transfer.

Thermal hydraulic effects are modeled in the code. Flow correlations model the effects of pressure drop and phase separation. Heat transfer correlations represent all regimes from liquid convection, through nucleate and transition boiling, to stable film boiling or forced convection vaporization and, finally, to steam forced convection. The flow and heat transfer correlations will be described in detail in Sections 5 and 6, respectively.

2.1 CODE COMPONENTS

A NOTRUMP network consists of a finite collection of flow and heat links which are joined at common fluid and metal nodes. In addition, controller equations are a part of the network.

The fluid nodes are labeled 1,...,I* where nodes 1,...,I are interior fluid nodes and nodes I+1,...,I* are boundary fluid nodes. Interior fluid nodes are described in Section 2.1.1 and boundary fluid nodes in Section 2.1.2.

The metal nodes are labeled 1,...,J* where nodes 1,...,J are interior metal nodes and nodes J+1,...,J* are boundary metal nodes. Interior and boundary metal nodes are described in Sections 2.1.3 and 2.1.4, respectively.

Flow links are labeled 1,...,K* where links 1,...,K are non-critical flow links and links K+1,...,K* are critical flow links. They are described in Sections 2.1.5 and 2.1.6.

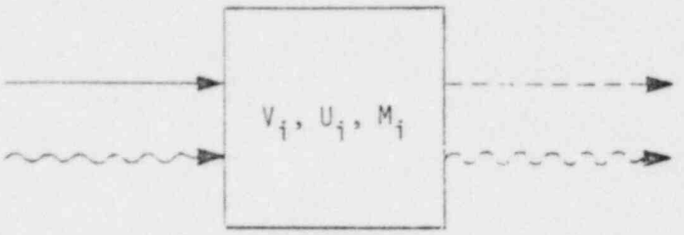
Heat links are labeled 1,...,L* where links 1,...,L are non-critical heat links and links L+1,...,L* are critical heat links. These heat links are described in Sections 2.1.7 and 2.1.8.

Controller equations are labeled 1,...M. They are described in Section 2.1.9.

2.1.1 INTERIOR FLUID NODES

An interior fluid node is defined as a fixed control volume containing fluid at thermodynamic equilibrium and having associated with it one conservation equation for total mass and one for total internal energy. No flow (only mass and energy inventory) is associated with a fluid node. An interior fluid node may be connected with other fluid nodes via flow links and with metal nodes via heat links. A schematic diagram of an interior fluid node is presented in Figure 2-1.

The energy and mass conservation equations for interior fluid node i in NOTRUMP are:



$$\dot{U}_i = \sum_{\kappa \varepsilon T_i{}^W} (hW)_\kappa - \sum_{\kappa \varepsilon I_i{}^W} (hW)_\kappa$$

$$+\sum_{\lambda \varepsilon T_i{}^Q} Q_\lambda - \sum_{\lambda \varepsilon I_i{}^Q} Q_\lambda$$

$$\dot{M}_i = \sum_{\kappa \varepsilon T_i{}^W} W_\kappa - \sum_{\kappa \varepsilon I_i{}^W} W_\kappa$$

FIGURE 2-1. NØTRUMP Interior Fluid Node

$$\dot{U}_i = \sum_{\kappa \varepsilon T_i^W} (hW)_\kappa - \sum_{\kappa \varepsilon I_i^W} (hW)_\kappa + \sum_{\lambda \varepsilon T_i^Q} Q_\lambda - \sum_{\lambda \varepsilon I_i^Q} Q_\lambda \qquad (2\text{-}1)$$

$$\dot{M}_i = \sum_{\kappa \varepsilon T_i^W} W_\kappa - \sum_{\kappa \varepsilon I_i^W} W_\kappa \qquad (2\text{-}2)$$

The set T_i^W is the set of flow links for which node i is the terminal node and I_i^W is the set of flow links for which node i is the initial node.

Likewise, T_i^Q is the set of heat links for which node i is the terminal node and I_i^Q is the set of heat links for which i is the initial node.

An interior fluid node has associated with it a number of important quantities. The total volume V [ft^3] is a constant. The total internal energy U [Btu/lbm] is the unknown in the energy conservation equation. The total mass M [lbm] is the unknown in the mass conservation equation. The pressure P [psia], temperature T [°F], thermodynamic quality χ [-], and various pressure and temperature derivatives are determined from the fluid equation of state given V, U, and M. Saturation properties are then found from P.

Although an interior fluid node is restricted to being in thermodynamic equilibrium, it need not be homogeneous. Stratified nodes are allowed. In these, there is a mixture of steam (bubbles) and liquid at the bottom of the node with a separated layer of steam at the top. A mixture elevation separates these two regions. Stratified nodes are discussed in detail in Appendix H.

2.1.2 BOUNDARY FLUID NODES

A boundary fluid node is defined as a control volume containing fluid at a specified pressure P [psia] and enthalpy h [Btu/lbm]. A boundary fluid node may be connected with other fluid nodes via flow links and with metal nodes via heat links. A schematic diagram of a boundary fluid node is presented in Figure 2-2.

The pressure and enthalpy for boundary fluid node i are specified as arbitrary functions of time.

$$P_i = P_i\ (t) \tag{2-3}$$

$$h_i = h_i\ (t) \tag{2-4}$$

Other important boundary fluid node quantities are the temperature T [°F], thermodynamic quality χ [-], and saturation properties. They are determined from the fluid equation of state given P and h.

Boundary fluid nodes provide a convenient means of imposing boundary conditions. A pressure boundary condition uses the specified pressure. If flow is out of the boundary fluid node, the donor enthalpy for the flow link is the specified enthalpy of the boundary fluid node. The temperature can also be used for a temperature boundary condition for heat transfer.

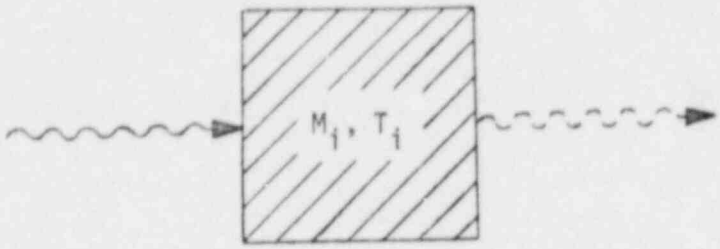
2.1.3 INTERIOR METAL NODES

An interior metal node is defined as a fixed control volume containing metal at thermodynamic equilibrium and having associated with it one conservation equation for total internal energy (actually, the equation is written in terms of the metal temperature). An interior metal node may be connected with fluid nodes via heat links. A schematic diagram of an interior metal node is presented in Figure 2-3.

$$P_i = P_i\ (t)$$

$$h_i = h_i\ (t)$$

FIGURE 2-2. NØTRUMP Boundary Fluid Node



$$\dot{T}_i = \frac{1}{(MC_p)_i}\left[\sum_{\lambda \epsilon T_i} Q_\lambda - \sum_{\lambda \epsilon I_i} Q_\lambda\right]$$

FIGURE 2-3. NØTRUMP Interior Metal Node

The energy conservation equation for interior metal node i in NOTRUMP is:

$$\dot{T}_i = \frac{1}{(MC_p)_i}\left[\sum_{\lambda \epsilon T_i^Q} Q_\lambda - \sum_{\lambda \epsilon I_i^Q} Q_\lambda\right] \qquad (2\text{-}5)$$

T_i^Q and I_i^Q are defined in Section 2.1.1.

An interior metal node has associated with it a number of important quantities. The total mass M [lbm] is a constant. The metal temperature T [°F] is the unknown in the energy conservation equation. The heat capacity C_p [Btu/lbm °F) and the thermal conductivity k [Btu/sec °F ft] are specified functions of temperature. The thermal conductivity is used in determining the heat transfer characteristics of heat links connected to the interior metal node. (See Section 6).

2.1.4 BOUNDARY METAL NODES

A boundary metal node is defined as a control volume containing metal at a specified temperature T [°F]. A boundary metal node may be connected with fluid nodes via heat links. A schematic diagram of a boundary metal node is presented in Figure 2-4.

The metal temperature for boundary metal node i is specified as an arbitrary function of time.

$$T_i = T_i\,(t) \qquad (2\text{-}6)$$

The other important boundary metal node quantity is the thermal conductivity k [Btu/sec °F ft] which is a specified function of temperature.

$$T_i = T_i\ (t)$$

FIGURE 2-4. NØTRUMP Boundary Metal Node

Boundary metal nodes provide a convenient means of imposing boundary conditions. A temperature boundary condition uses the specified temperature.

A special type of boundary metal node is used to model the primary water heater (See Appendix K). For these nodes, the temperature is given by:

$$T_i = A_i + B_i P_{IN}^{PH} \qquad (2\text{-}7)$$

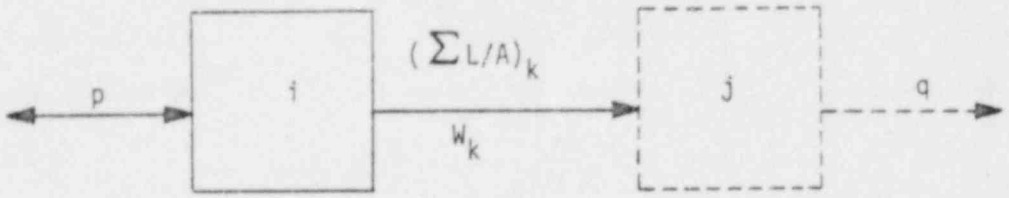
where P_{IN}^{PH} is the control setting for the primary heater and is found from the controller equations. This special boundary metal node is used to model the temperature of the heaters as a function of the control setting.

2.1.5 NON-CRITICAL FLOW LINKS

A non-critical flow link is defined as a path for fluid flow having associated with it a momentum conservation equation for the time rate of change of the total mass flow rate. No mass and energy inventories (only flow) are associated with a flow link. A non-critical flow link always connects two fluid nodes. A schematic diagram of a non-critical flow link is presented in Figure 2-5.

The momentum equation for non-critical flow link k, which has fluid node i as its upstream node and fluid node j as its downstream node, is:

$$\dot{W}_k = \frac{144\, g_c}{(\sum L/A)_k} \left[(P_u)_k - (P_d)_k - C_k |W_k| W_k + D_k \right.$$



$$\dot{W}_k = f_k\,(t, P_i, P_j, W_k, W_p, W_q)$$

FIGURE 2-5. NØTRUMP Non-Critical Flow Link

a,c

$$+\frac{1}{144\ g_c}\Big[\qquad\qquad\qquad\qquad\qquad\qquad\Big]$$

a,c

$$+\frac{1}{144\ g_c}\Big[\qquad\qquad\qquad\qquad\qquad\qquad\Big]$$

a,c

$$+\frac{1}{144\ g_c}\Big[\qquad\qquad\qquad\qquad\qquad\qquad\Big]\Big]. \qquad (2\text{-}8)$$

The first two terms on the right hand side of (2-8) represent the pressure driving force. The third and fourth terms represent friction and elevation terms, respectively. The remaining terms are momentum flux terms. They are described in detail in Appendix I. Suffice it to say here that p and q represent flow links which connect with fluid nodes i and j, respectively, but whose defined flow directions may be either into or out of those nodes.

A non-critical flow link has associated with it a number of quantities. The inertial length, $\sum L/A$ [ft^{-1}], is a constant. The total mass flow rate, W [lbm/sec], is the unknown in the momentum equation. The liquid mass flow rate, W_f [lbm/sec], and the steam mass flow rate, W_g [lbm/sec], are determined by a slip or drift flux model such that

$$W_f + W_g = W \ . \qquad (2\text{-}9)$$

The void fraction in a non-critical flow link, α [-], is determined from slip and drift flux models. The specific volume, v (ft^3/lbm), is found from the void fraction.

These models, described in detail in Appendix G, calculate W_f, W_g, and α in a flow link. They allow for relative motion, i.e., slip, between the liquid and steam phase, and even for counter-current flow. They are extremely useful in modeling natural or mechanical separation effects in vertical flow.

The momentum flux model, described in Appendix I, calculates the momentum flux terms in Equation (2-8). It also limits the flow in flow links to less than sonic flow.

The continuous flow link model, described in Appendix F, is used in conjunction with the stratified node model of Appendix H. It allows modeling of a flow link as a finite diameter circular pipe for the purpose of determining the flow composition at the intersection of the flow link with a stratified fluid node.

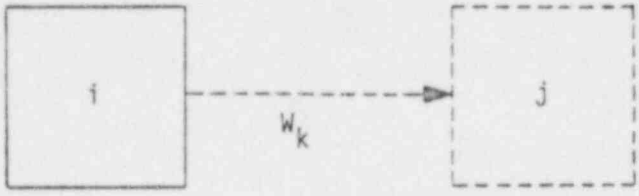
2.1.6 CRITICAL FLOW LINKS

A critical flow link is defined as a path for fluid flow having associated with it an equation for the total mass flow rate (rather than the time rate of change of the total mass flow rate). A critical flow link always connects two fluid nodes. A schematic diagram of a critical flow link is presented in Figure 2-6.

The equation for critical flow link k, with fluid node i as its upstream node and fluid node j as its downstream node, has the general form:

$$W_k = W_k\,(t, U_i, M_i, U_j, M_j) \quad . \tag{2-10}$$

Other than the fact that a critical flow link does not have a differential equation for the total mass flow rate, it is treated quite like a non-critical flow link. The quantities, W_f, W_g, α, and v are often found in the same way. The slip, drift flux, momentum flux, and continuous flow link models are available for use in critical flow links as well as non-critical flow links.



$$W_k = g_k\ (t,\ P_i,\ P_j)$$

FIGURE 2-6. NØTRUMP Critical Flow Link

Critical flow links provide a convenient means of imposing flow boundary conditions or modeling choked flow at pipe breaks (e.g., steam or feed line breaks). Remember that all flow links have both upstream and downstream fluid nodes. They can be either interior or boundary nodes. Often a boundary node is used as a donor node for a critical flow link so that the enthalpy as well as the flow in the link can be specified as a function of time.

2.1.7 NON-CRITICAL HEAT LINKS

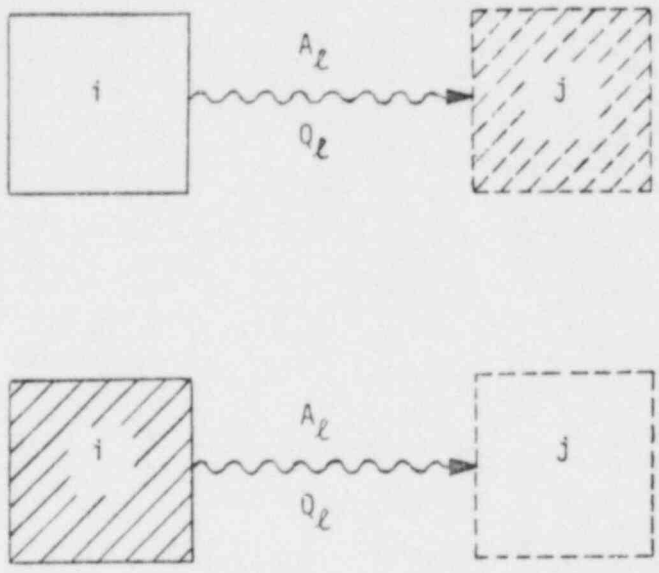
A non-critical heat link is defined as a path for energy flow having associated with it an equation for the energy flow (heat rate). Only energy flow is associated with a heat link. A heat link always connects a fluid node and a metal node. A schematic diagram of a non-critical heat link is presented in Figure 2-7.

The equation for the energy flow in non-critical heat link ℓ with node i as its upstream node and node j as its downstream node has the general form:

$$Q_\ell = Q_\ell \, (A_\ell, P_i, T_i, P_j, T_j) \quad . \tag{2-11}$$

The functional form depends on the heat transfer regime. NOTRUMP includes heat transfer correlations for all regimes from liquid natural or forced convection, through nucleate and transition boiling to stable film boiling or forced convection vaporization, and finally to steam natural or forced convection.

The major quantities associated with a non-critical heat link are the heat rate, Q [Btu/sec], which is obtained from Equation (2-11) and a constant heat transfer area, A [ft^2], which is used in defining the exact form of Equation (2-11).



$$Q_\ell = Q_\ell\ (A_\ell,\ P_i,\ T_i,\ P_j,\ T_j)$$

FIGURE 2-7. NØTRUMP Non-Critical Heat Link

2.1.8 CRITICAL HEAT LINKS

A critical heat link is defined as a path in which the energy flow is specified as a function of time only, i.e.,

$$Q_\ell = Q_\ell (t) \quad . \tag{2-12}$$

A heat link always connects a fluid node and a metal node. A schematic diagram of a critical heat link is presented in Figure 2-8. Critical heat links provide a convenient means of imposing heat flux boundary conditions.

2.1.9 CONTROLLER EQUATIONS

A controller equation is defined as a first order time differential equation for a control variable Z in terms of any control variables and any other system variables.

The controller equation for control variable i is:

$$Z_i = F_i (t, \underline{Z}, \underline{U}, \underline{M}, \underline{W}, \underline{T}) \, , \tag{2-13}$$

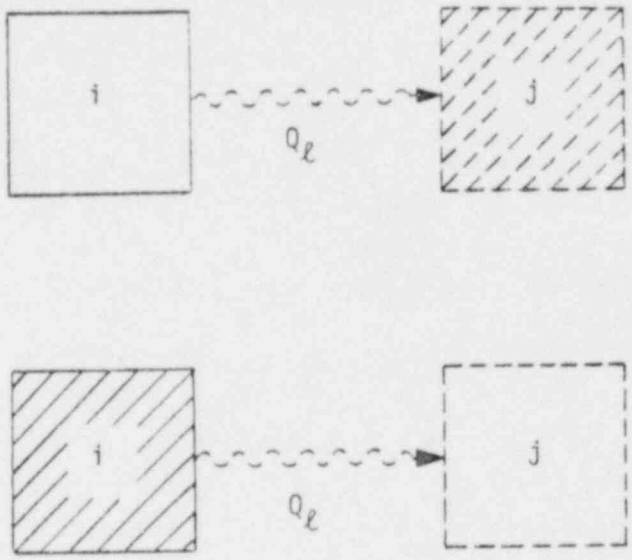
where the vectors represent all control variables, total internal energies, total masses, total mass flow rates, and metal temperatures in the system.

These control equations currently model fixed controllers. (See Appendix K). They could be modified, however, to model other controllers.

2.1.10 FLUID EQUATION OF STATE

All interior fluid nodes contain water and have the same equation of state for pressure, P [psia], and temperature T [°F]:

$$P_i = \pi (U_i/M_i, V_i/M_i) \, , \tag{2-14}$$



$$Q_\ell = Q_\ell\,(t)$$

FIGURE 2-8. NØTRUMP Critical Heat Link

$$T_i = \tau\,(U_i/M_i,\ V_i/M_i)\ . \qquad (2\text{-}15)$$

These equations are used to determine fluid properties in an interior fluid node once the total mass and internal energy in the node are known.

2.2 NOTRUMP IMPLICIT METHOD

In this section, an implicit method is developed for the numerical integration of the governing NOTRUMP conservation equations. This method, when used in conjunction with a block inversion technique, produces an efficient numerical integration procedure.

The conservation equations are written as a vector differential equation. A particular implicit method is then used to change the vector differential equation to a matrix difference equation. The details of the structure of the matrix equation and the solution technique are presented in Appendix E.

Consider now the NOTRUMP network consisting of K* flow links (numbered such that flow links 1,..,K are non-critical flow links and K+1,...,K* are critical flow links), I* fluid nodes (numbered such that fluid nodes 1,...,I are interior fluid nodes and I+1,...,I* are boundary fluid nodes), J* metal nodes (numbered such that metal nodes 1,...,J are interior metal nodes and J+1...,J* are boundary metal nodes), L* heat links (numbered such that heat links 1,...,L are non-critical heat links and L+1,...,L* are critical heat links), and M controller equations. The governing conservation equations, presented in Section 2.1, are then

$$\dot{W}_k = f_k\,(t,\ P_i,\ P_j,\ W_k,\ W_p,\ W_q) \qquad k=1,\ldots,K\ , \qquad (2\text{-}16)$$

$$\dot{U}_i = \sum_{\kappa\varepsilon T_i^W} (hW)_\kappa - \sum_{\kappa\varepsilon I_i^W} (hW)_\kappa + \sum_{\lambda\varepsilon T_i^Q} Q_\lambda - \sum_{\lambda\varepsilon I_i^Q} Q_\lambda \qquad i=1,\ldots,I\ , \qquad (2\text{-}17)$$

$$\dot{M}_i = \sum_{\kappa \in I_i^W} W_\kappa - \sum_{\kappa \in I_i^W} W_\kappa \qquad i=1,\ldots,I, \qquad (2\text{-}18)$$

$$\dot{T}_i = \frac{1}{(MC_p)_i}\left[\sum_{\lambda \in T_i^Q} Q_\lambda - \sum_{\lambda \in I_i^Q} Q_\lambda\right] \qquad i=1,\ldots,J, \qquad (2\text{-}19)$$

$$\dot{Z}_i = C_i\ (t, \underline{W}, \underline{U}, \underline{M}, \underline{T}, \underline{Z}) \qquad i=1,\ldots,M. \qquad (2\text{-}20)$$

Equations (2-17) and (2-18) are coupled to Equation (2-16) through the equations of state,

$$P_i = \pi_i\ (U_i, M_i) \qquad i=1,\ldots I. \qquad (2\text{-}21)$$

Furthermore, if I_i^W or T_i^W contain critical flow links, then

$$W_k = g_k\ (t, P_i, P_j) \qquad k=K+1,\ldots,K^* \qquad (2\text{-}22)$$

and Equation (2-21) create further couplings between Equations (2-17) and (2-18) and Equation (2-16).

Finally, if I_i^Q or T_i^Q contains non-critical heat links, then

$$Q_\ell = Q_\ell\ (A_\ell, P_i, T_i, P_j, T_j) \qquad \ell=1,\ldots,L \qquad (2\text{-}23)$$

together with Equation (2-21) and

$$T_i = \tau_i\ (U_i, M_i) \qquad i=1,\ldots,I \qquad (2\text{-}24)$$

create couplings between Equations (2-17) and (2-18) and Equation (2-19).

The problem to be considered is the following: Given an initial condition at $t=0$ determine the temporal behavior on an interval $[o, \tau]$ of the network mass flows, heat flows, energies, masses, metal temperatures, and control variables satisfying Equations (2-16) to (2-24).

Let $\underline{y} = \text{col}\,[W_1,\ldots,W_K,U_1,\ldots,U_I,M_1,\ldots,M_I,T_1,\ldots,T_J,Z_1,\ldots,Z_M]$ be a K+2I+J+M component column vector and let $\underline{F}=\text{col}\,[F_1,\ldots,F_{K+2I+J+M}]$ denote the column vector where the components F_i are the right-hand sides of Equations (2-16) - (2-20). Then these equations may be written in vector form as

$$\dot{\underline{y}} = \underline{F}\,(t, \underline{y})\,. \qquad (2\text{-}25)$$

In writing Equation (2-25), it is assumed that Equations (2-22) and (2-21) have been used to replace the flow rates for critical flow links in Equations (2-17) and (2-18) by equivalent expressions in terms of energies and masses. The initial condition corresponding to Equation (2-25) is $\underline{y}\,(0) = \underline{y}^o$.

A class of implicit methods is introduced and their convergent nature established in Reference 1. A particular implicit method is used here. Let $\underline{\underline{dF}}(t,\underline{y}) = [\partial F_i/\partial y_i]$ denote the K+2I+J+M square Jacobian matrix and let $\underline{\underline{I}}$ denote the identity matrix of order K+2I+J+M. Suppose now that an appropriate solution of Equations (2-16) - (2-20) is known at time t_n and that it is desired to compute the appropriate solution at time $t_{n+1}=t_n+\Delta t_{n+1}$ where Δt_{n+1} is the time step. Then for Δt_{n+1} sufficiently small, the matrix $[\underline{\underline{I}} - \Delta t_{n+1}\,\underline{\underline{dF}}(t^n,\underline{y}^n)]^{-1}$ exists and, if $\underline{\underline{dF}}(t,\underline{y}^n)$ has no real positive eigenvalues, then $[\underline{\underline{I}} - \Delta t_{n+1}\,\underline{\underline{dF}}(t^n,\underline{y}^n)]^{-1}$ exists for all $\Delta t_{n+1} >0$. The appropriate solution $\underline{y}^{n+1}$ to Equation (2-25) is generated by the one-step method defined by

$$\underline{y}^{n+1} = \underline{y}^n + \Delta t_{n+1}[\underline{\underline{I}} - \Delta t_{n+1}\underline{\underline{dF}}(t^n,\underline{y}^n)]^{-1}\underline{F}(t^n,\underline{y}^n)\,. \qquad (2\text{-}26)$$

Equation (2-26) may also be obtained by first linearizing Equation (2-25) about the point $(t^n,\underline{y}^n)$ and then applying the "backward" difference

method to the linearized system. Convergence and stability properties possessed by the numerical scheme defined by Equation (2-26) are discussed in Reference 1.

In practice, the inverse $[\underline{\underline{I}} - \Delta t_{n+1}\underline{\underline{dF}}(t^n,\underline{y}^n)]^{-1}$ in Equation (2-26) is not computed; instead Equation (2-26) is written in the equivalent form

$$[\underline{\underline{I}} - \Delta t_{n+1}\underline{\underline{dF}}(t^n,\underline{y}^n)]\Delta\underline{y}^{n+1} = \Delta t_{n+1}\underline{F}(t^n,\underline{y}^n) \qquad (2\text{-}27)$$

where $\Delta\underline{y}^{n+1} = \underline{y}^{n+1} - \underline{y}^n$. The determination of $\underline{y}^{n+1}$ then amounts to the determination of the increment $\Delta\underline{y}^{n+1}$, by the solution of the linear system, Equation (2-27).

The details of the structure of the matrix Equation (2-27) and the solution technique are presented in Appendix E. Because of the simple nature of Equations (2-17) and (2-18), the quantities $\Delta\underline{U}^{n+1}$ and $\Delta\underline{M}^{n+1}$ can be eliminated from Equation (2-27). The resultant matrix equation is of order K+J+M, as opposed to K+2I+J+M, the order of Equation (2-27). [,C

] Finally, efficient numerical techniques are used which take advantage of the structure of the reduced matrix equation, re-ordering the equations and using block elimination.

2.3 NOTRUMP CALCULATIONAL PROCEDURE

In this section, a summary description is given of the NØTRUMP calculational procedure. NOTRUMP is currently structured as an overlay program with two overlay levels, a zero and the primary levels. Calculations are grouped by function into different programs and subprograms. The calculational procedure is defined by the order in which the zero or main overlay, program NØTRUMP, calls the five primary overlays and the order in which these primary overlay programs call various subprograms.

Overlay (0,0) consists of program NØTRUMP and many commonly used subprograms. Program NØTRUMP consists simply of calls to the five primary

overlays. These three overlays can be called any number of times, thereby permitting the stacking of cases within a given run.

Overlay (1,0), program PUTIN, is the first primary overlay called by NØTRUMP. It reads, echoes, and processes the input data. For a non-restart run, this involves reading a title card, namelists, and formatted data for trace variables. For a restart run, it also involves reading a restart tape before being able to change variables through namelist input.

Overlay (2,0), program INIT, is the second primary overlay called by NØTRUMP. It initializes certain input-dependent variables. (See Section 9.) For a restart run, it initializes only a subset of those variables initialized on a non-restart run.

Overlays (3,0) and (4,0), programs PRINTIN and WRITIN, are the third and fourth overlays called by NØTRUMP. They edit the input data in two different ways.

Overlay (5,0), program TRANØUT, is the fifth primary overlay called by NØTRUMP. It calls overlays (5,1) and (5,2), programs TRANSNT and PUTØUT. TRANSNT contains the logic to calculate the transient for a given case after the input has been processed by PUTIN and the initialization performed by INIT. Figure 2-9 shows the TRANSNT logic involved in various major subroutines and PUTØUT. A brief description of each major subroutine and its function follows. PUTØUT selectively prints many of the variables of interest (a detailed output description appears in Appendix D).

Fluid node calculations are performed in subroutines FLUID, DIST, and STACK. Given a volume V, internal energy U, and mass M in each interior fluid node, FLUID calculates all other thermodynamic fluid properties from the equation of state. It also calculates all other fluid properties for each boundary fluid node given a pressure P and specific enthalpy h. While FLUID calculates thermodynamic equilibrium properties, subroutines DIST and STACK determine the phase distribution for stratified nodes. (See Appendices H and N.)

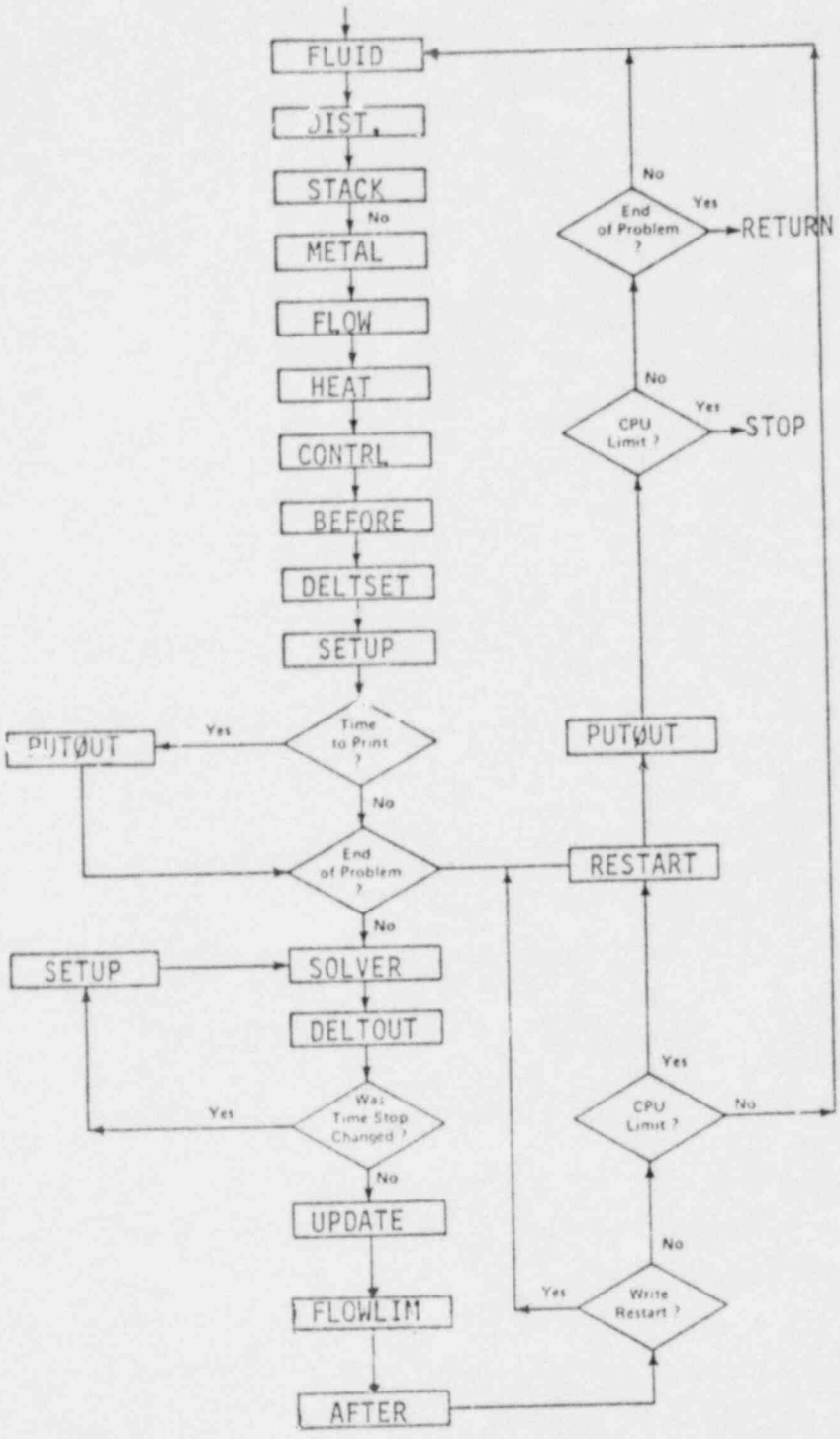


Figure 2-9. NOTRUMP Logic Diagram

Metal node calculations are performed in subroutine METAL. For each interior metal node, the mass times heat capacity, MC_p, is calculated. For each boundary metal node, the metal temperature is calculated.

Flow link calculations are performed in subroutine FLØW. For each flow link, the flow composition is determined. This includes the liquid and steam mass flow rates, the void fraction and the specific volume. The friction, elevation, and momentum flux terms for the momentum equation are also calculated. For each critical flow link, the total mass flow rate is calculated.

Heat link calculations are performed in subroutine HEAT. Metal node and fluid node heat transfer resistances are calculated and combined to find the energy flow Q for each non-critical heat link. For each critical heat link, Q is calculated as a function of time only.

Controller calculations are performed in subroutine CØNTRL. This includes the calculation of the steam generator level.

Subroutine BEFØRE is called before the time step selection process is begun. It finishes calculations from the previous time step (e.g., calculating time integrals) and does whatever calculations can be done before the matrix generation begins in SETUP.

Subroutine DELTSET is called after subroutine CØNTRL. It performs several calculations relating to time step size selection. In addition, at every time step, a check is made as to whether a user-specified output or restart time will occur within the determined time step. If so, the time step size is adjusted so that the user-specified time is obtained exactly with this one time step. The details of these calculations are given in Section 10.

Subroutine SETUP is called either directly after DELTSET or after DELTCUT (if the time step size has been modified). Here the matrix and source vector for the matrix difference equation are generated. The mathematical and calculational details are given in Appendix E and Section 8, respectively.

If it is time to print, program PUTØUT is called after subroutine SETUP. The reason for placing PUTØUT here is that it is immediately before subroutine SØLVER. Therefore, all variables at the old time have been calculated.

If the current problem is at an end (i.e., the maximum time or number of time steps has been reached), subroutine RESTART and program PUTØUT are called and then control is returned to NØTRUMP for the processing of the next case. Otherwise, subroutine SØLVER is called.

Subroutine SØLVER inverts the matrix equation representing Equation (2-27). Either Gaussian elimination or block elimination may be used for the inversion. The mathematical and calculational details are given in Appendix E and Section 8, respectively.

Subroutine DELTCUT is called directly after SØLVE. It performs several calculations relating to time step size modifications. If the time step size is to be increased, a check is made as to whether a user-specified output or restart time will occur within the determined time step. If so, the time step size is adjusted so that the user-specified time is obtained exactly with this one time step. The details of these calculations are given in Section 10.

If the time step size was changed in subroutine DELTCUT, control is returned to subroutine SETUP to begin re-doing the matrix equation for the new time step size. Otherwise, subroutine UPDATE is called.

Subroutine UPDATE updates the time step number, the time, and the differential equation vector ($\underline{y}$ from Equation (2-25)) to their new time values. The differential equation vector is simply obtained from the definition of $\Delta\underline{y}^{n+1}$, i.e.,

$$\underline{y}^{n+1} = \underline{y}^{n} + \Delta\underline{y}^{n+1}. \qquad (2\text{-}28)$$

Next subroutine FLØWLIM is called. It limits the mass flow rate in flow links if necessary and readjusts the appropriate nodal masses and energies The details of these calculations are given in Appendices I, P, and and Section 5.

Subroutine AFTER is called after the time step selection and time advance has been completed. It currently calculates Mach numbers for all flow links and certain time integrals.

If it is time to write on the restart tape, subroutine RESTART is called. It simply writes all variables necessary to restart the problem onto the restart tape. (See Appendix B for information on how to use the restart capability.) Program PUTØUT is always called directly after RESTART in order to allow the user to see the state of the problem at the time the restart was written. One important fact should be noted about this call to PUTØUT. Because of its placement after SØLVE and UPDATE, some variables (those from SØLVE and UPDATE) are printed at their new time values while others (those from FLUID through SETUP) are still at their old time values.

Finally, if the code has reached its CPU time limit, it calls RESTART and PUTØUT and terminates. Otherwise control is returned to subroutine FLUID to continue the problem.

3.0 FLUID NODE CALCULATIONS

In this section, a detailed description of the calculations performed for fluid nodes is given. These calculations occur in subroutines FLUID, DIST, and STACK.

Subroutine FLUID uses the assumption of thermodynamic equilibrium to obtain all the thermodynamic properties given two of them. For interior fluid nodes, the two known properties are the specific volume and the specific internal energy; for boundary fluid nodes they are the pressure and the enthalpy.

Interior fluid nodes are described in Section 2.1.1. The fluid equation of state is discussed in Section 2.1.10. For interior fluid node i, (see Figure 2-1), we know, at a given time, the constant nodal volume, V_i, the total internal energy, U_i, and the total mass, M_i. Using the fluid equations of state, Equations (2-14) and (2-15), we see that the pressure and temperature (and therefore all thermodynamic properties) are functions only of V_i, U_i, and M_i. The volume is constant, however, so that

$$P_i = P_i\ (U_i, M_i) = \pi(U_i/M_i, V_i/M_i), \tag{3-1}$$

$$T_i = T_i\ (U_i, M_i) = \tau(U_i/M_i, V_i/M_i), \tag{3-2}$$

Appendices L and R describe how the "pressure search" is performed to obtain P_i, T_i, and the other thermodynamic properties of regular and accumulator interior fluid nodes, respectively. These other properties are the specific volume,

$$v_i = \frac{V_i}{M_i} \quad ; \tag{3-3}$$

the enthalpy,

$$h_i = \frac{U_i}{M_i} + \frac{144}{J} P_i v_i = \frac{U_i}{M_i} + 0.18511 P_i v_i; \quad (3\text{-}4)$$

the saturation properties, $(T_{sat})_i$, $(h_f)_i$, $(h_g)_i$, $(v_f)_i$, and $(v_g)_i$; the thermodynamic quality,

$$\chi_i = \frac{h_i - (h_f)_i}{(h_g)_i - (h_f)_i}, \quad (3\text{-}5)$$

for saturated fluid; the derivatives,

$$\left(\frac{\partial P_i}{\partial U_i}\right)_{M_i}, \left(\frac{\partial T_i}{\partial U_i}\right)_{M_i}, \left(\frac{\partial P_i}{\partial M_i}\right)_{U_i}, \left(\frac{\partial T_i}{\partial M_i}\right)_{U_i}, \text{ and } \frac{\partial (T_{sat})_i}{\partial P_i};$$

and the void fraction,

$$\alpha_i = \frac{\chi_i (v_g)_i}{\chi_i (v_g)_i + (1-\chi_i)(v_f)_i}. \quad (3\text{-}6)$$

The liquid mass and gas mass in interior fluid node i are obtained from

$$(M_f)_i = (1 - \chi_i) M_i \quad (3\text{-}7)$$

and

$$(M_g)_i = \chi_i M_i. \quad (3\text{-}8)$$

For regular interior fluid nodes, some special logic is employed in subroutine FLUID in an attempt to avoid the problem of "water packing". Water packing refers to the pressure spike which may occur over a single time step when an interior fluid nodes goes from a two-phase mixture to subcooled liquid. The magnitude of such a pressure spike varies but is generally larger for smaller nodes. Water packing is a problem common to all nodal codes which "back out" nodal pressures from other thermodynamic properties.

Part of the problem is that derivatives at the old time are for two-phase fluid and are quite different from the derivatives for the subcooled liquid which exists at the new time. Even the implicit method (see Section 2.2) uses the derivatives from the previous time to integrate to the next time. Therefore, the wrong derivative is used over part of the time step. This may result in water packing.

[ ] a,c

a,c [ ]

Until now, we have been discussing interior fluid nodes. Boundary fluid nodes are described in Section 2.1.2. For boundary fluid node i, (see Figure 2-2), we know, at a given time, the pressure, P_i, from Equation (2-3) and the enthalpy, h_i, from Equation (2-4). Appendix L describes how the other properties are obtained, given the pressure and enthalpy. These other properties are the temperature, T_i; the specific volume, v_i; the saturation properties, $(T_{sat})_i$, $(h_f)_i$, $(h_g)_i$, $(v_f)_i$, and $(v_g)_i$; the thermodynamic quality, x_i, for saturated fluid (see Equation (3-5)); the derivative $\frac{\partial (T_{sat})_i}{\partial P_i}$; and the void fraction, α_i, (see Equation (3-6)).

Subroutine DIST determines the distribution of the phases in a fluid node. An interior fluid node can be either homogeneous or stratified. A boundary fluid node can only be homogeneous.

For a non-accumulator fluid node i which is homogeneous or which belongs to a stack but does not contain the stack's mixture elevation, the mixture quantities are set to the total nodal quantities; i.e.,

$$(V_{mix})_i = V_i, \tag{3-9}$$

$$(M_{gb})_i = (M_g)_i, \tag{3-10}$$

$$(E_{mix})_i = (E_{top})_i, \tag{3-11}$$

$$(x_{mix})_i = x_i, \tag{3-12}$$

$$(\alpha_{mix})_i = \alpha_i, \tag{3-13}$$

and

$$(v_{mix})_i = v_i \quad . \tag{3-14}$$

For a saturated stratified non-accumulator fluid node i, the bubble rise model described in Appendix H is used. At a given time t^{n+1}, the mass of steam bubbles in the mixture is obtained by explicit integration; i.e.,

$$(M_{gb})_i = (M_{gb})_i^{n+1} = (M_{gb})_i^n + \Delta t^{n+1} (\dot{M}_{gb})_i \tag{3-15}$$

where $(\dot{M}_{gb})_i$ is given by Equation (H-16). The other mixture quantities are obtained as follows:

$$(\chi_{mix})_i = \frac{(M_{gb})_i}{(M_{gb})_i + (M_f)_i} \quad , \tag{3-16}$$

$$(\alpha_{mix})_i = \frac{(\chi_{mix})_i (v_g)_i}{(\chi_{mix})_i (v_g)_i + (1-(\chi_{mix})_i)(v_f)_i} \quad , \tag{3-17}$$

$$(V_{mix})_i = (M_{gb})_i (v_g)_i + (M_f)_i (v_f)_i \quad . \tag{3-18}$$

If node i is a constant area interior fluid node, then

$$(E_{mix})_i = (E_{bot})_i + [(E_{top})_i - (E_{bot})_i] \frac{(V_{mix})_i}{V_i} \quad . \tag{3-19}$$

If it is a variable area interior fluid node, then

$$(E_{mix})_i = (E_{bot})_i + [(E_{top})_i - (E_{bot})_i] \cdot F_i ((V_{mix})_i / V_i) \quad . \tag{3-19.1}$$

$F_i((V_{mix})_i/V_i$ is a user-supplied external representing the mixture level fraction as a function of the mixture volume fraction. (This is, of course, simply $(V_{mix})_i/V_i$ for constant area nodes.

$$(v_{mix})_i = \frac{(V_{mix})_i}{(M_{gb})_i + (M_f)_i} \quad . \tag{3-20}$$

For a subcooled stratified interior fluid node i,

$$(M_{gb})_i = 0, \tag{3-21}$$

$$(\chi_{mix})_i = 0, \tag{3-22}$$

$$(\alpha_{mix})_i = 0, \tag{3-23}$$

$$(V_{mix})_i = V_i, \tag{3-24}$$

$$(E_{mix})_i = (E_{top})_i, \tag{3-25}$$

and

$$(v_{mix})_i = v_i \quad . \tag{3-26}$$

For a superheated stratified interior fluid node i,

$$(M_{gb})_i = 0, \tag{3-27}$$

$$(\chi_{mix})_i = 1, \tag{3-28}$$

$$(\alpha_{mix})_i = 1, \tag{3-29}$$

$$(V_{mix})_i = 0, \tag{3-30}$$

$$(E_{mix})_i = (E_{bot}) \quad , \tag{3-31}$$

and

$$(v_{mix})_i = v_i \quad . \tag{3-32}$$

For an accumulator interior fluid node i,

$$(M_{gb})_i = (M_g)_i \quad , \tag{3-33}$$

$$(\chi_{mix})_i = \chi_i \quad , \tag{3-34}$$

$$(\alpha_{mix})_i = \alpha_i \quad , \tag{3-35}$$

$$(v_{mix})_i = v_i \quad , \tag{3-36}$$

$$(V_{mix})_i = M_i \cdot (v_{mix})_i \quad . \tag{3-37}$$

Either Equation (3-19) or (3-19.1) is used to calculate $(E_{mix})_i$.

For a boundary fluid node i,

$$(E_{mix})_i = (E_{top})_i, \tag{3-38}$$

$$(\chi_{mix})_i = \chi_i, \tag{3-39}$$

$$(\alpha_{mix})_i = \alpha_i, \tag{3-40}$$

and

$$(v_{mix})_i = v_i \quad . \tag{3-41}$$

Subroutine STACK, which is called only if the stacking option is being used, performs the calculations involved in tracking a single mixture level within each vertical stack of regular interior fluid nodes. The node stacking and mixture level tracking model is described in detail in Appendix N.

4.0 METAL NODE CALCULATIONS

In this section, a detailed description is given of the calculations performed for metal nodes. These calculations are done in subroutine METAL.

For each interior metal node i, the mass times the heat capacity, $(MC_p)_i$, is calculated as

$$(MC_p)_i = M_i \cdot C_{P_i}^{metal}(T_i). \tag{4-1}$$

The function $C_{P_i}^{metal}(T_i)$ is specified as a user-supplied external.

For each boundary metal node i, except those used to model the MB-1 primary water heaters, the metal node temperature is calculated as

$$T_i = T_i^{metal}(t). \tag{4-2}$$

The function $T_i^{metal}(t)$ is specified as a user-supplied external.

For each boundary metal node i used to model the primary water heaters, the metal node temperature is calculated as

$$T_i = A_j^{PH} + B_j^{PH} P_{IN}^{PH} = A_j^{PH} + B_j^{PH} y_{K+2I+J+14} \tag{4-3}$$

The index j refers one of the five primary water heater boundary metal nodes which can be used. P_{IN}^{PH} or $y_{K+2I+J+14}$ is the primary water heater gas control setting, (see Appendix K).

5.0 FLOW LINK CALCULATIONS

In this section, a detailed description of the calculations performed for flow links is given. These calculations are done in subroutine FLØW.

For flow link k, the upstream fluid node, i = u(k), and the downstream fluid node, j = d(k), are found. These are based only on the defined flow link direction.

The upstream and downstream pressures for flow link k are determined next. If flow link k is a horizontal stratified non-critical flow link, then they are given by Equations (0-13) - (0-18). If flow link k is a point contact flow link, then

$$(P_u)_k = [P(0)]_i \tag{5-1}$$

and

$$(P_d)_k = [P(0)]_j \tag{5-2}$$

where

$$[P(R)]_i = P_i + \frac{g}{144\ g_c}\left[\frac{(E_{top})_i - \max\left[(E_{mix})_i,\ (E_u)_k + R\right]}{\max\left[(v_g)_i,\ v_i\right]} + \frac{\max\left[(E_{mix})_i,\ (E_u)_k + R\right] - \left[(E_u)_k + R\right]}{(v_{mix})_i}\right] \tag{5-3}$$

and

$$[P(R)]_j = P_j + \frac{g}{144\ g_c}\left[\frac{(E_{top})_j - \max\left[(E_{mix})_j,\ (E_d)_k + R\right]}{\max\left[(v_g)_j,\ v_j\right]} + \frac{\max\left[(E_{mix})_j,\ (E_d)_k + R\right] - \left[(E_d)_k + R\right]}{(v_{mix})_j}\right] \tag{5-4}$$

If flow link k is a continuous contact flow link with radius R, then

$$(P_u)_k = \frac{1}{\pi R^2} \left\{ \left[[P(R)]_i + \frac{g}{144\, g_c} \cdot \frac{R - (y_u)_k}{\max\left[(v_g)_i, v_i\right]} + \frac{g}{144\, g_c} \frac{(y_u)_k}{(v_{mix})_i} \right] \right.$$

$$\cdot \int_{-R}^{(y_u)_k} d\, A(y)$$

$$- \left[\frac{g}{144\, g_c} \frac{1}{(v_{mix})_i} \right] \cdot \int_{-R}^{(y_u)_k} y\, d\, A(y) \qquad (5\text{-}5)$$

$$+ \left[[P(R)]_i + \frac{g}{144\, g_c} \cdot \frac{R}{\max\left[(v_g)_i, v_i\right]} \right] \int_{(y_u)_k}^{R} d\, A(y)$$

$$\left. - \left[\frac{g}{144\, g_c} \frac{1}{\max\left[(v_g)_i, v_i\right]} \right] \cdot \int_{(y_u)_k}^{R} y\, d\, A(y) \right\}$$

and

$$(P_d)_k = \frac{1}{\pi R^2} \left\{ \left[[P(R)]_j + \frac{g}{144\, g_c} \cdot \frac{R - (y_d)_k}{\max\left[(v_g)_j, v_j\right]} + \frac{g}{144\, g_c} \frac{(y_d)_k}{(v_{mix})_j} \right] \cdot \int_{-R}^{(y_d)_k} d\, A(y) \right.$$

$$- \left[\frac{g}{144\, g_c} \frac{1}{(v_{mix})_j} \right] \cdot \int_{-R}^{(y_d)_k} y\, d\, A(y) \qquad (5\text{-}6)$$

$$+ \left[[P(R)]_j + \frac{g}{144\, g_c} \cdot \frac{R}{\max\left[(v_g)_j, v_j\right]} \right] \int_{(y_d)_k}^{R} d\, A(y)$$

$$\left. - \left[\frac{g}{144\, g_c} \frac{1}{\max\left[(v_g)_j, v_j\right]} \cdot \right] \int_{(y_d)_k}^{R} y\, d\, A(y) \right\}$$

where

$$(y_u)_k = \min(\max((E_{mix})_i - (E_u)_k, -R), R) \tag{5-7}$$

and

$$(y_d)_k = \min(\max((E_{mix})_j - (E_d)_k, -R), R) \tag{5-8}$$

The integrals are evaluated using Equations (0-5) and (0-6).

The upstream and downstream void fractions in flow link k are determined next. Each void fraction is determined from the mixture void fraction and mixture elevation of the appropriate fluid node at the location of contact between the link and the node. This is given by Equation (F-1) for the point contact flow link model and Equations (F-2) - (F-7) for the continuous contact model.

If flow link k is a horizontal stratified non-critical flow link, then the flow area, equivalent diameter, inertial length, and interfacial shear term are calculated as described in Appendix O. These quantities are re-calculated every time step.

If flow link k is a user-specified time-, pressure and enthalpy-dependent critical flow link, then

$$W_k = W_k\,(t, (P_u)_k, (P_d)_k, h_i, h_j) \tag{5-9}$$

$$\frac{\partial W_k}{\partial P_i} = \frac{\partial}{\partial (P_u)_k} W_k\,(t, (P_u)_k, (P_d)_k, h_i, h_j) \tag{5-10}$$

$$\frac{\partial W_k}{\partial P_j} = \frac{\partial}{\partial (P_d)_k} W_k\,(t, (P_u)_k, (P_d)_k, h_i, h_j) \tag{5-11}$$

$$\frac{\partial W_k}{\partial h_i} = \frac{\partial}{\partial h_i} W_k\,(t, (P_u)_k, (P_d)_k, h_i, h_j) \tag{5-12}$$

$$\frac{\partial W_k}{\partial h_j} = \frac{\partial}{\partial h_j} W_k \left(t, (P_u)_k, (P_d)_k, h_i, h_j\right) \tag{5-13}$$

If flow link k is a pseudo-steady state critical flow link, then

$$W_k = \pm \left[\frac{\left| (P_u)_k - (P_d)_k + D_k \right|}{C_k} \right]^{1/2} \tag{5-14}$$

$$\frac{\partial W_k}{\partial P_i} = \frac{1}{2} \left| \frac{W_k}{(P_u)_k - (P_d)_k + D_k} \right| \tag{5-15}$$

$$\frac{\partial W_k}{\partial P_j} = -\frac{1}{2} \left| \frac{W_k}{(P_u)_k - (P_d)_k + D_k} \right| \tag{5-16}$$

where the sign in Equation (5-14) is equal to the sign of $(P_u)_k - (P_d)_k + D_k$. If W_k is identically zero the derivatives are set to zero.

Special logic is used if flow link k is part of one of the mechanical models. If flow link k represents the swirl vane outlet, swirl vane drain, or Peerless separator drain, then one of the models described in Appendix J is used to modify the upstream and downstream void fraction.

The composition of flow in flow link k is determined next. First the mass flux, G_k, is calculated from

$$G_k = \pm \frac{W_k}{A_k} \quad . \tag{5-17}$$

The appropriate sign is given to G_k such that a positive value for G_k means upwards flow and a negative value means downwards flow. For horizontal flow, the sign does not matter. Next, the void fraction calculations at each end of flow link k may be overridden depending on the flow composition type. (See the description of the input array KTFL in Appendix B.) The drift flux model as described in Appendix G is then used to obtain $(W_f)_k$, $(W_g)_k$, $(hW)_k$ and $\frac{\partial (hW)_k}{\partial W_k}$ from Equations (G-30), (G-31), (G-36), and (G-37). The average void fraction in flow link k, α_k, is given by one of the two approaches described in Appendix G. The average specific volumes, $(\bar{v}_f)_k$ and

$(\bar{v}_g)_k$, are also obtained from the drift flux model. The specific volume in flow link k is then given by

$$v_k = \frac{1}{\alpha_k/(\bar{v}_g)_k + (1 - \alpha_k)/(\bar{v}_f)_k} \tag{5-18}$$

and the static quality by

$$X_k^s = \frac{\alpha_k}{\alpha_k + (1 - \alpha_k)\,(\bar{v}_g)_k/(\bar{v}_f)_k} \tag{5-19}$$

Finally, the flow quality for flow link k is given by

$$X_k^f = \frac{(W_g)_k}{(W_f)_k + (W_g)_k} \tag{5-20}$$

for co-current flow and is set to X_k^s for counter-current flow. This concludes the calculation of flow composition.

If flow link k is a critical flow link using one of various break models, then W_k, $(W_f)_k$, $(W_g)_k$, $(hW)_k$, $\frac{\partial(hW)_k}{\partial W_k}$, α_k, X_k^f, v_k, $\frac{\partial W_k}{\partial P_i}$, $\frac{\partial W_k}{\partial P_j}$, $\frac{\partial W_k}{\partial h_i}$, $\frac{\partial W_k}{\partial h_j}$, $\frac{\partial(hW)_k}{\partial P_i}$, $\frac{\partial(hW)_k}{\partial P_j}$, $\frac{\partial(hW)_k}{\partial h_i}$, and $\frac{\partial(hW)_k}{\partial h_j}$ are calculated as described in Appendix M. Note that these break models can predict either choked or unchoked flow conditions.

If the momentum flux option is on, certain momentum flux calculations are performed for flow link k. First, ρ_{js} is calculated from Equation (I-15). Next, the sonic velocity, c_k, is calculated using Equation (I-6) for subcooled or superheated fluid or Equation (I-7) for saturated fluid. A_{js} and A_{jL} are calculated from Equations (I-16) and (I-17), respectively. M_{js} is calculated from Equation (I-4). The maximum allowable value of M_{js}, $(M_{js})_{max}$, is calculated as follows. For a contraction (i.e., $A_{js} > A_{jL}$), the maximum allowable value of M_{jL} is known to be

$$(M_{jL})_{max} = \min(A_k/A_{jL},\ 1). \tag{5-21}$$

Using Equation (5-21) for M_{jL} in Equation (I-3), we obtain $(M_{js})_{max}$. For an expansion (i.e., $A_{js} \leq A_{jL}$), we have

$$(M_{js})_{max} = \min(A_k/A_{jL},\ 1). \tag{5-22}$$

Once $(M_{js})_{max}$ has been calculated, it is used to obtain

$$|W_k|_{max} = \rho_{js}\ A_{js}\ c_k\ (M_{js})_{max} \tag{5-23}$$

Finally, Equations (I-2) and (I-3) are solved simultaneously for ρ_{jL} and M_{jL} and Equations (I-18) and (I-19) are used to obtain $(\rho_{j1})_k$ and $(\rho_{j2})_k$.

The flow link momentum fluxes and derivatives are calculated next. For single phase flow or a non-drift flux flow link, we have

$$[\rho V^2]^k_{j1} = \frac{W_k^2}{(\rho_{j1})_k (A_i)_k^2}, \tag{5-24}$$

$$\frac{\partial}{\partial W_k}\ [\rho V^2]^k_{j1} = \frac{2W_k}{(\rho_{j1})_k (A_i)_k^2}, \tag{5-25}$$

$$[\rho V^2]^k_{j2} = \frac{W_k^2}{(\rho_{j2})_k (A_j)_k^2}, \tag{5-26}$$

and

$$\frac{\partial}{\partial W_k}\ [\rho V^2]^k_{j2} = \frac{2W_k}{(\rho_{j2})_k (A_j)_k^2}. \tag{5-27}$$

For a two phase ($0 < \alpha_k < 1$) drift flux flow link, we have

$$[\rho V^2]^k_{j1} = \frac{1}{(A_i)^2_k} \left[\frac{\bar{v}_g (W_g)^2_k}{\alpha_k} + \frac{\bar{v}_f (W_f)^2_k}{1-\alpha_k} \right], \tag{5-28}$$

$$\frac{\partial}{\partial W_k} [\rho V^2]^k_{j1} = \frac{2}{(A_i)^2_k} \left[\frac{(C_0)_k (W_g)_k + \frac{1-\alpha_k (C_0)_k}{1-\alpha_k} (W_f)_k}{\frac{\alpha_k (C_0)_k}{\bar{v}_g} + \frac{1-\alpha_k (C_0)_k}{\bar{v}_f}} \right], \tag{5-29}$$

$$[\rho V^2]^k_{j2} = \frac{1}{(A_j)^2_k} \left[\frac{\bar{v}_g (W_g)^2_k}{\alpha_k} + \frac{\bar{v}_f (W_f)^2_k}{1-\alpha_k} \right], \tag{5-30}$$

and

$$\frac{\partial}{\partial W_k} [\rho V^2]^k_{j1} = \frac{2}{(A_j)^2_k} \left[\frac{(C_0)_k (W_g)_k + \frac{1-\alpha_k (C_0)_k}{1-\alpha_k} (W_f)_k}{\frac{\alpha_k (C_0)_k}{\bar{v}_g} + \frac{1-\alpha_k (C_0)_k}{\bar{v}_f}} \right]. \tag{5-31}$$

The term D_k for the momentum equation for non-critical or pseudo-steady state critical flow link k, Equation (2-8), is calculated next. If flow link k is not the flow link which represents the Peerless separator drains, then

$$D_k = \frac{g}{144\, g_c} \cdot \frac{(E_u)_k - (E_d)_k}{v_k} \tag{5-32}$$

If flow link k represents the Peerless separator drains, then

$$D_k = \frac{g}{144\, g_c} \cdot \frac{(E_u)_k - (E_d)_k}{1 - \text{VFCPSD}} \cdot \left[\frac{\max(\alpha_i, \text{VFCPSD})}{(v_g)_i} + \frac{1 - \max(\alpha_i, \text{VFCPSD})}{(v_f)_i} \right] \tag{5-33}$$

a,c [ ]

If swirl vane model 1 is used, then Equation (J-21) is added to D_k. If swirl vane model 2 is used and the inlet, outlet and drain flows are positive, then Equation (J-3) is added to D_k.

The frictional terms for non-critical or pseudo-steady state critical flow link k are calculated next and are accumulated in the C_k term of Equation (2-8). These frictional terms consist of both those calculated from user-supplied loss factors (fl/D's) and those calculated from correlations.

The input frictional terms are accumulated first in C_k. User-supplied loss factors, $(fL/D)_p$ and $(fL/D)_a$, represent pointwise losses and average losses along a length. Point value factors are typically used for losses which occur over short lengths (such as tube support losses); average value factors are used for losses occurring over an entire region (such as skin friction).

If χ_k^f is zero or one, we have single phase flow and the contribution to C_k is calculated from

$$C_k^{new} = C_k^{old} + \frac{1}{144 g_c} \cdot \frac{1}{2} \frac{v_k}{A_k^2} \cdot \left[\left(\frac{fL}{D} \right)_p + \left(\frac{fL}{D} \right)_a \right] \qquad (5\text{-}34)$$

If $0 < \chi_k^f < 1$, we have two phase flow. Then,

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[ ] a,c

Next, the internally calculated frictional terms are accumulated in C_k. The calculations performed depend on the internally-calculated friction loss model.

For internally-calculated friction loss models 1 (TRANFLØ-type regular connector) and 2 (TRANFLØ-type tube bundle cross flow), we have

$$C_k^{new} = C_k^{old} + \frac{1}{144 g_c} \cdot \frac{1}{2} \cdot \frac{(v_{eff})_k}{A_k^2} \frac{0.316}{(Re_k)^{0.25}} \frac{Z_k}{(D_e)_k} \qquad (5\text{-}36)$$

and

[ ] a,c

respectively, where

$$(v_{eff})_k = \begin{cases} v_k & , 0 \le \alpha_k < 0.01 \\ (v_f)_{donor(k)} \dfrac{(1-\chi_k^f)^{1.75}}{(1-\alpha_k)^{1.42}} & , 0.01 \le \alpha_k < 0.61 \\ (v_f)_{donor(k)} \dfrac{0.48(1-\chi_k^f)^{1.75}}{(1-\alpha_k)^{2.20}} & , 0.61 \le \alpha_k < 0.90 \\ (v_f)_{donor(k)} \dfrac{1.73(1-\chi_k^f)^{1.75}}{(1-\alpha_k)^{1.64}} & , 0.90 \le \alpha_k < 0.95 \\ (v_g)_{donor(k)} \left(\chi_k^f + (1-\chi_k^f)^{1.26} \left[\dfrac{(v_f)_{donor(k)}}{(v_g)_{donor(k)}} \right]^{1/2} \right)^2 & , 0.95 < \alpha_k \le 0.99 \\ v_k & , 0.99 < \alpha_k \le 1. \end{cases} \quad (5\text{-}38)$$

and

$$Re_k = \begin{cases} \dfrac{|W_k| (D_e)_k}{A_k \mu_f} & , 0 \le \alpha_k \le 0.99 \\ \dfrac{|W_k| (D_e)_k}{A_k \mu_g} & , 0.99 < \alpha_k \le 1 \end{cases} \quad (5\text{-}39)$$

These equations are from Reference 4.

For friction model 3 (flow inside of tubes)

If $0 \le \alpha_k < 1$,

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where

$$Re_k = \frac{|W_k| (D_i)_k}{A_k \mu_f} . \qquad (5\text{-}41)$$

If $\alpha_k = 1$

[ ] a,c

where

$$Re_k = \frac{|W_k| (D_i)_k}{A_k \mu_g} . \qquad (5\text{-}43)$$

For friction model 4 (parallel flow along the outside of tubes),

If $0 \leq \alpha_k < 1$,

[ ] a,c

a,c [ ]

where Re_k is given by the lower part of Equation (5-39).

For friction model 5 and 8 (cross flow on the outside of tubes)

If $0 \leq \alpha_k < 1$

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[ ] a,c

For friction model 6 (cross flow in the U-bend region)

If $0 \leq \alpha_k <$.

[ ] a,c

a,c [ ]

The final frictional terms to be accumulated in C_k are the loss terms for the feedwater valve and the throttle valve. If the feedwater valve is in flow link k, then

$$C_k^{new} = C_k^{old} + \frac{v_k}{62.4} \left[\frac{(60)(7.4805)}{C_V^{FW} (F_{VP}^{FW})} \right]^2 . \quad (5\text{-}57)$$

If the throttle valve is in flow link k, then

$$C_k^{new} = C_k^{old} + \frac{v_k}{62.4} \left[\frac{(60)(7.4805)}{C_V^{TV} (F_{VP}^{TV})} \right]^2 . \quad (5\text{-}58)$$

The feedwater valve coefficient, C_v^{FW}, and the throttle valve coefficient, C_v^{TV} [gal-in/min-lbf$^{1/2}$], are functions of the feed valve position, F_{VP}^{FW}, and the throttle valve position, F_{VP}^{TV} [% valve lift], respectively. Both C_V^{FW} (F_{VP}^{FW}) and C_V^{TV} (F_{VP}^{TV}) are user-supplied functions. This concludes the calculation of frictional terms.

The next calculations performed in subroutine FLØW use previously calculated quan ities to calculate the following momentum flux terms and derivatives for the momentum equation of each non-critical flow link k:

$$(C_k^{MF})_k = \frac{1}{144 g_c} \left[(1-f_j^k) [\rho V^2]_{j2}^k + c_k^2 [(\rho_{j2})_k - (\rho_{j1})_k] - (1-f_i^k)[\rho V^2]_{j1}^k \right] , \quad (5\text{-}59)$$

$$(D_k^{MF})_k = \frac{\partial}{\partial W_k} (C_k^{MF})_k , \quad (5\text{-}60)$$

$$(C_p^{MF})_k = \begin{cases} 1 & \text{if } p \in T_i^W, \\ f_p^k \cdot [\rho V^2]_{j2}^p \cdot \frac{1}{144\ g_c} & \\ f_p^k \cdot [\rho V^2]_{j1}^p \cdot \frac{1}{144\ g_c} & \text{if } p \in I_i^W, \end{cases} \tag{5-61}$$

$$(D_p^{MF})_k = \frac{\partial}{\partial W_k} (C_p^{MF})_k \tag{5-62}$$

$$(C_q^{MF})_k = \begin{cases} f_q^k \cdot [\rho V^2]_{j2}^q \cdot \frac{1}{144\ g_c} & \text{if } q \in T_i^W \\ f_q^k \cdot [\rho V^2]_{j1}^q \cdot \frac{1}{144\ g_c} & \text{if } q \in I_i^W, \end{cases} \tag{5-63}$$

and

$$(D_q^{MF})_k = \frac{\partial}{\partial W_k} (C_q^{MF})_k . \tag{5-64}$$

These quantities are used in subroutine SETUP for the inclusion of momentum flux. The derivatives are used when the non-critical flow links are treated implicitly.

The last calculations performed in subroutine FLØW calculate the pressure difference across each flow link to which the reactor coolant pump model is applied. For pump type m with pump homologous curve type n and point of application (flow link) k, certain calculations are done in preparation for calling the pump module. User externals REVPUMP and CSTPUMP are called to determine, respectively, if reverse speed is currently allowed and if the pump is currently coasting. If the pump is not currently coasting, user external RPMPUMP is called to determine the pump speed.

Next the pressure and enthalpy at the "in-flow" end of the pump are determined. Next the pump module is called. It returns the "out-flow" end pressure and, if there is critical flow in the pump, the maximum allowable mass flow rate for flow link k. Finally, the term D_k in the momentum equation for non-critical flow link k is modified by adding the pressure difference across the pump.

$$D_k^{new} = D_k^{old} \pm (P_{in\text{-}flow})_m - (P_{out\text{-}flow})_m \qquad (5\text{-}65)$$

where the sign is dependent on flow direction.

6.0 HEAT LINK CALCULATIONS

In this section, a detailed description of the calculations performed for heat links is given. These calculations are done in subroutine HEAT.

A non-critical heat link always connects a metal and a fluid node. The first calculation done for non-critical heat link n is to see if the link has an upstream metal node and a downstream fluid node or if it has an upstream fluid node and a downstream metal node. A sign convention is established such ha' the rest of the calculations are done assuming the former. Appropriate signs are then changed at the end of the calculations if this is not the case.

If heat link n is a non-critical heat link with internally-calculated heat transfer, then the metal node heat transfer resistance is calculated next. For non-critical heat link type 1, i.e., heat transfer resistance is given by

$$R_m = \frac{D_i \ln (D_m/D_i)}{2k(T_m)} = \frac{1}{U_m} \tag{6-1}$$

For heat link type 2 or 3, i.e., heat transfer between fluid and the outer part of a tube, we have

$$R_m = \frac{D_o \ln (D_o/D_m)}{2k(T_m)} = \frac{1}{U_m}, \tag{6-2}$$

The metal surface resistance is

$$R_w = \max (R^n_{foul}, 10^{-10}) \tag{6-3}$$

where R^n_{foul} is a user-specified fouling factor.

The metal node to metal surface resistance is

$$R_{mw} = R_m + R_w. \qquad (6\text{-}4)$$

Next, the fluid node heat transfer resistance is calculated. This calculation is more complex than that for the metal node because the heat transfer mechanisms are dependent on heat transfer regime.

Many of the heat transfer correlations depend on the fluid velocity, flow quality, Reynolds number, and perhaps other flow dependent quantities. A heat link connects with a fluid node, which has no flow rate associated with it. It is therefore necessary to define flow quantities for use in the heat transfer correlations. The following quantities are defined for heat link n:

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The process of determining the heat transfer regime is now begun. If the fluid is subcooled, then we first check for possible subcooled natural or forced convection. The heat transfer correlation used for natural convection is the McAdams correlation[7],

$$Nu = 0.13\ (Gr\ Pr)^{1/3} \quad , \tag{6-10}$$

where

$$Nu = \frac{h_{SNC}\ L}{k(P_f,\ T_f)} \quad , \tag{6-11}$$

$$Gr = \frac{|g|\beta((T_w^{SNC})_n - T_f)\ L^3}{v\ (P_f,\ T_f)^2\ \mu\ (P_f,\ T_f)^2} \quad ,$$

and

$$Pr = \frac{C_p\ (P_f,\ T_f)\ \mu\ (P_f,\ T_f)}{k\ (P_f,\ T_f)} \tag{6-12}$$

L is a characteristic vertical length. β is the coefficient of volumetric expansion.

Defining

$$Gr^* = \frac{|g|\ \max(\beta,\ 0)}{(P_f,\ T_f)^2\ \mu(P_f,\ T_f)^2} \quad , \tag{6-13}$$

the heat flux for natural convection is given by

$$g_{SNC} = 0.13k\ (P_f,\ T_f)(Gr^*Pr)^{1/3}\ (T_w^{SNC} - T_f)^{4/3} \tag{6-14}$$

We assume that this heat flux is equal to the heat flux from the center of the tube to the tube wall, i.e.,

$$g_{SNC} = \frac{i}{R_{mw}} (T_m - T_w^{SNC}) \qquad (6\text{-}15)$$

Using Equations (6-14) and (6-15) and defining

$$\underline{\overline{X}} = \frac{(T_w^{SNC})_n - T_f}{T_m - T_f} \quad , \qquad (6\text{-}16)$$

we can eliminate g_{SNC} and solve for $\underline{\overline{X}}$. [$\underline{\overline{X}}$ is the largest real root of

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We next calculate the wall temperature for subcooled forced convection. It is given by

$$(T_w^{SFC})_n = \frac{T_m/R_{mw} + T_f/(R_f/C_f)}{1/R_{mw} + 1/(R_f/C_f)} \qquad (6\text{-}21)$$

where

$$R_f = \frac{(\overline{D_e})_n}{k(P_f, T_f)} \quad \frac{1}{(0.023\ Re^{0.8}\ Pr^{0.4})} \qquad (6\text{-}22)$$

for non-critical heat link types 1 and 2, i.e., parallel flow along the inside or outside of a tube, and

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for non-critical heat link type 3, i.e., crossflow across the outside of a tube. T_m and T_f are the metal node and fluid node temperatures, respectively, for heat link n. C_f is a user-supplied heat transfer resistance correction factor. It is often used to account for the effect of baffle leakage on heat transfer in a steam generator preheater region (see References 6). The Reynolds number is calculated using

$$Re = \frac{(\bar{W})_n \, (\overline{D_e})_n}{(\bar{A})_n \, \mu(P_f, T_f)} \quad . \tag{6-24}$$

[ ] a,c

We compare the wall temperature assuming natural convection, $(T_w^{SNC})_n$, and the wall temperature assuming forced convection, $(T_w^{SFC})_n$, to determine the wall temperature for convection, $(T_w^{SC})_n$. If $|(T_w)_n^{SFC} - T_f| < |(T_w)^{SNC} - T_f|$, then $(T_w^{SC})_n = (T_w)^{SFC}$, otherwise $(T_w^{SNC})_n$.

The wall temperature, $(T_w^{SC})_n$, is compared to the saturation temperature of the fluid, T_{sat}. If $(T_w^{SC})_n \leq T_{sat}$, then the heat transfer regime is subcooled convection. If not, we next check for possible subcooled boiling.

The heat flux for subcooled nucleate boiling is given either by the Thom correlation[8]

$$q_{SNB} = \frac{AKT^{-2}}{3600} e^{P/630((T_w^{SNB})_n - T_{sat})^2} , \quad (6\text{-}27)$$

or by the Jens-Lottes correlation[9]

$$q_{SNB} = \frac{AKJL^{-4}}{3600} e^{P/225((T_w^{SNB})_n - T_{sat})^4} . \quad (6\text{-}28)$$

We assume that this heat flux is equal to the heat flux from the center of the tube to the tube wall, i.e.,

$$q_{SNB} = \frac{1}{R_{mw}} (T_m - (T_w^{SNB})_n). \quad (6\text{-}29)$$

Using Equation (6-29) and either Equation (6-27) or (6-28) and defining

$$\overline{X} = \frac{(T_w^{SNB})_n - T_{sat}}{T_m - T_{sat}} , \quad (6\text{-}30)$$

we can eliminate q_{SNB} and solve for $\overline{X}$.

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We now compare the wall temperature assuming subcooled convection and the wall temperature assuming subcooled nucleate boiling. If[ ] a,c [ ]then the heat transfer regime is subcooled convection. If not, we have subcooled nucleate boiling unless the resulting heat flux, (q_{SNB}), is greater than the critical heat flux. a,c

The subcooled boiling critical heat flux is calculated using the MacBeth correlation[4]:

$$(q_{crit})_n = \max \left[\frac{1.7583\ (h_g - h_f)}{(\overline{D_e})_n^{0.1}} \left(\frac{3600\ \overline{W}_n}{10^6\ \overline{A}_n} \right)^{0.51}, \frac{90{,}000}{3600} \right]. \qquad (6\text{-}39)$$

If [ ]then the heat transfer regime is subcooled nucleate boiling. If not, we must check for possible subcooled transition boiling or subcooled film boiling. a,c

We next calculate the wall temperature assuming subcooled transition boiling. The heat transfer coefficient for subcooled transition boiling, U_{STB}, is calculated using the Westinghouse transition boiling correlation (function HTB[4] in the code). Then the wall temperature is calculated using

$$(T_w^{STB})_n = \frac{T_m/R_{mw} + T_f U_{STB}}{1/R_{mw} + U_{STB}} . \qquad (6\text{-}40)$$

U_{STB} depends on $(T_w^{STB})_n$, however, so an iterative procedure must be used. We simply iterate between function HTB and Equation (6-40) for up to ten iterations. The initial guess for $(T_w^{STB})_n$ is simply the average of T_m and T_f. The heat flux assuming subcooled transition boiling is calculated using

$$(q_{STB})_n = \frac{1}{R_{mw}} [T_m - (T_w^{STB})_n]. \qquad (6\text{-}41)$$

We next calculate the wall temperature assuming subcooled film boiling. The heat transfer coefficient for subcooled film boiling is calculated using the Sandberg correlation[4],

$$U_{SFB} = \max \left[\frac{k(P_f,(T_w^{SFB})_n)}{(\bar{D}_e)_n}(0.0193\ Re^{0.8}\ Pr^{1.23}) \right. \qquad (6\text{-}42)$$
$$\left. \times \left(\frac{v\ v_f}{(v_g)^2}\right)^{0.068}, \frac{2.0}{3600.0}\right]$$

We approximate $(T_w^{SFB})_n$ in Equation (6-42) as the maximum between T_{sat} and the average of T_m and T_f. The wall temperature is obtained using

$$(T_w^{SFB})_n = \frac{T_m/R_{mw} + T_f U_{SFB}}{1/R_{mw} + U_{SFB}} . \qquad (6\text{-}43)$$

The heat flux assuming subcooled film boiling is calculated using

$$(q_{SFB})_n = \frac{1}{R_{mw}} [T_m - (T_w^{SFB})_n]. \qquad (6\text{-}44)$$

If [ ] then the heat transfer regime is subcooled transition boiling; if not, it is subcooled film boiling. This concludes the process of determining the heat transfer regime for subcooled fluid. a,c

If the fluid is saturated, we first calculate heat transfer between the metal node and the saturated mixture in the fluid node. If the metal node temperature is less than the fluid temperature and the condensation option is on for the mixture, we assume that the heat transfer regime is saturated condensation. If not, we check for possible saturated natural or forced convection if the mixture void fraction is less than or equal to VFCFCV. The wall temperature for saturated convection, $(T_w^{SC})_n$, is found in exactly the same way as for subcooled convection, i.e., from Equations (6-10) through (6-26).

If $(T_w^{SC})_n \leq T_{sat}$, then the heat transfer regime is saturated convection. If not, we check for possible saturated boiling.

We now check for possible saturated nucleate boiling. The metal wall temperature assuming saturated nucleate boiling is obtained using Equations (6-31) - (6-38). The heat flux is then calculated using Equation (6-29). We now compare the wall temperature assuming saturated convection and the wall temperature assuming saturated nucleate boiling. If [ ] a,c then the heat transfer regime is saturated convection. If not, we have saturated boiling but we must check further to see what type of boiling.

The saturated nucleate boiling regime is checked next. The saturated boiling critical heat flux is calculated using the MacBeth correlation[4]:

$$(q_{crit})_n = \max \left[\frac{1.7583\ (h_g - h_f)}{(\bar{D}_e)^{0.1}} \left(\frac{3600\ [(W_f)_n + (W_g)_n]}{10^6\ \bar{A}_n} \right) 0.51 \right. \tag{6-45}$$

$$\left. (1 - (X_{mix})_{fluid(n)}),\ \frac{90,000}{3600} \right] .$$

a,c If [ ] then the heat transfer regime is saturated nucleate boiling. If not, we must check for possible saturated transition boiling or saturated film boiling.

We next calculate the wall temperature assuming saturated transition boiling. The procedure used for subcooled transition boiling is also used here. The wall temperature is given by Equation (6-40) and the heat flux assuming saturated transition boiling by Equation (6-41). We next calculate the wall temperature assuming saturated film boiling. The heat transfer coefficient for saturated film boiling is calculated using the correlation of Dougall and Rohsenow[4],

$$U_{cr_2} = \max \left[\frac{k(P_f, T_f)}{(\overline{D_e})_n} \; 0.023 \left(\frac{[(\overline{W_f})_n v_f + (\overline{W_g})_n v_g](\overline{D_e})_n}{v_g \bar{A} \mu_g(P_f)} \right)^{0.8} \right. \tag{6-46}$$

$$\left. \left(\frac{(C_p)_g (P_f) \mu_g (P_f)}{k_g (P_f)} \right)^{0.4}, \frac{2.0}{3600.0} \right]$$

The wall temperature is given by Equation (6-43) and the heat flux assuming saturated film boiling by Equation (6-44). If [ ]
a,c
a,c [ ] then the heat transfer regime is saturated transition boiling; if not, it is saturated film boiling.

If the void fraction in the saturated fluid is greater than VFCFCV, we check for possible forced convection vaporization. The heat transfer coefficient for forced convection vaporization is calculated using the correlation of Schrock and Grossman[4],

$$U_{FCV} = \max \left[\frac{2.5/R_f}{\left[\left(\frac{\mu_f}{\mu_g} \right)^{0.1} \left(\frac{v_f}{v_g} \right)^{0.5} \left(\frac{1 - (X_{mix})_{fluid(n)}}{(X_{mix})_{fluid(n)}} \right)^{0.9} \right]^{0.75}} \; 10^{-10} \right] \tag{6-47}$$

The metal wall temperature assuming forced convection vaporization is then calculated using

$$(T_w^{FCV})_n = \frac{T_m/R_{mw} + T_f U_{FCV}}{1/R_{mw} + U_{FCV}} \qquad (6\text{-}48)$$

and the heat flux using

$$(q_{FCV})_n = \frac{1}{R_{mw}} [T_m - (T_w^{FCV})_n]. \qquad (6\text{-}49)$$

The saturated boiling critical heat flux is calculated using the MacBeth correlation, Equation (6-45). If [ ] then the heat transfer regime is forced convection vaporization. If not, we return to the logic for choosing between saturated transition boiling and saturated film boiling. This concludes the process of determining the heat transfer regime for saturated mixture. a,c

If the fluid is superheated, we first check to see if the metal node temperature is less than the saturation temperature and the condensation option is on. If so, we check for possible superheated condensation. The wall temperature for superheated condensation is given by

$$(T_w)_n^{SC} = \frac{T_m U_{mw} + T_f U_{SC}}{U_{mw} - U_{SC}} \qquad (6\text{-}50)$$

where $U_{SC}(n, t, T_m, T_f)$ is a user-supplied function. If $(T_w)^{SC} > T_{sat}$ then the heat transfer regime is superheated condensation. If not, we check for possible superheated natural or forced convection. The wall temperature for superheated natural convection, $(T_w^{SNC})_n$, is found in the same way as for subcooled natural convection, i.e., from Equations (6-10) through (6-20). The wall temperature for superheated forced convection, $(T_w^{SFC})_n$, is calculated from

$$(T_w^{SFC})_n = \frac{T_m U_{mw} + T_f U_{SFC}}{U_{mw} + U_{SFC}} \qquad (6\text{-}51)$$

where the heat transfer coefficient for superheated forced convection is calculated using the correlation of Heineman[4],

$$U_{SFC} = \max \left[\frac{k(P_f,T_f)}{(\bar{D}_e)_n} 0.0133\ Re^{0.84}\ Pr^{0.333}\ ,\ 10^{-10}\right] \qquad (6\text{-}52)$$

If $|(T_w^{SNC})_n - T_f| \leq |(T_w^{SFC})_n - T_f|$, then the heat transfer regime is superheated natural convection. If not, the heat transfer regime is superheated forced convection. This concludes the process of determining the heat transfer regime for superheated fluid.

Knowing the heat transfer regime for a non-critical heat link, we now complete the calculations. It was stated earlier that a sign convention was established so that the calculations could be done assuming an upstream metal node and a downstream fluid node. In the following equations, the "$\pm$" is used to account for the actual defined heat link direction.

For the subcooled saturated or superheated natural convection heat transfer regimes we have

$$Q_n = \pm A_n \cdot CK \cdot |(T_w^{SNC})_n - T_f|^{4/3} , \tag{6-53}$$

if $(T_w^{SNC})_n \geq T_f$,

$$Q_n = \mp A_n \cdot CK \cdot |(T_w^{SNC})_n - T_f|^{4/3} \tag{6-54}$$

if $(T_w^{SNC})_n < T_f$,

$$\frac{\partial Q_n}{\partial T_m} = \pm \frac{4}{3} A_n \cdot CK \cdot |(T_w^{SNC})_n - T_f|^{1/3} \cdot \frac{\partial (T_w^{SNC})_n}{\partial T_m} , \tag{6-55}$$

$$\frac{\partial Q_n}{\partial T_f} = - \frac{\partial Q_n}{\partial T_m} , \tag{6-56}$$

and

$$\frac{\partial Q_n}{\partial P_f} = 0 \tag{6-57}$$

where CK is given by Equation (6-19) and where, from Equation (6-20),

$$\frac{\partial (T_w^{SNC})_n}{\partial T_m} = \overline{\underline{X}} \quad . \tag{6-58}$$

For the subcooled or saturated forced convection heat transfer regimes, we have

$$Q_n = \pm A_n U_{mwf} (T_m - T_f), \tag{6-59}$$

$$\frac{\partial Q_n}{\partial T_m} = \pm A_n \left[U_{mwf} + \frac{\partial U_{mwf}}{\partial T_m} (T_m - T_f)\right], \tag{6-60}$$

$$\frac{\partial Q_n}{\partial T_f} = \pm A_n \left[-U_{mwf} + \frac{\partial U_{mwf}}{\partial T_f} (T_m - T_f)\right], \tag{6-61}$$

and

$$\frac{\partial Q_n}{\partial P_f} = \pm A_n \left[\frac{\partial U_{mwf}}{\partial P_f} (T_m - T_f)\right] \tag{6-62}$$

where

$$U_{mwf} = \frac{1}{R_{mwf}} = \frac{1}{R_{mw} + R_f/C_f}, \tag{6-63}$$

$$\frac{\partial U_{mwf}}{\partial T_m} = \frac{U_{mwf}^2}{U_m} \frac{1}{k(T_m)} \cdot \frac{\partial k(T_m)}{\partial T_m}, \tag{6-64}$$

$$\frac{\partial U_{mwf}}{\partial T_f} = 0, \tag{6-65}$$

and

$$\frac{\partial U_{mwf}}{\partial P_f} = 0. \tag{6-66}$$

For the subcooled or saturated nucleate boiling heat transfer regimes, we have for the Thom correlation,

$$Q_n = \pm A_n \cdot CK \cdot \left[(T_w^{SNB})_n - T_{sat}(P_f)\right]^2, \tag{6-67}$$

$$\frac{\partial Q_n}{\partial T_m} = \pm A_n 2 \cdot CK \cdot [(T_w^{SNB})_n - T_{sat}(P_f)] \frac{\partial (T_w^{SNB})_n}{\partial T_m}, \quad (6\text{-}68)$$

$$\frac{\partial Q_n}{\partial T_f} = 0, \quad (6\text{-}69)$$

and

$$\frac{\partial Q_n}{\partial P_f} = \pm A_n \cdot CK \cdot [(T_w^{SNB})_n - T_{sat}(P_f)] \cdot \{[(T_w^{SNB})_n - T_{sat}(P_f)]/630 - 2 \frac{\partial T_{sat}(P_f)}{\partial P_f}\} \quad (6\text{-}70)$$

where CK is given by Equation (6-33) or for the Jens-Lottes correlation,

$$Q_n = \pm A_n \cdot CK \cdot [(T_w^{SNB})_n - T_{sat}(P_f)]^4, \quad (6\text{-}71)$$

$$\frac{\partial Q_n}{\partial T_m} = \pm 4 \cdot A_n \cdot CK \cdot [(T_w^{SNB})_n - T_{sat}(P_f)]^3 \cdot \frac{\partial (T_w^{SNB})_n}{\partial T_m}, \quad (6\text{-}72)$$

$$\frac{\partial Q_n}{\partial T_f} = 0 \quad (6\text{-}73)$$

$$\frac{\partial Q_n}{\partial P_f} = \pm A_n \cdot CK \cdot [(T_w^{SNB})_n - T_{sat}(P_f)]^3 \cdot \{[(T_w^{SNB})_n - T_{sat}(P_f)]/225 - 4 \frac{\partial T_{sat}(P_f)}{\partial P_f}\} \quad (6\text{-}74)$$

where CK is given by Equation (6-37) and where, from Equation (6-38),

$$\frac{\partial (T_w^{SNB})_n}{\partial T_m} = \overline{\overline{X}} \quad . \quad (6\text{-}75)$$

For forced convection vaporization, we use Equations (6-59) - (6-62) and (6-64) - (6-66) where

$$U_{mwf} = \frac{1}{R_{mwf}} = \frac{1}{R_{mw} + 1/U_{FCV}} \cdot \tag{6-76}$$

For subcooled or saturated transition boiling, we use Equations (6-59) - (6-62) and (6-64) - (6-66)

where

$$U_{mwf} = \frac{1}{R_{mwf}} = \frac{1}{R_{mw} + 1/U_{STB}} \cdot \tag{6-77}$$

For subcooled or saturated film boiling, we use Equations (6-59) - (6-62) and (6-64) - (6-66) where

$$U_{mwf} = \frac{1}{R_{mwf}} = \frac{1}{R_{mw} + 1/U_{SFB}} \cdot \tag{6-78}$$

For superheated forced convection, we use Equations (6-59) - (6-62) and (6-64) - (6-66) where

$$U_{mwf} = \frac{1}{R_{mwf}} = \frac{1}{R_{mw} + 1/U_{SFC}} \cdot \tag{6-79}$$

For saturated or superheated condensation, we use Equations (6-59) - (6-62) and (6-64) - (6-66) where

$$U_{mwf} = \frac{1}{R_{mwf}} = \frac{1}{R_{mw} + 1/U_{SC}} \tag{6-80}$$

where $U_{SC}(n, t, T_m, T_f)$ is a user-supplied function.

If heat link n is a non-critical heat link with a user-supplied overall heat transfer coefficient, then we have

$$Q_n = \pm A_n \cdot U_n \cdot (T_m - T_f) \quad , \tag{6-81}$$

$$\frac{\partial Q_n}{\partial T_m} = \pm A_n \cdot U_n \quad , \tag{6-82}$$

$$\frac{\partial Q_n}{\partial T_f} = \frac{\partial Q_n}{\partial T_m} \quad , \tag{6-83}$$

and

$$\frac{\partial Q_n}{\partial P_f} = 0 \quad . \tag{6-84}$$

If heat link n is a non-critical heat link with a user-supplied overall heat transfer coefficient which is modified by mixture height, then we have

$$Q_n = \pm A_n \cdot \frac{(E_{mix})_{fluid(n)} - (E_{bot})_{fluid(n)}}{(E_{top})_{fluid(n)} - (E_{bot})_{fluid(n)}} \cdot U_n \cdot (T_m - T_f) \quad , \tag{6-85}$$

$$\frac{\partial Q_n}{\partial T_m} = \pm A_n \cdot \frac{(E_{mix})_{fluid(n)} - (E_{bot})_{fluid(n)}}{(E_{top})_{fluid(n)} - (E_{bot})_{fluid(n)}} \cdot U_n \tag{6-86}$$

$$\frac{\partial Q_n}{\partial T_f} = - \frac{\partial Q}{\partial T_m} \tag{6-87}$$

and

$$\frac{\partial Q_n}{\partial P_f} = 0 \quad . \tag{6-88}$$

If non-critical heat link n has an upstream metal node and a downstream fluid node, we have

$$\frac{\partial Q_n}{\partial T_{u(n)}} = \frac{\partial Q_n}{\partial T_m} \quad , \tag{6-89}$$

$$\frac{\partial Q_n}{\partial P_{u(n)}} = 0 \,, \tag{6-90}$$

$$\frac{\partial Q_n}{\partial T_{d(n)}} = \frac{\partial Q_n}{\partial T_f}, \tag{6-91}$$

and

$$\frac{\partial Q_n}{\partial P_{d(n)}} = \frac{\partial Q_n}{\partial P_f} \,. \tag{6-92}$$

If non-critical heat link n has an upstream fluid node and a downstream metal node, we have

$$\frac{\partial Q_n}{\partial T_{u(n)}} = \frac{\partial Q_n}{\partial T_f} \,, \tag{6-93}$$

$$\frac{\partial Q_n}{\partial P_{u(n)}} = \frac{\partial Q_n}{\partial P_f} \,, \tag{6-94}$$

$$\frac{\partial Q_n}{\partial T_{d(n)}} = \frac{\partial Q}{\partial T_m} \,, \tag{6-95}$$

and

$$\frac{\partial Q}{\partial P_{d(n)}} = 0. \tag{6-96}$$

If heat link n is a non-critical heat link with internally-calculated heat transfer and the fluid node associated with this heat link is saturated, then the heat transfer to the separated vapor space in the fluid node must still be calculated and combined with the heat transfer to the saturated mixture. If the metal node temperature is less than the fluid temperature and the condensation option is on for the vapor space, we assume that the heat transfer regime is saturated condensation. If not, we check for possible natural or forced convection or assume zero heat transfer. For these calculations, the average vapor mass flow rate is defined as

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The wall temperature for saturated vapor natural convection, $(T_w^{SC})_n$, is found in the same way as for subcooled natural convection, i.e., from Equations (6-10) through (6-21) except that all thermodynamic and transport properties are those of saturated vapor. The wall temperature for saturated vapor forced convection is given by

$$(T_w^{SFC})_n = \frac{T_m U_{mw} + T_f U_{SFC}}{T_m + T_f} \qquad (6\text{-}98)$$

where the heat transfer coefficient for saturated vapor forced convection, U_{SFC}, is calculated using Equation (6-52). We compare the wall temperature assuming natural convection, $(T_w^{SNC})_n$, and the wall temperature assuming forced convection, $(T_w^{SFC})_n$, to determine the wall temperature for convection, $(T_w^{SC})_n$. If $|(T_w)_n^{SFC} < T_f| < |(T_w)^{SNC} - T_f|$, then $(T_w^{SC})_n = (T_w)_n^{SFC}$, otherwise $(T_w^{SC})_n = (T_w^{SNC})_n$.

Knowing the heat transfer regime for heat transfer between the metal node and the separated vapor space, we now complete the calculations. For the saturated vapor natural convection heat transfer regime, we use Equations (6-53) - (6-58). For saturated vapor forced convection, we use Equations (6-59) - (6-66). For saturated vapor condensation, we use Equations (6-59) - (6-62), (6-64) - (6-66) and (6-80).

Finally, for heat transfer to a stratified saturated fluid node, we combine the heat transfer to the mixture region with the heat transfer to the vapor region. We use Equations (6-89) - (6-96) times a weighting factor $((E_{mix}^{stack})_{fluid(n)} - (E_{bot})_n)/((E_{top})_n - (E_{bot})_n)$ for the mixture region and times a weighting factor $((E_{top})_n - (E_{mix}^{stack})_{fluid(n)})/((E_{top})_n - (E_{bot})_n)$ for the vapor region. $(E_{top})_n$ and $(E_{bot})_n$ are the top and bottom elevations, respectively, of heat link n. They are not currently input but rather are internally calculated. Ordinarily these elevations are set to the bottom and top elevations of the fluid node to which heat link n is connected. If, however, the metal node to which heat link n is connected is itself connected to another fluid node and if that fluid node has a lower top elevation and a higher bottom elevation that the other fluid node, then those elevations are used for both associated heat links.

The final calculation in subroutine HEAT is the setting of the heat rate for each critical heat link. The heat rate is a user-specified function of time; i.e.,

$$Q_n = Q_n(t) \quad . \tag{6-99}$$

7.0 CONTROLLER CALCULATIONS

In this section, a description of calculations performed for controllers is presented. These calculations are done in subroutine CØNTRL.

If controllers are being used or the level option is on, then the measured steam generator water level, X_{LM}^{FW}, is calculated according to Equation (K-1). It is used in Equation (K-50) for the feedwater valve controller.

8.0 GENERATION AND SOLUTION OF MATRIX EQUATION

In this section, we describe the details of generating and solving Equation (E-1). Subroutines SETUP and SØLVER perform the calculations. Before reading this section, the reader is urged to read Section 2.2 and Appendix E.

It should be pointed out here that subroutines SETUP and SØLVER are written such that the vector $\underline{y}$ given in Section 2.2 can be re-ordered to take advantage of the structure of the $\underline{\underline{A}}^*$ matrix through re-ordering of its rows and columns. The re-ordering is calculated during initialization and saved in various maps. [a,c

] If other ordering schemes are developed, only the generation of the maps will need to be modified.

It should also be pointed out that the following description applies to the case where all equations are solved implicitly. If certain equations are solved explicitly, appropriate simplifications result and are used.

Subroutine SETUP prepares for the generation of the matrix equation by setting the $\underline{\underline{A}}^*$ matrix from Equation (E-23) and the $\underline{B}$ vector from Equation (E-1) to zero.

Next the $\underline{B}$ vector is generated. The $\underline{B}$ vector consists of B_W from Equation (2-8), B_U from Equation (2-1) or (2-17), B_M from Equation (2-2) or (2-18), B_T from Equation (2-5) or (2-19), and B_Z from Equations (K-42)-(K-55).

The implicit interior fluid node constants are generated next and saved for later use. These constants are α_{1i}, β_{1i}, γ_{1i}, α_{2i}, β_{2i}, and γ_{2i} from Equations (E-48)-(E-53).

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This concludes the calculations in subroutine SETUP. The $\underline{\underline{A}}^*$ matrix and the $\underline{B}$ vector have been generated.

Subroutine SØLVER obtains the explicit solution to Equation (2-25), generates the $\underline{B}^*$ vector, and solves Equations (E-23), (E-60), and (E-61) to obtain the implicit solution for selected parts of Equation (2-25). The end result is the $\Delta \underline{y}^{n+1}$ vector.

The explicit solution to Equation (2-25) is simply

$$\Delta \underline{y}^{n+1} = \Delta t_{n+1} \; F\,(t^n, \underline{y}^n). \qquad (8\text{-}1)$$

This is in contrast to the implicit solution which must be obtained by solving Equation (2-27).

Subroutine SØLVER firsts calculates $\Delta \underline{y}^{n+1}$ from Equation (8-1). Selected implicit equations will later be solved to replace some of the components of $\Delta \underline{y}^{n+1}$ by implicit solution values. Next, the B_W^* and B_T^* subvectors are generated according to Equations (E-58) and (E-59), respectively. Now the matrix equation, Equation (E-23), is solved either by block elimination as described in Appendix E or by Gaussian elimination. Finally, Equations (E-60) and (E-61) are used to calculate the rest of the implicit solution. The $\Delta \underline{y}^{n+1}$ vector is now complete, some components having been calculated explicitly and some implicitly.

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9.0 INITIALIZATION CALCULATIONS

In this section, we give a detailed description of calculations which initialize certain quantities at the starting time of a problem and upon the restart of a problem. These calculations are performed in subroutine INIT.

Certain variables are initialized only for non-restart runs. Various counters are set to zero. A table for allowable trace variables is initialized. It contains the name and location of each trace variable. The desired trace variables are then checked against this table.

Variables related to the size of the problem are initialized next both for non-restart and restart runs. They are: the number of interior fluid nodes, boundary fluid nodes, interior metal nodes, boundary metal nodes, non-critical flow links, critical flow links, non-critical heat links, critical heat links, implicit interior fluid nodes, implicit interior metal nodes, and implicit non-critical flow links.

Next, various maps are generated for both non-restart and restart runs. They map each momentum equation for non-critical flow links, each energy and mass equation for interior fluid nodes, each energy equation for interior metal nodes, and each control equation into a specific row of Equation (2-25). Currently, the ordering of only the momentum equations is changed. They are re-ordered so as to give A* the structure shown in Equation (E-63), thus allowing the use of block elimination. If the user has specified that the code should choose between Gaussian elimination and block elimination, then Equations (E-68) and (E-69) are evaluated in order to make the choice. The code chooses the method which has the fewer number of multiplications and divisions as estimated by these equations.

For non-restart runs, all interior fluid nodes are initialized next. For interior fluid node i, v_i, T_i, $(T_{sat})_i$, $\frac{\partial (T_{sat})_i}{\partial P_i}$, $(v_f)_i$, $(v_g)_i$, $(h_f)_i$, $(h_g)_i$, and χ_i are calculated from P_i and h_i as described in Appendix L. α_i is calculated from Equation (3-6). The total mass, M_i, is initialized from

$$M_i = \frac{V_i}{v_i} \tag{9-1}$$

and the total internal energy, U_i, from

$$U_i = M_i\, h_i - 0.18511\, P_i\, V_i \tag{9-2}$$

If interior fluid node i is not an accumulator node and is subcooled, the following initialization is performed.

$$(E_{mix})_i = (E_{top})_i, \tag{9-3}$$

$$(V_{mix})_i = V_i, \tag{9-4}$$

$$(v_{mix})_i = v_i, \tag{9-5}$$

$$(\chi_{mix})_i = 0, \tag{9-6}$$

$$(\alpha_{mix})_i = 0, \tag{9-7}$$

and

$$(M_{gb})_i = 0. \tag{9-8}$$

If interior fluid node i is not an accumulator node and is superheated, we have:

$$(E_{mix})_i = (E_{bot})_i, \tag{9-9}$$

$$(V_{mix})_i = 0, \tag{9-10}$$

$$(v_{mix})_i = v_i, \tag{9-11}$$

$$(\chi_{mix})_i = 1, \tag{9-12}$$

$$(\alpha_{mix})_i = 1, \tag{9-13}$$

and

$$(M_{gb})_i = 0. \tag{9-14}$$

If interior fluid node i is not an accumulator node and is saturated:

$$(E_{mix})_i = \min\left[\max[(E_{mix})_i, (E^{min}_{mix})_i], (E_{top})_i\right] \tag{9-15}$$

where $(E_{mix})_i$ on the right hand side is input by the user and where

$$(E^{min}_{mix})_i = (E_{bot})_i + [(E_{top})_i - (E_{bot})_i](1 - \alpha_i). \tag{9-16}$$

We also have

$$(V_{mix})_i = \max[V_i \frac{(E_{mix})_i - (E_{bot})_i}{(E_{top})_i - (E_{bot})_i}, (1-\chi_i)M_i(v_f)_i], \tag{9-17}$$

$$(\alpha_{mix})_i = \frac{(V_{mix})_i - (1-\chi_i)M_i(v_f)_i}{(V_{mix})_i}, \tag{9-18}$$

$$(\chi_{mix})_i = \frac{(\alpha_{mix})_i/(v_g)_i}{(\alpha_{mix})_i/(v_g)_i + (1-(\alpha_{mix})_i)/v_f)_i}, \tag{9-19}$$

$$(M_{gb})_i = \frac{(V_{mix})_i - (1-\chi_i)M_i(v_f)_i}{(v_g)_i} , \tag{9-20}$$

and

$$(v_{mix})_i = \frac{(V_{mix})_i}{(M_{gb})_i + (1-\chi_i)M_i} . \tag{9-21}$$

For each interior fluid node i, we have:

$$(M_g)_i = \chi_i M_i \tag{9-22}$$

and

$$(M_f)_i = (1-\chi_i)M_i . \tag{9-23}$$

If interior fluid node i is an accumulator node:

$$(E_{mix})_i = \min[\max[(E_{mix})_i, (E_{bot})_i], (E_{top})_i] , \tag{9-24}$$

$$(V_{mix})_i = V_i \cdot \frac{(E_{mix})_i - (E_{bot})_i}{(E_{top})_i - (E_{bot})_i} , \tag{9-25}$$

$$M_i = \frac{(V_{mix})_i}{v_j} , \tag{9-26}$$

$$U_i = M_i \cdot h_i - 0.18511 \cdot P_i \cdot (V_{mix})_i , \tag{9-27}$$

$$(M_g)_i = \chi_i \cdot M_i , \tag{9-28}$$

$$(M_f)_i = (1 - \chi_i) \cdot M_i , \tag{9-29}$$

$$(v_{mix})_i = v_i , \tag{9-30}$$

$$(\chi_{mix})_i = \chi_i , \tag{9-31}$$

$$(\alpha_{mix})_i = \alpha_i , \tag{9-32}$$

$$(M_{gb})_i = (M_g)_i \quad , \tag{9-33}$$

$$P_i^o \cdot [(V_{N_2})_i^o]^\gamma = P_i \cdot [V_i - (V_{mix})_i^o]^\gamma \quad . \tag{9-34}$$

For both non-restart and restart runs the following calculations are performed. $v_f\ (P_{LM}^{FW})$ and $v_g\ (P_{LM}^{FW})$ are calculated. They are the saturated liquid and vapor specific volumes at the pressure P_{LM}^{FW} at which the taps for water level measurement were calibrated.

If the node stacking and mixture level tracking option is on, then stacking quantities are initialized. The horizontal stratified flow model quantities are checked for correctness and are initialized.

Finally, information regarding interdependence of implicit interior fluid nodes, implicit interior metal nodes, implicit non-critical flow links, critical flow links and heat links is generated and packed for later unpacking and used in vectorized versions of subroutines SETUP and SØLVER.

10.0 TIME STEP SIZE SELECTION AND TIME ADVANCE

In this section, we give a detailed description of the time step size selection procedures and the time advancing used in NOTRUMP. The setting of time step size is performed in subroutine DELTSET. Time step size modification, if necessary, is done in subroutine DELTCUT. Time advance is done in subroutine UPDATE.

Subroutine DELTSET is called before SETUP. Its sole purpose is to choose the time step size, Δt_{n+1}. For the original time step selection method, Δt_{n+1} is set to DELTMIN for the first time step. The time step size from the previous time step is used for subsequent time steps. For the optional time step selection method, described in Appendix S, the following algorithm is used:

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The mathematical aspects of this algorithm are described in Appendix S.

The time step size is bracketed between DELTMIN and DELTMAX. If a fixed print time or restart time occurs during the tentative time step, then the time step size is adjusted such that the new time is exactly equal to the fixed print or restart time. This concludes the description of the time step size setting performed in subroutine DELTSET.

Subroutine DELTCUT is called after subroutine SØLVE. Its purpose is to either increase the time step size, Δt_{n+1}, if possible or decrease it if necessary. If the time step size is changed, subroutines SETUP and SØLVE are re-done using the new time step size.

Problems can arise in NOTRUMP because convection terms in the energy equations, although they involve new time mass flow rates, do involve some old time quantities. These problems occur when mass flow rates change direction, especially if they change direction every time step. Donor quantities are based on the wrong node when flow changes direction. If this keeps happening, it can lead to the internal energy in a node either increasing or decreasing until the code "bombs" in the fluid property routines.

In order to minimize these problems we have developed smoothness criteria which look not only at the effect of the zeroeth order terms in the NOTRUMP implicit method but also at the first order terms. For the original time step selection method eight smoothness criteria are used in DELTCUT. [Specifically, we calculate

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Subroutine UPDATE is called after subroutine DELTCUT if the time step size has not been modified in DELTCUT. Its purpose is to update the time from t^n to t^{n+1} and to update other appropriate variables.

The time is updated using

$$t^{n+1} = t^n + \Delta t_{n+1} \qquad (10\text{-}40)$$

unless time step n+1 is a fixed print or restart time in which case t^{n+1} is simply set to the fixed time.

The number of time steps and the time elapsed since the last regular call to ØUTPUT (i.e., not including calls to ØUTPUT immediately after RESTART) are updated. The number of time steps and the time elapsed since the last call to RESTART and since the last call to TRACER are also updated. These quantities are necessary for the control of print, restart, and trace frequency.

For each non-critical flow link, the mass flow rate is updated, i.e.,

$$W_k^{n+1} = W_k^n + \Delta W_k^{n+1} \quad ; \; k = 1, \cdots, K \tag{10-41}$$

For each interior fluid node, the total internal energy and the total mass are updated, i.e.,

$$(U^{old})_i^{n+1} = U_i^n \quad ; \; i = 1, \ldots, I \tag{10-42}$$

$$U_i^{n+1} = U_i^n + \Delta U_i^{n+1} \; ; \; i = 1, \cdots, I \tag{10-43}$$

$$M_i^{n+1} = M_i^n + \Delta M_i^{n+1} \; ; \; i = 1, \cdots, I \tag{10-44}$$

and the values of M_g^n, M_f^n, and V_{mix}^n are saved as

$$(M_g^{old})_i^{n+1} = (M_g)_i^n \, , \tag{10-45}$$

$$(M_f^{old})_l^{n+1} = (M_f)_i^n \tag{10-46}$$

$$(V_{mix}^{old})_i^{n+1} = (V_{mix})_i^n \, . \tag{10-47}$$

and

$$(\dot{U}^{old})_i^{n+1} = U_i^n \tag{10-48}$$

The first two quantities are used to approximate $(\dot{M}_g)_i^{n+1}$ and $(\dot{M}_f)_i^{n+1}$ in Equation (H-16) as follows:

$$(\dot{M}_g)_i^{n+1} = \frac{(M_g)_i^{n+1} - (M_g^{old})_i^{n+1}}{\Delta t_{n+1}} \tag{10-49}$$

and

$$(\dot{M}_f)_i^{n+1} = \frac{(M_f)_i^{n+1} - (M_f^{old})_i^{n+1}}{\Delta t_{n+1}}. \qquad (10\text{-}50)$$

For each interior metal node, the temperature is updated, i.e.,

$$T_i^{n+1} = T_i^n + \Delta T_i^{n+1} \; ; \; i = 1, \cdots, J \qquad (10\text{-}51)$$

For each control equation, the control variable is updated, i.e.,

$$Z_i^{n+1} = Z_i^n + \Delta Z_i^{n+1}; \; i = 1, \cdots, M \qquad (10\text{-}52)$$

Subroutine FLØWLIM is called after subroutine UPDATE in order to limit the updated mass flow rates. For each non-critical flow link k, W_k^{n+1} is limited to be less (in absolute value) than $|W_k|^n_{max}$. For flow links to which pumps are applied, special flow limiting is also applied. It is described in Appendix P. For flow links connected to accumulator interior fluid nodes special flow limiting logic is used when the accumulator has just been emptied. It assures that the accumulator loses no more fluid than it has in the last time step of its emptying. For each flow rate modified, the appropriate nodal masses and internal energies are also modified.

11.0 CODE QUALIFICATION

This section contains a description of the analyses performed for the purpose of qualifying NOTRUMP against experimental data. Included are a number of experimental small vessel blowdowns.

11.1 FRANKFURT/MAIN TESTS[10]

Three of the blowdown tests done at Frankfurt/Main were analyzed with the code. Tests 7, 12, and 14 were chosen because they represent a variety of break sizes and initial water levels.

The test vessel schematic and the computer model used are shown in Figures 11-1 and 11-2. The heater bundle and supports are not modeled in these analyses. It is believed at this time that the heater bundle and supports act as inherent separators. The support structure is not defined in the published literature and, therefore, any separation which may occur could not be directly included in the computer model. An attempt has been made to indirectly model this separation by including a multiplier on the drift velocity V_{gj} (see Appendix G). This multiplier was applied to all vertical flow links. A multiplier of four was found to give the best overall results for the three tests.

11.1.1 FRANKFURT/MAIN TEST 7

For this test, the vessel is approximately half full of water. The break location is at 25.591 feet elevation and thus is initially located in the steam space. The break diameter is 5.71 inches. A discharge coefficient of 0.60 was used.

Comparisons between measured and predicted results are shown in Figures 11-3 through 11-6. The calculated flow rate shown in Figure 11-3 is low between about one and three seconds into the transient. It is then high between about four and nine seconds, then low again. It is believed that this is due to using a multiplier on V_{gj} for <u>all</u> vertical flow links. Where the calculated

flow rate is initially low, we are probably separating the two-phase mixture above the heater bundle (nodes 7 and 8) too much since it really does not "see" the separation due to the heater bundle. By four seconds there is appreciable flashing in the heater bundle region. Our single multiplier of four apparently gives too little separation to mixture which must pass through the heater bundle on its way to the break. The calculated mass flow rate is, therefore, high there. After about nine seconds, the separation appears to be too high in the region below the heater bundle, not even allowing much liquid in the mixture below the heater bundle to reach it. Figures 11-4 through 11-6 are consistent with these comments.

11.1.2 FRANKFURT/MAIN TEST 12

This test has a higher initial water level than Test 7 so that initially the break is covered by water. The break diameter is 5.5 inches. A discharge coefficient of 0.60 was used.

Comparisons between measured and predicted results are shown in Figures 11-7 through 11-10. The calculated flow rate shown in Figure 11-7 is high until about five seconds and then low. The high flow rates occur when the break is completely covered and has a low flow quality. The low flow rates occur as there is more flashing below the heater bundle. The comments in Section 11.1.1 also apply to Figures 11-7 through 11-10.

11.1.3 FRANKFURT/MAIN TEST 14

This test has the vessel almost completely filled with water when the break occurs. The break size is considerably smaller than for Tests 7 and 12, the break diameter being 1.97 inches. A discharge coefficient of 0.65 was used.

Comparison between measured and predicted results are shown in Figures 11-11 through 11-14. Since the break size is small, the transient is much slower than Tests 7 and 12 and natural separation is expected to occur throughout the test vessel for almost the entire transient. Liquid falls to the bottom of the vessel keeping the qualities low in nodes 1-4. From about 55 seconds

on, the break is essentially flowing all steam, which is flashing from the quiescent liquid and bubbling up to the mixture level. It was found that the pressure versus the mass remaining in the vessel was quite sensitive to the separation model. A value of four for the multiplier on V_{gj} was chosen because it resulted in good agreement to the test data, thus indicating that it modeled adequately both the natural separation and the inherent separation of the heater bundle and supports. Tests 7 and 12 also used this multiplier.

11.2 BATTELLE NORTHWEST TEST B53B[11]

The Battelle Northwest B53B test vessel schematic and the computer model used are shown in Figure 11-15. The initial pressure for this test was 980 psia, initial water level was 9.4 ft., and the orifice diameter was 1.687 inches. A discharge coefficient of 0.80 was used.

Experimental results for this test did not include the mass flow rate, but did indicate a water level in the vessel during the blowdown. The experimental data was taken from a Time Domain Reflectometer probe, which essentially gives the distance from the top of the vessel to an electronic impedance discontinuity caused by the upper surface of the liquid or foam. NOTRUMP predicts water level using a pressure difference between upper and lower pressure taps, measuring collapsed water level rather than a froth level. Therefore, this calculation was not included in this report since no meaningful comparison could be made between the two results.

Mass and pressure transients are compared in Figures 11-16 and 11-17. It is important to note that natural separation has a significant impact on these transients and that the close predictions of pressure and mass remaining in the vessel are further justification for the drift flux model described in Appendix G.

11.3 CISE TESTS [12, 13]

CISE, as part of the CIRENE-3 program, conducted a series of sixteen small vessel blowdowns at the Betulla plant of C.C.R. Euratom at Ispra. The tests were carried out on a $3m^3$ vessel using three different break locations, two sets of initial conditions, and five different break sizes. A tabulation of

test procedures and test results is given in Reference 17. Three of these tests were modeled using NOTRUMP to show the adequacy of the code in predicting blowdown results. The test vessel schematic and NOTRUMP noding scheme are shown in Figures 11-18 through 11-20.

11.3.1 CISE TEST 1

CISE Test 1 is a blowdown from the upper nozzle with initial pressure 725 psia and a break diameter of 5 inches. The initial water level is 8.14 feet below the upper nozzle.

Comparisons between the experimental data and NOTRUMP predictions for mass remaining in the vessel versus time and for vessel pressure versus time are shown in Figures 11-21 and 11-22, respectively. A discharge coefficient of 0.55 was used. The drift flux and momentum flux models were used. The agreement between experimental and predicted results is good.

11.3.2 CISE TEST 2

CISE Test 2 is a blowdown from the lower nozzle of the test vessel, with an initial pressure of 725 psia and an orifice diameter of 4 inches. The initial water level is 3.87 feet above the blowdown nozzle. A discharge coefficient of 1.00 was used because of the long extrance length to the discharge point and the low quality of the flow. Comparisons between experimental and predicted results are shown in Figures 11-23 and 11-24.

As can be seen from Figure 11-23, the predicted mass transient with time is very close to the experimental results. Again, the drift flux and momentum flux models in NOTRUMP were used. These models adequately handled the counter-current flow expected in the region near the blowdown nozzle. The pressure transient is shown in Figure 11-24. The predicted pressure shows the same trend as the experimental pressure.

11.3.3 CISE TEST 3

The third CISE test was a blowdown from the nozzle in the intermediate loca-

tion with an initial pressure of 725 psia, an orifice diameter of two inches, and an initial water level at the lower edge of the nozzle. A discharge coefficient of 0.85 was used in this test. Comparisons of results are shown in Figures 11-25 and 11-26. Again, agreement between the experimental and predicted masses and pressures is good.

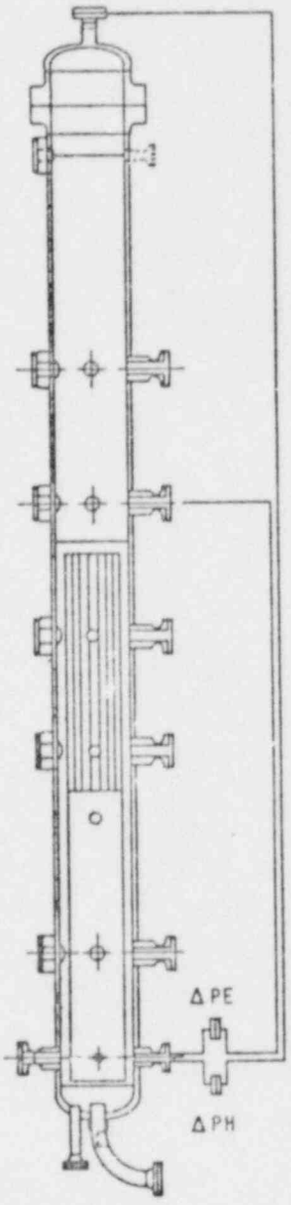

FIGURE 11-1 Frankfurt/Main Test Vessel Schematic

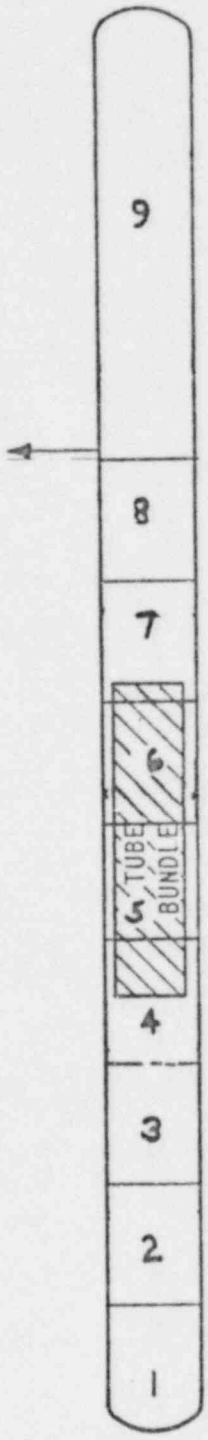

FIGURE 11-2 Computer Model Used for Frankfurt/Main Test Calculation

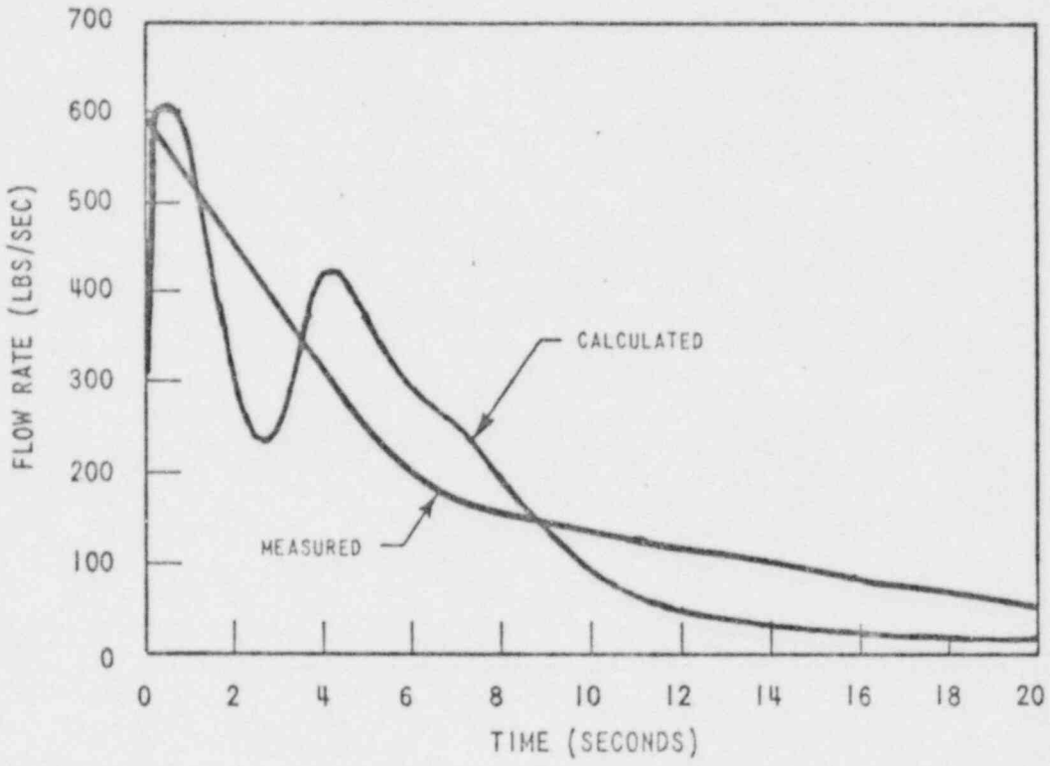

FIGURE 11-3 Comparison of Calculated and Measured Flow Rate for Frankfurt Test 7

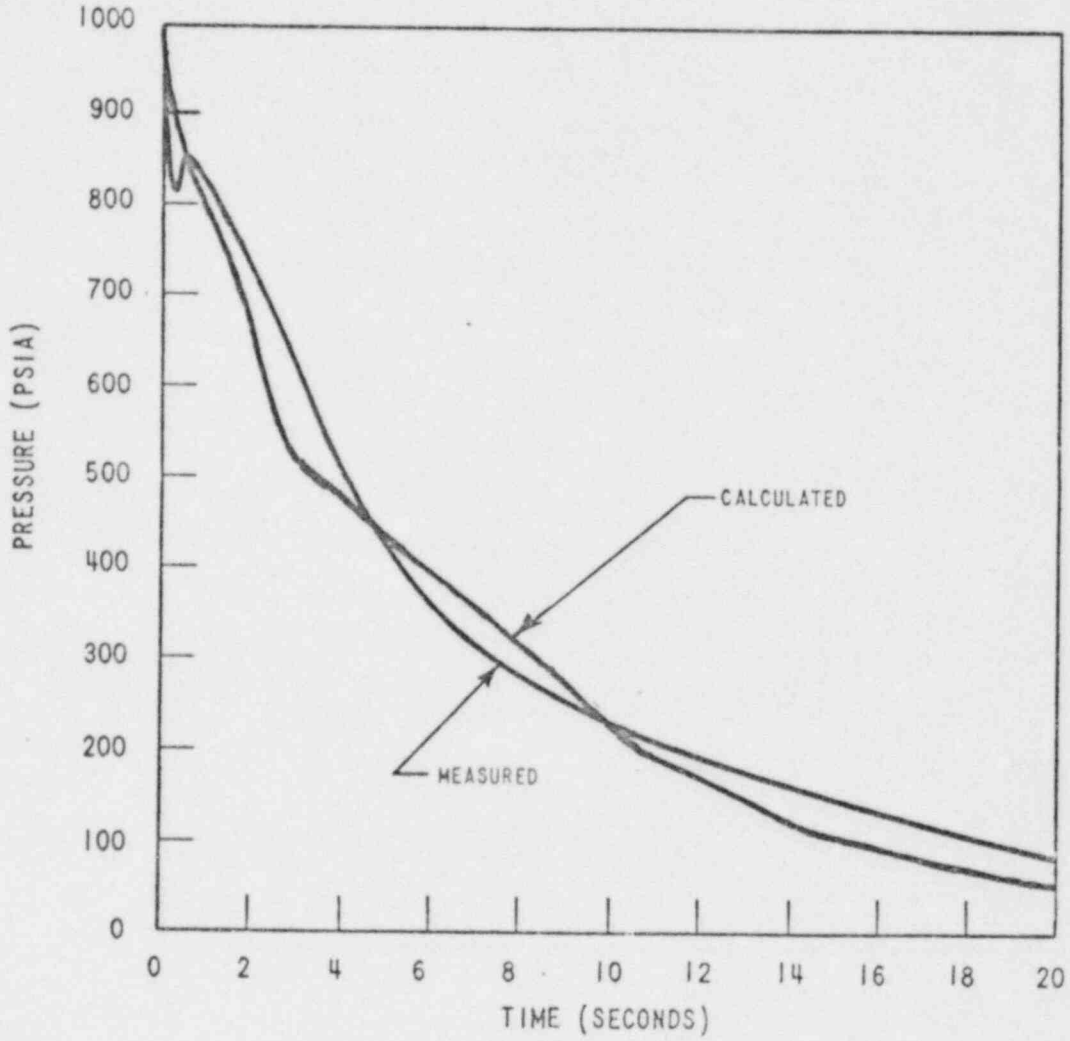

FIGURE 11-4 Comparison of Calculated and Measured Pressure for Frankfurt Test 7

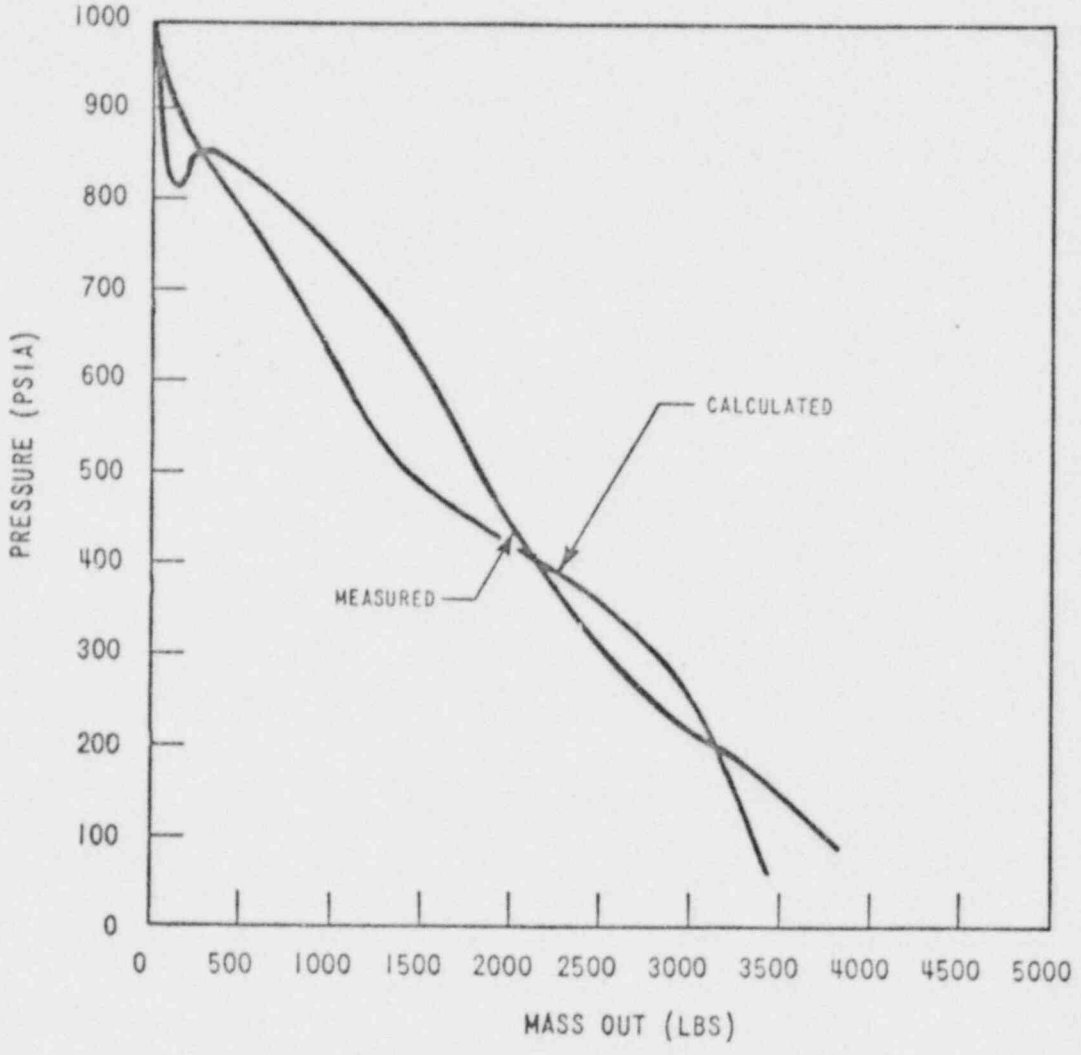

FIGURE 11-5 Comparison of Calculated and Measured Pressure Vs. Mass for Frankfurt Test 7

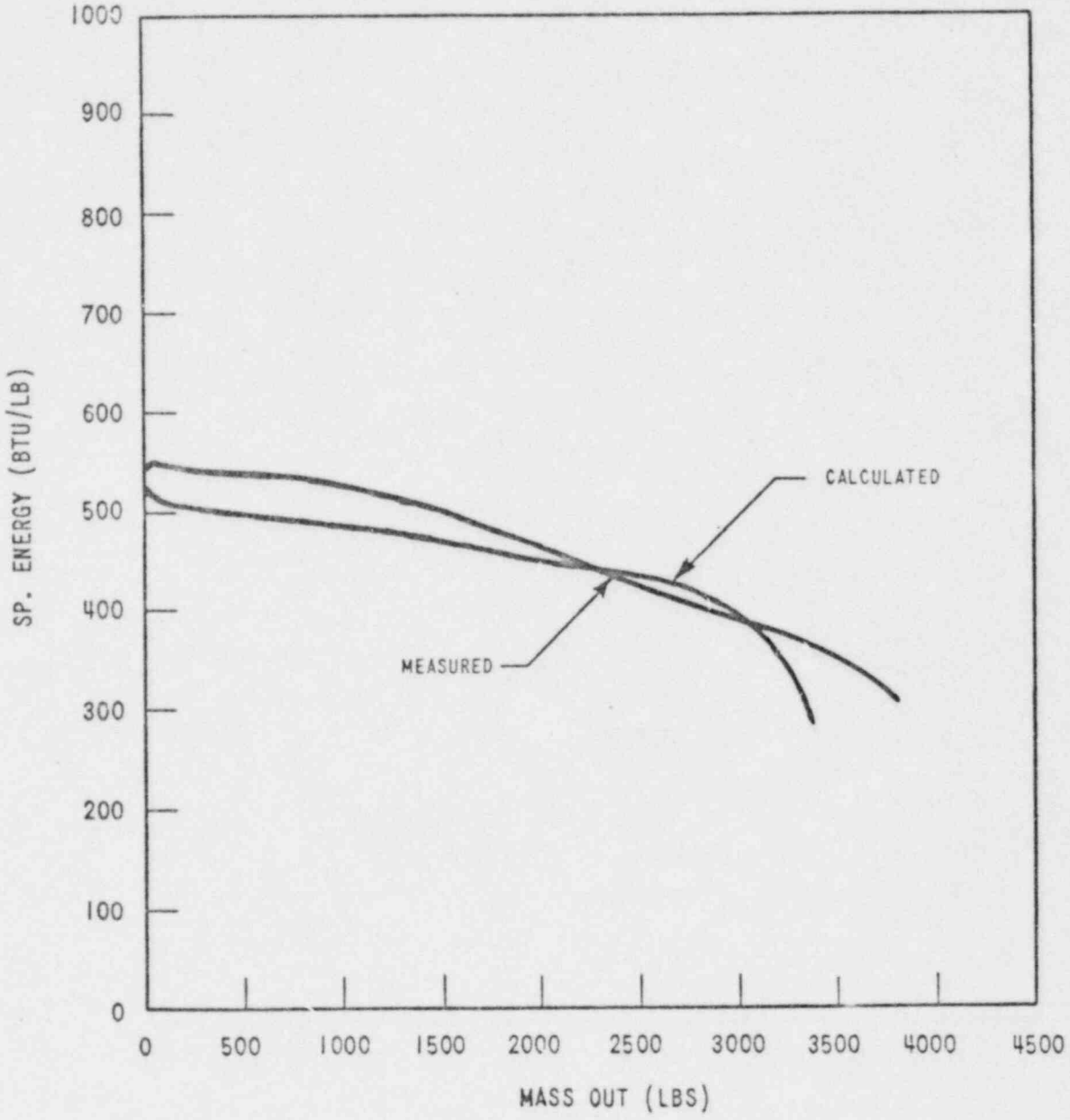

FIGURE 11-6 Comparison of Calculated and Measured Energy Vs Mass for Frankfurt Test 7

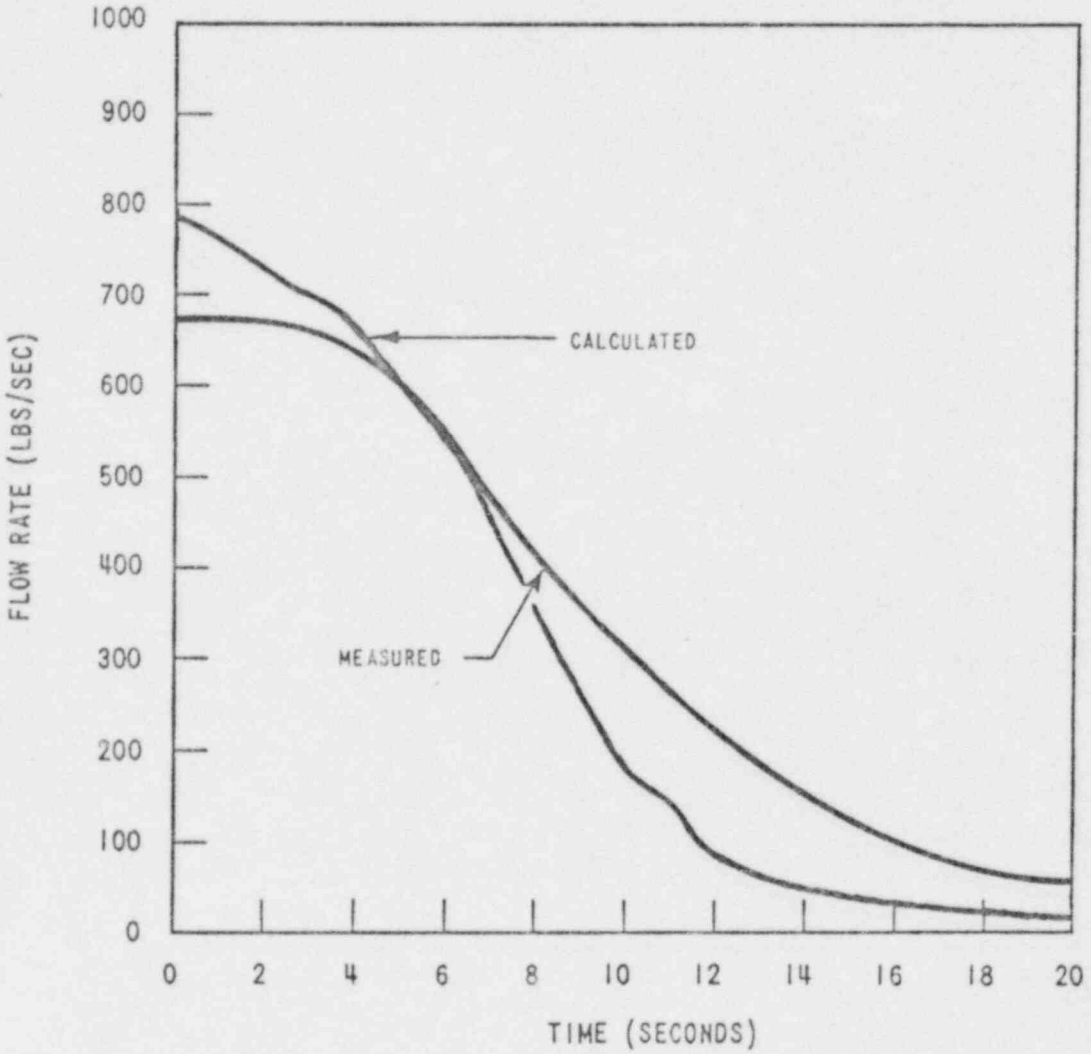

FIGURE 11-7 Comparison of Calculated and Measured Flow Rate for Frankfurt Test 12

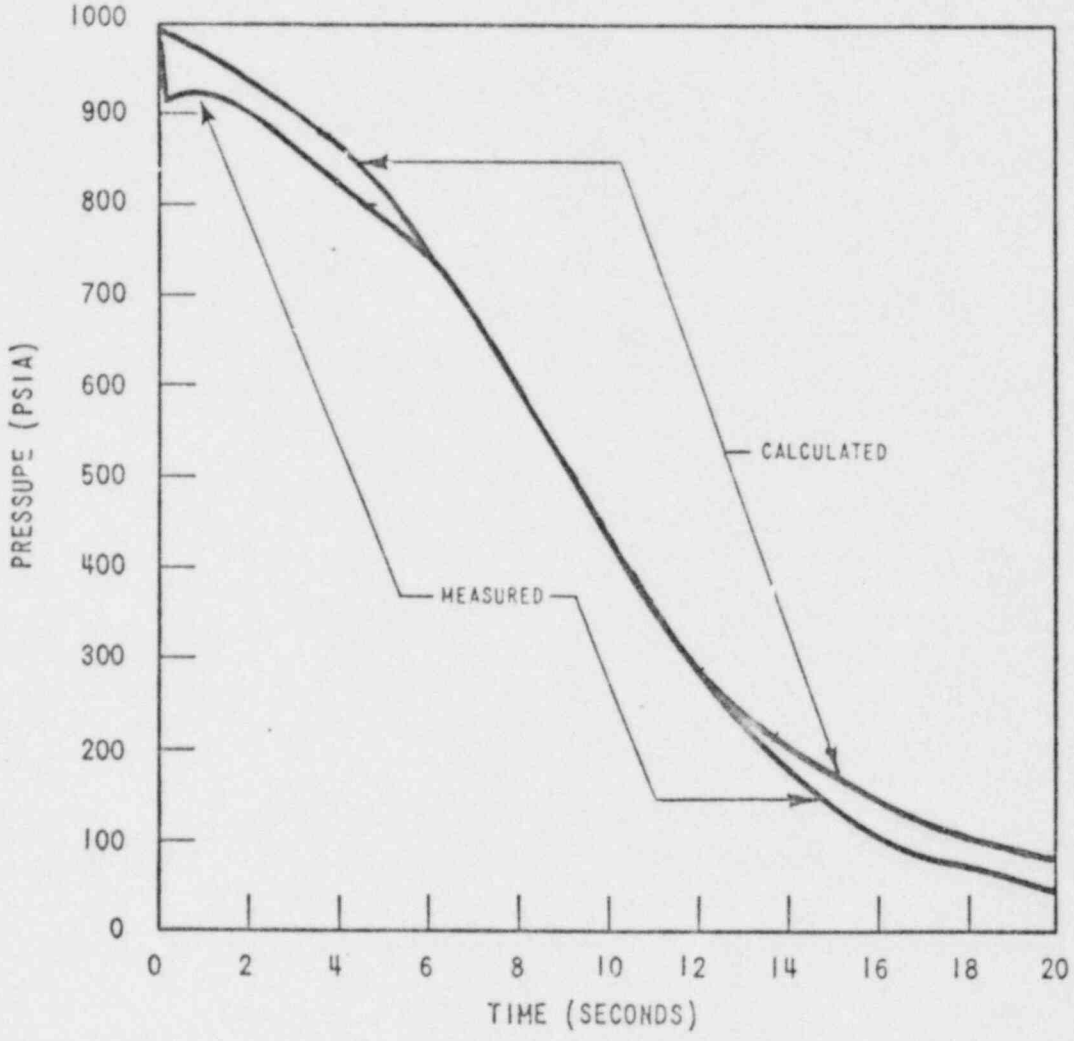

FIGURE 11-8 Comparison of Calculated and Measured Pressure for Frankfurt Test 12

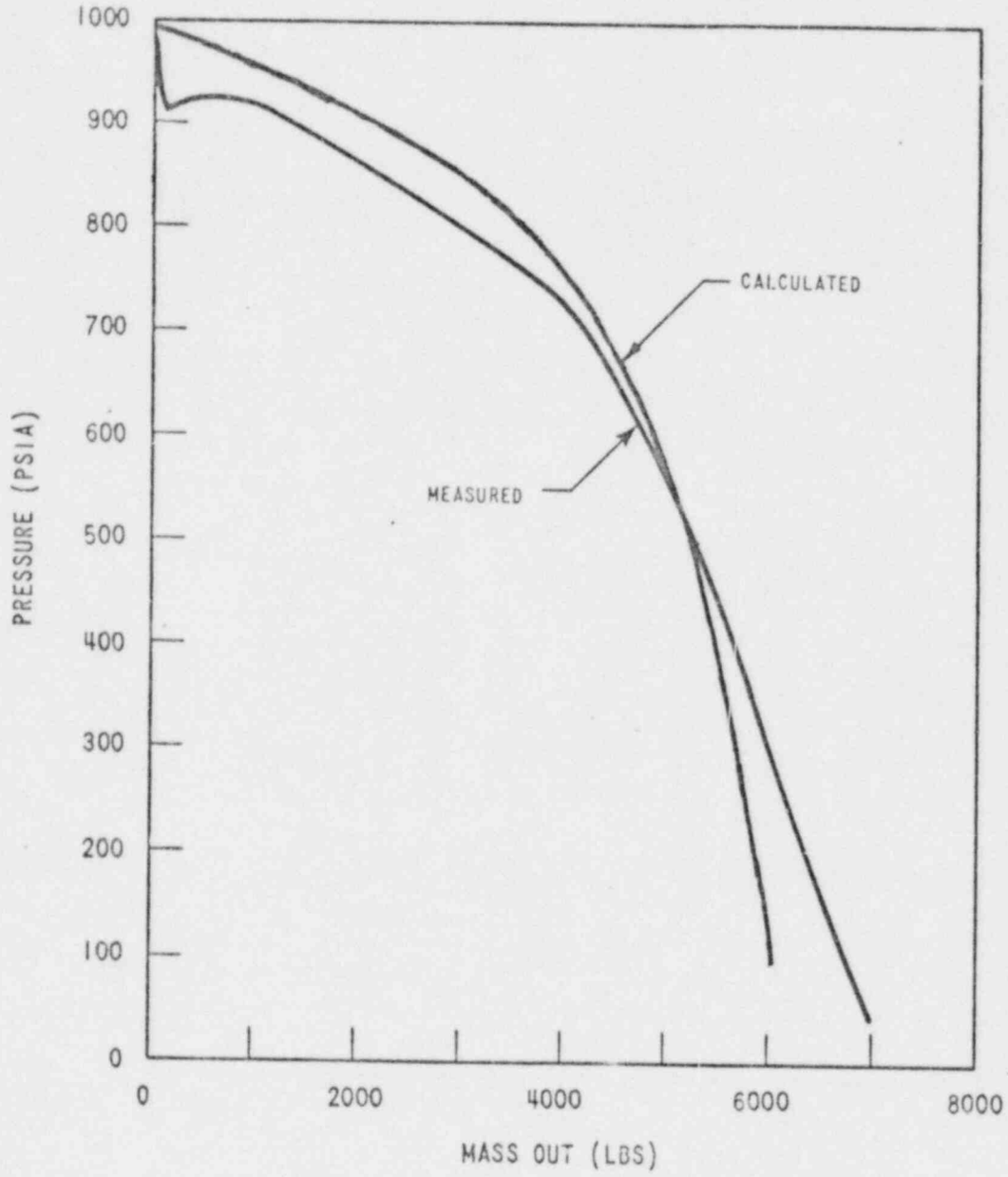

FIGURE 11-9 Comparison of Calculated and Measured Pressure Vs. Mass for Frankfurt Test 12

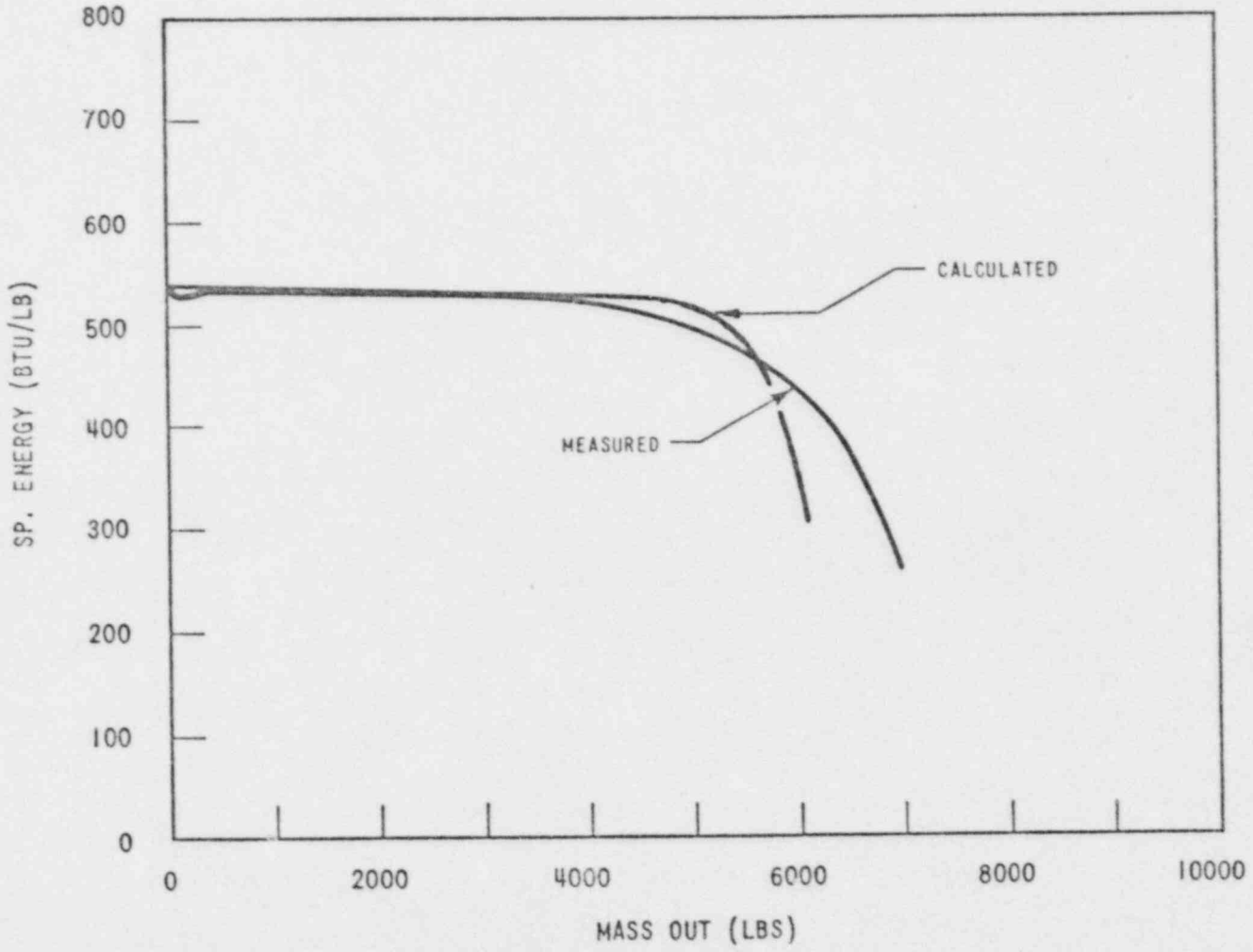

FIGURE 11-10 Comparison of Calculated and Measured Energy Vs. Mass for Frankfurt Test 12

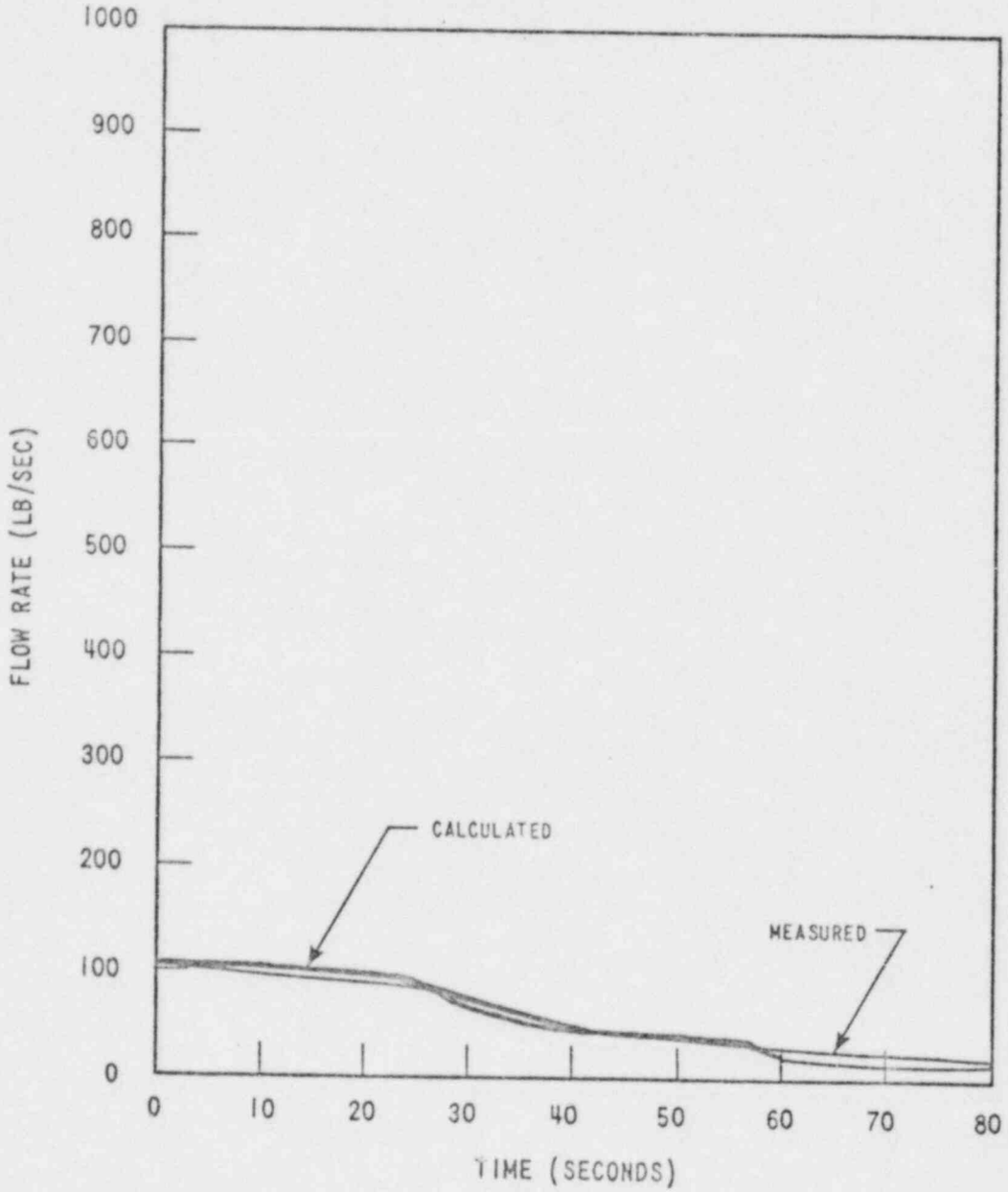

FIGURE 11-11 Comparison of Calculated and Measured Flow Rate for Frankfurt Test 14

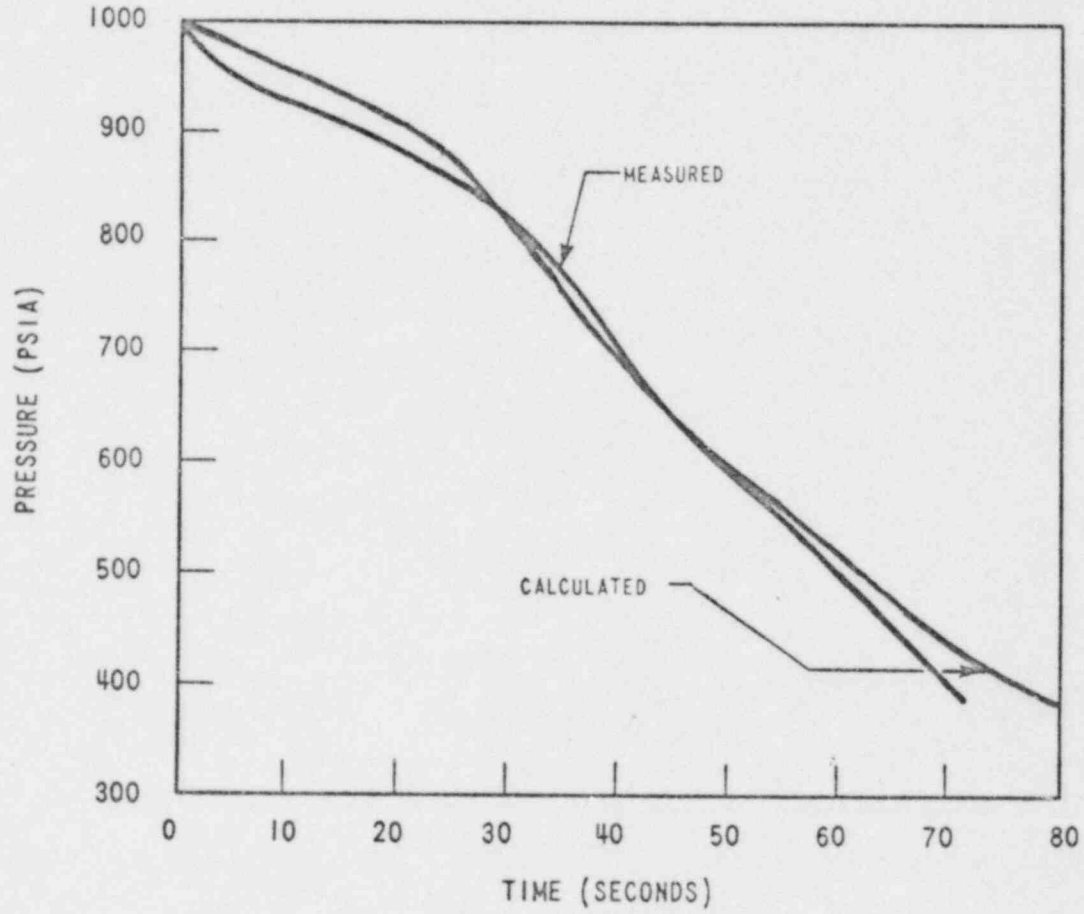

FIGURE 11-12 Comparison of Calculated and Measured Pressure for Frankfurt Test 14

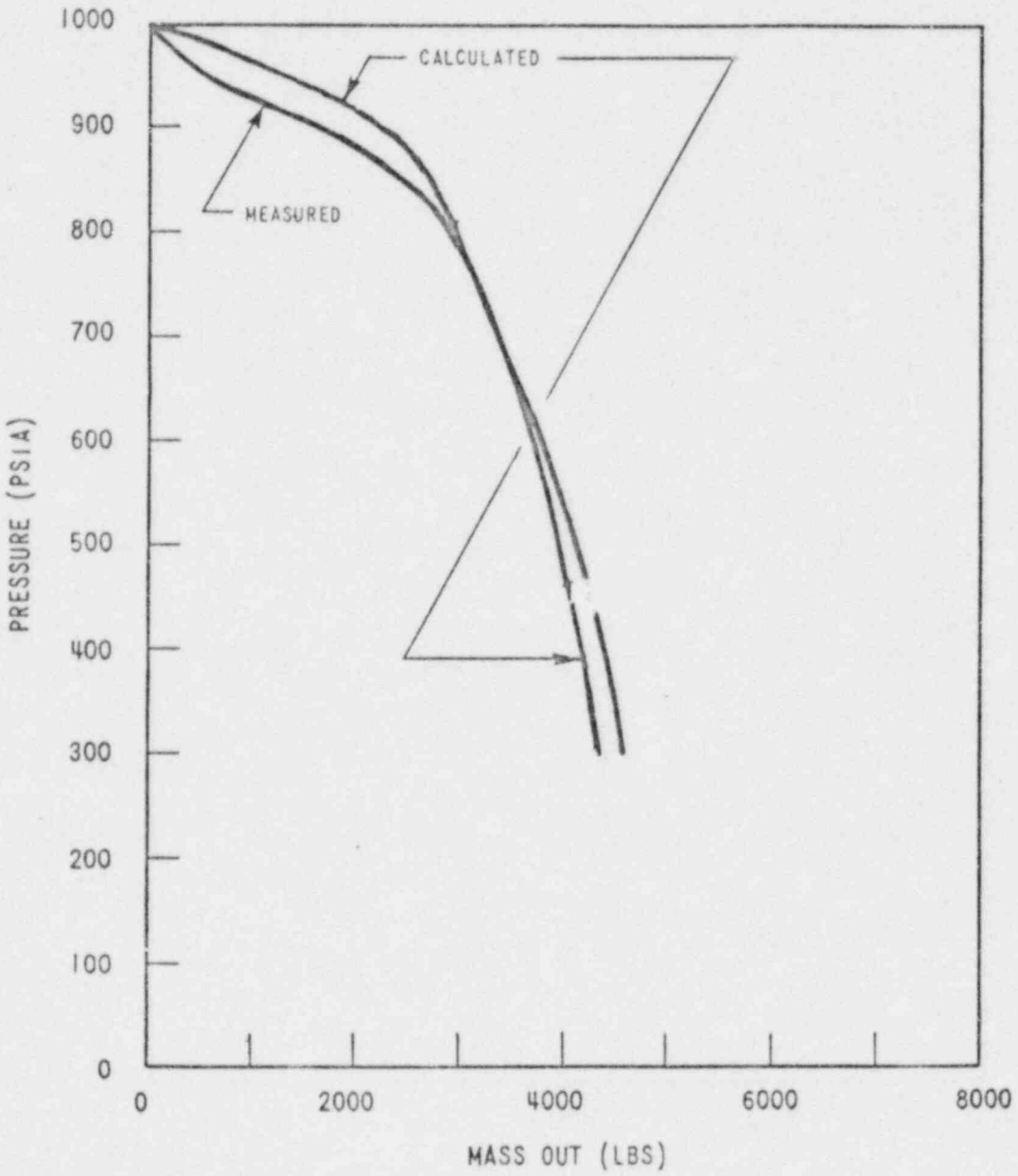

FIGURE 11-13 Comparison of Calculated and Measured Pressure Vs. Mass for Frankfurt Test 14

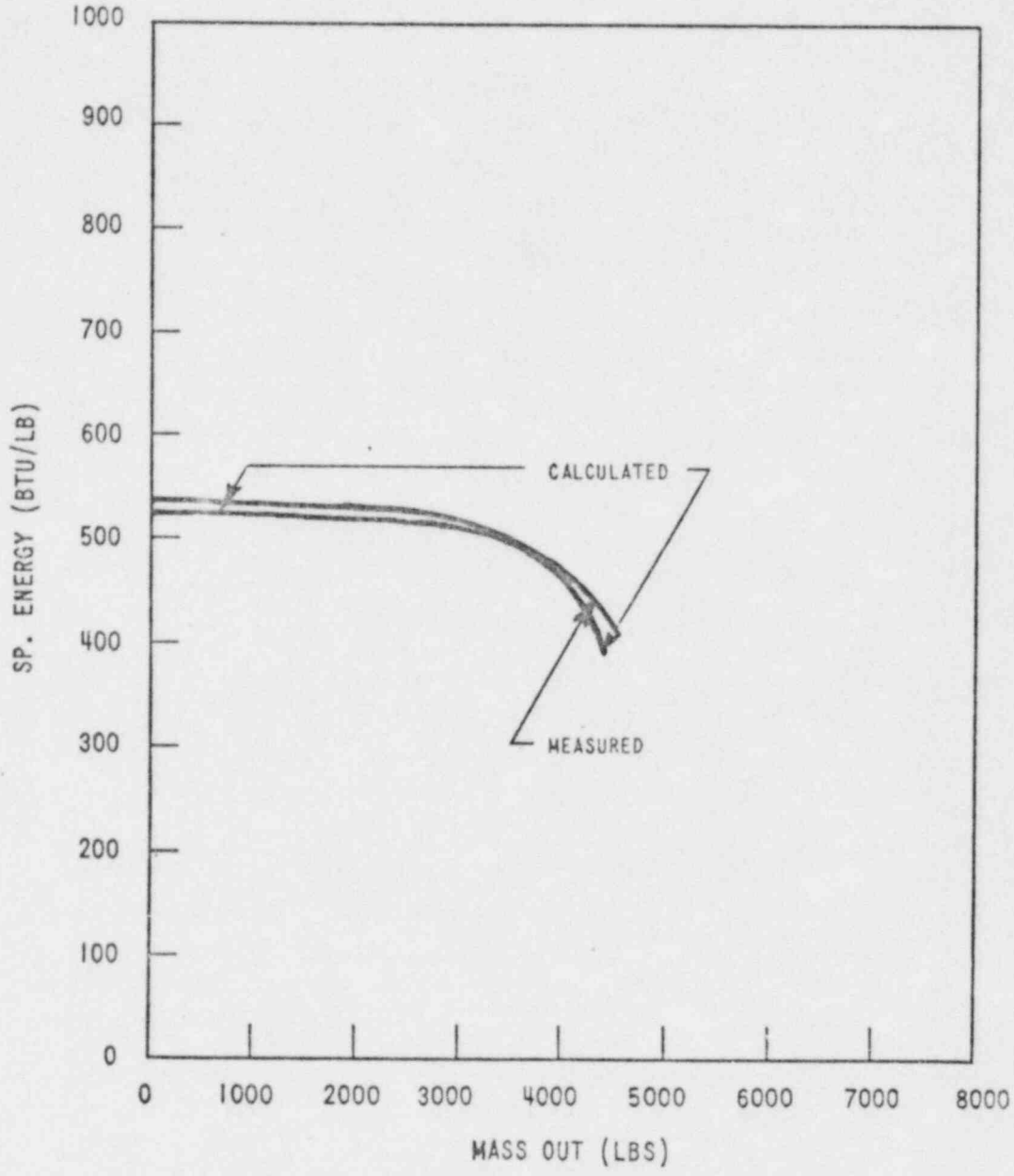

FIGURE 11-14 Comparison of Calculated and Measured Energy Vs. Mass for Frankfurt Test 14

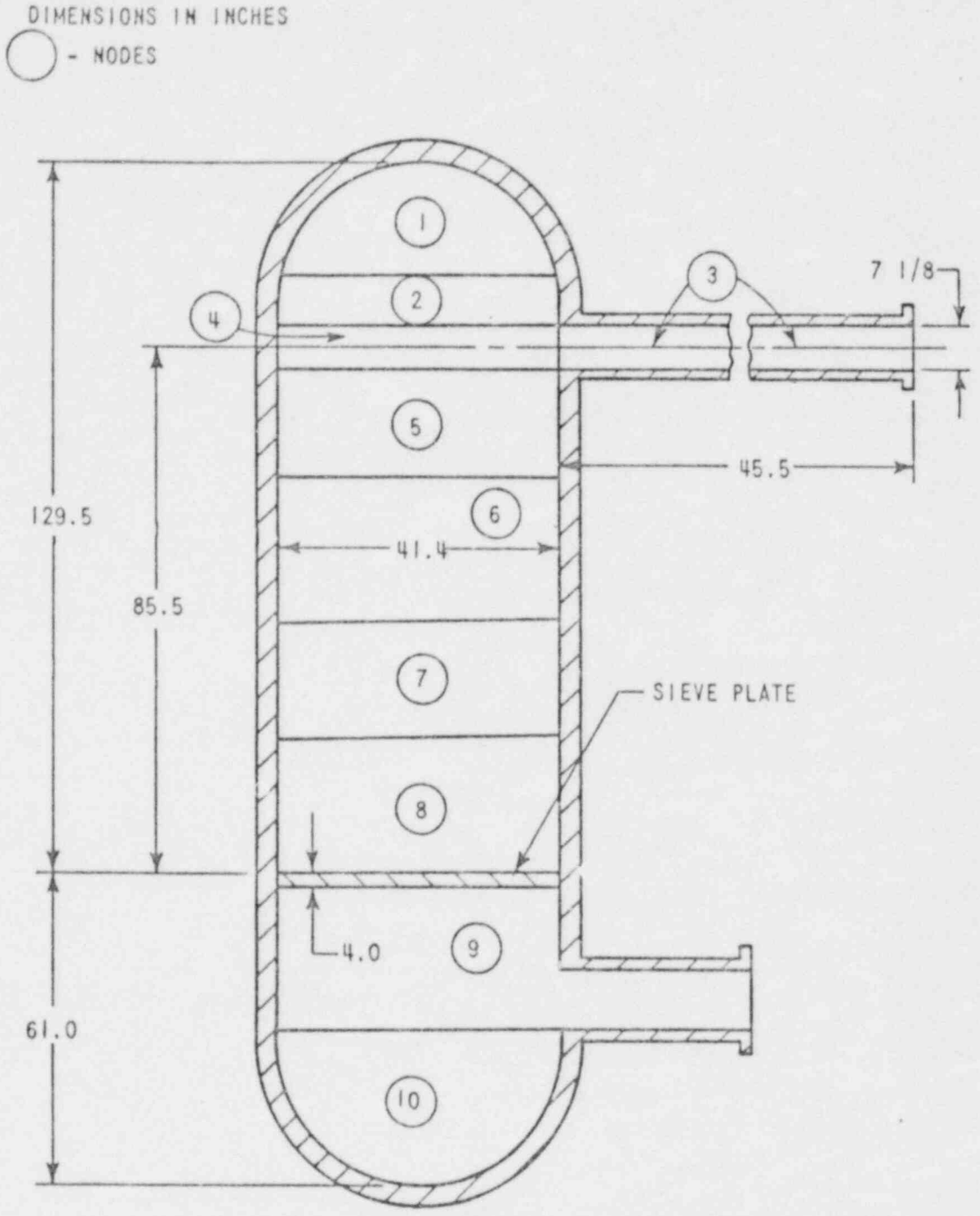

FIGURE 11-15 Battelle B53B Test Vessel Schematic

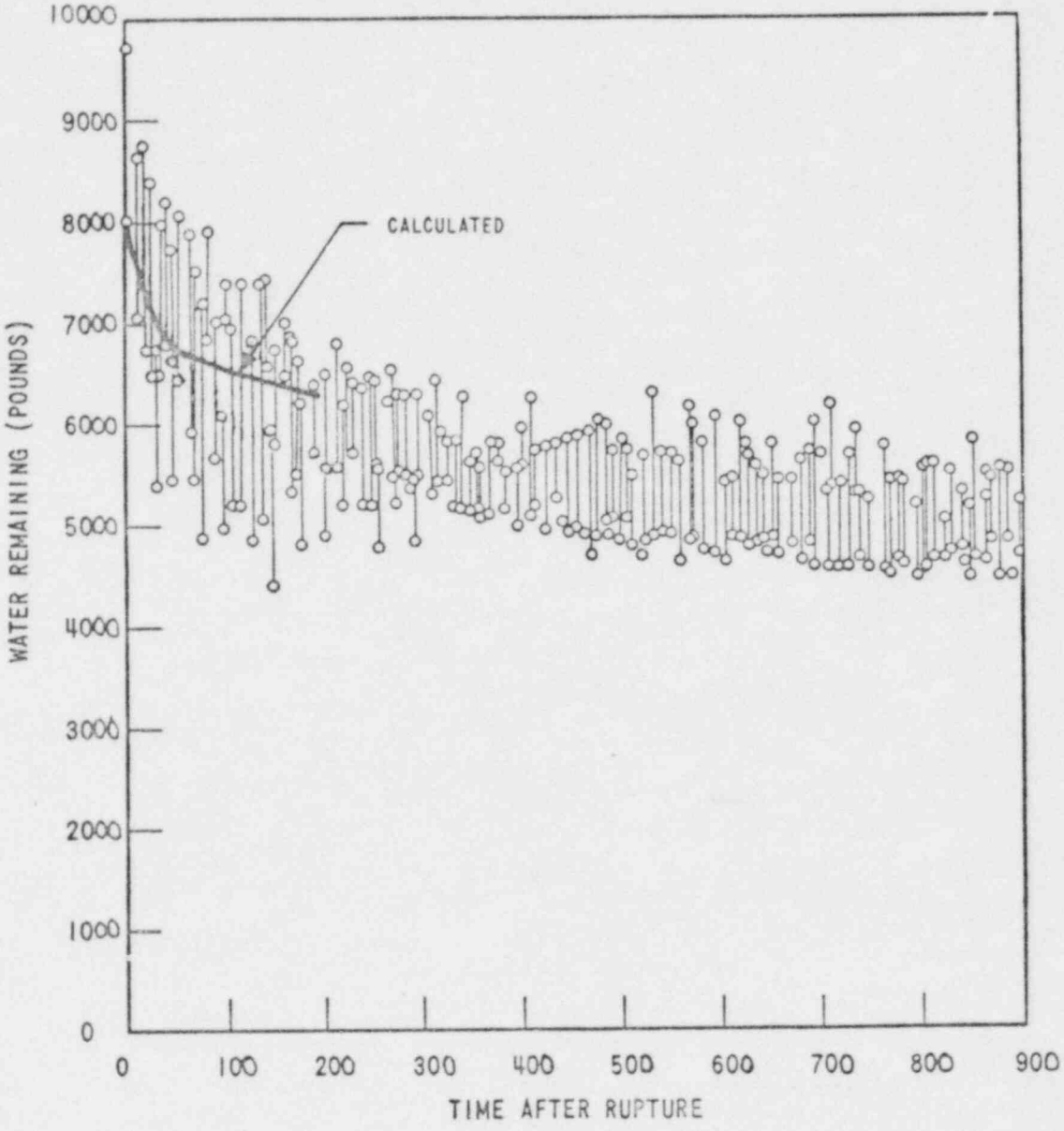

FIGURE 11-16 Weight of Water in Vessel as Function of Time for Battelle Test B53B

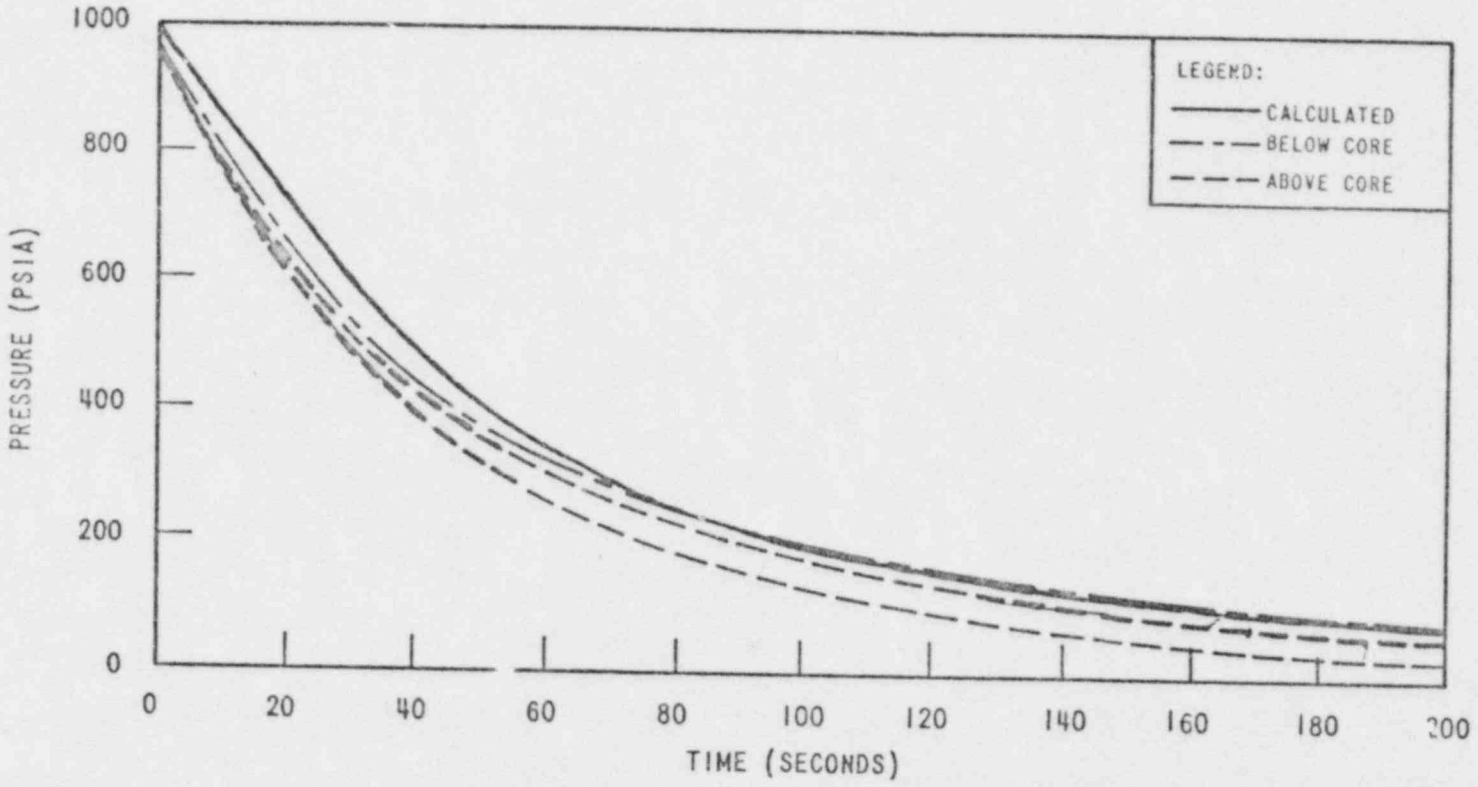

FIGURE 11-17 Comparison of Calculated and Measured Pressure for Battelle Test B53B

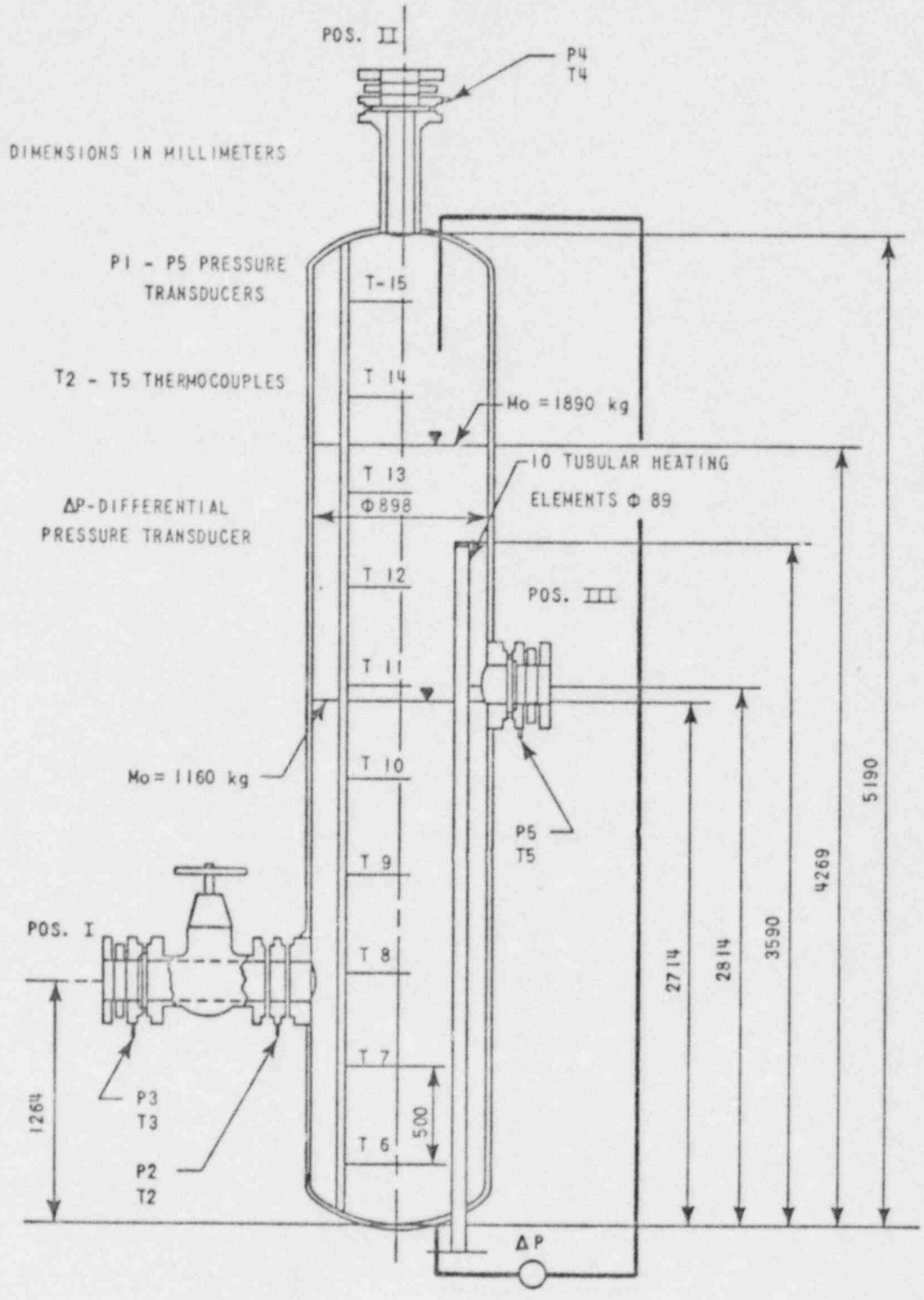

FIGURE 11-18 CISE Test Vessel Schematic

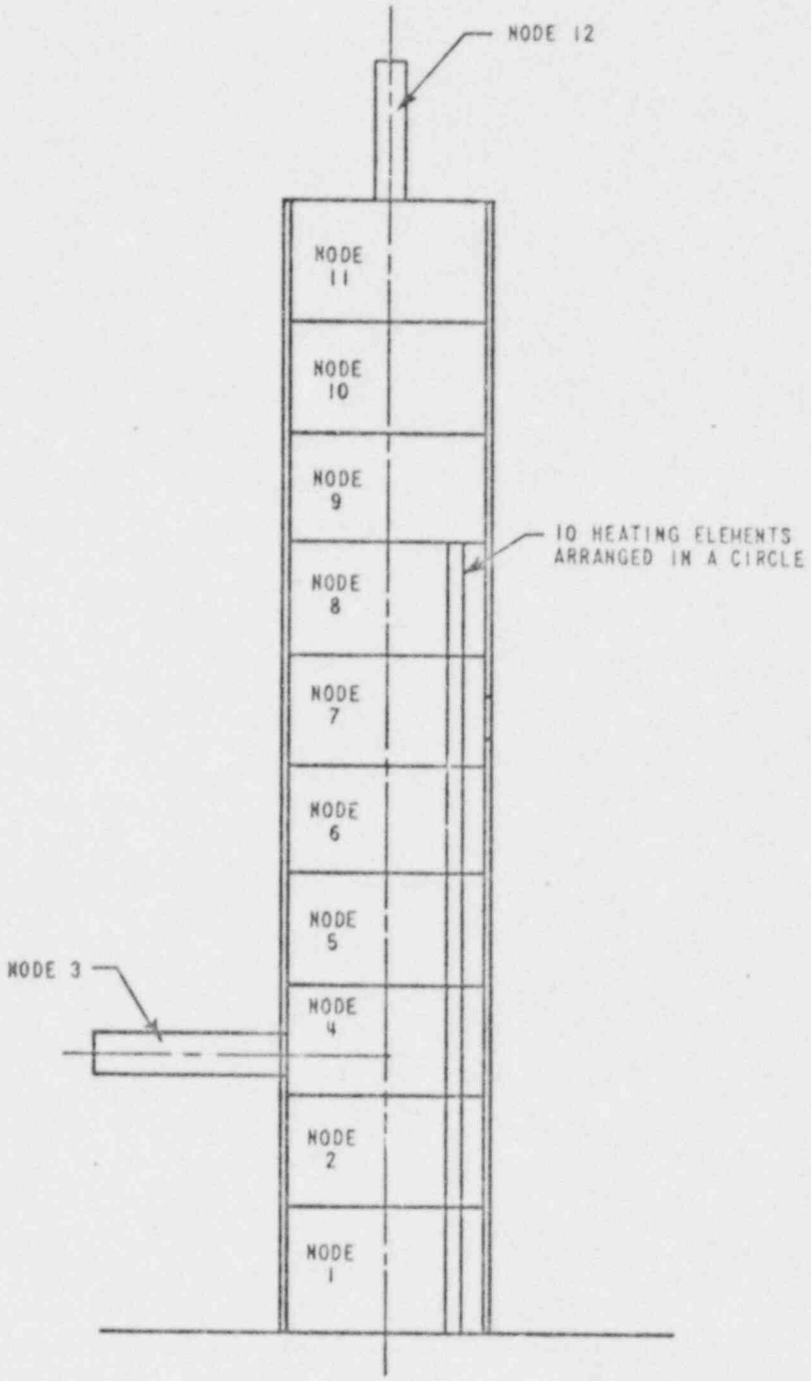

FIGURE 11-19 Computer Model Used for CISE Test Calculations

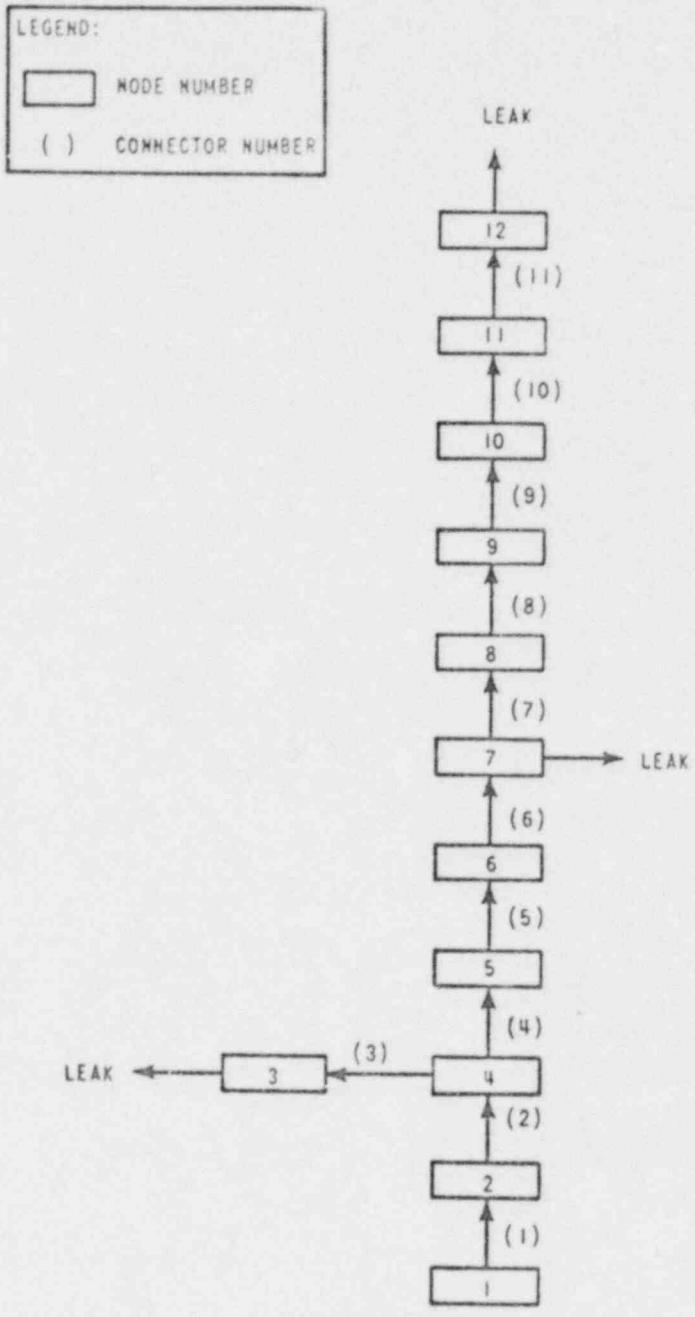

FIGURE 11-20 Computer Model Used for CISE Test Calculations

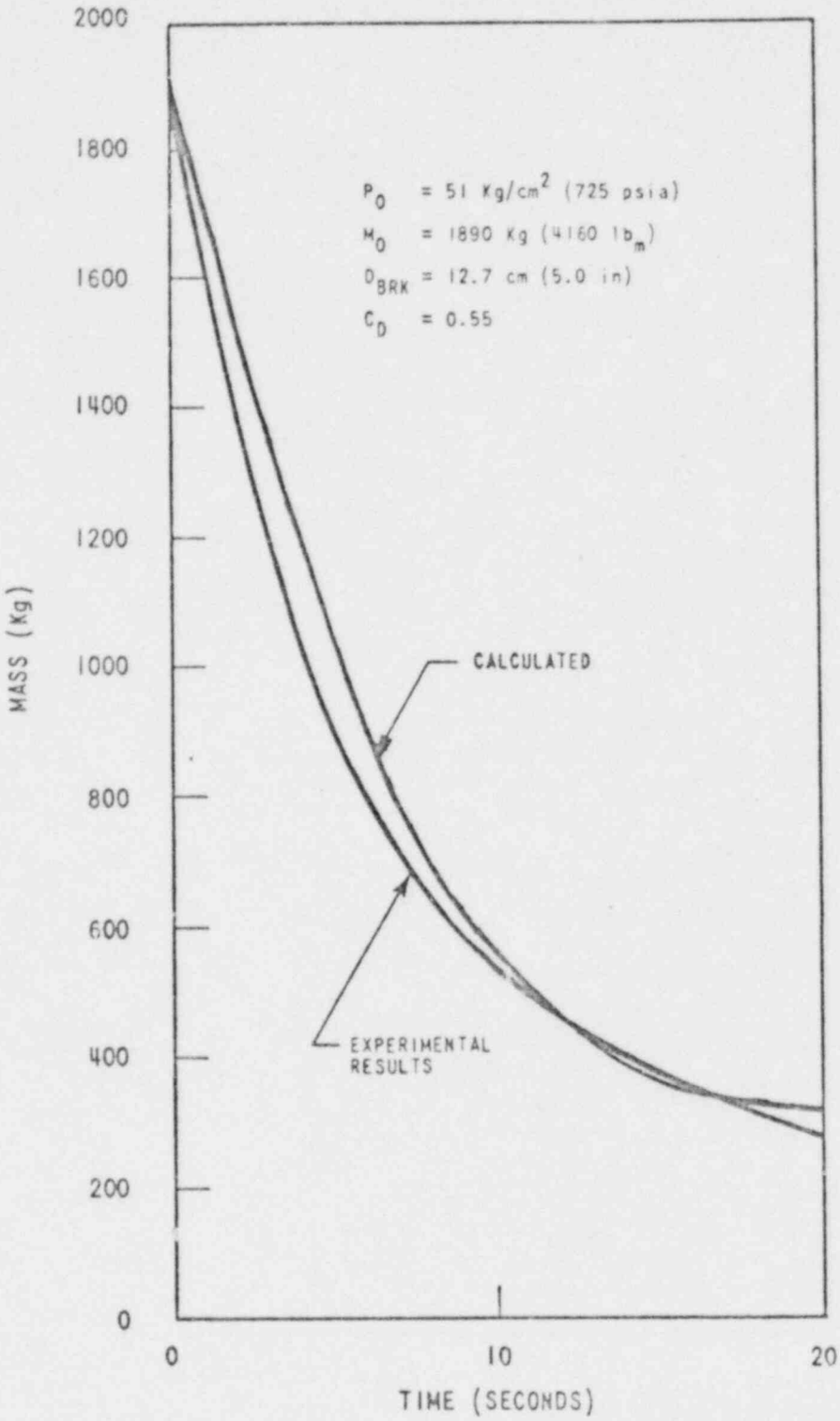

FIGURE 11-21 CISE Blowdown Test 1 - Mass Vs. Time

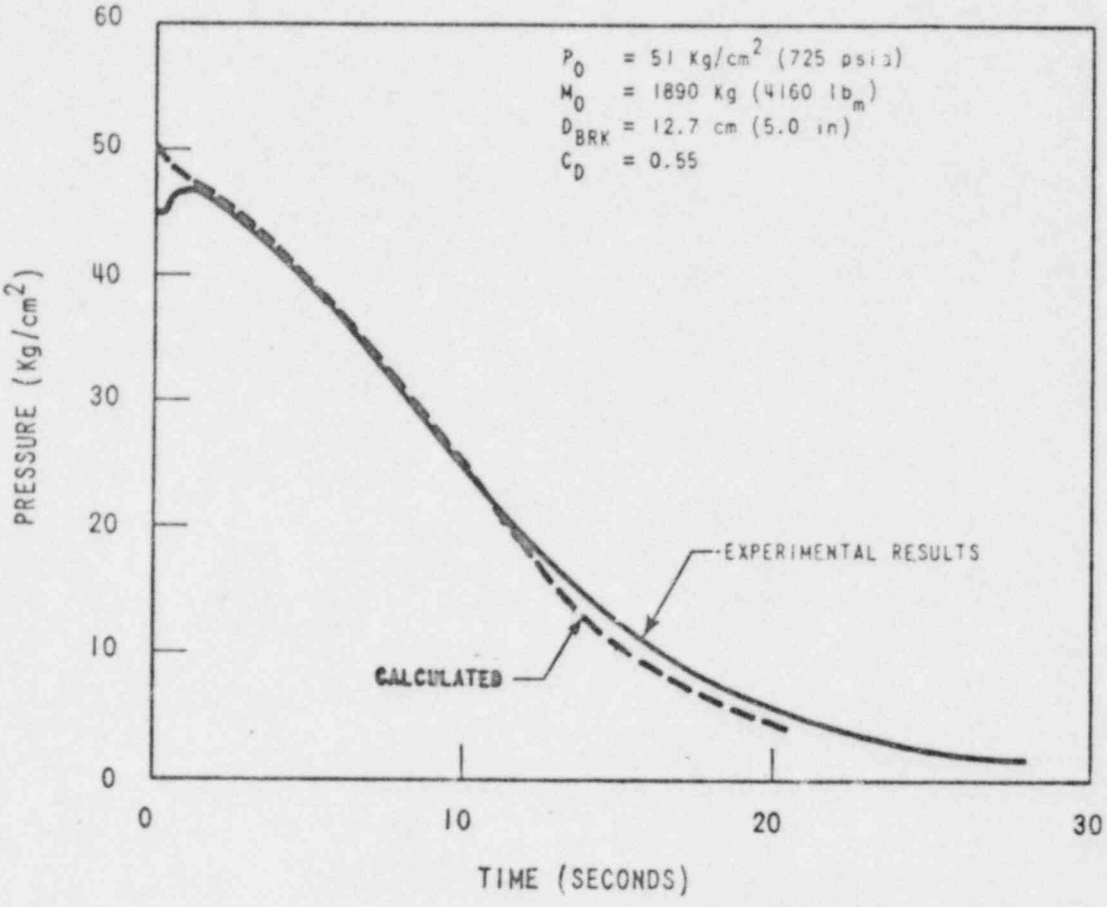

FIGURE 11-22 CISE Blowdown Test 1 - Pressure Vs. Time

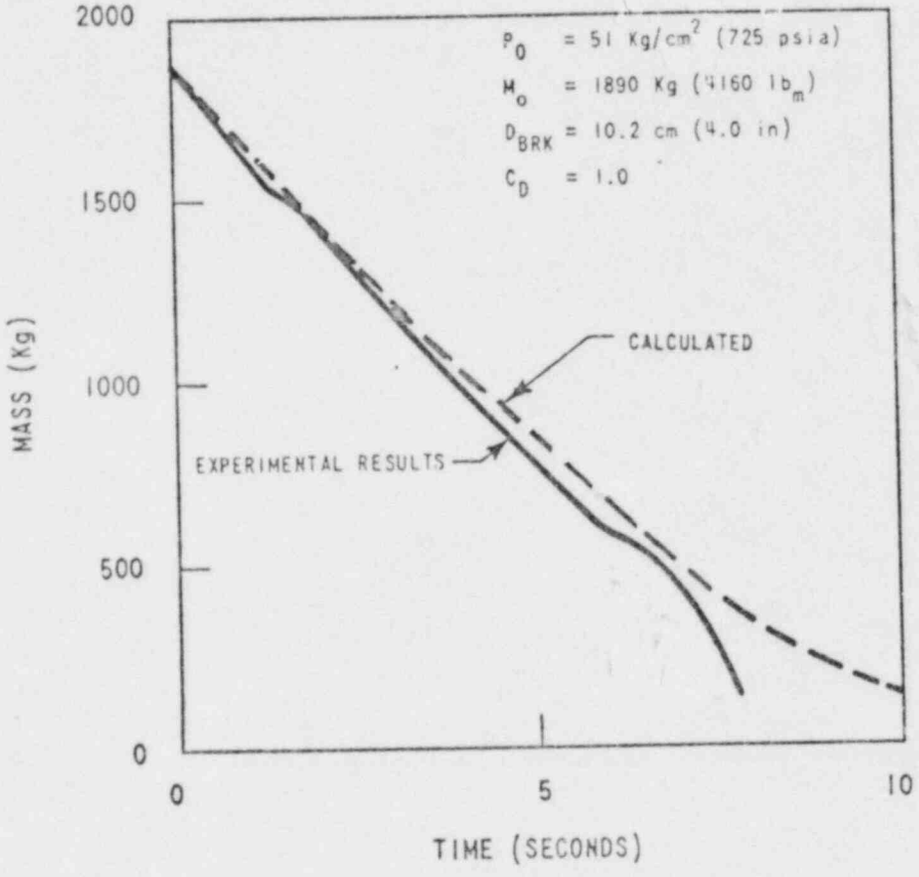

FIGURE 11-23 CISE Blowdown Test 2 Mass Vs. Time

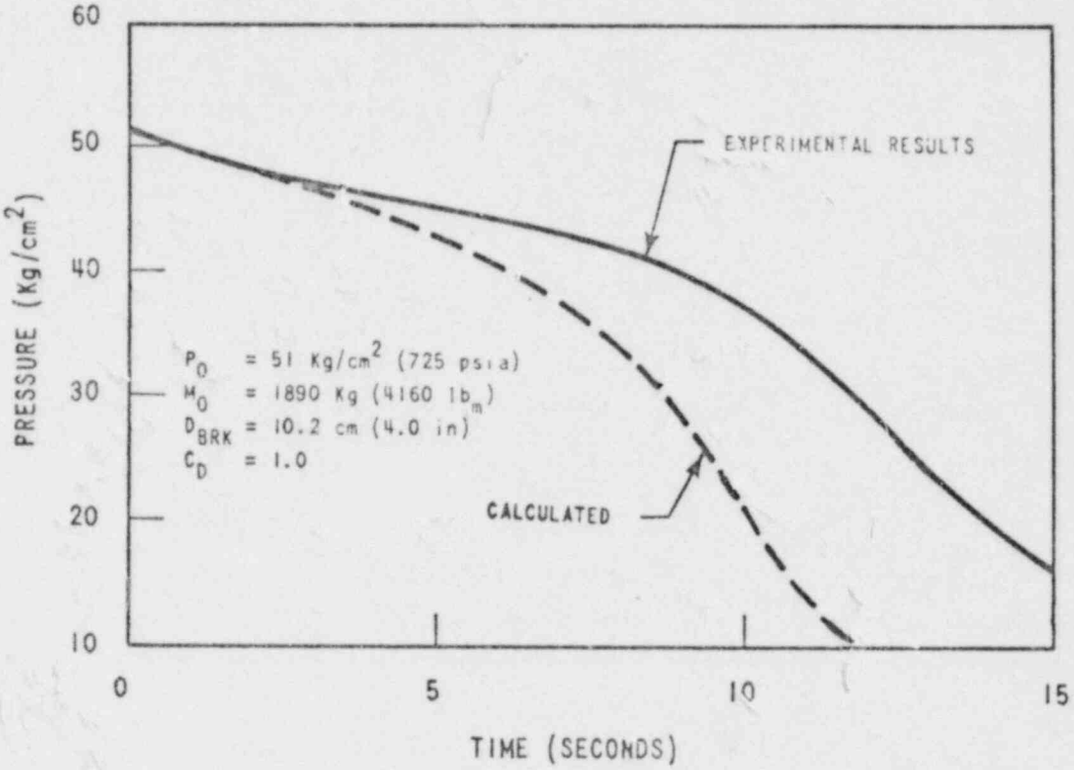

FIGURE 11-24 CISE Blowdown Test 2 - Pressure Vs. Time

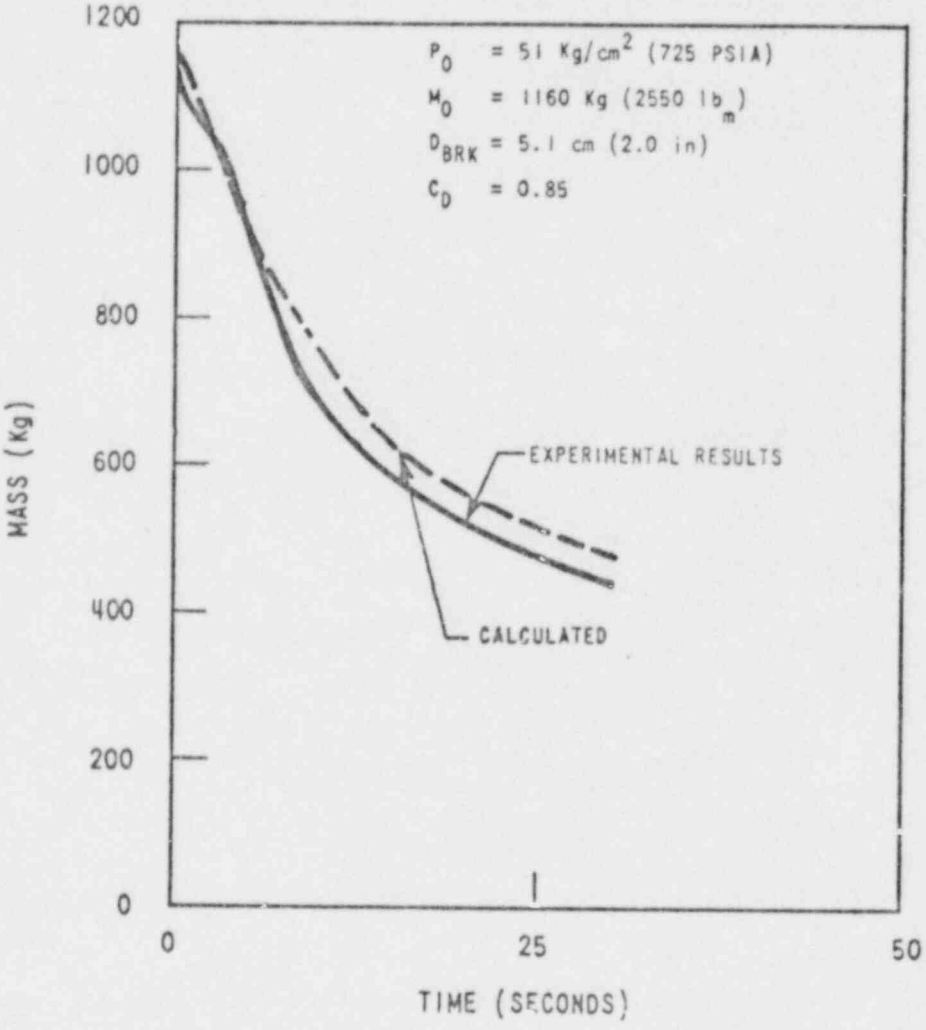

FIGURE 11-25 CISE Blowdown Test 3 - Mass Vs. Time

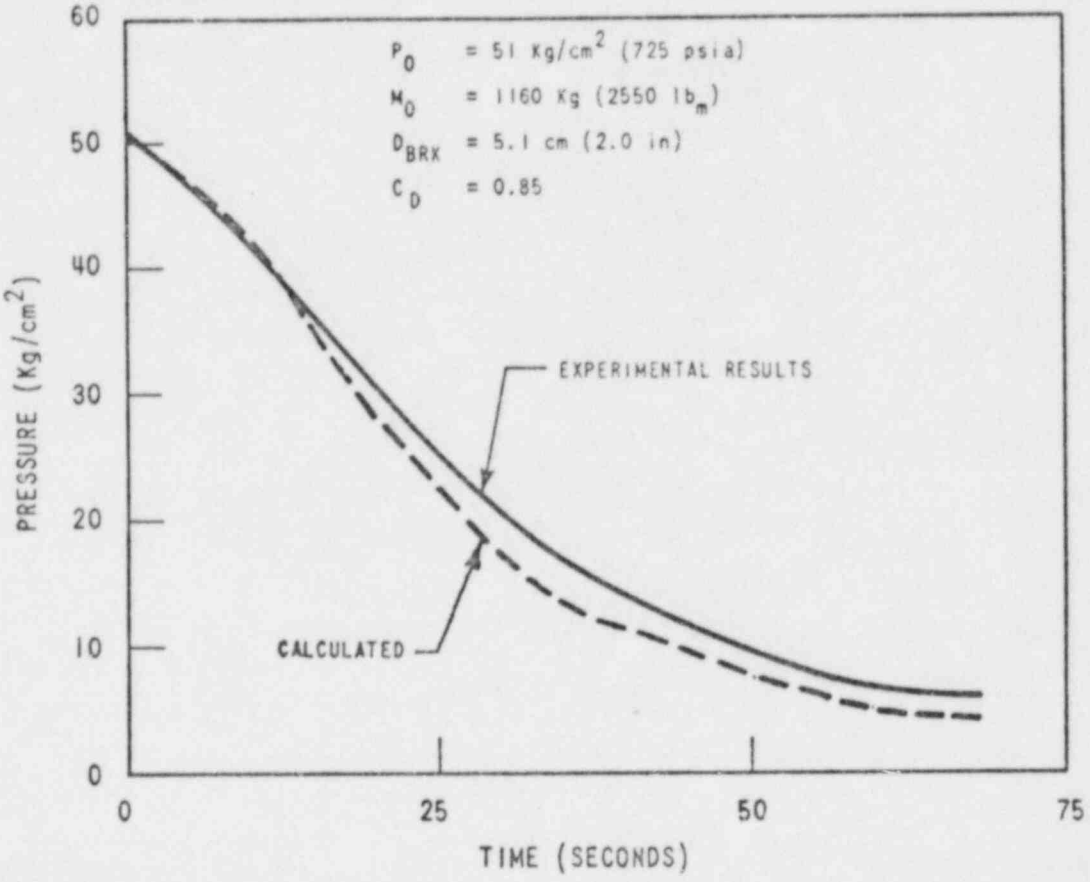

FIGURE 11-26 CISE Blowdown Test 3 - Pressure Vs. Time

12.0 CONCLUSIONS

The NOTRUMP computer code is capable of general thermal hydraulic network transients. It has extensive modeling capabilities including:

1. A momentum balance suitable for predicting time-dependent flows.

2. A suitable slip flow model for the thermal hydraulic conditions involved.

3. Natural and mechanical phase separation models, including countercurrent flow modeling capabilities.

4. The capability of incorporating time and spatial changes in operating conditions due to changes in boundary conditions or control systems.

5. Sufficient detail to represent the different physical and behavioral regions of steam generators.

6. Running times suitable for making a relatively large number of survey type runs.

NOTRUMP is a general one-dimensional network code. The spatial detail of a problem is modeled by fluid and metal nodes appropriately interconnected by flow and heat links. The spatial-temporal solution is then determined by numerical integration of the integral forms of the conservation equations.

Fluid nodes may be subcooled, saturated or superheated. They may also be either homogeneous or stratified.

A detailed momentum balance includes the effects of gravity, friction and momentum flux. The drift flux and bubble rise models permit modeling of

vertical slip flow, including counter-current flow. A horizontal stratified flow model is also available. Break models for either subcooled, saturated, or superheated fluid nodes are included.

Heat transfer correlations represent all regimes from subcooled natural or forced convection, through nucleate and transition boiling, to film boiling or forced convection vaporization and finally to superheated forced convection. Checks are made for critical heat flux conditions. A simple condensation model is also available.

Specific models are used for the mechanical phase separation in the swirl vanes and Peerless chevron separators. In addition, specific control systems are modeled.

Boundary fluid and metal nodes and critical flow and heat links permit a convenient way of imposing boundary conditions. These may be used instead of controllers for the modeling of certain transients.

The code has been qualified against experimental blowdown data. Most comparisons between the code and experimental data are favorable. For those comparisons where analytical and experimental results differ significantly, the reasons for the differences are identified.

NOTRUMP, with its extensive modeling capabilities, is capable of analyzing thermal hydraulic transients. There have been applications of the code to problems requiring general thermal hydraulic network analyses.

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APPENDIX A

NOMENCLATURE

A	Flow area of a flow link or heat transfer area of a heat link. [ft^2]
$\overline{A}$	Effective flow area for a heat link. [ft^2]
$\underline{\underline{A}}$	Matrix defined by Equation (E-2).
$\underline{\underline{A}}^*$	Matrix defined by Equations (E-10) - (E-19).
A_i	Upstream (with respect to the defined flow link direction) flow area of a flow link. [ft^2]
A_j	Downstream (with respect to the defined flow link direction) flow area of a flow link. [ft^2]
A_{jL}	Downflow (with respect to the net mass flow direction) flow area for a flow link. [ft^2]
A_{js}	Upflow (with respect to the net mass flow direction) flow area for a flow link. [ft^2]
ALFL	Baffle leakage flow area for a flow link. [ft^2]
ANRC	Number of tube rows in crossflow for a flow link.
ANS	Number of sealing strips for a flow link.
$\underline{B}$	Vector defined by Equation (E-4).

$\underline{B}^*$ Vector defined by Equations (E-20) - (E-22).

C_D Discharge coefficient for choked flow in a flow link.

C_f Correction factor on the forced convection heat transfer resistance.

C_p Heat capacity. [Btu/lbm-°F]

C_v^{FW} Feedwater valve coefficient. [gal/min-psi$^{1/2}$]

C_v^{TV} Throttle valve coefficient. [gal/min-psi$^{1/2}$]

C_o Drift flux distribution parameter.

c Sonic velocity. [ft/sec]

D_e Equivalent diameter of a flow link. [ft]

$\overline{D_e}$ Effective equivalent diameter for a heat link. [ft]

D_{fl} Diameter of a continuous contact flow link. [ft]

D_i Inside diameter of steam generator tubes. [ft]

D_m Middle diameter of steam generator tubes. [ft]

D_o Outside diameter of steam generator tubes. [ft]

D_{Taylor} Taylor instability diameter. [ft]

E_{bot} Bottom elevation of a fluid node. [ft]

E_{d} Downstream (with respect to the defined flow link direction) elevation of a flow link. [ft]

$E_{f\ell}$ Either the upstream or downstream elevation of a flow link. [ft]

E_{LT}^{FW} Elevation of lower tap for water level measurement. [ft]

E_{mix} Mixture elevation in a fluid node. [ft]

E_{top} Top elevation of a fluid node. [ft]

E_{u} Upstream (with respect to the defined flow link direction) elevation of a flow link. [ft]

E_{UT}^{FW} Elevation of upper tap for water level measurement. [ft]

$\underline{F}$ Vector defined by Equations (2-15) - (2-19).

F_{mix} The fraction of a given end of a continuous contact flow link which contacts mixture in the appropriate node.

F_{VP}^{FW} Feedwater valve position. [% lift]

F_{VP}^{TV} Throttle valve position. [% lift]

F_{VPD}^{FW} Feedwater valve position demand. [% lift]

F_{VPD}^{TV} Throttle valve position demand. [% lift]

FBP — Fraction of flow area in the bundle-to-wrapper bypass for a flow link.

f — Friction factor. Defined by $\Delta P = \frac{1}{144 g_c} \cdot \frac{1}{2} \frac{fL}{D_e} \rho V^2$.

$\underline{\underline{dF}}$ — Jacobian matrix of $\underline{F}(\underline{y})$.

G — Total mass flux. [lbm/sec-ft^2]

g — Acceleration of gravity. [ft/sec^2]

g_c — 32.174. [lbm ft/lbf-sec^2]

h — Enthalpy. [Btu/lbm]

h_f — Saturated liquid enthalpy. [Btu/lbm]

h_g — Saturated vapor enthalpy. [Btu/lbm]

hW — Enthalpy convection term in a flow link. [Btu/sec]

I — Number of interior fluid nodes.

$\underline{\underline{I}}$ — Identity matrix.

I* — Number of fluid nodes.

I_i^Q — Set of all heat links for which interior fluid or metal node i is the initial node.

I_i^W — Set of all flow links for which interior fluid node i is the initial node.

J	Number of interior metal nodes.
J	Joule's constant, 778.1. [ft-lbf/Btu]
J^*	Number of metal nodes.
j	Total volumetric flux. [$ft^3/sec\text{-}ft^2$]
j_f	Liquid volumetric flux. [$ft^3/sec\text{-}ft^2$]
j_{fg}	Drift flux of liquid component. [$ft^3/sec\text{-}ft^2$]
j_g	Vapor volumetric flux. [$ft^3/sec\text{-}ft^2$]
j_{gf}	Drift flux of vapor component. [$ft^3/sec\text{-}ft^2$]
K	Number of non-critical flow links.
K^*	Number of flow links.
K_{P1}^{FW}	Proportionality constant of the level error compensation PI controller for the MB-1 feedwater valve control. [lbm/sec-% span]
K_{P1}^{TV}	Proportionality constant of the throttle valve PI controller for the MB-1 throttle valve control. [% lift/Mwth]
K_{P2}^{FW}	Proportionality constant of the feedwater valve PI controller for the MB-1 feedwater valve control. [% lift/(lbm/sec)]
k	Thermal conductivity. [Btu/sec-ft-°F]

L	Number of non-critical heat links.
L	Length of a flow link. [ft]
L^*	Number of heat links.
L/A	Inertial length of a flow link. [ft^{-1}]
M	Number of controller equations.
M	Total fluid mass in an interior fluid node or total metal mass of an interior metal node. [lbm]
M_f	Liquid mass in an interior fluid node. [lbm]
M_g	Vapor mass in an interior fluid node. [lbm]
M_{gb}	Bubble mass in an interior fluid node. [lbm]
M_{jL}	Downflow (with respect to the net mass flow direction) Mach number for a flow link.
M_{js}	Upflow (with respect to the net mass flow direction) Mach number for a flow link.
P	Pressure in a fluid node. [psia]
P_{DTV}^{FW}	Measured pressure downstream of the throttle valve for the MB-1 feedwater valve control. [psia]
P_{DTV}^{TV}	Measured pressure downstream of the throttle valve for the MB-1 throttle valve control. [psia]

P_{IN}^{PH} Heater gas control setting for the MB-1 primary water heater control. [% setting]

P_{IND}^{PH} Demanded heater gas control setting for the MB-1 primary water heater control. [% setting]

P_{LM}^{FW} Pressure at which taps for water level measurement were calibrated. [psia]

P_{LT} Pressure at the top of the fluid node which contains the lower tap for water level measurement. [psia]

P_{UT} Pressure at the top of the fluid node which contains the upper tap for water level measurement. [psia]

P_{tube} Pitch of the steam generator tubes. [ft]

P_r Prandtl number.

Q Heat rate in a heat link. [Btu/sec]

q Number of equations not in disjoint chains.

q Heat flux in a heat link. [Btu/sec-ft^2]

R_f Fluid node heat transfer resistance. [°F/(Btu/sec-ft^2)]

R_{foul} Fouling factor. [°F/(Btu/sec-ft^2)]

R_m Metal node heat transfer resistance. [°F/(Btu/sec-ft^2)]

R_{mw} Metal node to metal surface heat transfer resistance. [°F/(Btu /sec-ft2)]

R_{w} Metal surface heat transfer resistance. [°F/(Btu/sec-ft^2)]

RCR Steady state re-circulation ratio.

S_{g} Vapor production rate in a fluid node. [lbm/sec]

S_{gb} Bubble production rate in a fluid node. [lbm/sec]

SP^{PH} Demanded primary water temperature at heater exit. [°F]

SV Fractional swirl vane efficiency.

T Temperature in a fluid or a metal node. [°F]

T_{i}^{Q} Set of all heat links for which interior fluid or metal node i is the terminal node.

T_{i}^{W} Set of all flow links for which interior fluid node i is the terminal node.

T_{HLA}^{PH} Measured mixed heater temperature for the MB-1 primary water heater control. [°F]

T_{HLM}^{PH} Filtered measured mixed heater temperature for the MB-1 primary water heater control. [°F]

T_{HOA}^{PH} Measured primary water temperature at heater exit for the MB-1 primary water heater control. [°F]

T_{HOM}^{PH} Filtered measured primary water temperature at heater exit for the MB-1 primary water heater control. [°F]

T_{sat} Saturation temperature. [°F]

T_w Metal surface temperature. [°F]

t Time. [sec]

U Total fluid internal energy in an interior fluid node. [Btu]

U Heat transfer coefficient. [Btu/sec-ft^2-°F]

U_m Metal node heat transfer coefficient. [Btu/sec-ft^2-°F]

U_{mw} Metal node to metal surface heat transfer coefficient. [Btu/sec-ft^2-°F]

U_{mwf} Metal node to fluid node heat transfer coefficient. [Btu/sec-ft^2-°F]

u Specific internal energy. [Btu/lbm]

V Volume of an interior fluid node. [ft^3]

V Fluid velocity. [ft/sec]

V_f Liquid velocity. [ft/sec]

V_g Vapor velocity. [ft/sec]

V_{gj} Drift velocity of vapor relative to the total volumetric flux. [ft/sec]

V_{fj} Drift velocity of liquid relative to the total volumetric flux. [ft/sec]

v Specific volume. [ft^3/lbm]

v_f Saturated liquid specific volume. [ft^3/lbm]

v_g Saturated vapor specific volume. [ft^3/lbm]

v_{mix} Specific volume of the mixture in a fluid node. [ft^3/lbm]

W Total mass flow rate in a flow link. [lbm/sec]

$\overline{W}$ Effective total mass flow rate for a heat link. [lbm/sec]

W_e Mass flow rate of bubbles escaping at the surface of the mixture of a stratified interior fluid node. [lbm/sec]

W_f Liquid mass flow rate in a flow link. [lbm/sec]

$\overline{W}_f$ Effective liquid mass flow rate for a heat link. [lbm/sec]

W_g Vapor mass flow rate in a flow link. [lbm/sec]

$\overline{W}_g$ Effective vapor mass flow rate for a heat link. [lbm/sec]

W_{FWP}^{FW} Measured feedwater flow rate for the MB-1 feedwater valve control. [lbm/sec]

W_{SGP}^{FW} Measured steam flow rate for the MB-1 feedwater valve control. [lbm/sec]

X_{LC}^{FW} Compensated steam generator level error for the MB-1 feedwater valve control. [lbm/sec]

X_{LCC}^{FW} Steam generator level error for the MB-1 feedwater valve control. [% span]

X_{LD}^{FW} Steam generator level setpoint for the MB-1 feedwater valve control. [% span]

X_{LM}^{FW} Measured steam generator level. [% span]

X_{LMF}^{FW} Filtered steam generator level for the MB-1 feedwater valve control. [% span]

X_{MWCC}^{TV} Load error for the MB-1 throttle valve control. [Mwth]

X_{MWD}^{TV} Load demand for the MB-1 throttle valve control. [Mwth]

X_{MWM}^{TV} Measured load for the MB-1 throttle valve control. [Mwth]

$\underline{x}$ Vector defined by Equation (E-3).

$\underline{y}$ Vector defined in Section 2.2.

Z Length of a flow link. [ft]

Z Control variable.

α Void fraction in a fluid node.

α_{fl} Void fraction in a flow link.

α_{mix} Void fraction in the mixture of a stratified fluid node.

β The angle of the swirl vane blades with the vertical.

$\delta_{i,j}$ Kronecker delta.

μ Fluid viscosity. [lbm/ft-sec]

μ_f Liquid viscosity. [lbm/ft-sec]

μ_g Vapor viscosity. [lbm/ft-sec]

ρ Density. [lbm/ft^3]

ρ_{jL} Downflow (with respect to the net mass flow direction) density for a flow link. [lbm/ft^3]

ρ_{js} Upflow (with respect to the net mass flow direction) density for a flow link. [lbm/ft^3]

ρ_{j1} Upstream (with respect to the defined flow link direction) density for a flow link. [lbm/ft^3]

ρ_{j2} Downstream (with respect to the defined flow link direction) density for a flow link. [lbm/ft^3]

σ Surface tension. [lbf/ft]

χ Thermodynamic quality in a fluid node.

$\bar{\chi}$ Effective quality for a heat link.

χ^f Flow quality.

χ^s Static quality.

APPENDIX B

INPUT DESCRIPTION

In this appendix, we describe the input to NOTRUMP. This input consists of a title card, a number of namelists, and possibly a list of TRACE variables.

The first namelist is RMISC. It contains variables pertinent to the writing and reading of restart tapes. There are two types of NOTRUMP cases: 1) non-restart cases, and 2) restart cases. The input for each type is somewhat different. The namelists required in addition to RMISC are FNØDES, MNØDES, FLINKS, HLINKS, CØNEQNS, PUMPS, MISC, and TRACES. Input variables are generally grouped functionally into these namelists. As the namelist names imply, the functional groupings pertain to miscellaneous restart variables, fluid nodes, metal nodes, flow links, heat links, controller equations, pumps, miscellaneous variables, and trace variables. For a restart run, RMISC is read first, a restart tape is read next, then the other namelists, and possibly a list of TRACE variables, are read to allow the changing of appropriate variables.

All variables are allowed to be modified upon restarting. This gives the user the greatest possible flexibility. Note that the flexibility allowed upon restarting together with the general ordering allowed for fluid nodes, metal nodes, flow links, and heat links allows these code components to be changed (even combined or divided) on restart runs. It is important, however, that the user be well aware of the consequence of modifying any variable.

Several points should be noted regarding default values of the input variables. By default values, we simply mean the values which the code assigns certain variables prior to processing the input for a non-restart run. Usually the defaults have the most reasonable value for the variables. In many cases, variables are defaulted such that calculations are not performed. For example, the number of controller equations, NCDE, defaults to 0, so that if the code is to be run without control-

lers (as may often be the case), the user need not explicitly specify NCDE. Variables with no default values still may not need to be specified if they will not be used. For example, most of the variables in CØNEQNS need not be specified if NCDE is zero, even though they have no default values and therefore must be specified if NCDE is non-zero.

We now describe the contents of each NAMELIST in detail. For rules regarding the use of NAMELIST input, the user is referred to any comprehensive reference on FØRTRAN.

Title Card: FØRMAT (8A10)

$RMISC

IRSTRT = flag for restart option. Default = 0
- IRSTRT > 0 : Restart case; read from tape NRIN and write on tape NRØUT all restart records up to and including step JRSTRT.
- IRSTRT < 0 : Restart case; read from tape NRIN and write on tape NRØUT only the restart record for step JRSTRT.
- IRSTRT = 0 : Non-restart case. Do not read from tape NRIN.

JRSTRT = step number of desired restart point from tape NRIN. Default = 0.

NRIN = number of tape from which restart information is to be read. Default = 7.

NRØUT = number of tape on which restart information is to be written. Default = 8.

NFRSTRT = number of fixed restart writing times. $0 \leq$ NFRSTRT ≤ 100. Default = 0.

NSRSTRT = maximum number of time steps between restart writing. Ignore if 0. NSRSTRT≥ 0. Default = 0.

TIRSTRT = maximum time interval between restart writing. Ignore if 0.0. TIRSTRT $\geq$ 0.0. Default = 0.0.

TFRSTRT (100) = fixed restart writing times. [sec] Only the first NFRSTRT of these are used. No default.

NOTE: The variables in namelist RMISC are not saved on restart tapes and, therefore, must be provided on each run. The variables in all other namelists are saved on restart tapes and therefore should only be provided when one wants to change them on a restart case.

ITYPEFN(80) = flag for fluid node type for each fluid node.
1 = non-accumulator interior fluid node
2 = accumulator interior fluid node
-1 = boundary fluid node
0 = no fluid node
Default = 0

Note: There are no restrictions on the ordering of fluid node types.

IMPFN (80) = flag for implicit method for each interior fluid node. Implicit if ≠ 0. Explicit = 0.
Default = 1.

VFN (80) = volume, V, of each interior fluid node. [ft^3].
No default.

EBØTFN (80) = bottom elevation, E_{bot}, of each fluid node. [ft].
No default.

ETØPFN (80) = top elevation, E_{top}, of each fluid node. [ft].
No default.

PFN (80) = initial pressure, P, of each interior fluid node. [psia.]. No default. Used only on non-restart cases.

SHFN (80) = initial enthalpy, h, of each interior fluid node. [Btu/lbm]. No default. Used only on non-restart cases.

EMIXFN (80) = mixture elevation, E_{mix}, of each interior fluid node. [ft]. No default. Used only on non-restart cases for saturated stratified interior fluid nodes. For non-accumulator interior fluid nodes, it is compared with the minimum mixture elevation required to accommodate the liquid with no bubbles. The maximum of these is used. Note, therefore, that to get collapsed liquid, one simply uses a sufficiently low value of EMIXFN.

For accumulator fluid nodes, the space above the mixture elevation is assumed to be nitrogen gas and below the mixture elevation is assumed to be fluid with initial enthalpy, h.

IBRTFN (80) = flag for bubble rise type for each interior fluid node. Homogeneous node if = 0. Stratified node if ≠ 0. Variable area node if < 0. Default = 0.

CDFMFN (80) = C from Equation (G-55). [-]. Used only if IDRFTFN array = 3-6. Default = 1.0.

EDFMFN (80) = n from Equations (G-54 and (G-58). [-]. Used only if IDRFTFN array = 3-6. n > 0.0 for IDRFTFN = 3,4 and n > 1.0 for IDRFTFN = 5,6. Default = 2.0.

DDFMFN (80) = D_e from Equations (G-56) and (G-60). [ft]. Used only if IDRFTFN array = 3-6,8,9,11, or 12. No default.

UFN (80) = total internal energy, U, in each interior fluid node. [Btu]. No default. Used only on restart cases to combine, divide, or add interior fluid nodes.

TMFN (80) = total mass, M, in each interior fluid node. [lbm]. No default. Used only on restart cases to combine, divide, or add interior fluid nodes.

TMBFN (80) = bubble mass, M_{gb}, in each interior fluid node. [lbm]. No default. Used only on restart cases to combine, divide, or add interior fluid nodes or to simply change the mixture.

TMGØFN (80) = total vapor mass from the previous time step, M_g^{old}, for each interior fluid node. (See Equation 10-22) [lbm]. No default. Used only on restart cases to combine, divide, or add interior fluid nodes or to simply change the mixture.

TMFØFN (80) = total liquid mass from the previous time step, M_f^{old}, for each interior fluid node. (See Equation 10-23). [lbm]. No default. Used only on restart cases to combine, divide, or add interior fluid nodes or to simply change the mixture.

ISTAKFN (80) = node stacking and mixture level tracking model flag for each interior fluid node.

1 = interior fluid node belongs to a stack and contains a mixture elevation.

-1 = interior fluid node belongs to a stack, but does not contain a mixture elevation.

0 = interior fluid node does not belong to a stack.

Default = 0.

IDRFTFN (80) = flag for drift velocity model for each stratified interior fluid node. See Appendix G. Used only if IBRTFN array ≠ 0.

0 = no drift, i.e., $\langle\langle V_{gj} \rangle\rangle = 0$.

1 = Zuber correlation limited by flooding. Uses flux-weighted void fraction approach. See Equations (G-50)-(G-53).

2 = same model as IDRFTFN=1 except uses void propagation approach.

3 = general bubbly flow correlation. Uses flux-weighted void fraction approach. See Equations (G-54)-(G-57).

4 = same model as IDRFTFN=3 except uses void propagation approach.

5 = general droplet flow correlation. Uses flux-weighted void fraction approach. See Equations (G-58)-(G-60).

6 = same model as IDRFTFN=5 except uses void propagation approach.

7 = "standard vertical flow" model. Uses void propagation approach.

8 = "non-quenched core vertical flow" model. Uses void propagation approach.

9 = "quenched core vertical flow" model. Uses void propagation approach.

10 = "accumulator bypass vertical flow" model. Uses void propagation approach.

11 = improved version of TRAC-P1 horizontal flow model. Uses void propagation approach.

12 = improved version of TRAC-P1 vertical flow model. Uses void propagation approach.

13 = simplified Yeh correlation. See Equations (G-83)-(G-86).

Default = 0.

ISLIPFN (80) = flag for distribution parameter model for each stratified fluid node. See Appendix G. Used only if IBRTFN≠0.

0 = no slip (C_o=1) if IDRFTFN $\leq$ 6 or IDRFTFN=13. C_o is calculated in conjunction with the drift velocity models if 7 $\leq$ IDRFTFN $\leq$ 12.

1 = modified Armand correlation (see Equations (G-40)-(G-47)) if IDRFTFN=0. Otherwise, same as ISLIPFN=0.

2 = GEND correlation (see Equations (G-48)-(G-49)) if IDRFTFN=0. Otherwise, same as ISLIPFN=0.

Default = 0.

ISFN (80) = flag for fluid thermodynamic state for each interior fluid node. -1 = subcooled. 0 = saturated. 1 = superheated. No default. Used only on restart cases when combining, dividing, or adding interior fluid nodes. It allows a user to correct possible problems with the water packing logic. (See Section 3)

GAMMAFN (80) = isentropic exponent, γ, for each accumulator interior fluid node. [-]. No default. Used only on non-restart cases to calculate $P_i^o \cdot [(V_{N_2})_i^o]^\gamma$.

PVGAMFN (80) = $P_i^o \cdot [(V_{N_2O})_i]^\gamma$ for each accumulator interior fluid node. [psia $(ft^3)^\gamma$]. No default. Used only on restart runs to define $P_i^o \cdot [(V_{N_2})_i^o]^\gamma$.

$MNØDES

ITYPEMN (40) = flag for metal node type for each metal node.
1 = interior metal node
-1 = boundary metal node
0 = no metal node

Note: There are no restrictions on the ordering of metal node types.

IMPMN (40) = flag for implicit method for each interior metal node. Implicit if ≠ 0. Explicit if = 0. Default = 1.

TMMN (40) = initial total mass, M, of each interior metal node. [lbm]. No default.

TMN (40) = initial temperature, T, of each interior metal node. [°F]. No default.

DIMN (40) = inner diamter, D_j, of tubes for each metal node. [ft]. Used only if the metal node connects to a non-critical heat link. No default.

DMMN (40) = middle diameter, D_m, of tubes for each metal node. [ft]. Used only if the metal node connects to a non-critical heat link. No default.

DØMN (40) = outer diamter, D_o, of tubes for each metal node. [ft]. Used only if the metal node connects to a non-critical heat link. No default.

$FLINKS

ITYPEFL (80) = flag for special flow link types for each flow link.
1 = non-critical flow link.
-1 = user-specified time-, pressure-, and enthalpy-dependent critical flow link.
-2 = upgraded break model critical flow link. Moody correlation for subcooled and saturated stagnation states; CRFLO for superheated stagnation state.

-3 = upgraded break model critical flow link. Moody correlation for subcooled and saturated stagnation states; Murdock and Baumann correlation for superheated stagnation state.

-4 = modified Zaloudek correlation for subcooled stagnation state; Moody correlation for saturated stagnation state; CRFLO for superheated stagnation state.

-5 = modified Zaloudek correlation for subcooled stagnation state; Moody correlation for saturated stagnation state; Murdock and Baumann correlation for superheated stagnation state.

-6 = orifice equation for subcooled stagnation state; Moody correlation for saturated stagnation state; CRFLO for superheated stagnation state.

-7 = orifice equation for subcooled stagnation state; Moody correlation for saturated stagnation state; Murdock and Baumann correlation for superheated stagnation state.

-8 = pseudo-steady state critical flow link.

0 = no flow link.

2 = lower (liquid) component of a horizontal stratified flow model non-critical flow link pair.

3 = upper (vapor) component of a horizontal stratified flow model non-critical flow link pair.

Default = 0.

NOTE: A "horizontal stratified flow model non-critical flow link pair" is defined as two flow links, one with ITYPEFL(80)=2 and one with ITYPEFL(80)=3, which have identical values for IUFL(80), IDFL(80), EUFL(80), EDFL(80), ZFL(80), and DCONTFL(80). In addition, DCONTFL(80) must be greater than zero, i.e., continuous flow links.

Note: There are no restrictions on the ordering of flow link types.

IMPFL (80) = flag for implicit method for each non-critical flow link. Implicit if $\neq 0$. Explicit if = 0. Default = 1.

KTFL (80) = flag for flow composition type for each flow link.

1 = no change.

2 = set α_{top} to 1.0 for net upflow.

3 = set α_{top} to 0.0 for net upflow

4 = set α_{bot} to 1.0 for net downflow.

5 = set α_{top} and α_{bot} to 1.0.

6 = set α_{top} to 0.0 for net upflow. Set α_{bot} to 1.0 for net downflow.

7 = set α_{bot} to 0.0 for net downflow.

8 = set α_{top} to 1.0 for net upflow. Set α_{bot} to 0.0 for net downflow.

9 = set α_{top} and α_{bot} to 0.0.

10 = set α_{bot} to α_{donor} and set α_{top} to 1.0. Assume net upflow.

11 = set α_{top} to α_{donor} and set α_{bot} to 0.0. Assume net downflow.

Default = 1

IUFL (80) = upstream fluid node for each flow link. No default.

IDFL (80) = downstream fluid node for each flow link. No default.

AFL (80) = flow area, A, for each flow link. [ft^2]. No default.

NOTE: For horizontal stratified flow links, AFL(80) is an initial flow area for the link. The only restrictions are that the areas of flow link pairs add to the total flow area of the horizontal pipe being modeled and that SLOAFL(80) is calculated using AFL(80). Likewise the initial values of DEFL(80), FLDAFL(80), and FLDPFL(80) should be consistent.

DEFL (80) = equivalent diameter, D_e, for each flow link. [ft]. No default.

ZFL (80) = length for internally-calculated friction or interfacial shear loss models for each non-critical or pseudo-steady state critical flow link. [ft]. Default = 0.0

SLØAFL (80) = inertial length $\Sigma L/A$ of each non-critical flow link. $[ft^{-1}]$. SLØAFL(80) > 0.0. No default.

CDFL (80) = discharge coefficient, C_D. Used only if ITYPEFL array = -1, -2, -3, -4, -5, -6, or -7. Default = 1.0.

EUFL (80) = elevation of upstream end of each flow link. [ft]. No default.

EDFL (80) = elevation of downstream end of each flow link. [ft]. No default.

FLDAFL (80) = constant fL/D for each non-critical flow link. If two-phase flow, it is corrected by the average value Martinelli-Nelson factor as modified by Thom (see Reference 5). Default = 0.0.

FLDPFL (80) = constant fL/D for each non-critical flow link. If two-phase flow, it is corrected by the point value Martinelli-Nelson factor as modified by Thom (see Reference 5). Default = 0.0.

ALFL (80) = baffle leakage flow area. Used only if IFRICFL array = 5. $[ft^2]$. Default = 0.0.

IMØMF = momentum flux flag. No momentum flux terms if = 0. Possible momentum flux terms if $\neq$ 0. Default = 0.

IUFLFL (80) = flow link, p, associated with upstream end of each non-critical flow link. Used only for momentum flux option. Default = 0.

IDFLFL (80) = flow link, q, associated with downstream end of each non-critical flow link. Used only for momentum flux option. Default = 0.

AUFL (80) = upstream area, A_i, of each non-critical flow link [ft^2]. Used only for momentum flux option. No default.

ADFL (80) = downstream area, A_j, of each non-critical flow link [ft^2]. Used only for momentum flux option. No default.

WFL (80) = initial mass flow rate, W, for each flow link. [lbm/sec] No default.

WFFL (80) = initial liquid mass flow rate, W_f, for each flow link [lbm/sec]. No default. Used only on restart cases when adding flow links.

WGFL (80) = initial vapor mass flow rate, W_g, for each flow link [lbm/sec]. No default. Used only on restart cases when adding flow links.

CDFMFL (80) = C from Equation (G-55). [-]. Used only if |IDRFTFL| = 3-6. Default = 1.0.

EDFMFL (80) = n from Equation (G-54) and (G-58). [-]. Used only if |IDRFTFL| = 3-6. n > 0.0 for |IDRFTFL| = 3,4 and n > 1.0 for |IDRFTFL| = 5,6. Default = 2.0.

DDFMFL (80) = D_e from Equatios (G-56) and (G-60). [ft]. Used only if |IDRFTFL| = 3-6, 8, 9, 11 or 12. No default.

DCØNTFL (80) = continuous contact flow link diameter for each flow link. [ft]. Default = 0.0.

FMFIFL (80) = f_i^k from Equation (I-9). Used only if IMØMF ≠ 0. Default = 0.5.

FMFJFL (80) = f_j^k from Equation (I-10). Used only if IMØMF ≠ 0. Default = 0.5.

FMFPFL (80) = f_p^k from Equations (I-9) and (I-10). Used only if IMØMF ≠ 0. Default = 0.5.

FMFQFL (80) = f_q^k from Equations (I-9) and (I-10). Used only if IMØMF = 0. Default = 0.5.

ADFMFL (80) = flow area to be used to obtain $G = \frac{W}{A}$ for each flow link. No default.

ISVMØDL = flag for swirl vane model
1 = swirl vane model described in Appendix J, pages J-2 through J-5
? = swirl vane model described in Appendix J, pages J-1 and J-2
Default = 1

ANRCFL (80) = number of tube rows in crossflow for each flow link. ANRCFL(80) > 0.0. Used only if IFRICFL array = 5. No default.

ANSFL (80) = number of sealing strips for each flow link. Used only if IFRICFL array = 5. ANSFL(80) $\geq$ 0.0. Default = 0.0.

ANUBCFL (80) = effective number of tubes in the U-bend region for each flow link. Used only if IFRICFL array = 6. Default = 0.0.

NOTE: Recommend $\frac{R_{ub} - 2.5\ D_o}{2(C.P.)P_{tube}}$ where R_{ub} is the maximum outside radius of the U-bend. D_o is the outer diameter of the tubes. C.P. is the pitch correction and is equal to 1.0 for a square pitch and 0.866 for a triangular pitch. P_{tube} is the tube pitch.

DIFL (80) = inner diameter, D_i, of tubes for each flow link. [ft]. Used only if IFRICFL array = 3. No default.

DØFL (80) = outer diameter, D_o, of tubes for each flow link. [ft]. Used only if IFRICFL array = 5 or 6. No default.

FBPFL (80) = fraction of crossflow area in the bundle-to-wrapper bypass for each flow link. Used only if IFRICFL array = 5. Default = 0.0.

PITCHFL (80) = tube pitch, P_{tube}, of tubes for each flow link. [ft]. Used only if IFRICFL array = 2 or 6. No default.

CØN1FL = C_1 from Appendix M. Default = 0.9.
CØN2FL = C_2 from Appendix M. Default = 1.0.
CØN3FL = C_3 from Appendix M. Default = 0.47.
CØN4FL = C_4 from Appendix M. Default = 1.0.
CØN5FL = C_5 from Appendix M. Default = 1.0.
CØN6FL = C_6 from Appendix M. [psi]. Default = 10.0.

IDRFTFL (80) = flag for drift velocity model for each flow link. See Appendix G. Positive if upward direction is same as defined flow link direction. Negative otherwise.

0 = no drift, i.e., $\langle\langle V_{gj} \rangle\rangle = 0$.

$\pm$1 = Zuber correlation limited by flooding. Uses flux-weighted void fraction approach. See Equations (G-50)-(G-53).

$\pm$2 = same model as IDRFTFN=1 except uses void propagation approach.

$\pm$3 = general bubbly flow correlation. Uses flux-weighted void fraction approach. See Equations (G-54)-(G-57).

$\pm$4 = same model as IDRFTFN=3 except uses void propagation approach.

$\pm$5 = general droplet flow correlation. Uses flux-weighted void fraction approach. See Equations (G-58)-(G-60).

$\pm$6 = same model as IDRFTFN=5 except uses void propagation approach.

$\pm$7 = "standard vertical flow" model. Uses void propagation approach.

$\pm$8 = "non-quenched core vertical flow" model. Uses void propagation approach.

±9 = "quenched core vertical flow" model.
Uses void propagation approach.

±10 = "accumulator bypass vertical flow" model.
Uses void propagation approach.

±11 = improved version of TRAC-P1 horizontal flow model. Uses void propagation approach.

±12 = improved version of TRAC-P1 vertical flow model. Uses void propagation approach.

±13 = simplified Yeh correlation. See Equations (G-83)-(G-86).

Default = 0.

ISLIPFL (80) = flag for distribution parameter model for each flow link. See Appendix G. Used only if IDRFTFL(80)=0.

0 = no slip (C_o=1).

1 = modified Armand correlation (see Equations (G-40)-(G-47)).

2 = GEND correlation (see Equations (G-48)-(G-49).

Default = 0.

IFRICFL (80) = flag for internally-calculated friction loss model for each non-critical or pseudo-steady state critical flow link.

0 = no internally-calculated friction losses.

1 = TRANFLO-type regular connector.

2 = TRANFLO-type tube bundle crossflow.

3 = inside of tubes.

4 = parallel flow on secondary side of steam generator tubes.

5 = crossflow on secondary side of steam generator tubes.

6 = crossflow in the U-bend region.

Default = 0.

$HLINKS

ITYPEHL (80) = flag for heat link type

1 = non-critical heat link with internally calculated heat transfer

2 = non-critical heat link with input overall heat transfer coefficient.

3 = non-critical heat link with input overall heat transfer coefficient modified by mixture height

4 = same as 1 except that for condensation a user-supplied heat transfer coefficient is used

5 = same as 4 except that for condensation in a saturated stratified fluid node, the user-supplied heat transfer coefficient is used only above the stack mixture elevation

6 = same as 4 except that for condensation in a saturated fluid node, the user-supplied heat transfer coefficient is used only below the stack mixture elevation

-1 = critical heat link

0 = no heat link.

Note: There are no restrictions on the ordering of heat link types.

LTHL (80) = flag for heat link type. Used only if ITYPEHL = 1,4,5.
1 = inside of tube
2 = outside of tube, parallel flow
3 = outside of tube, crossflow

No default.

IJUHL (80) = upstream node for each heat link. Fluid node if positive. Metal node if negative. No default.

IJDHL (80) = downstream node for each heat link. Fluid node if positive. Metal node if negative. No default.

AHL (80) = heat transfer area, A, for each non-critical heat link. [ft^2]. No default.

CØHL (80) = baffle leakage correction factor, C_o. Used only if ITYPEHL = 1,4,5. Default = 1.0.

AFLHL (80) = effective flow area, $\overline{A}$. [ft^2]. Used only if ITYPEHL = 1,4,5. No default.

DEFLHL (80) = effective equivalent diameter, $\overline{D}_e$. [ft]. Used only if ITYPEHL = 1,4,5. No default.

VFCFCV = void fraction where heat transfer regime changes from possible saturated forced convection to possible forced convection vaporization. Default = 0.90.

AKJL = coefficient used in Jens-Lottes heat transfer correlation. See Equation (6-28). Deafult = 0.87.

AKT = coefficient used in Thom heat transfer correlation. See Equation (6-28). Default=0.072.

KSNB = flag to indicate nucleate boiling heat transfer correlation
1 = Thom correlation
2 = Jens-Lottes correlation
Default = 1.

AØTCFHL (80) = exponenet on Reynolds number for outside-of-tube cross-flow heat transfer coefficient correlation. [-]. See Equation (6-23). Used only if ITYPEHL = 1,4,5 and LTHL=3. No default.

NOTE: Recommend $0.232 + 0.4347_{\chi} - 0.1173_{\chi}^{2}$ where χ = tube pitch/tube outside diameter.

CØTCFHL (80) = multiplier on outside-of-tube crossflow heat transfer coefficient correlation. [-]. See Equation (6-23). Used only if ITYPEHL = 1,4,5 and LTHL = 3.

NOTE: Recommend $1.886 - 1.84_{\chi} + 0.512_{\chi}^{2}$.

FØULFHL (80) = fouling factor, R_{foul}. [°F/(Btu/sec-ft^2)]. Used only if ITYPEHL = 1,4,5. Default = 0.0.

UHL (80) = overall heat transfer coefficient for each non-critical heat link. [Btu/sec-ft^2-°F]. Used only if ITYPEHL = 2 or 3. No default.

$CØNEQNS

NCDE = number of control differential equations. If input as non-zero, NCDE is set to 14. Default = 0.

IDTVFW = interior fluid node number downstream of throttle valve for feedwater valve controller. Used only if NCDE ≠ 0. No default.

KFWPFW = flow link number for feedwater flow measurement for feedwater valve controller. Used only if NCDE ≠ 0. No default.

KSGPFW = flow link number for steam flow measurement for feedwater valve controller. Used only if NCDE ≠ 0. No default.

TL1FW = τ_{L1}^{FW} [sec]. $\tau_{L1}^{FW} > 0.0$. Used only if NCDE ≠ 0. No default.

CP1FW = K_{P1}^{FW} [lbm/sec-% span]. $K_{P1}^{FW} \geq 0.0$. Used only if NCDE ≠ 0. No default.

TI1FW = τ_{I1}^{FW} [sec]. $\tau_{I1}^{FW} > 0.0$. Used only if NCDE ≠ 0. No default.

CP2FW = K_{P2}^{FW} [% lift/(lbm/sec)]. $K_{P2}^{FW} \geq 0.0$. Used only if NCDE ≠ 0. No default.

TI2FW = τ_{I2}^{FW} [sec]. $\tau_{I2}^{FW} > 0.0$. Used only if NCDE ≠ 0. No default.

ØMNFW = ω_n^{FW} [sec^{-1}] $\omega_n^{FW} \geq 0.0$. Used only if NCDE ≠ 0. No default.

RØNFW = ρ_n^{FW} [-] $\rho_n^{FW} \geq 0.0$. Used only if NCDE ≠ 0. No default.

IDTVTV = interior fluid node number downstream of throttle valve for throttle valve controller. Used only if NCDE ≠ 0. No default.

KTV = flow link number for throttle valve. Used only if NCDE ≠ 0. No default.

CP1TV = K_{P1}^{TV} [% lift/Mwth]. $K_{P1}^{TV} \geq 0.0$. Used only if NCDE ≠ 0. No default.

TI1TV = τ_{I1}^{TV} [sec]. $\tau_{I1}^{TV} > 0.0$. Used only if NCDE ≠ 0. No default.

ØMNTV = ω_n^{TV} [sec^{-1}]. $\omega_n^{FW} \geq 0.0$. Used only if NCDE ≠ 0. No default.

RØNTV = ρ_n^{TV} [-]. $\rho_n^{FW} \geq 0.0$. Used only if NCDE ≠ 0. No default.

IHLAPH = fluid node number for mixed heater temperature measurement for primary water heater controller. Used only if NCDE ≠ 0. No default.

IHØAPH = fluid node number for heater exit temperature measurement for primary water heater controller. Used only if NCDE ≠ 0. No default.

TCPH = τ_C^{PH} [sec]. $\tau_C^{PH} > 0.0$. Used only if NCDE ≠ 0. No default.

CPPH = K_P^{PH} [% setting/°F] $K_P^{PH} \geq 0.0$. Used only if NCDE ≠ 0. No default.

TIPH = τ_I^{PH} [sec]. $\tau_I^{PH} > 0.0$. Used only if NCDE ≠ 0. No default.

TDPH = τ_D^{PH} [sec]. $\tau_D^{PH} > 0.0$. Used only if NCDE ≠ 0. No default.

TAPH = τ_A^{PH} [sec]. $\tau_A^{PH} > 0.0$. Used only if NCDE ≠ 0. No default.

Z (14) = initial values of the 14 control variables. See Equations (K-27) - (K-40). Used only if NCDE ≠ 0. No default.

$PUMPS

ITYPEP (4) = flag for pump homologous curve type for each pump type.

0 = no pump.
1 = pump homologous curve type 1.
2 = pump homologous curve type 2.
3 = pump homologous curve type 3.
4 = pump homologous curve type 4.

Default = 0.

KFLP (4) = point of application for each pump type. The sign is positive if the pump type is applied in the same direction as the flow link is defined. It is negative otherwise. The absolute value is the flow link at which the pump type is applied. If ITYPEFL of the specified flow link is 0, 2, or 3 then the pump type is not applied. No default.

NPUMPSP (4) = number of pumps at the point of application for each pump type. Default = 0.

AINP (4) = pump inlet flow area <u>per pump</u> for each pump type. [ft^2]. No default.

AØUTP (4) = pump outlet flow area <u>per pump</u> for each pump type. [ft^2]. No default.

PMØMIP (4) = moment of inertia <u>per pump</u>, I_p, for each pump type. [$lbm-ft^2$]. No default.

P1P (4) = pump friction torque coefficient per pump, P_1, for each pump type. [ft-lbf]. No default.

P2P (4) = pump windage torque coefficient per pump, P_2, for each pump type. [ft-lbf]. No default.

ENP (4) = pump speed, N, for each pump type. [rpm]. No default.

IFLØCP (4) = flag for pump head and torque density models.

1 = pump head equivalent density model; pump torque inlet density model.

2 = pump head inlet density model; pump torque equivalent density model. (Not currently available).

3 = pump head inlet density model; pump torque inlet density model.

4 = pump head equivalent density model; pump torque density model uses 1/2 (inlet density + pump head equivalent density).

NWMAX = maximum allowable number of iterations for pump critical flow calculation. NWMAX $\geq$ 1. Default = 100.

EPSP = maximum allowable fractional error (relative to donor pressure) in the discharge pressure for the critical flow calculation and the discharge pressure calculation. EPSP > 0.0. Default = 0.01.

THØMACC = Thoma constant. Default = 0.05997601439 = $\frac{1}{\sqrt{278}}$.

ENR (4) = rated speed, N_R, for each pump homologous curve type. [rpm]. No default.

QR (4) = rated flow, Q_R, for each pump homologous curve type. [gpm]. No default.

RHØR (4) = rated density, ρ_R, for each pump homologous curve type. [lbm/ft^3]. No default.

HEDR (4) = rated head, H_R, for each pump homologous curve type. [ft]. No default.

TØRKR (4) = rated torque, T_R, for each pump homologous curve type. [ft-lbf]. No default.

PSHR (4) = rated net positive suction head, $NPSH_R$, for each pump homologous curve type. [ft]. No default.

NHVPF (4) = number of points (including both end points) on the HVPF curve for each homologous curve type. (See Figure B-1). No default but the code will force $2 \leq$ NHVPF(I) ≤ 21.

VPFH (21,4) = independent variables α/ν for each point of the HVPF curve for each homologous curve type. (See Figure B-1.) They must be in ascending order from - 1.0 to 1.0. No default but the code will force VPFH(1,I) = - 1.0 and VPFH(NHVPF(I),I) = 1.0.

HVPF (21,4) = dependent variables h/ν^2 for each point of the HVPF curve for each homologous curve type. (See Figure B-1.) No default but the code will force HVPF(NHVPF(I),I) = HAPS(1,I).

NHAPS (4) = number of points (including both end points) on the HAPS curve for each homologous curve type. (See Figure B-1.) No default but the code will force $2 \leq$ NHAPS(I) ≤ 21.

APSH (21,4) = independent variables ν/α for each point of the HAPS curve for each homologous curve type. (See Figure B-1.) They must be in descending order from 1.0 to - 1.0. No default but the code will force APSH(1,I) = 1.0 and APSH(NHAPS(I),I) = - 1.0.

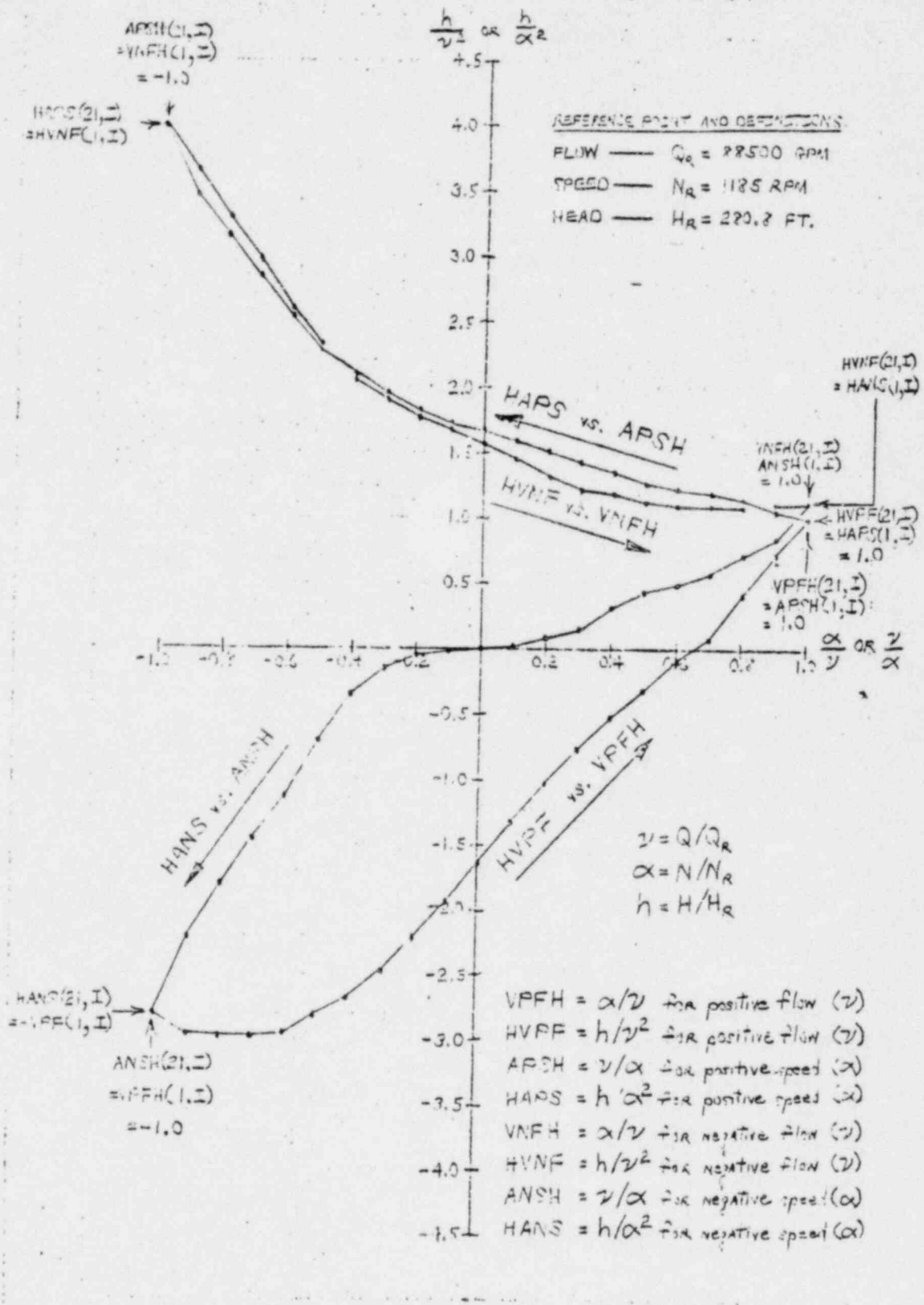


FIGURE B-1 Typical Head-Flow-Speed Homologous Curves

HAPS (21,4) = dependent variable h/α^2 for each point of the HAPS curve for each homologous curve type. (See Figure B-1). No default but the code will force HAPS(1,I) = 1.0 and HAPS(NHAPS(I),I) = HVNF(1,I).

NHVNF (4) = number of points (including both end points) on the HVNF curve for each homologous curve type. (See Figure B-1.) No default but the code will force $2 \leq$ NHVNF(I) ≤ 21.

VNFH (21,4) = independent variables α/ν for each point of the HVNF curve for each homologous curve type. (See Figure B-1). They must be in ascending order from - 1.0 to 1.0. No default but the code will force VNFH(1,I) = - 1.0 and VNFH(NHVNF(I),I) = 1.0.

HVNF (21,4) = dependent variables h/ν^2 for each point of the HVNF curve for each homologous curve type. (See Figure B-1). No default but the code will force HVNF(NHVNF(I),I) = HANS(1,I).

NHANS (4) = number of points (including both end points) on the HANS curve for each homologous curve type. (See Figure B-1.) No default but the code will force $2 \leq$ NHANS(I) ≤ 21.

ANSH (21,4) = independent variable ν/α for each point of the HANS curve for each homologous curve type. (See Figure B-1.) They must be in descending order from 1.0 to - 1.0. No default but the code will force ANSH(1,I) = 1.0 and ANSH(NHANS(I),I) = - 1.0.

HANS (21,4) = dependent variables h/α^2 for each point of the HANS curve for each homologous curve type. (See Figure B-1.) No default but the code will force HANS(NHANS(I),I) = HVPF(1,I).

NBVPF (4) = number of points (including both end points) on the BVPF curve for each homologous curve type. (See Figure B-2). No default but the code will force $2 \leq$ NBVPF(I) ≤ 21.

VPFB (21,4) = independant variables α/ν for each point of the BVPF curve for each homologous curve type. (See Figure B-2). They must be in ascending order from - 1.0 to 1.0. No default but the code will force VPFB(1,I) = - 1.0 and VPFB(NBVPF(I),I) = 1.0

BVPF (21,4) = dependent variables β/ν^2 for each point of the BVPF curve for each homologous curve type. (See Figure B-2.) No default but the code will force BVPF(NBVPF(I),I) = BAPS(1,I).

NBAPS (4) = number of points (including both end points) on the BAPS curve for each homologous curve type. (See Figure B-2). No default but the code will force $2 \leq$ NBAPS(I) ≤ 21.

APSB (21,4) = independent variables ν/α for each point of the BAPS curve for each homologous curve type. (See Figure B-2). They must be in descending order from 1.0 to - 1.0. No default but the code will force APSB(1,I) = 1.0 and APSB(NBAPS(I),I) = - 1.0.

BAPS (21,4) = dependent variables β/α^2 for each point of the BAPS curve for each homologous curve type. (See Figure B-2). No default but the code will force BAPS(1,I) = 1.0 and BAPS(NBAPS(I),I) = BVNF(1,I).

NBVNF (4) = number of points (including both end points) on the BVNF curve for each homologous curve type. (See Figure B-2.) No default but the code will force $2 \leq$ NBVNF(I) ≤ 21.

VNFB (21,4) = independent variables α/ν for each point of the BVNF

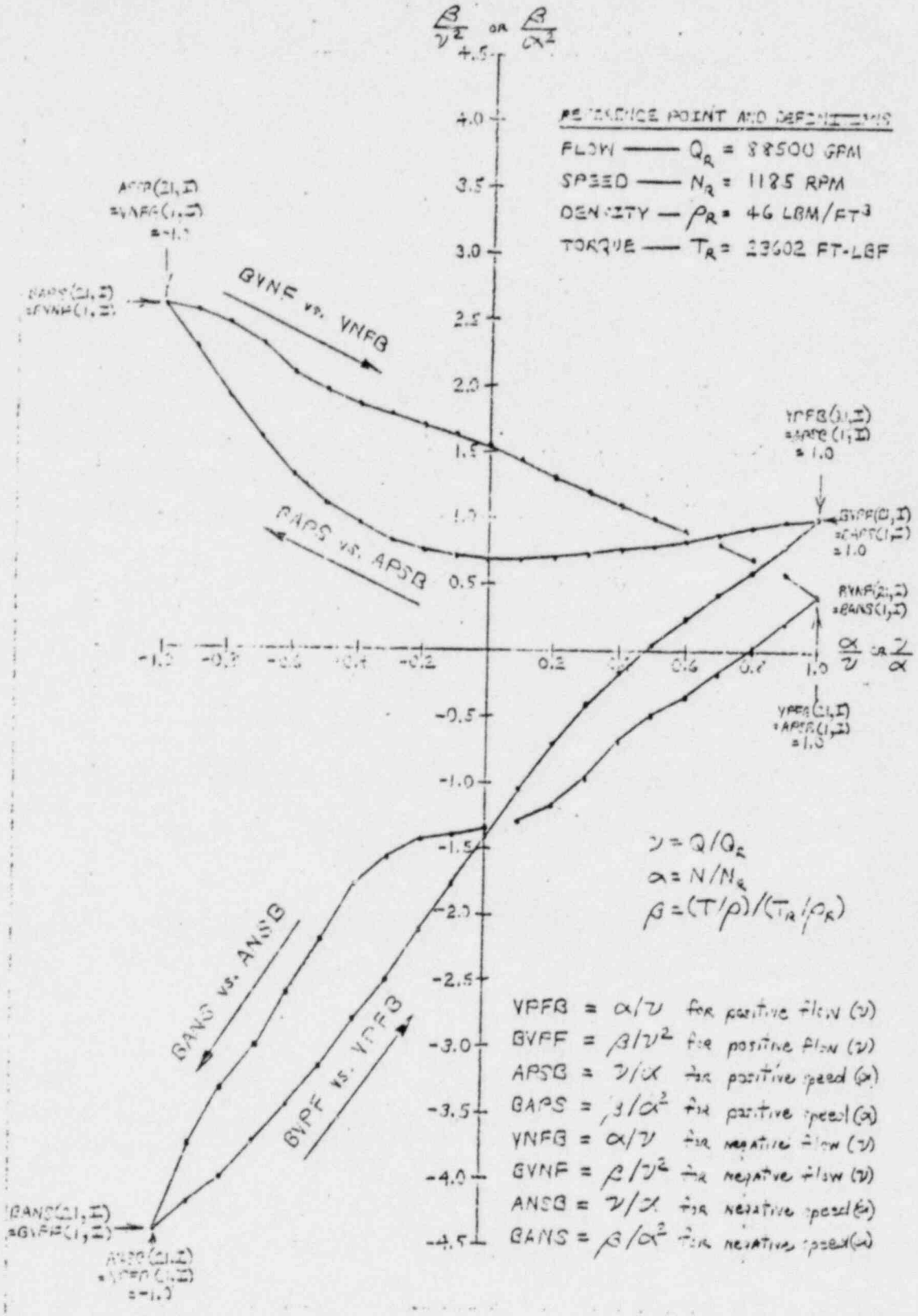


FIGURE B-2 Typical Torque-Flow-Speed Homologous Curves

curve for each homologous curve type. (See Figure B-2). They must be in ascending order from - 1.0 to 1.0. No default but the code will force VNFB(1,I) = - 1.0 and VNFB(NBVNF(I),I) = 1.0.

BVNF (21,4) = dependent variables β/ν^2 for each point of the BVNF curve for each homologous curve type. (See Figure B-2). No default but the code will force BVNF(NBVNF(I),I) = BANS(1,I).

NBANS (4) = number of points (including both end points) on the BANS curve for each homologous curve type. (See Figure B-2). No default but the code will force $2 \leq$ NBANS(I) ≤ 21.

ANSB (21,4) = independent variables ν/α for each point of the BANS curve for each homologous curve type. (See Figure B-2). They must be in descending order from 1.0 to - 1.0. No default but the code will force ANSB(1,I) = 1.0 and ANSB(NBANS(I),I) = - 1.0.

BANS (21,4) = dependent variables β/α^2 for each point of the BANS curve for each homologous curve type. (See Figure B-2). No default but the code will force BANS(NBANS(I),I) = BVPF(1,I).

NSVPF (4) = number of points (including both end points) on the BVPF curve for each homologous curve type. (See Figure B-3). No default but the code will force $2 \leq$ NSVPF(I) ≤ 21.

VPFS (21,4) = independent variables α/ν for each point of the SVPF curve for each homologous curve type. (See Figure B-3). They must be in ascending order from - 1.0 to 1.0. No default but the code will force VPFS(1,I) = - 1.0 and VPFS(NSVPF(I),I) = 1.0.

SVPF (21,4) = dependent variables h/ν^2 for each point of the SVPF curve for each homologous curve type. (See Figure B-3).

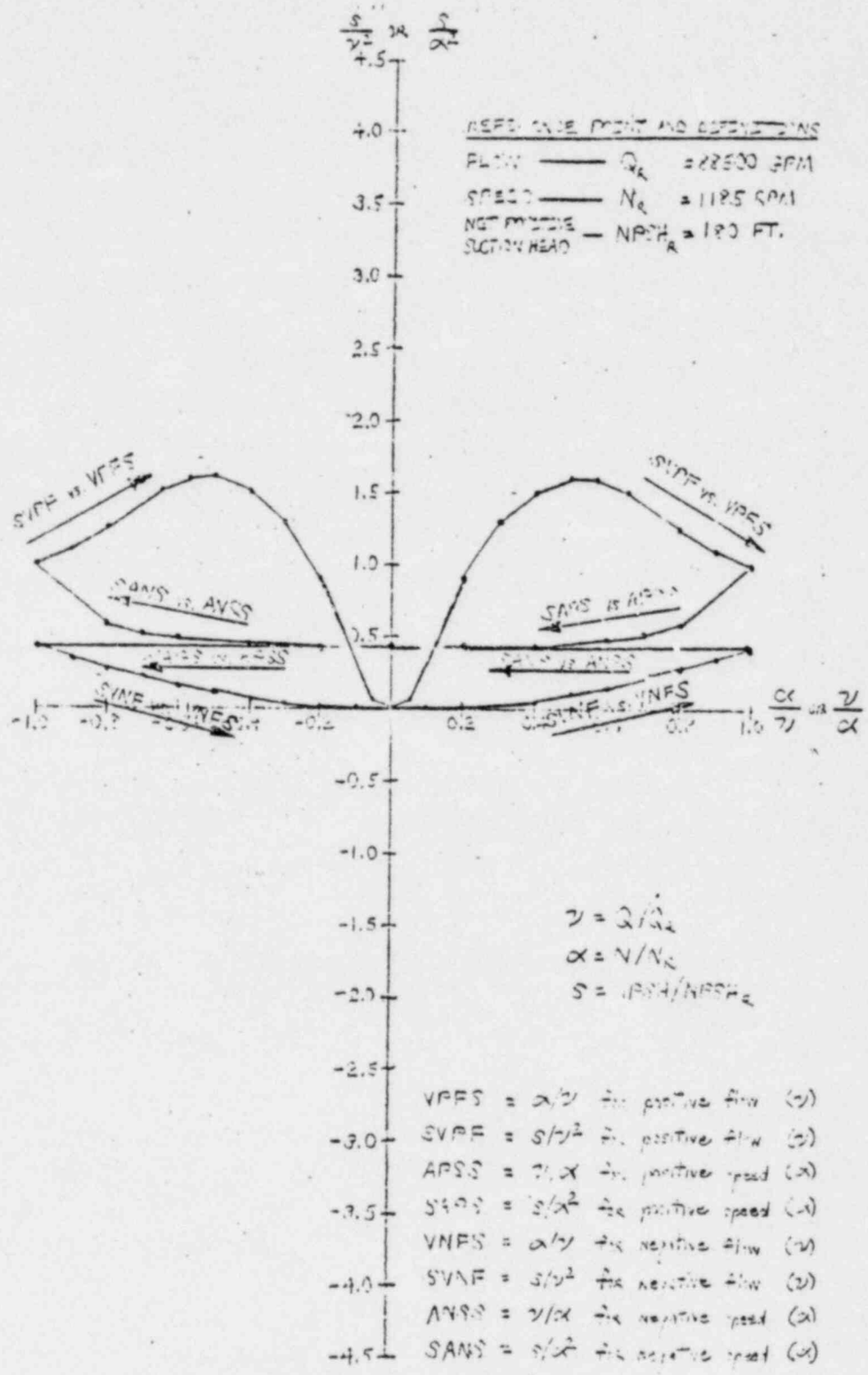


FIGURE B-3 Typical Net Positive Suction Head-Flow-Speed Homologous Curves

No default but the code will force SVPF(NSVPF(I),I) = SAPS(1,I).

NSAPS (4) = number of points (including both end points) on the SAPS curve for each homologous curve type. (See Figure B-3). No default but the code will force $2 \leq$ NSAPS(I) ≤ 21.

APSB (21,4) = independent variables ν/a for each point of the SAPS curve for each homologous curve type. (See Figure B-3). They must be in descending order from 1.0 to - 1.0. No default but the code will force APSS(1,I) = 1.0 and APSS(NSAPS(I),I) = - 1.0.

SAPS (21,4) = dependent variable h/a^2 for each point of the SAPS curve for each homologous curve type. (See Figure B-3.) No default but the code will force SAPS(1,I) = 1.0 and SAPS(NSAPS(I),I) = SVNF(1,I0).

NSVNF (4) = number of points (including both end points) on the SVNF curve for each homologous curve type. (See Figure B-3). No default but the code will force $2 \leq$ NSVNF(I) ≤ 21.

VNFS (21,4) = independent variables a/ν for each point of the SVNF curve for each homologous curve type. (See Figure B-3). They must be in ascending order from - 1.0 to 1.0. No default but the code will force VNFS(1,I) = - 1.0 and VNFS(NSVNF(I),I) = 1.0.

SVNF (21,4) = dependent variables h/ν^2 for each point of the BVNF curve for each homologous curve type. (See Figure B-3). No default but the code will force SVNF(NSVNF(I),I) = SANS(1,I).

NSANS (4) = number of points (including both end points) on the SANS curve for each homologous curve type. (See Figure

B-3). No default but the code will force 2 $\leq$ NSANS(I) $\leq$ 21.

ANSS (21,4) = independent variables v/a for each point of the SANS curve for each homologous curve type. (See Figure B-3). They must be in descending order from 1.0 to - 1.0. No default but the code will force ANSS(1,I) = 1.0 and ANSS(NSANS(I),I) = - 1.0.

SANS (21,4) = dependent variables h/a^2 for each point of the SANS curve for each homologous curve type. (See Figure B-3). No default but the code will force SANS(NSANS(I),I) = HVPS(1,I).

$MISC

IEDIT = output editing flag. IEDIT $\geq$ 0. Larger values obtain more output. Default = 1.

Note: For full output, use IEDIT = 5.

KSVI = flow link representing swirl vane inlet. Used only if ITYPEFL (KSVI) $\neq$ 0. No default.

Warning: Flow link KSVI must be defined such that the positive direction is toward swirl vane. If not, the results will be meaningless.

KSVØ = flow link representing swirl vane outlet. Used only if ITYPEFL (KSVØ) $\neq$ 0. No default

Warning: Flow link KSVØ must be defined such that the positive direction is away from swirl vane. If not, the results will be meaningless.

KSVD = flow link representing swirl vane drain. Used only if ITYPEFL (KSVD) $\neq$ 0. No default.

Warning: Flow link KSVD must be defined such that the positive direction is away from swirl vane. If not, the results will be meaningless.

SV = swirl vane fractional efficiency. [-]. Used only if ITYPEFL (KSVØ) ≠ 0 or ITYPEFL (KSVD) ≠ 0. No default.

RISV = inside radius of swirl vane housing. [ft]. Used only if ITYPEFL (KSVD) ≠ 0. RISV ≥ 0.0. No default.

RØSV = outside radius of swirl vane housing. [ft]. Used only if ITYPEFL (KSVD) ≠ 0. RØSV ≥ 0.0. No default.

TANBSV = tan β where β is the angle of the swirl vane blades with the vertical. [-]. Used only if ITYPEFL (KSVD) = Ø. No default.

VFCSVD = VFCSVD from Appendix J. [-]. Used only if ITYPEFL (KSVD) ≠ 0 AND ISVMØDL = 2. No default.

KPSD = flow link representing peerless separator drain. Used only if ITYPEFL (KPSD) ≠ 0. No default.

Warning: Flow link KPSD must be defined such that the positive direction is away from peerless separator. If not, the results will be meaningless.

VFCPSD = critical void fraction for peerless separator drain. [-]. Used only if ITYPEFL (KPSD) ≠ 0. No default.

NPHGN = number of primary water heater boundary metal nodes. 1 ≤ NPHGN ≤ 5. Used only if NCDE ≠ 0. No default.

JPHGN (5) = boundary metal node number of each primary water heater boundary metal node. Used only if NCDE ≠ 0 and ITYPEMN (JPHGN(I)) < 0. No default.

APHGN (5) = A_j^{PH} from Equation (4-3). [°F]. Used only if NCDE ≠ 0 and ITYPEMN (JPHGN(I)) < 0. No default.

BPHGN (5) = B_j^{PH} from Equation (4-3). [°F/% setting]. Used only if NCDE ≠ 0 and ITYPEMN (JPHGN(I)) < 0. No default.

GRAV = acceleration due to gravity. [ft/sec^2]. Default = 32.174.

DELTMIN = minimum allowable time step. [sec]. No default.

DELTMAX = maximum allowable time step. [sec]. No default.

NSTEPS = maximum allowable number of time steps. Default = 0.

NFPRINT = number of fixed output edit times. $0 \leq$ NFPRINT ≤ 100. Default = 0.

NSPRINT = maximum number of time steps between output editing. Ignore if 0. NSPRINT ≥ 0. Default = 0.

TIPRINT = maximum time interval between output editing. Ignore if 0.0. TIPRINT ≥ 0.0. Default = 0.0.

TFPRINT (100) = fixed output edit times. [sec]. Only the first NFPRINT of these are used. No default.

TIMEMAX = maximum time. [sec]. Default = 0.0.

EPCØFN = fraction for $|\Delta U/U|, |\Delta U_0/U|, |\Delta M/M|, |\Delta M_0/M|$ "smoothness" criteria for cutting or expending time step. See

Equations (10-1), (10-2), (10-4), and (10-5). EPCØFN> 0.0. Default = 0.01.

EPC1FN = fraction for $|\Delta U_1/U|$ and $|\Delta M_1/M|$ "smoothness" criteria for cutting or expanding time step. EPC1FN>0.0. See Equations (10-3) and (10-6). Default = 0.001.

EPCPFN = fraction for $|\Delta P/P|$ "smoothness" criterion for cutting or expanding time step. See Equation (10-7). EPCPFN > 0.0. Default = 0.01.

EPCTMN = fraction for $|\Delta T_{metal}/T_{metal}(°R)|$ "smoothness" criterion for cutting or expanding time step. See Equation (10-8). EPCTMN > 0.0. Default = 0.01.

FRACCUT = fraction of current time step above which time step will not be cut. See Section 10. 0.0 < FRACCUT < 1.0. Default = 0.8.

FRACEXP = multiplier on time step below which time step will not be expanded. See Section 10. 2.0 $\leq$ FRACEXP. Default = 2.0.

IINVERT = matrix inversion flag. If IINVERT = 1, use Gaussian elimination. If IINVERT = 2, use block inversion. If IINVERT = 0, the code decides which method to use. Default = 0.

PLEV = pressure at which taps for water level measurement were calibrated. [psia]. Default = 1000.0.

ILEV = flag to indicate whether or not a level calculation is desired
0 = no level calculation made if NCDE = 0 also
1 = level calculated
Default = 0.

ILTLEV = fluid node number for lower tap for water level measurement for feedwater valve controller. Used only if ILEV ≠ 0 or NCDE ≠ 0. No default.

IUTLEV = fluid node number for upper tap for water level measurement for feedwater valve controller. Used only if ILEV≠ 0 or NCDC ≠ 0. No default.

ELTLEV = elevation in fluid node ILTLEV of lower tap for water level measurement for feedwater valve controller. [ft]. Used only if ILEV ≠ 0 or NCDC ≠ 0. No default.

EUTLEV = elevation in fluid node IUTLEV of upper tap for water level measurement for feedwater valve controller. [ft]. Used only if ILEV ≠ 0 or NCDC ≠ 0. No default.

VØTØVT = VØTØVT from Appendix J. Used only if ITYPEFL (KSVØ) ≠ 0 or ITYPEGFL (KSVD) ≠ 0 and ISVMØDL = 1. No default.

TFRAC = fraction of total job time (as defined on job card) to be used for NØTRUMP calculations and intermediate output and restart writes; remainder of time will be used for restart write from last time step, edit of trace variables, and execution of remaining control card instructions. Default = 0.90.

TIME = time. [sec.]. Default = 0.0.

TIMEINT = time at which to start computing time integrals of various quantities. [sec]. If TIMEINT $\geq$ TIME, these integrals are re-initialized to 0.0.

ISTACK = node stacking and mixture level tracking model flag. Model not used if = 0. Model used if ≠ 0. Default = 0.

AP = A_p from Appendix G. Default = 1.41.

AM = m from Appendix G. Default = 0.7.

AK1 = A_{K1} from Appendix G. Default = 3.2.

AK2 = A_{K2} from Appendix G. Default = 10.0.

ILØCTA = flag for LOCTA tape option. Default = 0.

ILØCTA ≠ 0 : LØCTA tape written after time is greater than TSLØCTA. On a restart case, values from old LØCTA tape for time greater than TSLØCTA are first written to new LØCTA tape.

ILØCTA = 0 : No LØCTA tape written.

TSLØCTA = time after which LØCTA tape information is to be written onto tape NLØUT. Default = 0.0.

TPLØCTA = time after which LØCTA tape information is to be written to ØUTPUT. Default = 0.0.

NSLØCTA = maximum number of time steps between LØCTA tape writes. Ignore if 0. Default = 0.

TILØCTA = maximum time interval between LØCTA tape writes. Ignore if 0.0. Default = 0.0.

NLIN = number of tape from which LØCTA tape information is to be read on a restart case. Default = 18.

NLØUT = number of tape onto which LØCTA tape information is to be written. Default = 19.

DPACCUM = convergence criterion for accumulator interior fluid node iterative pressure calculation. Iteration stops if the magnitude of the difference between the last two pressure iterates is less than DPACCUM. [psi]. Default = 0.1.

NIACCUM = maximum number of iterations for accumulator interior

fluid node iterative pressure calculation. Default = 100.

IDELT = flag for time step selection method
0 = original time step selection method
1 = Alexander Gelman's time step selection method
Default = 0.

EPSISET = desired relative accuracy, ε, for Alexander Gelman's time step selection method. [-]. (See Appendix S) Used only if IDELT = 1. Default = 0.05.

$TRACES

ITRACE = flag for inputing trace variables.
ITRACE > 0 : Input NTRACE trace variables
ITRACE $\leq$ 0 : Input NTRACE trace variables only for a non-restart case, i.e., IRSTRT = 0.
Default = 0.

JSTRACE = step number after which trace information is to be written onto tape NTØUT. Default = 0.

JPTRACE = step number after which trace information is to be written to ØUTPUT. Default = 0.

NTRACE = number of variables to be traced through a run
0 $\leq$ NTRACE $\leq$100. Default = 0.

NSTRACE = maximum number of time steps between trace writes.
Ignore if 0. Default = 0.

TITRACE = maximum time interval between trace writes.
Ignore if 0.0. Default = 0.0.

NTIN = number of tape from which trace information is to be read on a restart run. Default = 9.

NTØUT = number of tape onto which trace information is to be written. Default = 10.

TRACE VARIABLES

If IRSTRT = 0 or ITRACE > 0, then NTRACE trace variables must be supplied. These are punched one variable or array name per card, left-justified in Columns 1-7 with the desired subscript punched right-justified in Columns 8-10. (For a non-array variable, a 1 should be punched in Column 10.) A list of allowable trace variables follows. The numbers in parentheses are the dimensions of the arrays.

DELT : Time step size, Δt_n. [sec].

DHWFL (80) : $\frac{\partial (hW)_k}{\partial W_k}$ for each flow link k. [Btu/lbm].

DPFFL (80) : Friction pressure drop in Equation (2-8), i.e., $- C_k |W_k| W_k$, for each non-critical flow link k. [psi].

DPMFFL (80) : Momentum flux pressure drop in Equation (2-8), i.e., $CMFKFL_k + CMFPFL_k + CMFQFL_k$, for each non-critical flow link k. [psi].

DPTØTFL (80) : Total pressure drop in Equation (2-8), i.e., $PUFL_k - PDFL_k + DKFL_k + DPFFL_k + DPMFFL_k$, for each non-critical flow link k. [psi].

DTHL (80) : $T_{u(n)} - T_{d(n)}$ for each non-critical heat link n. [°F].

EMIXFN (80) : Mixture elevation, $(E_{mix})_i$, for each interior fluid node. [ft].

EMIXSFN (80) : Mixture elevation of the stack of interior fluid nodes to which a given interior node belongs for each interior fluid node. [ft]. If the fluid node does not belong to a stack or if ISTACK = 0, it is simply the mixture elevation in the node itself.

ENP (4) : Pump speed for each pump type [rpm].

HHL (80) : Overall heat transfer coefficient for each non-critical heat link. [(Btu/ft^2 sec)/^{o}F].

HP (2,4) : Pump inlet and outlet enthalpies for each pump type [Btu/lbm]

HTP (3,4) : Pump head, torque and net positive suction head (NPSH) for each pump type [ft, ft-lbf, and ft].

HWFL (80) : Total energy flow rate , $(hW)_k$, for each flow link k. [Btu/sec].

HWFLI (80) : Time integral of the energy flow rate $(hW)_k$ from time TIMEINT to TIME for each flow link k. [Btu].

IQHL (80) : Flag for heat transfer regime for each non-critical heat link.

1 = subcooled (or saturated) forced convection, (SCFC).
2 = subcooled (or saturated) nucleat boiling, (NB).
3 = forced convection vaporization, (FCV).
4 = transition boiling, (TB).
5 = film boiling, (FB).
6 = superheated forced convection (SHFC).
7 = no heat transfer regime since input heat transfer coefficients used.
8 = subcooled (or saturated) natural convection, (SCNC).
9 = superheated natural convection, (SHNC).
10 = saturated condensation, (SC).
11 = superheated condensation, (SHC).

ISFN (80) : Flag for thermodynamic state for each fluid node.

-1 = subcooled.
0 = saturated.
1 = superheated.

ISTAKFN (80) : Flag for node stacking and mixture level tracking model for each interior fluid node.
1 = interior fluid node belongs to a stack and contains a mixture elevation.
-1 = interior fluid node belongs to a stack but does not contain a mixture elevation.
0 = interior fluid nodes does not belong to a stack.

ISTEP : time step number.

PCRITP (4) : Critical pressure for choking in each pump type [psia].

PDFL (80) : Downstream pressure for each flow link [psia].

PPN (80) : Pressure for each fluid node. [psia].

PP (2,4) : Pump inlet and outlet prssures for each pump. [psia].

PUFL (80) : Upstream pressure for each flow link [psia].

QFLUXHL (80) : Heat flux for each non-critical heat link. [Btu/ft^2 sec].

QHL (80) : Heat rate Q_n for each heat link n. [Btu/sec].

QHLI (80) : Time integral of the heat rate Q_n from time TIMEINT to TIME for each heat link n. [Btu].

RHØT (4) : Torque density for each pump type. [lbm/ft^3].

RMACHFL (80) : Mach number for each flow link k. [-]. Available only if IMØMF ≠ 0 for non-critical flow links.

SHFFN (80) : Saturated liquid specific enthalpy $(h_g)_i$ for each fluid node i. [Btu/lbm].

SHFN (80) : Specific enthalpy h_i for each fluid node i. [Btu/lbm].

SHGFN (80) : Saturated vapor specific enthalpy $(h_g)_i$ for each fluid node i. [Btu/lbm].

SVFFN (80) : Saturated liquid specific volume $(v_f)_i$ for each fluid node i. [ft^3/lbm].

SVFL (80) : Specific volume v_k for each flow link k. [ft^3/lbm].

SVFN (80) : Specific volume v_i for each fluid node i. [ft^3/lbm].

SVGFN (80) : Saturated vapor specific volume $(v_g)_i$ for each fluid node i. [ft^3/lbm].

SVMFN (80) : Specific volume of the mixture, $(v_{mix})_i$, for each interior fluid node. [ft^3/lbm].

TDØTMN (80) : $\dot{T}_i$ for each interior metal node i. [°F/sec].

TFN (80) : Temperature, T_i, for each fluid node i. [°F].

TIME : Time. [sec].

TMBFN (80) : Mass of bubbles in mixture, $(M_{gb})_i$, for each interior fluid node. [lbm].

TMCPMN (80) : Mass times heat capacity, $(MC_p)_i$, for each interior metal node. [Btu/°F].

TMDØTFN (80) : $\dot{M}_i$ for each interior fluid node i. [lbm/sec].

TMFFN (80) : Liquid mass, $(M_f)_i$, for each interior fluid node i. [lbm].

TMFN (80) : Total mass, M_i, for each interior fluid node i. [lbm].

TMGFN (80) : Vapor mass, $(M_g)_i$, for each interior fluid node i. [lbm].

TMN (80) : Temperature, T_i, for each metal node i. [°F].

TSATFN (80) : Saturation temperature, $(T_{sat})_i$, for each fluid node i. [°F].

UDØTFN (80) : $\dot{U}_i$ for each interior fluid node i. [Btu/sec].

UFN (80) : Total internal energy, U_i, for each interior fluid node i. [Btu].

VFFL (80) : Void fraction, α_k, for each flow link k. [-].

VFFN (80) : Void fraction, α_i, for each fluid node i. [-].

VFMFN (80) : Void fraction of the mixture, $(\alpha_{mix})_i$ for each interior fluid node i. [-].

VMFN (80) : Volume of the mixture, $(V_{mix})_i$, for each interior fluid node i. [ft^3].

VSP (2,4) : Pump inlet and outlet slip specific volumes for each pump type. [ft^3/lbm].

WDØTFL (80) : $\dot{W}_k$ for each non-critical flow link k. [lbm/sec^2].

WFFL (80) : Liquid mass flow rate, $(W_f)_k$, for each flow link k. [lbm/sec].

WFFLI (80) : Time integral of the liquid mass flow rate $(W_f)_k$ from time TIMEINT to TIME for each flow link k. [lbm].

WFL (80) : Total mass flow rate, W_k, for each flow link k. [lbm/sec].

WFLI (80) : Time integral of the total mass flow rate, W_k, from time TIMEINT to TIME for each flow link k. [lbm].

WGFL (80) : Vapor mass flow rate, $(W_g)_k$, for each flow link k. [lbm/sec].

WGFLI (80) : Time integral of the vapor mass flow rate $(W_g)_k$ from time TIMEINT to TIME for each flow link k. [lbm].

WMAXP (4) : Pump maximum allowable flow for each pump type. [lbm/sec]

XFFL (80) : Flow quality, x_k^f, for each flow link k. [-].

XFN (80) : Static quality, x_i^s, for each fluid node i. [-].

XLMLEV : Steam generator level. [% span].

XMFN (80) : Static quality of the mixture, $(x_{mix}^s)_i$, for each internal fluid node i. [-].

XSFL (80) : Static quality, x_k^s, for each flow link k. [-].

Z (14) : Control variable $y_{K+2I+J+i}$ (see Equations (K-36)-(K-49)) for each control differential equation i.

ZDØT (14) : Right hand side $F_{K+2I+J+i}$ (see Equations (K-36)-(K-49)) for each control differential equation i.

APPENDIX C

USER-SUPPLIED EXTERNALS

In this appendix, we describe the externals which the user must supply when running NØTRUMP. Some of these externals may be obtained from libraries; some must be written by the user. We shall describe each external's name and argument list, its function, externals which it uses and information on supplying it. First, however, we describe "generalized user-supplied externals".

Generalized User-Supplied Externals

This section describes two modifications which together make the user-supplied externals in NØTRUMP more powerful while, at the same time, assuring adequate safeguards against their misuse. The modifications are (1) value access functions, and (2) a user-supplied common block.

Value Access Functions RVALUE And IVALUE

The purpose of the value access functions is to give the NØTRUMP user access to the values (but not locations) of certain common variables in NØTRUMP. Thus, the user has, in a sens, "read only" access to these variables; he can obtain but not change their value.

The FUNCTIØN statements in NØTRUMP which define the two value access functions are:

```
FUNCTIØN RVALUE(NAME,INDEX)
```

and

```
FUNCTIØN IVALUE(NAME,INDEX).
```

NAME is the name of the variable or array to be accessed. It is used as a FØRTRAN hollerith constant left justified with blank fill. INDEX is an integer constant or variable which is the subscript used to indicate the element of the array to be accessed. (It should have the value 1 if a variable rather than an array is to be accessed.) RVALUE or IVALUE

contain the value of the variable or array element which has been accessed. RVALUE should be used to access real variables or arrays. IVALUE should be used for integer variables or arrays.

Currently the variab[illegible] NØTRUMP which are accessible using RVALUE and IVALUE are the so-called trace variables. (See Appendix B)

We now give several examples of the use of RVALUE and IVALUE. Page D-13 contains the user-supplied external CPMETAL(J,TMN) for a NØTRUMP sample problem. CPMETAL is defined by the single FØRTRAN statement:

```
CPMETAL = 0.106 + 2.5E - 05 * TMN      .
```

An alternate way to access TMN and use it to evaluate CPMETAL is now:

```
CPMETAL = 0.106 + 2.5E - 05 * RVALUE(3HTMN,J)      .
```

Other examples of the use of RVALUE and IVALUE are:

```
RVALUE(3HPFN,42)      ,
RVALUE(3HPFN,I)       ,
RVALUE(4HTIME,1)      ,
IVALUE(7HISTAKFN,9)   ,
```

and

```
IVALUE(4HISFN,I)      .
```

The value access functions RVALUE and IVALUE make it unnecessary for the NØTRUMP user to know the location of certain variables in common in order to access their values. It also prevents the user from inadvertently or intentionally changing variables to which he should have "read only" access.

User-Supplied Common Block /EXTSAVE/

One problem with the user-supplied externals has been that there was no simple way for the NØTRUMP user to save for restart purposes variables

internal to these user-supplied externals. A second problem has been that any communication strictly between user-supplied externals in the form of shared common blocks has had the drawback that these common blocks were not easily saved for restart purposes. The purpose of the user-supplied common block /EXTSAVE/ is to remedy these problems by giving the user reserved space in which to save variables for restart purposes and to communicate between user-supplied externals.

The definition of the common block in NØTRUMP is

```
CØMMØN/EXTSAVE/XBEGIN,XTERNAL(510),XEND.
```

Therefore, 512 (or 1000_8) locations are available in /EXTSAVE/. The NØTRUMP user can, of course, use different names within /EXTSAVE/ in his user-supplied externals. He should <u>not</u>, however, use more than the 512 locations set aside for him. NØTRUMP itself makes no use of common block /EXTSAVE/ other than to save or restore it from XBEGIN to XEND on or from the NØTRUMP restart tape.

SUBRØUTINE SUB (H,P,T,RHØ,DVDHP,DVDPH,X,ENTH)

This subroutine exists on the Configuration Control library file SALIBRARY4. It calculates the temperature T, density RHØ, and derivatives DVDHP and DVDPH given the enthalpy H and the pressure P. The fluid is assumed to be subcooled.

SUBRØUTINE SUP (H,P,T,RHØ,DVDHP,DVDPH,X,ENTH)

This subroutine exists on the Configuration Control library file SALIBRARY4. It calculates the temperature T, density RHØ, and derivatives DVDHP and DVDPH given the enthalpy H and the pressure P. The fluid is assumed to be superheated.

SUBRØUTINE SATURE (P,HF,HG,T,VF,VG,DVFDP,DVGDP,DHFDP,DHGDP,H,KSTATE, TEMP)

This subroutine exists on the Configuration Control library file

SALIBRARY4. It calculates the saturated liquid enthalpy HF, saturated vapor enthalpy HG, saturation temperature T, saturated liquid specific volume VF, saturated vapor specific volume VG, and derivatives DVFDP, DVGDP, DHFDP, and DHGDP given the pressure P. The fluid is assumed to be saturated.

SUBRØUTINE GPMØØDY (PSTAGI.SHSTRGI,GSTATØ,PSTATØ,DGDPØ,DGDHØ)

This subroutine exists on the Configuration Control library file SALIBRARY46. It calculates the maximum mass flux and its derivatives with respect to pressure and enthalpy, as well as the throat pressure as functions of the stagnation pressure. The Moody correlation for subcooled or two-phase water is used.

FUNCTIØN SIGMA (T)

This function exists on the Configuration Control library file SALIBRARY46. It calculates the surface tension of water SIGMA [lbf/ft] given the temperature T [^{o}F].

SUBRØUTINE PERRØR

This subroutine exists on the Configuration Control library file SALIBRARY46. It is an error traceback routine.

The preceding externals all exist on the Configuration Control library file SALIBRARY46. The user could, of course, supply these externals in some other way, but it is recommended that he simply attach SALIBRARY46. The following externals do not exist on any libraries. By their nature, they depend on the individual user's problem. The user must supply those which he needs.

FUNCTIØN PFLUID (I,TIME)

This function returns the pressure PFLUID [psia] for boundary fluid node I at time TIME [sec]. It need not be provided if there are no boundary fluid nodes.

FUNCTIØN HFLUID (I,TIME)

This function returns the enthalpy HFLUID [Btu/lbm] for boundary fluid node I at time TIME [sec]. It need not be provided if there are no boundary fluid nodes.

FUNCTIØN FEMIXFN (I,FVMIXFN)

This function returns in FEMIXFN the mixture level fraction for interior fluid node I as a function of the mixture volume fraction FVMIXFN. It need not be provided if there are no interior fluid nodes with negative IBRTFN values.

FUNCTIØN FVMIXFN (I,FEMIXFN)

This function returns in FVMIXFN the mixture volume fraction for interior fluid node I as a function of the mixture level fraction FEMIXFN. It only needs to be provided for interior fluid nodes with negative IBRTFN values and non-zero ISTAKFN values. Note that this function is the "inverse" of function FEMIXFN and therefore should be consistent with it.

FUNCTIØN CPMETAL (J,T)

This function returns the heat capacity CPMETAL [Btu/lbm-°F] of interior metal node J at a metal temperature T [°F]. It need not be provided if there are no interior metal nodes.

FUNCTIØN CMETAL (J,T)

This function returns the metal thermal conductivity CMETAL [Btu/sec-ft-F°] for metal node J at a metal temperature T [°F]. It need not be provided if there are no non-critical heat links.

FUNCTIØN DCMETAL (J,T)

This function returns the derivative of the thermal conductivity with

respect to temperature, DCMETAL [Btu/sec-[illegible]] for metal node J at a metal temperature T [°F]. It need not be provided if there are no non-critical heat links.

FUNCTIØN TMETAL (J,TIME)

This function returns the metal temperature TMETAL [°F] for boundary metal node J at time TIME [sec]. It need not be provided if there are no boundary metal nodes.

FUNCTIØN WFLØW (K,TIME,PI,PJ,HI,HJ)

This function returns the total mass flow rate WFLØW [lbm/sec] for critical flow link K at time TIME [sec] if the flow link has an ITYPEFL value of -1. PI and PJ are the pressures [psia] at the upstream and downstream ends of the flow link, respectively. HI and HJ are the enthalpies [Btu/lbm] at the upstream and downstream ends of the flow link, respectively.

FUNCTIØN DWFLPI (K,TIMEPI,PJ,HI,HJ)

This function returns the derivative of the total mass flow rate with respect to the pressure of the upstream node, DWFLPI [lbm/sec/psia], for critical flow link K if it has an ITYPEFL value of -1. The argument list is the same as for WFLØW.

FUNCTIØN DWFLPJ (K,TIME,PI,PJ,HI,HJ)

This function returns the derivative of the total mass flow rate with respect to the pressure of the downstream node, DWFLPJ [lbm/sec/psia], for critical flow link K if it has an ITYPEFL value of -1. The argumenet lists is the same as for WFLØW.

FUNCTIØN DWFLHI (K,TIME,PI,PJ,HI,HJ)

This function returns the derivative of the total mass flow rate with respect to the enthalpy of the upstream node, DWFLHI (lbm/sec)/(Btu/lbm) , for

critical flow link K if it has an ITYPEFL value of -1. The argument list is the same as for WFLØW.

FUNCTIØN DWFLHJ (K,TIME,PI,PJ,HI,HJ)

This function returns the derivative of the total mass flow rate with respect to the enthalpy of the downstream node, DWFLHJ (lbm/sec)/(BTU/sec) , for critical flow link K if it has an ITYPEFL value of -1. The argument list is the same as for WFLØW.

FUNCTIØN HCØNDEN (N,TIME,TMETAL,TFLUID)

This function is a condensation heat transfer coefficient. HCØNDEN [Btu/ft^2 sec °F] for non-critical heat link N at time TIME [sec] if the heat link has an ITYPEHL value of 4 or 5. TMETAL and TFLUID are the temperatures [°F] in the metal and fluid nodes, respectively, which are connected by this heat link.

FUNCTIØN QFLØW (N,TIME)

This function returns the heat rate Q [Btu/sec] for critical heat link N at time TIME [sec]. It need not be provided if there are no critical heat links.

FUNCTIØN XLDFW (PDTVFW)

This function returns in XLDFW the steam generator level setpoint, X_{LD}^{FW} [% span], calculated as a function of the measured pressure downstream of the throttle valve, P_{DTV}^{FW} [psia]. It is used for the MB-1 feedwater valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN YLDFW (WSGPFW)

This function returns in YLDFW the steam generator level setpoint, Y_{LD}^{FW} [% span], calculated as a function of the measured steam flow rate, W_{SGP}^{FW} [lbm/sec]. It is used for the MB-1 feedwater valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN CVFW (FVPFW)

This function returns in CVFW the feedwater valve coefficient, C_v^{FW} [gal/min-psi$^{1/2}$], calculated as a function of the feedwater valve position, F_{VP}^{FW} [% lift]. It is used for the MB-1 feedwater valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN XMWMTV (PDTVTV)

This function returns in XMWMTV, the measured load, X_{MWM}^{TV} [Mwth], calculated as a function of the measured pressure downstream of the throttle valve, P_{DTV}^{TV} [psia]. It is used for the MB-1 throttle valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN XMWDTV (TIME)

This function returns in XMWDTV the load demand, X_{MWD}^{TV} [Mwth], calculated as a function of time, t [sec]. It is used for the MB-1 throttle valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN P7TV (TIME)

This function returns in P7TV the perturbation, P_7^{TV} [Mwth], (see Figure K-2), calculated as a function of time, t [sec]. It is used for the MB-1 throttle valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN XMWCTV (XMWCCTV)

This function returns in XMWCTV the non-linear gain, X_{MWC}^{TV} (X_{MWCC}^{TV}) [Mwth], (see Figure K-2). It is used for the MB-1 throttle valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN P8TV (TIME)

This function returns in P8TV the perturbation P_8^{TV} [Mwth], (see Figure K-2), calculated as a function of time, t [sec]. It is used for the MB-1 throttle valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN CVTV (FVPTV)

This function returns in CVTV the throttle valve coefficient, C_v^{TV} [gal/min-psi$^{1/2}$], calculated as a function of the throttle valve position, F_{VP}^{TV} [% lift]. It is used for the MB-1 throttle valve control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN SPPH (TIME)

This function returns in SPPH the demanded primary water temperature at the heat exit, SP^{PH} [°F], calculated as a function of time, t [sec]. It is used for the MB-1 primary water heater control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

FUNCTIØN DSPPH (TIME)

This function returns in DSPPH the derivative dSP^{PH}/dt. It is used for the MB-1 primary water heater control. It need not be provided if there are no controller equations, i.e., NCDE = 0.

LØGICAL FUNCTIØN REVPUMP (I,TIME)

This function returns in REVPUMP a logical flag for pump type I at time TIME [sec]. If it is .TRUE. then the pump will be allowed to operate in the reverse speed mode. If it is .FALSE. then the pump will not be allowed to operate in the reverse speed mode. It need not be provided if there are no pumps.

LØGICAL FUNCTIØN CSTPUMP (I,TIME)

This function returns in CSTPUMP a logical flag for pump type I at time TIME [sec]. If it is .TRUE. then the pump is coasting and the pump speed

is calculated internally. If it is .FALSE. then the pump is not coasting and the pump speed must be provided using RPMPUMP. It need not be provided if there are no pumps.

FUNCTIØN RPMPUMP (I,TIME)

This function returns in RPMPUMP the pump speed N [rpm] for pump type I at time TIME [sec]. It need not be provided if CSTPUMP is .TRUE. or if there are no pumps.

FUNCTIØN FAFL (K)

This function returns in FAFL the multiplier on AFL(K) for flow link K. It need not be provided if only a multiplier of 1.0 is desired for <u>all</u> flow links. See Appendix Q for more details.

FUNCTIØN FADFMFL (K)

This function returns in FADFMFL the multiplier ADFMFL(K) for flow link K. It need not be provided if only a multiplier of 1.0 is desired for <u>all</u> flow links. See Appendix Q for more details.

FUNCTIØN FAHL (N)

This function returns in FAHL the multiplier on AHL(N) for heat link N. It need not be provided if only a multiplier of 1.0 is desired for <u>all</u> heat links.

SUBRØUTINE WHLØCTA

This subroutine is called from program PUTIN if a LØCTA tape is to be written. It is called only at the beginning of a run and is intended to allow the user to write a header title record on tape NLØUT. It need not be provided if ILØCTA = 0.

SUBRØUTINE EHLØCTA

This subroutine is called from program TRANSNT if a LØCTA tape has been written. It is called only at the end of a run and is intended to allow the user to read and echo the header title record written by WHLØCTA on tape NLØUT. It need not be provided if ILØCTA = 0.

SUBRØUTINE WRLØCTA

This subroutine is called from program TRANSNT whenever a LØCTA tape record is to be written and is intended to allow the user to write a LØCTA tape record on tape NLØUT. It need not be provided if ILØCTA = 0.

SUBRØUTINE PUTINUS

This subroutine is called from program PUTIN. It is called only at the beginning of a run and is intended to allow the user a place to read in input to be saved in the user-supplied common block /EXTSAVE/.

APPENDIX D

OUTPUT DESCRIPTION

In this appendix, we describe the output from NØTRUMP. For each case, this output consists of the input card images, the input NAMELISTs, optional output edits at various time steps, and an edit of all TRACE variables selected (if any) at all time steps after JPTRACE for which trace information has been written on tape NTØUT. Sample output is included at the end of this appendix.

The set of card images which make up a given run are printed first in exactly the form they have been read and processed. This card image listing is extremely valuable in checking the input to NØTRUMP.

The input NAMELISTs are printed next. They are helpful in checking the values of all NAMELIST variables. In particular, default values for variables not read in can be checked.

The optional output edits depend on the values of the input variables IEDIT, NFPRINT, NSPRINT, and TIPRINT and the input array TFPRINT. (See Appendix B) These edits are printed at the first time step for either a non-restart or a restart case, at the fixed output edit times given by the first NFPRINT values of the TFPRINT array, and at a maximum time interval of TIPRINT or time step interval of NSPRINT. The amount of editing depends on IEDIT. A zero value for IEDIT gives no optional output edits. Non-zero values will be described below.

The contents of the optional output edits will now be described. The output is organized according to code components, i.e., interior fluid nodes, boundary fluid nodes, interior metal nodes, boundary metal nodes, non-critical flow links, critical flow links, non-critical heat links, critical heat links, and control differential equations. The description follows:

Interior Fluid Nodes:

IEDIT $\geq$ 1:

INTERIØR FLUID NØDE: Interior fluid node number.

Fluid State: L = liquid (subcooled).
M = mixture (saturated).
V = vapor (superheated).

PRESSURE: P, [psia].

TEMPERATURE: T, [°F].

SPECIFIC ENTHALPY: h, [Btu/lbm].

TØTAL MASS: M, [lbm].

LIQUID MASS: M_f, [lbm].

VAPØR MASS: M_g, [lbm]. This includes both the bubble mass and separated steam mass in a stratified node.

BUBBLE MASS: M_{gb}, [lbm].

TØTAL INTERNAL ENERGY: U, [Btu].

IEDIT $\geq$ 1:

INTERIØR FLUID NØDE: Interior fluid node number.

STATIC QUALITY: x^s

VØID FRACTIØN: α

SPECIFIC VØLUME: v, [ft^3/lbm].

SATURATIØN TEMPERATURE: T_{sat}, [°F].

LIQUID SPECIFIC VØLUME: Saturated liquid specific volume, v_f, [ft^3/lbm].

VAPØR SPECIFIC VØLUME: Saturated vapor specific volume, v_g, [ft^3/lbm].

LIQUID SPECIFIC ENTHALPY: Saturated liquid enthalpy, h_f, [Btu/lbm].

VAPØR SPECIFIC ENTHALPY: Saturated vapor enthalpy, h_g, [Btu/lbm].

IEDIT $\geq$ 1:

INTERIØR FLUID NØDE: Interior fluid node number.

STACK MIXTURE ELEVATION: Mixture elevation of the stack to which this interior fluid node belongs. [ft].

NODE MIXTURE ELEVATION: Z_{fix} [ft].

MIXTURE STATIC QUALITY: x^s for the mixture.

MIXTURE VØID FRACTIØN: α for the mixture.

MIXTURE SPECIFIC VØLUME: v for the mixture, [ft^3/lbm].

U DØT: $\dot{U}$, [Btu/sec].

M DØT: $\dot{M}$, [lbm/sec].

IEDIT $\geq$ 1:

INTERIØR FLUID NØDE: Interior fluid node number.

DELTA U/U: $\Delta U/U$

DELTA U O/U: $\Delta U_o/U$

DELTA U 1/U: $\Delta U_1/U$

DELTA M/M: $\Delta M/M$

DELTA M O/M: $\Delta M_o/M$

DELTA M 1/M: $\Delta M_1/M$

DELTA P/P: $\Delta P/P$

IEDIT $\geq$ 5:

INTERIØR FLUID NØDE: Interior fluid node number.

DPUFN: $(\partial P/\partial U)_M$, [psia/Btu].

DPMFN: $(\partial P/\partial M)_U$, [psia/lbm].

DTUFN: $(\partial T/\partial U)_M$, [°F/Btu].

DTMFN: $(\partial T/\partial M)_U$, [°F/lbm].

DTSPFN: $\partial(T_{sat})/\partial P$, [°F/psia].

Boundary Fluid Nodes:

IEDIT $\geq$ 1:

BØUNDARY FLUID NØDE: Boundary fluid node number.

Fluid State: L = liquid (subcooled).

M = mixture (saturated).

V = vapor (superheated).

PRESSURE: P, [psia].

TEMPERATURE: T, [°F].

SPECIFIC ENTHALPY: h, [Btu/lbm].

IEDIT $\geq$ 1:

BØUNDARY FLUID NØDE: Boundary fluid node number.

STATIC QUALITY: x^s.

VØID FRACTIØN: α.

SPECIFIC VØLUME: v, [ft^3/lbm].

SATURATIØN TEMPERATURE: T_{sat}, [°F].

LIQUID SPECIFIC VØLUME: Saturated liquid specific volume, v_f, [ft^3/lbm].

VAPØR SPECIFIC VØLUME: Saturated vapor specific volume, v_g, [ft^3/lbm].

LIQUID SPECIFIC ENTHALPY: Saturated liquid enthalpy, h_f, [Btu/lbm].

VAPØR SPECIFIC ENTHALPY: Saturated vapor enthalpy, h_g, [Btu/lbm].

Interior Metal Nodes:

IEDIT $\geq$ 1:

INTERIØR METAL NØDE: Interior metal node number.

TEMPERATURE: T, [°F].

MASS TIMES HEAT CAPACITY: MC_p, [Btu/°F].

T DØT: $\dot{T}$, [°F/sec].

DELTA T/T: $\Delta T/(T-32\ °F)$.

Boundary Metal Nodes:

IEDIT $\geq$ 1:

BØUNDARY METAL NØDE: Boundary metal node number.

TEMPERATURE: T, [°F].

Non-Critical Flow Links:

IEDIT $\geq$ 1:

NØN-CRIT FLØW LINK: Non-critical flow link number.

UP NØDE: Upstream fluid node.

DØWN NØDE: Downstream fluid node.

LIQUID MASS FLØW RATE: W_f, [lbm/sec].

VAPOR MASS FLØW RATE: W_g, [lbm/sec].

TØTAL MASS FLØW RATE: W, [lbm/sec].

TØTAL ENERGY FLØW RATE: hW, [Btu/sec].

DHWFL: $\partial(hW)/\partial W$, [Btu/lbm].

DØT: $\dot{W}$, [lbm/sec/sec].

MACH NUMBER (Only if IMØMF $\neq$ 0): $|W|/|W_{max}|$.

IEDIT $\geq$ 1:

NØN-CRIT FLØW LINK: Non-critical flow link number.

UP NØDE: Upstream fluid node.

DØWN NØDE: Downstream fluid node.

STATIC QUALITY: χ^s.

FLØW QUALITY: χ^f. For counter-current flow, it is set to χ^s.

VØID FRACTIØN: α.

SPECIFIC VØLUME: v, [ft^3/lbm].

DELTA P FRICTIØN: Friction pressure drop term in the momentum equation, i.e., $-C_k|W_k|W_k$ in Equations (2-8) and (I-8). [psi].

DELTA P MØMENTUM FLUX (Only if IMØMF $\neq$ 0): Momentum flux pressure drop terms in the momentum equation, i.e., the sum of the bracketed terms in Equations (2-8) and (I-8), [psi].

DELTA P TØTAL: Total pressure drop in the momentum equation, i.e., $PUFL_k - PDFL_k + DKFL_k + DPFFL_k + DPMFFL_k$ in Equations (2-8) and (I-8), [psi].

IEDIT $\geq$ 1

NØN-CRIT FLØW LINK: Non-critical flow link number.

UP NØDE: Upstream fluid node.

DØWN NØDE: Downstream fluid node.

INTEGRATED LIQUID MASS FLØW RATE: $\int_{TIMEINT}^{TIME} W_f dt$ [lbm].

INTEGRATED VAPØR MASS FLØW RATE: $\int_{TIMEINT}^{TIME} W_g dt$ [lbm].

INTEGRATED TØTAL MASS FLØW RATE: $\int_{TIMEINT}^{TIME} W \, dt$ [lbm].

INTEGRATED TØTAL ENERGY FLØW RATE: $\int_{TIMEINT}^{TIME} (hW)dt$ [lbm].

IEDIT $\geq$ 5:

NØN-CRIT FLØW LINK: Non-critical flow link number.

CKFL: C_k in Equations (2-8), [psi/(lbm/sec)^2].

DKFL: D_k in Equation (2-8), [psi].

CMFKFL: The first bracketed term in Equation (2-8), [psi].

CMFPFL: The second bracketed term in Equation (2-8), [psi].

CMFQFL: The third bracketed term in Equation (2-8), [psi].

DMFKFL: ∂(CMFKFL)/ W_k, [psi/(lbm/sec)].

DMFPFL: ∂(CMFPFL)/ W_p, [psi/(lbm/sec)].

DMFQFL: ∂(CMFQFL)/ W_q, [psi/(lbm/sec)].

IEDIT $\geq$ 5 And IMØMF $\neq$ 0:

NØN-CRIT FLØW LINK: Non-critical flow link number.

RJ1FL: ρ_{j1}, (see Equation (I-18), [lbm/ft^3].

RJ2FL: ρ_{j2}, (see Equation (I-19), [lbm/ft^3].

RVVJ1FL: $[\rho V^2]^k_{j1}$, (see Equations (I-11) and (I-13)), [lbm/(ft sec^2)].

RVVJ2FL: $[\rho V^2]^k_{j2}$, (see Equations (I-12) and (I-14)), [lbm/(ft sec^2)].

DVVJ1FL: $\partial[\rho V^2]^k_{j1} / \partial W_k$, [1/(ft sec)].

DVVJ2FL: $\partial[\rho V^2]^k_{j2} / \partial W_k$, [1/(ft sec)].

C**2 DELTA RHØ: $C_k^2 (\rho_{j2} - \rho_{j1})$ in Equations (2-8) and (I-8). [lbm/(ft sec^2)].

Critical Flow Links:

IEDIT $\geq$ 1:

CRITICAL FLØW LINK: Critical flow link number.

UP NØDE: Upstream fluid node.

DØWN NØDE: Downstream fluid node.

LIQUID MASS FLØW RATE: W_f, [lbm/sec].

VAPØR MASS FLØW RATE: W_g, [lbm/sec].

TØTAL MASS FLØW RATE: W, [lbm/sec].

TØTAL ENERGY FLØW RATE: hW, [Btu/sec].

DHWFL: $\partial(hW)/\partial W$, [Btu/lbm].

IEDIT $\geq$ 1:

CRITICAL FLØW LINK: Critical flow link number.

UP NØDE: Upstream fluid node.

DØWN NØDE: Downstream fluid node.

STATIC QUALITY: χ^s.

FLØW QUALITY: χ^f. For counter-current flow, it is set to χ^s.

VØID FRACTIØN: α

SPECIFIC VØLUME: v, [ft^3/lbm].

IEDIT $\geq$ 1:

CRITICAL FLØW LINK: Critical flow link number.

UP NØDE: Upstream fluid node.

DØWN NØDE: Downstream fluid node.

INTEGRATED LIQUID MASS FLØW RATE: $\int_{TIMEINT}^{TIME} W_f dt$ [lbm].

INTEGRATED VAPØR MASS FLØW RATE: $\int_{TIMEINT}^{TIME} W_g dt$ [lbm].

INTEGRATED TØTAL MASS FLØW RATE: $\int_{TIMEINT}^{TIME} W\, dt$ [lbm].

INTEGRATED TØTAL ENERGY FLØW RATE: $\int_{TIMEINT}^{TIME} (hW)dt$ [lbm].

IEDIT $\geq$ 5:

CRITICAL FLØW LINK: Critical flow link number.

DWIFL: $\partial W_k / \partial P_{u(k)}$, [(lbm/sec)/psi].

DWJFL: $\partial W_k / \partial P_{d(k)}$, [(lbm/sec)/psi].

DHWIFL: $\partial (hW)_k / \partial P_{u(k)}$, [(lbm/sec)/psi].

DHWJFL: $\partial (hW)_k / \partial P_{d(k)}$, [(lbm/sec)/psi].

IEDIT $\geq$ 5 And IMØFM $\neq$ 0:

CRITICAL FLØW LINK: Critical flow link number.

RJ1FL: ρ_{j1}, (see Equation (I-18)), [lbm/ft^3].

RJ2FL: ρ_{j2}, (see Equation (I-19)), [lbm/ft^3].

RVVJ1FL: $[\rho V^2]^k_{j1}$, (see Equations (I-11) and (I-13)), [lbm/(ft sec^2)].

RVVJ2FL: $[\rho V^2]^k_{j2}$, (see Equations (I-12) and (I-14)), [lbm/(ft sec^2)].

DVVJ1FL: $\partial [\rho V^2]^k_{j1} / \partial W_k$, [1/(ft sec)].

DVVJ2FL: $\partial [\rho V^2]^k_{j2} / \partial W_k$, [1/(ft sec)].

C**2 DELTA RHØ: $C^2_k (\rho_{j2} - \rho_{j1})$ in Equations (2-8) and (I-8), [lbm/(ft sec^2)].

Non-Critical Heat Links:

IEDIT $\geq$ 1:

NØN-CRIT HEAT LINK: Non-critical heat link number.

UP NØDE: Upstream node, (fluid node if positive, metal node if negative).

DØWN NØDE: Downstream node, (fluid node if positive, metal node if negative).

DELTA T: $T_{u(n)} - T_{d(n)}$, (°F).

HEAT FLUX: q_n, [Btu/sec-ft^2].

HEAT RATE: Q_n, [Btu/sec].

HEAT TRANSFER REGIME:

SCFC = subcooled forced convection.

NB = nucleate boiling.

FCV = forced convection vaporization.

TB = transition boiling.

FB = film boiling.

SHFC = superheated forced convection.

HEAT TRANSFER COEFFICIENT:

$h = q/(t_{u(n)} - T_{d(n)})$ [Btu/ft^{2}sec°F].

INTEGRATED HEAT RATE: $\int_{TIMEINT}^{TIME} Q_n dt$ [Btu].

NON-CRIT HEAT LINK: Non-critical heat link number.

UP NODE: Upstream node, (fluid node if positive, metal node if negative).

DOWN NODE: Downstream node, (fluid node if positive, metal node if negative).

DQTUHL: $\partial Q_n/\partial T_{u(n)}$, (see Equations (6-89) and (6-93)). [Btu/sec-°F].

DQTDHL: $\partial Q_n/\partial T_{d(n)}$, (see Equations (6-91) and (6-95)). [Btu/sec-°F].

DQPUHL: $\partial Q_n/\partial P_{u(n)}$, (see Equations (6-90) and (6-94)). [Btu/sec-psi].

DQPDHL: $\partial Q_m/\partial P_{d(n)}$, (see Equations (6-92) and (6-96)). [Btu/sec-psi].

Critical Heat Links:

IEDIT $\geq$ 1:

CRITICAL HEAT LINK: Critical heat link number.

UP NODE: Upstream node, (fluid node if positive, metal node if negative).

DOWN NODE: Downstream node, (fluid node if positive, metal node if negative).

HEAT RATE: Q_m, [Btu/sec].

INTEGRATED HEAT RATE: $\int_{TIMEINT}^{TIME} Q_n dt$ [Btu].

Control Differential Equations:

IEDIT $\geq$ 1:

CØNTRØL DIFFERENTIAL EQUATIØN: Control differential equation number.

Ø: Control variable, $y_{K+2I+J+i}$, (see Equations (K-36) - (K-49)).

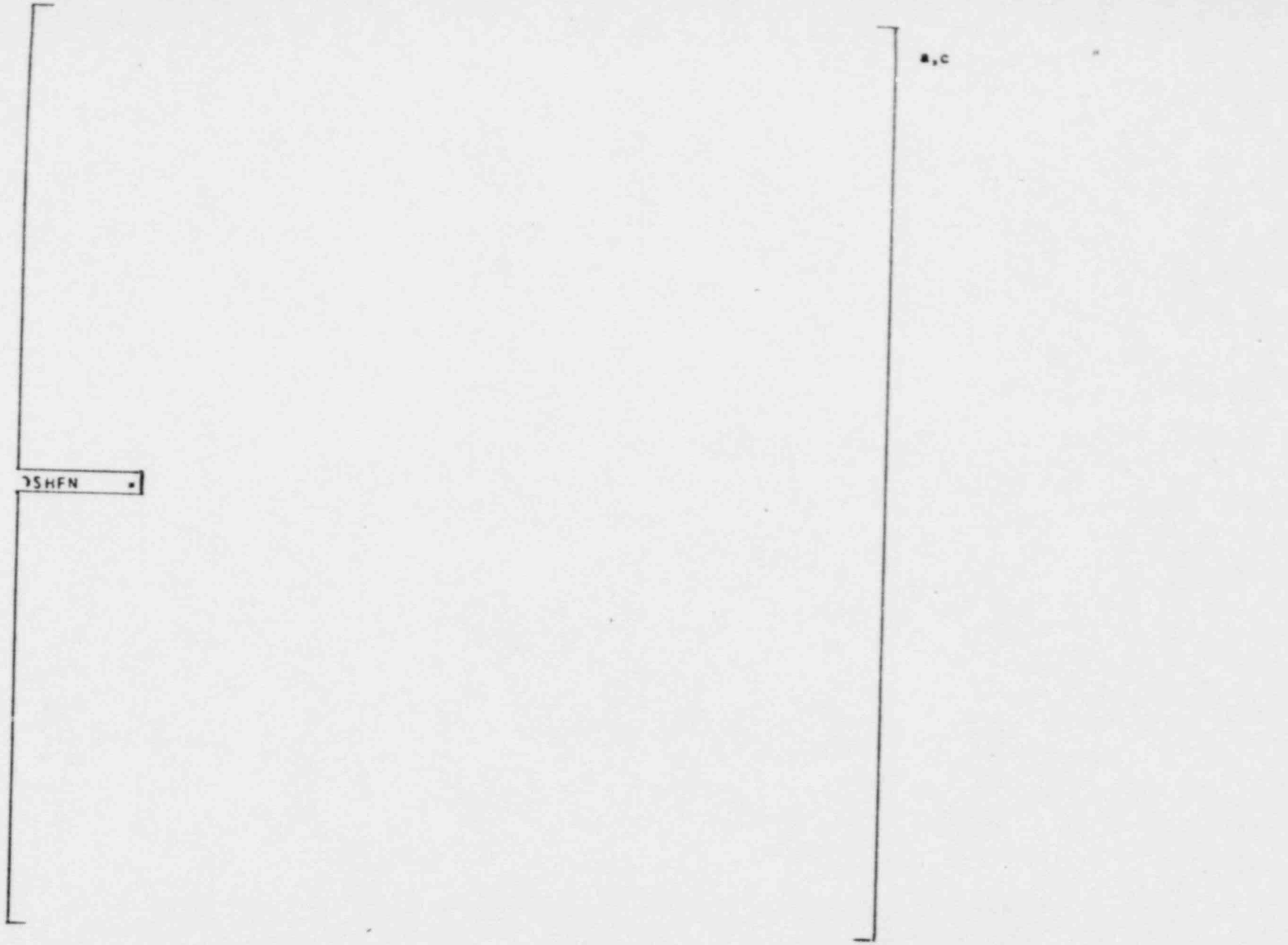
Ø DØT: Right hand side of control differential equation, $F_{K+2I+J+i}$, (see Equations (K-50) - (K-63)).

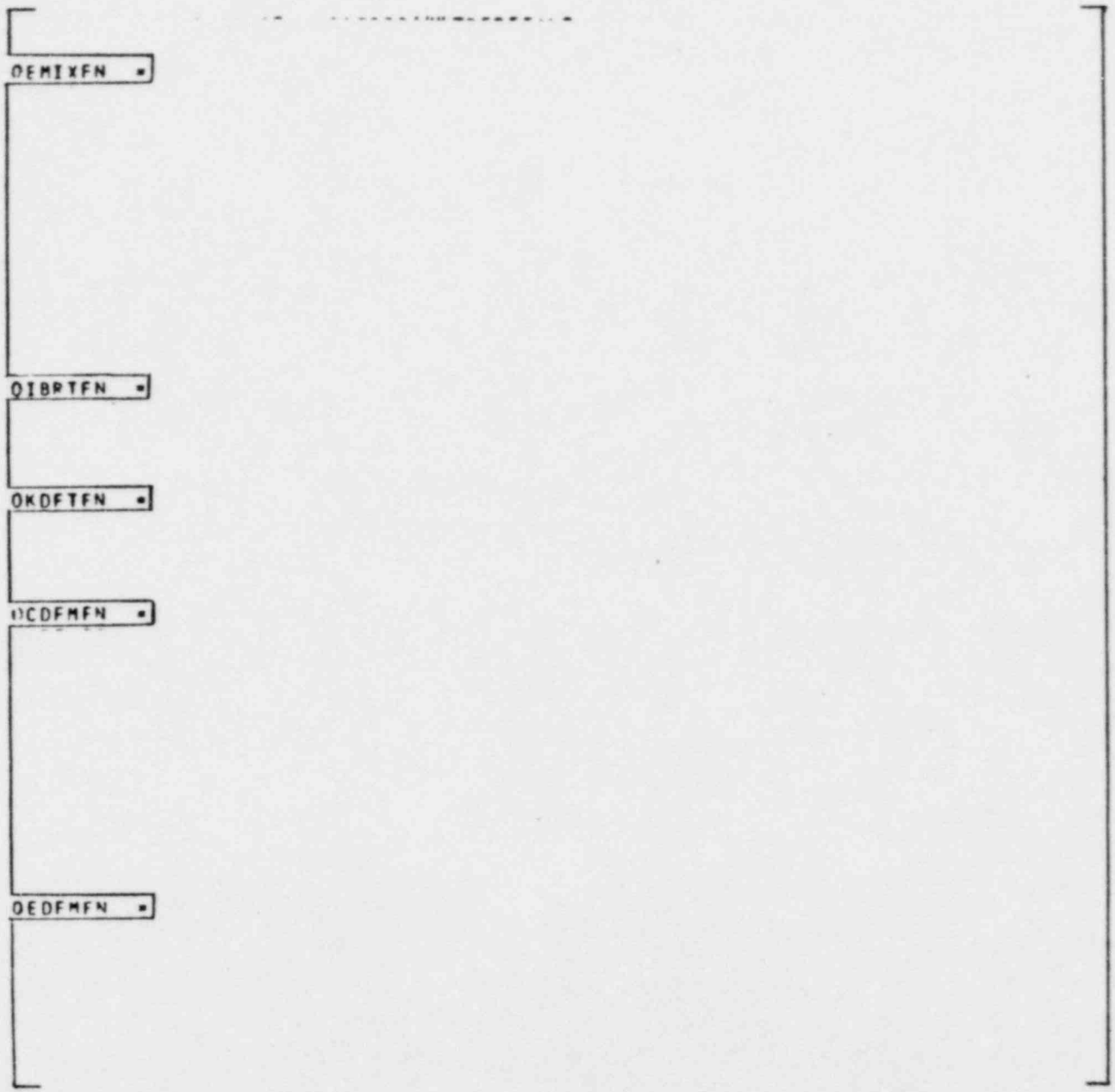
At the end of a case, all trace variables (if any) are printed at all time steps after JPTRACE for which information was written on tape NTØUT. This information is valuable when it is desired to see certain variables at many time steps, e.g., for plotting.

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR

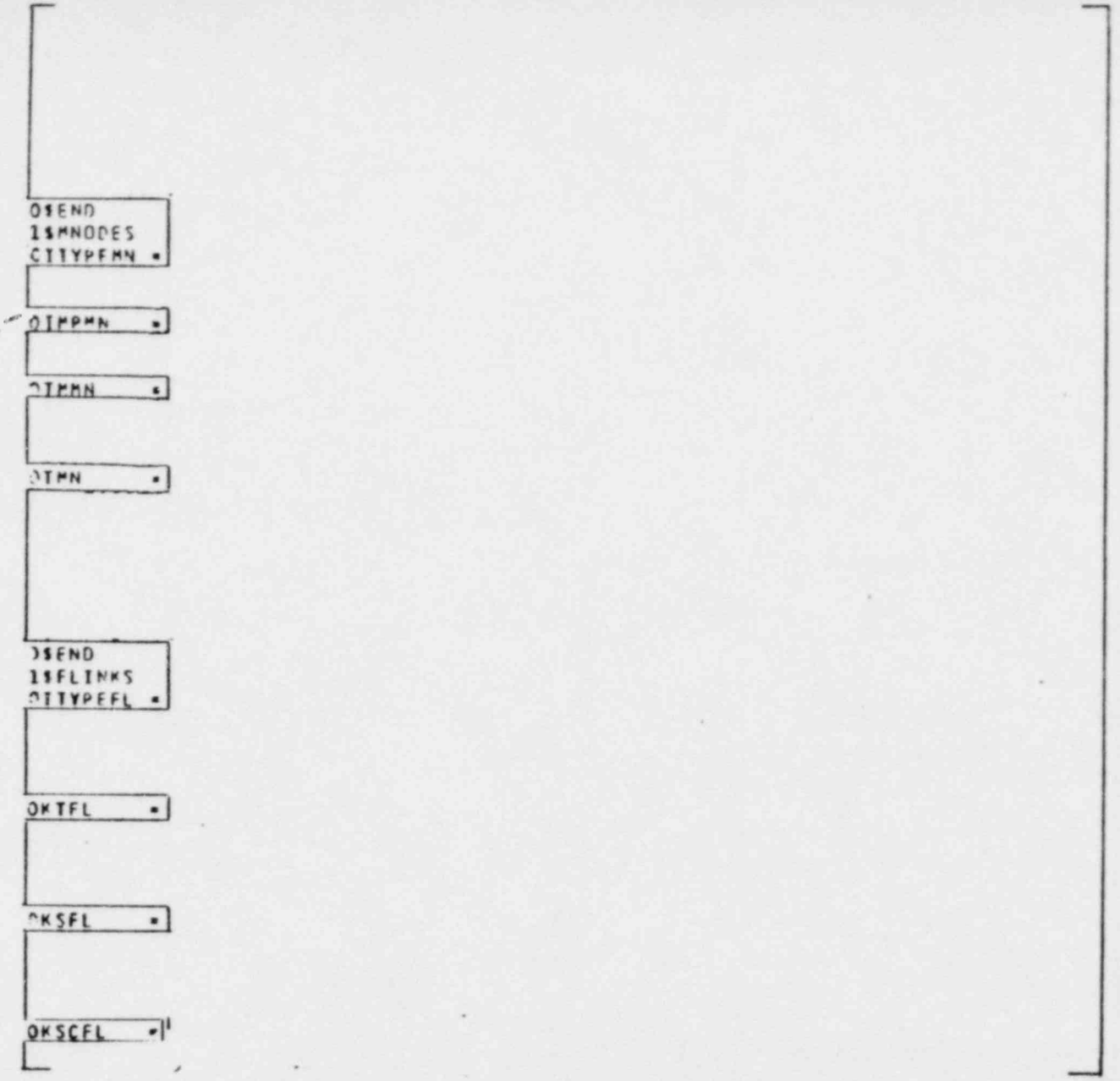
```
1$RMISC
0$END
1$FNODES
0ITYPEFN *
0VFN *
0EBOTFN *
0EIOPFN *
0PFN *
```

a,c


a,c
DSHFN



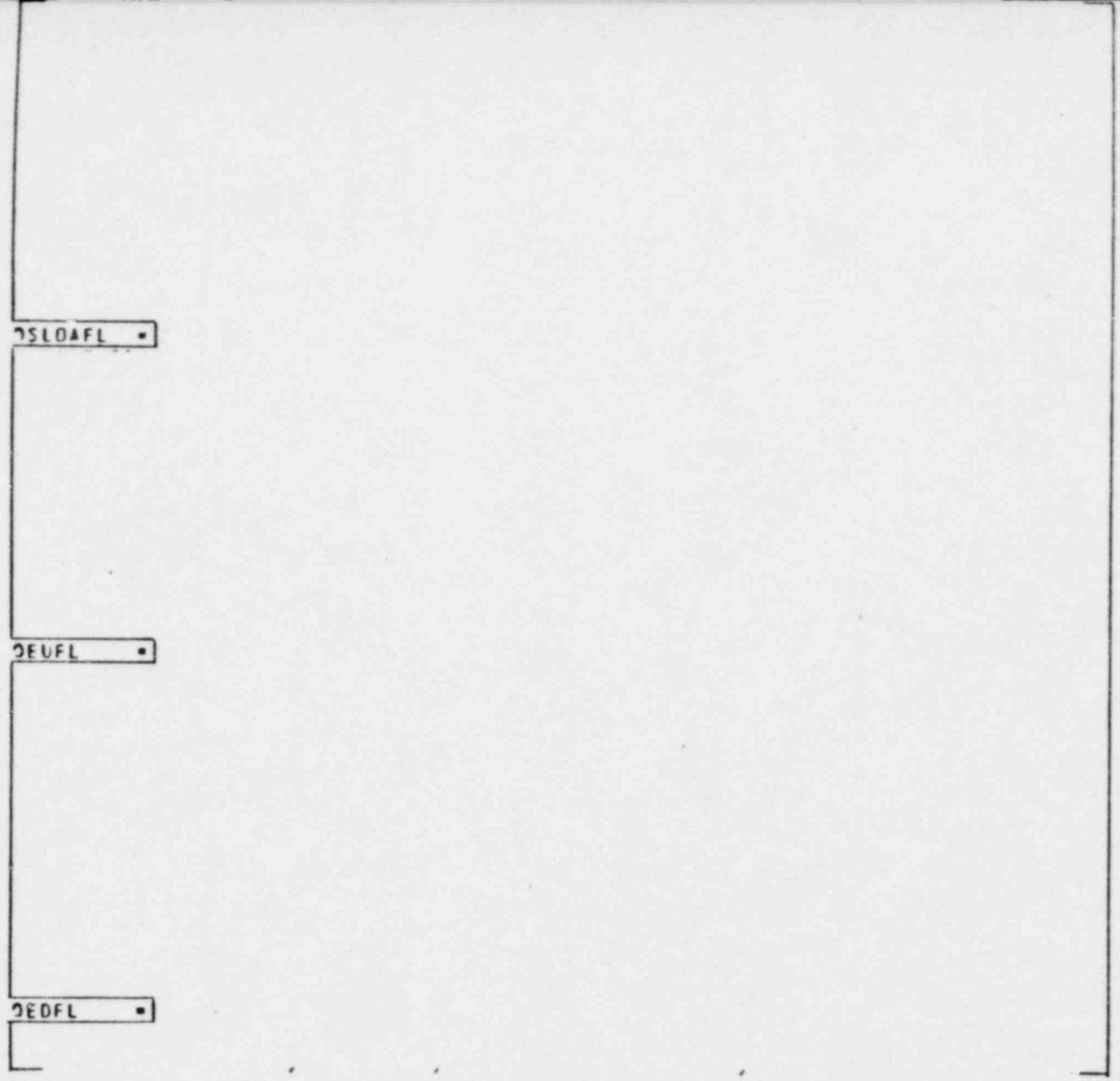
a,c


0$END
1$MNODES
CTTYPEMN *
0IMPMN *
0IMMN *
0TMN *
0$END
1$FLINKS
0ITYPEFL *
0KTFL *
0KSFL *
0KSCFL *

a,c


OIUFL
OIDFL
OAFL
ODEFL
OZFL
a,c

a,c



a,c

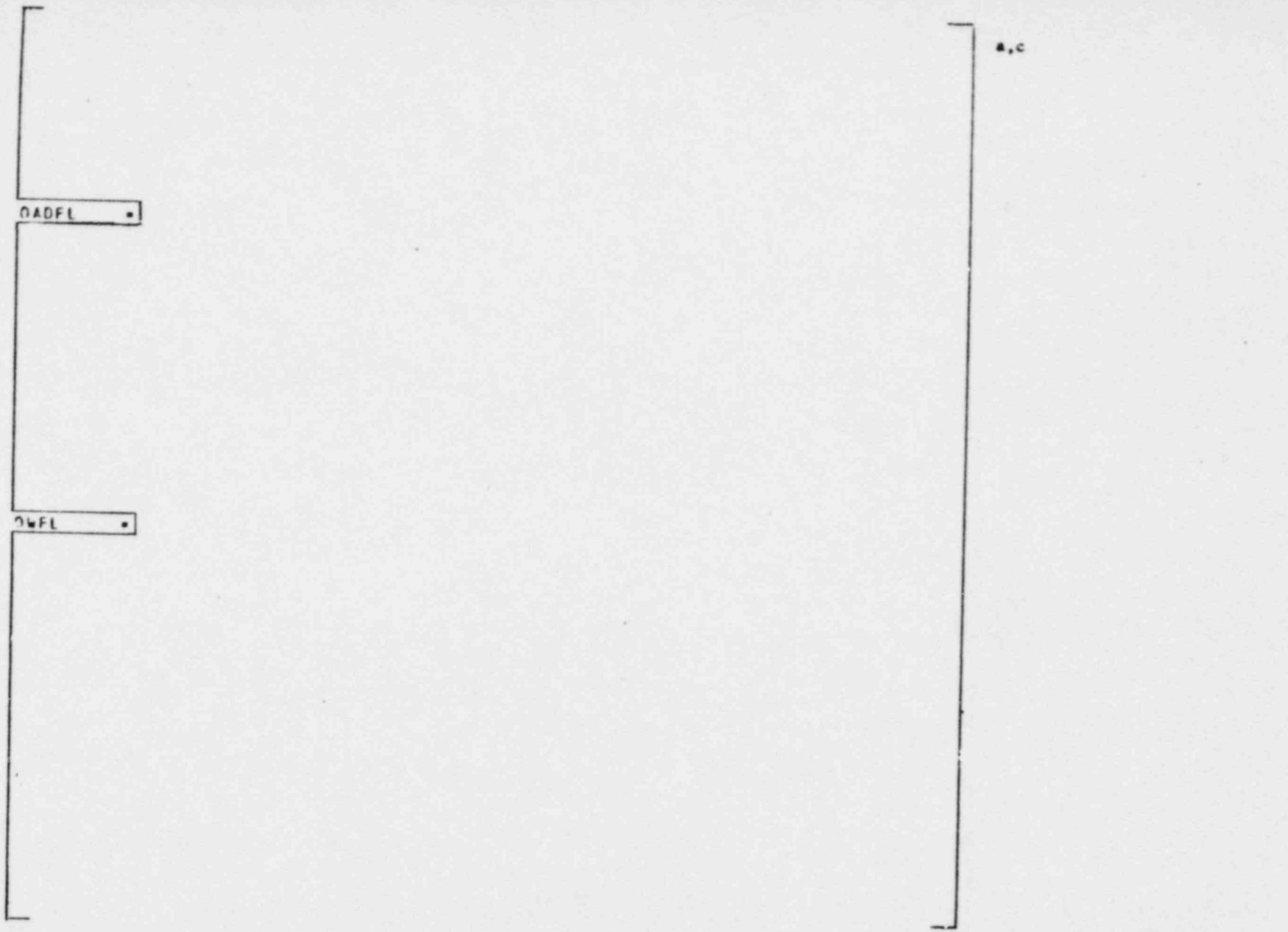
OFLOPFL •

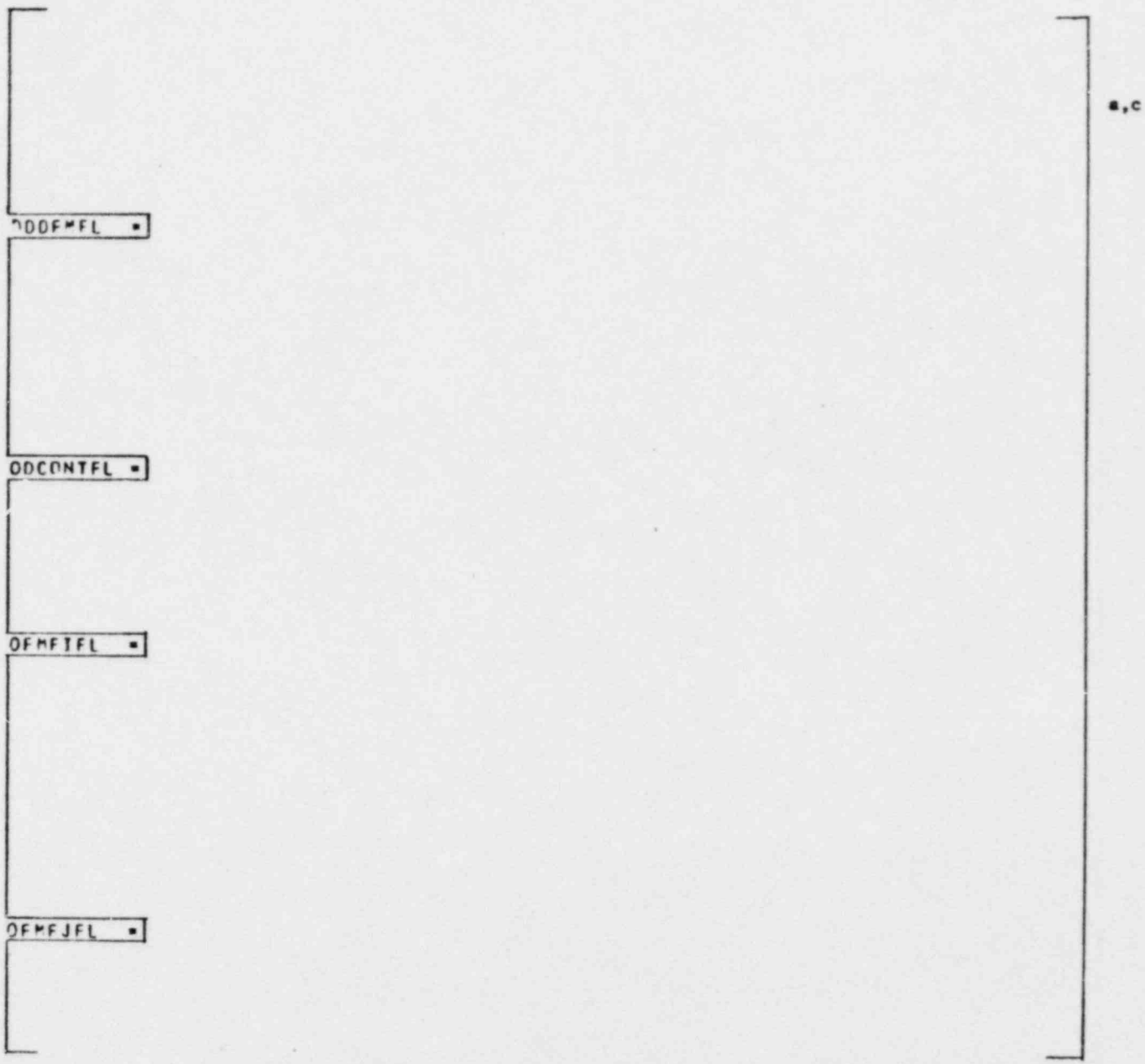
OKDFTFL •

IMOMF•1,
OIUFLFL •

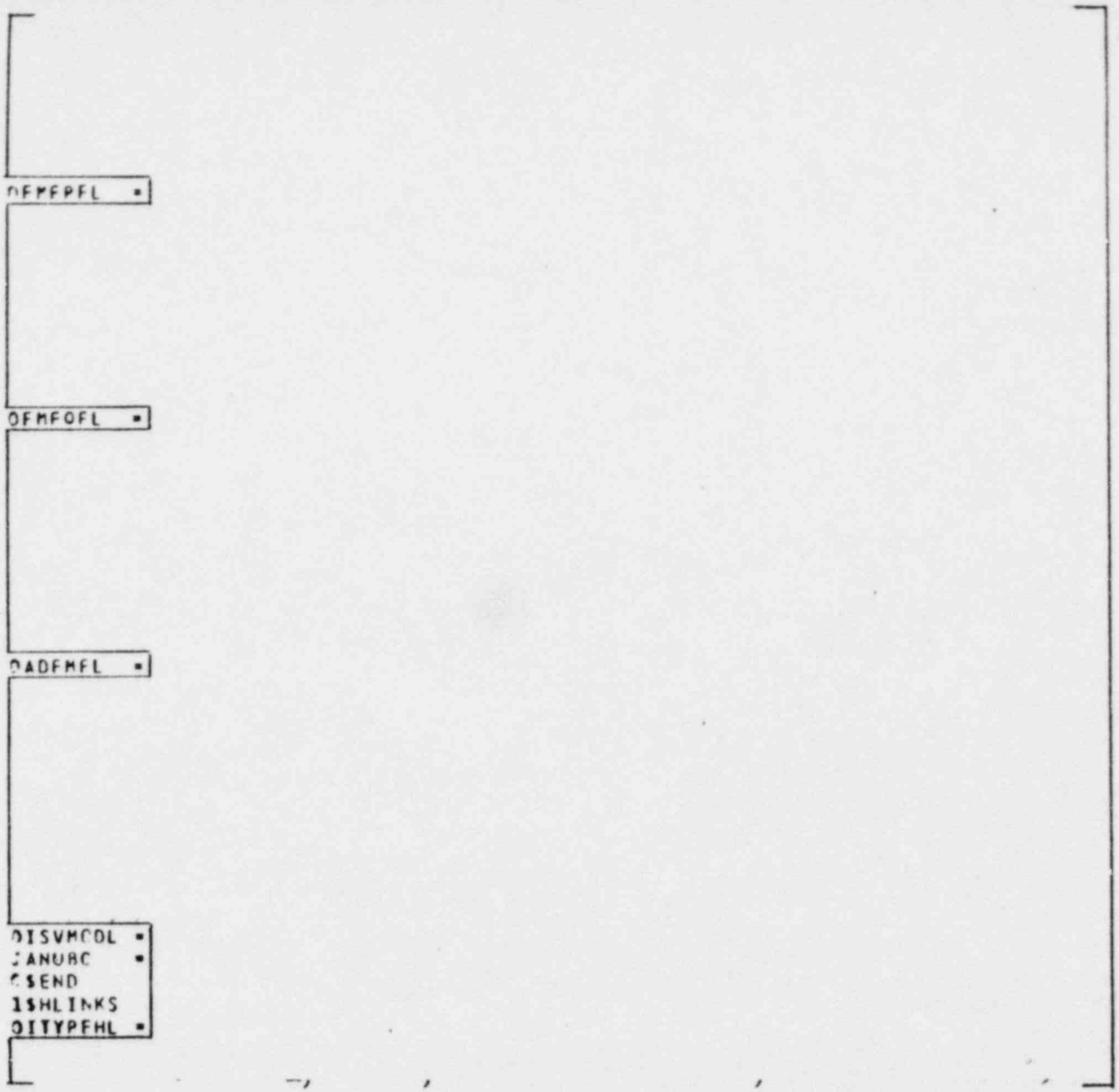
CIOFLFL •

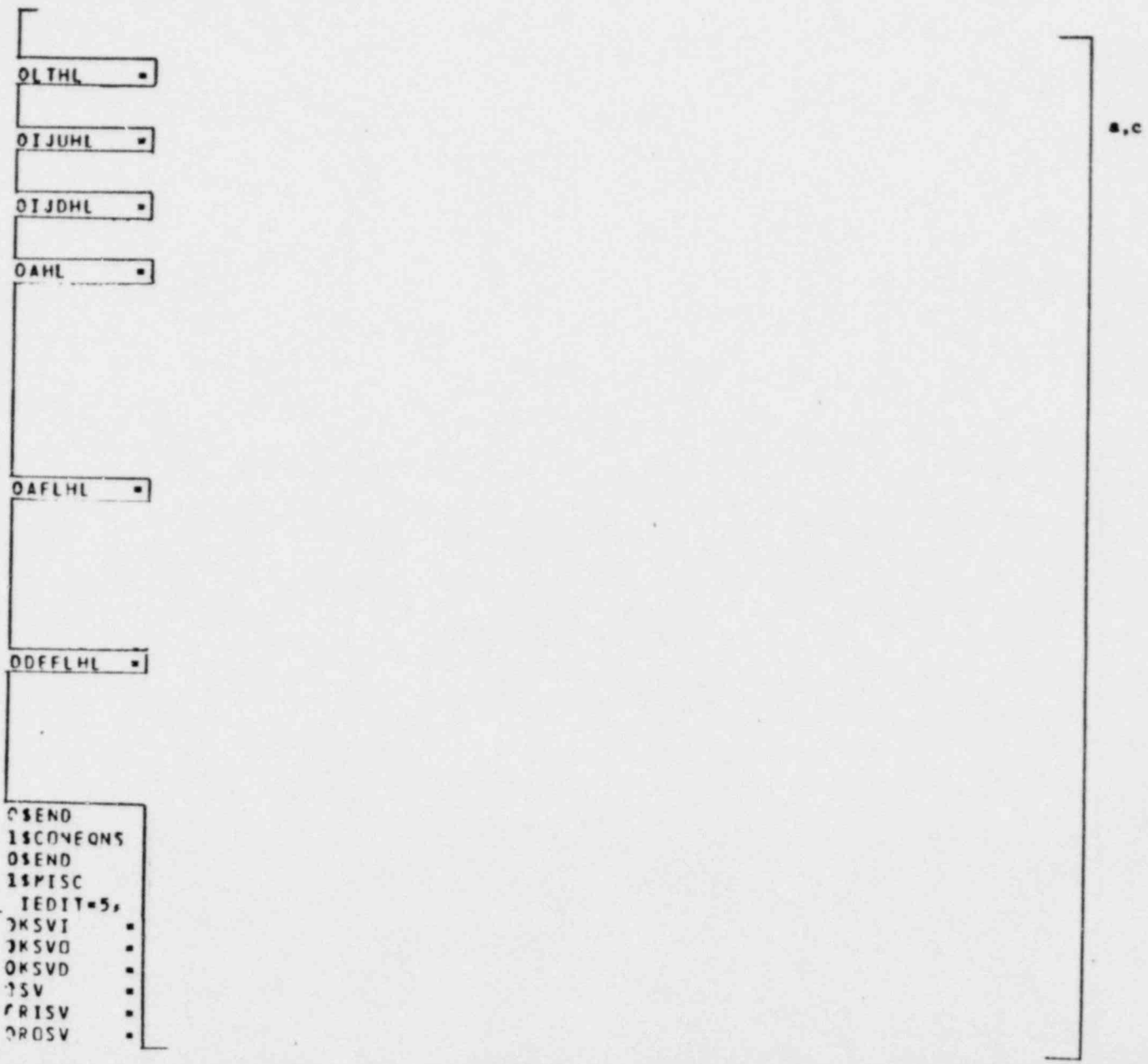
OAUFL •


a,c
DADFL
DWFL



a,c


a,c
DFMFPFL =
DFMFOFL =
DADFMFL =
DISVMODL =
;ANUBC =
CSEND
1$HLINKS
DITYPFHL =


OLTHL
OIJUHL
OIJDHL
OAHL
OAFLHL
ODFFLHL
OSEND
1$CONFONS
OSEND
1$MISC
IEDIT=5,
OKSVI
OKSVO
OKSVD
OSV
ORISV
OROSV
a,c

```
 OTANBSV  =
 OVFCSVD  =
 OKPSD    =
 OVFCPSD  =
 ODITURE  =
 ODMTURE  =
 ODDTURE  =
 OPITURE  =
 OFOULF   =
```

[ ] a,c

```
 OAGTURE  =
 OCOTURE  =
 OANRC    =
```

12-0

```
ODELTMIN = .1E-03,
ODELTMAX = .1[illegible]2E+02,
 NSTEPS=100000,
ONFPRINT = 25,
ONSPRINT = 5[illegible],
OTIPRINT = .5E+01,
OTFPRINT = .1E+01, .1E+02, .2E+02, .3E+02, .4E+02, .5E+02, .6E+02, .7E+02,
 .8E+02, .9E+02, .1E+03, .11E+03, .12E+03,
          .13E+03, .14E+03, .15E+03, .16E+03, .17E+03, .18E+03, .19E+03,
 .2E+03, .21E+03, .22E+03, .23E+03,
          .24E+03,
OTIMEMAX = .302E+02
OPLEV [                ] a,c
```

```
QILEV     .[                ]
QILTLEV   =[                ]
QIUTLEV   =[                ] a,c
QELTLEV   =[                ]
QEUTLEV   =[                ]
QTFRAC    = .35E+00;
)$END
 $TRACES
  NSTRACE = 1,
  NTRACE = 100,
 $END
XLMLEV  01
TMFN    20
TMFN    21
TMFN    22
TMFN    23
TMFN    24
TMFN    25
TMFN    26
TMFN    27
TMFN    28
TMFN    29
TMFN    30
TMFN    31
TMFN    32
TMFN    33
TMFN    34
TMFN    35
TMFN    36
TMFN    37
TMFN    38
TMFN    39
TMFN    40
TMFN    41
TMFN    43
TMFN    44
TMFN    45
TMFN    46
TMFN    51
TMFN    52
TMFN    53
TMFN    54
TMFN    55
TMFN    56
TMFN    57
QHL     21
QHL     22
```

QHL	23
QHL	24
QHL	25
QHL	26
QHL	27
QHL	28
QHL	29
QHL	30
QHL	31
QHL	32
QHL	33
QHL	34
CHL	35
QHL	36
QHL	37
QHL	38
QHL	39
QHL	40
PFN	01
PFN	46
PFN	54
PFN	57
PFN	49
PFN	55
EMIXFN	45
EMIXFN	51
EMIXFN	53
EMIXFN	54
EMIXFN	57
EMIXFN	55
PFN	41
PFN	57
WFL	01
WFL	47
WFL	45
WFL	52
WFL	53
WFL	56
WFL	57
WFL	71
WFL	63
WFL	69
WFL	51
WFL	73
WFL	76
WFL	61
WFL	58

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR PAGE 169
ISTEP = 334 TIME = 30.0000 DELT = 9.90100CE-02 CASE 1

a,c

INTERIOR FLUID NODE	PRESSURE	TEMPERATURE	SPECIFIC ENTHALPY	TOTAL MASS	LIQUID MASS	VAPOR MASS	BUBBLE MASS	TOTAL INTERNAL ENERGY
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
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16								
17								
18								
20								
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30								
31								
32								
33								
34								
35								
36								
37								
38								
39								
40								
41								

INTERIOR FLUID NODE	PRESSURE	TEMPERATURE	SPECIFIC ENTHALPY	TOTAL MASS	LIQUID MASS	VAPOR MASS	BUBBLE MASS	TOTAL INTERNAL ENERGY
43								
44								
45								
46								
47								
49								
51								
52								
53								
54								
55								
56								
57								

a,c

MEASURED LEVEL PERCENT OF SPAN FEET a,c

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR

ISTEP = 334 TIME = 30.0000 DELT = 9.9010C6E-02

INTERIOR FLUID NODE	STATIC QUALITY	VOID FRACTION	SPECIFIC VOLUME	SATURATION TEMPERATURE	LIQUID SPECIFIC VOLUME	VAPOR SPECIFIC VOLUME	LIQUID SPECIFIC ENTHALPY	VAPOR SPECIFIC ENTHALPY
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
20								
21								
22								
23								
24								
25								
26								
27								
28								
29								
30								
31								
32								
33								
34								
35								
36								
37								
38								
39								
40								
41								

a,c

INTERIOR FLUID NODE	STATIC QUALITY	VOID FRACTION	SPECIFIC VOLUME	SATURATION TEMPERATURE	LIQUID SPECIFIC VOLUME	VAPOR SPECIFIC VOLUME	LIQUID SPECIFIC ENTHALPY	VAPOR SPECIFIC ENTHALPY
43								
44								
45								
46								
47								
49								
51								
52								
53								
54								
55								
56								
57								

a,c

0-26

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR PAGE 173
ISTEP = 334 TIME = 30.6003 DELT = 9.9010CCE-02 CASE 1

INTERIOR FLUID NODE	MIXTURE ELEVATION	MIXTURE STATIC QUALITY	MIXTURE VOID FRACTION	MIXTURE SPECIFIC VOLUME	U DOT	M DOT	DELTA U/U	DELTA M/M
1	[							a,c
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
20								
21								
22								
23								
24								
25								
26								
27								
28								
29								
30								
31								
32								
33								
34								
35								
36								
37								
38								
39								
40								
41	]							

INTERIOR FLUID NODE	MIXTURE ELEVATION	MIXTURE STATIC QUALITY	MIXTURE VOID FRACTION	MIXTURE SPECIFIC VOLUME	U DOT	P DOT	DELTA U/U	DELTA M/M a,c
43	[							]
44								
45								
46								
47								
49								
51								
52								
53								
54								
55								
56								
57								

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR PAGE 175
ISTEP = 334 TIME = 30.0[illegible] DELT = 9.901[illegible]OCE-02 CASE 1

INTERIOR
FLUID
NODE DPUFN DPMFN DTUFN DTMFN DTSPFN

NODE	DPUFN	DPMFN	DTUFN	DTMFN	DTSPFN
1					a,c
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
21					
22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37					
38					
39					
4[illegible]					
41					

INTERIOR
FLUID
NODE DPUFN DPMFN DTUFN DTMFN DTSPFN

NODE	DPUFN	DPMFN	DTUFN	DTMFN	DTSPFN
43					
44					
45					
46					
47					
49					
51					
52					
53					
54					
55					
56					
57					

a,c

BOUNDARY FLUID NODE	PRESSURE	TEMPERATURE	SPECIFIC ENTHALPY	
61	[		]	a,c
62	[		]	
63	[		]	

BOUNDARY FLUID NODE	STATIC QUALITY	VOID FRACTION	SPECIFIC VOLUME	SATURATION TEMPERATURE	LIQUID SPECIFIC VOLUME	VAPOR SPECIFIC VOLUME	LIQUID SPECIFIC ENTHALPY	VAPOR SPECIFIC ENTHALPY
61								
62								
63								

a,c

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR

ISTEP = 334 TIME = 37.2000 DELT = 9.9010CE-02 PAGE 179
CASE 1

INTERIOR METAL NODE	TEMPERATURE	MASS TIMES HEAT CAPACITY	T DOT	DELTA T/T
1	[			
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20	]			] a,c

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR

ISTEP = 334 TIME = 3...

DELT = 9.911...E-02

a,c

NON-CRIT FLOW LINK	UP NODE	DOWN NODE	LIQUID MASS FLOW RATE	VAPOR MASS FLOW RATE	TOTAL MASS FLOW RATE	TOTAL ENERGY FLOW RATE	DHWFL	W DOT	MACH NUMBER
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
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22									
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27									
28									
29									
30									
31									
32									
33									
34									
35									
36									
37									
38									
39									
40									
41									

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR

ISTEP = 334 TIME = 30.000 DELT = 9.9010CCE-02

NON-CRIT FLOW LINK	UP NODE	DOWN NODE	LIQUID MASS FLOW RATE	VAPOR MASS FLOW RATE	TOTAL MASS FLOW RATE	TOTAL ENERGY FLOW RATE	DHWFL	W DOT	MACH NUMBER
42									
43									
45									
46									
47									
48									
49									
50									
51									
52									
53									
54									
55									
56									
57									
58									
59									
61									
63									
64									
65									
66									
67									
68									
69									
71									
72									
73									
75									
76									

a,c

D-37

a,c

NON-CRIT FLOW LINK	UP NODE	DOWN NODE	STATIC QUALITY	FLOW QUALITY	VOID FRACTION	SPECIFIC VOLUME	DELTA P FRICTION	DELTA P MOMENTUM FLUX	DELTA P TOTAL
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
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32									
33									
34									
35									
36									
37									
38									
39									
40									
41									

NON-CRIT FLOW LINK	UP NODE	DOWN NODE	STATIC QUALITY	FLOW QUALITY	VOID FRACTION	SPECIFIC VOLUME	DELTA P FRICTION	DELTA P MOMENTUM FLUX	DELTA P TOTAL
42									
43									
45									
46									
47									
48									
49									
50									
51									
52									
53									
54									
55									
56									
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58									
59									
61									
63									
64									
65									
66									
67									
68									
69									
71									
72									
73									
75									
76									

a,c

NON-CRIT FLOW LINK

	CKFL	DKFL	CMFKFL	CMFPFL	CMFQFL	DMFKFL	DMFPFL	DMFQFL
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
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37								
38								
39								
40								
41								

a,c

SAMPLE OUTPUT --- NON-PREHEAT STEAM GENERATOR PAGE 185
ISTEP = 334 TIME = 30.0000 DELT = 9.9713006E-02 CASE 1

NON-CRIT FLOW LINK	CKFL	DKFL	CMFKFL	CMFPFL	CMFQFL	DMFKFL	DMFPFL	DMFQFL
42	[							a,c
43								
45								
46								
47								
48								
49								
51								
51								
52								
53								
54								
55								
56								
57								
58								
59								
61								
63								
64								
65								
66								
67								
68								
69								
71								
72								
73								
75								
76	]							]

NON-CRIT FLOW LINK	RJ1FL	RJ2FL	RVVJ1FL	RVVJ2FL	DVVJ1FL	DVVJ2FL	C**2 DELTA RHO
1	[						a,c
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
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32							
33							
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35							
36							
37							
38							
39							
40							
41	]						

NON-CRIT FLOW LINK	RJ1FL	RJ2FL	RVVJ1FL	RVVJ2FL	DVVJ1FL	DVVJ2FL	C**2 DELTA RHO
42	[						] a,c
43							
45							
46							
47							
48							
49							
50							
51							
52							
53							
54							
55							
56							
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59							
61							
63							
64							
65							
66							
67							
68							
69							
71							
72							
73							
75							
76	]						]

CRITICAL FLOW LINK	UP NODE	DOWN NODE	LIQUID MASS FLOW RATE	VAPOR MASS FLOW RATE	TOTAL MASS FLOW RATE	TOTAL ENERGY FLOW RATE	DHWFL
78	[						] a,c
79							
80							

CRITICAL FLOW LINK	UP NODE	DOWN NODE	STATIC QUALITY	FLOW QUALITY	VOID FRACTION	SPECIFIC VOLUME	
78	[						] a,c
79							
80							

CRITICAL FLOW LINK	DWIFL	DWJFL	DHWIFL	DHWJFL	
78	[				a,c
79					
80				]	

CRITICAL FLOW LINK	RJ1FL	RJ2FL	RVVJ1FL	RVVJ2FL	DVVJ1FL	DVVJ2FL	C**2 DELTA RHO	
78	[							a,c
79								
80	[							

LINK	NON-CRIT HEAT UP NODE	DOWN NODE	DELTA T	HEAT FLUX	TOTAL HEAT RATE	HEAT TRANSFER REGIME	DQTUHL	DCTDHL	DQPUHL	DQPDHL
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
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28										
29										
30										
31										
32										
33										
34										
35										
36										
37										
38										
39										
40										

a,c

ISTEP	TIME	XLMLEV 1	TMFN 20	TMFN 21	TMFN 22	TMFN 23	TMFN 24	TMFN 25	TMFN 26	TMFN 27	TMFN 28
0	0.										
1	4.194304E-04										
2	1.258291E-03										
3	2.936013E-03										
4	6.291456E-03										
5	1.300234E-02										
6	2.684589E-02										
7	5.668943E-02										
8	9.353294E-02										
9	1.237765E-01										
10	1.472201E-01										
11	1.740636E-01										
12	2.199372E-01										
13	2.545943E-01										
14	3.082613E-01										
15	3.351249E-01										
16	3.619884E-01										
17	3.888512E-01										
18	4.155553E-01										
19	4.424991E-01										
20	4.693426E-01										
21	4.961862E-01										
22	5.230297E-01										
23	5.498733E-01										
24	5.767168E-01										
25	6.035604E-01										
26	6.304039E-01										
27	6.572474E-01										
28	6.840910E-01										
29	7.109345E-01										
30	7.377781E-01										
31	7.646216E-01										
32	7.914652E-01										
33	8.183087E-01										
34	8.451523E-01										
35	8.719958E-01										
36	8.988393E-01										
37	9.256829E-01										
38	9.525264E-01										
39	9.793700E-01										

a,c

ISTEP	TIME	XLMLEV 1	TMFN 20	TMFN 21	TMFN 22	TMFN 23	TMFN 24	TMFN 25	TMFN 26	TMFN 27	TMFN 28
320	2.96[illegible]E+01										
321	2.97[illegible]E+01										
322	2.98[illegible]E+01										
323	2.99[illegible]E+01										
324	2.9[illegible]E+01										
325	2.91[illegible]E+01										
326	2.92[illegible]92E+01										
327	2.93[illegible]93E+01										
328	2.94[illegible]94E+01										
329	2.95[illegible]95E+01										
330	2.96[illegible]96E+01										
331	2.97[illegible]97E+01										
332	2.98[illegible]98E+01										
333	2.99[illegible]99E+01										
334	3.[illegible]E+01										
335	3.01[illegible]1E+01										

a,c

APPENDIX E

DETAILED NUMERICAL EQUATIONS AND SOLUTION TECHNIQUE

In this appendix, the structure of the matrix equation, (2-27) is examined and used to advantage in devising an efficient numerical solution technique.

Equation (2-27) may be rewritten as

$$\underline{\underline{A}}\ \underline{x} = \underline{B} \tag{E-1}$$

where

$$\underline{\underline{A}} \equiv \underline{\underline{I}} - \Delta t_{n+1}\ \underline{\underline{dF}}\ (t^n, \underline{y}^n), \tag{E-2}$$

$$\underline{x} \equiv \Delta \underline{y}^{n+1}, \tag{E-3}$$

and

$$\underline{B} \equiv \Delta t_{n+1}\ \underline{F}(t^n, \underline{y}^n). \tag{E-4}$$

$\underline{\underline{A}}$, $\underline{x}$, and $\underline{B}$ will now be partitioned. For convenience, the underlining designating vectors and matrices will be dropped for the partitioned sub-vectors and sub-matrices. Examining the structure of Equations (E-2) - (E-4), it may be seen that Equation (E-1) can be partitioned to give

$$\begin{bmatrix} A_{WW} & A_{WU} & A_{WM} & 0 & A_{WZ} \\ A_{UW} & D_{UU} & D_{UM} & A_{UT} & A_{UZ} \\ A_{MW} & D_{MU} & D_{MM} & 0 & A_{MZ} \\ 0 & A_{TU} & A_{TM} & D_{TT} & A_{TZ} \\ A_{ZW} & A_{ZU} & A_{ZM} & A_{ZT} & A_{ZZ} \end{bmatrix} \cdot \begin{bmatrix} \Delta W \\ \Delta U \\ \Delta M \\ \Delta T \\ \Delta Z \end{bmatrix} = \begin{bmatrix} B_W \\ B_U \\ B_M \\ B_T \\ B_Z \end{bmatrix}. \tag{E-5}$$

ΔW and B_W are column vectors of length K; ΔU, B_U, ΔM, and B_M are of length I; ΔT and B_T are of length J; and ΔZ and B_Z are of length M. The $\underline{\underline{A}}$ matrix has been partitioned consistently with the $\underline{x}$ and $\underline{B}$ column vectors. D denotes a square diagonal matrix with no zero elements on the diagonal whereas D denotes a square diagonal matrix where some of the diagonal elements may be zero.

The simple nature of the D_{UU}, D_{UM}, D_{MU}, and D_{MM} sub-matrices allows for the elimination of ΔU and ΔM from Equation (E-5). This reduces the matrix equation to be solved from order K+2I+J+M to order K+J+M. To effect the elimination of ΔU and ΔM, note that

$$\begin{bmatrix} D_{UU} & D_{UM} \\ D_{MU} & D_{MM} \end{bmatrix} \cdot \begin{bmatrix} \Delta U \\ \Delta M \end{bmatrix} = \begin{bmatrix} B_U - A_{UW}\Delta W - A_{UT}\Delta T - A_{UZ}\Delta Z \\ B_M - A_{MW}\Delta W \qquad\qquad - A_{MZ}\Delta Z \end{bmatrix}. \tag{E-6}$$

Therefore, using Cramer's Rule, ΔU and ΔM are

$$\begin{aligned} \Delta U = {} & [\ \mathrm{Det}^{-1}\ D_{MM}\ B_U - \mathrm{Det}^{-1}\ D_{UM}\ B_M\ ] \\ & + [-\mathrm{Det}^{-1}\ D_{MM}\ A_{UW} + \mathrm{Det}^{-1}\ D_{UM}\ A_{MW}]\ \Delta W \\ & + [-\mathrm{Det}^{-1}\ D_{MM}\ A_{UT}\ ]\ \Delta T \\ & + [-\mathrm{Det}^{-1}\ D_{MM}\ A_{UZ} + \mathrm{Det}^{-1}\ D_{UM}\ A_{MZ}]\ \Delta Z \end{aligned} \tag{E-7}$$

and

$$\begin{aligned} \Delta M = {} & [-\mathrm{Det}^{-1}\ D_{MU}\ B_U + \mathrm{Det}^{-1}\ D_{UU}\ B_M\ ] \\ & + [\ \mathrm{Det}^{-1}\ D_{MU}\ A_{UW} - \mathrm{Det}^{-1}\ A_{MW}]\ \Delta W \\ & + [\ \mathrm{Det}^{-1}\ D_{MU}\ A_{UT}\ ]\ \Delta T \\ & + [\ \mathrm{Det}^{-1}\ D_{MU}\ A_{UZ} - \mathrm{Det}^{-1}\ D_{UU}\ A_{MZ}]\ \Delta Z \end{aligned} \tag{E-8}$$

where

$$\mathrm{Det} = D_{UU}\ D_{MM} - D_{UM}\ D_{MU}. \tag{E-9}$$

Det is a diagonal non-singular matrix. Therefore, Det^{-1} is easily calculated. This is the reason that the simple nature of D_{UU}, D_{UM}, D_{MU} and D_{MM} is so important.

Equations (E-7) and (E-8) are now used in Equation (E-5) to eliminate ΔU and ΔM, giving

$$\begin{bmatrix} A^{*}_{WW} & A^{*}_{WT} & A^{*}_{WZ} \\ A^{*}_{TW} & A^{*}_{TT} & A^{*}_{TZ} \\ A^{*}_{ZW} & A^{*}_{ZT} & A^{*}_{ZZ} \end{bmatrix} \cdot \begin{bmatrix} \Delta W \\ \Delta T \\ \Delta Z \end{bmatrix} = \begin{bmatrix} B^{*}_{W} \\ B^{*}_{T} \\ B^{*}_{Z} \end{bmatrix} \qquad \text{(E-10)}$$

where

$$A^{*}_{WW} \equiv A_{WW} + A_{WU} \left[-Det^{-1} D_{MM} A_{UW} + Det^{-1} D_{UM} A_{MW}\right] + A_{WM} \left[Det^{-1} D_{MU} A_{UW} - Det^{-1} D_{UU} A_{MW}\right], \qquad \text{(E-11)}$$

[a,c

]

a,c [ ]

$$B_W^* \equiv B_W - A_{WU} \left[\text{Det}^{-1} D_{MM} B_U - \text{Det}^{-1} D_{UM} B_M \right] - A_{WM} \left[-\text{Det}^{-1} D_{MU} B_U + \text{Det}^{-1} D_{UU} B_M \right], \quad \text{(E-20)}$$

a,c [ ]

Equation (E-10) is a matrix equation of order K+J+M.

a,c [ ]

The structure of the pertinent sub-matrices will now be examined. Appropriate intermediate variables will be defined and used to generate Equation (E-23) in a natural and efficient manner.

Upon examination, it is seen that the elements of the sub-matrices are

$$(A_{WW})_{k,\nu} = \delta_{k,\nu} - \Delta t_{n+1} \frac{\partial F_k}{\partial W_\nu} , \tag{E-24}$$

$$(A_{WU})_{k,i} = -\Delta t_{n+1} \frac{\partial F_k}{\partial U_i} , \tag{E-25}$$

$$(A_{WM})_{k,i} = -\Delta t_{n+1} \frac{\partial F_k}{\partial M_i} , \tag{E-26}$$

$$(A_{UW})_{i,k} = [\delta_{i,u(k)} - \delta_{i,d(k)}] \Delta t_{n+1} \frac{\partial (hW)_k}{\partial W_k} , \tag{E-27}$$

$$(D_{UU})_{i,i} = 1 + \Delta t_{n+1} [\frac{\partial HG}{\partial U_i} + \frac{\partial Q}{\partial U_i}], \tag{E-28}$$

$$(D_{UM})_{i,i} = \Delta t_{n+1} [\frac{\partial HG}{\partial M_i} + \frac{\partial Q}{\partial M_i}], \tag{E-29}$$

$$(A_{UT})_{i,\ell} = -\Delta t_{n+1} (\frac{\partial Q}{\partial T_\ell})_i , \tag{E-30}$$

$$(A_{MW})_{i,k} = [\delta_{i,u(k)} - \delta_{i,d(k)}] \Delta t_{n+1} , \tag{E-31}$$

$$(D_{MU})_{i,i} = \Delta t_{n+1} \frac{\partial G}{\partial U_i} \tag{E-32}$$

$$(D_{MM})_{i,i} = 1 + \Delta t_{n+1} \frac{\partial G}{\partial M_i} , \tag{E-33}$$

[ ] a,c

where

$$\frac{\partial HG}{\partial U_i} \equiv \frac{\partial P_i}{\partial U_i}\left(\sum_{\substack{\nu \in I_i^W \\ \nu > K}} \frac{\partial (hW)_\nu}{\partial P_i} - \sum_{\substack{\nu \in T_i^W \\ \nu > K}} \frac{\partial (hW)_\nu}{\partial P_i}\right), \tag{E-37}$$

$$\frac{\partial HG}{\partial M_i} \equiv \frac{\partial P_i}{\partial M_i}\left(\sum_{\substack{\nu \in I_i^W \\ \nu > K}} \frac{\partial (hW)_\nu}{\partial P_i} - \sum_{\substack{\nu \in T_i^W \\ \nu > K}} \frac{\partial (hW)_\nu}{\partial P_i}\right), \tag{E-38}$$

$$\frac{\partial Q}{\partial U_i} \equiv \frac{\partial T_i}{\partial U_i}\left(\sum_{\substack{\nu \in I_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial T_i} - \sum_{\substack{\nu \in T_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial T_i}\right),$$

$$+ \frac{\partial P_i}{\partial U_i}\left(\sum_{\substack{\nu \in I_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial P_i} - \sum_{\substack{\nu \in T_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial P_i}\right), \tag{E-39}$$

$$\frac{\partial Q}{\partial M_i} \equiv \frac{\partial T_i}{\partial M_i}\left(\sum_{\substack{\nu \in I_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial T_i} - \sum_{\substack{\nu \in T_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial T_i}\right),$$

$$+ \frac{\partial P_i}{\partial M_i}\left(\sum_{\substack{\nu \in I_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial T_i} - \sum_{\substack{\nu \in T_i^Q \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial P_i}\right), \tag{E-40}$$

[ ] a,c

$$\frac{\partial G}{\partial U_i} \equiv \frac{\partial P_i}{\partial U_i}\left(\sum_{\substack{\nu \epsilon I_i \\ \nu > K}}^{w} \frac{\partial W_\nu}{\partial P_i} - \sum_{\substack{\nu \epsilon T_i \\ \nu > K}}^{w} \frac{\partial W_\nu}{\partial P_i}\right), \tag{E-42}$$

$$\frac{\partial G}{\partial M_i} \equiv \frac{\partial P_i}{\partial M_i}\left(\sum_{\substack{\nu \epsilon I_i \\ \nu > K}}^{w} \frac{\partial W_\nu}{\partial P_i} - \sum_{\substack{\nu \epsilon T_i \\ \nu > K}}^{w} \frac{\partial W_\nu}{\partial P_i}\right), \tag{E-43}$$

$$\begin{aligned}\left(\frac{\partial Q}{\partial U_i}\right)_\ell \equiv \frac{\partial T_i}{\partial U_i}\Bigg(&\sum_{\substack{\nu \epsilon I_{i_Q} \\ \nu \epsilon T_\ell \\ \nu \le L}}^{Q} \frac{\partial Q_\nu}{\partial T_i} - \sum_{\substack{\nu \epsilon T_{i_Q} \\ \nu \epsilon I_\ell \\ \nu \le L}}^{Q} \frac{\partial Q_\nu}{\partial T_i}\Bigg) \\ + \frac{\partial P_i}{\partial U_i}\Bigg(&\sum_{\substack{\nu \epsilon I_{i_Q} \\ \nu \epsilon T_\ell \\ \nu \le L}}^{Q} \frac{\partial Q_\nu}{\partial P_i} - \sum_{\substack{\nu \epsilon T_{i_Q} \\ \nu \epsilon I_\ell \\ \nu \le L}}^{Q} \frac{\partial Q_\nu}{\partial P_i}\Bigg),\end{aligned} \tag{E-44}$$

$$\left(\frac{\partial Q}{\partial M_i}\right)_\ell \equiv \frac{\partial T_i}{\partial M_i}\Bigg(\sum_{\substack{\nu \epsilon I_{i_Q} \\ \nu \epsilon T_\ell \\ \nu \le L}}^{Q} \frac{\partial Q_\nu}{\partial T_i} - \sum_{\substack{\nu \epsilon T_{i_Q} \\ \nu \epsilon I_\ell \\ \nu \le L}}^{Q} \frac{\partial Q_\nu}{\partial T_i}\Bigg) \tag{E-45}$$

$$+ \frac{\partial P_i}{\partial M_i} \left(\sum_{\substack{Q \\ \nu \epsilon I_{i_Q} \\ \nu \epsilon T_\ell \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial P_i} - \sum_{\substack{Q \\ \nu \epsilon T_{i_Q} \\ \nu \epsilon I_\ell \\ \nu \leq L}} \frac{\partial Q_\nu}{\partial P_i} \right),$$

and

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$\delta_{i,j}$ is the Kronecker delta. The notations u(k) and d(k) signify the upstream and downstream fluid node, respectively, for flow link k.

Defining

$$D_i \equiv \text{Det} = D_{MM} D_{UU} - D_{MU} D_{UM}$$

$$= (1 + \Delta t_{n+1} \frac{\partial G}{\partial M_i}) (1 + \Delta t_{n+1} [\frac{\partial HG}{\partial U_i} + \frac{\partial Q}{\partial U_i}]) \qquad \text{(E-47)}$$

$$- (\Delta t_{n+1})^2 \frac{\partial G}{\partial U_i} [\frac{\partial HG}{\partial U_i} + \frac{\partial Q}{\partial M_i}],$$

$$\alpha_{1i} \equiv -\text{Det}^{-1} D_{UM}$$

$$= - \frac{\Delta t_{n+1}}{D_i} [\frac{\partial HG}{\partial M_i} + \frac{\partial Q}{\partial M_i}], \qquad \text{(E-48)}$$

$$\beta_{1i} \equiv \text{Det}^{-1} D_{MM}$$

$$= \frac{1}{D_i} (1 + \Delta t_{n+1} \frac{\partial G}{\partial M_i}), \qquad \text{(E-49)}$$

$$\gamma_{1i} \equiv \frac{1}{\Delta t_{n+1}} \left[Det^{-1} D_{MM} B_U - Det^{-1} D_{UM} B_M \right]$$

$$= \beta_{1i} F_{K+i} + \alpha_{1i} F_{K+N+i} , \qquad \text{(E-50)}$$

$$\alpha_{2i} \equiv Det^{-1} D_{UU}$$

$$= \frac{1}{D_i} \left(1 + \Delta t_{n+1} \left[\frac{\partial HG}{\partial U_i} + \frac{\partial Q}{\partial U_i}\right]\right) , \qquad \text{(E-51)}$$

$$\beta_{2i} \equiv -Det^{-1} D_{MU}$$

$$= - \frac{\Delta t_{n+1}}{D_i} \frac{\partial G}{\partial U_i} , \qquad \text{(E-52)}$$

and

$$\gamma_{2i} \equiv \frac{1}{\Delta t_{n+1}} \left[Det^{-1} D_{UU} B_M - Det^{-1} D_{MU} B_U \right]$$

$$= \alpha_{2i} F_{K+N+i} + \beta_{2i} F_{K+i} , \qquad \text{(E-53)}$$

the following expressions are obtained for the elements of Equation (E-23):

$$(A^*_{WW})_{k,\kappa} = A^*_{k,\kappa}$$

$$\equiv \delta_{k,\kappa} - \Delta t_{n+1} \frac{\partial F_k}{\partial W_\kappa}$$

$$- (\Delta t_{n+1})^2 \{ [\delta_{u(k),d(\kappa)} - \delta_{u(k),u(\kappa)}] \qquad \text{(E-54)}$$

$$\cdot \left[\frac{\partial F_k}{\partial U_{u(k)}} (\alpha_{1u(k)} + \beta_{1u(k)} \frac{\partial (hW)_\kappa}{\partial W_\kappa} + \frac{\partial F_k}{\partial M_{u(k)}} (\alpha_{2u(k)} + \beta_{2u(k)} \frac{\partial (hW)_\kappa}{\partial W_\kappa})\right]$$

$$+ [\delta_{d(k),d(\kappa)} - \delta_{d(k),n(\kappa)}]$$

$$\cdot \left[\frac{\partial F_k}{\partial U_{d(k)}} \left(\alpha_{1d(k)} + \beta_{1d(k)} \frac{\partial (hW)_\kappa}{\partial W_\kappa}\right) + \frac{\partial F_k}{\partial M_{d(k)}} \left(\alpha_{2d(k)} + \beta_{2d(k)} \frac{\partial (hW)_\kappa}{\partial W_\kappa}\right)\right] \} ;$$

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$$(B_w^*)_k = b_k^*$$

$$\equiv \Delta t_{n+1} F_k \qquad \text{(E-58)}$$

$$+ (\Delta t_{n+1})^2 \left[\frac{\partial F_k}{\partial U_{u(k)}} \gamma_{1u(k)} + \frac{\partial F_k}{\partial M_{u(k)}} \gamma_{2u(k)} + \frac{\partial F_k}{\partial M_{d(k)}} \gamma_{1d(k)}\right.$$

$$\left. + \frac{\partial F_k}{\partial M_{d(k)}} \gamma_{2d(k)}\right] ;$$

and

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] Equations (E-7) and (E-8) can be written (using the above definitions and the fact that [the controller equations are treated] a,c

[ ] as: a,c

$$\Delta U_i^{n+1} = \Delta t_{n+1} \left[\gamma_{1i} + \sum_{\substack{\nu \in T_i^W \\ \nu \le K}} \left(\alpha_{1i} + \beta_{1i} \frac{\partial (hW)_\nu}{\partial W_\nu} \right) \Delta W_\nu^{n+1} \right.$$

$$- \sum_{\substack{\nu \in I_i^W \\ \nu \le K}} \left(\alpha_{1i} + \beta_{1i} \frac{\partial (hW)_\nu}{\partial W_\nu} \right) \Delta W_\nu^{n+1} \qquad \text{(E-60)}$$

$$\left. + \beta_{1i} \sum_{\ell=1}^{J} \left(\frac{\partial Q}{\partial T_\ell} \right)_i \Delta T_\ell^{n+1} \right]$$

and

$$\Delta M_i^{n+1} = \Delta t_{n+1} \left[\gamma_{2i} + \sum_{\substack{\nu \in T_i^W \\ \nu \le K}} \left(\alpha_{2i} + \beta_{2i} \frac{\partial (hW)_\nu}{\partial W_\nu} \right) \Delta W_\nu^{n+1} \right.$$

$$- \sum_{\substack{\nu \in I_i^W \\ \nu \le K}} \left(\alpha_{2i} + \beta_{2i} \frac{\partial (hW)_\nu}{\partial W_\nu} \right) \Delta W_\nu^{n+1} \qquad \text{(E-61)}$$

$$\left. + \beta_{2i} \sum_{\ell=1}^{J} \left(\frac{\partial Q}{\partial T_\ell} \right)_i \Delta T_\ell^{n+1} \right] .$$

a,c After solving the matrix equation [ ] Equations (E-60) and (E-61) are used to obtain ΔU^{n+1} and ΔM^{n+1}.

In general, the solution of the reduced system, Equation (E-23), must be accomplished by Gaussian elimination. It is not uncommon, however, for flow networks to possess one or more subnetworks called chains. In this case, it is usually more efficient to perform the elimination by blocks since the blocks of A^*_{WW} corresponding to the chains assume the tridiagonal form.

Formally, a subnetwork of implicit non-critical flow links connecting fluid nodes i and j, $i \neq j$, is defined to be a chain of length p if it contains exactly $p + 1$ fluid nodes (including fluid nodes i and j) and if any node $\ell \neq i,j$ is an implicit interior fluid node such that $T_\ell^W \cup I_\ell^W$ contains exactly two implicit non-critical flow links. Two chains are said to be disjoint if they share no common implicit interior fluid nodes. If the flow links of a given chain are consecutively labeled, then the principal submatrix of A^*_{WW} corresponding to that chain will be tridiagonal. Moreover, submatrices corresponding to disjoint chains are themselves disjoint.

Suppose now that the network contains s disjoint chains of lengths $p_1,\ldots p_s$ and let

$$q = K + J - \sum_{i=1}^{s} p_i \,. \tag{E-62}$$

If the flow links of each chain are consecutively labeled, then A^* can be made to assume the form,

$$\begin{bmatrix} D_1 & & & R_1 \\ & D_2 & & R_2 \\ & & \ddots & \vdots \\ & & D_s & R_s \\ B_1 & B_2 & B_s & V \end{bmatrix}$$

where D_i is a $p_i \times p_i$ tridiagonal matrix, and V is a $q \times q$ matrix. By compatibly partitioning the vectors W^{n+1}, T^{n+1}, and B^*, Equation (E-23) may be written as:

$$\begin{bmatrix} D_1 & & & R_1 \\ & D_2 & & R_2 \\ & & \ddots & \vdots \\ & & D_s & R_s \\ B_1 & B_2 & & B_s \quad V \end{bmatrix} \cdot \begin{bmatrix} \Delta\omega_1 \\ \Delta\omega_2 \\ \vdots \\ \Delta\omega_s \\ \Delta\omega_{s+1} \end{bmatrix} = \begin{bmatrix} \zeta_1 \\ \zeta_2 \\ \vdots \\ \zeta_s \\ \zeta_{s+1} \end{bmatrix} \tag{E-63}$$

which is equivalent to the equations

$$D_i \Delta\omega_i + R_i \Delta\omega_{s+1} = \zeta_i, \qquad i = 1, \ldots, s, \tag{E-64}$$

$$\sum_{i=1}^{s} B_i \Delta\omega_i + V\Delta\omega_{s+1} = \zeta_{s+1} . \tag{E-65}$$

If each D_i is nonsingular, it follows that

$$\Delta\omega_i = D_i^{-1} \zeta_i - D_i^{-1} R_i \Delta\omega_{s+1}, \quad i = 1, \ldots, s. \tag{E-66}$$

Using Equation (E-66) in Equation (E-65) gives

$$[V - \sum_{i=1}^{s} B_i D_i^{-1} R_i] \Delta\omega_{s+1} = \zeta_{s+1} - \sum_{i=1}^{s} B_i D_i^{-1} \zeta_i. \tag{E-67}$$

The q x q system, Equation (E-67), may now be solved for $\Delta\omega_{s+1}$ and the remainder of the solution recovered by back substitution in Equation (E-66).

Let #BE and #GE denote, respectively, the total number of multiplications and divisions required to solve Equation (E-63) by block and Gaussian elimination. It has been shown[1] that

$$\#BE = q^3/3 + (2s-3)\ q^2 + (4(K+J) - 7\tfrac{1}{3})\ q + 7(K+J) - 6s \qquad \text{(E-68)}$$

and

$$\#GE = (K+J)^3/3 + (K+J)^2 - (K+J)/3. \qquad \text{(E-69)}$$

It can therefore be seen that block elimination has an advantage over direct Gaussian elimination for a network containing significant chains, (i.e. $q << K+J$). NOTRUMP has the capability to decide, based on Equations (E-68) and (E-69), which method to use.

It should be pointed out that the preceding description assumes that all equations for interior fluid nodes, non-critical flow links, and interior metal nodes are solved implicitly. If certain nodes or links are treated explicitly, certain simplications results and are used. One final point of clarification is necessary. While we speak of implicit and explicit nodes and links, we should speak of which unknowns are included in the implicit linearization. If an interior fluid node, non-critical flow link, or interior metal node is "implicit", all equations are linearized with respect to U and M, W, or T, respectively. If an interior fluid node, non-critical flow link, or interior metal node is "explicit", none of the equations are linearized with respect to the associated unknowns.

APPENDIX F

POINT AND CONTINUOUS CONTACT FLOW LINK MODELS

In this appendix, the concepts of point and continuous contact flow links are introduced. Their effect on the flow composition in the flow links is discussed.

The void fraction at each end of a flow link is needed for the various calculations of flow composition in the flow link. These quantities are defined by the void fraction in the fluid nodes connected by the flow link at the locations of contact between the link and the nodes.

In the simpler of the two models, the point contact flow link model, the void fraction α^s_{fl} at a given end of a flow link can have one of two values depending on the relative values of the appropriate nodal mixture elevation E_{mix} and flow link elevation E_{fl}.

$$\alpha^s_{fl} = \begin{cases} \alpha^s_{mix} & \text{if } E_{mix} \geq E_{fl}. \\ 1 & \text{if } E_{mix} < E_{fl}. \end{cases} \qquad \text{(F-1)}$$

α^s_{mix} is the void fraction in the fluid node mixture.

In the continuous contact flow link model, the flow link is assumed to be [a,c

] Then the void fraction α^s_{fl} at a given end of a flow link is given by

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It should be noted that the point contact model permits the void fraction and static quality to change discontinuously as the mixture elevation crosses the flow link elevation. The continuous contact model eliminates this discontinuity. Care should be taken in deciding which model to use for a given physical situation. If one is modelling a situation where the flow is primarily horizontal the continuous contact model may be appropriate, particularly if the flow area is large with respect to the height of a fluid node. On the other hand, for vertical flow links the continuous contact model is not appropriate and for small flow area horizontal links it is probably not necessary.

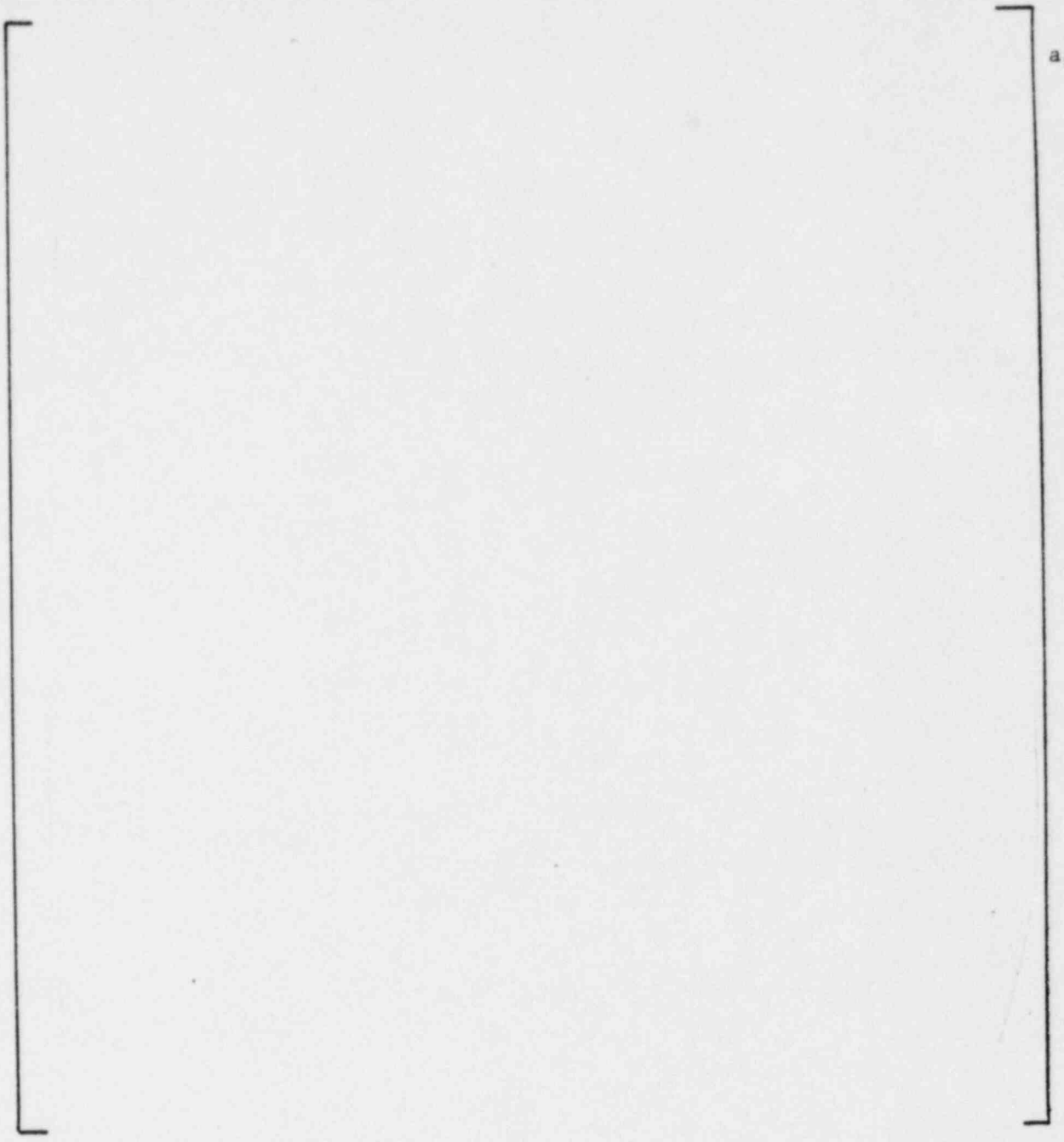

FIGURE F-1. Continuous Contact Flow Link

APPENDIX G

DRIFT FLUX MODEL

The purpose of this appendix is to describe how drift flux models are used in NOTRUMP. These models relate the individual component volumetric fluxes to the total volumetric flux and the void fraction. The energy conservation equation for each interior fluid node is affected through the enthalpy convection terms which account for the enthalpy convection of the two components separately. The mass equation is unaffected since the drift flux model does not change the net mass flow rate in a flow link; it merely gives individual component flow rates which sum to the net mass flow rate. The momentum equation is affected through the momentum flux terms and through the use of the void fraction in calculating frictional and gravitational terms.

The general drift flux model is introduced and the important drift flux relations are given. Specific drift flux models are then described, correlations for the drift velocity and distribution parameter are introduced, and appropriate solution techniques are developed.

The drift flux model is described extensively by Wallis.[14] It is essentially a separated flow model in which attention is focused on the relative motion rather than on the motion of the individual phases. Although the theory can be developed in a way which is quite general, it is particularly useful if the relative motion is determined by a few key parameters and is independent of the flow rate of each phase.

Drift velocities are defined as the difference between the component velocities and the average as follows:

$$V_{gj} = V_g - j, \tag{G-1}$$

$$V_{fj} = V_f - j \tag{G-2}$$

where j is the total volumetric flux, i.e., volumetric flow per unit area.

The drift flux represents the volumetric flux of a component relative to a surface moving at the average velocity, i.e.,

$$j_{gf} = \alpha(V_g - j) = \alpha V_{gj}, \tag{G-3}$$

$$j_{fg} = (1 - \alpha)(V_f - j) = (1 - \alpha)V_{fj}. \tag{G-4}$$

Using

$$j = j_f + j_g \tag{G-5}$$

in Equation (G-3) and using

$$j_g = \alpha V_g, \tag{G-6}$$

we obtain

$$j_{gf} = j_g - \alpha(j_f + j_g) = (1 - \alpha)\, j_g - \alpha j_f. \tag{G-7}$$

Similarly, using

$$j_f = (1 - \alpha)\, V_f \tag{G-8}$$

we obtain

$$j_{fg} = j_f - (1 - \alpha)(j_f + j_g) = j_f\alpha - (1 - \alpha)\, j_g \qquad \text{(G-9)}$$

Therefore

$$j_{gf} = -j_{fg}. \qquad \text{(G-10)}$$

This symmetry is an important and useful property of the drift flux. Substituting for j_f and j_g in Equation (G-9) by using Equations (G-8) and (G-6), we get

$$j_{fg} = \alpha(1 - \alpha)(V_f - V_g). \qquad \text{(G-11)}$$

Therefore, the drift flux is proportional to the relative velocity.

Using Equation (G-5), Equation (G-7) can be expressed in the alternative forms

$$j_f = (1 - \alpha)j - j_{gf}, \qquad \text{(G-12)}$$

$$j_g = \alpha j + j_{gf}. \qquad \text{(G-13)}$$

Using (G-3), we obtain

$$j_f = (1 - \alpha)j - \alpha V_{gj}, \qquad \text{(G-14)}$$

$$j_g = \alpha\,(j + V_{gj}). \qquad \text{(G-15)}$$

Thus far we have not taken into account variations in concentration and velocity across the cross section of the flow link. We shall not derive the equations here but simply state that for these variations, Equations (G-14) and (G-15) become

$$\langle j_f \rangle = (1 - \langle \alpha \rangle C_o)\langle j \rangle - \langle \alpha \rangle \langle\langle V_{gj} \rangle\rangle \tag{G-16}$$

$$\langle j_g \rangle = \langle \alpha \rangle (C_o \langle j \rangle + \langle\langle V_{gj} \rangle\rangle) \tag{G-17}$$

where the distribution parameter C_o is defined by

$$C_o = \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle} \tag{G-18}$$

and the weighted mean drift velocity by

$$\langle\langle V_{gj} \rangle\rangle = \frac{\langle \alpha V_{gj} \rangle}{\langle \alpha \rangle} = \frac{j_{gf}}{\langle \alpha \rangle} \ . \tag{G-19}$$

$\langle\langle V_{gj} \rangle\rangle$ accounts for drift and C_o accounts for slip in the drift flux models.

The $\langle\rangle$'s denote averages over the cross section defined by the equation

$$\langle x \rangle \quad \frac{\int x dA}{A} \ . \tag{G-20}$$

From Equations (G-18) and (G-19), we see that

$$\lim_{\langle \alpha \rangle \to 1} C_o = 1 \tag{G-21}$$

and

$$\lim_{\langle \alpha \rangle \to 1} \langle\langle V_{gj} \rangle\rangle = 0. \tag{G-22}$$

Equations (G-16) and (G-17) relate the volumetric fluxes of each component to the total volumetric flux and the void fraction. In order to use the drift flux model in NOTRUMP, we must relate the volumetric fluxes of each

component to the total mass flux and the void fraction. Continuity gives

$$G = \frac{\langle j_f \rangle}{v_f} + \frac{\langle j_g \rangle}{v_g} \quad . \tag{G-23}$$

Using this equation in Equations (G-16) and (G-17), we obtain the following expressions for $\langle j_f \rangle$ and $\langle j_g \rangle$ in terms of G, v_f, v_g, and $\langle \alpha \rangle$:

$$\langle j_f \rangle = \frac{(1 - \langle \alpha \rangle C_o)G - \frac{\langle \alpha \rangle}{v_g} \langle\langle V_{gj} \rangle\rangle}{\rho_m^*} \tag{G-24}$$

and

$$\langle j_g \rangle = \frac{(\langle \alpha \rangle C_o)G + \frac{\langle \alpha \rangle}{v_f} \langle\langle V_{gj} \rangle\rangle}{\rho_m^*} \tag{G-25}$$

where

$$\rho_m^* \equiv \frac{1 - \langle \alpha \rangle C_o}{v_f} + \frac{\langle \alpha \rangle C_o}{v_g} \quad . \tag{G-26}$$

We now describe specific applications of the drift flux model to NOTRUMP flow links. $G = W/A$ is known since W in the flow link is known. However, v_f, v_g, and $\langle \alpha \rangle$ are known only for fluid nodes, not for flow links. In order to apply Equations (G-24) and (G-25) to determine $\langle j_f \rangle$ and $\langle j_g \rangle$ in a flow link, we must, therefore, define appropriate average values for v_f, v_g, and $\langle \alpha \rangle$.

One way of defining these average values is the "flux-weighted void fraction" approach. [

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A second way of defining the average values of v_f, v_g, and $\langle\alpha\rangle$ is the "void propagation" approach.

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Referring to Section 2.2 and Appendix E, we see that the quanitites which must be calculated from the drift flux model are hW and $\frac{\partial}{\partial W}$ (hW) for specified flow links. These are obtained from the drift flux relations as follows. From the definitions of the volumetric fluxes, we have

$$W_f = \pm A \frac{\langle j_f \rangle}{v_f} \qquad \text{(G-30)}$$

and

$$W_g = \pm A \frac{\langle j_g \rangle}{v_g} \quad . \qquad \text{(G-31)}$$

The sign accounts for the fact that a positive sign means upflow for $\langle j_g \rangle$ and $\langle j_g \rangle$, while for W_f and W_g it meas flow from the upstream to downstream node.

From

$$G = \pm \frac{W}{A} \qquad \text{(G-32)}$$

we have

$$\frac{\partial G}{\partial W} = \pm \frac{1}{A} \quad . \qquad \text{(G-33)}$$

Therefore,

$$\frac{\partial W_f}{\partial W} = \frac{\partial W_f}{\partial G} \cdot \frac{\partial G}{\partial W} = \frac{1}{A} \frac{\partial W_f}{\partial G} = \frac{1}{v_f} \frac{\partial \langle j_f \rangle}{\partial G} \quad , \qquad \text{(G-34)}$$

$$\frac{\partial W_g}{\partial W} = \frac{\partial W_g}{\partial G} \cdot \frac{\partial G}{\partial W} = \frac{1}{A} \frac{\partial W_g}{\partial G} = \frac{1}{v_g} \frac{\partial \langle j_g \rangle}{\partial G} \quad , \qquad \text{(G-35)}$$

$$hW = h_f W_f + h_g W_g = \pm A \left(\frac{h_f}{v_f} \langle j_f \rangle + \frac{h_g}{v_g} \langle j_g \rangle\right) \quad , \tag{G-36}$$

and

$$\frac{\partial}{\partial W}(hW) = \frac{\partial}{\partial W}(h_f W_f + h_g W_g) = \frac{h_f}{v_f} \frac{\partial \langle j_f \rangle}{\partial G} + \frac{h_g}{v_g} \frac{\partial \langle j_g \rangle}{\partial G} \quad . \tag{G-37}$$

From Equations (G-22) - (G-25), we have

$$\frac{\partial \langle j_f \rangle}{\partial G} = \frac{(1 - \langle \alpha \rangle C_o) - \frac{\langle \alpha \rangle}{v_g}\left[\frac{\partial}{\partial G} \langle\langle V_{gj} \rangle\rangle + \langle j \rangle \frac{\partial C_o}{\partial G}\right]}{\rho_m^*} \tag{G-38}$$

and

$$\frac{\partial \langle j_g \rangle}{\partial G} = \frac{\langle \alpha \rangle C_o + \frac{\langle \alpha \rangle}{v_f}\left[\frac{\partial}{\partial G} \langle\langle V_{gj} \rangle\rangle + \langle j \rangle \frac{\partial C_o}{\partial G}\right]}{\rho_m^*} \quad . \tag{G-39}$$

NOTRUMP contains different models for $\langle\langle V_{gj} \rangle\rangle$. With some of these models, different models for C_o can be used, while with others, the model for C_o is not independent of the model for $\langle\langle V_{gj} \rangle\rangle$.

We first describe some of the models for C_o. One model uses the modified Armand correlation.

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Another model for C_o uses the GEND correlation[17],

[ ] a,c

Finally, the non-slip model can be used for C_o, i.e., $C_o = 1$. Other models for C_o are dependent on specific models for $\langle\langle V_{gj} \rangle\rangle$ and will be described with them.

We now describe the models for $\langle\langle V_{gj} \rangle\rangle$. The first model uses the "flux-weighted void fraction" approach. It uses the Zuber correlation for churn-turbulent bubbly flow limited by the Wallis flooding correlation, i.e.,

$$\langle\langle V_{gj} \rangle\rangle = \min (V^{z}_{gj}, V^{F}_{gj}) \qquad \text{(G-50)}$$

where

$$V^{z}_{gj} = A_p \left[\frac{\sigma g g_c (\rho_f - \rho_g)}{\rho_f^2}\right]^{1/4} \qquad \text{(G-51)}$$

$$V^{F}_{gj} = \frac{V_{gc} (1 - \langle\alpha\rangle)}{\alpha + m^2 \left(\frac{\rho_f}{\rho_g}\right) (1 - \langle\alpha\rangle)^{1/2}} , \qquad \text{(G-52)}$$

and

$$V_{gc} = A_{K1} \left[\frac{\sigma g g_c (\rho_f - \rho_g)}{\rho_g^2}\right]^{1/4} . \qquad \text{(G-53)}$$

A non-iterative method of solving Equations (G-24) - (G-27) with Equations (G-49) - (G-52) as the $\langle\langle V_{gj} \rangle\rangle$ correlation is coded in the modular subroutine, DRIFTF. The non-iterative approach in DRIFTF eliminates the problems of non-convergence and convergence to a non-appropriate solution which may occur with iterative methods. For this model, $C_o = 1$.

The second model for $\langle\langle V_{gj} \rangle\rangle$ uses the same correlation as the first but uses the "void propagation" approach.

The third model for $\langle\langle V_{gj} \rangle\rangle$ uses the "flux-weighted void fraction" approach and a general bubbly flow correlation:

$$\langle\langle V_{gj} \rangle\rangle = V_{gc} (1 - \langle\alpha\rangle)^n \qquad \text{(G-54)}$$

where

$$V_{gc} = C^2 \left[\frac{(\rho_f - \rho_g) g D_{bubble}}{\rho_f}\right]^{1/2} , \qquad \text{(G-55)}$$

$$D_{bubble} = \min (D_{Taylor}, D_e) , \qquad \text{(G-56)}$$

and

$$D_{Taylor} = 2 \left[\frac{\sigma g_c}{g (\rho_f - \rho_g)}\right]^{1/2} . \qquad \text{(G-57)}$$

The approach used here is to approximate Equation (G-54) by a piecewise linear continuous function which equals (G-54) at $\langle\alpha\rangle$ = 0.0, 0.1, ... 0.9, 0.91,. . ., 0.99, 1.0. Then the modular subroutine DFMFIT is used. DFMFIT uses a non-iterative approach similar to that in DRIFTF but for specified tables representing priecewise linear continuous functions for $\langle\langle V_{gj}\rangle\rangle$. For this model, C_o = 1.

The fourth model for $\langle\langle V_{gj}\rangle\rangle$ uses the same correlation as the third but uses the "void propagation" approach.

The fifth model for $\langle\langle V_{gj}\rangle\rangle$ uses the "flux-weighted void fraction" approach and general droplet flow correlation:

$$\langle\langle V_{gj}\rangle\rangle = V_{fc} (1 - \langle\alpha\rangle) \langle\alpha\rangle^{n-1} \qquad \text{(G-58)}$$

where

$$V_{fc} = C^2 \left[\frac{(\rho_f - \rho_g) g D_{drop}}{\rho_g}\right]^{1/2} \qquad \text{(G-59)}$$

and

$$D_{drop} = \min (D_{Taylor}, D_e) \qquad \text{(G-60)}$$

For this model, C_o = 1.

The sixth model for $\langle\langle V_{gj}\rangle\rangle$ uses the same correlation as the fifth but uses the "void propagation" approach.

The seventh model for $\langle\langle V_{gj}\rangle\rangle$ and C_o uses the "void propagation" approach and the "standard vertical flow" correlations.

The eighth model for $\langle\langle V_{gj}\rangle\rangle$ and C_o uses the "void propagation" approach and the "non-quenched core vertical flow" correlations.

The ninth model for $\langle\langle V_{gj} \rangle\rangle$ and C_o uses the "void propagation" approach and the "quenched core vertical flow" correlations.

The tenth model for $\langle\langle V_{gj} \rangle\rangle$ and C_o uses the "void propagation" approach and the "accumulator bypass vertical flow" correlations.

The eleventh model for $\langle\langle V_{gj} \rangle\rangle$ and C_o is an improved version of the TRAC-P1 horizontal flow model described in Reference 21. $\langle\langle V_{gj} \rangle\rangle$ is assumed to be zero. C_o is obtained from the correlation for revised TRAC-P1 region 1 if $\langle\alpha\rangle \leq 0.95$ and from the correlation for revised TRAC-P1 region 2 if $\langle\alpha\rangle > 0.95$. These correlations are described below as part of the revised TRAC-P1 vertical flow model. The model uses the "void propagation" approach.

The twelfth model for $\langle\langle V_{gj} \rangle\rangle$ and C_o is an improved version of the TRAC-P1 vertical flow model described in Reference 21. The model uses the flow regime map shown in Figure G-1. This map is two-dimensional in that the flow regime is assumed to be a function of $|G|$ and $\langle\alpha\rangle$. It consists of 13 distinct regions. Regions 1, 4, and 6 represent the bubbly/churn-turbulent, slug, and annular regimes, respectively. The other regions are transition regions. For these transition regions, linear or bi-linear interpolation between neighboring regions is used to obtain $\langle\langle V_{gj} \rangle\rangle$ and $\langle\alpha\rangle C_o$. At $\langle\alpha\rangle = 1$, we must satisfy the conditions, $\langle\langle V_{gj} \rangle\rangle = 0$ and $C_o = 1$. This flow regime map, while quite simplistic, does model different flow regimes and provides for continuous transitions between regimes.

The bubbly/churn-turbulent flow regime correlations are based on the work of Ishii[22].

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[ ] a,c

The annular flow regime correlations are based on Reference 23.

[ ] a,c

a,c [

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[a,c]

The thirteenth model for $\langle\langle V_{gj} \rangle\rangle$ uses the "void propagation" approach and is based on the Yeh void fraction correlation.

Yeh proposed the following correlation for the void fraction in a vessel based on analysis of small break test data:

$$\langle \alpha \rangle = 0.925 \left(\frac{\rho_g}{\rho_f}\right)^{0.239} \left(\frac{\langle j_g \rangle}{V_{bcr}}\right)^{a} \left(\frac{\langle j_g \rangle}{\langle j_g \rangle + \langle j_f \rangle}\right)^{0.6} \qquad \text{(G-82)}$$

where

$$V_{bcr} = 1.53 \left[\frac{\sigma\, g\, g_c\, (\rho_f - \rho_g)}{\rho_f^{\,2}}\right]^{1/4} \qquad \text{(G-83)}$$

and

$$a = \begin{cases} 0.67 & \text{if } \langle j_g \rangle / V_{bcr} < 1. \\ 0.47 & \text{if } \langle j_g \rangle / V_{bcr} \geq 1. \end{cases} \qquad \text{(G-84)}$$

[a,c]

[a,c]

For drift flux models 1, 2, 3, 4, 7, 9, 10, 12, and 13, we check whether to use flooding relationships. If the void fraction of the top node is equal to one, then there can be no flooding. For drift flux model 9, we do not use the flooding relationships if $\langle\alpha\rangle$ is less than 0.8 or if $\langle j_f \rangle$ is greater than 0.0 or if $\langle j_g \rangle$ is less than zero. For drift flux models 1, 2, 3, 4, 7, 10, 12, and 13, we do not use the flooding relationships if the void fraction of the bottom node is not equal to one or $\langle\alpha\rangle$ is not equal to one.

The flooding relationships are defined and used as follows.

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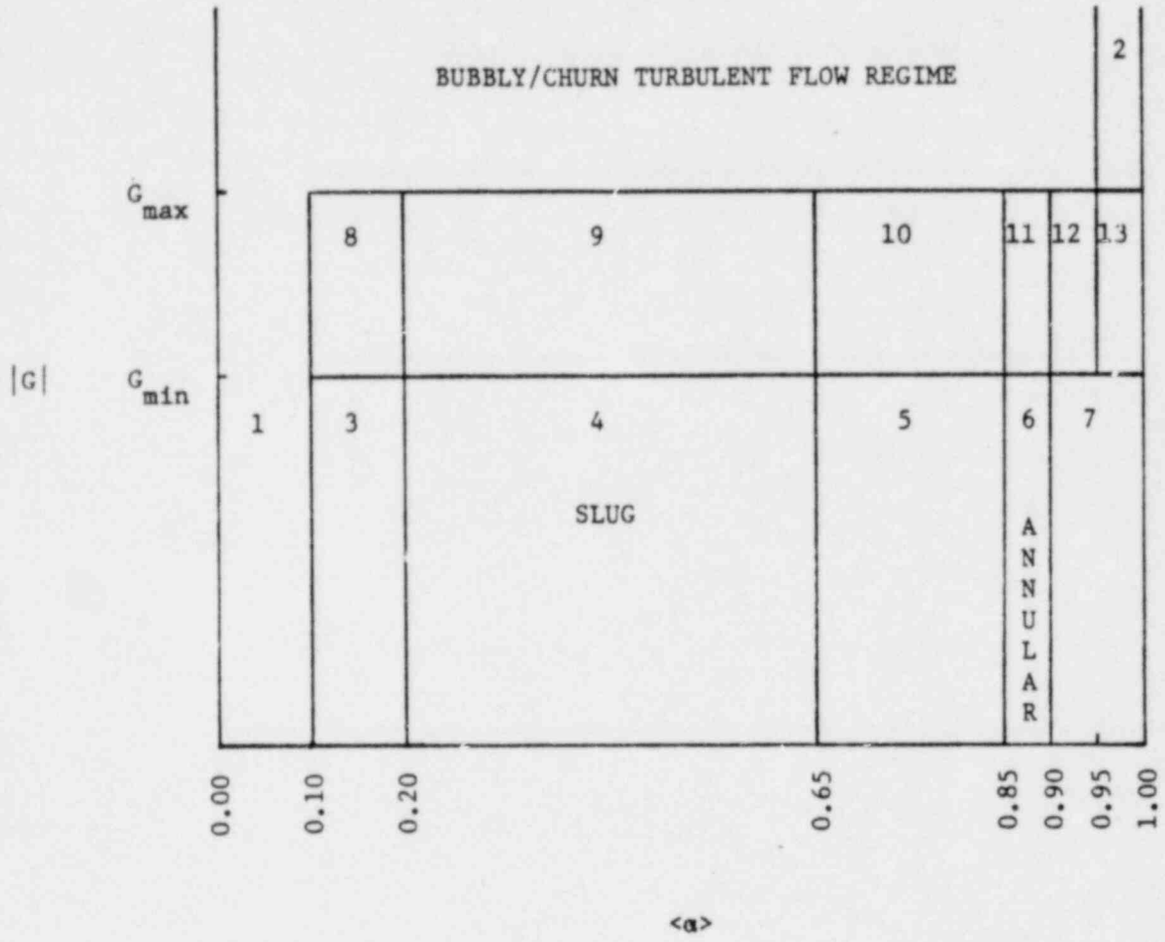

G_{min} = 2000 kg/sec/m^2 = 409.6322872 lbm/sec/ft^2

G_{max} = 3000 kg/sec/m^2 = 614.4484308 lbm/sec/ft^2

FIGURE G-1. Improved TRAC-P1 Flow Regime Map

APPENDIX H

BUBBLE RISE MODEL

In this appendix, we discuss the bubble rise (or phase separation) model which is used for stratified interior fluid nodes in NOTRUMP. This model calculates the distribution of the gas and liquid phases when the node is two-phase. The two-phase node is represented as a two region volume, the upper region consisting of a steam space and the lower containing a mixture of steam bubbles and liquid.

The bubble rise model determines the steam-mixture interface (commonly referred to as the nodal mixture elevation) in a two-phase interior stratified node. This affects the flow composition in flow links connected to the node. (See Appendix F). Stratified fluid nodes are particularly useful for modelling regions which can be characterized by a definite water level, (e.g., the downcomer region in a steam generator).

Consider Figure H-1 in which a stratified interior fluid node is shown with various flow links connecting above and below the nodal mixture elevation. The height of the two-phase mixture in the node is determined by the volume of liquid and the volume of steam bubbles trapped in the liquid.

A mass balance on the steam bubbles in interior fluid node i is given by

$$(\dot{M}_{gb})_i = (S_{gb})_i + \sum_{\kappa \epsilon T_i^W} C_{i\kappa} (W_g)_\kappa - \sum_{\kappa \epsilon I_i^W} C_{i\kappa} (W_g)_\kappa - (W_e)_i \qquad \text{(H-1)}$$

where, for point contact flow links,

$$C_{i\kappa} = \begin{cases} 1.0 & \text{if } (E_{mix})_i \geq (E_{fl})_\kappa \\ 0.0 & \text{if } (E_{mix})_i < (E_{fl})_\kappa \end{cases} \qquad \text{(H-2)}$$

and, for continuous contact flow links,

a,c [ ]

where F_{mix} is given by Equation (F-3).

The first term on the right hand side of Equation (H-1) represents the steam bubble production rate. The second and third terms represent the net gain of steam bubbles due to convection from flow links. The last term represents the steam bubble escape rate from the mixture.

A mass balance on the total steam in interior fluid node i is given by

$$(\dot{M}_g)_i = (S_g)_i + \sum_{\kappa \epsilon T_i^W} (W_g)_\kappa - \sum_{\kappa \epsilon I_i^W} (W_g)_\kappa \quad . \qquad \text{(H-4)}$$

$(S_g)_i$ represents the total steam production rate.

Assuming that the steam bubble production rate equals the total steam production, i.e.,

$$(S_{gb})_i = (S_g)_i, \tag{H-5}$$

Equations (H-1) and (H-4) are combined to give

$$(\dot{M}_{gb})_i = (\dot{M}_g)_i - \sum_{\kappa \epsilon T_i^W} (1-C_{i\kappa})(W_g)_\kappa + \sum_{\kappa \epsilon I_i^W} (1-C_{i\kappa})(W_g)_\kappa - (W_e)_i . \tag{H-6}$$

The steam bubble escape rate from the mixture is given by

$$W_e = (\alpha \rho_g A)_m (V_g - V_f)_m \tag{H-7}$$

We have dropped the nodal subscript i. The subscript m refers to the location at the steam-mixture interface. V_g and V_f here represent the gas and liquid component velocities, respectively. Assuming no variation of α, ρ_g, or A in the mixture, we can write

$$W_e = \alpha_{mix} \rho_g A \quad (V_g - V_f)_m \tag{H-8}$$

From Equation (G-17), we see that, at the steam-mixture interface,

$$(V_g)_m = C_o \langle j \rangle_m + \langle\langle V_{gj} \rangle\rangle \tag{H-9}$$

where

$$\langle j \rangle_m = \alpha_{mix} (V_g)_m + (1-\alpha_{mix}) (V_f)_m \tag{H-10}$$

Combining these two equations, we obtain

$$(V_g - V_f)_m = \frac{\langle\langle V_{gj} \rangle\rangle + (V_f)_m (C_o - 1)}{1 - \alpha_{mix} C_o} \qquad \text{(H-11)}$$

Note that the liquid velocity at the steam-mixture interface is

$$(V_f)_m = \dot{V}_{mix}/A \cdot \qquad \text{(H-12)}$$

Since

$$V_{mix} = M_{gb} v_g + M_f v_f, \qquad \text{(H-13)}$$

we have

$$\dot{V}_{mix} = \dot{M}_{gb} v_g + \dot{M}_f v_f \cdot \qquad \text{(H-14)}$$

Therefore using Equations (H-11), (H-12), and (H-14) in Equation (H-8), we obtain

$$W_e = \frac{\alpha_{mix}}{1 - \alpha_{mix} C_o} \frac{v_f}{v_g} \left[\frac{\langle\langle V_{gj} \rangle\rangle A}{v_f} + (C_o - 1) \left(\frac{v_g}{v_f} \dot{M}_{gb} + \dot{M}_f \right) \right] \qquad \text{(H-15)}$$

Using this in Equation (H-6) gives

$$(\dot{M}_{gb})_i = \frac{1 - C_o \alpha_{mix}}{1 - \alpha_{mix}} \left[\right.$$

$$\left. - \frac{\alpha_{mix}}{1 - \alpha_{mix}} \frac{v_f}{v_g} \left[\frac{\langle\langle V_{gj} \rangle\rangle A}{v_f} + (C_o - 1)(\dot{M}_f)_i \right] \right] \qquad \text{if} \qquad \text{(H-16)}$$

$(M_{gb})_i$ is calculated at a new time by an explicit integration of Equation (H-16). The mixture volume is then obtained from Equation (H-13) and the nodal mixture elevation from

$$(E_{mix})_i = (E_{bot})_i + [(E_{top})_i - (E_{bot})_i] \frac{(V_{mix})_i}{V_i} \qquad \text{(H-17)}$$

The correlations available for drift flux in flow links are also available for bubble rise in stratified interior fluid nodes. The $\langle\langle V_{gj} \rangle\rangle$ calculations for bubble rise are simpler than for drift flux since $\langle\langle V_{gj} \rangle\rangle$ is evaluated at the known void fraction α_{mix}. However, an effective mass flux in the mixture, G_{mix}, must be defined for use in the drift flux correlations. The following definition is used:

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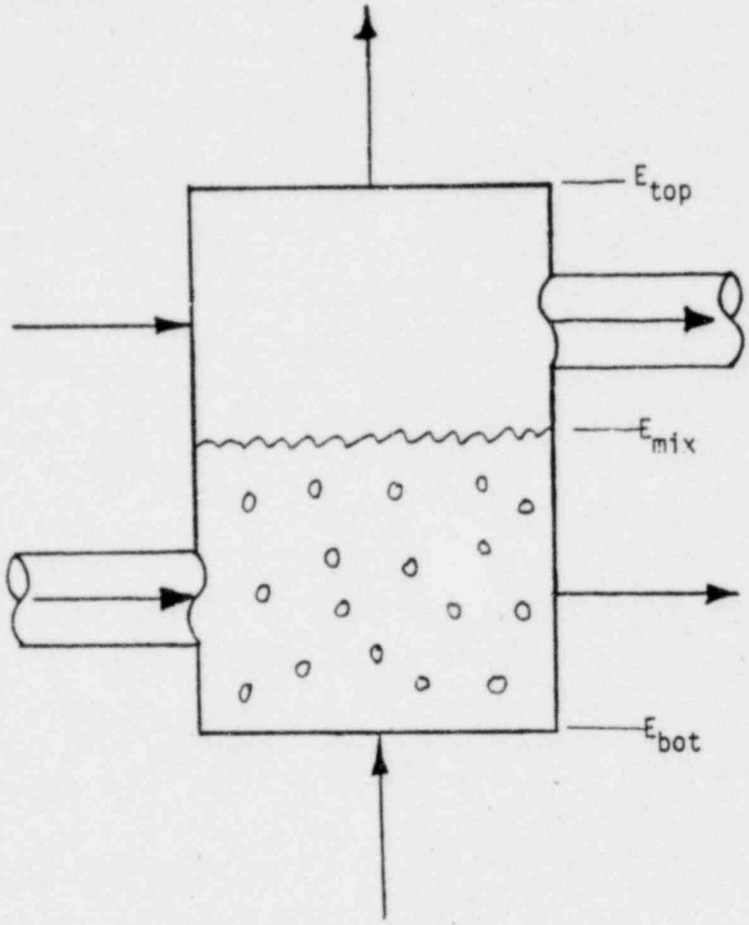

FIGURE H-1. NØTRUMP Stratified Interior Fluid Node

APPENDIX I

MOMENTUM FLUX MODEL

The purpose of this appendix is to describe how the momentum flux model is used in NOTRUMP. It accounts for momentum fluxes arising from density changes and/or abrupt area changes. It is applicable to all non-critical flow links in NOTRUMP. The NOTRUMP momentum conservation equations for these non-critical flow links are affected by the inclusion of the momentum flux terms. In addition, the model limits the flow in all flow links to sonic flow.

The governing equation for determining the mass flow rate in a given non-critical flow link in NOTRUMP is the momentum conservation equation. For non-critical flow link k shown in Figure I-1, it takes the following form:

$$\dot{W}_k = \frac{144\ g_c}{\frac{L_i}{A_i} + \frac{L_j}{A_j}} \left[(P_u)_k - (P_d)_k - C_k |W_k| W_k + D_k \right. \tag{I-1}$$

$$\left. + \frac{1}{144\ g_c} \left\{ [\rho V^2]_1 - [\rho V^2]_{j1} + c^2 (\rho_{j2} - \rho_{j1}) + [\rho V^2]_{j2} - [\rho V^2]_2 \right\} \right] .$$

The first four terms on the right hand side are the non-momentum flux terms. The remaining terms are the momentum flux terms. They will not be derived here. See Reference 25 for derivations.

The inclusion of momentum flux in Equation (I-1) necessitates solving two auxiliary equations at the area change. Let subscripts s and L refer to locations just upstream and downstream (with respect to net mass

flow direction) of the abrupt area change. For steady, frictionless isentropic flow, assuming that the sonic velocity and flow rate are constant across the area change, it can be shown that

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[ ] a,c

Equation (I-1) is the general form of the momentum equation to be solved in NOTRUMP. Unfortunately, not all the quantities needed to evaluate it are directly available in NOTRUMP. Mass flow rates are known only in flow links. Therefore, for non-critical flow link k joining fluid nodes i and j, we must approximate the momentum fluxes $[\rho V^2]_1$ and $[\rho V^2]_2$ by average nodal momentum fluxes $\overline{[\rho V^2]}_i$ and $\overline{[\rho V^2]}_j$, respectively. Equation (I-1) becomes

$$\dot{W}_k = \frac{144 g_c}{\frac{L_i}{A_i} + \frac{L_j}{A_j}} \left[(P_u)_k - (P_d)_k - C_k |W_k| W_k + D_k \right. \qquad \text{(I-8)}$$

$$\left. + \frac{1}{144 g_c} \left\{ \overline{[\rho V^2]}_i - [\rho V^2]_{j1} + c^2 (\rho_{j2} - \rho_{j1}) + [\rho V^2]_{j2} - \overline{[\rho V^2]}_j \right\} \right] .$$

We now define the average nodal momentum fluxes as follows:

[ ] a,c

and

a,c [ ]

Flow link momentum fluxes are evaluated as follows: For single phase or non-drift flux flow,

$$[\rho V^2]^k_{j1} = \frac{W_k^2}{\rho_{j1} A_i^2} \qquad \text{(I-11)}$$

and

$$[\rho V^2]^k_{j2} = \frac{W_k^2}{\rho_{j2} A_j^2} \quad . \qquad \text{(I-12)}$$

For two phase ($0 < \alpha < 1$) drift flux flow,

$$[\rho V^2]^k_{j1} = \frac{1}{A_i^2} \left[\frac{W_f^2}{\rho_f (1-\alpha)} + \frac{W_g^2}{\rho_g \alpha} \right]^k_{j1} \qquad \text{(I-13)}$$

and

$$[\rho V^2]^k_{j2} = \frac{1}{A_j^2} \left[\frac{W_f^2}{\rho_f (1-\alpha)} + \frac{W_g^2}{\rho_g \alpha} \right]^k_{j2} \quad . \qquad \text{(I-14)}$$

As tated above, the inclusion of momentum flux terms in Equation (I-1) necessitates solving Equations (I-2) and (I-3) for ρ_{jL} and M_{jL}. ρ_{js}, A_{js}, and A_{jL} are given by,

$$\rho_{js} = \rho_k, \tag{I-15}$$

$$A_{js} = \begin{cases} A_i & \text{if } W_k \geq 0, \\ A_j & \text{if } W_k < 0, \end{cases} \tag{I-16}$$

and

$$A_{jL} = \begin{cases} A_j & \text{if } W_k \geq 0. \\ A_i & \text{if } W_k < 0. \end{cases} \tag{I-17}$$

Equations (I-2) and (I-3) are then solved for ρ_{jL} and M_{jL}. Finally, ρ_{j1} and ρ_{j2} are given by

$$\rho_{j1} = \begin{cases} \rho_{js} & \text{if } W_k \geq 0 \\ \rho_{jL} & \text{if } W_k < 0 \end{cases} \tag{I-18}$$

and

$$\rho_{j2} = \begin{cases} \rho_{jL} & \text{if } W_k \geq 0 \\ \rho_{js} & \text{if } W_k < 0 \end{cases} \tag{I-19}$$

The mass flow rate is limited to sonic conditions, i.e., so that neither M_{js}, M_{jL}, nor

$$M_k = \left| \frac{W_k}{\rho_k A_k c} \right| \qquad \text{(I-20)}$$

a,c exceed unity. [

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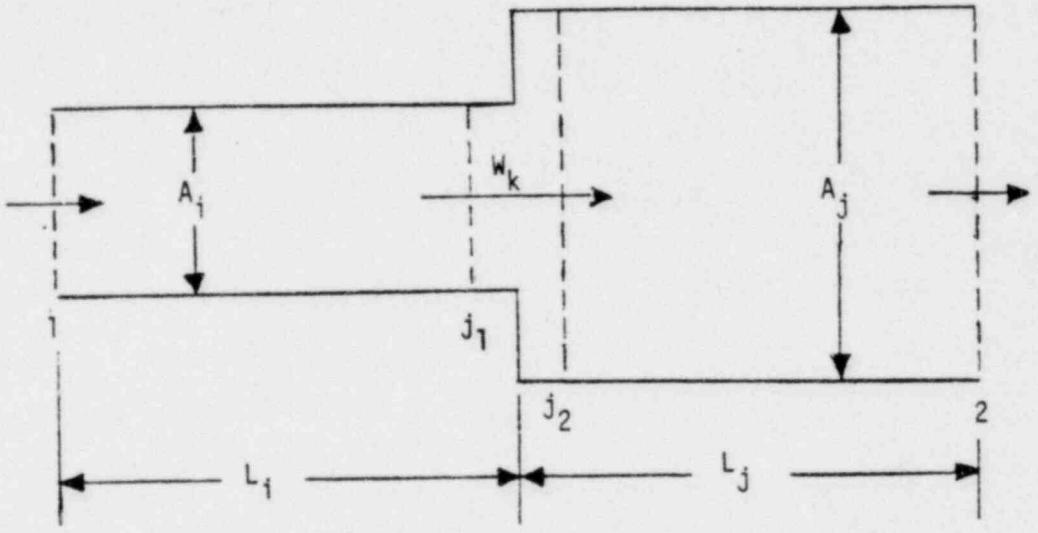

FIGURE I-1. NØTRUMP Non-Critical Flow Link

APPENDIX J

MECHANICAL SEPARATOR MODELS

The purpose of this appendix is to describe the mechanical separator models currently used in NOTRUMP. The swirl vane model consists of special logic for the flow links representing the inlets to the swirl vanes, the outlets above the swirl vanes, and the swirl vane drains. The Peerless vane model consists of special logic for the flow link representing the Peerless vane drains. The current models are from TRANFLO. As better mechanical separator models of the swirl vanes or Peerless vanes are developed, they may be included in NOTRUMP.

NOTRUMP currently contains two swirl vane models. The first model is described in Reference 4. Let the flow link representing the inlets to the swirl vanes be denoted by KSVI, the flow link for the swirl vane outlets by KSVO, and the flow link for the swirl vane drains by KSVD. The void fraction in flow link KSVO is given by

[ ] a,c

where $\alpha_{\mu(KSVO)}$ is the void fraction in the fluid node upstream of KSVO and SV is the fractional swirl vane efficiency.

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An additional swirl vane calculation is the addition of the centrifugal term in the momentum equation for flow link KSVD. The quantity

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is added to D_k in Equation (2-8) for k = KSVD. (The nomenclature is given in Appendix A.)

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[

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[ ] a,c

An additional swirl vane calculation is the addition of the centrifugal term in the momentum equation for flow link KSVD.

The quantity

[ ] a,c

is added to D_k in Equation (2-8) for k=KSVD. (The nomenclature is given in Appendix A.)

[ ] a,c

The Peerless vane model used in NOTRUMP will now be described. Let the flow link representing the Peerless vane drains be denoted by KPSD. The D_k term in Equation (2-8) is modified for k = KPSD by adding

[ ] a,c

APPENDIX K

CONTROLLERS

The purpose of this appendix is to describe the controllers and how they are modelled in NOTRUMP. The controllers are 1) the feedwater valve controller, 2) the throttle valve controller, and 3) the primary water heater controller. Figures (K-1) - (K-3) are the control logic diagrams for these controllers. Each control logic diagram can be represented in NOTRUMP by a set of first order time differential equations. These controller equations are NOTRUMP components (see Section 2.1.9) and are included as part of the governing differential equations (see Section 2.2). We shall now develop the pertinent equations for the controllers.

The feedwater valve control and response logic diagram is shown in Figure K-1. The measured steam generator level is given in terms of percent span of the narrow range level taps. It is calculated in NOTRUMP as

$$X_{LM}^{FW} = \frac{\left\{ P_{LT} + \frac{g}{144g_c}\left[\frac{(E_{top})_{LT}^{FW} - \max[(E_{mix})_{LT}^{FW}, E_{LT}^{FW}]}{\max[(v_g)_{LT}^{FW}, v_{LT}^{FW}]} + \frac{\max[(E_{mix})_{LT}^{FW}, E_{LT}^{FW}] - E_{LT}^{FW}}{(v_{mix})_{LT}^{FW}}\right]\right\}}{\left\{ -P_{UT} + \frac{g}{144g_c}\left[\frac{(E_{top})_{UT}^{FW} - \max[(E_{mix})_{UT}^{FW}, E_{UT}^{FW}]}{\max[(v_g)_{UT}^{FW}, v_{UT}^{FW}]} + \frac{\max[(E_{mix})_{UT}^{FW}, E_{UT}^{FW}] - E_{UT}^{FW}}{(v_{mix})_{UT}^{FW}}\right]\right\}} \times 100. \quad \text{(K-1)}$$

$$- \frac{g}{144g_c}\left[\frac{E_{UT}^{FW} - E_{LT}^{FW}}{v_g(P_{LM}^{FW})}\right]$$

$$\frac{g}{144g_c}\left[E_{UT}^{FW} - E_{LT}^{FW}\right]\left[\frac{1}{v_f(P_{LM}^{FW})} - \frac{1}{v_g(P_{LM}^{FW})}\right]$$

The nomenclature is given in Appendix A.

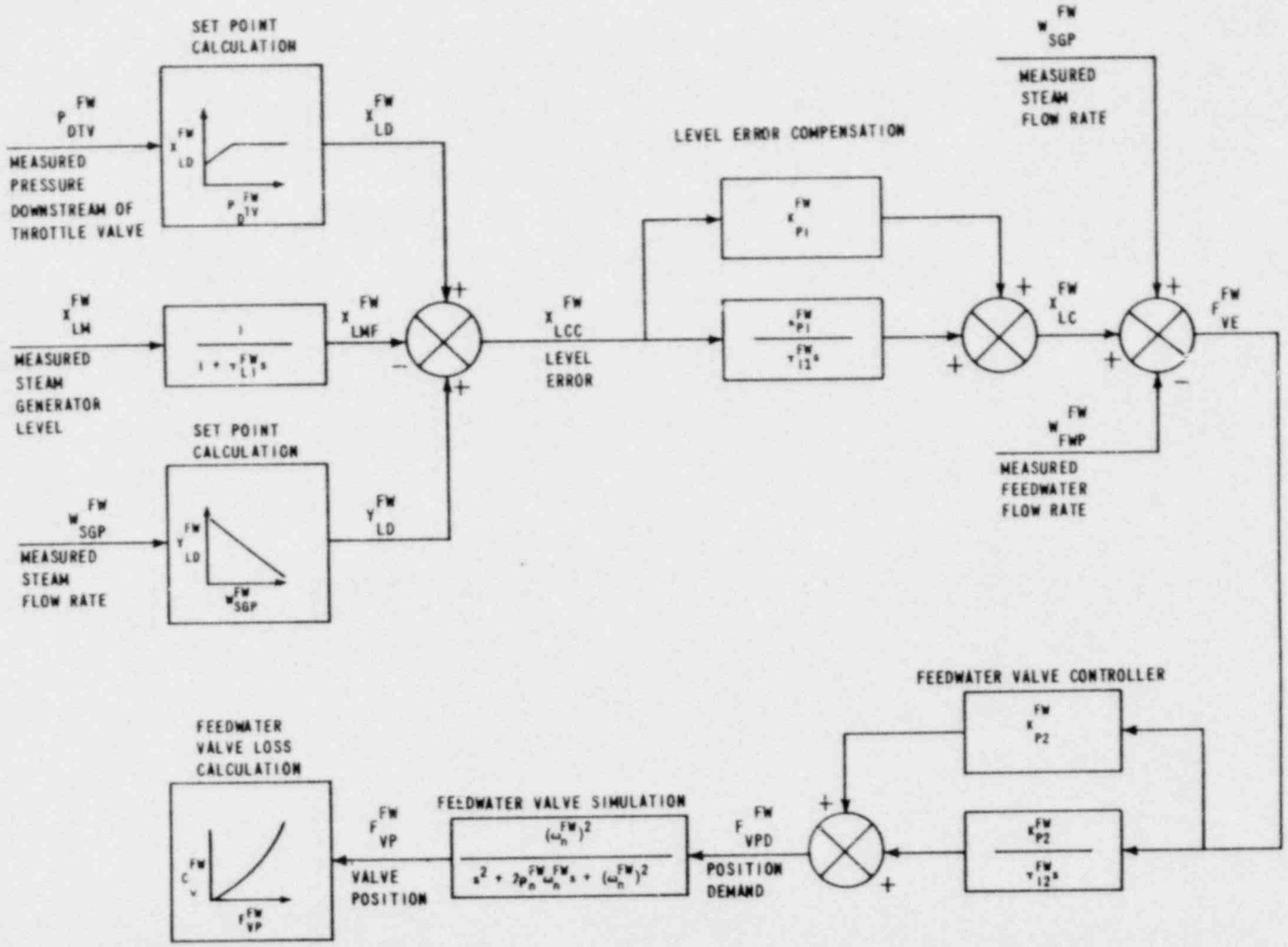

Figure K-1. Feedwater Valve Control and Response

X_{LM}^{FW} is processed by a filter to give X_{LMF}^{FW}. This is represented by the first order differential equation

$$\dot{X}_{LMF}^{FW} = \frac{1}{\tau_{L1}^{FW}} (X_{LM}^{FW} - X_{LMF}^{FW}) \quad . \tag{K-2}$$

The measured pressure downstream of the throttle valve, P_{DTV}^{FW}, is converted into a level set point, X_{LD}^{FW}, by a set point calculation. It is represented by

$$X_{LD}^{FW} = X_{LD}^{FW} (P_{DTV}^{FW}) \quad . \tag{K-3}$$

The measured steam flow rate, W_{SGP}^{FW}, is converted into a level set point Y_{LD}^{FW}, by a set point calculation. It is represented by

$$Y_{LD}^{FW} = Y_{LD}^{FW} (W_{SGP}^{FW}) \tag{K-4}$$

The level error, X_{LCC}^{FW}, is determined from

$$X_{LCC}^{FW} = X_{LD}^{FW} + Y_{LD}^{FW} - X_{LMF}^{FW} \quad . \tag{K-5}$$

Next, level error compensation is performed by a PI controller, processing X_{LCC}^{FW} into X_{LC}^{FW}, the compensated level error. This is represented by

$$X_1^{FW} = K_{P1}^{FW} \; X_{LCC}^{FW}, \tag{K-6}$$

$$\dot{Z}_1^{FW} = \frac{K_{P1}^{FW}}{\tau_{I1}^{FW}} \; X_{LCC}^{FW}, \tag{K-7}$$

and

$$X_{LC}^{FW} = X_1^{FW} + Z_1^{FW}. \tag{K-8}$$

The compensated level error, measured steam flow rate and measured feedwater flow rate are processed by a summer to give F_{VE}^{FW} where

$$F_{VE}^{FW} = X_{LC}^{FW} + W_{SGP}^{FW} - W_{FWP}^{FW} \quad . \tag{K-9}$$

Feedwater valve control is now performed by a PI controller, processing F_{VE}^{FW} into the feedwater valve position demand, F_{VPD}^{FW}. This is represented by

$$X_2^{FW} = K_{P2}^{FW} \; F_{VE}^{FW}, \tag{K-10}$$

$$\dot{Z}_2^{FW} = \frac{K_{P2}^{FW}}{\tau_{I2}^{FW}} \; F_{VE}^{FW}, \tag{K-11}$$

and

$$F_{VPD}^{FW} = X_2^{FW} + Z_2^{FW} \; . \tag{K-12}$$

The simulation of the feedwater valve response to the valve position demand, F_{VPD}^{FW}, is represented by

$$\dot{Z}_3^{FW} = (\omega_n^{FW})^2 \; (F_{VPD}^{FW} - F_{VP}^{FW}) - 2\rho_n^{FW}\omega_n^{FW} \; Z_3^{FW} \tag{K-13}$$

and

$$\dot{F}_{VP}^{FW} = Z_3^{FW} \; . \tag{K-14}$$

F_{VP}^{FW} is the actual feedwater valve position. It ranges from fully closed (0%) to fully open (100%). If the valve is fully closed, negative values of Z_3^{FW} (the valve velocity) are not allowed. If the valve is fully open, positive values of Z_3^{FW} are not allowed.

Finally, the feedwater valve position is used to calculate a feedwater valve loss coefficient.

$$C_v^{FW} = C_v^{FW} \; (F_{VP}^{FW}) \; . \tag{K-15}$$

The loss coefficient will be used in the flow link representing the feedwater valve to modify the frictional loss term and thereby account for the pressure drop through the valve.

The throttle valve control and response logic diagram is shown in Figure K-2. The measured pressure downstream of the throttle valve, P^{TV}_{DTV}, is converted into the measured load, X^{TV}_{MWM}, by the relationship

$$X^{TV}_{MWM} = X^{TV}_{MWM} \left(P^{TV}_{DTV}\right) \quad . \tag{K-16}$$

The measured load X^{TV}_{MWM}, the load demand $X^{TV}_{MWD}(t)$, and another arbitrary function of time $P^{TV}_{7}(t)$ are processed by a summer to give the load error X^{TV}_{MWCC} where

$$X^{TV}_{MWCC} = X^{TV}_{MWD} + P^{TV}_{7} - X^{TV}_{MWM} \quad . \tag{K-17}$$

The load error is then processed into X^{TV}_{MWC} by a non-linear gain where

$$X^{TV}_{MWC} = X^{TV}_{MWC} \left(X^{TV}_{MWCC}\right) \tag{K-18}$$

X^{TV}_{MWC} and $P^{TV}_{8}(t)$ are processed by a summer to give F^{TV}_{VE} where

$$F^{TV}_{VE} = X^{TV}_{MWC} + P^{TV}_{8} \tag{K-19}$$

Throttle valve control is now performed by a PI controller, processing F^{TV}_{VE} into the throttle valve position demand, F^{TV}_{VPD}. This is represented by

$$X^{TV}_{1} = K^{TV}_{P1} \; F^{TV}_{VE}, \tag{K-20}$$

$$\dot{Z}^{FW}_{1} = \frac{K^{TV}_{P1}}{\tau^{TV}_{I1}} \; F^{TV}_{VE} \, , \tag{K-21}$$

and

$$F^{TV}_{VPD} = X^{TV}_{1} + Z^{TV}_{1} \quad . \tag{K-22}$$

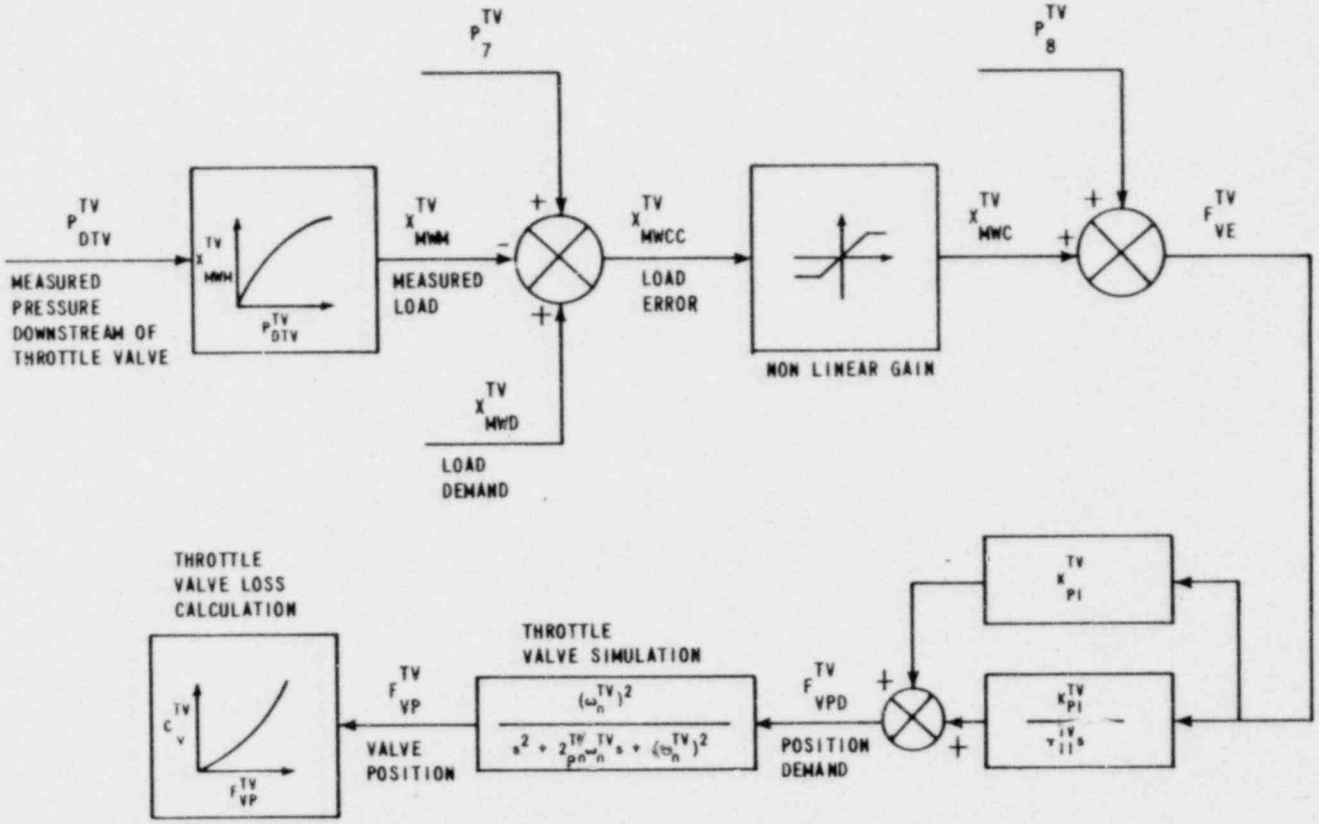

Figure K-2. Throttle Valve Control and Response

The simulation of the throttle valve response to the valve position demand F_{VPD}^{TV} is represented by two first order differential equations,

$$\dot{Z}_2^{TV} = (\omega_n^{TV})^2 (F_{VPD}^{TV} - F_{VP}^{TV}) - 2\rho\omega_n^{TV} Z_2^{TV} \qquad \text{(K-23)}$$

and

$$\dot{F}_{VP}^{TV} = Z_2^{TV} \quad . \qquad \text{(K-24)}$$

F_{VP}^{TV} is the actual throttle valve position. It ranges from fully closed (0%) to fully open (100%). If the valve is fully closed, negative values of Z_2^{TV} (the valve velocity) are not allowed. If the valve is fully open, positive values of Z_2^{TV} are not allowed.

Finally, the throttle valve position is used to calculate a throttle valve loss coefficient

$$C_v^{TV} = C_v^{TV} (F_{VP}^{TV}) \qquad \text{(K-25)}$$

The loss coefficient will be used in the flow link representing the throttle valve to modify the frictional loss term and thereby account for the pressure drop through the valve.

The primary water heater control logic diagram is shown in Figure K-3. The measured mixed heater temperature, T_{HLA}^{PH}, is processed by a filter to give T_{HLM}^{PH}. This is represented by the first order differential equation

$$\dot{T}_{HLM}^{PH} = T_{HLA}^{PH} - T_{HLM}^{PH} \quad . \qquad \text{(K-26)}$$

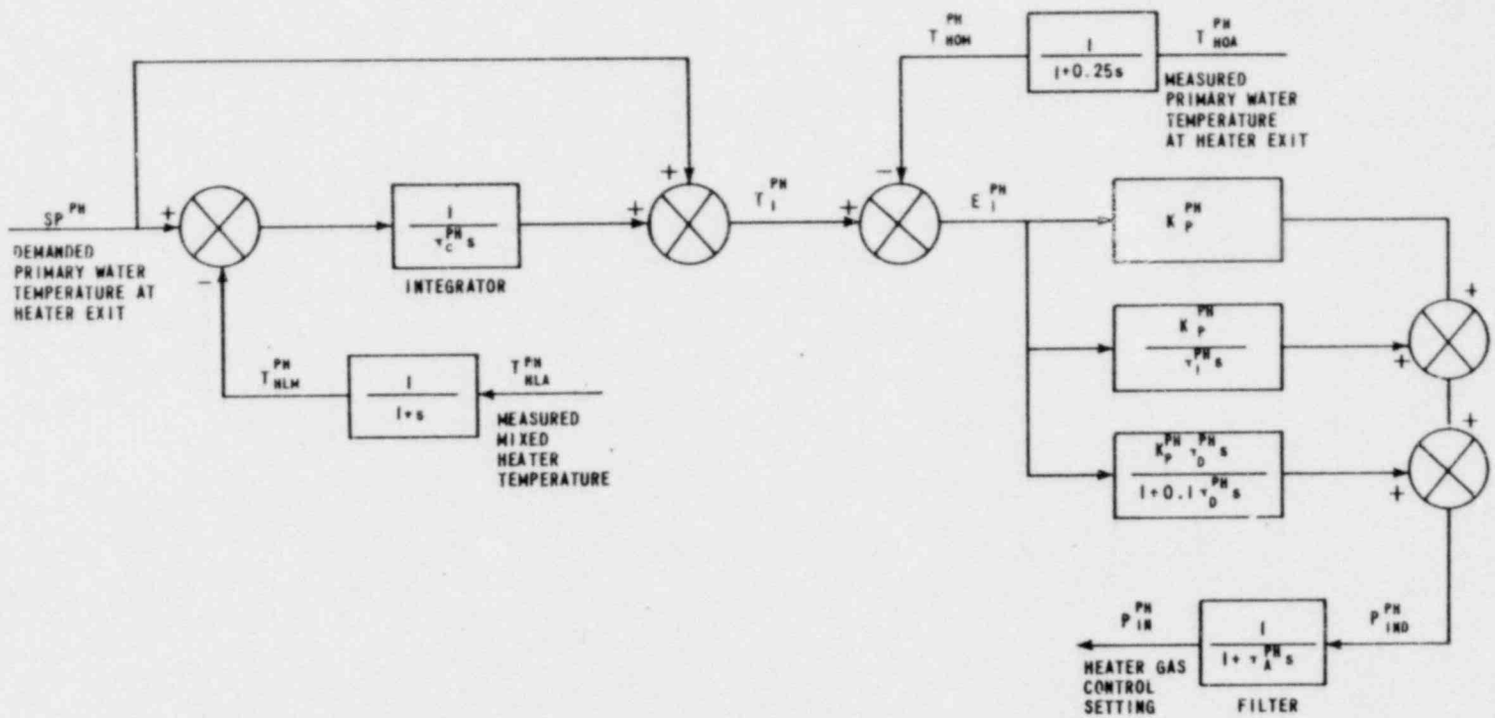

Figure K-3. Primary Water Heater Control

The demanded primary water temperature at the heater exit, SP^{PH}, and T^{PH}_{HLM} are processed by a summer and then by an integrator to give the first order differential equation

$$\dot{Z}^{PH}_1 = \frac{1}{\tau^{PH}_c} (SP^{PH} - T^{PH}_{HLM}) \quad . \tag{K-27}$$

Then SP^{PH} and X^{PH}_1 are summed to give

$$T^{PH}_1 = Z^{PH}_1 + SP^{PH} \quad . \tag{K-28}$$

The measured primary water temperature at the heater exit, T^{PH}_{HOA}, is processed by a filter to give T^{PH}_{HOM}. This is represented by the first order differential equation

$$\dot{T}^{PH}_{HOM} = \frac{1}{0.25} (T^{PH}_{HOA} - T_{HOM}) \quad . \tag{K-29}$$

Then T^{PH}_1 and T^{PH}_{HOM} are summed to give

$$E^{PH}_1 = T^{PH}_1 - T^{PH}_{HOM} \quad . \tag{K-30}$$

Primary water heater control is now performed by a PID controller, processing E^{PH}_1 into the heater gas control setting demand, P^{PH}_{IND}. This is represented by

$$X^{PH}_1 = K^{PH}_P E^{PH}_1 , \tag{K-31}$$

$$\dot{Z}^{PH}_2 = \frac{K^{PH}_P}{\tau^{PH}_1} E^{PH}_1 , \tag{K-32}$$

$$\dot{Z}^{PH}_3 = \frac{K^{PH}_P}{0.1} \dot{E}^{PH}_1 - \frac{Z^{PH}_3}{0.1\ \tau^{PH}_D} , \tag{K-33}$$

and

$$P^{PH}_{IND} = X^{PH}_1 + Z^{PH}_2 + Z^{PH}_3 \quad . \tag{K-34}$$

Finally P_{IND}^{PH} is processed into the heater gas control setting, P_{IN}^{PH}, by a filter. This is represented by the first order differential equation

$$\dot{P}_{IN}^{PH} = \frac{1}{\tau_A^{PH}} (P_{IND}^{PH} - P_{IN}^{PH}) \quad . \tag{K-35}$$

P_{IN}^{PH} ranges from fully closed (0%) to fully open (100%).

Referring to Equation (2-24), we order the controller differential equation variables as follows:

$$y_{K+2I+J+1} = X_{LMF}^{FW}, \tag{K-36}$$

$$y_{K+2I+J+2} = Z_1^{FW}, \tag{K-37}$$

$$y_{K+2I+J+3} = Z_2^{FW}, \tag{K-38}$$

$$y_{K+2I+J+4} = Z_3^{FW}, \tag{K-39}$$

$$y_{K+2I+J+5} = F_{VP}^{FW}, \tag{K-40}$$

$$y_{K+2I+J+6} \quad Z_1^{TV}, \tag{K-41}$$

$$y_{K+2I+J+7} = Z_2^{TV}, \tag{K-42}$$

$$y_{K+2I+J+8} = F_{VP}^{TV}, \tag{K-43}$$

$$y_{K+2I+J+9} = T_{HLM}^{PH}, \tag{K-44}$$

$$y_{K+2I+J+10} = Z_1^{PH}, \tag{K-45}$$

$$y_{K+2I+J+11} = T_{HOM}^{PH}, \tag{K-46}$$

$$y_{K+2I+J+12} = Z_2^{PH}, \tag{K-47}$$

$$y_{K+2I+J+13} = Z_3^{PH}, \tag{K-48}$$

$$y_{K+2I+J+14} = P_{IN}^{PH}, \tag{K-49}$$

Using Equations (K-1) - (K-49), we can rewrite the right hand sides of the controller differential equations as follows:

$$F_{K+2I+J+1} = \frac{1}{\tau_{L1}^{FW}} \left[X_{LM}^{FW} - y_{K+2I+J+1} \right], \tag{K-50}$$

$$F_{K+2I+J+2} = \frac{K_{P1}^{FW}}{\tau_{I1}^{FW}} X_{LCC}^{FW}, \tag{K-51}$$

$$F_{K+2I+J+3} = \frac{K_{P2}^{FW}}{\tau_{I2}^{FW}} F_{VE}^{FW}, \tag{K-52}$$

$$F_{K+2I+J+4} = (\omega_n^{FW})^2 [F_{VPD}^{FW} - y_{K+2I+J+5}] - 2 \rho_n^{FW} \omega_n^{FW} y_{K+2I+J+4}, \tag{K-53}$$

$$F_{K+2I+J+5} = y_{K+2I+J+4}, \tag{K-54}$$

$$F_{K+2I+J+6} = \frac{K_{P1}^{TV}}{\tau_{I1}^{TV}} F_{VE}^{TV}, \tag{K-55}$$

$$F_{K+2I+J+7} = (\omega_n^{TV}) [F_{VPD}^{TV} - y_{K+2I+J+8}] - 2\rho_n^{TV} \omega_n^{TV} y_{K+2I+J+7}, \tag{K-56}$$

$$F_{K+2I+J+8} = y_{K+2I+J+7}, \tag{K-57}$$

$$F_{K+2I+J+9} = T_{HLA}^{PH} - y_{K+2I+J+9}, \tag{K-58}$$

$$F_{K+2I+J+10} = \frac{1}{\tau_c^{PH}} \left[SP^{PH} - y_{K+2I+J+9} \right], \tag{K-59}$$

$$F_{K+2\,I+J+11} = \frac{1}{0.25}\left[T^{PH}_{HOA} - y_{K+2\,I+J+11}\right] , \qquad \text{(K-60)}$$

$$F_{K+2\,I+J+12} = \frac{K^{PH}_P}{\tau^{PH}_I} E^{PH}_1 , \qquad \text{(K-61)}$$

$$F_{K+2\,I+J+13} = \frac{K^{PH}_P}{0.1} \dot{E}^{PH}_1 - \frac{1}{0.1\,\tau^{PH}_D} y_{K+2\,I+J+13} , \qquad \text{(K-62)}$$

$$F_{K+2\,I+J+14} = \frac{1}{\tau^{PH}_A}\left[P^{PH}_{IND} - y_{K+2\,I+J+14}\right] . \qquad \text{(k-63)}$$

NOTRUMP currently treats Equations (K-50) - (K-63) explicitly. Therefore, the numerous derivatives which would otherwise be required for the generation of A_{ZW}, A_{ZU}, A_{ZM}, A_{ZT}, A_{WZ}, A_{UZ}, A_{MZ}, A_{TZ}, and A_{ZZ} from Equation (E-5) need not be calculated. If Equations (K-50) -(K-63) were treated implicitly, a large number of derivative calculations would have to be "hard-wired" into the code logic. In addition, the matrix of Equation (E-10) would have to be larger.

APPENDIX L

THERMODYNAMIC WATER PROPERTIES

The purpose of this appendix is to describe the set of thermodynamic water properties currently used in NOTRUMP. In Section 3.0, we discussed the "pressure search" for interior fluid nodes but only to the extent that the pressure in a node is a function of the internal energy and mass in the node, i.e. $P = P(U,M)$. We shall describe here how the pressure search is performed. We shall also describe how all other properties (including derivatives) are obtained. Finally, we shall show how all properties (excluding derivatives) are calculated given the pressure, P, and the enthalpy, h. This calculation is performed for boundary fluid nodes and for the initialization of all fluid nodes.

The properties are given in tabular form. Table L-1 gives P_{sat}, T_{sat}, h_f, u_f, ρ_f, $(\partial P/\partial u)\rho_f$, $(\partial h/\partial P)\rho_f$, and $(\partial T/\partial P)\rho_f$. Table L-2 gives P_{sat}, T_{sat}, h_g, u_g, ρ_g, $(\partial P/\partial u)\rho_g$, $(\partial h/\partial P)\rho_g$, and $(\partial T/\partial P)\rho_g$. The derivatives are evaluated at constant saturation densities.

We now describe the pressure search using these properties. The pressure in interior fluid node i is determined from the requirement that the total fluid mass in the node, M_i, with total internal energy, U_i, must fill the total volume of the node, V_i. For the properties being used, pressure is an independent variable rather than a dependent variable. Therefore, the pressure must be determined iteratively.

Enthalpy is the other independent variable. From the definition of enthalpy, we can relate it to U_i, M_i, and V_i as follows:

$$h_i = u_i + \frac{144}{J} P_i v_i = \frac{U_i}{M_i} + 0.18511\, P_i \frac{V_i}{M_i} . \qquad \text{(L-1)}$$

Specific volume is a thermodynamic function of pressure and enthalpy. The product of the total mass and the specific volume must equal the total volume of the node, i.e.,

$$M_i \, v(P_i, h_i) = V_i \quad . \tag{L-2}$$

Combining Equations (L-1) and (L-2), we obtain a transcendental equation for P_i in terms of U_i, M_i, and v_i,

$$M_i \, v(P_i, \frac{U_i}{M_i} + 0.18511 \, P_i \frac{V_i}{M_i}) = V_i \quad . \tag{L-3}$$

We must solve Equation (L-3) iteratively for P_i.

The following procedure is used to solve Equation (L-3) for P_i given U_i, M_i, and V_i:

1. Guess an initial P_i.

2. Calculate h_i using Equation (L-1)

3. Calculate $v'(P_i, h_i)$.

4. If v' equals v_i, then the search is over.

5. If v' is not equal to v_i, then the pressure guess is incremented in the appropriate direction and steps 1-5 are repeated.

When successive values of v' are just above and below v_i, a linear interpolation on the last two pressure guesses is made to determine the final value for P_i. The error in this search procedure is limited to the non-linearity of the P-v relationship over the pressure increment. A 10 psi increment is used for pressures above 25 psia and a 0.2 psi increment is used for pressures below 25 psia. The initial pressure guess is always taken as the pressure from the previous time step for the particular node.

The above procedure is used only for a two-phase mixture. For subcooled liquid, the pressure is calculated from

$$P_i = \bar{P}(\rho_f - \frac{M_i}{V_i}) + [\overline{(\frac{\partial P}{\partial u})\rho_f} - \frac{M_i}{V_i}] \cdot [\frac{U_i}{M_i} - \bar{u}_f(\rho_f - \frac{M_i}{V_i})] \tag{L-4}$$

where the "barred" quantities refer to linearly interpolated values from Table L-1 with ρ_f as the independent variable having the value M_i/V_i. For superheated steam, Table L-2 is used to give

$$P_i = \bar{P}(\rho_g = \frac{M_i}{V_i}) + [\overline{(\frac{\partial P}{\partial u})\rho_g} = \frac{M_i}{V_i}] \quad [\frac{U_i}{M_i} - \bar{u}_g(\rho_g = \frac{M_i}{V_i})] \tag{L-5}$$

Other properties are calculated during or after the pressure search. They are temperature, the saturation properties, quality, and enthalpy.

For a two-phase mixture, the temperature, the saturation properties, and the quality x_i are calculated at each step of the iterative pressure search from

$$(T_f)_i = \overline{T_{sat}}\ (P_i) \tag{L-6}$$

$$(T_{sat})_i = \overline{T_{sat}}\ (P_i) \tag{L-7}$$

$$(h_f)_i = \overline{h_f}\ (P_i) \tag{L-8}$$

$$(h_g)_i = \overline{h_g}\ (P_i) \tag{L-9}$$

$$(v_f)_i = [\bar{\rho}_f\ (P_i)]^{-1} \tag{L-10}$$

$$(v_g)_i = [\bar{\rho}_g\ (P_i)]^{-1} \tag{L-11}$$

$$x_i = \frac{\frac{U_i}{M_i} + 0.18511\ P_i \frac{V_i}{M_i} - (h_f)_i}{(h_g)_i - (h_f)_i} \tag{L-12}$$

After the pressure search, the enthalpy is obtained from

$$h_i = x_i\ (h_g)_i + (1-x_i)(h_f)_i \tag{L-13}$$

For subcooled liquid, the temperature is calculated from

$$T_i = \overline{T_{sat}}\ (\rho_f = \frac{M_i}{V_i}) + [\overline{(\frac{\partial P}{\partial u})\rho_f} = \frac{M_i}{V_i}]\quad [\overline{(\frac{\partial T}{\partial P})\rho_f} = \frac{M_i}{V_i}] \cdot [\frac{U_i}{M_i} - \bar{u}_f\ (\rho_f = \frac{M_i}{V_i})]\ . \tag{L-14}$$

The saturation properties are calculated from Equations (L-7) - (L-11). The quality is set to zero. The enthalpy is obtained from Equation (L-1).

For superheated steam, the temperature is calculated from

$$T_i = \bar{T}_{sat}\ (\rho_g = \frac{M_i}{V_i}) + [\overline{(\frac{\partial P}{\partial u})\rho_g} = \frac{M_i}{V_i}]\quad [(\frac{\partial \bar{T}}{\partial P})\rho_g = \frac{M_i}{V_i}] \cdot [\frac{U_i}{M_i} - \bar{u}_g\ (\rho_g = \frac{M_i}{V_i})]\ . \tag{L-15}$$

The saturation properties are calculated from Equations (L-7) - (L-11). The quality is set to one. The enthalpy is obtained from Equation (L-1).

In addition to all the other properties, certain derivatives are also calculated during or after the pressure search. They are $(\frac{\partial P_i}{\partial U_i})_{M_i}$, $(\frac{\partial T_i}{\partial U_i})_{M_i}$, $(\frac{\partial P_i}{\partial M_i})_U$, $(\frac{\partial T_i}{\partial M_i})_{U_i}$, and $(\frac{\partial (T_{sat})_i}{\partial P_i})$.

For a two-phase mixture,

$$(\frac{\partial P_i}{\partial U_i})_{M_i} = \frac{1}{M_i}\ [\frac{1}{v_i^2}\ (\frac{\partial P_i}{\partial \rho_i})_{u_i} \cdot (\frac{\partial v_i}{\partial u_i})_{P_i}], \tag{L-16}$$

$$(\frac{\partial T_i}{\partial U_i})_{M_i} = \frac{1}{M_i}\ [\frac{1}{v_i^2}\ (\frac{\partial T_i}{\partial \rho_i})_{u_i} \cdot (\frac{\partial v_i}{\partial u_i})_{P_i}], \tag{L-17}$$

$$(\frac{\partial P_i}{\partial M_i})_{U_i} = \frac{1}{V_i}\ [(\frac{\partial P_i}{\partial \rho_i})_{u_i} - u_i\ v_i (\frac{\partial P_i}{\partial u_i})_{v_i}], \tag{L-18}$$

and

$$\left(\frac{\partial T_i}{\partial M_i}\right)_{U_i} = \frac{1}{V_i}\left[\left(\frac{\partial T_i}{\partial \rho_i}\right)_{u_i} - u_i\, v_i \left(\frac{\partial T_i}{\partial u_i}\right)_{v_i}\right] \tag{L-19}$$

where

$$\left(\frac{\partial P_i}{\partial \rho_i}\right)_{u_i} = \frac{P_i' - P_i''}{\rho' - \rho''}, \tag{L-20}$$

$$\left(\frac{\partial T_i}{\partial \rho_i}\right)_{u_i} = \frac{T_i' - T_i''}{\rho' - \rho''}, \tag{L-21}$$

$$\left(\frac{\partial P_i}{\partial u_i}\right)_{v_i} = M_i \left(\frac{\partial P_i}{\partial u_i}\right)_{M_i}, \tag{L-22}$$

and

$$\left(\frac{\partial T_i}{\partial u_i}\right)_{v_u} = M_i \left(\frac{\partial T_i}{\partial u_i}\right)_{M_i} . \tag{L-23}$$

The primed and double-primed quantities refer to the last and next-to-last iterations in the pressure search.

For subcooled liquid,

$$\left(\frac{\partial P_i}{\partial U_i}\right)_{M_i} \approx \frac{1}{M_i} \cdot \left[\overline{\left(\frac{\partial P}{\partial u}\right)_{\rho_f}} = \frac{M_i}{V_i}\right], \tag{L-24}$$

$$\left(\frac{\partial T_i}{\partial U_i}\right)_{M_i} \approx \frac{1}{M_i} \cdot \left[\overline{\left(\frac{\partial P}{\partial u}\right)_{\rho_f}} = \frac{M_i}{V_i}\right] \cdot \left[\overline{\left(\frac{\partial T}{\partial P}\right)_{\rho_f}} = \frac{M_i}{V_i}\right] \tag{L-25}$$

$$\left(\frac{P_i}{M_i}\right)_{U_i} \approx \frac{P_{sat}^{n} + \left(\frac{\partial P}{\partial u}\right)_{\rho_f}^{n} \cdot [u_i - u_f^n] - P_{sat}^{n-1} - \left(\frac{\partial P}{\partial u}\right)_{\rho_f}^{n-1} \cdot \left[u_i \frac{\rho_f^n}{\rho_f^{n-1}} - u_f^{n-1}\right]}{\rho_f^n - \rho_f^{n-1}} , \tag{L-26}$$

and

$$\left(\frac{\partial T_i}{\partial M_i}\right)_{U_i} \approx \frac{T_{sat}^{n} + \left(\frac{\partial P}{\partial u}\right)_{\rho_f}^{n} \left(\frac{\partial T}{\partial P}\right)_{\rho_f}^{n} \cdot [u_i - u_f^n] - T_{sat}^{n-1} - \left(\frac{\partial P}{\partial u}\right)_{\rho_f}^{n-1} \cdot \left(\frac{\partial T}{\partial P}\right)_{\rho_f}^{n-1} \cdot \left[u_i \frac{\rho_f^n}{\rho_f^{n-1}} - u_f^{n-1}\right]}{\rho_f^n - \rho_f^{n-1}} \tag{L-27}$$

The indices n and n-1 refer to two contiguous rows in Table L-1 such that ρ_f^n and ρ_f^{n-1} bracket $1/v_i$.

For superheated steam,

$$\left(\frac{\partial P_i}{\partial U_i}\right)_{M_i} = \frac{1}{M_i} \left[\left(\frac{\partial P}{\partial u}\right)_{\rho_g} = \frac{M_i}{V_i}\right], \tag{L-28}$$

$$\left(\frac{\partial T_i}{\partial U_i}\right)_{M_i} = \frac{1}{M_i} \left[\left(\frac{\overline{\partial P}}{\partial u}\right)_{\rho_g} = \frac{M_i}{V_i}\right] \cdot \left[\left(\frac{\overline{\partial T}}{\partial P}\right)_{\rho_g} = \frac{M_i}{V_i}\right], \tag{L-29}$$

$$\left(\frac{\partial P_i}{\partial M_i}\right)_{U_i} = \frac{P_{sat}^n + \left(\frac{\partial P}{\partial u}\right)_{\rho_g}^n \cdot [u_i - u_g^n] - P_{sat}^n - \left(\frac{\partial P}{\partial u}\right)_{\rho_f}^{n-1} \left[u_i \frac{\rho_g^n}{\rho_g^{n-1}} - u_g\right]}{\rho_g^n - \rho_g^{n-1}} \tag{L-30}$$

and

$$\left(\frac{\partial T_i}{\partial M_i}\right)_{U_i} = \frac{T_{sat}^n + \left(\frac{\partial P}{\partial u}\right)_{\rho_g}^n \left(\frac{\partial T}{\partial P}\right)_{\rho_g}^n [u_i - u_g^n] - T_{sat}^{n-1} - \left(\frac{\partial P}{\partial u}\right)_{\rho_g}^{n-1} \left(\frac{\partial T}{\partial P}\right)_{\rho_g}^{n-1} \left[u_i \frac{\rho_g^n}{\rho_g^{n-1}} - u_g\right]}{\rho_g^n - \rho_g^{n-1}} . \tag{L-31}$$

The indices n and n-1 refer to two contiguous rows in Table L-2 such that ρ_g^n and ρ_g^{n-1} bracket $1/v_i$.

The derivative $\frac{\partial (T_{sat})_i}{\partial P_i}$ is calculated from

$$\frac{\partial (T_{sat})_i}{\partial P_i} = \frac{T_{sat}^n - T_{sat}^{n-1}}{P^n - P^{n-1}} \tag{L-32}$$

where the indices n and n-1 refer to two contiguous rows in either Table L-1 or L-2 such that P^n and P^{n-1} bracket P_i.

We have described the pressure search, where U, M, and V in an interior fluid node are known and where P and the other properties (including derivatives) are calculated. We now describe how, given P and h, other properties are calculated. This calculation is done for boundary fluid nodes and for the initialization of all fluid nodes.

For fluid node i, given P_i and h_i, the saturation temperature and the saturation properties are calculated from Equations (L-7) - (L-11). The derivative $\frac{\partial (T_{sat})_i}{\partial P_i}$ is calculated from Equation (L-32).

If $(h_f)_i < h_i < (h_g)_i$, the fluid is a two-phase mixture. Therefore, T_i is set to $(T_{sat})_i$ and the quality χ_i is calculated from

$$\chi_i = \frac{h_i - (h_f)_i}{(h_g)_i - (h_f)_i} \quad . \tag{L-33}$$

The specific volume is calculated from

$$v_i = \chi_i \, (v_g)_i + (1 - \chi_i)(v_f)_i \quad . \tag{L-34}$$

If $h_i \leq (h_f)_i$, the fluid is subcooled. The quality χ_i is set to zero. The temperature and specific volume are calculated from

$$T_i = T^*_{sat} + \left(\frac{\partial T}{\partial P}\right)^*_{\rho_f} \cdot [P_i - P^*_{sat}] \tag{L-35}$$

and

$$v_i = \frac{1}{\rho^*_f} \tag{L-36}$$

where

$$T^*_{sat} = F^n \, T^n_{sat} + F^{n-1} \, T^{n-1}_{sat} \quad , \tag{L-37}$$

$$\left(\frac{\partial T}{\partial P}\right)^{*}_{\rho_f} = F^n \left(\frac{\partial T}{\partial P}\right)^{n}_{\rho_f} + F^{n-1} \left(\frac{\partial T}{\partial P}\right)^{n-1}_{\rho_f}, \tag{L-38}$$

$$P^{*}_{sat} = F^n P^{n}_{sat} + F^{n-1} P^{n-1}_{sat}, \tag{L-39}$$

$$\rho_f^{*} = F^n \rho_f^{n} + F^{n-1} \rho_f^{n-1}, \tag{L-40}$$

$$F^n = \frac{h_i - h^{n-1}}{h^n - h^{n-1}}, \tag{L-41}$$

$$F^{n-1} = \frac{h^n - h_i}{h^n - h^{n-1}}, \tag{L-42}$$

$$h^n = h_f^n + \left(\frac{\partial h}{\partial P}\right)^{n}_{\rho_f} \cdot [P_i - P^{n}_{sat}], \tag{L-43}$$

and

$$h^{n-1} = h_f^{n-1} + \left(\frac{\partial h}{\partial P}\right)^{n-1}_{\rho_f} \cdot [P_i - P^{n-1}_{sat}]. \tag{L-44}$$

The indices n and n-1 refer to two contiguous rows in Table L-1 such that h^n and h^{n-1} bracket h_i.

If $h_i \geq (h_g)_i$, the fluid is superheated. The quality χ_i is set to one. The temperature and specific volume are calculated from

$$T_i = T^{*}_{sat} + \left(\frac{\partial T}{\partial P}\right)^{*}_{\rho_g} \cdot [P_i - P^{*}_{sat}] \tag{L-45}$$

and

$$v_i = \frac{1}{\rho_g^{*}} \tag{L-46}$$

where

$$\left(\frac{\partial T}{\partial P}\right)^{*}_{\rho_g} = F^n \left(\frac{\partial T}{\partial P}\right)^{n}_{\rho_g} + F^{n-1} \left(\frac{\partial T}{\partial P}\right)^{n-1}_{\rho_g}, \tag{L-47}$$

$$\rho_g^{*} = F^n \rho_g^{n} + F^{n-1} \rho_g^{n-1}, \tag{L-48}$$

$$h^n = h_g^n + \left(\frac{\partial h}{\partial P}\right)_{\rho_g}^n \cdot [P_i - P_{sat}^n] \quad , \tag{L-49}$$

and

$$h^n = h_g^n + \left(\frac{\partial h}{\partial P}\right)_{\rho_g}^{n-1} [P_i - P_{sat}^{n-1}] \; . \tag{L-50}$$

T_{sat}^*, P_{sat}^*, F^n, and F^{n-1} are given by Equations (L-37), (L-39), (L-41), and (L-42), respectively.

TABLE L-1

SUBCOOLED AND SATURATED WATER THERMODYNAMIC PROPERTIES

P_{sat}	T_{sat}	h_f	u_f	ρ_f	$(\frac{\partial P}{\partial u})_{\rho_f}$	$(\frac{\partial h}{\partial P})_{\rho_f}$	$(\frac{\partial T}{\partial P})_{\rho_f}$
-1.000	-10000.000	-10000.000	-10000.000	151.00000	100.0	.01038	.01038
.200	53.140	23.701	23.700	62.33300	98.1	.01316	.00800
1.000	101.740	71.203	71.200	61.96000	115.7	.01163	.00850
3.000	141.480	110.169	110.160	61.35000	125.5	.01099	.00840
5.000	162.240	130.195	130.180	60.98000	139.5	.01020	.00833
9.000	188.280	156.028	156.000	60.38650	144.1	.01001	.00829
14.696	212.000	181.265	181.220	59.81000	155.2	.00954	.00824
30.000	250.330	219.924	219.830	58.78900	162.0	.00932	.00770
50.000	281.010	250.700	250.540	57.90000	163.0	.00933	.00718
100.000	327.810	298.400	298.072	56.37000	164.0	.00938	.00762
200.000	381.790	355.400	354.719	54.38000	163.0	.00954	.00743
400.000	444.590	424.000	422.568	51.71000	158.0	.00991	.00873
600.000	486.210	471.600	469.364	49.68000	149.0	.01044	.00941
800.000	518.230	508.800	506.710	47.92000	140.0	.01101	.01012
1000.000	544.610	542.400	538.404	46.32000	132.0	.01157	.01094
1200.000	567.220	571.700	566.744	44.82000	124.0	.01219	.01160
1400.000	587.100	598.700	592.725	43.37000	115.0	.01296	.01238
1600.000	604.900	624.200	617.135	41.92000	107.0	.01376	.01386
1800.000	621.030	648.300	640.063	40.45000	98.0	.01478	.01439
2000.000	635.820	671.700	662.193	38.94000	90.0	.01586	.01608
2200.000	649.460	694.800	683.902	37.37000	82.0	.01715	.01818
2400.000	662.120	718.400	705.966	35.73000	75.0	.01851	.01947
2600.000	673.940	743.000	728.802	33.89830	67.0	.02039	.02265
2800.000	684.990	770.100	753.773	31.74600	59.0	.02278	.02905
3000.000	695.360	802.500	783.284	28.90000	47.0	.02768	.03571
3206.200	705.400	902.700	872.847	19.88070	32.0	.04056	.04717

TABLE L-2

SUPERHEATED AND SATURATED WATER THERMODYNAMIC PROPERTIES

P_{sat}	T_{sat}	h_g	u_g	ρ_g	$(\frac{\partial P}{\partial u})_{\rho_g}$	$(\frac{\partial h}{\partial P})_{\rho_g}$	$(\frac{\partial T}{\partial P})_{\rho_g}$
0.		1100.000	1038.000	10.0E-10	10.0E-10	10.0E-10	10.0E-10
.200	53.140	1081.496	1025.000	.00066	.00100	1282.48131	3000.00000
1.000	101.740	1106.000	1044.297	.00300	.00476	272.00000	559.13001
3.000	141.480	1120.922	1055.000	.00842	.01000	121.97412	280.00000
5.000	162.240	1131.100	1063.045	.01360	.02237	58.31667	122.96000
9.000	188.280	1139.638	1069.000	.02358	.03500	36.42006	70.00000
14.696	212.000	1150.380	1077.467	.03731	.05779	22.26616	40.98859
30.000	250.330	1165.334	1089.000	.07275	.09000	13.65558	24.00000
50.000	281.010	1174.100	1095.290	.11744	.16885	7.49875	13.99987
100.000	327.810	1187.200	1105.159	.22563	.36124	3.58864	7.12716
200.000	381.790	1198.400	1113.693	.43706	.69314	1.86625	3.55131
400.000	444.590	1204.500	1118.512	.86110	1.36420	.94800	1.72109
600.00	486.210	1203.200	1117.701	1.29904	1.97627	.64850	1.12974
800.000	518.230	1198.600	1114.383	1.75840	2.42056	.51840	.88177
1000.000	544.610	1191.800	1109.315	2.24417	3.49370	.36871	.61099
1200.000	567.220	1183.400	1103.010	2.78319	4.24242	.30271	.48987
1400.000	587.100	1173.400	1095.343	3.32005	4.96168	.25730	.39895
1600.000	604.900	1162.100	1086.634	3.92465	4.96168	.25730	.32374
1800.000	621.030	1149.400	1076.796	4.58926	6.06477	.21705	.25462
2000.000	635.820	1135.100	1065.573	5.32481	7.98889	.15994	.20261
2200.000	649.460	1119.200	1053.023	6.15385	9.10939	.13986	.16467
2400.000	662.120	1101.100	1038.592	7.10732	11.50000	.11300	.14534
2600.000	673.940	1080.200	1021.820	8.24400	13.15000	.09850	.12044
2800.000	684.990	1054.900	1001.156	9.66200	15.50000	.08367	.10682
3000.000	695.360	1020.500	972.653	11.65500	18.92000	.06874	.07732
3206.200	705.400	902.700	872.847	19.88070	32.00000	.04056	.04717

APPENDIX M
BREAK FLOW MODELS

In this appendix, we discuss the various break flow models included in NOTRUMP. They are incorporated as critical flow links and are treated implicitly. For critical flow link k the following quantities are calculated: the total mass flow rate W_k, the liquid mass flow rate $(W_f)_k$, the vapor mass flow rate $(W_g)_k$, total enthalpy flow rate $(hW)_k$, the void fraction α_k, the flow quality X^f_k, the derivative $\partial(hW)_k/\partial W_k$, the specific volume v_k, and the derivatives $\partial W_k/\partial P_{u(k)}$, $\partial W_k/\partial h_{u(k)}$, $\partial W_k/\partial P_{d(k)}$, $\partial W_k/\partial h_{d(k)}$, $\partial(hW)_k/\partial P_{u(k)}$, $\partial(hW)_k/\partial h_{u(k)}$, $\partial(hW)_k/\partial P_{d(k)}$, and $\partial(hW)_k/\partial h_{d(k)}$.

M.1 Preliminary Calculations

The break flow models use the donor stagnation pressure, the recipient stagnation pressure, and the donor stagnation enthalpy as the independent variables. For most break flow models, they are calculated as follows:

For critical flow link k, the upstream and downstream stagnation pressures are calculated first from

$$P^{stag}_{u(k)} = (P_u)_k \tag{M-1}$$

and

$$P^{stag}_{d(k)} = (P_d)_k \tag{M-2}$$

The donor and recipient nodes are then determined as follows: donor (k) = u(k) and recipient (k) = d(k) if $P^{stag}_{u(k)} \geq P^{stag}_{d(k)}$; donor (k) = d(k) and recipient (k) = u(k) if $P^{stag}_{u(k)} < P^{stag}_{d(k)}$. Thus, $P^{stag}_{donor(k)}$ and $P^{stag}_{recipient(k)}$ are set.

The donor stagnation enthalpy is calculated next.

$$h^{stag}_{donor(k)} = (1 - X^s) \cdot \min\left[(h_f)_{donor(k)}, h_{donor(k)}\right] + X^s \cdot \max\left[(h_g)_{donor(k)}, h_{donor(k)}\right], \tag{M-3}$$

where

$$\chi^s = \frac{\alpha}{\alpha + (1 - \alpha)\,\gamma} \quad , \tag{M-4}$$

$$\alpha = \begin{cases} (\alpha_{mix})_{donor(k)} & \text{if} \quad y_{pipe} \geq R_{pipe} \\ F_{mix}(\alpha_{mix})_{donor(k)} + (1-F_{mix}) \cdot 1 & \text{if} \quad -R_{pipe} < y_{pipe} < R_{pipe} \\ 1 & \text{if} \quad -R_{pipe} > y_{pipe} \end{cases} \tag{M-5}$$

$$F_{mix} = \min[\max[(\theta+\tfrac{\pi}{2})R_{pipe}^2 + \frac{x_{pipe}\, y_{pipe}}{\pi\, R_{pipe}^2}, 0], 1], \tag{M-6}$$

$$\theta = \sin^{-1} \frac{y_{pipe}}{x_{pipe}} \quad , \tag{M-7}$$

$$x_{pipe} = (R_{pipe}^2 - y_{pipe}^2)^{1/2} \quad , \tag{M-8}$$

$$y_{pipe} = (E_{mix})_{donor(k)} - (E_{donor})_k \quad , \tag{M-9}$$

and

$$R_{pipe} = \max(\tfrac{1}{2}(D_{cont})_k, 0). \tag{M-10}$$

α_{mix} is the void fraction in the fluid node mixture. D_{cont} is the continuous flow link diameter (D_{cont} is zero for point contact flow links). The donor stagnation state is determined to be subcooled if $h^{stag}_{donor(k)} \leq h_f(P^{stag}_{donor(k)})$, saturated if $h_f(P^{stag}_{donor(k)}) < h^{stag}_{donor(k)} < h_g(P^{stag}_{donor(k)})$, and superheated if $h^{stag}_{donor(k)} > h_g(P^{stag}_{donor(k)})$.

M.2 Choked Flow Models

The following available models all assume choked flow. The model actually used will depend on user specifications and the donor stagnation state.

M.2.2 Moody Correlation[26]

The Moody correlation can be used for a subcooled or saturated donor stagnation state. For critical flow link k, subroutine GPMØØDY is called to give the maximum mass flux $G(P^{stag}_{donor(k)}, h^{stag}_{donor(k)})$, the static throat pressure $P^t(P^{stag}_{donor(k)}, h^{stag}_{donor(k)})$, and the partial derivatives $\frac{\partial G}{\partial P^{stag}_{donor(k)}}$ and $\frac{\partial G}{\partial h^{stag}_{donor(k)}}$. Since the

Moody correlation assumes an isentropic flow process, the donor static state at the throat can be found by comparing $s(P^{stag}_{donor(k)}, h^{stag}_{donor(k)})$ with saturation entropies at the throat.

For a subcooled or saturated donor stagnation state, we have

$$\frac{\partial(hW)_k}{\partial W_k} = h^{stag}_{donor(k)} \quad , \tag{M-11}$$

$$v_k = v(P^{stag}_{donor(k)}, h^{stag}_{donor(k)}) \tag{M-12}$$

$$\frac{\partial G}{\partial P^{stag}_{recipient(k)}} = 0 \tag{M-13}$$

and

$$\frac{\partial G}{\partial h^{stag}_{recipient(k)}} = 0 \quad . \tag{M-14}$$

M.2.3 Modified Zaloudek Correlation

The modified Zaloudek correlation can be used for a subcooled donor stagnation state. The original Zaloudek correlation[28] is

$$G(P^{stag}_{donor(k)}, h^{stag}_{donor(k)}) = 0.95\left[\frac{288 g_c (P^{stag}_{donor(k)} - P_{sat}(h^{stag}_{donor(k)}))}{v(P^{stag}_{donor(k)}, h^{stag}_{donor(k)})}\right]^{1/2} . \tag{M-15}$$

This has been modified as follows:

[a,c

]

a,c [

]

[

a,c

]

a,c

[ ]

M.2.4 Orifice Equation

The orifice equation can be used for a subcooled donor stagnation state. The mass flux is given by

$$G(p^{stag}_{donor(k)}, p^{stag}_{recipient(k)}, h^{stag}_{donor(k)}) = C_2\left[\frac{288 g_c (p^{stag}_{donor(k)} - p^{stag}_{recipient(k)})}{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}\right]^{1/2}. \quad \text{(M-31)}$$

C_2 is a user-specified constant. The static throat pressure is given by

$$p^t(p^{stag}_{donor(k)}) = 0.58\, p^{stag}_{donor(k)}. \quad \text{(M-32)}$$

The remaining quantities are calculated as follows:

$$\frac{\partial G}{\partial p^{stag}_{donor(k)}} = \frac{1}{2}\,\frac{G(p^{stag}_{donor(k)}, p^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{p^{stag}_{donor(k)} - p^{stag}_{recipient(k)}}$$

$$- \frac{1}{2}\,\frac{G(p^{stag}_{donor(k)}, p^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}\left(\frac{-\partial v}{\partial p^{stag}_{donor(k)}}\right)_{h^{stag}_{donor(k)}}. \quad \text{(M-33)}$$

$$\frac{\partial G}{\partial h^{stag}_{donor(k)}} = -\frac{1}{2}\,\frac{G(p^{stag}_{donor(k)}, p^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}\left(\frac{\partial v}{\partial h^{stag}_{donor(k)}}\right)_{p^{stag}_{donor(k)}}. \quad \text{(M-34)}$$

$$\frac{\partial G}{\partial p^{stag}_{recipient(k)}} = -\frac{1}{2}\frac{G(p^{stag}_{donor(k)}, p^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{p^{stag}_{donor(k)} - p^{stag}_{recipient(k)}} \quad . \tag{M-35}$$

$$\frac{\partial G}{\partial h^{stag}_{recipient(k)}} = 0 \quad . \tag{M-36}$$

$$\alpha_k = 0 \tag{M-37}$$

$$X^f_k = 0 \quad . \tag{M-38}$$

$$\frac{\partial (hW)_k}{\partial W_k} = h^{stag}_{donor(k)} \tag{M-39}$$

$$v_k = v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) \tag{M-40}$$

The derivatives $(\frac{\partial v}{\partial p^{stag}_{donor(k)}})_{h^{stag}_{donor(k)}}$ and $(\frac{\partial v}{\partial h^{stag}_{donor(k)}})_{p^{stag}_{donor(k)}}$ are given by Equations (M-46) and (M-47), respectively.

M.2.5 Murdock And Baumann Correlation

The Murdock and Baumann correlation can be used for a superheated donor stagnation state. The mass flux is given by

$$G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) = C_3\left[\frac{288 g_c p^{stag}_{donor(k)}}{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}\right]^{1/2} \quad . \tag{M-41}$$

C_3 is a user-specified constant. The static throat pressure is given by

$$p^t(p^{stag}_{donor(k)}) = 0.58\ p^{stag}_{donor(k)} \quad . \tag{M-42}$$

The remaining quantities are calculated as follows:

$$\frac{\partial G}{\partial p^{stag}_{donor(k)}} = \frac{1}{2}\frac{G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}{p^{stag}_{donor(k)} - p^{stag}_{recipient(k)}}$$

$$- \frac{1}{2}\frac{G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}\left(\frac{\partial v}{\partial p^{stag}_{donor(k)}}\right)_{h^{stag}_{donor(k)}} \quad . \tag{M-43}$$

$$\frac{\partial G}{\partial h^{stag}_{donor(k)}} = \frac{-1}{2} \frac{G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})} \left(\frac{\partial v}{\partial h^{stag}_{donor(k)}}\right)_{p^{stag}_{donor(k)}} . \quad \text{(M-44)}$$

$$\frac{\partial G}{\partial p^{stag}_{recipient(k)}} = 0 . \quad \text{(M-45)}$$

$$\frac{\partial G}{\partial h^{stag}_{recipient(k)}} = 0 . \quad \text{(M-46)}$$

$$\alpha_k = 1 . \quad \text{(M-47)}$$

$$X^f_k = 1 . \quad \text{(M-48)}$$

$$\frac{\partial (hW)_k}{\partial W_k} = h^{stag}_{donor(k)} . \quad \text{(M-49)}$$

$$v_k = v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) . \quad \text{(M-50)}$$

$$\left(\frac{\partial v}{\partial p^{stag}_{donor(k)}}\right)_{h^{stag}_{donor(k)}} = - \frac{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) - v(p^{stag}_{donor(k)} - 10, h^{stag}_{donor(k)})}{10} . \quad \text{(M-51)}$$

$$\left(\frac{\partial v}{\partial h^{stag}_{donor(k)}}\right)_{p^{stag}_{donor(k)}} = \frac{v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)} + 10) - v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}{10} . \quad \text{(M-52)}$$

M.2.6 ASME Steam Property Sub-Program (CRFLØ)

ASME steam property sub-program CRFLØ returns $G^*(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})$, the mass flux of superheated steam in units of lbm/hr/in^2. The mass flux in units of lbm/sec/ft^2 is given by

$$G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) = C_4 \frac{144}{3600} G^*(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) . \quad \text{(M-53)}$$

C_4 is a user-specified constant. The static throat pressure is given by

$$p^t(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) = \left(\frac{2}{\gamma + 1}\right)^{\left(\frac{\gamma}{\gamma - 1}\right)} \quad \text{(M-54)}$$

where γ is the isentropic exponent and is given by

$$\gamma = \frac{C_p(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}{C_v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})} \quad . \tag{M-55}$$

γ is returned by sub-program CRVEL.

The remaining quantities are calculated as follows:

$$\frac{\partial G}{\partial p^{stag}_{donor(k)}} = \frac{G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) - G(p^{stag}_{donor(k)} - 10, h^{stag}_{donor(k)})}{10} \quad . \tag{M-56}$$

$$\frac{\partial G}{\partial h^{stag}_{donor(k)}} = \frac{G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)} + 10) - G(p^{stag}_{donor(k)}, h^{stag}_{donor(k)})}{10} \tag{M-57}$$

$$\frac{\partial G}{\partial p^{stag}_{recipient(k)}} = 0 \quad . \tag{M-58}$$

$$\frac{\partial G}{\partial h^{stag}_{recipient(k)}} = 0 \quad . \tag{M-59}$$

$$\alpha_k = 1 \quad . \tag{M-60}$$

$$X^f_k = 1 \quad . \tag{M-61}$$

$$\frac{\partial (hW)_k}{\partial W_k} = h^{stag}_{donor(k)} . \tag{M-62}$$

$$v_k = v(p^{stag}_{donor(k)}, h^{stag}_{donor(k)}) \tag{M-63}$$

M.3 Unchoked Flow Model

For totally unchoked flow the following model is used:

$$G(p^{stag}_{donor(k)}, p^{stag}_{recipient(k)}, h^{stag}_{donor(k)}) = C_5 \left[\frac{288 g_c (p^{stag}_{donor(k)} - p^{stag}_{recipient(k)})}{v(p^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}\right]^{1/2} . \tag{M-64}$$

C_5 is a user-specified constant. The remaining quantities are calculated as follows:

$$\frac{\partial G}{\partial P^{stag}_{donor(k)}} = \frac{1}{2}\frac{G(P^{stag}_{donor(k)}, P^{stag}_{recipient(k)}, h^{stag}_{donor(k)}}{P^{stag}_{donor(k)} - P^{stag}_{recipient(k)}} \quad . \tag{M-65}$$

$$\frac{\partial G}{\partial h^{stag}_{donor(k)}} = -\frac{1}{2}\frac{G(P^{stag}_{donor(k)}, P^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{v(P^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}\left(\frac{\partial v}{\partial h^{stag}_{donor(k)}}\right)_{P^{stag}_{donor(k)}} . \tag{M-66}$$

$$\frac{\partial G}{\partial P^{stag}_{recipient(k)}} = -\frac{1}{2}\frac{G(P^{stag}_{donor(k)}, P^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{P^{stag}_{donor(k)} - P^{stag}_{recipient(k)}} \quad .$$

$$-\frac{1}{2}\frac{G(P^{stag}_{donor(k)}, P^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{}\left(\frac{\partial v}{\partial P^{stag}_{recipient(k)}}\right)_{h^{stag}_{donor(k)}} . \tag{M-67}$$

$$\frac{\partial G}{\partial h^{stag}_{recipient(k)}} = 0 \quad . \tag{M-68}$$

If $h^{stag}_{donor(k)} \leq h_f(P^{stag}_{recipient(k)})$, then the flow is subcooled and we have:

$$\left(\frac{\partial v}{\partial h^{stag}_{donor(k)}}\right)_{P^{stag}_{recipient(k)}} = \frac{v(P^{stag}_{recipient(k)}, h^{stag}_{donor(k)}) - v(P^{stag}_{recipient(k)}, h^{stag}_{donor(k)} - 10)}{10} \tag{M-69}$$

and

$$\left(\frac{\partial v}{\partial P^{stag}_{recipient(k)}}\right)_{h^{stag}_{donor(k)}} = \frac{v(P^{stag}_{recipient(k)} + 10, h^{stag}_{donor(k)}) - v(P^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{10} \tag{M-70}$$

If $h_f(P^{stag}_{recipient(k)}) < h^{stag}_{donor(k)} < h_g(P^{stag}_{recipient(k)})$, then the flow is saturated and we have

$$\left(\frac{\partial v}{\partial h^{stag}_{donor}}\right)_{P^{stag}_{recipient(k)}} = \frac{v_g(P^{stag}_{recipient(k)}) - v_f(P^{stag}_{recipient(k)})}{h_g(P^{stag}_{recipient(k)}) - h_f(P^{stag}_{recipient(k)})} \tag{M-71}$$

and

$$\left(\frac{\partial v}{\partial P^{stag}_{recipient(k)}}\right)_{h^{stag}_{donor(k)}} = (1-X)\frac{dv_f}{dP^{stag}_{recipient(k)}} + X\frac{dv_g}{dP^{stag}_{recipient(k)}} \tag{M-72}$$

$$- \left(\frac{\partial v}{\partial h^{stag}_{donor(k)}}\right)_{p^{stag}_{recipient(k)}} \cdot \left[(1-X)\frac{dh_f}{dp^{stag}_{recipient(k)}} + X\frac{dh_g}{dp^{stag}_{recipient(k)}}\right]$$

where

$$X = \frac{h^{stag}_{donor(k)} - h_f(p^{stag}_{recipient(k)})}{h_g(p^{stag}_{recipient(k)}) - h_f(p^{stag}_{recipient(k)})} \quad . \tag{M-73}$$

If $h^{stag}_{donor(k)} > h_g(p^{stag}_{recipient(k)})$, then the flow is superheated and we have

$$\left(\frac{\partial v}{\partial h^{stag}_{donor(k)}}\right)_{p^{stag}_{recipient(k)}} = \frac{v(p^{stag}_{recipient(k)}, h^{stag}_{donor(k)}+10) - v(p^{stag}_{recipient(k)}, h^{stag}_{donor(k)})}{10} \tag{M-74}$$

and

$$\left(\frac{\partial v}{\partial p^{stag}_{recipient(k)}}\right)_{h^{stag}_{donor(k)}} = \frac{v(p^{stag}_{recipient(k)}, h^{stag}_{donor(k)}) - v(p^{stag}_{recipient(k)}-10, h^{stag}_{donor(k)})}{10} \quad . \tag{M-75}$$

M.4 Choked Flow Conditions

For the choked flow models described in Sections M.2.2 through M.2.6, a test is made as to whether the flow is indeed choked. If $p^{stag}_{recipient(k)} \leq p^t$, then choked flow conditions are assumed and the following quantities are calculated:

$$W_k = \pm (C_D)_k \cdot A_k \cdot G \quad . \tag{M-76}$$

$$(W_f)_k = (1 - X^f_k)\, W_k \quad . \tag{M-77}$$

$$(W_g)_k = X^f_k\, W_k \quad . \tag{M-78}$$

$$(hW)_k = \frac{\partial (hW)_k}{\partial W_k} W_k$$

$$\frac{\partial W_k}{\partial p_{u(k)}} = \begin{cases} (C_n)_k \cdot A_k \cdot \dfrac{\partial G}{\partial p^{stag}_{donor(k)}} & \text{if } W_k \geq 0. \\ -(C_D)_k \cdot A_k \cdot \dfrac{\partial G}{\partial p^{stag}_{recipient(k)}} & \text{if } W_k < 0. \end{cases} \tag{M-79}$$

W_k is positive if $p^{stag}_{u(k)} \geq p^{stag}_{d(k)}$ and negative otherwise.

$$\frac{\partial W_k}{\partial h_{u(k)}} = \begin{cases} (C_D)_k \cdot A_k \cdot \dfrac{\partial G}{\partial h^{stag}_{donor(k)}} & \text{if } W_k \geq 0. \\ -(C_D)_k \cdot A_k \cdot \dfrac{\partial G}{\partial h^{stag}_{recipient(k)}} & \text{if } W_k < 0. \end{cases} \tag{M-80}$$

$$\frac{\partial W_k}{\partial P_{d(k)}} = \begin{cases} (C_D)_k \cdot A_k \cdot \dfrac{\partial G}{\partial p^{stag}_{recipient(k)}} & \text{if } W_k \geq 0. \\ -(C_D)_k \cdot A_k \cdot \dfrac{\partial G}{\partial p^{stag}_{donor(k)}} & \text{if } W_k < 0. \end{cases} \tag{M-81}$$

$$\frac{\partial W_k}{\partial h_{d(k)}} = \begin{cases} (C_D)_k \cdot A_k \cdot \dfrac{\partial G}{\partial h^{stag}_{recipient(k)}} & \text{if } W_k \geq 0. \\ -(C_D)_k \cdot A_k \cdot \dfrac{\partial G}{\partial h^{stag}_{donor(k)}} & \text{if } W_k < 0. \end{cases} \tag{M-82}$$

$$\frac{\partial (hW)_k}{\partial P_{u(k)}} = \frac{\partial (hW)_k}{\partial W_k} \cdot \frac{\partial W_k}{\partial P_{u(k)}} \cdot \tag{M-83}$$

$$\frac{\partial (hW)_k}{\partial h_{u(k)}} = \frac{\partial (hW)_k}{\partial W_k} \cdot \frac{\partial W_k}{\partial h_{u(k)}} \cdot \tag{M-84}$$

$$\frac{\partial (hW)_k}{\partial P_{d(k)}} = \frac{\partial (hW)_k}{\partial W_k} \cdot \frac{\partial W_k}{\partial P_{d(k)}} \cdot \tag{M-85}$$

$$\frac{\partial (hW)_k}{\partial h_{d(k)}} = \frac{\partial (hW)_k}{\partial W_k} \cdot \frac{\partial W_k}{\partial h_{d(k)}} \cdot \tag{M-86}$$

M.5 Unchoked Flow Conditions

For the choked flow models described in Sections M.2.2 through M.2.6, a test is made as to whether the flow is indeed choked. If $p^{stag}_{recipient(k)} > p^{t}$, then it is not.

A user-specified constant C_6 is used to provide a smooth transition between choked and totally unchoked flow conditions. A weighting factor for unchoked flow is defined as

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APPENDIX N

NODE TRACKING AND MIXTURE LEVEL TRACKING MODEL

In this appendix, we discuss the node stacking and mixture level tracking model. This model allows any number of vertical stacks of regular interior fluid nodes, each stack connected by any number of point contact flow links. Within each stack, the mixture level is tracked.

Before describing the model itself, let us examine the motivation for such a model. A non-homogeneous or stratified interior fluid node has a mixture elevation. All fluid in this node, however, must be in thermodynamic equilibrium. In order to model a region which is expected to have a single mixture level, but which is not expected to be in thermodynamic equilibrium, a single node would not appear to be adequate. One can model the region with more than one node vertically. However, when doing this in the past, one had to specify each node as always being stratified or homogeneous. Using homogeneous nodes precluded having the detail of a mixture elevation in those nodes. Using stratified nodes often led to the "layer cake" effect where the region consisted of alternating layers of mixture and separated steam. This is a physically unrealistic situation. It causes particular problems in the flow links connecting the nodes in the stack.

The model to be described here gives the advantages of stacked nodes without the disadvantages described above. Mixture elevations in nodes in the stack are created and destroyed as necessary to track a mixture level in the stack.

We now describe the node stacking and mixture level tracking model in detail.

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APPENDIX O

HORIZONTAL STRATIFIED FLOW MODEL

In this appendix, we discuss the horizontal stratified flow model. This model represents stratified flow in horizontal circular pipes. It allows for the possibility of co-current or counter-current vapor-liquid flow. The model is similar to the horizontal slip model in RELAP4/MOD5[29]. It models the horizontal pipe with a pair of non-critical flow links, one link representing the lower (liquid) component and the other link representing the upper (vapor) component of the stratified flow regime. The links have variable flow areas, inertial lengths, and equivalent diameters. The model accounts for both wall friction and interfacial shear pressure losses.

A pair of non-critical flow links consists of one link representing the lower (liquid) component and the other link representing the upper (vapor) component. These two links must have the same upstream node, downstream node, upstream elevation, downstream elevation, non-zero continuous contact flow link diameter, and length.

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APPENDIX P

PUMP MODEL

The purpose of this Appendix is to describe the pump model in NOTRUMP. This model may be used in up to four flow links of any type except horizontal stratified flow model links. The model is primarily designed to simulate reactor coolant pumps but, due to its generality, could be used for other pumps. Five major calculations make up the model. First, donor flow conditions are determined. Next, these conditions are used together with the speed of the pump to determine the pump head. Either an inlet density model or an equivalent density model is used together with the single-phase head-flow-speed homologous curves. Next, the pump discharge pressure is calculated from the energy equation for an isentropic process given the pump head, mass flow rate, and donor flow conditions. If no discharge pressure can be calculated, a critical flow calculation is performed in which the flow rate is reduced to its choked flow value and the discharge pressure is then calculated. Finally, a coastdown calculation is performed. Either the inlet density, an average of the inlet density, and the equivalent density is used together with the single-phase torque-flow-speed homologous curves to determine the pump hydraulic torque. If the pump is coasting, the hydraulic torque, friction and windage torque, and the electrical torque are used in the integration of the pump angular momentum equation to obtain a new pump speed. We now describe the calculations in detail.

Donor flow conditions are determined first. The donor prssure, P_D, and enthalpy, h_D, are based on the direction of the net mass flow rate through the pump. Knowing P_D and h_D, we now calculate all other donor conditions. First, the saturation properties are calculated; i.e., $(T_{sat})_D$, $(h_f)_D$, $(h_g)_D$, $(v_f)_D$, $(v_g)_D$, $(s_f)_D$, and $(s_g)_D$. Next the donor fluid state is determined. It is subcooled if $h_D \leq (h_f)_D$, saturated if $(h_f)_D < h_D < (h_g)_D$, and superheated if $h_D \geq (h_g)_D$. For a subcooled donor fluid state, we have

$$s_D = s\ (P_D,\ h_D) \quad , \tag{P-1}$$

$$T_D = T\ (P_D,\ h_D) \quad , \tag{P-2}$$

$$(P_{sat})_D = P_{sat}\ (T_D) \quad , \tag{P-3}$$

$$v_D = v\ (P_D,\ T_D) \quad , \tag{P-4}$$

$$\chi_D = 0 \quad , \tag{P-5}$$

$$\alpha_D = 0 \quad , \tag{P-6}$$

$$(\alpha_{slip})_D = 0 \quad , \tag{P-7}$$

and

$$(v_{slip})_D = v_D \quad . \tag{P-8}$$

For a saturated donor fluid state, we have

$$\chi_D = \frac{h_D - (h_f)_D}{(h_g)_D - (h_f)_D} \quad , \tag{P-9}$$

$$s_D = (1 - \chi_D) \cdot (s_f)_D + \chi_D \cdot (s_g)_D \quad , \tag{P-10}$$

$$T_D = (T_{sat})_D \quad , \tag{P-11}$$

$$v_D = (1 - \chi_D) \cdot (v_f)_D + \chi_D \cdot (v_g)_D \quad , \tag{P-12}$$

$$(P_{sat})_D = P_D \quad , \tag{P-13}$$

$$\alpha_D = \frac{\chi_D \cdot (v_g)_D}{v_D} \quad , \tag{P-14}$$

$$(\alpha_{slip})_D = \alpha_{ARMAND}\ (\chi_D,\ P_D,\ (v_f)_D,\ (v_g)_D) \quad , \tag{P-15}$$

and

$$(v_{slip})_D = [(1 - (\alpha_{slip})_D)/(v_f)_D + (\alpha_{slip})_D/(v_g)_D]^{-1} \quad . \tag{P-16}$$

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evaluated at the donor fluid state where

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For a superheated donor fluid state, we have

$$s_D = s\ (P_D,\ h_D) \quad , \tag{P-19}$$

$$T_D = T\ (P_D,\ h_D) \quad , \tag{P-20}$$

$$v_D = v\ (P_D,\ h_D) \quad , \tag{P-21}$$

$$(P_{sat})_D = P_{sat}\ (T_D) \quad , \tag{P-22}$$

$$\chi_D = 1 \quad , \tag{P-23}$$

$$\alpha_D = 1 \quad , \tag{P-24}$$

$$(\alpha_{slip})_D = 1 \quad , \tag{P-25}$$

and

$$(v_{slip})_D = v_D \quad . \tag{P-26}$$

Pump head calculations are performed next. These calculations consist of two parts. First, we must determine the density to be used to obtain a volumetric flow rate from the mass flow rate in the pump. Second, we use this volumetric flow and the pump speed together with the single phase head-flow-speed homologous curves to calculate the pump head.

The pump density calculation uses one of two models. The pump head "inlet density" model simply uses the donor specific volume for the head specific volume; i.e.,

$$v_H = v_D \qquad \text{(P-27)}$$

a,c The pump head "equivalent density" model is more involved. [

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and

$$\left(\frac{\partial \rho}{\partial P}\right)_s = - \frac{\dfrac{v\,(P_D,\ s_D) - v\,(0.99\ P_D,\ s_D)}{0.01\ P_D}}{[v\,(P_D,\ s_D)]^2} \quad . \qquad \text{(P-34)}$$

Now that we have the head density for any donor fluid state, we calculate the volumetric flow rate [gpm] from the mass flow as follows:

$$Q_H = (7.4085195) \cdot (60) \cdot W \cdot v_H \quad .$$

Then we use this volumetric flow rate and the pump speed together with the single phase head-flow-speed homologous curves to calculate the pump heat H [ft].

The discharge pressure is calculated next from the energy equation for an isentropic process given the pump head, mass flow rate, and donor flow conditions. The energy equation to be satisfied by the discharge pressure, P_R, is

$$J \cdot \left(\left[h\,(P_R,\ s_D) + \frac{\left[\dfrac{W \cdot (v_{slip})_R}{A_R}\right]^2}{2 \cdot J \cdot g_c}\right] - \left[h_D + \frac{\left[\dfrac{W \cdot (v_{slip})_D}{A_D}\right]^2}{2 \cdot J \cdot g_c}\right]\right) \cdot \qquad \text{(P-35)}$$

$$- \frac{g}{g_c} \cdot H = 0$$

Note that P_R appears in $h\ (P_R,\ s_D)$. It also appears implicitly in $(v_{slip})_R$ which is simply $v_{slip}\ (P_R,\ s_D)$. Equation (P-35) is, therefore, a transcendental equation for P_R and must be solved accordingly.

Any solution method will need to evaluate recipient flow conditions, in particular, $h\ (P_R,\ s_D)$ and $v_{slip}\ (P_R,\ s_D)$. Since we have assumed an isentropic process, the recipient entropy is known to be equal to the donor entropy s_D. If we know P_R and s_D, we can calculate all other recipient conditions. First, the saturation properties are calculated; i.e., $(T_{sat})_R$, $(h_f)_R$, $(h_g)_k$, $(v_f)_R$, $(v_g)_R$, $(s_f)_R$, and $(s_g)_R$. Next the recipient fluid state is determined. It is subcooled if $s_D \leq (s_f)_R$, saturated if $(s_f)_R < s_D < (s_g)_R$, and superheated ir $s_D \geq (s_g)_R$. For a subcooled recipient fluid state, we have

$$h_R = h\ (P_R,\ s_D) \quad , \tag{P-36}$$

$$T_R = T\ (P_R,\ s_D) \quad , \tag{P-37}$$

$$(P_{sat})_R = P_{sat}\ (T_R) \quad , \tag{P-38}$$

$$v_R = v\ (P_R,\ T_R) \quad , \tag{P-39}$$

$$\chi_R = 0 \quad , \tag{P-40}$$

$$\alpha_R = 0 \quad , \tag{P-41}$$

and

$$(v_{slip})_R = v_R \quad . \tag{P-42}$$

For a saturated recipient fluid state, we have

$$\chi_R = \frac{s_D - (s_f)_R}{(s_g)_R - (s_f)_R} \quad , \tag{P-43}$$

$$h_R = (1 - \chi_R) \cdot (h_f)_R + \chi_R \cdot (h_g)_R \quad , \tag{P-44}$$

$$T_R = (T_{sat})_R \quad , \tag{P-45}$$

$$v_R = (1 - \chi_R) \cdot (v_f)_R + \chi_R \cdot (v_g)_R \quad , \qquad \text{(P-46)}$$

$$(P_{sat})_R = P_R \quad , \qquad \text{(P-47)}$$

$$R = \frac{\chi_R \cdot (v_g)_R}{v_R} \quad , \qquad \text{(P-48)}$$

$$(\alpha_{slip})_R = [\qquad]^{a,c}$$

and

$$(v_{slip})_R = [(1 - (\alpha_{slip})_R)/(v_f)_R + (\alpha_{slip})_R/(v_g)_R]^{-1} \quad . \qquad \text{(P-50)}$$

$$\left[\qquad \right]^{a,c}$$

$$h_R = h\ (P_R,\ s_D) \quad , \qquad \text{(P-51)}$$

$$T_R = T\ (P_R,\ s_D) \quad , \qquad \text{(P-52)}$$

$$v_R = v\ (P_R,\ s_D) \quad , \qquad \text{(P-53)}$$

$$(P_{sat})_R = P_{sat}\ (T_R) \quad , \qquad \text{(P-54)}$$

$$\chi_R = 1 \quad , \qquad \text{(P-55)}$$

$$\alpha_R = 1 \quad , \qquad \text{(P-56)}$$

$$(\alpha_{slip})_R = 1 \quad , \qquad \text{(P-57)}$$

and

$$(v_{slip})_R = v_R \quad . \qquad \text{(P-58)}$$

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When we have successfully found P_R, we need not perform a critical flow calculation.

If a solution cannot be successfully bracketed in n attempts, we go to the critical flow calculation if the calculated pump head H is negative, the input variable NWMAX is greater than zero and we have not yet been to the critical flow calculation. Otherwise, the calculation aborts.

The critical flow calculation is performed next if necessary. For this calculation we do up to NWMAX iterations on mass flow rate. For each flow rate we do up to n_{MAX} iterations on discharge pressure where

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The pump coastdown calculations are performed next. The calculations consist of two parts. First we calculate the torques acting on the pump. Second, if the pump is in the coastdown mode, we integrate the angular momentum equation for the pump to obtain a new pump speed.

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APPENDIX Q

VARIABLE AREA FLOW LINKS

This Appendix describes the NØTRUMP variable area flow link models, addresses modeling considerations, and indicates how the models can be accessed.

User-Supplied Externals FAFL(K) And FADFMFL(K)

The variable area flow link models are accessed via two new user-supplied externals:

```
FUNCTIØN FAFL(K)
```

and

```
FUNCTIØN FADFMFL(K).
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FAFL(K) is a multiplier on AFL(K) for flow link K. FADFMFL(K) is a multiplier on ADFMFL(K) for flow link K. Both are described in Appendix C. We shall now describe in detail where the multipliers are applied.

Several points should be noted about these user-supplied externals. First, since all user-supplied externals are now "generalized" (see Appendix C), the flow areas can be functions of numerous variables. Second, if a user does not supply FAFL or FADFMFL, NØTRUMP provides default versions which have values of 1.0. However, if a user supplies FAFL or FADFMFL in order to vary the flow area of any flow links, he must make sure that in his versions of FAFL or FADFMFL all other flow links still have multipliers of 1.0. For example, if flow link 80 is to go from fully closed to fully open in 2.0 seconds beginning at 60.0 seconds but all other flow links are to be constant flow area links, the following FAFL could be used:

```
FUNCTIØN FAFL(K)
FAFL=1.0
IF(K.NE.80)RETURN
TIME=RVALUE(4HTIME,1)
FAFL=AMIN1(AMAX1((TIME-60.0)/2.0,0.0),1.0)
RETURN
END
```

Variable Area Flow Link Models

The multipliers FAFL and FADFMFL are used in the calculation of frictional terms, momentum flux flow limiting, break models, and drift flux models. We now describe in detail where the multipliers are applied.

FAFL is used in calculating frictional terms for non-critical and pseudo-steady state critical flow links (ITYPEFL(K)=1,2,3,-8). Specifically, the multiplier is applied to A_k in Equations (5-34), (5-35), (5-36), (5-37), (5-39), (5-40), (5-41), (5-42), (5-43), (5-44), (5-45), (5-46), (5-47), (5-50), (5-51), (5-52), (5-53), and (5-55). Note that since A_k appears in the denominator of most of these equations, FAFL should be non-zero. Therefore to model a fully closed flow link, one might use an FAFL value of 1.0E-10.

FAFL is also used in calculating flow limiting for the momentum flux model (Appendix I of Reference 1). In particular, it is applied to A_k in Equations (I-20), (5-21), and (5-22) of Reference 1.

Finally, FAFL is used directly as a flow area multiplier for break flow model critical flow links (ITYPEFL(K)=-2,-3,-4,-5,-6,-7). Specifically, it is applied to A_k in Equations (M-93) and (M-105) of Reference 1. FAFL can be zero for this use.

FADFMFL is used with the drift flux models. Specifically, it is applied to A in Equations (G-30), (G-31), and (G-32) and to A_k in Equation (5-17) of Reference 1.

Modeling Considerations

A primary use of the variable area flow links is anticipated to be for the modeling of various types of valves. Friction effects, flow limiting effects, and the effects of flow area on break models can be modeled using FAFL. It is not clear whether or not separation effects should be modeled. FADFMFL is available, however, so that these effects can be modeled if desired.

APPENDIX R

ACCUMULATOR MODEL

The purpose of this appendix is to describe the accumulator model currently used in NOTRUMP. In Section 3.0, we discussed the "pressure search" for interior fluid nodes but only to the extent that the pressure in a node is a function of the internal energy and mass in the node; i.e., P = P (U,M). For accumulator interior fluid nodes, special nodes with an upper region of nitrogen and a lower "mixture" region of water, the pressure is also a function of the initial pressure and nitrogen volume. We shall describe here how the pressure search is performed. We shall also describe how all other properties (including derivatives) are obtained.

The properties of water in the accumulator model are those used in regular fluid nodes. They are given in tabular form by Tables L-1 and L-2. The use of these tables to calculate all properties (excluding derivatives) given the pressure, P, and the enthalpy, h, is described in Appendix L.

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Once the pressure and fluid enthalpy have been obtained, the other properties are calculated just as in a regular fluid node. These calculations are given by Equations (L-7) to (L-11) and (L-33) to (L-50). In addition to these properties, certain derivatives are also calculated using the pressure search with perturbed values of U_i^n and M_i^n. They are calculated as follows:

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APPENDIX S

AN OPTIONAL TIME STEP SIZE SELECTION METHOD

In this Appendix, we discuss the theoretical and mathematical aspects of a time step selection method.[ ] The actual algorithm used is described in Section 10. In this Appendix we begin with a discussion of two concepts of accuracy, those of "local relative error" and "general relative error". Next, we show the application of these concepts to time step selection in areas of continuity of the system of differential equations being solved. A linear extrapolation concept is developed for application to the two primary areas of discontinuity.[ ] Other considerations which affect the time step selection are introduced. Finally, the actual algorithm used is explained step-by-step. a,c

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GPU Nuclear

GPU Nuclear
P.O. Box 388
Forked River, New Jersey 08731
609-693-6000
Writer's Direct Dial Number:

January 21, 1982

Mr. Ronald C. Haynes, Administrator
U.S. Nuclear Regulatory Commission
Region I
631 Park Avenue
King of Prussia, PA 19406

Dear Mr. Haynes:

Subject: Oyster Creek Nuclear Generating Station
Docket No. 50-219
Coordinated Emergency Exercise

In accordance with FEMA Guideline Memorandum No. 17, enclosed is a listing of the objectives for the NRC/FEMA Observed Emergency Exercise currently scheduled for March 16, 1982, at the Oyster Creek Station. These objectives have been developed in conjunction with state and local governmental authorities.

If you should have any questions, please contact Mr. Michael Laggart at (609) 693-6932.

Very truly yours,

J. T. Carroll, Jr.
Acting Director - Oyster Creek

JTC:GWB:lse

enclosure

cc: Director
Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

NRC Resident Inspector
Oyster Creek Nuclear Generating Station
Forked River, NJ 08731

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Objectives for the 1982
C/FEMA Observed OCNGS Exercise

In order to demonstrate the radiological preparedness of the Oyster Creek Nuclear Generating Station (OCNGS), General Public Utilities Nuclear (GPU Nuclear), the State of New Jersey, Ocean County, and a number of Municipalities, (names to be supplied), an integrated radiological emergency exercise will be conducted.

The onsite and offsite objectives of the exercise are as follows:

A. Accident Assessment

1. Demonstrate the ability of licensee personnel to recognize an emergency intitiating event and properly characterize and classify the emergency according to the pre-established Emergency Action Levels and make proper notifications to offsite agencies.

2. Demonstrate that New Jersey and GPU Nuclear personnel can perform offsite dose projections and accident assessment for both radioactive noble gases and radioiodine quickly and accurately.

3. Demonstrate the field monitoring capability of the licensee, State, and County, for (1) predetermined area radiation levels, and (2) air sampling and analysis for radioiodine and particulates in the plume exposure EPZ for plume exposure rate verification; demonstrate that results can be effectively used in determining protective action recommendations.

4. Demonstrate that appropriate sampling can be done in the ingestion EPZ. Samples will be forwarded to a laboratory although no radioactivity analyses will be performed. I-131 concentration in milk will be predetermined to demonstrate that the results of such analyses could be effectively used to determine ingestion protective action recommendations.

5. Demonstrate that independent accident assessment can be accomplished by the Department of Environmental Protection of the State of New Jersey; that they are capable of recommending appropriate protective actions and that information is communicated between the licensee and the State accident assessment personnel.

6. Demonstrate that the field monitoring teams of the licensee, state and county can be dispatched and deployed in a timely manner; that communications are adequate; that radiological monitoring equipment is functional; that simulated data are accurately obtained and transmitted through their respective channels.

7. Demonstrate the ability of the licensee to obtain and analyze a post accident sample.

B. Activation of Emergency Facilities

1. Demonstrate the ability of the licensee to activate and man the emergency response facilities as appropriate for the existing emergency class and to transfer functional responsibilities to the appropriate operations center when escalating or de-escalating to a different emergency class.

2. Demonstrate the ability of the State of New Jersey, Ocean County and the participating municipalities to activate and man the emergency operations centers as appropriate for the existing emergency class.

C. Notification and Communication

1. Demonstrate that licensee and offsite notification and alerting of officials and staff can be accomplished in a timely manner and that all initial notification and updating is verified and logged.

2. Demonstrate that the State and County can establish notification and communication links with all municipalities.

3. Demonstrate the ability of the licensee to communicate with their monitoring teams, rescue parties, and other personnel as needed.

4. Demonstrate that the state's decision to notify the public can be accomplished in an effective and timely manner.

5. Demonstrate that the communication systems between the licensee, the EOC's, the Federal agencies, and the continguous States are operable.

6. Demonstrate that messages are transmitted in an accurate and timely manner; that messages are properly logged; that status boards are accurately maintained and updated; that appropriate briefings are held and incoming EOC personnel are briefed and updated.

7. Demonstrate the ability to establish a public information center; that there are accurate and timely press releases and briefings and that designated public information personnel are implementing their procedures.

8. Demonstrate the Emergency Broadcast System procedure by having the standard EBS test message transmitted.

D. Licensee Health Physics and Security

1. Demonstrate the ability to account for personnel onsite and to provide adequate radiation protection services such as dosimetry and personnel monitoring (frisking) and the ability to perform area surveys under emergency conditions.

2. Demonstrate the ability to enter a highly contaminated area for the purpose of rescuing casualties.

3. Demonstrate the ability to provide first aid and transport to a suitably prepared medical facility for an injured individual who has been contaminated or has received a high radiation dose.

4. Demonstrate the ability to perform personnel monitoring and decontamination.

E. Direction and Control

1. Demonstrate that State, County, and Municipal elected and appointed officials and local offsite agencies such as first aid squads, police, and fire companies will provide timely support.

2. Demonstrate that the designated State, County, and Municipal officials in each EOC are in command; that officials designated in the plan are actually in charge of the overall coordination of the response; and that designated offsite officials are represented in the EOF in accordance with the existing emergency plans.

3. Demonstrate that licensee management is in control in accordance with the existing emergency plan.

4. Demonstrate coordination between State, County, Municipal, and Federal agencies and between those agencies and the licensee.

5. Demonstrate that all agencies have 24 hour capability and that all agency representatives who are assigned emergency responsibilities can effectively operate from their planned location inside or outside the EOC.

F. Protective Actions

1. Demonstrate protective actions (including mock evacuation and sheltering) by preparing an exercise scenario which provides for a hypothetical total integrated whole body or thyroid dose exceeding the evacuation PAGs for at least the nearest residents.

2. Demonstrate the ability of the licensee to assess the accident and provide appropriate protective action recommendations.

3. Demonstrate the ability of the the State to evaluate and make decisions to take protective actions based on recommendations from the licensee and other independent assessments.

4. Demonstrate that access control points are established promptly and according to the plan, and that access and traffic control can be effectively implemented with 24 hour capabilities.

5. Demonstrate the capability for evacuation of the general public through a limited evacuation.

G. Parallel and Other Actions

1. Demonstrate the ability of the designated hospital to treat a hypothetically contaminated injured patient and that the ambulance service can effectively transport hypothetically contaminated injured personnel to the hospital. Demonstrate that the ambulance and associated equipment can be decontaminated and that contaminated clothing and disposable materials are properly discarded.

2. Demonstrate that offsite agencies with onsite support responsibilities such as fire and first aid squad personnel can gain access to the site and proceed to the correct location.

3. Demonstrate that State, County and Municipal emergency workers are briefed and receive dosimeters (and simulated KI supplies if necessary) before assignments; that permanent records are maintained; and that the opened decontamination centers are properly manned and supplied.

4. Demonstrate the following for at least one congregate care/decontamination center: that it can be opened and staffed on a timely basis; that records can be maintained; that adequate provisions for the care of the evacuees can be located; and that health and sanitation requirements can be met.

5. Demonstrate that licensee, State and local re-entry procedures such as health and sanitation, safety criteria for acceptable radioactive contamination levels, re-entry access control, and public information are implemented.

H. Miscellaneous

1. Demonstrate that each EOC and emergency response facility has adequate access control and that adequate security can be maintained.

2. Demonstrate that each EOC and emergency response facility has adequate space, equipment, and supplies.

3. Demonstrate the capability of the State, County, and Municipal agencies and the licensee for self-critique.