AAEC/E378

AAEC/E378

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

NAIAD - A COMPUTER PROGRAM FOR CALCULATION OF THE STEADY STATE AND TRANSIENT BEHAVIOUR (INCLUDING LOCA) OF COMPRESSIBLE TWO-PHASE COOLANT IN NETWORKS

by

G.D. TRIMBLE
W.J. TURNER

April 1976
ISBN 0 642 99746 2

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

NAIAD - A COMPUTER PROGRAM FOR CALCULATION OF THE STEADY STATE AND TRANSIENT BEHAVIOUR (INCLUDING LOCA) OF COMPRESSIBLE TWO-PHASE COOLANT IN NETWORKS

by

G.D. TRIMBLE
W.J. TURNER

ABSTRACT

The three one-dimensional conservation equations of mass, momentum and energy are solved by a stable finite difference scheme which allows the time step to be varied in response to accuracy requirements.

Consideration of numerical stability is not necessary. Slip between the phases is allowed and descriptions of complex hydraulic components can be added into specially provided user routines. Intrinsic choking using any of the nine slip models is possible. A pipe or fuel model and detailed surface heat transfer are included.

National Library of Australia card number and ISBN 0 642 99746 2

The following descriptors have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA-INIS-12 (INIS: Manual for Indexing) and IAEA-INIS-13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

COMPUTER CALCULATIONS; COMPRESSIBLE FLOW; FINITE DIFFERENCE METHOD; HEAT TRANSFER; LOSS OF COOLANT; N CODES; SLIP; STEADY-STATE CONDITIONS; ONE-DIMENSIONAL CALCULATIONS; TRANSIENTS; TWO-PHASE FLOW; BLOWDOWN; SIMULATION; FLOW MODELS; CRITICAL FLOW; CONSERVATION LAWS;

CONTENTS

		Page
1.	INTRODUCTION	1
	1.1 Very Short Time Steps	1
	1.2 Slip Not Allowed	1
	1.3 Inadequate Momentum Flux Treatment	1
	1.4 Inconsistent Choke Flow Treatment	2
2.	GENERAL DESCRIPTION	2
	2.1 Geometry	3
	Figure 1 - Connections and Flow Paths for a BWR	3
	2.2 Initial Condition Calculations	4
	2.3 Transient Calculations	5
	2.4 Equation of State	6
	2.5 Slip Model	6
	2.6 Heat Transfer	7
	2.7 Friction	7
	2.8 Choke Flow	7
3.	METHOD OF CALCULATION	8
4.	CONSERVATION EQUATIONS	9
	4.1 One-dimensional Conservation Equations	9
	Figure 2 - Boiling Boundary	14
	4.2 Fuel	14
	4.3 Connections	16
	Table 1 - Flow Path Equations	17
5.	METHOD OF SOLUTION	20
	5.1 Elimination of Surface Heat Flux and Fuel Temperature	20
	5.2 Solution of Flow Path Equations	20
	5.3 Connection Balance	22
	5.4 Back Substitution	24
6.	DESCRIPTION OF ROUTINES	24
	6.1 Introduction	24
	Figure 3 - Structure of NAIAD	24
	6.2 Service Routines	25
	Table 2 - Equation of State Mesh	26
	Table 3 - Correlations for Surface Heat Transfer Coefficient	34
	6.3 Special Routines	35
	Table 4 - Blank Common	36
	Table 5 - Labelled Common "BCOND$"	38
	Table 6 - Labelled Common "POWER$"	39
	Table 7 - Labelled Common "COEFF$"	39
	Table 8 - Labelled Common "BAL$"	39
	Table 9 - Labelled Common "CRIT$"	40
	Table 10 - Labelled Common "HEAD$"	40
	Table 11 - Labelled Common "STEP$"	41
	6.4 Other Routines	43
7.	TIME STEP CONTROL	45
8.	INPUT DATA	47
	8.1 General	47

CONTENTS (Continued)

		Page
8.2	Title Card	47
8.3	Controls	47
8.4	Flow Path Data	48
8.5	Connection Data	50
8.6	Initial Condition Data	50
9.	CATALOGUED PROCEDURES	53
9.1	NAIADCLG	53
9.2	NAIADG	53
9.3	PROGRUN	54
10.	SAMPLE RUN	54
	Figure 4 - Nuclear Power for Sample Problem	54
10.1	Nuclear Power	55
10.2	Heat Sink	55
10.3	Steam Generator	55
10.4	Makeup System	55
10.5	Secondary Pump	55
10.6	Primary Pump	56
	Figure 5 - Makeup System for Sample Problem	57
	Figure 6 - Sample Problem	57
10.7	Initial State	58
10.8	Transient Calculation	58
10.9	Sample Run Output	58
11.	PLOTTING	58
	Figure 7 - Pressure at Break	59
	Figure 8 - Time Step	59
	Figure 9 - Flow at Break	60
11.1	Plot Data File	60
11.2	Plot Program	61
12.	REFERENCES	64

APPENDIX A - Partial Listing of Sample Run Output

APPENDIX B - Notation

1. INTRODUCTION

Computer codes for simulation of loss-of-coolant accidents (LOCA) in nuclear power reactors have been written at many reactor research establishments throughout the world. All these codes suffer from one or more of the following problems.

1.1 Very Short Time Steps

In most codes, the time step is limited in size by numerical instability; usually the time step must be less than the time for a pressure or sound wave to cross one segment in the finite difference mesh. Because of the high speed of sound, particularly in sub-cooled water, this time step restriction can lead to very long computation times.

In 1971, Porsching *et al.* published an implicit finite difference method which allowed larger time steps for some calculations. This method was first incorporated in the FLASH-4 code [Porsching *et al.* 1969] and, more recently, in RELAP-4 [Moore & Rettig 1973] and FIREBIRD [Tong 1975]. In practice, the method has not removed the time step problem [Spinks 1975, Sullivan 1975].

The finite difference scheme used in NAIAD has been found stable for all calculations to date and the time step size can be chosen on accuracy considerations alone. This finite difference method is a further development of Turner [1969, 1972] and Turner & Trimble [1974(a)].

1.2 Slip Not Allowed

It is well known that in most two-phase flows the two phases move at different velocities. In such situations, flow (or mass velocity weighted) enthalpy

$$H = < uhd >/G$$

is larger than static (or density weighted) enthalpy

$$H_s = < hd >/\rho \quad .$$

Thus, enthalpy storage and flow cannot both be correct if slip is not allowed for. Nine slip models are available in NAIAD and others may easily be added.

1.3 Inadequate Momentum Flux Treatment

Several codes neglect this term of the momentum equation [Rettig *et al.* 1970; Porsching *et al.* 1969]. The treatment of Moore *et al.* [1973] has been incorporated in RELAP-4 [Moore & Rettig 1973]. However, this model (homogeneous flow and thermodynamic equilibrium) was shown by

Isbin *et al.* [1962] to give far too large an acceleration pressure drop for nearly choked two-phase flows, the flows at which momentum flux is important. The AECL code RODFLOW [Elliott 1968] satisfactorily includes momentum flux. The treatment in NAIAD gives reasonable agreement with the pressure drop measurement of Fauske [1962] for nearly choked flow [Turner & Trimble 1974(b)].

1.4 Inconsistent Choke Flow Treatment

The assumption of thermodynamic equilibrium and the specification of a slip model fully determine choke flow rate as a function of throat pressure and quality. In most codes both assumption and specification are made hence a choke flow function is fully determined. This intrinsic choke flow rate will only agree with experiment if the slip model is correct and the assumption of thermodynamic equilibrium holds. In most codes, the slip model assumed is homogeneous flow which is well known to give choke flow rates and pressure drops for near choke flow (those for which the acceleration pressure drop dominates) which do not agree with measured values. In these codes a choke flow rate function calculated using a more realistic flow model is applied as a boundary condition, and near choke flow is avoided as far as possible in the calculation. Thus one slip model is assumed everywhere except at the throat which requires another slip model. In NAIAD, the chosen slip model is used both to determine the pressure gradient near the throat and to calculate the choke flow rate. The fact that such a procedure can give agreement with steady state measurements of both choke flow rate and near choke pressure gradients was shown by Nahavandi & Von Hollen [1965], Turner & Trimble [1974(b)] and Tremblay & Andrews [1971].

2. GENERAL DESCRIPTION

The NAIAD code solves the one-dimensional equations of conservation of mass, momentum and energy by means of a stable finite difference scheme. The code is not specific to any reactor type or, indeed, to any particular pump, steam generator or other hydraulic component. The components required for any problem are, if possible, described in the input data in terms of variable area heated flow paths. The description of these flow paths requires specification of geometric parameters and selection of friction, slip and heat transfer options. Any components that cannot be so described must be described in special FORTRAN routines which are written by the code user for his particular problem or class of problems.

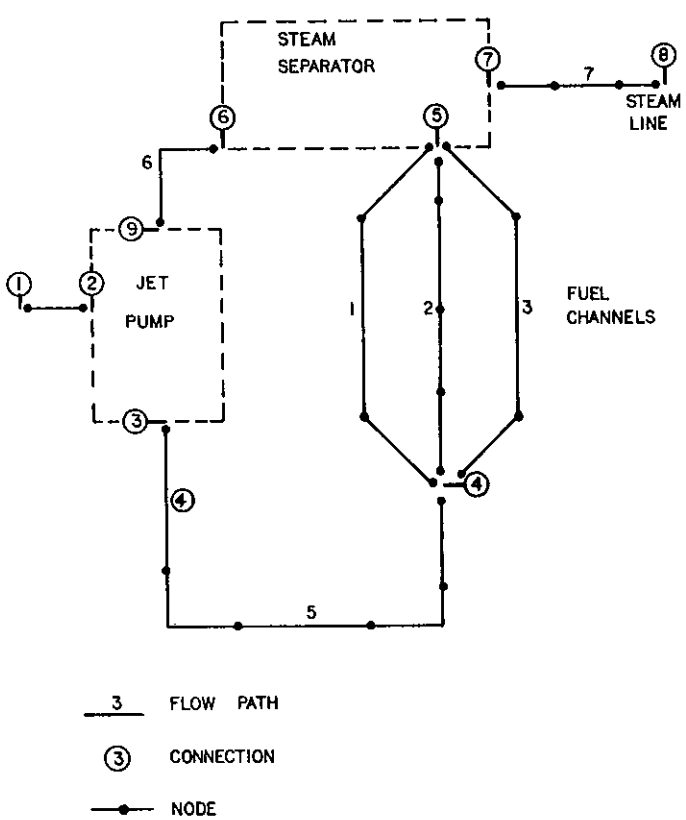
Thus a NAIAD run consists of two parts. In the first part, the special routines written for the problem in hand are compiled and linked with the standard code to form a composite code. For many problems, the standard code suffices and this step can be omitted. In the second part, the required calculation is done using the composite code. The calculations that can be done with composite codes are described in Sections 2 and 3. The instructions for writing the special routines and using the composite codes are contained in Sections 4 to 11.

2.1 Geometry

The NAIAD code may be used to calculate steady state and transient behaviour in complex flow networks containing a compressible fluid in both single and two-phase states. In the calculation, the flow network is treated as a set of one-dimensional flow paths each of which begins and ends at a connection, *e.g.* the flow network shown in Figure 1 can be treated as seven flow paths and nine connections. Nodes are placed at the start, finish and at any required intermediate positions in each flow path so that an implicit finite difference method can be used for

FIGURE 1

Connections and Flow Paths for a BWR



each flow path. The only limits on network topology result from upper limits of 10, 10 and 49 on the number of connections, flow paths and nodes respectively. A possible arrangement for a Boiling Water Reactor (BWR) is shown in Figure 1.

There are four types of connections: internal, choked, explicit and implicit. Internal connections are points at which two or more flow paths join. Choked connections are placed at points where choked flow is expected to occur, *e.g.* at a pipe burst or pressure vessel crack. Explicit and implicit connections are placed at boundaries of the network, *e.g.* connections 1 and 8 in Figure 1, and at interfaces between complex hydraulic components and the network, *e.g.* connections 2, 3, 9, 5, 6 and 7 in Figure 1.

The behaviour at connections is governed by the connection equations. The standard code includes connection equations for choked and internal connections, and for explicit connections at which either the mass flow rate or pressure is constant. The connection equations describing the behaviour of more complex hydraulic components are not in the standard code; they must be put into finite difference form and coded into the special routines mentioned above. If these difference equations are explicit, then the connections on the interface are all specified as explicit in the input data. If the difference equations are implicit, then at least one interface connection must also be specified as implicit so that the difference equations can be solved iteratively. The sample problem (Figure 6) contains connections of all types. Special routines written for this problem represent a pump between two connections, and a pressure controller which varies the inlet flow at one connection in response to pressure at another connection.

The walls of flow paths in the network may be heated as in a reactor core, or cooled as in heat exchangers or steam generators. A single node fuel or pipe wall model is coupled to each hydraulic node. Heat energy flow is to or from this node.

2.2 Initial Condition Calculations

The initial condition section of the code is designed for setting initial values of mass flow rate, pressure, enthalpy and fuel temperature at every node. The steady state routine for this is useful as a code in its own right since a whole range of steady states can be calculated in a single NAIAD run. After all geometry, flow model and fuel

model data have been read, sets of data specifying the initial condition calculations are read. Each set of data initiates one initial condition calculation in one flow path. The flow paths may be done in any order and a particular flow path can be done more than once to give a series of steady state results. Three parameters must be specified in the input data set for each flow path calculation: pressure and enthalpy at one node, and either pressure at another node or mass flow rate in the flow path. These parameters can be specified by value or by selecting a node in another flow path at which the parameter has the same value.

For example, a steady state could be set up in the network of Figure 1 as follows:

- Flow, pressure and enthalpy at a node in flow path 3 is read and a steady state is calculated for this flow path. This gives the pressures at connections 4 and 5 and the enthalpies of fluid entering and leaving the flow path.
- Assuming the flow in both flow paths 2 and 3 is from connection 4 to 5, then the enthalpies of fluid streams entering flow paths 2 and 3 are equal. The steady state of flow path 2 is then calculated from this enthalpy and the pressures at connections 4 and 5.
- The remaining flow paths are done in a similar way.

If required, a series of initial condition calculations on one or a group of flow paths can be done and the results printed after each calculation.

2.3 Transient Calculations

The transient calculation begins from the initial conditions and proceeds time step by time step. The user has complete control of the calculation in that major changes in the calculation may be made between time steps, *e.g.* input data, boundary conditions and heating power may be changed and output written. Each time step is essentially a new calculation in that entries are made into the special routines which exercise this control at critical points in the calculation. Any coupling between nodes not routinely allowed for in the standard code can be incorporated in these special routines. If no changes are made, then the time step is done using the same boundary conditions, heating power and input data as the previous time step. The node couplings in the standard code are the hydraulic conservation equations, constant pressure boundary conditions, constant flow boundary conditions, and choke flow

boundary conditions. Special routines are required for any other coupling. For example, a calculation of both primary and secondary coolant loops is done in the test problem. In the special routines for this problem, the heat flux from one loop to the other through the steam generator is calculated at the start of each time step using the temperatures from the previous time step. Powers for nodes within the steam generator are updated each time step and the correct coupling is made.

Special routines can easily be written to do a series of transient calculations, each one using results from earlier calculations. It is possible, for example, to do a search for the break size giving the largest peak fuel temperature.

2.4 Equation of State

Thermodynamic equilibrium is assumed at each node and an equation of state routine for light water is supplied with the code. This routine interpolates from tables calculated with the ASTEM code [Moore 1971].

2.5 Slip Model

A slip model must be specified for each node so that momentum flux, static enthalpy, and kinetic energy density and flux can be calculated. The slip models in the code are:

- Homogeneous flow
- CISE [Di Francesco *et al.* 1971]
- Beattie [Beattie 1974]
- Jones [Jones & Dight 1962]
- Smith [1970]
- Fauske [1962]
- Moody [1965]
- Small Bubble [Beattie 1975]
- Modified CISE

Other slip models may easily be added, including ones which take into account the local distribution of voidage and velocity. The only limitation is that at any axial cross section the average mass, energy and kinetic energy densities and fluxes can be calculated from the values of mass flow rate, pressure and mean enthalpy at that axial cross section plus all geometry information. This excludes counter current flow and any effect of upstream flow structure.

Some of these slip models are well known; others are new [Beattie 1974, 1975] or their use in this way is new [Fauske 1962; Moody 1965].

The selection of the slip model is largely a matter of experience and evaluation of steady state data. These slip models should only be used in a calculation if they are physically possible in the range over which they are applied.

A necessary condition for this is that all three characteristics of the three coupled first order partial differential conservation equations be real over this range. The regions over which the above slip models have complex characteristics are given by Trimble & Turner [1976]. Of course with homogeneous flow there are no complex regions. This is also true for Beattie slip for flows less than choke flow. Jones, Smith and CISE all have complex characteristics in the low quality, low pressure, near choke flow region. Our experience is that calculations in which many points of the finite difference time-space mesh are in the regions of complex characteristics are numerically unstable. However in actual calculations with Jones, Smith and CISE slip we find this to be a rare occurrence.

2.6 Heat Transfer

A heat transfer package must be specified at each node. This package gives the surface heat transfer coefficient as a function of the state and flow of the coolant, the fuel surface temperature and geometry data. At present, only one package is available; it is designed for flow in round tubes and contains correlations for most flow situations including condensation and post dryout.

2.7 Friction

A friction relation must be specified at each node for the frictional pressure gradient calculation. At present, eight options are available; these are described in Section 6. Selection of the friction model should be based on steady state data.

A friction coefficient to cover pressure drops due to valves, bends, *etc.* is required for each segment of flow path between two nodes. Either an equivalent length or an equivalent fL/D may be specified.

2.8 Choke Flow

Choke flow relations of two types are available from the literature. In the first type, the choke flow is given as a function of the stagnation conditions; in the second, it is a function of the throat conditions. Both types may be applied in NAIAD by means of the special routines. However, as discussed in Section 1.4, it is desirable that choking be a consequence of the conservation equations and the slip

model, not an external condition imposed on them. This intrinsic choking is used in NAIAD. Intrinsic choking occurs when either of the two sonic characteristic velocities is zero [Turner & Trimble 1975]. However, characteristic velocities are not continuous functions of thermodynamic quality across the single-phase two-phase boundaries. Nevertheless, it is clear that choking will occur where the characteristic velocity changes sign. This is the criterion for choke flow used in NAIAD. A node can be located at the break and the geometric information and slip model specified for that node used to determine the choke flow rate.

3. METHOD OF CALCULATION

Each flow path in the problem is treated as one-dimensional and all quantities are evaluated at every node. All nodes are treated identically. The finite difference equations are derived in Section 4 from the conservation equations for the coolant and fuel. These equations, together with the boundary conditions and the connection equations, fully determine the system. Once all the coefficients are calculated at the start of a time step, the difference equations, boundary conditions and connection equations are solved for the values of the mass flow rate, pressure, enthalpy and fuel temperature at every node in the network at the end of the time step. The details of the solution method are given in Section 5. With mass flow rate, pressure, enthalpy and fuel temperature at every node determined, the equation of state, slip, friction and heat transfer routines are used to find all the coefficients for the next time step and so calculation proceeds.

As with any numerical calculation, some errors are to be expected. Because of the implicit formulation of the finite difference equations, one effect of these errors is that mass and energy are not exactly conserved. Thus errors arising from the numerical methods can be evaluated by checking the departure from conservation. As usual, these errors may be reduced by decreasing the time and space steps.

The computation time per time step per node depends on the problem being solved. This is because the number of iterations required to converge the network solution at each time step varies, the various slip heat transfer and friction options take different times, and the number of choked connections is important. However, on the AAEC's IBM360 model 65, central processor times of 10 to 20 milliseconds per time step per node have been experienced. The sample problem, which has 22 nodes and

1 choked connection, took 44 and 100 seconds respectively to complete the coarse and fine time step calculations of the first 25 seconds.

The NAIAD code is written in the IBM360 language FORTRAN IV except for the matrix inversion routine and the AAEC input routine SCAN [Bennett & Pollard 1967] which are in 360 assembler language. The plot program uses many local features of the AAEC computing network and transfer of this program is not envisaged.

4. CONSERVATION EQUATIONS

The set of equations solved in the standard code are derived in this section.

4.1 One-dimensional Conservation Equations

Following Meyer [1960], we assume that the pressure P is constant over any cross-section of the flow path perpendicular to the z or flow direction, and write the conservation equations in terms of averages $< >$ of local density d, velocity u and enthalpy h over such cross sections.

$$a\frac{\partial \rho}{\partial t} + \frac{\partial W}{\partial z} = 0$$

$$\frac{1}{a}\frac{\partial W}{\partial t} + \frac{1}{a}\frac{\partial}{\partial z}\left(\frac{M}{a}\right) + \frac{\partial P}{\partial z} = -F - \rho g \sin\theta$$

$$\frac{\partial}{\partial t}(a\rho H_s - aP + \frac{M}{2a}) + \frac{\partial}{\partial z}(WH + K) = pq - Wg\sin\theta$$

where $\rho = < d >$,

$W = a< ud >$,

$M = a^2< u^2 d >$,

$\rho H_s = < hd >$,

$WH = a < hud >$, and

$K = \frac{a}{2} < u^3 d >$.

Many finite difference representations of these equations are possible. Here, the finite difference equations have been chosen to be numerically stable and to give good agreement with steady state results. Local stability analysis was used as a guide to the finite difference form. This indicated that evaluation of all space derivatives at the end of each time step was necessary. Actual calculations indicated that numerical instability could arise also if the friction and heat flux terms were evaluated at the start of each time step. Thus, implicit finite difference forms of these terms have been used in the equations

described below. Further discussion of the form of the finite difference equation is given in earlier work [Turner 1972; Turner & Trimble 1975].

We first define a slip-equation-of-state combination as the specification of ρ, M, H_s and K as single valued functions of both the geometric parameters (a, equivalent diameter, roughness, *etc.*) at this or other z locations, and of W, P and H. An example of a slip-equation-of-state combination is Jones' slip [Jones & Dight 1962] together with the thermodynamic equilibrium equation of state for light water. We can now write

$$\frac{\partial \rho}{\partial t} = \frac{\partial \rho}{\partial W}\frac{\partial W}{\partial t} + \frac{\partial \rho}{\partial P}\frac{\partial P}{\partial t} + \frac{\partial \rho}{\partial H}\frac{\partial H}{\partial t} \equiv \frac{\partial \rho}{\partial X} \cdot \frac{\partial X}{\partial t}$$

where $$X \equiv \begin{pmatrix} W \\ P \\ H \end{pmatrix},$$

and write similar expressions for the time derivatives of the other variables.

Consider a one-dimensional flow path for which the spatial finite difference mesh is the set of nodes m to n inclusive where

$$z_m < z_{m+1} < \ldots < z_n$$

and the finite time step is Δt. The finite difference equations for each conservation equation are described in the following sections.

4.1.1 Mass equation

This may be written

$$a \frac{\partial \rho}{\partial X} \cdot \frac{\partial X}{\partial t} + \frac{\partial W}{\partial z} = 0 \quad .$$

The finite difference equation is:

$$\left(\frac{a_i + a_{i+1}}{2\Delta t}\right)\left[\begin{array}{l} \left\{R\left(\frac{\partial \rho}{\partial X}\right)_i + (\rho_i - \rho_{i+1})\frac{\partial R}{\partial X_i}\right\} \cdot (X'_i - X_i) \\ + \left\{(1-R)\left(\frac{\partial \rho}{\partial X}\right)_{i+1} + (\rho_i - \rho_{i+1})\frac{\partial R}{\partial X_{i+1}}\right\} \cdot (X'_{i+1} - X_{i+1}) \end{array}\right] + \frac{W'_{i+1} - W'_i}{z_{i+1} - z_i} = 0$$

for i = m, m + 1, ..., n - 1.

The interpolation factor R is one half, and all its derivatives are zero unless a change of sign of the thermodynamic quality x occurs within the

segment. Its value and derivatives in this circumstance are discussed in Section 4.1.4. The truncation errors [Richmyer & Morton 1967] are

$$0(\Delta z^2) + 0(\Delta t) \ .$$

4.1.2 Momentum equation

The finite difference equation is

$$\frac{1}{2\Delta t}\left(\frac{1}{a_i} + \frac{1}{a_{i+1}}\right)\left[\begin{array}{l} R(W'_i - W_i) + (1-R)\ (W'_{i+1} - W_{i+1}) \\ + \left\{\frac{\partial R}{\partial X_i}\cdot(X'_i - X_i) + \frac{\partial R}{\partial X_{i+1}}\cdot(X'_{i+1} - X_{i+1})\right\}\ (W_i - W_{i+1}) \end{array}\right]$$

$$+\left(\frac{1}{a_i} + \frac{1}{a_{i+1}}\right)\frac{1}{2(z_{i+1} - z_i)}\left[\begin{array}{l} \frac{1}{a_{i+1}}\left\{M_{i+1} + \left(\frac{\partial M}{\partial X}\right)_{i+1}\cdot(X'_{i+1} - X_{i+1})\right\} \\ - \frac{1}{a_i}\left\{M_i + \left(\frac{\partial M}{\partial X}\right)_i\cdot(X'_i - X_i)\right\} \end{array}\right]$$

$$+ \frac{P'_{i+1} - P'_i}{z_{i+1} - z_i} + F + [R\rho_i + (1-R)\rho_{i+1}]\ g\sin\theta_{i,i+1} = 0$$

for $i = m, m+1, \ldots, n-1$.

The treatment of the momentum flux term is such that, for incompressible flow (where the term depends only on the end points), exact agreement with the Bernoulli equation is obtained. The truncation error for the momentum equation is

$$0(\Delta z^2) + 0(\Delta t) \ .$$

The friction term F is the sum of contributions from wall friction and pressure losses due to fittings *etc.*

$$F = \left(\frac{W'|G|v_f}{a}\right)_i\left[\frac{f_i}{D_{ei}} + \left(\frac{f_i K_{ei} + K_{fi}}{z_{i+1} - z_i}\right)\right]$$
$$+ \left(\frac{W'|G|v_f}{a}\right)_{i+1}\left[\frac{f_{i+1}}{D_{ei+1}} + \left(\frac{f_{i+1}K_{ei} + K_{fi}}{z_{i+1} - z_i}\right)\right] \ ,$$

where $v_f = \langle u \rangle / G$.

Only one of the two types of friction coefficients can be used in any one segment, so that either K_e or K_f is zero.

4.1.3 Energy equation

It is essential that the finite difference energy equations are able to handle the change in number of boundary conditions that occurs when the direction of flow at either end of the flow path changes. Such a finite difference scheme was formulated for single phase acoustics by Rose *et al.* [1967]. The way in which the present scheme overcomes this problem is described by Turner & Trimble [1975]; the scheme is given in full below.

First, the mass equation is used to eliminate the density derivative from the energy equation. Then

$$a\rho \frac{\partial H_s}{\partial X} \cdot \frac{\partial X}{\partial t} + (H-H_s) \frac{\partial W}{\partial z} - a \frac{\partial P}{\partial t} + \frac{1}{2a} \frac{\partial M}{\partial X} \cdot \frac{\partial X}{\partial t} +$$

$$+ \frac{W\partial H}{\partial z} + \frac{\partial K}{\partial z} = pq - Wg\sin\theta \quad .$$

We evaluate space derivatives over the segment of flow path on the upstream side of the node, and all other terms at the node. The difference equation is

$$\frac{a_i \rho_i}{\Delta t} \left(\frac{\partial H_s}{\partial X}\right)_i \cdot (X_i' - X_i) + (H_i - H_{si}) \left(\frac{W_i' - W_j'}{z_i - z_j}\right)$$

$$- a_i \frac{(P_i' - P_i)}{\Delta t} + \frac{1}{2a_i \Delta t} \left(\frac{\partial M}{\partial X}\right)_i \cdot (X_i' - X_i) + W_i \left(\frac{H_i' - H_j'}{z_i - z_j}\right)$$

$$+ \frac{1}{(z_i - z_j)} \left[K_i + \left(\frac{\partial K}{\partial X}\right)_i (X_i' - X_i) - K_j - \left(\frac{\partial K}{\partial X}\right)_j \cdot (X_j' - X_j) \right]$$

$$= p_i q_i' - W_i \, g\sin\theta_{ij}$$

where $j = i - 1$ if $W_i \geq 0$,

$= i + 1$ if $W_i < 0$, or $i = m$ and $W_m = 0$,

and i takes all integer values such that i and j are in the range m to n. Thus the number of energy equations depends on the flow directions at the flow path ends. This is further discussed in Section 4.3. The truncation error is

$$O(\Delta z) + O(\Delta t) \quad .$$

4.1.4 Boiling boundary

Some of the derivatives of ρ, M, H_s and K with respect to W, P and H, are not continuous across the single-phase two-phase boundaries, the zero quality discontinuity being of much greater significance than that at unit quality. Segments which include this zero quality discontinuity are given special treatment. The position of the boiling boundary is determined by assuming that

$$y = H - H_\ell = y(X)$$

varies linearly over the segment. The density and flow rate are assumed to be constant over the liquid portion of the segment and to vary linearly with z over the two-phase portion (Figure 2). Then, for the segment between nodes i and i+1 for which

$$y_{i+1} > 0 \text{ and } y_i \leqslant 0 \quad ,$$

$$\int_{z_i}^{z_{i+1}} \rho dz = [R\rho_i + (1-R)\rho_{i+1}](z_{i+1}-z_i) \quad ,$$

where $$R = 1 - \frac{y_{i+1}}{2(y_{i+1}-y_i)} \quad .$$

Similarly, if $y_{i+1} \leqslant 0$ and $y_i > 0$

$$R = \frac{y_i}{2(y_i-y_{i+1})} \quad .$$

If no boiling boundary is present, $y_i\, y_{i+1} \geqslant 0$ and R = 1/2. In general,

$$R = R(X_i, X_{i+1}) \quad .$$

This defines the interpolation factor used in the mass and momentum equations.

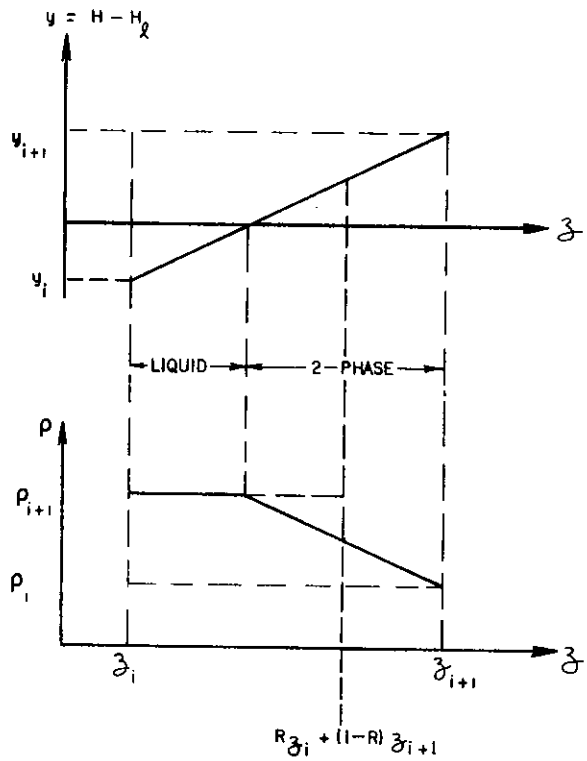
The special treatment of the boiling boundary may be removed from the difference scheme either at the start of or during the calculation by including the statement

CALL GAMOFF

in the special routines MAIN or BCSETM. After execution of this statement, R is always one half and its derivatives are zero. It is also

FIGURE 2

Boiling Boundary



possible to include the variation of R at boiling boundary segments but set all the derivatives of R to zero. This is achieved by execution of the statement

CALL GAMDOF .

These options are included because we have, as yet, little experience with the special treatment of the boiling boundary. However, we recommend using the treatment unless problems arise.

4.2 Fuel

At each node, heat is assumed to be generated in a fuel node connected to the coolant by a surface heat transfer coefficient. If the heat capacity λ of this fuel node is zero,

$$q' = Q', \quad T' = T'_c$$

and no fuel model calculation is required for this node as all generated power flows directly into the coolant. If λ is not zero, the finite difference equation (applicable to any geometry) is:

$$\frac{\lambda(T'-T)}{\Delta t} = Q'-q' \quad .$$

The surface heat flux is obtained from

$$q' = q + \frac{\partial q}{\partial X} \cdot (X'-X) + \frac{\partial q}{\partial T} (T'-T) \quad ,$$

where $q = h_T(T-T_c) = q(X,T)$ at each node,

and $$h_T = \frac{h\, h_f}{h+h_f} \quad .$$

Two ways of obtaining the derivatives of q are available.

4.2.1 Implicit h

As $T_c = T_c(X)$, $h = h(X,T)$ and h_F is constant,

$$\frac{\partial q}{\partial X} = (T-T_c) \frac{\partial h_T}{\partial X} - h_T \frac{\partial T_c}{\partial X} \quad ,$$

and $$\frac{\partial q}{\partial T} = (T-T_c) \frac{\partial h_T}{\partial T} + h_T \quad .$$

The derivatives of T_c are carried in the equation-of-state tables. The derivatives of h are evaluated by numerical differentiation of the heat transfer coeffient correlation used to obtain h. This evaluation can be quite time consuming and is only necessary for stability when large time steps are used.

4.2.2 Explicit h

The parameter h is assumed constant in the determination of the derivatives of q. Then

$$\frac{\partial q}{\partial X} = -h_T \frac{\partial T_c}{\partial X} \quad ,$$

and $$\frac{\partial q}{\partial T} = h_T \quad .$$

This has no significant effect on accuracy as the difference equations already contain order Δt truncation errors. With this option the heat flux q* from the previous time step is used to obtain an estimate of the fuel surface temperature which is then used to obtain h.

$$T_{Fs} = T - q^*/h_F$$

$$h = h(X,T_{Fs}) \quad .$$

This procedure can be unstable for large time steps and hence it is not used with the previous option (Section 4.2.1). It can be suppressed by making h_F very large.

4.3 Connections

In general, several flow paths terminate at each connection. At some of these terminations the flow will be from connection to flow path; at others it will be from flow path to connection. The connection enthalpy η is defined as the enthalpy of fluid passing in the former direction. The second connection parameter ψ is called the connection control and may be pressure or mass flow rate.

Consider a flow path which begins at connection α node m and ends at connection β node n. The connections α and β are the flow path boundaries. The conditions within the flow path are calculated from the conservation equations described above and the flow path boundary conditions. The form of the boundary conditions depends on the sign of the flow at the flow path end and on the type of control at the connection. At the α connection, the boundary conditions are:

For α pressure controlled $P'_m = \psi'_\alpha$.

For α flow controlled $W'_m = \psi'_\alpha$.

Also $H'_m = \eta'_\alpha$ if $W_m > 0$.

The number of boundary conditions depends on the direction of flow between the connection and the flow path - the enthalpy boundary condition is only used where flow is from the connection to the flow path.

Similarly, at the β connection

$P'_n = \psi'_\beta$ or

$W'_n = \psi'_\beta$, and

$H'_n = \eta'_\beta$ if $W_n < 0$.

Hence the number of boundary conditions may be two, three or four, depending on the flow directions. However, the total number of equations is always 4(n-m+1) as shown in Table 1.

TABLE 1

FLOW PATH EQUATIONS

Equation Type	Number of Equations		
Mass	n-m		
Momentum	n-m		
		$W_n \geqslant 0$	$W_n < 0$
Energy	$W_m > 0$	n-m	n-m-1
	$W_m \leqslant 0$	n-m+1	n-m
Fuel	n-m+1		
ψ boundary	2		
		$W_n \geqslant 0$	$W_n < 0$
Enthalpy boundary	$W_m > 0$	1	2
	$W_m \leqslant 0$	0	1
Total	4(n-m+1)		

Consider now a network containing n nodes and b connections. The 4n flow path equations have been described above. These contain up to 2b connection parameters, hence an equal number of connection equations are required. At internal connections, two equations are always required, while at other types either one or two equations are required depending on flow direction. The connection equations for each connection type are described below. Input parameters specify which connections are of each type.

4.3.1 Internal

An internal connection is pressure controlled and must be common to more than one flow path. Each of these flow paths has a node at the common connection and the ψ boundary conditions are such that the pressures at these nodes are all equal to ψ. The pressure losses at such junctions can be included in friction coefficients or area changes in the last segment of the flow paths joining the connection so it is unnecessary to include them here. Internal connections are assumed to have zero volume, hence there is at least one flow towards and one away from the connection.

Let node i be a node for which flow at the start of the time step is towards the connection and let node j be one for which flow is away from it. In this section, the convention is adopted that all flows out of the connection are positive; thus

$$W_i \leqslant 0 \text{ and } W_j > 0.$$

As connections have zero volume, the total flow is zero

$$\Sigma_{\text{all}} W' = 0 \quad .$$

It is assumed that kinetic energy can be neglected and that the stagnation enthalpies of all fluid streams leaving the connection are equal. Therefore

$$\eta'_\alpha = \Sigma_{\text{in}} W'H' / \Sigma_{\text{in}} W' \quad .$$

These are the two equations for an internal connection.

4.3.2 Explicit

The connection equations in the standard code are:

$$\left.\begin{matrix}\psi'_\alpha \\ \eta'_\alpha\end{matrix}\right\} = \text{values at the start of the first time step,}$$

where ψ is flow or pressure depending on whether connection α is flow or pressure controlled.

More complex equations giving ψ'_α and η'_α in terms of quantities at the start of each time step, (flows, pressures, qualities, void fractions, *etc.*) may be coded in the special routine BCSETM which is called at every time step. An example is provided in the test problem.

4.3.3. Implicit

The connection equations must be coded in the special routine BPWIMP. These connection equations are solved by an iterative method discussed in Section 5. The special routine BPWIMP(KC) is called once at each iteration for each connection KC declared implicit in the input data. Any boundary conditions may be applied to explicit and implicit connections. The difference is that in BPWIMP, the enthalpies, pressures and flows for all connections at the end of the time step are available, as well as all parameters at the start of the time step. Thus implicit connection equations can be used, *e.g.* in the test problem, a pump model is set up using one implicit and one explicit connection.

4.3.4 Choked

The conditions for choke flow or zero sonic characteristic velocity are [Turner & Trimble 1975]

$$\gamma \equiv \left[\frac{\partial}{\partial P}\left(P + \frac{M}{a^2}\right)\right]_* = 0$$

where * means at constant stagnation enthalpy H_o, G and geometric parameters (D_e, ε, a, *etc.*). However, γ is a discontinuous function across single-phase two-phase boundaries and, in some situations, γ changes sign across these boundaries. In these cases, choking occurs at the boundary, thus choke conditions are those on the surface in W, P, H space which separates the positive and negative γ regions. The zero γ surfaces for liquid, two-phase and superheated steam are parts of this more general choke flow surface. The liquid and two-phase zero γ surfaces are joined by a surface on which x is zero and across which a step change in γ from positive (liquid) to negative (two-phase) occurs. The two-phase and superheat zero γ surfaces are joined by a surface on which x is one and across which a step change in γ from positive (superheat) to negative (two-phase) occurs.

To determine γ, consider

$$WH_o = WH + K$$

where H_o is a stagnation enthalpy. This is a function of the components of X, *i.e.* W, P and H, hence

$$\left[\frac{\partial}{\partial P}(WH_o)\right]_* = \frac{\partial}{\partial X}(WH_o) \cdot \left(\frac{\partial X}{\partial P}\right)_*$$

$$= \frac{\partial K}{\partial P} + \left(W + \frac{\partial K}{\partial H}\right)\left(\frac{\partial H}{\partial P}\right)_*$$

which $= 0$ as * means constant G, H_o and a.

Therefore, $\left(\frac{\partial H}{\partial P}\right)_* = -\frac{\partial K/\partial P}{W+\partial K/\partial H}$.

Similarly, M is a function of X hence

$$\gamma = 1 + \frac{1}{a^2}\frac{\partial M}{\partial X} \cdot \left(\frac{\partial X}{\partial P}\right)_*$$

$$= 1 + \frac{1}{a^2}\left[\frac{\partial M}{\partial P} + \frac{\partial M}{\partial H}\left(\frac{\partial H}{\partial P}\right)_*\right]$$

$$= 1 + \frac{1}{a^2}\left[\frac{\partial M}{\partial P} - \frac{\partial M}{\partial H}\ \frac{\partial K/\partial P}{(W+\partial K/\partial H)}\right] \quad .$$

The value of γ' at the end of the time step is evaluated as a function of the pressure ψ'_α at the choke connection. The choking pressure P'_c at the connection is the pressure at which γ' changes sign.

Now choking only occurs for throat pressures above the receiver pressure, hence the connection equation is

$$\psi'_\alpha = \text{Max}\ (P'_r,\ P'_c) \quad ,$$

where the receiver pressure P'_r is linearly reduced to the input pressure PAT over the break opening time TOPEN. These two quantities are the input data for a choked connection.

5. METHOD OF SOLUTION

The solution of the set of equations described in Section 4 is done in four stages.

5.1 Elimination of Surface Heat Flux and Fuel Temperature

The surface heat flux q' appears in the energy, the fuel and the surface heat flux equations, while T occurs in only the last two of these three equations. T is eliminated from these to give

$$q' = \frac{q + \frac{\partial q}{\partial X} \cdot (X'-X) + \frac{\partial q}{\partial T} Q' \frac{\Delta t}{\lambda}}{1 + \frac{\partial q}{\partial T}\ \frac{\Delta t}{\lambda}} \quad ,$$

which is used to eliminate q' from the energy equation.

5.2 Solution of Flow Path Equations

Consider a flow path which includes nodes m to n and joins connections α and β. There are 4(n-m+1) equations; elimination of the fuel temperatures reduces this to 3(n-m+1). In this stage of the network solution, these equations are solved for all W', P', and H', which are then determined as linear functions of the four connection parameters. The first step is to write the 3(n-m+1) equations in groups of three in the following way:

Group m

ψ'_α boundary condition

Node m, m+1 momentum equation

η'_α boundary condition if $W_m > 0$

Node m energy equation if $W_m \leq 0$

Only unknowns at nodes m and m+1 appear.

Group j j = m+1 to n-1

Node j-1, j mass equation

Node j, j+1 momentum equation

Node j energy equation

Only unknowns at nodes j-1, j and j+1 appear.

Group n

Node n-1, n mass equation

ψ'_β boundary condition

η'_β boundary condition if $W_n < 0$

Node n energy equation if $W_n \geq 0$

Only unknowns at nodes n-1 and n appear.

This set is now written as the matrix equation:

$$\begin{bmatrix} B_m & C_m & & & & & \\ A_{m+1} & B_{m+1} & C_{m+1} & & & 0 & \\ & A_{m+2} & B_{m+2} & C_{m+2} & & & \\ & & & & & & \\ & 0 & & A_{n-1} & B_{n-1} & C_{n-1} & \\ & & & & A_n & B_n & \end{bmatrix} \begin{bmatrix} X'_m \\ X'_{m+1} \\ \\ \\ X'_{n-1} \\ X'_n \end{bmatrix} = d^{(0)} + \psi'_a d^{(1)} + \eta'_\alpha d^{(2)} + \psi'_\beta d^{(3)} + \eta'_\beta d^{(4)} ,$$

where A, B, C are 3 by 3 matrices and the d vectors have 3(n-m+1) components. The A, B and C matrices are removed by forward elimination and back substitution to yield a solution of the form

$$X'_j = Y_j^{(0)} + \psi'_\alpha Y_j^{(1)} + \eta'_\alpha Y_j^{(2)} + \psi'_\beta Y_j^{(3)} + \eta'_\beta Y_j^{(4)}$$

$$j = m, m+1, \ldots, n \quad ; \qquad \ldots(1)$$

where the Y vectors have three components.

This procedure requires that all the B matrices be non-singular. The determinant of a B matrix is a cubic polynomial in $1/\Delta t$. We are not able to make any general statement about the roots of this polynomial, except that in some situations a positive root exists. This is only a

problem if W, P and H are nearly equal at several equally spaced, geometrically identical nodes, in which case the B matrices for these nodes will all be singular for almost the same values of Δt. In practice, the problem is easily overcome by using unequal node spacings, thus ensuring that, at most, only one near singular B matrix is present.

5.3 Connection Balance

Next, the connection equations are solved for the connection parameters

$$(\psi'_\alpha, \eta'_\alpha) \quad \text{for } \alpha = 1, \ldots, b \quad .$$

In the simplest case, the connection equations are those given in Section 4.3.2, and no solution procedure is needed as the values from the last time step are correct. For more complex explicit connections, solution is a simple matter as the connection equations are in terms of quantities at the start of the time step. These connection parameters are calculated in BCSETM at the start of the time step.

The remaining connections are solved by an iterative procedure beginning with the values from the last time step. Each internal, choked and implicit connection is considered in turn. For internal and choked connections, the equations in which ψ'_α or η'_α occur are the matrix equations for flow paths connecting to connection α and the connection equations for connection α. At each iteration these equations are solved for ψ'_α and η'_α using the most recent values of ψ'_β, η'_β for $\beta \neq \alpha$. For each implicit connection the statement

```
CALL BPWIMP(KC,N,ω)
```

is executed, where KC is the connection number, N the iteration number and ω the relaxation parameter. Thus, the solution procedure for implicit connection equations must be coded into the special routine BPWIMP.

In general, ψ'_α and η'_α for an implicit connection will not only appear in the matrix equations for flow paths connecting to α and the connection equations for α, but also in the connection equations for other connections. For example, in Figure 1 the connection parameters for connection 5 would appear in the connection equations for connections 5, 6 and 7. In this case, one of the group of connections is designated implicit in the input data and the rest explicit, and all the connection equations for the group are solved together when the special routine BPWIMP is called with KC equal to the number of the implicit connection.

This is essentially a Gauss-Siedel iteration procedure and can be expected to converge provided the connection groups are sufficiently independent. The degree of independence will determine the convergence, or sometimes divergence of the iteration scheme. If the latter occurs, it is assumed that the connections are made more independent by reducing the time step. Either a time step is found which gives convergence, or the final estimate of the connection parameters for the minimum time step is accepted and an error message printed. We have found the convergence to be almost linear, *i.e.* if

$$\Psi^{(n)} = \begin{bmatrix} \psi_1' \\ \eta_1' \\ \cdot \\ \cdot \\ \cdot \\ \psi_b' \\ \eta_b' \end{bmatrix}$$

is the estimate of the connection parameters after n iterations and

$$\Delta\Psi^{(n)} = \Psi^{(n)} - \Psi^{(n-1)} \quad ,$$

then for n sufficiently large,

$$||\Delta\Psi^{(n)}|| = e||\Delta\Psi^{(n-1)}||$$

where $e < 1$, constant and independent of n.

Hence, an acceleration scheme is used which corresponds to successive line over-relaxation in the iterative solution of linear systems. The relaxation is applied to the calculated change in the parameters. If at any iteration the change in ψ_α is $\Delta\psi_\alpha$, the relaxed ψ_α is $\psi_\alpha+\omega\Delta\psi_\alpha$. As highly non-linear conditions may be present at implicit connections, this acceleration scheme is only applied to internal and choke connections. The relaxation constant ω is available in the special routine BPWIMP for use at implicit connections and should be used unless convergence problems arise.

The network convergence criterion is that

$$\sum_{\alpha=1}^{b} \left[\left(\frac{\Delta\psi_\alpha'}{\psi_\alpha'} \right)^2 + \left(\frac{\Delta\eta_\alpha'}{\eta_\alpha'} \right)^2 \right] < TOL^2 \quad .$$

Both TOL and the maximum number of network interations are input parameters. Values of 10^{-5} to 10^{-10} have been used for TOL and up to 50 iterations allowed. The error in the internal connection balances can easily be checked from the output. If significant errors are found, the value of TOL should be reduced.

In general, any convergence problems will be due to too close a coupling between connection groups. This can be overcome by keeping connections well separated. If this is not feasible, the closely coupled connections can be placed in a group and solved together in the special routine BPWIMP.

5.4 Back Substitution

Once all the connection parameters are knowm, the values of W', P' and H' at all nodes are determined from Equation (1). Then the fuel temperatures are determined from the fuel equation (Section 4.1.2).

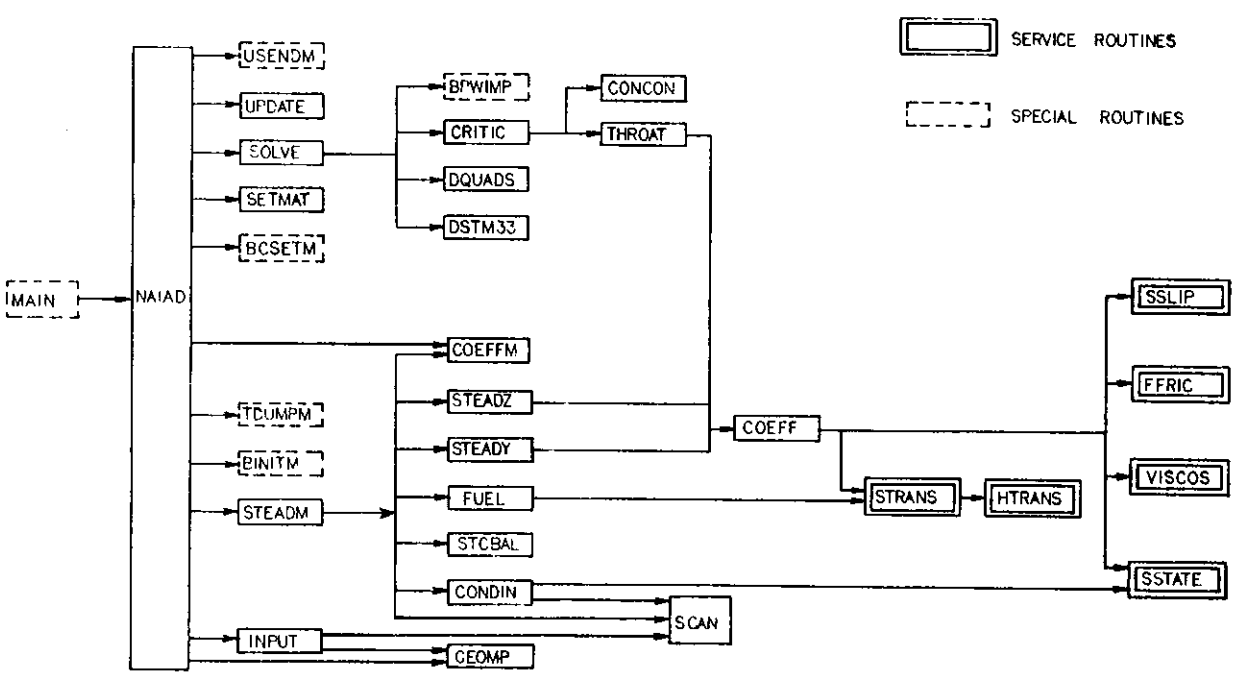
6. DESCRIPTION OF ROUTINES

6.1 Introduction

The general structure of the code is shown in Figure 3. The routines which make up the code are either service routines, special routines or ordinary routines.

FIGURE 3

Structure of NAIAD



The service routines are those which supply data on the coolant in the flow network and on the heat transfer. The standard service routines are for light water. They may need to be changed or extended if problems outside the range of these standard routines are to be done. For example, all service routines would need to be replaced for NAIAD to be used for sodium-cooled networks. The standard service routines and the requirements for new service routines are described in Section 6.2.

The special routines are intended to provide a simple way to expand the standard code in order to:

- compute and write additional output either for printing or plotting;
- impose time dependent boundary conditions;
- include any coupling between connections or nodes not routinely allowed for in the standard code, *e.g.* as required to simulate pumps, steam generators, pressure controllers, *etc*; and
- include NAIAD runs as part of a higher calculational procedure, *e.g.* a search for maximum fuel temperature as a function of break size.

The sample problem includes examples of all special routines except MAIN. The special routines supplied with NAIAD are given in Section 6.3 together with requirements for new special routines.

The remaining routines are briefly outlined in Section 6.4.

6.2 Service Routines

6.2.1 SSTATE

This is the equation of state routine. The assumption of thermodynamic equilibrium enables the coolant state to be determined from the pressure and static enthalpy which are the input data. The output is the remaining items in the call statement argument list which is given below:

$$P, S, \rho, x_s, \left(\frac{\partial \rho}{\partial H_s}\right)_P, \left(\frac{\partial \rho}{\partial P}\right)_{H_s}, T_c, T_s, \alpha, H_\ell, H_v,$$

$$\rho_\ell, \rho_v, S_\ell, S_v, \left(\frac{\partial T_c}{\partial P}\right)_{H_s}, \left(\frac{\partial T_c}{\partial H_s}\right)_P, H_s, \frac{d\rho_v}{dP},$$

$$\frac{d\rho_\ell}{dP}, \frac{dH_v}{dP}, \frac{dH_\ell}{dP}, \frac{dT_s}{dP},$$

where x_s is static thermodynamic quality $\frac{H_s - H_\ell}{H_v - H_\ell}$. In the two-phase

region, all output quantities except S, x_s, α, ρ and its derivatives, are functions of P only. In the single phase region, the saturation line values are those at pressure P.

The standard SSTATE is for light water over the range 0.045 to 16 MPa and 273 to 1073 K. The required quantities are obtained by interpolation in tables read from disk at the first entry to SSTATE. The tables have been generated from the state equations for water [Meyer 1967] by means of the ASTEM code [Moore 1971]. The pressure/temperature mesh used is given in Table 2.

TABLE 2

EQUATION OF STATE MESH

Pressures (MPa)	
0.045 to 0.09	at intervals of 0.003
0.090 to 0.200	at intervals of 0.005
0.20 to 0.7	at intervals of 0.01
0.7 to 1.50	at intervals of 0.02
1.50 to 4.00	at intervals of 0.05
4.00 to 10.0	at intervals of 0.1
10.0 to 16.0	at intervals of 0.2

Temperatures (K)	
At each pressure point, 5 liquid and 6 vapour points.	
Liquid: T_{sat}	Vapour: T_{sat}
T_{sat-10}	T_{sat+10}
T_{sat-20}	T_{sat+20}
T_{sat-50}	T_{sat+50}
273.15	$T_{sat+100}$
	1073.15

6.2.2 Viscos

The liquid and vapour viscosities μ_f and μ_g are calculated in this routine. Two formulae of Bruges & Gibson [1969] are used. The first (Equation 2, United Kingdom Committee on the Properties of Steam 1970) specifies the viscosity of saturated liquid light water as a function of

temperature in the range 375 to 623 K. The viscosity of both saturated and compressed water are calculated from this formula. For compressed water, the values are accurate to within a few per cent over the above temperature range and up to 16 MPa.

The second formula (Equation 4, United Kingdom Committee on the Properties of Steam 1970) specifies the viscosity μ_g of superheated steam, including saturated steam, as a function of the vapour density ρ_g and the temperature T_c in the ranges 375 to 600 K and 0 to 16.5 MPa.

The call statement argument list is

T_c, ρ_g (input data)

and μ_f, μ_g (output) .

6.2.3 FFRIC

This is the friction routine; in it, the Fanning friction factor is evaluated. The input data defining the state of the coolant and the node i at which friction is to be evaluated is in the call statement argument list which is

$$i,\ W,\ x,\ 1\text{-}x,\ \rho_\ell,\ \rho_v,\ \mu_f,\ \mu_g,\ \mu_h,\ T_s,\ f,$$

where here x equals physical quality which is always in the range 0 to 1, and μ_h is the viscosity used in the homogeneous friction model (see below).

The input data defining the geometry at node i (roughness, equivalent diameter, flow area, *etc.*) and the required friction model are taken from BLANK common. This division of input must be adhered to when new friction models are added because sometimes $W \neq W_i$ and $\rho_v \neq \rho_{vi}$ *etc.*

The standard routine contains four basic models and an optional boiling wall correlation to allow for regime changes at high quality, making eight friction options in all. In each of the basic models, the viscosity used to obtain the Reynolds number is calculated in a different way:

(a) Homogeneous

The viscosity used here is calculated in COEFF.

$$\frac{1}{\mu} = \frac{1}{\mu_h} = \frac{x}{\mu_g} + \frac{1-x}{\mu_f} \quad .$$

(b) *Bubbly Flow* [Beattie 1973]

$$\mu = \mu_f \left[1 + \frac{x}{v_f \rho_v}\right] \left[1 + \frac{1.5\ \mu_v}{\mu_g + \mu_f}\right] ,$$

where $v_f = \frac{x}{\rho_v} + \frac{1-x}{\rho_\ell}$ is the flow specific volume.

(c) *Wavy gas liquid interface* [Beattie 1973]

e.g. annular flow

$$\mu = \frac{1}{v_f} \left[\frac{1-x}{\rho_\ell}\ \mu_f + \frac{x}{\rho_v}\ \mu_g\right] .$$

(d) *Small bubble* [Beattie 1973]

$$\mu = \mu_\ell \left(1 + \frac{2.5\ x}{v_f \rho_v}\right) .$$

In all cases, the Reynolds number R_e is $R_e = \frac{D_e\ G}{\mu}$, and the Fanning friction factor f is the solution of one of the following equations depending on the value of R_e.

Turbulent Flow $R_e \geqslant 4000$

$$\frac{1}{\sqrt{f}} = -4 \log_{10} \left[\frac{\varepsilon}{3.7 D_e} + \frac{1.255}{R_e \sqrt{f}}\right] .$$

Interpolation Region $4000 > R_e > 2000$

$$f = \frac{16}{R_e} + (f_* - 0.004) \left[\frac{R_e}{2000} - 1\right] .$$

where f_* is the solution of the turbulent flow equation.

Laminar Flow $R_e \leqslant 2000$

$$f = \frac{16}{R_e} .$$

Near Zero Flow $R_e \leqslant 0.0016$

$$f = 10000 .$$

Often, a Reynolds number of 2000 is taken as the boundary between laminar and turbulent flow. The interpolation region removes the discontinuity that such a procedure entails and gives reasonable agreement with the pressure drop measurements of Nikuradse [1933].

The optional boiling wall friction factor [Beattie 1973] is the solution of

$$\frac{1}{\sqrt{f}} = 14 \log_{10} (f W_e) - 10.4 \quad ,$$

where the Weber number W_e is $\frac{G^2 D_e v_f}{\sigma}$ and σ is the surface tension. Rather than solve this equation at every node and time step, the solution has been evaluated for Weber numbers in the range 10^2 to 10^{22} and fitted as a quadratic polynomial in log W_e. The liquid surface tension is calculated from a straight line fit to the saturation line surface tension as a function of saturation temperature. If the boiling wall extension is specified, then f is the lower of the friction factors from the boiling wall extension and the specified basic model.

6.2.4 SSLIP

This is the slip routine. The call statement argument list is

$$i, \rho_\ell, \rho_v, H_\ell, H_v, W, P, H, T_s, \mu_f$$

which are input data, and

$$\rho, K, M, H_s, \alpha, k, \langle u_\ell \rangle$$

which are the output. The parameter k is the slip ratio $\langle u_v \rangle / \langle u_\ell \rangle$. These input data define the state of the coolant. Input data defining the slip model and the geometry at node i are taken from BLANK common. This division of input must be adhered to when new slip models are added because sometimes $P \neq P_i$, $H_v \neq H_{vi}$, *etc*. The slip routine is only called for two-phase non-homogeneous flow. Single phase and homogeneous flow are done in COEFF. In all cases, the quality is

$$x = \frac{H - H_\ell}{H_v - H_\ell}$$

and the flow void fraction is

$$\beta = \frac{x\rho_\ell}{x\rho_\ell + (1-x)\rho_v} \quad .$$

The standard slip routine contains eight slip models. In seven of these, separated flow is assumed *i.e.* all vapour moves at velocity u_v, all liquid at velocity u_ℓ. For these either the slip ratio k or the void fraction α is calculated.

(a) *Jones* [Jones & Dight 1962]

The void fraction α is the solution of

$$\frac{\alpha}{\beta} = E + (1-E)\alpha^r \quad ,$$

where $$r = 3.33 + 0.577\,\frac{P}{P_c} + 4.735\left(\frac{P}{P_c}\right)^2 \quad ,$$

$$E = 0.71 + 0.29\,\frac{P}{P_c} \quad , \text{ and}$$

P_c = critical pressure (22.12 MPa).

(b) *CISE* [Di Francesco *et al.* 1971]

$$k = 1+E\sqrt{\text{Max}\left[\frac{V}{1+cV} - cV,\ 0\right]} \quad ,$$

where $$V = \frac{\beta}{1-\beta} \quad ,$$

$$E = 1.578\left(\frac{\mu_\ell}{GD_e}\right)^{0.19}\left(\frac{\rho_\ell}{\rho_v}\right)^{0.22} \quad ,$$

$$c = 0.0273\,\frac{G^2 D_e}{\sigma_\ell \rho_\ell}\left(\frac{\mu_\ell}{GD_e}\right)^{0.51}\left(\frac{\rho_v}{\rho_\ell}\right)^{0.08} \quad , \text{ and}$$

σ_ℓ = liquid surface tension.

(c) *Beattie*

The Beattie slip model is defined as follows. Let

$$c = (3.125f)^{-\frac{1}{2}} \quad ,$$

$$w = \ell n[2(e^c-1)] - \tfrac{1}{2} \quad , \text{ and}$$

$$s = 1+2\,\exp[-w-\tfrac{1}{2}] \quad .$$

Then the void fraction is the solution of

$$(1-\beta) = (1-\alpha)\left[w + \frac{1}{2} + \ell n\left(\frac{s-\alpha}{2}\right)\right] \quad .$$

In the original form of the model [Beattie 1974], $s = 1$ and $w = c$, which gave small errors at $x = 0$ and 1. The forms of s and w given above eliminate these errors.

(d) *Fauske* [1962]

$$k = (\rho_\ell/\rho_v)^{\frac{1}{2}} \quad .$$

(e) *Moody* [1965]

$$k = (\rho_\ell/\rho_v)^{1/3} \quad .$$

(f) *Modified CISE*

The modifed CISE correlation is the same as the CISE correlation except that the dimensionless parameter c is replaced by

$$\frac{2E}{\pi} \arctan \frac{\pi c}{2E}$$

where $E = \frac{\sqrt{1+4V}-1}{2V}$ and V and c are defined in Section 6.2.4(b) for the CISE model. This modification was made because of the non-hyperbolic character of the conservation equations with CISE slip in conditions of high quality and mass velocity [Trimble & Turner 1976]. The modification has greatly reduced this non-hyperbolic region and, from a preliminary assessment, not altered the agreement of the correlation with measured density data.

(g) *Smith* [1970]

$$k = E + (1-E)\sqrt{\frac{x\rho_\ell + E(1-x)\rho_v}{x\rho_v + E(1-x)\rho_v}} \quad ,$$

where $E = 0.4$.

Thus either algorithms for α or k have been given for each of the seven separated flow slip models. If α has been calculated then

$$k = \frac{x(1-\alpha)\rho_\ell}{(1-x)\alpha\rho_v} \quad .$$

If k has been calculated then

$$\alpha = \frac{x\rho_v k}{x\rho_v k + (1-x)\rho_\ell} \quad .$$

Then the velocities are given by

$$u_v = \frac{Gx}{\alpha\rho_v} \quad , \quad u_\ell = \frac{G(1-x)}{(1-\alpha)\rho_\ell} \quad ,$$

and

$$\rho = \alpha\rho_v + (1-\alpha)\rho_\ell \quad ,$$

$$H_s = [\alpha H_v \rho_v + (1-\alpha)H_\ell\rho_\ell]/\rho \quad ,$$

$$K = \frac{a}{2}\left[\alpha\rho_v u_v^3 + (1-\alpha)\rho_\ell u_\ell^3\right] \quad ,$$

$$M = a^2\left[\alpha\rho_v u_v^2 + (1-\alpha)\rho_\ell u_\ell^2\right] \quad .$$

Separated flow is not assumed in the Small Bubble slip model hence none of these relations apply.

(h) Small Bubble [Beattie 1975]

The Beattie small bubble correlation should only be used for void fractions below about 0.6. It is defined as follows:

$$C_0 = 1 + 2.65\sqrt{f} \quad ,$$

$$\alpha = \frac{x\rho_\ell}{[x\rho_\ell + (1-x)\rho_v]C_0} \quad ,$$

$$K = \frac{G^3}{2\rho_\ell^2}\left[1+x\left(\frac{\rho_\ell}{\rho_v} - 1\right)\right]^2\left[1 - (C_0^2-1)x\left(\frac{\rho_\ell}{\rho_v} - 1\right)\right] ,$$

$$M = \frac{G^2}{\rho_\ell}\left[1+x\left(\frac{\rho_\ell}{\rho_v} - 1\right)\right]\left[1 - (C_0-1)x\left(\frac{\rho_\ell}{\rho_v} - 1\right)\right] .$$

The density ρ and static enthalpy H_s are given by the separated flow equations. This slip model should be used with the small bubble friction option so that the evaluation of the Fanning friction factor f is consistent with the slip model.

6.2.5 HTRANS and STRANS

The surface heat transfer coefficient is calculated in HTRANS. The call statement argument list is h and THT which are the output data, and

$$D_e,\ p,\ G,\ P,\ T_c,\ T_s,\ T_{FS},\ \rho_\ell,\ \rho_v,\ x,\ H_\ell, \text{ and } H_v$$

which are the input data. In general, a number of correlations are needed to cover all situations. Such a group of correlations together with the rules determining which is to be used, is a heat transfer package. The indicator THT is available to record which correlations are used in determining the heat transfer coefficient. The package is used to evaluate the heat transfer coefficient h and its derivatives by five entries for slightly different values of W, P, H and T_{FS}. As the package rules only need to be evaluated once, the input value of THT determines whether these rules are to be used or not. If it is positive, then the rules are used. If it is negative, the correlation used on the last entry to HTRANS is used again.

The standard routine contains only one package which is designed for round tubes. Steady state heat transfer correlations expressed as a function of local conditions (coolant temperature, pressure, quality and pipe surface temperature) were assumed applicable to transient situations. This is the local condition hypothesis of Hassid & Rychlicki [1971] which predicts dryout somewhat sooner than it occurred in experiments.

Heat transfer correlations included to cover all situations are summarised in Table 3. Condensing heat transfer correlations are needed when steam or two-phase coolant heated in a heated pipe section moves to sections in which the pipework is considerably cooler. They may be required also if the pipe model is used to simulate a heat exchanger. Akers *et al.* [1959] gives a Reynolds number of 50000 for the boundary between their two condensing heat transfer correlations. However, the correlations actually intersect at 76228 and this value is used here. Also the correlations of Akers *et al.* only cover the two-phase region. McAdams [1954 p.351] recommended that heat flux is almost independent of superheating of the vapour; this is followed in the superheat region. In the boiling non-dryout region, the heat transfer coefficient corresponding to three correlations is calculated and the largest taken. This ensures continuity of surface heat transfer rate in this region as a function of coolant conditions and fuel surface temperature.

At each heat transfer coefficient calculation, pipe surface temperature and coolant state are known from the previous time step. The heat transfer coefficient is evaluated assuming no dryout then, if appropriate, tested to determine if the dryout limit is exceeded. If this is so, the appropriate dryout heat transfer coefficient is calculated. In the steady state calculations, heat flux is known and surface temperature must be determined. Here an iterative procedure is used. In those steady state calculations where dryout and non-dryout solutions exist, the latter solution is used.

An indicator THT is available to show which heat transfer correlations are used in evaluating the heat transfer coefficient:

$$THT = \ell + m + n \quad ,$$

where ℓ and m indicate the correlation used to evaluate the coefficient assuming no dryout, m indicates the dryout correlation used to determine if the dryout limit is exceeded, and n the post-dryout correlation used.

In some situations, a dryout correlation is not appropriate, *e.g.* during condensation; zero values of m and n indicate these. Possible values of ℓ, m and n and their meanings are given in Table 3. For example, THT = 313 would indicate that:

- the heat transfer coefficient, assuming no dryout, was evaluated using the nucleate boiling correlation;
- the dryout limit on the heat transfer coefficient was determined from Bernath's correlation;
- dryout was found to be present; and
- Beattie's post-dryout correlation was used to evaluate the actual heat transfer coefficient used.

HTRANS is coded in Btu, foot, second units and conversion to SI units is carried out in STRANS.

TABLE 3

CORRELATIONS FOR SURFACE HEAT TRANSFER COEFFICIENT

Heat Transfer Indicator THT = ℓ + m + n

Surface temperature (T_s)	Quality x		
	$x \leq 0$	$1 > x > 0$	$x \geq 1$
$T_s < T_{sat}$	Liquid Dittus & Boelter [1930] ℓ = 1, m = 0, n = 0	Condensing Akers *et al.* [1959] m = 0, n = 0 $R_e \leq 76228$ ℓ = 3 $R_e > 76228$ ℓ = 4	
$T_s \geq T_{sat}$	Boiling Non-dryout Largest of - subcooled liquid Dittus & Boelter [1930] - nucleate boiling ℓ = 5 Tong [1965 p.118] - forced convection boiling ℓ = 3 Shrock & Grossman [1959] with coefficient from Wright [1961] ℓ = 2 Dryout $x \leq 0$, Bernath - Tong [1965 p.156] m = 10 $x > \rho_v/(\rho_v+\rho_L)$, Biasi *et al.* [1967] low quality m = 30 high quality m = 40 Other x, linear interpolation on x between Bernath & Biasi low quality m = 20 Post Dryout - Dryout limit not exceeded n = 0 $x \leq 0.05$ - Tong [1965 p.129] low speed flow n = 100 high speed flow n = 200 $x > 0.05$, $\frac{h_s D_e}{k_v} = 0.0192\left(\frac{GD_e x}{\mu_v}\right)^{0.8}\left(\frac{C_{pv}\mu_v}{k_v}\right)^{0.4}$ evaluated at temperature T_s Beattie [1972] n = 300		Superheat Heineman [1960] ℓ = 2 m = 0 n = 0

6.3 Special Routines

6.3.1 General

All quantities likely to be used within the special routines are in the various common blocks described in Tables 4 to 11. The required common blocks must be included in the special routines. The labelled commons BCONDS and POWER$ are of particular importance in that they contain the connection parameters ψ and η in the arrays BPW and BHO, and the flow path powers in PGENP, these quantities being those most likely to be required. Any service routine may be called by any special routine. All arithmetic and REAL arrays are double precision hence an

```
IMPLICIT REAL*8 (A-H, O-Z)
```

card must be included in each subroutine. All the standard special routines consist of the three cards

```
SUBROUTINE name
RETURN
END
```

except for MAIN which is

```
CALL NAIAD
STOP
END
```

Thus, an actual NAIAD run is initiated in the special routine MAIN by this CALL statement. Each standard special routine except MAIN is automatically inserted in composite codes if no other routine of that name is provided. The standard MAIN is included by using the CINSERT card described in Section 9.1 and demonstrated in the sample problem.

6.3.2 BINITM

This routine is called once by NAIAD just before the transient calculation commences (*i.e.* after INPUT and STEADM). Any initial conditions (which are W, P, H and T at all nodes) or input data for the transient calculation may be modified here. The effects of these modifications appear in the time zero and subsequent output. Also any time independent constants in the connection equations should be calculated here.

6.3.3 TDUMPM

This routine is called each time step immediately after the state of the flow network has been completely evaluated and printed. Instructions for any additional output required should be placed in TDUMPM. The call statement argument list contains one variable, IPRINT which indicates

(continued p.42)

TABLE 4

BLANK COMMON

Variable name and dimension	Description	Algebraic symbol
Z(50)	Displacement along pipe	z
A(50)	Pipe area	a
DE(50)	Pipe equivalent diameter	D_e
GSINT(50)	Value of g (acceleration due to gravity) times Δ height/Δz	$g\sin\theta$
ORIK(50)	Value of friction coefficient if $\geqslant 0$	K_e
	< 0	K_f
PD(50)	Power distribution (per unit length per unit heated wetted perimeter) (m^{-2})	Q/PGENP
CP(50)	Heat capacity of fuel (J m^{-2} K^{-1})	λ
HP(50)	Heated wetted perimeter	p
HF(50)	Fuel centre to suface heat transfer coefficient	h_F
W(50)	Mass flow rate	W
P(50)	Pressure	P
H(50)	Flow enthalpy	H
HS(50)	Static enthalpy	H_s
X(50)	Thermodynamic quality	x
RHO(50)	Static density	ρ
VOLF(50)	Flow specific volume	v_f
DEFR(50)	Fanning friction factor divided by equivalent diameter	f/D_e
FK(50)	Kinetic Energy Flow (W)	K
BM(50)	Area times Momentum Flow (kg m^3 s^{-2})	M
S(50)	Entropy	S
CT(50)	Coolant temperature	T_c
CTS(50)	Coolant saturation temperature	T_s
TFC(50)	Fuel temperature	T
TFS(50)	Fuel surface temperature	T_{FS}
HT(50)	Fuel centre to coolant heat transfer coefficient	h_T
THT(50)	Heat transfer indicator	THT
FLUX(50)	Fuel to coolant heat fluxes (W m^{-2})	q
CRSL(50)	Saturation liquid density	ρ_ℓ
CRSV(50)	Saturation vapour density	ρ_v
CHSL(50)	Saturation liquid enthalpy	H_ℓ

TABLE 4 (continued)

Variable name and dimension	Description	Algebraic symbol
CHSV(50)	Saturation vapour enthalpy	H_v
CRLP(50)		$d\rho_\ell/dP$
CRVP(50)		$d\rho_v/dP$
CHLP(50)		dH_ℓ/dP
CHVP(50)		dH_v/dP
CSSL(50)	Saturation liquid entropy	S_ℓ
CSSV(50)	Saturation vapour entropy	S_v
DRDW(50)		$\partial\rho/\partial W$
DRDP(50)		$\partial\rho/\partial P$
DRDH(50)		$\partial\rho/\partial H$
DMDW(50)		$\partial M/\partial W$
DMDP(50)		$\partial M/\partial P$
DMDH(50)		$\partial M/\partial H$
DHDW(50)		$\partial H_s/\partial W$
DHDP(50)		$\partial H_s/\partial P$
DHDH(50)		$\partial H_s/\partial H$
DKDW(50)		$\partial K/\partial W$
DKDP(50)		$\partial K/\partial P$
DKDH(50)		$\partial K/\partial H$
DTDW(50)		$\partial T_c/\partial W$
DTDP(50)		$\partial T_c/\partial P$
DTDH(50)		$\partial T_c/\partial H$
DOTDR(50)		$X.\partial\rho/\partial X$
DOTDM(50)		$X.\partial M/\partial X$
DOTDH(50)		$X.\partial H_s/\partial X$
DOTDK(50)		$X.\partial K/\partial X$
DOTDT(50)		$X.\partial T_c/\partial X$
DQDW(50)		$\partial q/\partial W$
DQDP(50)		$\partial q/\partial P$
DQDH(50)		$\partial q/\partial H$
DQDT(50)		$\partial q/\partial T$
DOTDQ(50)		$X.\partial q/\partial X$
AMAT(3,3,50)	A matrices	A
BMAT(3,3,50)	B matrices	B
CMAT(3,3,50)	C matrices	C
DVEC(3,50,5)	Y vectors	Y

TABLE 5

LABELLED COMMON "BCONDS"

Variable Name and Dimension	Description	Algebraic symbol
BPW(10)	Connection control (pressure or flow)	ψ
BHO(10)	Connection enthalphy	η
TIME	Time	t
DELT	Time step	Δt
LC(10)	Connection type indicator	
LCB(10)	Boundary condition type indicator	
NSN(10)	Node number of the first node in flow path	
NFN(10)	Node number of the last node in flow path	
NSC(10)	Connection at start of flow path	
NFC(10)	Connection at finish of flow path	
MMAT(10,10)	Connection matrix	
NP	Number of pipes	
NC	Number of connections	
N	Total number of nodes	

NOTES:

(i) *The LC and LCB indicators correspond to LC and LCB in the connection input data.*

(ii) *NSN and NFN are the node numbers at the beginning and end of each pipe, e.g. pipe 3 begins at node NSN(3) and ends at node NFN(3).*

(iii) *NSC and NFC are the connection numbers at the ends of each pipe, e.g. pipe 3 joins connections NSC(3) and NFC(3).*

(iv) *The connection matrix defines the network. The first index is the pipe number and the second the connection number. If MMAT(KP,KC) is +1 then the first node of pipe KP joins connection KC. If -1 then the last node of pipe KP joins connection KC.*

(v) *The subscripts of BPW, BHO, LC and LCB are connection numbers. The subscripts of NSN, NFN, NSC, NFC are pipe numbers.*

TABLE 6

LABELLED COMMON "POWER$"

Variable name and dimension	Description
PTCTP(10)	Power to coolant in each pipe
PGENP(10)	Power generated in each pipe
PTCT	Total power to coolant
PGEN	Total power generated

TABLE 7

LABELLED COMMON "COEFF$"

Variable name and dimension	Description	Algebraic symbol
ROUGH(50)	Surface roughness	ϵ
IFR(50)	Friction correlation indicator	
ISLIP(50)	Slip correlation indicator	
IHTRAN(50)	Implicit heat flux indicator	

TABLE 8

LABELLED COMMON "BAL$"

Variable name and dimension	Description
TOL	Tolerance in network balance
ITMAX	Max number of iterations in network balance

TABLE 9

LABELLED COMMON "CRIT$"

Variable name and dimension	Description	Algebraic symbol
PAT(10)	Pressure of choke flow receiver	P_r
TOPEN(10)	Break opening time	
PTHROT(10)	Throat pressure	P_c
LT(10)	Logical variable which is TRUE if choke flow is present at the connection	

TABLE 10

LABELLED COMMON "HEAD$"

Variable name and dimension	Description
HEAD(10)	Title card
DAY(3)	Date (single precision REAL*4 array)

TABLE 11

LABELLED COMMON "STEP$"

Variable name and dimension	Description
SMIN	Minimum time step allowed
SMAX	Maximum time step allowed
CTAR	Target fractional change
CMAX	Maximum fractional change
RCMAX	Maximum fractional density error at a phase change
CINC	Maximum time step increase
DELTR	Estimated time step to achieve "RCMAX"
TMAX	Maximum time required in transient calculation
TSFP	Time at which full printout commences
KW(50)	Print mask for partial printout
KFP	Full printout frequency
KKW	Number of nodes in partial printout

the type of listing that has been produced by the standard code for this time step:

IPRINT > 0 full listing

IPRINT = 0 no listing at all

IPRINT < 0 partial listing.

Its use is illustrated in the sample problem.

6.3.4 BCSETM

This routine is called at the start of every time step, including those time steps which are later rejected for reasons given in Section 7. Any explicit connection equations should be solved here. Also boundary conditions and heating power at the end of the time step (at time TIME+DELT from common BCONDS) can be changed.

6.3.5 BPWIMP

All implicit connection equations must be solved in this routine. BPWIMP is called once in each network balance iteration for each connection declared implicit. However, as described in Section 5.3, conditions at connections declared explicit may also be updated in BPWIMP. This allows connections with strong coupling to be handled together, one being declared implicit and the others declared explicit. The pump model in the sample problem is an example of this.

The call statement argument list is

α the connection number,

N the network balance iteration number, and

ω the relaxation constant.

It is recommended that the relaxation constant should be used as described in Section 5.3.

Consider node n which is at the junction of flow path k and connection α. W'_n, P'_n and H'_n are given as a function of the connection parameters in a component of Equation (1) (Section 5). During the network iteration at connection α, the connection parameters ψ'_β, η'_β at the other end of flow path k are assumed constant. Therefore from Equation (1), Section 5;

$$X'_n = \begin{pmatrix} W'_n \\ P'_n \\ H'_n \end{pmatrix} = \begin{pmatrix} W_* \\ P_* \\ H_* \end{pmatrix} + \psi'_\alpha \begin{pmatrix} W_P \\ P_P \\ H_P \end{pmatrix} + \eta'_\alpha \begin{pmatrix} W_H \\ P_H \\ H_H \end{pmatrix}$$

where $\begin{pmatrix} W_* \\ P_* \\ H_* \end{pmatrix} = Y_n^{(0)} + \psi'_\beta \; Y_n^{(3)} + \eta'_\beta \; Y_n^{(4)}$,

$\begin{pmatrix} W_P \\ P_P \\ H_P \end{pmatrix} = Y_n^{(1)}$ and $\begin{pmatrix} W_H \\ P_H \\ H_H \end{pmatrix} = Y_n^{(2)}$

are all constant.

A subroutine CONCON is available for calculation of these coefficients. The argument list for CONCON is k and α (input) and

$n, W_*, W_P, W_H, P_*, P_P, P_H, H_*, H_P, H_H, \phi$ (output) and & m,

where & m is an error return if pipe k and connection α do not connect, ϕ is an orientation parameter, and the other arguments are the coefficients. The value of ϕ is 1 if node n is the beginning of pipe k and -1 if node n is the end of pipe k. Thus $\phi \, W'_\alpha$ is positive for flow out of connection α into pipe k regardless of whether α is at the start or finish of pipe k.

6.3.6 USENDM

This routine is called only at the end of a NAIAD run. Instructions for any final output should be coded into this routine.

6.4 Other Routines

NAIAD

This subroutine, is essentially the mainline of the code. It controls time stepping and output.

INPUT

Most of the input data are read here. Also the power distributions are normalised and various other variables and arrays set to their initial values.

STEADM

The initial condition input data are read and the required initial states calculated.

GEOMP

A table of the geometry of the system is printed. Also the connection variables ψ and η are evaluated from the initial condition of the network.

COEFFM

This is an interface between NAIAD and COEFF. The output at each time step is printed.

SETMAT

The matrix equations are set up from the difference equations and boundary conditions.

SOLVE

The matrix equations are solved and the network is converged.

UPDATE

All the new values of W, P and H are calculated from the converged set of connection parameters. Also heat fluxes, power to coolant and new fuel temperatures are calculated.

CONDIN

This is called by STEADM to read the initial condition input data.

STCBAL

This is called by STEADM to balance a connection.

FUEL

Steady state fuel temperatures are generated.

STEADY

The steady state hydraulic difference equations are solved along a flowpath.

STEADZ

The steady state, zero-flow mass and momentum conservation equations are solved along a flowpath. The enthalpy at each node is required input data for this.

DSTM33

The block tridiagonal system of 3 x 3 matrices with multiple right hand sides is solved.

DQUADS

The relaxation constant ω is calculated.

CRITIC

The connection equations for choked connections are solved.

THROAT

The choke flow parameter γ is calculated.

CONCON

This has been described in Section 6.3.5.

COEFF

All the parameters required to evaluate the coefficients in the matrix equations are calculated. This includes the partial derivatives of h, H_s, K, ρ and M which are evaluated by repeated calls to the heat transfer and slip routines. Thermodynamic equilibrium of the coolant is assumed.

7. TIME STEP CONTROL

It is usually desirable to take long time steps when conditions are changing slowly, and small time steps when rapid changes are occurring. This is done in NAIAD in the following way. Let

$$\Phi = \underset{\text{all nodes}}{\text{Max}} \left(\left|1 - \frac{P'}{P}\right|, \left|1 - \frac{H'}{H}\right| \right) .$$

The next time step is chosen to meet the following criteria:

- Always in the range SMIN to SMAX.
- Never larger than CINC * (t'-t) ,
- Otherwise equal to $\frac{CTAR}{\Phi}$ * (t'-t) .

Thus a new t' is defined and the old t' becomes t.
This time step is then completed to the stage at which the new Φ has been calculated. If Φ < CMAX or t' - t = SMIN, then the time step is accepted, otherwise the time step is redone with

$$\Delta t = \text{Max } [\text{SMIN}, \frac{CTAR}{\Phi} * (t'-t)].$$

There is another factor in the time step control which has been omitted in the above discussion. To derive the finite difference equations, the approximation

$$\frac{\partial \rho}{\partial t} \approx \frac{\partial \rho}{\partial X} \cdot \frac{(X'-X)}{\Delta t} \qquad \ldots(2)$$

is used. This is a very poor approximation if there is a change from liquid to two-phase or *vice versa* during the time step. If such a change of phase is estimated to have occurred during the time step, an estimate of ρ_e, the fractional density error resulting from use of Equation (2), is obtained as follows. At this stage, all W', P' and H' are known but no other parameters have been evaluated at the end of the time step. First, we obtain estimates (indicated by a superscript *) of the saturation line densities and enthalpies at the end of the time step.

$$H_\ell^* = \frac{dH_\ell}{dP}\,(P'-P) + H_\ell, \quad H_v^* = \text{etc.}$$

We also define

$$\rho^* = \frac{\partial\rho}{\partial X} \cdot (X'-X) + \rho \quad ,$$

and $$x^* = \frac{H'-H_\ell^*}{H_v^*-H_\ell^*} \quad .$$

If $xx^* \geqslant 0$ then there is no liquid two-phase transition and ρ^* is a good estimate of ρ'. Then $\rho_e = |1-\rho^*/\rho'| \approx 0$.

Two-phase to liquid $x > 0$, $x^* < 0$

Because water is nearly incompressible

$$\rho' \approx \rho_\ell^*$$

hence $$\rho_e = |1-\rho^*/\rho_\ell| \quad .$$

Liquid to two-phase $x < 0$, $x^* > 0$

We estimate ρ' from

$$\frac{1}{\rho'} \approx \frac{x^*}{\rho_v^*} + \frac{(1-x^*)}{\rho_\ell^*} \quad .$$

This rather poor estimate (slip is neglected) is sufficiently accurate for the present purpose. Then

$$\rho_e = |1-\rho^*/\rho'| \quad .$$

Now if we assume that x varies linearly during the time step the error in density only occurs (in time) after the phase change has taken place. The time at which the phase change takes place is estimated as

$$t_0 = t + \frac{(t'-t)x}{x-x^*}$$

and it is assumed that ρ_e varies linearly with time in the interval t_0 to t'. If

$$\rho_e < \text{RCMAX}$$

the time step density error is deemed acceptable. Otherwise a time step of

$$(t_0-t) + (t'-t_0)\,\frac{\text{RCMAX}}{2\rho_e}$$

is tested against the criteria described in the first paragraph. All the time step control parameters (given in capitals above), are specified

in the input data and stored in the labelled common STEP$.

8. INPUT DATA

8.1 General

The finite difference method relies on the continuity of the derivatives being approximated by finite differences. Unfortunately, some problems involve discontinuities (or, at least, large spatial derivatives) in some parameters, *e.g.* flow path area, surface heat flux. Such discontinuities are best treated by placing nodes close to either side of and at equal distances from the discontinuity.

Except for the title card, all data are read with the AAEC free input subroutine SCAN [Bennett & Pollard 1967]. Data may be punched anywhere on a card with numbers separated by blanks or commas. Alphabetic comments may be placed amongst the data and comment cards (* in column one) may be used. Other features are:

- repeat notation
  e.g. 5*1.47
  is equivalent to 1.47 1.47 1.47 1.47 1.47
- fixed increment notation
  e.g. 1.(0.5)3.
  is equivalent to 1. 1.5 2. 2.5 3.
- a decimal point is not needed for real numbers with integral values
- the data cards are listed in the output.

All input and output data are in SI units.

8.2 Title Card

HEAD Title card

8.3 Controls

±NP NP is the number of flow paths in the network. If negative a printout of the pipe data interpreted by the code is produced after each set of pipe data is read.

NC Number of connections in the network.

GRAV Acceleration due to gravity, g ($m\ s^{-2}$).

TOL Tolerance in network balance (suggest 10^{-8}).

ITMAX Maximum number of iterations in network balance (suggest 15).

SMIN Minimum time step to be used (s)

SMAX Maximum time step to be used (s).

CTAR Target maximum fractional change in P or H in a time step (suggest 0.01).

CMAX — Maximum allowable fraction change in P or H in a time step (suggest 0.02)..

RCMAX — Maximum allowable fractional density error in a time step involving a liquid to two-phase transition (suggest 0.01).

CINC — Maximum ratio between successive time steps, *e.g.* 2 means at most double the time step.

TMAX — Maximum time required (s).

KFP — Frequency of full listing, *e.g.* 5 means full listing every 5th time step and partial listing at other time steps. A partial listing covers only those nodes specified below in KW, and, if KFP positive, details of time step change and elapsed CPU time. If no nodes are specified below and KFP is negative, then no partial listing appears.

TSFP — A full printout will be produced at every time step after this time.

A dashed line is printed in the output immediately after this data is read and printed.

8.4 Flow Path Data

The following set of data is required for each pipe or flow path beginning with pipe 1. Each set must start on a new card:

NODE — Number of nodes in flow path.

KA — Connection at start of flow path.

KB — Connection at end of flow path.

PGENP — Total power generated in this flow path (W).

ISLIP — NODE integers specifying which slip relation is to be used at each node:

- 0 - homogeneous (no slip)
- 1 - Jones
- 2 - CISE
- 3 - Beattie
- 4 - Beattie small bubble
- 5 - Fauske
- 6 - Moody
- 7 - modified CISE
- 8 - Smith.

IFR NODE integers specifying which friction relation is to be used:

±1 - homogeneous

±2 - bubbly

±3 - annular

±4 - small bubbles.

If negative the boiling wall extension will be used.

IHTRAN NODE integers specifying differencing of the surface heat transfer coefficient:

0 - explicit heat transfer coefficient

1 - implicit heat transfer coefficient.

KW NODE integers specifying which nodes are to be printed in partial printouts:

0 - do not print the node

1 - print it.

Z NODE value of the axial displacement (m) along the flow path (arbitrary origin but strictly increasing).

SINT NODE-1 values of $\frac{\Delta \text{ height}}{\Delta z}$ for segment of flow path between adjacent nodes.

DE NODE values of equivalent diameter D_e (m).
If DE(I) is given as zero it is calculated from A(I) assuming a round pipe.

A NODE values of cross sectional area a (m^2).
If A(I) is given as zero, it is calculated from DE(I) assuming a round pipe.

HP NODE values of heated wetted perimeters p (m).
If HP(I) is given as zero, it is calculated from DE(I) assuming a round pipe.

ROUGH NODE values of absolute surface roughness ε (m) .

CP NODE values of fuel heat capacity λ (J m^{-2} K^{-1}).
If zero, generated power passes directly to coolant.

HF NODE values of fuel centre to fuel surface heat transfer coefficient h_F (W m^{-2} K^{-1}).
If given as zero set to 10^{10} (zero resistance).

ORIK NODE-1 values of friction coefficient.
If > 0 then taken as K_e
If < 0 then taken as $-K_f$.

PD NODE values specifying an equivalent heat flux distribution P_D (m^{-2}) (the given distribution is normalised within the code so that $P_{Di} = Q_i/PGENP$ hence

$$\sum_{i=1}^{NODE-1} (P_{Di}p_i+P_{Di+1}p_{i+1})(z_{i+1}-z_i) = 1 \quad .$$

A dashed line is printed in the output after each set of flow path data is read and printed.

8.5 Connection Data

The following set of data is required for all connections which are not internal. The first set must start on a new card.

KC CONNECTION number

LC CONNECTION type

0 - explicit

1 - internal

2 - choked (burst)

3 - implicit.

Only one flow path can connect to a choked connection, and the connection number allotted to a choked connection must be larger than that of the connection at the other end of the flow path involved.

If LC = 0 or 3

LCB type of connection control

1 Flow

2 Pressure.

If LC = 2

PAT Pressure downstream of burst (final receiver pressure) (Pa)

TOPEN Opening time of break(s).

A zero marks the end of the connection data. A dashed line follows the listing of the connection data in the output.

8.6 Initial Condition Data

The initial condition calculation is a series of steady state calculations. Any number of calculations may be done on one flow path. If a steady state calculation is not done on a flow path, then its initial state must be specified in the special routine BINITM.

In the following specification an asterisk as a superscript on a flow, pressure or enthalpy means that it is specified by two numbers IP and Q where

IP = Pipe number or zero.

If IP = 0

Q = COND = the actual value of the quantity.

If IP ≠ 0

Q = Node number. Then the condition is set equal to its counterpart at the Qth node of pipe IP.

Also, this node number Q is the position in the flow path containing the node, not the node number appearing in the code output. This allows extra nodes to be added with minimum impact on the input data.

The following set of data is required for each steady state calculation:

KP Pipe number.

IOPT Specifies which type of calculation is required.

- ±1 Conditions known at a single node.
- ±2 Pressure known at two nodes and enthalpy at one of them.
- ±3 Zero flow in flow path, enthalpy known at all nodes, pressures determined from gravitational head.
- ±4 Conditions known in all but one of the flow paths terminating at a connection. The enthalpy and flow at the terminal node of the unknown flow path are chosen to give zero net enthalpy and mass flow through the connection. The pressure is chosen equal to that of the other terminal nodes. This process is called a connection balance.
- ±5 Constant gravity head pump with head and flow path power determined to give connection balances at both ends of flow path.

If IOPT is negative, a listing of the calculated steady state for this flow path will be produced before any further initial state calculations are done.

The data required for each option is given below:

IOPT = ±1

J Node number

W^*_J Flow at node J in flow path KP (kg s^{-1})

P^*_J Pressure at node J in flow path KP (Pa)

H^*_J Enthalpy or thermodynamic quality at node J ($J\ kg^{-1}$) in flow path KP.

For example, to produce a steady state in pipe 1 with flow 4 $Mg\ s^{-1}$ and at node 2 a pressure and quality of 8.6 MPa and -0.14 respectively

KP = 1

IOPT = 1

J = 2

W^*_J = 0, 4.E3

P^*_J = 0, 8.6E6

H^*_J = 0, -0.14.

The steady state finite difference equation will then be solved along flow path KP in both directions from node J.

IOPT = ±2

J Node number

W^*_J Estimate of flow at node J in flow path KP ($kg\ s^{-1}$)

P^*_J Pressure at node J in flow path KP (Pa)

H^*_J Enthalpy or thermodynamic quality at node J ($J\ kg^{-1}$) in flow path KP

K Node number

P^*_K Pressure at node K in flow path KP (Pa).

The flow will then be found by iteration and finally the steady state finite difference equations solved along flow path KP:

IOPT = ±3

J Node number

P^*_J Pressure at node J of flow path KP (Pa)

H Enthalpies at each node of flow path KP ($J\ kg^{-1}$)

TFC Fuel temperatures at each node of flow path KP (K).

The steady state zero flow momentum equation will then be solved along flow path KP. Any fuel temperatures specified to be zero are set equal to the coolant temperature for that node:

IOPT = ±4

KC Connection number.

Conditions at the node of flow path KP which connects to connection KC will be determined from a connection balance. The steady state finite difference equations will then be solved along flow path KP:

IOPT = ±5

J Segment at which pump is to be inserted (between node J and node J + 1).

Conditions at each end of the pipe will be determined by connection balances. The head (Δ height) at segment J and power to coolant are then varied to achieve the required conditions.

Zero marks the end of steady state data. This is the end of the standard NAIAD input data. Any input for special routines will follow.

9. CATALOGUED PROCEDURES

All three procedures are used in the test problem.

9.1 NAIADCLG

This procedure is used to compile, link and execute a composite program. The procedure has four steps:

(a) PREP - In this step common blocks and other groups of cards can be copied into the FORTRAN source decks by including "CINSERT" cards in the FORTRAN program. By this means, the tedious process of duplicating common blocks is avoided. The format of this card is

CINSERT COM1, COM2, COM3

where the letters CINSERT followed by a blank must be in columns 1 to 8 of the source card and COM1, COM2, COM3, *etc.* are the names of common blocks required in the FORTRAN routine. Any of the common blocks of Tables 4 to 11 may be inserted in this way, BLANK common having the label "BLANK". The default MAIN routine (Section 6.3.1) may be generated with a

CINSERT MAIN

card and the IMPLICIT REAL*8 statement with a

CINSERT R8

card.

(b) FORT - FORTRAN H compilation step

(c) LKED - linkage editor

(d) GO - execution of the composite program load module.

This load module may be placed in a private program library by including two symbolic parameters LIB and MEM. LIB is the private library name and MEM the member name under which the load module is to be stored.

9.2 NAIADG

In this procedure composite program load modules specified by the

two symbolic parameters LIB and MEM can be executed. The GO step is the only step in this procedure. If LIB and MEM parameters are not specified, then the standard NAIAD code is executed.

9.3 PROGRUN

The plot program is executed in this procedure. It is used as shown in the sample problem.

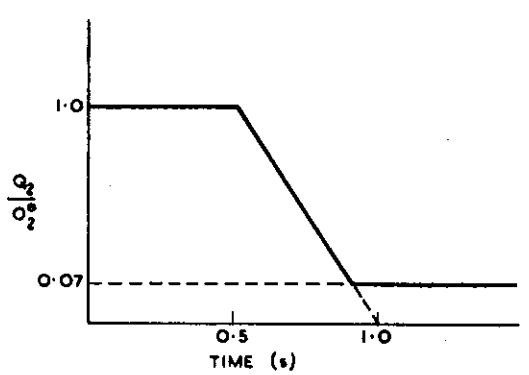
10. SAMPLE RUN

The sample problem is the blowdown of a CANDU nuclear reactor through a small hole in an outlet header. The problem has been chosen to illustrate the use of most NAIAD options, to show simple examples of special routines and to demonstrate the advantages of NAIAD. In the sample run, a composite program for this problem is formed, the problem is run twice with target fractional changes of 10 and 1 per cent, and graphs are plotted comparing the coarse and fine solutions.

Both primary and secondary coolant loops are simulated together with their pumps and the steam generator coupling the two loops. The flow network is shown in Figure 6. A very coarse spatial mesh is used to keep the computation time and output quantity small. The lower part of the primary system simulates the flow path from inlet header to outlet header through the feeders and fuel channels. The conditions in the 195 channels are assumed identical so that they can be combined into one flow path. Similarly, in the upper part of the primary system, the 15600 steam generator tubes are combined into one flow path and the sets of six pipes connecting the headers to the steam generators are combined into one flow path. The secondary system includes a constant volume pump, the steam generator and a heat sink. The transient is initiated

FIGURE 4

Nuclear Power for Sample Problem



by a burst in the outlet header and it is assumed a reactor shutdown occurs.

10.1 Nuclear Power

The power generated in the fuel, which is in flow path 2, is assumed to vary as shown in Figure 4. It is calculated at the beginning of each time step in the special routine BCSETM.

10.2 Heat Sink

The heat removed from the secondary coolant within the heat sink, which is in pipe 6, is

$$Q_6 = \left(\frac{\bar{T} - T_{sink}}{\bar{T}^0 - T_{sink}} \right) Q_6^0 \quad ,$$

where $\bar{T}$ = mean temperature of coolant in the heat sink. Q_6 is calculated in the special routine BCSETM at the start of each time step using the coolant temperatures from the previous time step.

10.3 Steam Generator

The heat flow from the primary side (pipe 1) to the secondary side (pipe 5) of the steam generator is assumed proportional to the mean temperature difference:

$$Q_5 = -Q_1 = \left(\frac{\bar{T}_p - \bar{T}_t}{\bar{T}_p^0 - \bar{T}_t^0} \right) Q_5^0 \quad ,$$

where $\bar{T}_p$ = mean temperature of primary coolant in the steam generator, and $\bar{T}_t$ = mean temperature of secondary coolant in the steam generator. The heat flows are calculated each time step in the special routine BCSETM.

10.4 Makeup System

The makeup or pressure control system is simulated by a flow boundary condition at connection 1. The flow ψ_1 is a function of the outlet header pressure ψ_3 as shown below, except that a limit of 20 kg s^{-2} is imposed on the rate of increase or decrease in the flow rate. It is calculated at the start of each time step in BCSETM.

10.5 Secondary Pump

The secondary pump is represented by connection 7 which is an implicit flow controlled connection, connection 5 which is an explicit flow controlled connection, and a special routine BPWIMP. As the flow is always from connection 5 to 7 *via* 6, the quantities to be determined from the pump characteristic are

$$\psi'_7, \quad \psi'_5, \text{ and } \eta'_5 \quad ,$$

which are the connection parameters for connections 5 and 7. Let n be the node at connection 5 and m be that at connection 7. Then the pump equations are

$$\psi'_5 = \psi'_7$$

(the pump is assumed to have zero volume),

$$\frac{\psi'_7}{\rho'_m} = \frac{W^0_m}{\rho^0_m}$$

(the volumetric flow into the pump is constant), and

$$\eta'_5 - H'_m = H^0_n - H^0_m$$

(the enthalpy change across the pump is constant).

To avoid calling SSTATE and SSLIP to obtain the density of the coolant at the end of the time step, the following estimate is used

$$\rho'_m = \rho_m + \left(\frac{\partial \rho}{\partial W}\right)_m \left(W'_m - W_m\right) +$$

$$\left(\frac{\partial \rho}{\partial P}\right)_m (P'_m - P_m) + \left(\frac{\partial \rho}{\partial H}\right)_m (H'_m - H_m) \quad .$$

These four equations have introduced new unknowns W'_m, P'_m and H'_m. The required three equations are components of Equation (1) Section 6. These equations are obtained by the CONCON subroutine. The seven equations are solved for ψ'_7, ψ'_5, and η'_5 in BPWIMP.

Note that although connection 5 is an explicit connection its boundary conditions are set in BPWIMP and hence updated each network balance iteration.

10.6 Primary Pump

The primary pump is represented as a fixed gravitational head. The head required is determined in the steady state calculation. No special routines are needed. The gravitational potential energy from this head appears in the primary coolant, hence in the initial steady state the heat flow through the steam generator is the sum of this gravitational power and the nuclear power.

FIGURE 5

Makeup System for Sample Problem

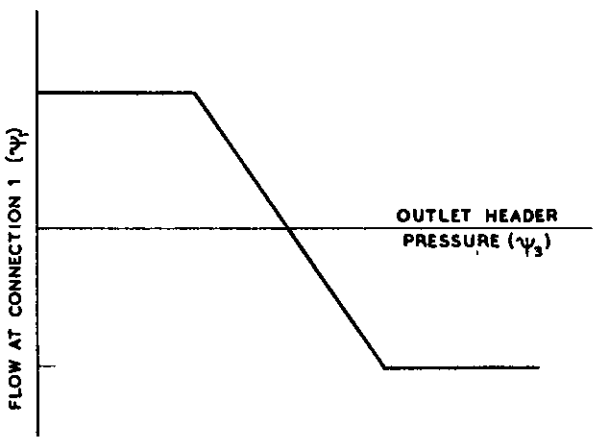
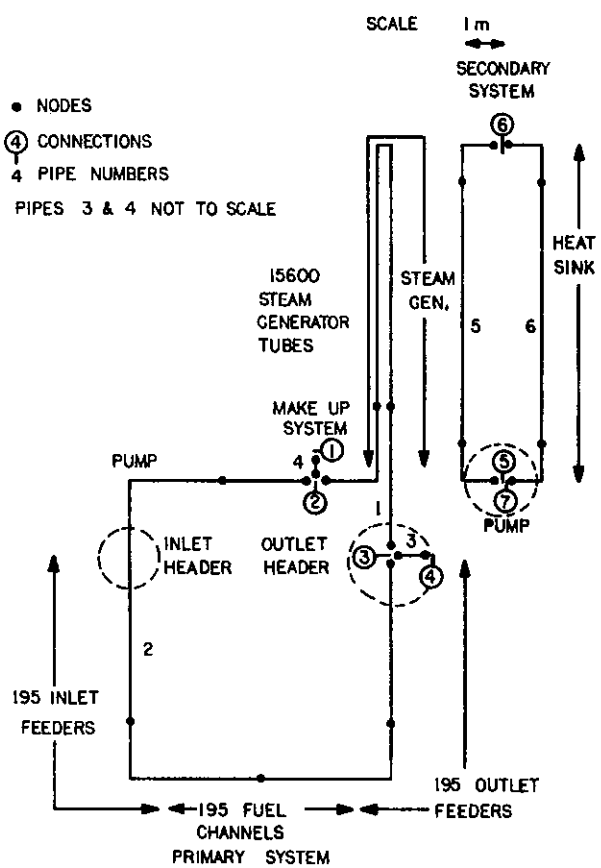


FIGURE 6

Sample Problem



10.7 Initial State

In the coarse time step calculation, the first two initial state calculations demonstrate the use of initial state options 3 and 2 respectively; the rest set the initial state for the transient calculation using the other three options.

10.8 Transient Calculation

The transient is initiated by a burst of area 1 cm^2 in the outlet header, pipe 3 being entirely within the header. The receiver pressure at the break is reduced to atmospheric over the first ten milliseconds. The difference between the receiver pressure and the header pressure is not sufficient to cause choking until the quality at the break becomes positive. Once choking occurs, the throat and receiver pressures are no longer equal and the throat pressure only changes slowly as shown in Figure 7. The time step in the fine time step calculation (Figure 8) which is at the lower limit of 0.1 milliseconds before choking, increases rapidly soon after choking until reaching 0.1 seconds. Roughly, this time step is maintained for the remainder of the calculation. The flow at the break rises rapidly to 4 kg s^{-1}. This is not sufficient to depressurise the system and, in fact, after 0.5 seconds the makeup system flow has exceeded the break flow. However, the drop in nuclear power which begins at 0.5 seconds, coupled with the nearly constant heat removal to the heat sink, causes a slow decrease in system pressure.

The flow at the break from the coarse and fine calculations are compared in Figure 9. The difference is quite tolerable for many applications and illustrates the value of coarse NAIAD calculations where precise results are not required.

10.9 Sample Run Output

A listing of the sample run output is given in Appendix A. A listing of the input is not given as the SCAN input subroutine lists all input data as it is read and the FORTRAN compiler lists all the user routines. Note however that the IMPLICIT and COMMON statements in these routines were inserted by the CINSERT procedure described in Section 9. The graphs from this sample run are shown in Figures 7, 8 and 9.

11. PLOTTING

Graphs are easily produced by including special instructions for writing a plot data file in the special routine BINITM and TDUMP, and executing the NAIAD plot catalogued procedure PROGRUN which reads this plot file and plots the graphs specified in the input data. In this

FIGURE 7

Pressure at Break (Fine Calculation)

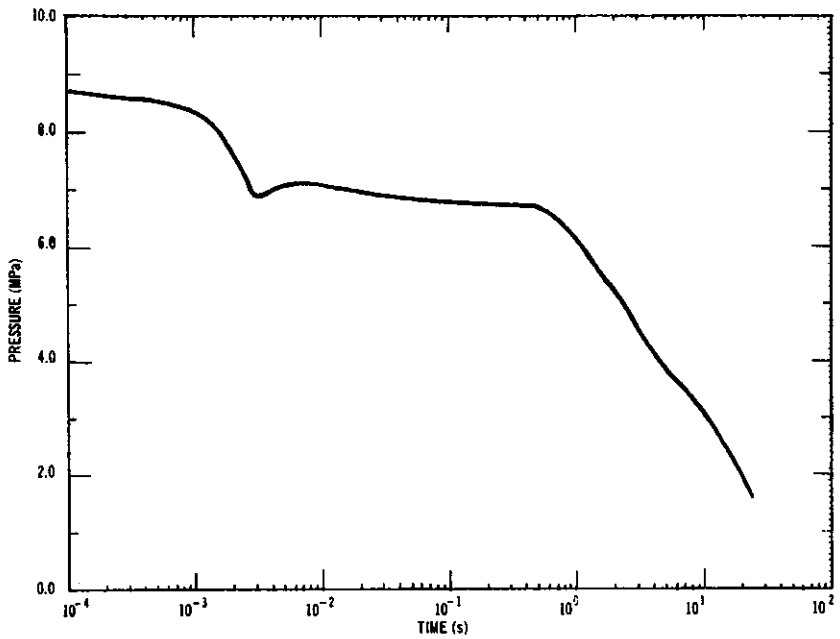


FIGURE 8

Time Step (Fine Calculation)

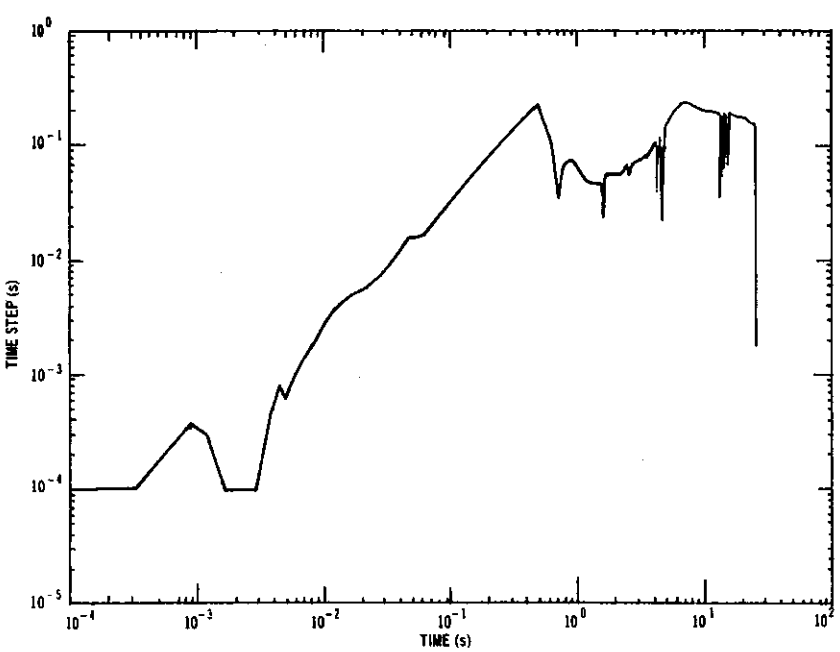
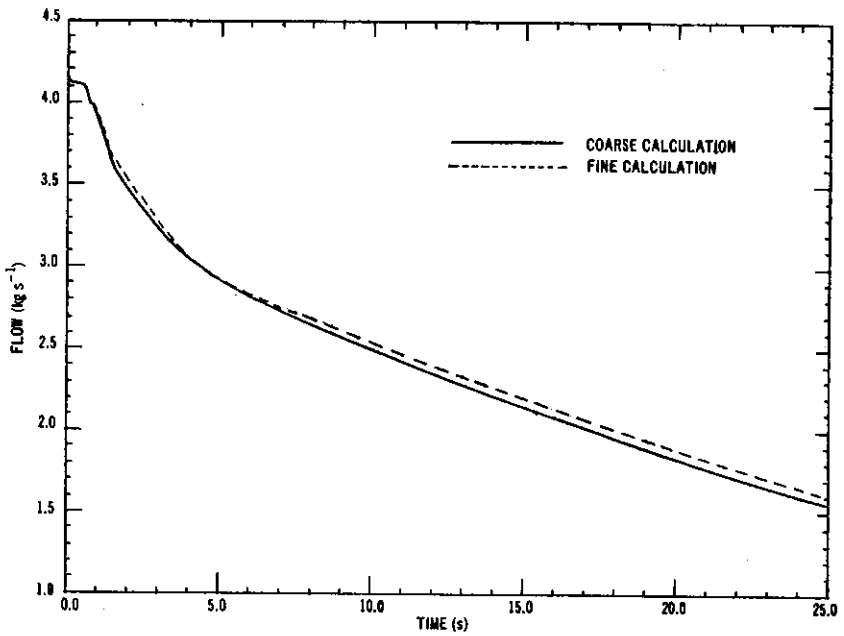


FIGURE 9

Flow at Break



way, graphs can be produced of data in the plot data file from one or more NAIAD runs, *e.g.* pressure at a node as a function of time can be plotted for a number of NAIAD runs, pressure can be plotted against flow rate, *etc.* Points or lines of many kinds can be used and labelled, axes can be labelled and headings written. Also, experimental data can be plotted for comparison with the NAIAD results.

11.1 Plot Data File

This file is a sequential data set, each record corresponding to a single time step and containing up to 200 double precision words. Output from several runs may be assembled into one long file with the start of each pseudo file marked by TIME equal zero. Thus, the first item of each record must be the variable TIME.

Two routines are available for writing the plot data file. They are TAPSET which locates the required pseudo file and TDUMP which writes a record.

The routines are used as follows:

(i) CALL TAPSET(IU,NF)

where IU - FORTRAN logical unit number;

NF - output control;

NF≠0 - replace NF^{th} pseudo file with results of this run. All old files past this point will then be lost; and

NF=0 - add output of this run to the end of existing file.

TAPSET is normally called from the special routine BINITM.

(ii) CALL TDUMP(IU,TIME,1,A1,N1,A2,N2,...,AK,NK)

where IU - FORTRAN logical unit number;

A1,...,AK - variable or array names; and

N1,...,NK - number of data items to be written from the corresponding variable or array.

TDUMP is normally called from the special routine TDUMPM. Both these routines are used in the sample problem.

11.2 Plot Program

This program is separate from NAIAD and runs in two phases, a data input phase and a plot phase. The data input phase requires the following data (all read using SCAN):

IFN - pseudo file number;

NENT - number of items in each record (max. 200);

NG - number of these items actually required for plotting (max. 20); and

NP - an array of NG numbers giving the positions in the NAIAD output record of the NG items required.

For example, considering the sample problem (Section 10) which has 22 nodes and 6 flow paths, the record structure is

TIME	position 1
W	positions 2 to 23
P	positions 24 to 45
X	positions 46 to 67
PTCTP	positions 68 to 73
PTCT	position 74
DELT	position 75

The input data needed to retrieve TIME and flow, pressure and quality at the break (node 12) are:

1 75 4 1 13 35 57 .

The total number of words that can be retrieved in this way is limited by storage to 5000.

When we enter the plot phase, the items retrieved are identified by the numbers 1 to NG rather than their initial positions in the NAIAD record. Thus in the above example, TIME is now item 1, flow at the break is item 2, *etc.* The plot phase is controlled by 'keyword and data' cards. Each individual plot is initiated by a card beginning with the keyword PAPE (a PAPE card). This card defines the graph paper required. The PAPE card defines the plot axes explicitly or implicity. The explicit form is:

```
PAPE   XP   YP   XMIN   XMAX   YMIN   YMAX
```

where |XP| = length of x-axis in inches,

|YP| = length of y-axis in inches,

XP, YP < 0 linear scale, or

> 0 log scale,

XMIN = minimum x (usually time) value required,

XMAX = maximum x value required,

YMIN = minimum y value required, and

YMAX = maximum y value required.

The implicit form is:

$$\text{PAPE}\ \ 0\ \ XP\ \ YP\ \ \begin{Bmatrix} 0 & XMIN & XMAX \\ NX & IX(1),\ldots,IX(NX) \end{Bmatrix}\ \ \begin{Bmatrix} 0 & YMIN & YMAX \\ NY & IY(1),\ldots,IY(NY) \end{Bmatrix}$$

where the upper and lower lines inside the braces are alternatives. In this form, the x limits are either on the PAPE card (NX = 0) or they are the range of a specified subgroup of the items loaded in the input phase. NX is the number of items in this subgroup and the item numbers are IX. The y limits are specified in the same way. Returning to our example

```
PAPE   0   -10   -8   1   1   1   4
```

specifies 10 in. x 8 in. linear graph paper with the x limits given by the range of TIME values and the y limits given by the range of quality values. If NY is negative, the cards

```
LINE   IX(1)   IY(1)   1
LINE   IX(1)   IY(2)   2
LINE   IX(1)   IY(NY)  NY
```

are executed after the PAPE card. If the x limits were given explicity, then IX(1)=1 is assumed. The LINE card is described below.

Once the PAPE card has been read, data may be plotted on the graph by means of LINE or PNTS cards.

```
LINE   IX   IY   NL
```

connects the given data by straight lines

where IX = item number for the x variable,

IY = item number for the y variable,

NL = line type, where NL=1 is a solid line, and NL=2,...,10 are distinct dashed lines.

LINE 0 NP NL X(1),Y(1),...,X(NP),Y(NP)

connects the NP given data pairs by straight lines of type NL. This card can be used for plotting experimental results.

PNTS IX IY NS ISIZE

draws a plot symbol at each data point,

where IX = item number for the x variable,

IY = item number for the y variable,

NS = plot symbol number, where NS=1,...,8 are distinct plot symbols,

ISIZE = plot symbol size, where the actual size is 0.04* ISIZE inches.

PNTS 0 NP NS ISIZE X(1), Y(1),...,X(NP), Y(NP)

draws a plot symbol at each given data point.

The plot can be labelled by the following keyword cards:

HEAD "TITLE FOR PLOT"

NAMX "X AXIS LABEL"

NAMY "Y AXIS LABEL"

where the required labels are placed between the double quote characters ".

Legends describing the plot symbols or lines (see Figure 8) may be added to the plot by use of further keyword cards. Each legend entry consists of two fields. The first field contains a symbol or line while the second contains text.

LEGO HO VO

defines the top left hand corner or 'origin' of the legend. HO and VO are given in inches from the bottom left hand corner of the graph. If this statement is omitted, HO = |XP| + 0.5, VO = |YP| - 0.5 is assumed.

LEGH "HEADING" provides a heading for the legend.

LEG K "LABEL" generates a legend entry, where

K = 1 gives the latest plot symbol followed by LABEL

= 2 gives the latest line type followed by LABEL

= 0 just gives LABEL starting in the symbol or line field.

LEGS SIZE WIDTH SPACE

enables changing of the controlling parameters.

SIZE - character height in inches (default 0.14)

WIDTH - width of symbol or line field in inches (default 1.2)

SPACE - entry spacing (vertical) in inches (default 0.25).

The data may also be scaled for plotting by use of the statement

CONS A B

where all 'y-ordinate' data will be scaled so that the plotted data is A + By. The scale remains in force until a new PAPE or CONS card is read.

Finally, it is possible to return to the data input phase by use of the command

DATA .

This allows a new set of data to be read which can then be plotted either on a new graph or on the previous graph if no new PAPE card has been read.

12. REFERENCES

Akers, W.W., Deans, H.A. & Crosser, O.K. [1959] - *Chem. Eng. Progr. Symp. Ser.* No. 29 (55) 171.

Beattie, D.R.H. [1972] - AAEC, private communication.

Beattie, D.R.H. [1973] - *Nucl. Eng. Des.*, 25 : 395.

Beattie, D.R.H. [1974] - Slip Model. AAEC, private communication.

Beattie, D.R.H. [1975] - AAEC, private communication.

Bennett, N.W. & Pollard, J.P. [1967] - AAEC/TM399.

Biasi, L., Clerici, G.C., Gerribba, S., Sala, R. & Tozzi, A. [1967] - *Energ. Nucl.* (Milan), 14 (9) 530.

Bruges, E.A. & Gibson, M.R. [1969] - *J. Mech. Eng. Sci.*, 11 (2) 189.

Di Francesco, D., Premoli, A. & Prina, A. [1971] - CISE-800.

Dittus, F.W. & Boelter, L.M.K. [1930] - Univ. of Calif. Pub. Eng., 2 : 443. (cited in McAdams [1954]).

Elliott, J.N. [1968] - AECL Power Projects, TDAI-11.

Fauske, H.K. [1962] - ANL-6633.

Hassid, A. & Rychlicki, R. [1971] - *Energ. Nucl.* (Milan), 18 (6) 333.

Heineman, J.B. [1960] - ANL-6213.

Isbin, H.S., Fauske, H., Grace, T. & Garcia, Jr. I. [1962] - Symp. Two-phase Fluid Flow, Proc. Inst. Mech. Eng. (London), February, 81.

Jones, A.B. & Dight, D.G. [1962] - KAPL-2208.

McAdams, W.H. [1954] - Heat Transmission, McGraw-Hill, New York, (3rd ed.).

Meyer, C.A., McClintoch, R.B., Silvester, G.J., & Spencer. R.C. Jr. [1967] - ASME Steam Tables, American Society of Mechanical Engineers, New York.

Meyer, J.E. [1960] - WAPD-BT-20.

Moody, F.J. [1965] - *J. Heat Transfer*, 134.

Moore, K.V. [1971] - ANCR-1026.

Moore, K.V., Slater, C.E., Ybarrondo, L.J. & Gruen, G.E. [1973] CONF-730304 Topical Meeting on Water Reactor Safety, Salt Lake City, March 26, 522.

Moore, K.V. & Rettig, W.H. [1973] - RELAP 4. ANCR-1127.

Nahavandi, A.N. & Von Hollen, R.F. [1965] - *Nucl. Sci. & Eng.*, 22 : 463.

Nikuradse, J. [1933] - VDI Forschungsheft (cited in Prandl, L. [1952] - Essentials of Fluid Dynamics, Blackie, London.)

Porsching, T.A., Murphy, J.H., Redfield, J.A. & Davis, V.C. [1969] - FLASH-4. WAPD-TM-840.

Porsching, T.A., Murphy, J.H. & Redfield, J.A. [1971] - *Nucl. Sci. Eng.*, 43 : 218.

Rettig, W.H., Jayne, G.A., Moore, K.V., Salter, C.E. & Uptmoor, M.L. [1970] - RELAP 3, IN-1321.

Richmyer, R.D. & Morton, K.W. [1967] - Difference Methods for Initial-value Problems (2nd end.) Interscience Publishers, New York.

Rose, R.P., Hanson, G.H. & Jayne, G.A. [1967] - IDO-17254.

Schrock, V.E. & Grossman, L.M. [1959] - TID-14632.

Smith, S.L. [1970] - *Proc. Inst. Mech. Eng.* (London), 184 : 1.

Spinks, N.J. [1975] - AECL, private communication.

Sullivan, H.H. [1975] - USAEC, private communication.

Tong, J.S.E. [1975] - AECL, private communication.

Tong, L.S. [1965] - Boiling Heat Transfer and Two-phase flow, John Wiley, New York.

Tremblay, P.E. & Andrews, D.G. [1971] - *Nucl. Sci. & Eng.*, 44 : 1.

Trimble, G.D. & Turner, W.J. [1975] - Unpublished report.

Turner, W.J. [1969] - CREST Specialist Meeting, Frankfurt, June.

Turner, W.J. [1972] - *Energy. Nucl.* (Milan), 19 (5) 317.

Turner, W.J. & Trimble, G.D. [1974a] - NEA-CPL Seminar on Computer Programs for the Analysis of Certain Problems in Thermal Reactor Safety, Ispra, October 23-25.

Turner, W.J. & Trimble, G.D. [1974b] - 5th Australas. Conf. on Hydraulics and Fluid Mechanics, Christchurch, New Zealand, 9-13 December.

Turner, W.J. [1975] - OWEN-1, AAEC/E342.

Turner, W.J. & Trimble, G.D. [1975] - 3rd National Computational Physics Conf., University of Glasgow, 27 August.

United Kingdom Committee on the Properties of Steam [1970] - UK Steam Tables in SI Units, Arnold, London.

Wright, R.M. [1961] - USAEC Report UCRL-9744.

APPENDIX A

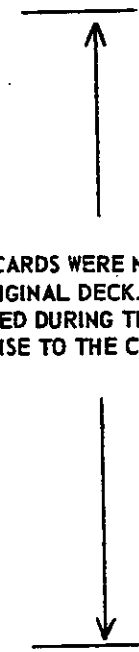
PARTIAL LISTING OF SAMPLE RUN OUTPUT

```
//GDTNAIAD JOB ('PHL13994/P22PHLCA',N1),G.D.TRIMBLE,                    JOB 322
//             CLASS=B,
//             TIME=7
//  EXEC  NAIADCLG,PARM.FORT='OPT=2',LIB='GDT.NAIADP',MEM=TESTCASE
//SYSIN     DD *                  GENERATED STATEMENT
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /PREP     / START 76145.1752
IEF374I STEP /PREP     / STOP  76145.1752 CPU    0MIN 02.30SEC MAIN  40K LCS    0K
*** CONDITION CODE =  000(HEX)
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /FORT     / START 76145.1752
IEF374I STEP /FORT     / STOP  76145.1752 CPU    0MIN 04.64SEC MAIN 240K LCS    0K
*** CONDITION CODE =  000(HEX)
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /LKED     / START 76145.1752
IEF374I STEP /LKED     / STOP  76145.1753 CPU    0MIN 03.52SEC MAIN  96K LCS    0K
*** CONDITION CODE =  000(HEX)
//GO.FT08F001 DD DSN=GDT.TESTPLT,DISP=OLD
//SYSIN     DD *                  GENERATED STATEMENT
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /GO       / START 76145.1753
IEF374I STEP /GO       / STOP  76145.1759 CPU    0MIN 54.80SEC MAIN 220K LCS    0K
*** CONDITION CODE =  000(HEX)
//  EXEC  NAIADG,MEM=TESTCASE,LIB='GDT.NAIADP'
//GO.FT08F001 DD DSN=GDT.TESTPLT,DISP=OLD
//SYSIN     DD *                  GENERATED STATEMENT
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /GO       / START 76145.1759
IEF374I STEP /GO       / STOP  76145.1804 CPU    2MIN 07.52SEC MAIN 220K LCS    0K
*** CONDITION CODE =  000(HEX)
//  EXEC  BUFFPROG,PRG=VPLOT
//SYSOUT2 DD SYSOUT=F
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /PGM      / START 76145.1804
IEF374I STEP /PGM      / STOP  76145.1804 CPU    0MIN 00.24SEC MAIN  14K LCS    0K
*** CONDITION CODE =  000(HEX)
//  EXEC  PROGRUN,LIB='GDT.NAIAD',MEM=PLOTPGM,REGGO=140K
//GO.AEPLOT DD SYSOUT=F
//GO.FT08F001 DD DSN=GDT.TESTPLT,DISP=SHR
//SYSIN     DD *                  GENERATED STATEMENT
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /GO       / START 76145.1804
IEF374I STEP /GO       / STOP  76145.1804 CPU    0MIN 05.22SEC MAIN 110K LCS    0K
*** CONDITION CODE =  000(HEX)
IEF375I  JOB /GDTNAIAD/ START 76145.1752
IEF376I  JOB /GDTNAIAD/ STOP  76145.1804 CPU    3MIN 18.24SEC
HIGHEST CONDN CODE =  000(HEX)
```

```
LEVEL 20.1 (AUG 71)                    OS/360  FORTRAN H                    DATE  75.349/14.03.42

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=55,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,NOID,NOXREF
               CINSERT MAIN
   ISN 0002            CALL MAIAD
   ISN 0003            STOP
   ISN 0004            END

*OPTIONS IN EFFECT*       NAME=  MAIN,OPT=02,LINECNT=55,SIZE=0000K,

*OPTIONS IN EFFECT*       SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,NOID,NOXREF

*STATISTICS*     SOURCE STATEMENTS =        3 ,PROGRAM SIZE =       180

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                    107K BYTES OF CORE NOT USED
```

THESE CARDS WERE NOT INCLUDED IN THE ORIGINAL DECK. THEY HAVE BEEN INSERTED DURING THE PREP STEP IN RESPONSE TO THE CINSERT CARD.

```
        COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=55,SIZE=0000K,
                           SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,NOID,NOXREF
ISN 0002            SUBROUTINE BINITM
                  CINSERT R8,BLANK,BCONDS,CRIT$,POWER$,STEP$,BAL$
ISN 0003            IMPLICIT REAL*8 (A-H,O-Z)
                  COMMON MARK IV
ISN 0004            COMMON Z(50),A(50),DE(50),GSINT(50),ORIK(50)
ISN 0005            COMMON PD(50),CP(50),HP(50),HF(50)
ISN 0006            COMMON W(50),P(50),H(50)
ISN 0007            COMMON HS(50),X(50),RHO(50),VOLF(50),DEFP(50),FK(50),BM(50),S(50)
ISN 0008            COMMON CT(50),CTS(50),TFC(50),TFS(50)
ISN 0009            COMMON HT(50),THT(50),FLUX(50)
ISN 0010            COMMON CRSL(50),CRSV(50),CHSL(50),CHSV(50)
ISN 0011            COMMON CRLP(50),CRVP(50),CHLP(50),CHVP(50)
ISN 0012            COMMON CSSL(50),CSSV(50)
ISN 0013            COMMON DRDW(50),DRDP(50),DRDH(50)
ISN 0014            COMMON DMDW(50),DMDP(50),DMDH(50)
ISN 0015            COMMON DHDW(50),DHDP(50),DHDH(50)
ISN 0016            COMMON DKDW(50),DKDP(50),DKDH(50)
ISN 0017            COMMON DTDW(50),DTDP(50),DTDH(50)
ISN 0018            COMMON DOTDR(50),DOTDM(50),DOTDH(50),DOTDK(50),DOTDT(50)
ISN 0019            COMMON DQDW(50),DQDP(50),DQDH(50),DQDT(50),DOTDQ(50)
ISN 0020            COMMON AMAT(3,3,50),BMAT(3,3,50),CMAT(3,3,50),DVEC(3,50,5)
                  COMMON END
ISN 0021            COMMON /BCONDS/ BPW(10),BHO(10),TIME,DELT,LC(10),LCR(10),NSN(10),
                   & NFN(10),NSC(10),NFC(10),MMAT(10,10),NP,NC,N
ISN 0022            COMMON /CRIT$/ PAT(10),TOPEN(10),PTHROT(10),LT(10)
ISN 0023            LOGICAL LT
ISN 0024            COMMON /POWER$/ PTCTP(10),PGENP(10),PTCT,PGEN
ISN 0025            COMMON /STEP$/ SMIN,SMAX,CTAR,CMAX,RCMAX,CINC,DELTP,TMAX,TSFP,
                   &               KW(50),KFP,KKW
ISN 0026            COMMON /BAL$/ TOL,ITMAX
ISN 0027            DATA NP1,NP2,NS1,NK1,NB,TSINK,WLIM,IC,CMASS ,PLIM,NFV,NOH,WRMAX  /
                   & 2,3,16,20,12 ,400.D0,2.D1,81,0.D0 ,8.75D6 ,13,1,2.D1           /
                   & ,NS2,NK2/17,21/
                  C
                  C
ISN 0028            CMASS=0.D0
ISN 0029            PK = PGENP(5)/(TFC(NP1)+TFC(NP2)-TFC(NS1)-TFC(NS2))
ISN 0030            PS = PGENP(6)/(CT(NK1) -CT(NK2)-TSINK*2.D0)
ISN 0031            PSET=(PLIM*W(NFV)-WLIM*P(NOH))/(W(NFV)-WLIM)
ISN 0032            FSC=WLIM/(PSET-PLIM)
ISN 0033            PNUC=PGENP(2)
ISN 0034            LT(4)=.FALSE.
ISN 0035            CALL SCAN(1,1,IC,NFP,1)
ISN 0036            CALL TAPSET(8,NFP)
ISN 0037            RETURN
                  C
ISN 0038            ENTRY RCSETM
ISN 0039            IF(TIME+DELT.GT.TMAX) DELT=TMAX-TIME+1.D-7
ISN 0041            WSTRT=W(NB)
                  C MAKE FEED VALVE CONTROLLED BY OUTLET HEADER P
ISN 0042            WFV   =DMAX1(DMIN1(FSC*(PSET-P(NOH)),WLIM),-WLIM)
```



THESE CARDS WERE NOT INCLUDED IN THE ORIGINAL DECK. THEY HAVE BEEN INSERTED DURING THE PREP STEP IN RESPONSE TO THE CINSERT CARD.

```
ISN 0043            WFVRC=WRMAX*DELT
ISN 0044            DW=WFV-W(NFV)
ISN 0045            IF(DABS(DW).LE.WFVRC)GO TO 20
ISN 0047            WFV=W(NFV)+DSIGN(WFVRC,DW)
ISN 0048         20 HPW(1)=WFV
                 C POWER THROUGH STEAM GENERATOR
ISN 0049            PGENP(5) = PK*(TFC(NP1)+TFC(NP2)-TFC(NS1)-TFC(NS2))
ISN 0050            PGENP(1) = -PGENP(5)
                 C POWER TO HEAT SINK
ISN 0051            PGENP(6) = PS*(CT(NK1)-CT(NK2)-TSINK*2.D0)
                 C NUCLEAR POWER
ISN 0052            TEND=TIME+DELT
ISN 0053            PGENP(2)=PNUC*DMAX1(DMIN1(1.D0,2.D0-2.D0*TEND),7.D-2)
ISN 0054            RETURN
                 C
ISN 0055            ENTRY TDUMPM(IPRINT)
ISN 0056            IF(IPRINT.NE.0) WRITE(3,120)
ISN 005A         120 FORMAT('0',T 6,'TIME',T19,'THROAT PRESSURE AND QUALITY',
                    &     T50,'INLET FOR FLOW AND QUALITY',T79,'CHOKED'/)
ISN 0059          40 WRITE(3,100) TIME,P(NB),X(NB),W(7),X(7),LT(4)
ISN 0060         100 FORMAT(1P5G15.6,4X,G3.0)
ISN 0061            IF(TIME.EQ.0.D0) GO TO 50
ISN 0063            CMASS=DELT*.500*(W(NB)+WSTRT) +CMASS
ISN 0064          50 CALL TDUMP(8,TIME,1,W,N,P,N,X,N,PTCTP,NP
                    &  ,PTCT,1,DELT,1)
ISN 0065            RETURN
                 C
ISN 0066            ENTRY USENDM
ISN 0067            WRITE (3,110) CMASS
ISN 0068         110 FORMAT('0TOTAL STEAM IN CONTAINMENT ',1PG15.5,' KG')
ISN 0069            RETURN
                 C
ISN 0070            END

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=55,SIZE=0000K,

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,NOID,NOXREF

*STATISTICS*     SOURCE STATEMENTS =      69 ,PROGRAM SIZE =     1832

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                  95K BYTES OF CORE NOT USED
```

```
          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=55,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,NOID,NOXREF
ISN 0002            SUBROUTINE BPWIMP(KI,NIT,OM)
                  CINSERT R8,BLANK,BCONDS
ISN 0003            IMPLICIT REAL*8 (A-H,O-Z)
                  COMMON MARK IV
ISN 0004            COMMON Z(50),A(50),DE(50),GSINT(50),ORIK(50)
ISN 0005            COMMON PD(50),CP(50),HP(50),HF(50)
ISN 0006            COMMON W(50),P(50),H(50)
ISN 0007            COMMON HS(50),X(50),RHO(50),VOLF(50),DEFR(50),FK(50),BM(50),S(50)
ISN 0008            COMMON CT(50),CTS(50),TFC(50),TFS(50)
ISN 0009            COMMON HT(50),THT(50),FLUX(50)
ISN 0010            COMMON CRSL(50),CRSV(50),CHSL(50),CHSV(50)
ISN 0011            COMMON CRLP(50),CRVP(50),CHLP(50),CHVP(50)
ISN 0012            COMMON CSSL(50),CSSV(50)
ISN 0013            COMMON DRDW(50),DRDP(50),DRDH(50)
ISN 0014            COMMON DMDW(50),DMDP(50),DMDH(50)
ISN 0015            COMMON DHDW(50),DHDP(50),DHDH(50)
ISN 0016            COMMON DKDW(50),DKDP(50),DKDH(50)
ISN 0017            COMMON DTDW(50),DTDP(50),DTDH(50)
ISN 0018            COMMON DOTDR(50),DOTDM(50),DOTDH(50),DOTDK(50),DOTDT(50)
ISN 0019            COMMON DQDW(50),DQDP(50),DQDH(50),DQDT(50),DOTDQ(50)
ISN 0020            COMMON AMAT(3,3,50),BMAT(3,3,50),CMAT(3,3,50),DVEC(3,50,5)
                  COMMON END
ISN 0021            COMMON /BCONDS/ BPW(10),RHO(10),TIME,DELT,LC(10),LCB(10),NSN(10),
                   & NFN(10),NSC(10),NFC(10),MMAT(10,10),NP,NC,N
ISN 0022            LOGICAL L
                  C COOLANT PUMPED FROM IMPLICT FLOW CONNECTION KI (PIPE KPI ) TO EXPLICT
                  C     FLOW CONNECTION KO ( PIPE KPO ),CONSTANT VOLUMETRIC FLOW RATE
ISN 0023            DATA KO,L,KPI,KPO                                          /
                   & 5,.FALSE.,6,5    /
                  C
ISN 0024            CALL CONCON(KPI,KI,NI,WOI,WPWI,WHOI,
                   &                  POI,PPWI,PHOI,
                   &                  HOI,HPWI,HHOI,WORI,&100)
ISN 0025            CALL CONCON(KPO,KO,NO,WOO,WPWO,WHOO,
                   &                  POO,PPWO,PHOO,
                   &                  HOO,HPWO,HHOO,WORO,&100)
ISN 0026            IF (L) GO TO 10
ISN 0028            HH = H(NI)-H(NO)
ISN 0029            RW0=RHO(NI)/W(NI)
ISN 0030            L = .TRUE.
ISN 0031         10 BPWR=    (RHO(NI)+DRDW(NI)*(WOI-W(NI))
                   &                  +DRDP(NI)*(POI-P(NI))
                   &                  +DRDH(NI)*(HOI-H(NI)))
                   & /(RW0-  DRDW(NI)*WPWI-DRDP(NI)*PPWI-DRDH(NI)*HPWI)
ISN 0032            BPW(KI)=BPW(KI)+OM*(BPWR-BPW(KI))
ISN 0033            BHO(KO)=HOI-HH+BPW(KI)*HPWI
ISN 0034            BPW(KO)=-BPW(KI)*WORI*WORO
ISN 0035            RETURN
ISN 0036         100 STOP 111
ISN 0037            END

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=55,SIZE=0000K,
```

THESE CARDS WERE NOT INCLUDED IN THE ORIGINAL DECK. THEY HAVE BEEN INSERTED DURING THE PREP STEP IN RESPONSE TO THE CINSERT CARD.

INPUT DATA AS READ :-

```
6 PIPES   7 CONNECTIONS        GRAVITY 9.8043     TOL 1.D-5    ITMAX 30
*  TIME STEPPING CONTROLS
 STEP LIMITS  .0001 40.  CHANGE  TARGET .07  MAX .10    DENSITY ERRMAX .07
 MAX DT INCREASE 2  TMAX 25  FULL PRINT EACH -20 STEPS OR IF DT>100
-------------------------------------------------------------------------------
* PIPE 1  OUTLET HEADER THROUGH STEAM GEN TO MAKE-UP SYSTEM JUNCTION
4 NODES  CONN 3 TO 2     POWER  -8.3D+8      SLIP 4*1
FRICTION  4*4        IHTRAN 4*0              PRINT 0 0 0 0  Z 0  4  18  22
DH/DZ 1 0  -.5       DE  .308   2*.01  .308 A  .447  2*1.22  .447
HP 5.8  2*490 5.8    ROUGH 4.D-5    2*4.D-6  4.D-5     CP  4*0
HF 4*0  ORIK  3*0  PD  0  1  1  0
-------------------------------------------------------------------------------
*PIPE  2  MAKE-UP SYSTEM JCT THROUGH PUMP,INLET HDR,FUEL & FEEDER TO OUTLET HDR
6 NODES  CONN 2 TO 3     POWER   8.3D+8      SLIP 6*1
FRICTION  6*4        IHTRAN 0 0 4*1          PRINT 4*0 0 0
Z 0 2.5 11.5 16.5 21.5 26  DH/DZ 0 -0.722 -0.3 0.3 1
DE 2*.308  .05  .007  2*.05
A   2*.447  .374  .491   2*.374
HP  2*5.8   30.2  220.3  2*30.2
ROUGH 3*4.D-5  4.D-6  2*4.D-5      CP 0 0  22100 6950 2*22100
HF 6*0  ORIK 0 0 50 0 0   PD 0 0 0 1 0 0
-------------------------------------------------------------------------------
* PIPE 3  BROKEN PIPE FROM OUTLET HEADER
2 3 4 0 1 1 4 4 0 0 0 0 0 .01  0  .308  0 .447 .0001 5.8 0 2*4.D-4  7*0
-------------------------------------------------------------------------------
* PIPE 4  MAKE-UP SYSTEM
2 1 2 0 1 1 4 4  4*0  0 .01  -1  .1 .308  0 .447  0  5.8  2*4.D-5  7*0
-------------------------------------------------------------------------------
* PIPE 5  SECONDARY LOOP  PUMP THROUGH STEAM GEN
4 NODES  CONN 5 TO 6    POWER 8.3D+8          SLIP 4*1
 FRICTION 4*4 IHTRAN 4*0  PRINT 4*0  Z 0 2 9 11
 DH/DZ .5 1 .5  DE .308 2*.05 .308  A .447 2*3. .447
HP  5.8  2*490  5.8  ROUGH 4.D-4 2*4.D-6 4.D-4  CP 4*0  HF  4*0
ORIK 3*0  PD 0 1 1 0
-------------------------------------------------------------------------------
* PIPE 6  SECONDARY LOOP  HEAT SINK TO PUMP
4 NODES   CONN 6 TO 7     POWER -8.3D+8          SLIP 4*1
 FRICT 4*4   IHTRAN 4*0  PRINT 4*0   Z 0 2 9 11
 DH/DZ  -.5 -1 -.5   DE .308 2*.05 .308   A .447 2*3.  .447
HP  5.8  2*490  5.8  ROUGH 4.D-4 2*4.D-6 4.D-4  CP 4*0  HF  4*0
ORIK 3*0  PD 0 1 1 0
-------------------------------------------------------------------------------
* CONNECTIONS
1 0  1
4  2  1.D5  .01
5 0 1
7  3  1
0
-------------------------------------------------------------------------------
* INITIAL CONDITIONS
*  FOLLOWING STEADY STATES DEMONSTRATE IMMEDIATE PRINT OPTION
* THE STEADY STATES FOR THESE PIPES ARE REDEFINED LATER
 PIPE 1 OPTION -2  NODE 2 0 4000 0 8.6E6 0 -.14  NODE 3 0 8.4E6
```

```
      IN PIPE  1  POWER GENERATED -8.30000D+08  POWER TO COOLANT -8.30000D+08

NODE     Z          W            P            H            X         ALPHA        RHO        T          TFC        THT        FLUX

  1     0.0    4.44427D+03  8.60899D+06  1.19009D+06 -0.110836 -0.085423    768.80     544.03     544.03      0.0       0.0
  2     4.00   4.44427D+03  8.60000D+06  1.14862D+06 -0.140000 -0.105925    782.62     535.73     535.73      0.0      -9.41043D+04
  3    18.00   4.44427D+03  8.40000D+06  1.00336D+06 -0.234647 -0.177021    834.22     506.53     506.53      0.0      -9.41043D+04
  4    22.00   4.44427D+03  8.33223D+06  1.00332D+06 -0.231742 -0.174394    833.90     506.49     506.49      0.0       0.0

        PIPE 4 OPTION -3 AT NODE 2 PRESSURE IS 0  .9D+5 ,ENTHALPIES 2*3.9D5
            FUEL TEMPS 0 400.


      IN PIPE  4  POWER GENERATED  0.0          POWER TO COOLANT  0.0

NODE     Z          W            P            H            X         ALPHA        RHO        T          TFC        THT        FLUX

 13     0.0    0.0          8.99056D+04  3.90000D+05 -0.006658 -0.002597    962.98     366.25     366.25      0.0       0.0
 14     0.01   0.0          9.00000D+04  3.90000D+05 -0.006712 -0.002619    962.98     366.25     400.00      0.0       0.0

        *
        PIPE 1 OPTION 1 AT NODE 4 FLOW IS 0 4179 PRESSURE 0 8.6D6 X IS 0 -.14
        PIPE 4 OPTION  1 AT NODE 2 0  1   1 4  1 4
        PIPE 3 OPTION 1 AT NODE 1 FLOW IS 4 1 PRESSURE 1 1 X IS 1 1
        PIPE 2 OPTION 5 SEGMENT 2
        PIPE 5 OPTION 1 NODE 1 0 3000 0 5.5D6  0 -.05
        PIPE 6 OPTION 4 CONNECTION 6
        0  END STEADY STATE
        *
         OUTPUT ON FILE 1

*** OUTPUT ON PSEUDO FILE  1
```

NAIAD SAMPLE PROBLEM - COARSE CALCULATION 15 DEC 75

PIPE NUMBER 1 JOINS CONNECTIONS 3 AND 2

CONNECTION 3 IS INTERNAL

CONNECTION 2 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
1	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	1	9.804D+00	0.0
2	4.00	0.0100	490.00	1.220D+00	0.0	1.000D+10	1.134D-04	4.00D-06	JONS	SBBL	0	2	0.0	0.0
3	18.00	0.0100	490.00	1.220D+00	0.0	1.000D+10	1.134D-04	4.00D-06	JONS	SBBL	0	3	-4.902D+00	0.0
4	22.00	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0			

PIPE NUMBER 2 JOINS CONNECTIONS 2 AND 3

CONNECTION 2 IS INTERNAL

CONNECTION 3 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
5	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	5	0.0	0.0
6	2.50	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	6	-2.115D+02	0.0
7	11.50	0.0500	30.20	3.740D-01	2.210D+04	1.000D+10	0.0	4.00D-05	JONS	SBBL	1	7	-2.941D+00	50.00
8	16.50	0.0070	220.30	4.910D-01	6.950D+03	1.000D+10	9.079D-04	4.00D-06	JONS	SBBL	1	8	2.941D+00	0.0
9	21.50	0.0500	30.20	3.740D-01	2.210D+04	1.000D+10	0.0	4.00D-05	JONS	SBBL	1	9	9.804D+00	0.0
10	26.00	0.0500	30.20	3.740D-01	2.210D+04	1.000D+10	0.0	4.00D-05	JONS	SBBL	1			

PIPE NUMBER 3 JOINS CONNECTIONS 3 AND 4

CONNECTION 3 IS INTERNAL

CONNECTION 4 WILL BURST OPEN OVER TIME 1.0D-02 TO PRESSURE 1.000000D+05

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
11	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0	11	0.0	0.0
12	0.01	0.0113	0.04	1.000D-04	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0			

PIPE NUMBER 4 JOINS CONNECTIONS 1 AND 2

CONNECTION 1 HAS GIVEN MASSFLOW BOUNDARY CONDITION

CONNECTION 2 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
13	0.0	0.1000	0.31	7.854D-03	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	13	-9.804D+00	0.0
14	0.01	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0			

PIPE NUMBER 5 JOINS CONNECTIONS 5 AND 6

CONNECTION 5 HAS GIVEN MASSFLOW BOUNDARY CONDITION

CONNECTION 6 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
15	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0	15	4.902D+00	0.0
16	2.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	16	9.804D+00	0.0
17	9.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	17	4.902D+00	0.0
18	11.00	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0			

PIPE NUMBER 6 JOINS CONNECTIONS 6 AND 7

CONNECTION 6 IS INTERNAL

CONNECTION 7 HAS IMPLICIT MASSFLOW BOUNDARY CONDITION

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
19	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0	19	-4.902D+00	0.0
20	2.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	20	-9.804D+00	0.0
21	9.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	21	-4.902D+00	0.0
22	11.00	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0			

NAIAD SAMPLE PROBLEM - COARSE CALCULATION 15 DEC 75

TIME 0.0 POWER GENERATED -7.33831D+06 POWER TO COOLANT -7.33831D+06

IN PIPE	1	POWER GENERATED	-8.30000D+08	POWER TO COOLANT	-8.30000D+08
IN PIPE	2	POWER GENERATED	8.22662D+08	POWER TO COOLANT	8.22662D+08
IN PIPE	3	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE	4	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE	5	POWER GENERATED	8.30000D+08	POWER TO COOLANT	8.30000D+08
IN PIPE	6	POWER GENERATED	-8.30000D+08	POWER TO COOLANT	-8.30000D+08

NODE	Z	W	P	H	X	ALPHA	RHO	T	TFC	THT	FLUX
1	0.0	4.17900D+03	8.85947D+06	1.34724D+06	-0.007265	-0.005998	711.63	573.54	573.54	0.0	0.0
2	4.00	4.17900D+03	8.85217D+06	1.30314D+06	-0.038750	-0.032535	729.27	565.75	565.75	0.0	-9.41043D+04
3	18.00	4.17900D+03	8.66381D+06	1.14866D+06	-0.142468	-0.107915	782.70	535.74	535.74	0.0	-9.41043D+04
4	22.00	4.17900D+03	8.60000D+06	1.14862D+06	-0.140000	-0.105925	782.62	535.73	535.73	0.0	0.0
5	0.0	4.18000D+03	8.60000D+06	1.14862D+06	-0.140000	-0.105925	782.62	535.73	535.73	0.0	0.0
6	2.50	4.18000D+03	8.59426D+06	1.14862D+06	-0.139775	-0.105744	782.62	535.73	535.73	0.0	0.0
7	11.50	4.18000D+03	9.91841D+06	1.15049D+06	-0.191751	-0.149330	784.62	536.33	536.33	1.00	0.0
8	16.50	4.18000D+03	9.49275D+06	1.34735D+06	-0.028483	-0.024196	712.57	573.67	582.84	15.00	7.46856D+05
9	21.50	4.18000D+03	9.03838D+06	1.34728D+06	-0.013195	-0.010958	711.82	573.57	573.57	1.00	0.0
10	26.00	4.18000D+03	8.85947D+06	1.34724D+06	-0.007265	-0.005998	711.63	573.54	573.54	1.00	0.0
11	0.0	1.00000D+00	8.85947D+06	1.34724D+06	-0.007265	-0.005998	711.63	573.54	573.54	0.0	0.0
12	0.01	1.00000D+00	8.78729D+06	1.34714D+06	-0.004943	-0.004082	711.60	573.52	573.52	0.0	0.0
13	0.0	1.00000D+00	8.59991D+06	1.14862D+06	-0.139997	-0.105922	782.62	535.73	535.73	0.0	0.0
14	0.01	1.00000D+00	8.60000D+06	1.14862D+06	-0.140000	-0.105925	782.62	535.73	535.73	0.0	0.0
15	0.0	3.00000D+03	5.50000D+06	1.10464D+06	-0.050000	-0.036372	794.77	527.00	527.00	0.0	0.0
16	2.00	3.00000D+03	5.51778D+06	1.16614D+06	-0.012340	-0.009084	774.24	539.36	539.36	0.0	1.88209D+05
17	9.00	3.00000D+03	5.47363D+06	1.38125D+06	0.123181	0.656796	282.05	542.77	542.77	0.0	1.88209D+05
18	11.00	3.00000D+03	5.37661D+06	1.38089D+06	0.126033	0.664060	276.95	541.64	541.64	0.0	0.0
19	0.0	3.00000D+03	5.37661D+06	1.38089D+06	0.126033	0.664060	276.95	541.64	541.64	0.0	0.0
20	2.00	3.00000D+03	5.45727D+06	1.31977D+06	0.085467	0.584200	335.88	542.58	542.58	0.0	-1.88209D+05
21	9.00	3.00000D+03	5.50057D+06	1.10466D+06	-0.050006	-0.036377	794.76	527.00	527.00	0.0	-1.88209D+05
22	11.00	3.00000D+03	5.47854D+06	1.10464D+06	-0.049160	-0.035744	794.74	527.00	527.00	0.0	0.0

TIME	THROAT PRESSURE AND QUALITY		INLET FDR FLOW AND QUALITY		CHOKED
0.0	8.787295D+06	-4.942834D-03	4180.00	-0.191751	F
1.000000D-04	8.700422D+06	-2.214430D-03	4180.07	-0.191749	F
3.000000D-04	8.526676D+06	3.299138D-03	4180.02	-0.191750	F
7.000000D-04	8.426086D+06	4.238425D-03	4180.46	-0.191596	T
1.500000D-03	8.196903D+06	8.787412D-03	4180.91	-0.191690	T
3.100000D-03	7.511546D+06	1.995933D-02	4179.19	-0.191874	T
4.439526D-03	6.932976D+06	2.557461D-02	4178.57	-0.191806	T
5.654895D-03	6.932932D+06	2.847964D-02	4180.48	-0.191604	T
8.091634D-03	7.056729D+06	3.223353D-02	4182.21	-0.191681	T
1.296111D-02	7.026012D+06	3.720366D-02	4178.17	-0.191876	T
2.270006D-02	6.946520D+06	4.326466D-02	4178.61	-0.191988	T
4.217797D-02	6.870791D+06	4.911717D-02	4180.52	-0.191929	T
8.113379D-02	6.802131D+06	5.421731D-02	4180.29	-0.191754	T
0.159045	6.764612D+06	5.673557D-02	4180.11	-0.191478	T
0.314869	6.745426D+06	5.772992D-02	4180.14	-0.191151	T
0.423945	6.741600D+06	5.794071D-02	4180.34	-0.191106	T
0.500298	6.740273D+06	5.800027D-02	4180.38	-0.191076	T

0.553746	6.720588D+06	5.826118D-02	4185.27	-0.190121	T
0.660641	6.532791D+06	6.237124D-02	4202.10	-0.182685	T
0.698255	6.452606D+06	6.389634D-02	4208.74	-0.179385	T

TIME 7.73483D-01 POWER GENERATED -4.57310D+08 POWER TO COOLANT -2.31169D+08

IN PIPE	1	POWER GENERATED	-8.19721D+08	POWER TO COOLANT	-8.19721D+08
IN PIPE	2	POWER GENERATED	3.72693D+08	POWER TO COOLANT	5.98835D+08
IN PIPE	3	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE	4	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE	5	POWER GENERATED	8.19721D+08	POWER TO COOLANT	8.19721D+08
IN PIPE	6	POWER GENERATED	-8.30003D+08	POWER TO COOLANT	-8.30003D+08

NODE	Z	W	P	H	X	ALPHA	RHO	T	TFC	THT	FLUX
1	0.0	4.14461D+03	8.51353D+06	1.34576D+06	0.003110	0.038179	688.07	572.49	572.49	0.0	0.0
2	4.00	4.18627D+03	8.50464D+06	1.30255D+06	-0.027214	-0.022420	728.70	565.54	565.54	0.0	-9.29389D+04
3	18.00	4.19703D+03	8.31258D+06	1.14828D+06	-0.129049	-0.097183	782.38	535.65	535.65	0.0	-9.29389D+04
4	22.00	4.19949D+03	8.24737D+06	1.14818D+06	-0.126593	-0.095243	782.35	535.63	535.63	0.0	0.0
5	0.0	4.20782D+03	8.24737D+06	1.14818D+06	-0.126593	-0.095243	782.35	535.63	535.63	0.0	0.0
6	2.50	4.20854D+03	8.24097D+06	1.14817D+06	-0.126354	-0.095055	782.34	535.63	535.63	0.0	0.0
7	11.50	4.21107D+03	9.56021D+06	1.15013D+06	-0.177245	-0.136842	783.86	536.17	536.28	1.00	6.48146D+03
8	16.50	4.17155D+03	9.13917D+06	1.33099D+06	-0.028443	-0.023911	718.55	570.73	577.35	1.00	5.35927D+05
9	21.50	4.11841D+03	8.69546D+06	1.34234D+06	-0.005336	-0.004392	713.38	572.67	573.29	1.00	4.20790D+04
10	26.00	4.14836D+03	8.51353D+06	1.34576D+06	0.003110	0.038179	688.07	572.49	573.43	22.00	1.62534D+04
11	0.0	3.73429D+00	8.51353D+06	1.34576D+06	0.003110	0.038179	688.07	572.49	572.49	0.0	0.0
12	0.01	3.98733D+00	6.38476D+06	1.33810D+06	0.066743	0.500417	391.79	552.78	552.78	0.0	0.0
13	0.0	8.28853D+00	8.24662D+06	1.14862D+06	-0.126259	-0.095007	782.20	535.72	535.72	0.0	0.0
14	0.01	8.29052D+00	8.24737D+06	1.14827D+06	-0.126530	-0.095199	782.32	535.65	535.65	0.0	0.0
15	0.0	3.00000D+03	5.49863D+06	1.10463D+06	-0.049947	-0.036332	794.77	527.00	527.00	0.0	0.0
16	2.00	2.99976D+03	5.51641D+06	1.16608D+06	-0.012326	-0.009073	774.26	539.35	539.35	0.0	1.85878D+05
17	9.00	2.99225D+03	5.47238D+06	1.38104D+06	0.123090	0.656689	282.13	542.76	542.76	0.0	1.85878D+05
18	11.00	2.99021D+03	5.37620D+06	1.38079D+06	0.125982	0.663995	277.00	541.63	541.63	0.0	0.0
19	0.0	2.99021D+03	5.37620D+06	1.38079D+06	0.125982	0.663995	277.00	541.63	541.63	0.0	0.0
20	2.00	2.99011D+03	5.45655D+06	1.31976D+06	0.085484	0.584266	335.84	542.57	542.57	0.0	-1.88209D+05
21	9.00	2.99998D+03	5.49991D+06	1.10466D+06	-0.049982	-0.036359	794.76	527.00	527.00	0.0	-1.88209D+05
22	11.00	3.00000D+03	5.47788D+06	1.10463D+06	-0.049135	-0.035725	794.74	527.00	527.00	0.0	0.0

TIME	THROAT PRESSURE AND QUALITY		INLET FOR FLOW AND QUALITY		CHOKED
0.773483	6.384758D+06	6.674303D-02	4211.07	-0.177245	T
0.923940	6.220784D+06	6.966432D-02	4226.42	-0.170410	T
1.22485	5.807017D+06	7.339343D-02	4224.70	-0.151086	T
1.54154	5.424732D+06	7.335385D-02	4223.41	-0.131677	T
1.87450	5.179434D+06	6.778474D-02	4250.82	-0.116933	T
2.30092	4.917247D+06	6.031364D-02	4247.71	-0.100625	T
2.75721	4.666012D+06	5.502789D-02	4239.71	-8.581033D-02	T
3.25844	4.426938D+06	5.234400D-02	4229.81	-7.310836D-02	T
3.85256	4.193708D+06	5.204973D-02	4218.35	-6.245910D-02	T
4.60874	3.964721D+06	5.335172D-02	4208.36	-5.403357D-02	T
4.81486	3.905472D+06	5.369430D-02	4209.12	-5.218833D-02	T
5.15972	3.816787D+06	5.454426D-02	4207.23	-4.961576D-02	T
5.84943	3.674531D+06	5.617964D-02	4200.37	-4.701294D-02	T
7.14480	3.458061D+06	5.788414D-02	4204.06	-4.597220D-02	T
8.63063	3.230186D+06	5.853350D-02	4203.82	-4.653087D-02	T

10.1818	3.017955D+06	5.799609D-02	4209.87	-4.773821D-02 T
11.6506	2.815247D+06	5.760113D-02	4213.18	-4.858697D-02 T
13.0641	2.640529D+06	5.646595D-02	4224.25	-4.976747D-02 T
14.4281	2.468574D+06	5.583399D-02	4237.30	-5.085211D-02 T
15.7516	2.321599D+06	5.445797D-02	4245.11	-5.232092D-02 T

TIME 1.70485D+01 POWER GENERATED -7.80223D+08 POWER TO COOLANT -7.38281D+08

IN PIPE 1	POWER GENERATED -4.62404D+08	POWER TO COOLANT	-4.62404D+08
IN PIPE 2	POWER GENERATED 5.75863D+07	POWER TO COOLANT	9.95281D+07
IN PIPE 3	POWER GENERATED 0.0	POWER TO COOLANT	0.0
IN PIPE 4	POWER GENERATED 0.0	POWER TO COOLANT	0.0
IN PIPE 5	POWER GENERATED 4.62404D+08	POWER TO COOLANT	4.62404D+08
IN PIPE 6	POWER GENERATED -8.37809D+08	POWER TO COOLANT	-8.37809D+08

NODE	Z	W	P	H	X	ALPHA	RHO	T	TFC	THT	FLUX
1	0.0	4.23080D+03	2.89949D+06	1.03092D+06	0.017441	0.380078	516.76	505.11	505.20	0.0	0.0
2	4.00	4.24129D+03	2.91088D+06	1.01611D+06	0.008670	0.248416	623.22	505.32	505.41	0.0	-5.24268D+04
3	18.00	4.22096D+03	2.68737D+06	9.74922D+05	-0.002804	-0.001824	831.71	499.86	499.87	0.0	-5.24268D+04
4	22.00	4.23146D+03	2.61647D+06	9.79167D+05	0.003212	0.126557	728.47	499.52	499.64	0.0	0.0
5	0.0	4.25151D+03	2.61647D+06	9.79968D+05	0.003650	0.140631	716.94	499.52	499.64	0.0	0.0
6	2.50	4.27169D+03	2.59813D+06	9.82392D+05	0.005932	0.206022	663.76	499.15	499.27	0.0	0.0
7	11.50	4.26407D+03	4.01158D+06	9.96470D+05	-0.053597	-0.036384	826.74	504.42	505.39	1.00	6.02295D+04
8	16.50	4.25597D+03	3.62881D+06	1.02092D+06	-0.022304	-0.015133	818.97	509.62	510.57	1.00	7.09454D+04
9	21.50	4.24632D+03	3.21241D+06	1.02633D+06	-0.000078	-0.000102	816.96	510.78	515.83	15.00	3.06725D+04
10	26.00	4.23281D+03	2.89949D+06	1.03092D+06	0.017441	0.380078	516.76	505.11	506.28	42.00	6.25352D+04
11	0.0	2.00190D+00	2.89949D+06	1.03092D+06	0.017441	0.380078	516.76	505.11	505.20	0.0	0.0
12	0.01	2.01243D+00	2.17319D+06	1.02819D+06	0.053537	0.649840	302.84	489.76	489.85	0.0	0.0
13	0.0	2.00000D+01	2.60195D+06	1.14862D+06	0.096592	0.721119	241.56	499.23	499.34	0.0	0.0
14	0.01	2.00385D+01	2.61647D+06	1.14915D+06	0.096191	0.719757	242.62	499.52	499.64	0.0	0.0
15	0.0	3.19387D+03	2.51748D+06	9.23891D+05	-0.021655	-0.013753	846.12	488.83	488.83	0.0	0.0
16	2.00	3.18058D+03	2.53557D+06	9.72619D+05	0.003902	0.152287	709.20	497.84	497.93	0.0	1.04854D+05
17	9.00	3.19536D+03	2.49322D+06	1.10735D+06	0.079400	0.695660	262.95	496.95	497.03	0.0	1.04854D+05
18	11.00	3.21168D+03	2.36415D+06	1.10726D+06	0.085861	0.715151	247.49	494.14	494.24	0.0	0.0
19	0.0	3.21168D+03	2.36415D+06	1.10726D+06	0.085861	0.715151	247.49	494.14	494.24	0.0	0.0
20	2.00	3.22779D+03	2.46669D+06	1.05731D+06	0.053562	0.630227	316.99	496.38	496.47	0.0	-1.89979D+05
21	9.00	3.20555D+03	2.51014D+06	9.21011D+05	-0.022822	-0.014494	846.94	488.20	488.21	0.0	-1.89979D+05
22	11.00	3.19387D+03	2.48665D+06	9.23891D+05	-0.019966	-0.012644	846.08	488.82	488.83	0.0	0.0

TIME	THROAT PRESSURE AND QUALITY		INLET FDR FLOW AND QUALITY		CHOKED
17.0485	2.173190D+06	5.353738D-02	4264.07	-5.359673D-02	T
18.2822	2.054479D+06	5.280201D-02	4253.79	-5.574018D-02	T
19.5077	1.926991D+06	5.197359D-02	4271.20	-5.736022D-02	T
20.6789	1.825142D+06	5.027959D-02	4269.00	-5.932379D-02	T
21.8287	1.716300D+06	4.933370D-02	4277.43	-6.103180D-02	T
22.9416	1.626248D+06	4.793708D-02	4271.84	-6.307636D-02	T
24.0390	1.532632D+06	4.700060D-02	4279.70	-6.500268D-02	T

TIME 2.50000D+01 POWER GENERATED -7.81070D+08 POWER TO COOLANT -7.33819D+08

IN PIPE 1	POWER GENERATED -4.53233D+08	POWER TO COOLANT	-4.53233D+08
IN PIPE 2	POWER GENERATED 5.75863D+07	POWER TO COOLANT	1.04838D+08

IN PIPE 3 POWER GENERATED 0.0 POWER TO COOLANT 0.0
IN PIPE 4 POWER GENERATED 0.0 POWER TO COOLANT 0.0
IN PIPE 5 POWER GENERATED 4.53233D+08 POWER TO COOLANT 4.53233D+08
IN PIPE 6 POWER GENERATED -8.38657D+08 POWER TO COOLANT -8.38657D+08

NODE	Z	W	P	H	X	ALPHA	RHO	T	TFC	THT	FLUX
1	0.0	4.23468D+03	1.93095D+06	9.30211D+05	0.015678	0.437888	483.21	483.75	483.80	0.0	0.0
2	4.00	4.22685D+03	1.94790D+06	9.15248D+05	0.006729	0.273894	620.98	484.19	484.24	0.0	-5.13870D+04
3	18.00	4.19937D+03	1.71822D+06	8.74089D+05	-0.000051	-0.000080	859.09	477.95	477.96	0.0	-5.13870D+04
4	22.00	4.23416D+03	1.61781D+06	8.77186D+05	0.008406	0.348838	564.45	475.05	475.12	0.0	0.0
5	0.0	4.25419D+03	1.61781D+06	8.78466D+05	0.009069	0.363513	551.92	475.05	475.12	0.0	0.0
6	2.50	4.27553D+03	1.58880D+06	8.80232D+05	0.011997	0.422028	502.46	474.18	474.26	0.0	0.0
7	11.50	4.27175D+03	3.06921D+06	8.94677D+05	-0.066927	-0.041977	854.20	482.30	483.35	1.00	6.22379D+04
8	16.50	4.26425D+03	2.69604D+06	9.19347D+05	-0.033776	-0.021468	847.52	487.81	488.81	1.00	7.16215D+04
9	21.50	4.25666D+03	2.29022D+06	9.26132D+05	-0.007764	-0.004844	845.24	489.32	490.34	1.00	6.11607D+04
10	26.00	4.23623D+03	1.93095D+06	9.30211D+05	0.015678	0.437888	483.21	483.75	484.79	42.00	5.91051D+04
11	0.0	1.55021D+00	1.93095D+06	9.30211D+05	0.015678	0.437888	483.21	483.75	483.80	0.0	0.0
12	0.01	1.55143D+00	1.46009D+06	9.28407D+05	0.045882	0.682382	280.78	470.16	470.20	0.0	0.0
13	0.0	2.00000D+01	1.59098D+06	1.14862D+06	0.150598	0.830471	153.05	474.25	474.32	0.0	0.0
14	0.01	2.00200D+01	1.61781D+06	1.14921D+06	0.149270	0.828133	155.00	475.05	475.12	0.0	0.0
15	0.0	3.29049D+03	1.64118D+06	8.25506D+05	-0.020009	-0.011847	871.76	467.14	467.14	0.0	0.0
16	2.00	3.27680D+03	1.65959D+06	8.72602D+05	0.003149	0.179575	707.90	476.28	476.34	0.0	1.02774D+05
17	9.00	3.25737D+03	1.61537D+06	1.00219D+06	0.073296	0.739011	231.15	474.98	475.04	0.0	1.02774D+05
18	11.00	3.27149D+03	1.44248D+06	1.00158D+06	0.084625	0.771069	204.53	469.59	469.67	0.0	0.0
19	0.0	3.27149D+03	1.44248D+06	1.00158D+06	0.084625	0.771069	204.53	469.59	469.67	0.0	0.0
20	2.00	3.28918D+03	1.57220D+06	9.52762D+05	0.050617	0.687505	275.48	473.68	473.74	0.0	-1.90172D+05
21	9.00	3.30128D+03	1.61459D+06	8.22630D+05	-0.019617	-0.011583	872.47	466.50	466.50	0.0	-1.90172D+05
22	11.00	3.29049D+03	1.59040D+06	8.25506D+05	-0.016407	-0.009656	871.68	467.14	467.14	0.0	0.0

TIME	THROAT PRESSURE AND QUALITY		INLET FDR FLOW AND QUALITY		CHOKED
25.0000	1.460095D+06	4.588224D-02	4271.75	-6.692750D-02	T

TOTAL STEAM IN CONTAINMENT 60.695 KG

INPUT DATA AS READ :-

```
4 PIPES   7 CONNECTIONS        GRAVITY 9.8043    TOL 1.D-5   ITMAX 30
*  TIME STEPPING CONTROLS
STEP LIMITS .0001 40.   CHANGE  TARGET .01  MAX .02  DENSITY ERRMAX .01
MAX DT INCREASE 2  TMAX 25  FULL PRINT EACH -20 STEPS OR IF T > 100
-------------------------------------------------------------------------------
* PIPE 1  OUTLET HEADER THROUGH STEAM GEN TO MAKE-UP SYSTEM JUNCTION
4 NODES  CONN 3 TO 2    POWER  -8.3D+8      SLIP 4*1
FRICTION  4*4        IHTRAN 4*0             PRINT 0 0 0 0  Z 0  4  18  22
DH/DZ 1 0  -.5       DE  .308   2*.01  .308 A  .447  2*1.22  .447
HP 5.8  2*490 5.8    ROUGH 4.D-5   2*4.D-6  4.D-5    CP  4*0
HF 4*0  ORIK  3*0  PD  0  1  1  0
-------------------------------------------------------------------------------
*PIPE  2  MAKE-UP SYSTEM JCT THROUGH PUMP,INLET HDR,FUEL & FEEDER TO OUTLET HDR
6 NODES  CONN 2 TO 3    POWER   8.3D+8      SLIP 6*1
FRICTION  6*4        IHTRAN 0 0 4*1         PRINT 4*0 0 0
Z 0 2.5 11.5 16.5 21.5 26  DH/DZ 0 -0.722 -0.3 0.3 1
DE 2*.308  .05  .007  2*.05
A   2*.447  .374  .491  2*.374
HP  2*5.8   30.2  220.3  2*30.2
ROUGH 3*4.D-5  4.D-6  2*4.D-5     CP 0 0  22100 6950 2*22100
HF 6*0  ORIK 0 0 50 0 0   PD 0 0 0 1 0 0
-------------------------------------------------------------------------------
* PIPE 3  BROKEN PIPE FROM OUTLET HEADER
2 3 4 0 1 1 4 4 0 0 0 0 0 .01  0  .308  0 .447 .0001 5.8 0 2*4.D-4  7*0
-------------------------------------------------------------------------------
* PIPE 4  MAKE-UP SYSTEM
2 1 2 0 1 1 4 4  4*0  0 .01  -1  .1 .308  0 .447  0  5.8  2*4.D-5  7*0
-------------------------------------------------------------------------------
* PIPE 5  SECONDARY LOOP  PUMP THROUGH STEAM GEN
4 NODES  CONN 5 TO 6    POWER 8.3D+8        SLIP 4*1
 FRICTION 4*4 IHTRAN 4*0  PRINT 4*0  Z 0 2 9 11
 DH/DZ .5 1 .5  DE .308 2*.05 .308  A .447 2*3. .447
HP  5.8  2*490  5.8  ROUGH 4.D-4 2*4.D-6 4.D-4  CP 4*0  HF  4*0
ORIK 3*0  PD 0 1 1 0
-------------------------------------------------------------------------------
* PIPE 6  SECONDARY LOOP  HEAT SINK TO PUMP
4 NODES   CONN 6 TO 7     POWER -8.3D+8         SLIP 4*1
 FRICT 4*4   IHTRAN 4*0  PRINT 4*0   Z 0 2 9 11
 DH/DZ  -.5 -1 -.5   DE .308 2*.05 .308   A .447 2*3.  .447
HP  5.8  2*490  5.8  ROUGH 4.D-4 2*4.D-6 4.D-4  CP 4*0  HF  4*0
ORIK 3*0  PD 0 1 1 0
-------------------------------------------------------------------------------
* CONNECTIONS
1 0  1
4  2  1.D5  .01
5 0 1
7  3  1
0
-------------------------------------------------------------------------------
* INITIAL CONDITIONS
PIPE 1 OPTION 1 AT NODE 4 FLOW IS 0 4179 PRESSURE 0 8.6D6 X IS 0 -.14
PIPE 4 OPTION  1 AT NODE 2 0  1   1 4  1 4
PIPE 3 OPTION 1 AT NODE 1 FLOW IS 4 1 PRESSURE 1 1 X IS 1 1
PIPE 2 OPTION 5 SEGMENT 2
PIPE 5 OPTION 1 NODE 1 0 3000 0 5.5D6  0 -.05
```

```
        PIPE 6 OPTION 4 CONNECTION 6
        0  END STEADY STATE
        *
         OUTPUT CONTROL 0    (ADD TO DATA FILE)

*** OUTPUT ON PSEUDO FILE  2
```

PIPE NUMBER 1 JOINS CONNECTIONS 3 AND 2

CONNECTION 3 IS INTERNAL

CONNECTION 2 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
1	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	1	9.804D+00	0.0
2	4.00	0.0100	490.00	1.220D+00	0.0	1.000D+10	1.134D-04	4.00D-06	JONS	SBBL	0	2	0.0	0.0
3	18.00	0.0100	490.00	1.220D+00	0.0	1.000D+10	1.134D-04	4.00D-06	JONS	SBBL	0	3	-4.902D+00	0.0
4	22.00	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0			

PIPE NUMBER 2 JOINS CONNECTIONS 2 AND 3

CONNECTION 2 IS INTERNAL

CONNECTION 3 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
5	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	5	0.0	0.0
6	2.50	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	6	-2.115D+02	0.0
7	11.50	0.0500	30.20	3.740D-01	2.210D+04	1.000D+10	0.0	4.00D-05	JONS	SBBL	1	7	-2.941D+00	50.00
8	16.50	0.0070	220.30	4.910D-01	6.950D+03	1.000D+10	9.079D-04	4.00D-06	JONS	SBBL	1	8	2.941D+00	0.0
9	21.50	0.0500	30.20	3.740D-01	2.210D+04	1.000D+10	0.0	4.00D-05	JONS	SBBL	1	9	9.804D+00	0.0
10	26.00	0.0500	30.20	3.740D-01	2.210D+04	1.000D+10	0.0	4.00D-05	JONS	SBBL	1			

PIPE NUMBER 3 JOINS CONNECTIONS 3 AND 4

CONNECTION 3 IS INTERNAL

CONNECTION 4 WILL BURST OPEN OVER TIME 1.0D-02 TO PRESSURE 1.000000D+05

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
11	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0	11	0.0	0.0
12	0.01	0.0113	0.04	1.000D-04	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0			

PIPE NUMBER 4 JOINS CONNECTIONS 1 AND 2

CONNECTION 1 HAS GIVEN MASSFLOW BOUNDARY CONDITION

CONNECTION 2 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
13	0.0	0.1000	0.31	7.854D-03	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0	13	-9.804D+00	0.0
14	0.01	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-05	JONS	SBBL	0			

PIPE NUMBER 5 JOINS CONNECTIONS 5 AND 6

CONNECTION 5 HAS GIVEN MASSFLOW BOUNDARY CONDITION

CONNECTION 6 IS INTERNAL

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
15	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0	15	4.902D+00	0.0
16	2.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	16	9.804D+00	0.0
17	9.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	17	4.902D+00	0.0
18	11.00	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0			

PIPE NUMBER 6 JOINS CONNECTIONS 6 AND 7

CONNECTION 6 IS INTERNAL

CONNECTION 7 HAS IMPLICIT MASSFLOW BOUNDARY CONDITION

NODE	Z	DE	HP	A	CP	HF	PD	ROUGH	SLIP	FRIC	DHT	SEG	GSINT	ORIF
19	0.0	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0	19	-4.902D+00	0.0
20	2.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	20	-9.804D+00	0.0
21	9.00	0.0500	490.00	3.000D+00	0.0	1.000D+10	2.268D-04	4.00D-06	JONS	SBBL	0	21	-4.902D+00	0.0
22	11.00	0.3080	5.80	4.470D-01	0.0	1.000D+10	0.0	4.00D-04	JONS	SBBL	0			

TIME 0.0 POWER GENERATED -7.33831D+06 POWER TO COOLANT -7.33831D+06

IN PIPE	1	POWER GENERATED	-8.30000D+08	POWER TO COOLANT	-8.30000D+08
IN PIPE	2	POWER GENERATED	8.22662D+08	POWER TO COOLANT	8.22662D+08
IN PIPE	3	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE	4	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE	5	POWER GENERATED	8.30000D+08	POWER TO COOLANT	8.30000D+08
IN PIPE	6	POWER GENERATED	-8.30000D+08	POWER TO COOLANT	-8.30000D+08

NODE	Z	W	P	H	X	ALPHA	RHO	T	TFC	THT	FLUX
1	0.0	4.17900D+03	8.85947D+06	1.34724D+06	-0.007265	-0.005998	711.63	573.54	573.54	0.0	0.0
2	4.00	4.17900D+03	8.85217D+06	1.30314D+06	-0.038750	-0.032535	729.27	565.75	565.75	0.0	-9.41043D+04
3	18.00	4.17900D+03	8.66381D+06	1.14866D+06	-0.142468	-0.107915	782.70	535.74	535.74	0.0	-9.41043D+04
4	22.00	4.17900D+03	8.60000D+06	1.14862D+06	-0.140000	-0.105925	782.62	535.73	535.73	0.0	0.0
5	0.0	4.18000D+03	8.60000D+06	1.14862D+06	-0.140000	-0.105925	782.62	535.73	535.73	0.0	0.0
6	2.50	4.18000D+03	8.59426D+06	1.14862D+06	-0.139775	-0.105744	782.62	535.73	535.73	0.0	0.0
7	11.50	4.18000D+03	9.91841D+06	1.15049D+06	-0.191751	-0.149330	784.62	536.33	536.33	1.00	0.0
8	16.50	4.18000D+03	9.49275D+06	1.34735D+06	-0.028483	-0.024196	712.57	573.67	582.84	15.00	7.46856D+05
9	21.50	4.18000D+03	9.03838D+06	1.34728D+06	-0.013195	-0.010958	711.82	573.57	573.57	1.00	0.0
10	26.00	4.18000D+03	8.85947D+06	1.34724D+06	-0.007265	-0.005998	711.63	573.54	573.54	1.00	0.0
11	0.0	1.00000D+00	8.85947D+06	1.34724D+06	-0.007265	-0.005998	711.63	573.54	573.54	0.0	0.0
12	0.01	1.00000D+00	8.78729D+06	1.34714D+06	-0.004943	-0.004082	711.60	573.52	573.52	0.0	0.0
13	0.0	1.00000D+00	8.59991D+06	1.14862D+06	-0.139997	-0.105922	782.62	535.73	535.73	0.0	0.0
14	0.01	1.00000D+00	8.60000D+06	1.14862D+06	-0.140000	-0.105925	782.62	535.73	535.73	0.0	0.0
15	0.0	3.00000D+03	5.50000D+06	1.10464D+06	-0.050000	-0.036372	794.77	527.00	527.00	0.0	0.0
16	2.00	3.00000D+03	5.51778D+06	1.16614D+06	-0.012340	-0.009084	774.24	539.36	539.36	0.0	1.88209D+05
17	9.00	3.00000D+03	5.47363D+06	1.38125D+06	0.123181	0.656796	282.05	542.77	542.77	0.0	1.88209D+05
18	11.00	3.00000D+03	5.37661D+06	1.38089D+06	0.126033	0.664060	276.95	541.64	541.64	0.0	0.0
19	0.0	3.00000D+03	5.37661D+06	1.38089D+06	0.126033	0.664060	276.95	541.64	541.64	0.0	0.0
20	2.00	3.00000D+03	5.45727D+06	1.31977D+06	0.085467	0.584200	335.88	542.58	542.58	0.0	-1.88209D+05
21	9.00	3.00000D+03	5.50057D+06	1.10466D+06	-0.050006	-0.036377	794.76	527.00	527.00	0.0	-1.88209D+05
22	11.00	3.00000D+03	5.47854D+06	1.10464D+06	-0.049160	-0.035744	794.74	527.00	527.00	0.0	0.0

TIME	THROAT PRESSURE AND QUALITY		INLET FDR FLOW AND QUALITY		CHOKED
0.0	8.787295D+06	-4.942834D-03	4180.00	-0.191751	F
1.000000D-04	8.700422D+06	-2.214430D-03	4180.07	-0.191749	F
2.011511D-04	8.612549D+06	5.759260D-04	4180.07	-0.191747	F
3.013022D-04	8.576701D+06	1.027552D-03	4180.19	-0.191547	T
5.016044D-04	8.532039D+06	2.097983D-03	4180.62	-0.191429	T
8.862619D-04	8.422374D+06	4.514311D-03	4181.26	-0.191538	T
1.185529D-03	8.283679D+06	6.304215D-03	4181.55	-0.191656	T
1.367262D-03	8.164290D+06	7.442809D-03	4181.62	-0.191755	T
1.493354D-03	8.066679D+06	8.262083D-03	4181.60	-0.191824	T
1.598820D-03	7.978877D+06	8.957987D-03	4181.52	-0.191920	T
1.698820D-03	7.892288D+06	9.641228D-03	4181.39	-0.191951	T
1.798820D-03	7.803414D+06	1.032056D-02	4181.21	-0.192056	T
1.898820D-03	7.712236D+06	1.101603D-02	4180.98	-0.192109	T
1.998820D-03	7.619149D+06	1.171411D-02	4180.70	-0.192145	T
2.098820D-03	7.525464D+06	1.239206D-02	4180.38	-0.192249	T
2.198820D-03	7.432544D+06	1.307796D-02	4180.01	-0.192264	T
2.298820D-03	7.341896D+06	1.373884D-02	4179.59	-0.192324	T

10 PAGES OF OUTPUT OMITTED

TIME	THROAT PRESSURE AND QUALITY		INLET FOR FLOW AND QUALITY		CHOKED
22.0502	1.771358D+06	4.653208D-02	4345.28	-6.299226D-02	T
22.2135	1.757252D+06	4.636137D-02	4346.21	-6.326888D-02	T
22.3749	1.743432D+06	4.619658D-02	4347.13	-6.354393D-02	T
22.5349	1.729836D+06	4.603815D-02	4348.11	-6.381471D-02	T
22.6934	1.716371D+06	4.587433D-02	4348.86	-6.408777D-02	T
22.8507	1.703065D+06	4.571269D-02	4349.70	-6.435847D-02	T
23.0072	1.689979D+06	4.555942D-02	4350.46	-6.462660D-02	T
23.1631	1.676965D+06	4.540512D-02	4351.11	-6.489868D-02	T
23.3185	1.664003D+06	4.525160D-02	4351.83	-6.516929D-02	T
23.4742	1.651084D+06	4.509519D-02	4352.45	-6.544023D-02	T
23.6301	1.638315D+06	4.494692D-02	4353.04	-6.571786D-02	T
23.7866	1.625475D+06	4.479881D-02	4353.69	-6.599507D-02	T
23.9441	1.612605D+06	4.464496D-02	4354.20	-6.627502D-02	T
24.1026	1.599727D+06	4.449102D-02	4354.80	-6.656453D-02	T
24.2613	1.587018D+06	4.434529D-02	4355.43	-6.685244D-02	T
24.4188	1.574391D+06	4.419707D-02	4355.92	-6.714019D-02	T
24.5752	1.561920D+06	4.404742D-02	4356.54	-6.743426D-02	T
24.7319	1.549512D+06	4.389276D-02	4357.17	-6.772638D-02	T
24.8872	1.537416D+06	4.374678D-02	4357.67	-6.801795D-02	T

TIME 2.50000D+01 POWER GENERATED -7.80007D+08 POWER TO COOLANT -7.33839D+08

IN PIPE 1	POWER GENERATED	-4.55635D+08	POWER TO COOLANT	-4.55635D+08
IN PIPE 2	POWER GENERATED	5.75863D+07	POWER TO COOLANT	1.03754D+08
IN PIPE 3	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE 4	POWER GENERATED	0.0	POWER TO COOLANT	0.0
IN PIPE 5	POWER GENERATED	4.55635D+08	POWER TO COOLANT	4.55635D+08
IN PIPE 6	POWER GENERATED	-8.37593D+08	POWER TO COOLANT	-8.37593D+08

NODE	Z	W	P	H	X	ALPHA	RHO	T	TFC	THT	FLUX
1	0.0	4.32930D+03	2.00847D+06	9.35377D+05	0.013676	0.403015	511.29	485.74	485.74	0.0	0.0
2	4.00	4.32919D+03	2.02688D+06	9.21175D+05	0.005040	0.219221	665.17	486.20	486.20	0.0	-5.16593D+04
3	18.00	4.27869D+03	1.80462D+06	8.80406D+05	-0.002482	-0.001520	857.43	479.34	479.34	0.0	-5.16593D+04
4	22.00	4.31401D+03	1.71619D+06	8.83794D+05	0.005141	0.249159	647.19	477.92	477.92	0.0	0.0
5	0.0	4.33402D+03	1.71619D+06	8.85020D+05	0.005779	0.269157	630.19	477.92	477.92	0.0	0.0
6	2.50	4.36065D+03	1.68645D+06	8.86886D+05	0.008748	0.348706	563.14	477.06	477.07	0.0	0.0
7	11.50	4.35814D+03	3.16234D+06	9.00808D+05	-0.068234	-0.042976	852.58	483.64	484.63	1.00	6.07423D+04
8	16.50	4.35086D+03	2.77509D+06	9.24779D+05	-0.034963	-0.022314	846.07	488.99	489.96	1.00	7.11511D+04
9	21.50	4.34349D+03	2.35445D+06	9.31278D+05	-0.008626	-0.005404	843.85	490.44	491.40	1.00	5.96106D+04
10	26.00	4.33090D+03	2.00847D+06	9.35377D+05	0.013676	0.403015	511.29	485.74	486.77	42.00	5.87025D+04
11	0.0	1.59672D+00	2.00847D+06	9.35377D+05	0.013676	0.403015	511.29	485.74	485.74	0.0	0.0
12	0.01	1.60312D+00	1.52863D+06	9.33425D+05	0.043639	0.667907	292.64	472.33	472.33	0.0	0.0
13	0.0	2.00000D+01	1.69115D+06	1.14862D+06	0.144566	0.820820	161.09	477.20	477.20	0.0	0.0
14	0.01	2.00200D+01	1.71619D+06	1.14916D+06	0.143373	0.818608	162.92	477.92	477.92	0.0	0.0
15	0.0	3.28776D+03	1.70450D+06	8.28562D+05	-0.022832	-0.013613	871.06	467.82	467.82	0.0	0.0
16	2.00	3.27491D+03	1.72351D+06	8.77074D+05	0.001150	0.074873	795.19	478.12	478.12	0.0	1.03319D+05
17	9.00	3.22248D+03	1.67685D+06	1.00661D+06	0.071618	0.731216	237.45	476.79	476.79	0.0	1.03319D+05
18	11.00	3.24686D+03	1.51364D+06	1.00569D+06	0.081864	0.761550	212.37	471.86	471.86	0.0	0.0
19	0.0	3.24686D+03	1.51364D+06	1.00569D+06	0.081864	0.761550	212.37	471.86	471.86	0.0	0.0
20	2.00	3.27127D+03	1.63568D+06	9.56033D+05	0.048046	0.673496	286.79	475.58	475.58	0.0	-1.89930D+05
21	9.00	3.29838D+03	1.67910D+06	8.25709D+05	-0.022552	-0.013413	871.77	467.19	467.19	0.0	-1.89930D+05
22	11.00	3.28776D+03	1.65496D+06	8.28562D+05	-0.019393	-0.011494	870.97	467.82	467.82	0.0	0.0

TIME	THROAT PRESSURE AND QUALITY		INLET FDR FLOW AND QUALITY		CHOKED
25.0000	1.528628D+06	4.363929D-02	4358.14	-6.823383D-02	T

TOTAL STEAM IN CONTAINMENT 61.661 KG

```
*
* INPUT FILE STRUCTURE IS:-
*
*      VARIABLE                POSITION(S)
*
*        TIME                      1
*        FLOWS                   2-23
*      PRESSURES                24-45
*      QUALITIES                46-67
*       POWERS                  68-73
*      TOT POWER                  74
*      TIME STEP                  75
*
*   DATA INPUT PHASE FOR COARSE CALCULATION
*
 FILE 1 75 ENTRIES
 GET 2 1 13
*
* PLOT PHASE
*
PAPE 0 -8 -6 1 1 -1 2

LEGO 4 5
LEG 2 "COARSE CALCN."
HEAD "FLOW AT BREAK"
NAMX "TIME (SECONDS)"
NAMY "FLOW (KG/S)"
* RETURN TO INPUT PHASE TO ACCESS OUTPUT OF FINE CALCN
DATA
FILE 2 75
 4 1 13 35 75
* THIS GOES ON PREVIOUS PLOT
LINE 1 2 2
LEG 2 "FINE CALCN."
* NOW COMMENCE NEW PLOT
PAPE 8 -6 1.E-4 25 0 10
* SCALE PASCALS DOWN TO MPA
CONS 0 1.E-6
LINE 1 3 1
HEAD "PRESSURE AT BREAK (FINE CALCULATION)"
NAMX "TIME (SECONDS)"
NAMY "PRESSURE (MEGAPASCALS)"
PAPE 8 6 1.E-4 25 1.E-5 1
LINE 1 4 1
HEAD "TIME STEP (FINE CALCULATION)"
NAMX "TIME (SECONDS)"
NAMY "TIME STEP (SECONDS)"


END OF FILE ON UNIT  1

EXECUTION TERMINATED
```