AAEC/E342

AAEC/E342

AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS

OWEN-1 - A CODE FOR ANALYSIS OF TWO-PHASE COMPRESSIBLE FLOW TRANSIENTS IN A SINGLE CHANNEL

by

W. J. TURNER

May 1975

ISBN 642 99688 1

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

OWEN-1 - A CODE FOR ANALYSIS OF TWO-PHASE COMPRESSIBLE FLOW TRANSIENTS IN A SINGLE CHANNEL

by

W.J. TURNER

ABSTRACT

A computer code for simulating two-phase compressible flow transients including loss-of-coolant in a single water cooled channel is described. The momentum flux term is included and slip between the phases is allowed. A pipe model and detailed surface heat transfer is included. The conservation equations are solved by means of an implicit numerically stable finite difference scheme so that time step size can be chosen on accuracy considerations alone.

National Library of Australia Card number and ISBN 642 99688 1

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.

BOUNDARY CONDITIONS; EQUATIONS OF STATE; FINITE DIFFERENCE METHOD; HEAT TRANSFER; LOSS OF COOLANT; MATHEMATICAL MODELS; O CODES; PIPES; REACTOR CHANNELS; SIMULATION; TRANSIENTS; TWO-PHASE FLOW; WATER COOLED REACTORS

CONTENTS

	Page
1. INTRODUCTION	1
2. CONSERVATION EQUATIONS	2
3. FINITE DIFFERENCE EQUATIONS	3
4. EQUATION OF STATE	6
5. SLIP MODEL	6
5.1 No Slip and Single Phase	6
5.2 Jones' Slip	7
6. FRICTION	8
7. PIPE MODEL	9
8. HEAT TRANSFER	9
9. BOUNDARY CONDITIONS	10
9.1 Moody Model	10
9.2 Rodflow Model	11
9.3 Fauske Model	11
10. SOLUTION OF FINITE DIFFERENCE EQUATIONS	12
11. INPUT DATA	13
11.1 Title Card	13
11.2 Control Array	13
11.3 Boundary Condition Table	16
11.4 Geometry Table	16
11.5 Restart Table	17
11.6 Output Table	17
12. COMPUTING TIME	17
13. OUTPUT	17
13.1 Error Messages	18
14. PLOTTING	19
15. ACKNOWLEDGEMENTS	20
16. REFERENCES	20

Table 1 Orifice Friction Specific Volume v_o

(continued)

CONTENTS (continued)

Table 2 Pipe Friction Specific Volume v_p

Table 3 Correlations for Surface Heat Transfer Coefficient

Table 4 Rodflow Choked Flow Model

Table 5 REAL*8 Arrays in Common Area DIM

Table 6 Equation of State Mesh

Table 7 REAL*8 Arrays in Common Area DATA

Appendix A Input Data for Sample Problem

Appendix B Output from Sample Source

Appendix C Notation

1. INTRODUCTION

Many finite difference digital computer programs have been written to analyse two-phase compressible flow transients in water cooled nuclear power reactors. Most of these (Elliott 1968, Redfield *et al.* 1967, Rettig *et al.* 1970) are limited to time steps of order of the time taken for a sound wave to cross one space segment. This is also true of most programs written to analyse the loss-of-coolant accident in sodium cooled fast reactors (Sha & Hughes 1970, Carter *et al.* 1970). In many transients of interest, conditions are changing sufficiently slowly that consideration of accuracy alone would allow much larger time steps.

This problem is overcome in the family of codes, HYDNA (Currin *et al.* 1961), POISE (Carver 1967) and SLIP (Moxon 1968), derived from the momentum integral method (Meyer 1961). In this method dependence of steam and water densities on pressure is neglected thus eliminating sonic effects and permitting larger time steps. The codes are suitable only for transients in which small pressure changes occur; even then neglect of compressibility is an uncertainty in the results. The method is not suitable for loss-of-coolant analysis where larger pressure changes occur. Thus a finite difference scheme is desirable which includes compressibility and is stable for large time steps.

Such a scheme has been given by Turner & Wendroff (1964) for a perfect gas. In FLASH-4 (Porshing *et al.* 1969) a partially implicit method is used which is described by Porshing *et al.* (1971), but in practice this scheme is only conditionally stable.

The code described in this report uses a fully implicit scheme for two-phase compressible flow with slip between the steam and water phases. It is a further development of the method of Turner (1969) and includes the spatial acceleration or momentum flux term. The scheme has been found stable for time steps of any size. Running times are comparable with the momentum integral codes mentioned above where both methods are applicable.

Input data required are geometric and thermohydraulic descriptions of the channel from inlet to outlet, parameters to determine space and time step sizes, boundary conditions at the channel inlet and outlet, and specification of the initial state of the system. Usually this initial state is a steady state calculated from input data giving pressure, thermodynamic quality and flow rate at a specified point in the channel. However, a restart option is available in which the initial state at every node is taken from input data.

The calculation consists mainly of computation of pressure, quality, pipe temperature, *etc.*, at each space node for each time step. Four types of transients can be computed, depending on the three boundary conditions specified. These are inlet enthalpy; inlet pressure or inlet flow; and the boundary condition at the outlet, either outlet pressure or one of the choked flow conditions. Three such conditions between pressure, enthalpy and flow at the outlet are incorporated in the code.

The code is so written that the equations of state for other coolants are easily added in place of those for light water. Similarly additional heat transfer relations can be included.

The principal limitation of the code is that flow reversal must not occur at either the channel inlet or outlet. Reverse flow within the channel is allowed.

2. CONSERVATION EQUATIONS

Consider a channel or pipe of cross section area a, which is a function of Z, the distance along the channel. The conservation equations are (Meyer 1960):

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

momentum $$\frac{1}{a}\frac{\partial W}{\partial t} + \frac{1}{a}\frac{\partial}{\partial Z}\left(\frac{M}{a}\right) + \frac{\partial P}{\partial Z} + F + \rho g\frac{dy}{dZ} = 0$$

energy $$\frac{\partial}{\partial t}\left[a\rho H - aP + \frac{M}{2a}\right] + \frac{\partial}{\partial Z}(E + aK) + Wg\frac{dy}{dZ} = a\phi$$

where the pressure P is considered constant over each plane normal to the Z axis; h, d and u vary across this plane; and averages over the plane are

density $\rho = \frac{1}{a}\int_a d\,da$,

static enthalpy $H = \frac{1}{\rho a}\int_a h\,d\,da$,

mass flowrate $W = \int_a u\,d\,da$,

momentum flowrate $\frac{M}{a} = \int_a u^2\,d\,da$,

energy flow $E = \int_a u\,h\,d\,da$, and

kinetic energy flux $K = \frac{1}{2a}\int_a d\,u^3\,da$.

Flow enthalpy, as distinct from static enthalpy H given above, is E/W.

We assume thermodynamic equilibrium and take the equation of state in the form (Meyer 1961)

$$\rho = \rho(P,H)$$

then $$\frac{\partial \rho}{\partial t} = R_P \frac{\partial P}{\partial t} + R_H \frac{\partial H}{\partial t} \quad .$$

We assume that M and E are not explicit functions of the channel geometry or surface heat flux, *i.e.* given W, P and H the quantities M and E can be calculated, excluding such effects as subcooled boiling and diameter effect on slip ratio. Then the conservation equations may be written

mass $$aR_P \frac{\partial P}{\partial t} + aR_H \frac{\partial H}{\partial t} + \frac{\partial W}{\partial Z} = 0$$

momentum $$\frac{1}{a}\frac{\partial W}{\partial t} + \frac{1}{a^2}\frac{\partial M}{\partial X} \cdot \frac{\partial X}{\partial Z} + \frac{M}{a}\frac{d}{dZ}\left(\frac{1}{a}\right) + \frac{\partial P}{\partial Z} + F = -\rho g \frac{dy}{dZ}$$

energy $$a\rho \frac{\partial H}{\partial t} - H \frac{\partial W}{\partial Z} - a \frac{\partial P}{\partial t} + \frac{\partial E}{\partial X} \cdot \frac{\partial X}{\partial Z} + \frac{1}{2a}\frac{\partial M}{\partial X} \cdot \frac{\partial X}{\partial t} + \frac{\partial}{\partial Z}(aK) =$$

$$= a\phi - Wg \frac{dy}{dZ}$$

where $$\frac{\partial}{\partial X} = \begin{pmatrix} \partial/\partial W \\ \partial/\partial P \\ \partial/\partial H \end{pmatrix} \quad .$$

This form has the advantage that, except for the time independent derivatives and $\frac{\partial}{\partial Z}(aK)$ (usually small), only components of X appear in time or space differentials which therefore can be forward averaged. If this is done local stability (Richtmyer 1967) of the finite difference scheme, neglecting the small $\frac{\partial}{\partial Z}(aK)$ term, can be proved (Turner 1972). The drawback is that the derivatives of M and E with respect to P and H may be discontinuous at the boundaries between the two-phase and single phase regions. This is discussed in Section 3.

3. FINITE DIFFERENCE EQUATIONS

Finite differencing sets up averages over the space step Z_1 to Z_2 and over the time step t to t'. The space derivative terms of the form Q(Z,W,P, H) $\partial R/\partial Z$ are approximated by

$$\frac{(Q_1 + Q_2)}{2} \left(\frac{R_2' - R_1'}{Z_2 - Z_1}\right) \qquad \ldots (1)$$

and the time derivative terms $Q(Z,W,P,H)\ \partial R/\partial t$ by

$$\frac{Q_1(R_1' - R_1) + Q_2(R_2' - R_2)}{2(t' - t)}$$

where $Q_1 = Q(Z_1,W_1,P_1,H_1)$ *etc*. The terms containing $\frac{dy}{dZ}$ are treated as follows:

$$\rho g\frac{dy}{dZ} = \frac{(\rho_1 + \rho_2)}{2}\left(\frac{y_2 - y_1}{Z_2 - Z_1}\right)g \quad .$$

The power term is approximated by

$$a\phi = \frac{a_1\ \phi_1 + a_2\ \phi_2}{2} \quad .$$

The term F in the momentum equation is made up of contributions of friction at the pipe wall and at an orifice between the nodes. These two friction terms are specially treated to give better accuracy and to improve numerical stability at high flow rates; both were assumed to vary as $W|W|$ rather than to remain constant over a time step. Then

$$\partial F/\partial W = 2F/W \quad \text{and} \quad \frac{F_1 + F_1'}{2} \approx \frac{F_1\ W_1'}{W_1} \quad .$$

Thus F is represented by

$$F = \frac{W_1'|G_1|v_{p1}}{a_1\ D_{e1}} + \frac{W_2'|G_2|v_{p2}}{a_2\ D_{e2}} + \frac{K_o}{Z_2-Z_1}\left(\frac{W_1'|G_1|v_{o1}}{a_1} + \frac{W_2'|G_2|v_{o2}}{a_2}\right)$$

where K_o and D_e are input quantities and the friction specific volumes v_o and v_p contain the friction factors. Definitions of v_o and v_p are given in Section 6.

The coefficients of the derivatives of E and M are also given special treatment. Consider the expression

$$[w\ (\frac{\partial E}{\partial X})_1 + (1 - w)\ (\frac{\partial E}{\partial X})_2] \cdot \left(\frac{X_2' - X_1'}{Z_2 - Z_1}\right) \quad .$$

For $w = \frac{1}{2}$ this expression is the form of finite difference approximation given in Equation 1. The truncation error (Richtmyer 1967) in this approximation is of order

$$[(\frac{\partial E}{\partial X})_1 - (\frac{\partial E}{\partial X})_2] \cdot \frac{\partial X}{\partial Z} \quad .$$

If $\partial E/\partial X$ is continuous this is of order ∂Z. If $\partial E/\partial X$ is not continuous the truncation error on a segment spanning the discontinuity is not small, and its effect on the solution is not reduced by choosing ∂Z small. Also in such cases a steady state solution to the finite difference equations for such a segment, may not exist. Both these problems are overcome by choosing

$$w = e \equiv \frac{E_2 - E_1 - (\frac{\partial E}{\partial X})_2 \cdot (X_2 - X_1)}{\left[(\frac{\partial E}{\partial X})_1 - (\frac{\partial E}{\partial X})_2\right] \cdot (X_2 - X_1)} \quad \text{for} \quad 0 \leqslant e \leqslant 1 \qquad \ldots (2)$$

$$w = 0 \text{ for } e < 0$$

$$w = 1 \text{ for } e > 1 \quad .$$

Then, provided ∂Z is not too large a steady state solution always exists and the truncation error is of order ∂Z plus order ∂t.

For single phase flow or if zero slip between the phases is assumed

$$E = H W$$

$$\frac{\partial E}{\partial X} = \begin{pmatrix} H \\ O \\ W \end{pmatrix}$$

and $w = \frac{1}{2}$.

Similarly, an interpolation coefficient $0 \leqslant S \leqslant 1$ is defined for the term $a^{-2} \frac{\partial M}{\partial Z}$ such that

$$\frac{1}{2}\left(\frac{1}{a_1^2} + \frac{1}{a_2^2}\right)(M_2 - M_1)$$

$$= \left[\frac{S}{a_1^2}\left(\frac{\partial M}{\partial X}\right)_1 + \frac{(1 - S)}{a_2^2}\left(\frac{\partial M}{\partial X}\right)_2\right] \cdot (X_2 - X_1) \quad . \qquad \ldots (3)$$

Then $\frac{1}{a^2}\frac{\partial M}{\partial Z}$ is approximated by

$$\left[\frac{S}{a_1^2} \cdot \left(\frac{\partial M}{\partial X}\right)_1 + \frac{(1 - S)}{a_2^2}\left(\frac{\partial M}{\partial X}\right)_2\right] \cdot \frac{(X_2' - X_1')}{(Z_2 - Z_1)} \quad .$$

The resulting three finite difference equations are such that mass flows from one segment appear unchanged in the next, and acceleration (including the effects of area change), friction and gravitational pressure drops in steady state agree with the usual formulations.

The coefficients R_P, R_H, ρ and other properties needed *e.g.* void fraction and temperature, are evaluated in the equation of state routine described in Section 4. The coefficients $\frac{\partial M}{\partial X}$, $\frac{\partial E}{\partial X}$, K and other quantities such as quality and E, are evaluated in the slip routine described in Section 5. Evaluation of the friction terms is described in Section 6 and of the power-to-coolant in Section 7.

4. EQUATION OF STATE

The assumption of thermodynamic equilibrium allows the static quantities required for the difference equation coefficients and slip model to be determined from pressure and static enthalpy. The quantities are obtained by interpolation of tables read in from disk at the start of the calculation. The tables have been generated from the state equations for water (Meyer 1967) by means of the ASTEM code (Moore 1971). The pressure and temperature mesh used in the current tables is given in Table 6. Tables with a different mesh can easily be generated if required. The void fraction is always calculated from

$$\alpha = \frac{\rho - \rho_L}{\rho_V - \rho_L} \quad .$$

5. SLIP MODEL

In the slip routine quantities P, H and those calculated in the equation of state routine are used to find flow quality

$$x = \frac{H_L - E/W}{H_L - H_V} \quad ,$$

E, M, K and derivatives $\partial E/\partial X$ and $\partial M/\partial X$. Both of the two slip models available make the approximation that u_V and u_L do not vary across the pipe cross section.

5.1 No Slip and Single Phase

If all the coolant is assumed to move at the same speed, then

$$E = HW$$

$$\frac{\partial E}{\partial X} = \begin{pmatrix} H \\ 0 \\ W \end{pmatrix}$$

$$M = W^2/\rho$$

$$\frac{\partial M}{\partial Z} = M \begin{pmatrix} 2/W \\ -R_P/\rho \\ -R_H/\rho \end{pmatrix}$$

$$K = \frac{G^3}{2\rho^2}$$

and $$x = \frac{H - H_L}{H_V - H_L} \quad .$$

In the single phase regions the value of x indicates the degree of subcooling or superheating.

5.2 Jones' Slip (Jones & Dight 1962)

In this case

$$u_V = \frac{\alpha u_V + (1-\alpha)u_L}{\gamma}$$

where $\gamma = (0.71 + 0.29P/P_C)\ (1-\alpha^r) + \alpha^r$,

$r = 3.33 + (0.18 + 0.46 \times 10^{-3}P)P/1000$

and P_C, the pressure at the critical point, and P are in psia. Now

$$\alpha = \frac{\rho - \rho_L}{\rho_V - \rho_L}$$

is a function of P and H only. Also

$$G = \alpha\rho_V u_V + (1-\alpha)\rho_L u_L \quad .$$

Therefore $x = \dfrac{\alpha\rho_V}{\gamma\rho_L - \alpha(\rho_L - \rho_V)}$ is also a function of P and H only.

Thus
$$\begin{aligned} M &= a^2[\alpha\rho_V u_V^2 + (1-\alpha)\rho_L u_L^2] \\ &= W^2 \frac{\left[\alpha\rho_V + \rho_L\dfrac{(\gamma-\alpha)^2}{(1-\alpha)}\right]}{[\alpha\rho_V + \rho_L(\gamma-\alpha)]^2} \quad , \end{aligned}$$

and
$$\begin{aligned} E &= a[(1-\alpha)\rho_L u_L H_L + \alpha\rho_V u_V H_V] \\ &= \frac{W[(\gamma-\alpha)\rho_L H_L + \alpha\rho_V H_V]}{[\alpha\rho_V + (\gamma-\alpha)\rho_L]} \end{aligned}$$

are functions W, P and H only. As the derivatives of H_V, H_L, ρ_V, ρ_L are obtained in the equation of state routine, the derivatives of M and E with respect to W, P and H, may be simply obtained. The kinetic energy flux is given by

$$K = \tfrac{1}{2}[(1-\alpha)\rho_L u_L^3 + \alpha\rho_V u_V^3] \quad .$$

6. FRICTION

The friction F depends on the two friction specific volumes, v_p (a function of the relative pipe roughness ε/D) and v_o (a function of the orifice coefficient used for orifices and fittings). The latter depends on quality and the value of S_T (an input quantity specifying the friction model) as shown in Table 1. In single phase regions the orifice pressure drop is assumed proportional to G^2/ρ. In the two-phase region two options are available: if $S_T = 0$ friction corresponding to homogeneous flow is used; if $S_T = 1$, a separated flow model is used, except at high quality where the homogeneous model is used. To remove a discontinuity between separated and homogeneous flow regions an interpolation region is inserted.

The Φ in Tables 1 and 2 is the product of approximations from Cowking & Enderby (1966) to the Martinelli-Nelson (1948) two-phase pressure drop multiplier and Collier (1964) mass velocity correction term. At low qualities this product becomes less than 1. If this occurs Φ is taken to be 1.

To specify v_p we first define a Fanning friction factor f as a function of μ, a viscosity. The Reynolds number is given by

$$Re = \frac{GD_e}{\mu} \quad .$$

If Re < 2000, laminar flow is assumed and

$$f(\mu) = \frac{16}{Re} \quad .$$

If Re $\geqslant$ 4000, the Colebrook equation for the transition and turbulent flow regions is used.

$$\frac{1}{\sqrt{f}} = -1.73716 \;\ell n \left(\frac{\varepsilon}{3.7D} + \frac{1.26}{Re\sqrt{f}} \right) \quad .$$

Often a Reynolds number of 2000 is taken as the boundary between the laminar flow equation and the Colebrook equation. To avoid the discontinuity that such an assumption would introduce, the following interpolation relation, which gives reasonable agreement with Nikuradse (1933) was introduced for Reynolds numbers between 2000 and 4000.

$$f(\mu) = \frac{16}{Re} + [f(Re{=}4000) - 0.004\,]\,\frac{(Re-2000)}{2000} \quad .$$

The function $f(\mu)$ is used in Table 2 to define v_p. The input quantity S_T also determines the option used for v_p in the same way as for v_o.

7. PIPE MODEL

A single region heat storage model was used with forward averaging of the fuel temperature to improve stability. The finite difference equation is

$$\frac{\lambda(T' - T)}{\delta t} = q - h_c(T' - T_c) \qquad \ldots(4)$$

where $$h_c = \frac{h_F h_s}{h_F + h_s} \quad ;$$

then $$a\phi = p h_c(T' - T_c) \quad .$$

The pipe surface temperature needed to estimate h_s for the next time step is obtained by assuming the heat flux from pipe to pipe surface is equal to that from pipe surface to coolant:

$$h_F(T - T_s) = h_s(T_s - T_c) \quad .$$

8. HEAT TRANSFER

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 similate a constant temperature heat sink (*e.g.* heat exchanger) by giving the pipe a very large heat capacity. Akers *et al.* (1959) gives a Reynolds number of 50 000 for the boundary between their two condensing heat transfer correlations. However, the correlations actually intersect at 76 228 and this value is used here. Also Akers correlations only cover the two-phase region. McAdams' (p.351 1954) recommendation that heat flux is almost independent of superheating of the vapour, 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 it is, 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.

$$\text{THT} = \ell + m + n$$

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.

9. BOUNDARY CONDITIONS

Three boundary conditions are needed for solution of the 3J-3 difference equations containing the 3J unknowns, W_i, P_i, H_i, i = 1 to J:

- inlet enthalpy;
- inlet flow or inlet pressure; and
- pressure or a choked flow model $W_J = W_J(P_J, H_J)$ at the outlet.

These boundary conditions are given in the input data as a function of time.

9.1 Moody Model

The choked or critical mass velocity is contained in tables (Redfield *et al.* 1967) as a function of stagnation pressure and enthalpy. Pressure at the last node is taken as stagnation pressure, and stagnation enthalpy is given by

$$H_O = \frac{E_J + a_J K_J}{W_J} \quad .$$

Mass flow at node J is then the product of choked mass velocity and break-area given in the input data.

9.2 Rodflow Model

This method, taken from Elliott (1968), uses a function fit to Moody results to give choked mass velocity at the end of a pipe from a large reservoir, as a function of stagnation pressure, stagnation enthalpy and fL/D of the pipe. An fL/D of zero gives results close to those obtained using the Moody table of 9.1 above. The relation is

$$G_C = I \left(\frac{P_J}{H_O - 300} \right)^Y$$

where I and Y are obtained from Table 4 and the units of G_C, H_O and P_J are lb ft^{-2} s^{-1}, Btu lb^{-1} and psi, respectively. The stagnation quantities are obtained as for the Moody model.

9.3 Fauske Model

Discharge is assumed to occur through a pipe of diameter and length specified in the input data. Conditions at the end of the pipe are determined from conditions at node J by assuming the following:

- steady state;
- adiabatic flow;
- thermodynamic equilibrium between phases;
- Jones' slip correlation;
- annular friction with zero roughness (Beattie 1973); and
- choked flow as described below at the pipe exit.

These assumptions have been found to give reasonable agreement with Fauske's measured pressure profiles (Turner & Trimble 1974).

From conditions at the throat, choked flow is determined as follows. In the quality range 0.0025 to 0.99 the Fauske model, as specified by Hsu (1972), is used. In the single phase regions, flow at sonic speed is assumed. As problems in which a transfer between the single and two-phase region occurs can only be handled if choked flow is a continuous function of its parameters (here quality and pressure), the following joining functions are used:

$$0 < x < 0.0025, \quad G_C = G_F^{\,400x} \, G_L^{\,(1-400x)}$$

where G_F = Fauske choked mass velocity for quality x, and G_L = liquid choked mass velocity for $x = 0$ at the same pressure;

$$0.99 < x < 1, \quad G_c = 100\ [(1-x)G_F + (x-0.99)G_s]$$

where G_s = steam choked mass velocity for $x = 1$ at the same pressure. Liquid and steam mass velocities are both calculated from the usual single phase speed of sound formulae

$$\left(\frac{\rho}{G}\right)^2 = \left(\frac{\partial\rho}{\partial P}\right)_{\text{entropy}} = R_p + \frac{R_H}{\rho} \quad .$$

10. SOLUTION OF FINITE DIFFERENCE EQUATIONS

The fuel temperature T' at the end of the time step is first eliminated from the finite difference conservation of energy equation (Section 3) using the pipe model equation (Section 7). The resulting three finite difference equations are linear in the values of W, P and H at the end of the time step. These equations may be written

$$A_jX'_j + B_jX'_{j+1} = C_j \ , \quad j = 1,2,\dots,J-1 \qquad \dots (5)$$

where the three-component vector $X'_j = \begin{pmatrix} W'_j \\ P'_j \\ H'_j \end{pmatrix}$,

A and B are 3 x 3 matrices and C is a three-component vector. A, B and C are not functions of W'_j, P'_j or H'_j. The three boundary condition equations involving components of X'_1 and X'_J, and the (J-1) matrix equations are solved by an elimination method as follows.

Define matrices D and vectors V such that

$$X'_j + D_{j-1}\ X'_1 = V_{j-1} \ , \quad j = 2,3,\dots,J \quad . \qquad \dots (6)$$

Eliminating X'_j from Equations 5 and 6 we get

$$X'_{j+1} - B_j^{-1}A_jD_{j-1}X'_1 = B_j^{-1}(C_j - A_jV_{j-1}) \quad .$$

Therefore

$$D_j = -B_j^{-1}A_jD_{j-1} \qquad \dots (7)$$

and $$V_j = B_j^{-1}(C_j - A_jV_{j-1}) \quad \text{for} \quad j = 2,3,\dots,J-1 \quad .$$

Also from Equations 5 and 6

$$D_1 = B_1^{-1}A_1$$

and $$V_1 = B_1^{-1}C_1 \quad . \qquad \ldots (8)$$

Using Equations 7 and 8, D_{J-1} and V_{J-1} can be found. Equation 6 with j = J and the three boundary conditions are solved for X'_1 and X'_J. Then Equation 6 is used to find all X'_j. 2J matrix multiplications and (J-1) inversions of 3 x 3 matrices are the main computations required. The quantity

$$R_{off} = \mathrm{MAX}\left|\frac{i^{th} \text{ component of } (A_jX'_j + B_jX'_{j+1} - C_j)}{i^{th} \text{ component of } C_j}\right|$$

for all i j such that the denominator is non-zero, is a measure of accuracy of the solution of the difference equations. A message (Section 13.2) is printed if it exceeds 10^{-7}.

This solution procedure assumes that the determinate of B_j is non-zero. In fact, if this determinate is treated as a function of the time step, it has 3 zeros. These zeros have been evaluated for limited situations and are approximated by

$$\frac{\delta Z}{2\delta t} = \frac{G}{\rho} \ , \ -\frac{G}{\rho} \pm c$$

where c is the thermodynamic equilibrium speed of sound. The only case where the presence of these zeros affected calculation was when a number of segments of equal length contained fluid in nearly the same state, so that the zeros for each B-determinate almost coincided. In these cases, for some time steps close to one of the zeros, the solution procedure failed and high values of R_{off} resulted. However, changing the finite difference mesh to segments of unequal length removed this difficulty.

11. INPUT DATA

Input data for a sample problem are shown in Appendix A. Each problem requires a title card, a control array and a number of tables.

11.1 Title Card - 1 card

Any 80 characters.

11.2 Control Array - 5 cards

Six numbers per card in format 6D12.3, containing:

CC(1)	Not used.
CC(2)	Initial pressure in psia at node CC(8). This is used only if an initial steady state calculation is specified, *i.e.* CC(8) >0.

CC(3)	Initial value of the time step(s). This time step is only used if it satisfies the time step controls CC(13) to CC(16).
CC(4)	Inlet boundary condition indicator: if CC(4)=0 then inlet flow is a boundary condition; if CC(4)=1 then inlet pressure is a boundary condition. All boundary conditions are given in the boundary condition table (Section 11.3).
CC(5)	Finish time(s).
CC(6)	Number of space nodes J, $2 < J < 50$.
CC(7)	Relative roughness of channel walls ε/D_e.
CC(8)	Initial condition indicator: . <0 if conditions at each space node stored in the computer from a case immediately before are used. (Such a case must not have fewer nodes than the present one.); . =0 if initial conditions at each space node are read in from the restart table (Section 11.5). (Cards for a restart are punched out on completion of every case.); or . >0 if initial steady state conditions are calculated. Four input data specify this steady state: mass velocity for time zero in the boundary condition table; pressure P and thermodynamic quality x at a specified node given as CC(2) and CC(10) respectively; CC(8) is the number of the specified node.
CC(9)	Not used.
CC(10)	Initial thermodynamic quality x at node CC(8). This is only if initial steady state calculation is specified, *i.e.* CC(8) >0.
CC(11)	Number of time entries one to a card in the boundary condition table; $\leqslant 24$.
CC(12)	Output indicator: 0, if the full printout consists of only the first row of quantities at each node shown in Appendix B; -2, if all quantities used in evaluating the difference equation coefficients are included in each full printout as shown in Appendix B. (CC(20) specifies how often a full printout occurs.)
CC(13) to CC(16)	Time step controls. Values of the absolute fractional changes in pressure P and static enthalpy H are calculated for each node. If B is the largest of these, then for B<CC(13) the

	time step is multiplied by CC(14); alternatively if B>CC(15) the time step is multiplied by CC(16) and repeated. Messages indicate changes in time step. Values of 0.01, 2.0, 0.05, 0.5 usually give reasonable accuracy.
CC(17)	Not used.
CC(18)	Maximum number of time steps for this case.
CC(19)	Not used.
CC(20)	At the first, the last and every CC(20)th time step the full printout as specified by CC(13) is produced. At other time steps the output specified by CC(21) and the output table (Section 11.6) is given.
CC(21)	The number of quantities in addition to time, to be printed at every time step. Any quantity stored in the main common area DIM (Table 5) may be so printed. The quantities are specified in the output table (Section 11.6). Any function of DIM quantities and desired input data can be specified in a special output routine, SOUT, and stored in the spare AZ array in DIM. The location of input data in common area DATA is given in Table 7. SOUT is called by the OUTPUT routine at every time step.
CC(22)	Choked flow indicators. If CC(23) >0 the boundary condition at the channel outlet is one of three choked flow models described in Section 9: . ≥ 0, Rodflow (CC(22) = fL/D ≤ 20); . -1, Moody; or . -2, Fauske.
CC(23)	Choked flow indicator: >0 if the boundary condition at the channel outlet is a choked flow relation with a break area of CC(23) ft^2.
CC(24)	Break opening time(s). The break area is assumed to increase linearly from 0 to CC(23) ft^2 over CC(24) seconds and then remain constant.
CC(25)	Not used.
CC(26)	Hydraulic diameter of the discharge pipe (ft). Only used if the Fauske choked flow model is specified, *i.e.* CC(22) = -2.
CC(27)	Length of the discharge pipe (ft). Only used if the Fauske choked flow model is specified, *i.e.* CC(22) = -2.

CC(28) Minimum value of the time step. A message is printed if this limit is applied.

CC(29) Slip indicator: 0 if no slip, 1 if Jones' slip correlation. The slip models are described in Section 5.

11.3 Boundary Condition Table

CC(11) cards in format 6D12.3. On each card (enter zero if not required):

(a) time(s);

(b) inlet mass velocity G (lb s^{-1} ft^{-2}) (only required if CC(4)=0 or CC(8)>0);

(c) change in inlet pressure from the initial value (psia) (only required if CC(4)=1);

(d) change in inlet enthalpy from the initial value (Btu lb^{-1});

(e) change in outlet pressure from the initial value (psia) (only required if CC(23) $\leqslant 0$); and

(f) total power (MW).

11.4 Geometry Table

Two cards per node in format 6D12.3. For each node:

(a) area a (ft^2);

(b) length to the next node δZ (ft);

(c) increase in height to the next node δy (ft);

(d) equivalent diameter D_e (ft), used in the friction and heat transfer calculation;

(e) power into the pipe per unit heated wetted surface area q - in any units since within the code these numbers are renormalised to give the total power of the boundary condition table;

(f) orifice coefficient K_o for pressure losses in fittings, bends or orifices between this and the next node. (Note that the effect of accelerations due to area changes specified in (a) above must not be included here. See Section 3.);

(g) heat capacity of fuel per unit heated wetted surface λ (Btu ft^{-2} F^{-1}). (If 0 then no pipe model calculation is needed and the power if any, is put directly into the coolant.)

(h) heated wetted perimeter p (ft);

(i) pipe surface to pipe centre heat transfer coefficient h_F (Btu s^{-1} ft^{-2} F^{-1}) - see Section 7. (Not used if λ = 0.);

(j) friction model indicator S_T: 0 if the homogeneous model, 1 if Martinelli-Nelson.

Note that entries for δZ, δy and K_o for the last node are not used as there is no 'next node'.

11.5 Restart Table

Contains 2*CC(6)+1 cards in format 3D24.10.

The first card is

time(s), power (MW);

then two cards per node containing

flow (lb s^{-1}),

pressure (psia)

enthalpy (Btu lb^{-1}), and

pipe temperature (F) at the node.

11.6 Output Table - format 6(A8,I4)

The values of quantities specified in this table and the time are printed at every time step - the first 9 on FORTRAN Unit 10, the next 9 on Unit 11, the next 9 on Unit 12, *etc*. Note that the required FORTRAN units must be specified by control cards, *e.g.* the sample problem in Appendix A. The quantities are also written on Unit 9 in unformatted records suitable for input to the PLOT program. The first case is put on the first file (FT09F001), and the second on the next (FT09F002), *etc*.

Output quantities are specified by their position in the common area DIM (Table 5). For each quantity there must be an 8-character heading to appear in the output and an integer giving the position of the quantity in DIM. Six quantities are specified per card.

12. COMPUTING TIME

The computing time on an IBM360/50 for problems not involving a choked flow model is approximately

$$(2.5 + N/10)J \text{ seconds}$$

where N is the number of time steps. Choked flow problems may take up to 50 per cent more time. The sample problem in the appendices took 75 s for a 12 s transient using 14 nodes.

A full printout of the last time step is always given since the remaining time before a system abend is monitored and no more time steps are computed when there is insufficient time.

13. OUTPUT

Output from the sample problem is shown in Appendix B. A listing of the control array appears first followed by a table giving the channel geometry, the same as in the geometry table of input data, except that power distribution data are normalised to Btu ft^{-2} s^{-1} per MW total power. The output table is given unchanged. The boundary condition table follows, giving values of actual boundary conditions, rather than changes from the initial values as was specified in most of the input data boundary condition table. The remainder of the output consists of quantities specified in the output table (Section 11.6) at every time step, and a full printout when specified. Some columns in this full printout are headed by symbols which are explained in Table 5. If CC(12) = 0 these columns are not printed.

13.1 Error Messages

The code user specifies the finite difference mesh, *i.e.* the geometry and time step size criteria to be used in the calculation. If this mesh is too coarse the results are inaccurate. The effect of changing the mesh should be evaluated. If the mesh is very coarse the finite difference scheme breaks down and extreme pressures or enthalpies may be calculated. This is the most common cause of code failure. Error messages are:

(a) TIME STEP LIMIT Although the maximum fractional change in pressure and enthalpy is greater than CC(13), the time step reduction CC(14), is not made because of the minimum time step restriction, CC(28). The calculation continues. The effect of this restriction can be evaluated by running cases with different values of the restriction CC(28).

(b) **WARNING-ROFF d R_{off} is a measure of the error in the solution of the difference equations (Section 10). This message appears if the value of R_{off} exceeds 10^{-7}; d is its actual value. Calculation continues. If d is of order 1 the solution is not acceptable. Changing the mesh to avoid the singularities discussed in Section 10 has always removed this difficulty.

(c) RANGE OF TABLE TOO SMALL The time interval covered by the boundary condition table is insufficient to perform the calculation specified in the input data. The calculation stops.

(d) NODE i ONLY CONVERGED TO x In the steady state calculation pressure and enthalpy at each node are obtained by a convergence procedure. At node i, x is the fractional difference between the pressures or enthalpies from the last two iterations. If $|x|>10^{-14}$ the message appears and calculation continues with the unconverged value.

(e) LEAKAGE FLOW NOT CONVERGED x y Application of the choked flow correlation involves an iteration procedure. If the Fauske model is being used then x is the sum of the squares of the fractional errors in stagnation enthalpy and pressure. The message appears if $x > 10^{-4}$, although convergence is generally much better than this. For other critical flow nodes x should be small compared to the critical flow y. Then the message appears if $|\frac{x}{y}| > 10^{-5}$. Calculation continues.

(f) FUEL TEMPERATURE AT NODE i FAILED TO CONVERGE d, T, h THT In the steady state calculation fuel surface temperature is calculated by an iteration procedure. If this fails at node i this message is printed with values from the last iteration: d is the difference in fuel temperature between the last two iterations, T is the fuel surface temperature, h is the fuel surface to coolant heat transfer coefficient and THT is the heat transfer indicator (Table 3).

(g) FRICTION FACTOR AT NODE i NOT CONVERGED x y The Colebrook equation is solved by an iteration procedure. If the procedure fails at node i the last two values of $f^{-0.5}$ are printed. Calculation continues.

(h) CRITICAL FLOW FAILED x y For meaningful pressure P_J as calculated from the finite difference equations, W_J must be between the limits x, y. No such choked flowrate was found. Calculation stops.

(i) **H x OUT OF RANGE - EXTRAPOLATING An enthalpy of x Btu lb^{-1}, which was outside the range of the table, was passed to the equation of state routine. The tables were extrapolated and calculation continued.

(j) **P x OUT OF RANGE - EXTRAPOLATING As for i, but with pressure (psi).

14. PLOTTING

Any quantity stored in the main common area DIM (Table 5) may be plotted against time. One or more quantities may be plotted per graph in combination with points or curves from input cards. Calculated quantities to be plotted must be specified in the output table (Section 11.6). Appendix A contains an example of input data to the PLOT routine. Input data are as follows:

(a) First set of cards (6I12)

NC	number of quantities to be plotted on this plot with scales and axes as specified below. Must be >0.
KQ(I),I=1,NC	Positions in the output table (Section 11.6) of the quantities to be plotted.

(b) Next card (2F12.3,I12,F12.3,I12,F12.3)

YMIN	minimum value on y axis. This is compared with the lowest value of the quantity to be plotted and the lower used.
YMAX	maximum value on y axis. This is compared with the highest value of the quantity to be plotted and the higher used.
NE	number of curves to be plotted from cards on this plot with the scales and axes as specified.

XMAX	the maximum value on the x or time axis is the larger of XMAX and the time at the end of the calculation.
NU	if positive the quantities are plotted on a new plot; if negative they are plotted on the most recent plot, however the new x and y scales are not drawn. $|\mathrm{NU}|$ is the number of the FORTRAN Unit containing the necessary OWEN-1 output (Section 11.6).
CF	conversion factor. All y values including those from cards are multiplied by CF before plotting. YMAX and YMIN are not changed.

(c) Next card (2F12.2)

XS	>0, for log scale on x axis, <0 for a linear scale. $|\mathrm{XS}|$ is the length of the x axis in inches.
YS	same as XS but for the y axis.

(d) Input data curves (I12,/(6F12.3))

Only required if NE >0.

One set of cards for each of the NE input data curves, containing

NP	>0, if lines joining the points are drawn; <0 if only points are plotted.

Y(J),X(J),J=1,NP coordinates of points to be plotted.

15. ACKNOWLEDGEMENTS

The author is grateful to Mr. A.G. Chapman for information on dryout limits and condensing heat transfer; to Mr. D.R.H. Beattie for advice on post dryout heat transfer and two-phase friction; to Mr. V. Ilic for helpful discussions of choked flow; and to Mr. G.D. Trimble for improving the solution of the difference equations and coding the equation of state routine.

16. REFERENCES

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

Beattie, D.R.H. (1972) - AAEC private communication.

Beattie, D.R.H. (1973) - Nucl. Eng. Des. 25 : 395.

Biasi, L., Clerici, G.C., Gerribba, S., Sala, R., Tozzi, A. (1967) - Energia Nucleare, 14 (9) 530.

Carter, J.C., Fischer, G.J., Heames, T.J., MacFarlane, D.R., *et al.* (1970) - SASIA. ANL7607.

Carver, M.B. (1967) - ASME Paper 67-HT-66 presented at the ASME-AICHE National Heat Transfer Conference, Seattle, August.

Collier, J.G. (1964) - AERE Report RS/L207.

Currin, H.B., Hunin, C.M., Rivlin, L. & Tong, L.S. (1961) - CVNA-77.

Dittus, F.W. & Boelter, L.N.K. (1930) - Univ. of Calif. Pub. Eng., 2 : 443.

Elliott, J.N. (1968) - RODFLOW. A Program for Studying Transients in a Power Reactor Coolant Circuit. AECL Power Projects. TDAI-11.

Fauske, H.K. (1962) - ANL-6633.

Hassid A. & Rychlicki, R. (1971) - Energia Nucleare 18 (6) 333.

Heineman, J.B. (1960) - ANL-6213.

Hsu, Y.Y. (1972) - NASA TN D-6814.

Jones, A.B. & Dight, D.G. (1962) - KAPL-2208.

McAdams, W.H. (1954) - Heat Transmission. 3rd Ed. McGraw-Hill, N.Y.

Martinelli, R.C. & Nelson, D.B. (1948) - Trans. ASME (August).

Meyer, C.A. *et al.* (1967) - ASME Steam Tables. ASME, N.Y.

Meyer, J.E. (1960) - WAPD-BT-20.

Meyer, J.E. (1961) - Nucl. Sci. Eng. 10 : 269.

Moore, K.V. (1971) - ANCR-1026.

Moxon, D. (1968) - AEEW-R448.

Nikuradse, J. (1933) - VDI Forschungshaft. 361.

Porsching, T.A., Murphy, J.H., Redfield, J.A., *et al.* (1969) - FLASH-4. WAPD-TM-840.

Porsching, T.A., Murphy, J.H. & Redfield, J.A. (1971) - Nucl. Sci. Eng. 43 : 218.

Premoli, A. (1969) - Energia Nucleare, 16 (10) 625.

Redfield, J.A., Murphy, J.H. & Davis, V.C. (1967) - FLASH-2. WAPD-TM-666.

Rettig, W.H., Jayne, G.A., Moore, K.V., Slater, C.E. & Uptmoor, M.L. (1970) - RELAP 3. IN-1321.

Richtmyer, R.D. & Morton, K.W. (1967) - Difference Methods for Initial-value Problems. 2nd Ed. Interscience Publishers, N.Y.

Sha, W.T. & Hughes, T.H. (1970) - VENUS. ANL-7701.

Shrock, V.E. & Grossman, L.M. (1959) - TID-14632.

Tong, L.S. (1965) - Boiling Heat Transfer and Two-phase Flow. Wiley, N.Y.

Turner, J. & Wendroff, B. (1964) - LA-3007.

Turner, W.J. (1969) - CREST Specialist Meeting, Frankfurt.

Turner, W.J. (1972) - Energia Nucleare, 19 (5) 317.

Turner, W.J. & Trimble, G.T. (1974) - Fifth Australasian Conference of Hydraulics and Fluid Mechanics, Christchurch, NZ, 9-13 December.

Wright, R.M. (1961) - USAEC Report UCRL-9744.

TABLE 1

ORIFICE FRICTION SPECIFIC VOLUME v_o

Quality	$S_T = 0$	$S_T = 1$
$x \leqslant 0$	$\frac{1}{\rho}$	
$0 < x \leqslant 0.8$		$\frac{\Phi}{\rho_L}$
$0.8 < x < 0.9$		$10\left[(0.9-x)\Phi/\rho_L + (x-0.8)\left(\frac{1-x}{\rho_L}+\frac{x}{\rho_V}\right)\right]$
$0.9 \leqslant x < 1$	$\frac{1-x}{\rho_L} + \frac{x}{\rho_V}$	
$x \geqslant 1$	$\frac{1}{\rho}$	

TABLE 2

PIPE FRICTION SPECIFIC VOLUME v_p

Quality	$S_T = 0$	$S_T = 1$
$x \leqslant 0$	$f(\mu_L)/\rho$	
$0 < x \leqslant 0.8$		$\Phi f(\mu_L)/\rho_L$
$0.8 < x < 0.9$		$10 \left\{ \begin{array}{l} (0.9-x)\Phi f(\mu_L)/\rho_L \\ + (x-0.8) \left(\frac{1-x}{\rho_L} + \frac{x}{\rho_v}\right) f\left[\frac{\mu_L \mu_v}{(1-x)\mu_v + x\mu_L}\right] \end{array} \right\}$
$0.9 \leqslant x < 1$	$\left(\frac{1-x}{\rho_L} + \frac{x}{\rho_v}\right) f\left[\frac{\mu_L \mu_v}{(1-x)\mu_v + x\mu_L}\right]$	
$x \geqslant 1$	$f(\mu_v)/\rho$	

TABLE 3

CORRELATIONS FOR SURFACE HEAT TRANSFER COEFFICIENT

Heat Transfer Indicator THT = $\ell + m + n$

Surface Temperature T_s	Quality x		
	$x \leqslant 0$	$1 > x > 0$	$x \geqslant 1$
$T_s < T_{sat}$	<u>Liquid</u> Dittus, Boelter (1930) $\ell = 1,\ m = 0,\ n = 0$	<u>Condensing</u> Akers (1959) $R_e \leqslant 76228$ $\ell = 3$ $m = 0,\ n = 0$ $R_e > 76228$ $\ell = 4$	
$T_s \geqslant T_{sat}$	<u>Boiling</u> <u>Non-dryout</u> Largest of - subcooled liquid Dittus, Boelter (1930) $\ell = 5$ - nucleate boiling Tong p.118 (1965) $\ell = 3$ - forced convection boiling Shrock & Grossman (1959) with coefficient from Wright (1961) $\ell = 2$ <u>Dryout</u> $x \leqslant 0$, Bernath (Tong p.156, 1965) $m = 10$ $x > \rho_V/(\rho_V + \rho_L)$, Biasi (1967) low quality $m = 30$ high quality $m = 40$ Other x, linear interpolation on x between Bernath & Biasi low quality $m = 20$ <u>Post Dryout</u> - Dryout limit not exceeded $n = 0$ $x \leqslant 0.05$, Tong p.129 (1965) 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) $n = 300$		<u>Superheat</u> Heineman (1960) $\ell = 2$ $m = 0$ $n = 0$

TABLE 4

RODFLOW CHOKED FLOW MODEL

(Section 9.2)

fL/D	I	Y
0	1850	1.073
1	1500	1.088
2	1140	1.175
3	920	1.227
4	788	1.261
5	674	1.290
10	442	1.373
20	306	1.359

TABLE 5

REAL*8 ARRAYS IN COMMON AREA DIM

Dimensioned Array	Location	Definition - i, j and k are the first, second and third subscripts respectively
A(3,3,50)	1	Coefficients in the difference equations
B(3,3,50)	451	$\sum_{j=1}^{3} [A_{ijk}X_{jk} + B_{ijk}X_{j(k+1)}] = C_{ik}$
C(3,50)	901	k = 1, 2 and 3 for the mass, momentum and energy equations respectively
X(3,50)	1051	For i = 1,2,3 this is W_j, P_j, H_j in lb s^{-1}, psia, Btu lb^{-1} respectively at the end of the time step
U(50)	1201	Internal energy Btu lb^{-1}
R(50)	1251	Density ρ lb ft^{-3}
E(50)	1301	Product of flow enthalpy and flow rate (Section 2) E Btu s^{-1}
DM(3,50)	1351	$\partial M_j/\partial X_{ij}$ (Section 3)
RLP(50)	1501	$d\rho_L/dP$ lb ft^{-3} psi^{-1}
XQ(50)	1551	Static quality calculated from static enthalpy
T(50)	1601	Coolant temperature T_c (°F)
TS(50)	1651	Coolant saturation temperature (°F)
RH(50)	1701	R_H lb^2 ft^{-3} Btu^{-1}
RP(50)	1751	R_P lb ft^{-3} psi^{-1}
F(50)	1801	Frictional force/unit volume of coolant F (poundal ft^{-3})
D(3,3,50)	1851	Equation 6 of Section 10 is
W(3,50)	2301	$X_{ik} + \sum_{j=1}^{3} D_{ijk}X_{ij} = W_{ik}$
G(50)	2451	Mass velocity G lb ft^{-2} s^{-1}
XS(3,50)	2501	X at the start of a time step
XC(3,50)	2651	X at the start of a time step
RS(50)	2801	Not used
AL(50)	2851	Void fraction
HSL(50)	2901	Saturated liquid enthalpy H_L Btu lb^{-1}
HSV(50)	2951	Saturated vapour enthalpy H_V Btu lb^{-1}
RSL(50)	3001	Saturated liquid density ρ_L lb ft^{-3}
RSV(50)	3051	Saturated vapour density ρ_V lb ft^{-3}
XF(50)	3101	Quality x
RM(50)	3151	M lb ft^3 s^{-2}
RVP(50)	3201	$d\rho_V/dP$ lb ft^{-3} psi^{-1}
GS(50)	3251	$2G\|G\|v_o$ (Section 6)
RITP(50)	3301	Momentum equation interpolation factor S (Section 3)

(continued)

TABLE 5 (continued)

Dimensioned Array	Location	Definition - i, j and k are the first, second and third subscripts respectively
HVP(50)	3351	dH_V/dP, Btu lb^{-1} psi^{-1}
HLP(50)	3401	dH_L/dP, Btu lb^{-1} psi^{-1}
DE(3,50)	3451	$\partial E_j/\partial X_{ij}$
EITP(50)	3601	Energy equation interpolation factor w (Section 3)
TPR1	3651	Power at the start of the time step, MW
ROFF	3652	Fractional error in solution of difference equations (Section 10)
AZ(38)	3653	Not used, available to code user for output from SOUT
XO	3691	Quality at exit of discharge pipe if Fauske choked flow model used
HO	3692	Stagnation enthalpy in discharge pipe, Btu lb^{-1}
P2	3693	Pressure at exit of discharge pipe if Fauske choked flow model used, psi
H2	3694	Static enthalpy at exit of discharge pipe if Fauske choked flow model used, Btu lb^{-1}
DET(50)	3701	Determinate of matrix B for segment i
BI(3,3,50)	3750	Inverse of B for node k
EX(3,50)	4200	Change in X_{ij} over the time step
Q(3,50)	4350	Working area for solution of the difference equations
TF(50)	4501	Pipe temperature T_F at the end of the time step (°F)
TFC(50)	4551	Pipe temperature T_F at the start of the time step (°F)
HT(50)	4601	Heat transfer coefficient h_C (Section 7) Btu ft^{-2} s^{-1} $°F^{-1}$
THT(50)	4651	Heat transfer indicator (Table 3)
QC(50)	4701	Power to coolant per unit length along channel, Btu ft^{-1}
PC	4751	Total power to coolant, MW
TPR2	4752	Power at the end of the time step, MW
TFS(50)	4753	Fuel surface temperature, T_S °F
EK(50)	4803	Kinetic energy flux lb s^{-3}

TABLE 6

EQUATION OF STATE MESH

Pressures (MPa)

0.090 to 0.200 at intervals of 0.005

0.20 to 1.00 at intervals of 0.01

1.00 to 1.50 at intervals of 0.02

1.50 to 4.00 at intervals of 0.05

4.0 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:	Vapour:
T_{sat}	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

TABLE 7

REAL*8 ARRAYS IN COMMON AREA DATA

Dimensioned Array	Location	Definition	Units
CC(50)	1	Control array	
TIME	76	t	s
		Boundary conditions	
TI(24)	127	Time	s
GI1(24)	151	Inlet mass velocity	lb $ft^{-1} s^{-2}$
PI1(24)	175	Inlet pressure	psia
HI1(24)	199	Inlet enthalpy	Btu lb^{-1}
PIN(24)	223	Outlet pressure	psia
POW(24)	247	Power	MW
TITLE(20)	271	Title card in A format	
		Geometry	
AR(50)	293	Area at node i	ft^2
SL(50)	343	Segment length L node i to i+1	ft
SH(50)	393	Segment height y node i to i+1	ft
SD(50)	443	Hydraulic diameter D_e	ft
PD(50)	493	Power distribution	$\frac{\text{Btu ft}^{-2}\ \text{s}^{-1}}{\text{MW total power}}$
CORIF(50)	549	Orifice coefficient K_o for segment	
CP(50)	699	Pipe heat capacity λ	Btu ft^{-2} $°F^{-1}$
HP(50)	749	Heated perimeter p	ft
HF(50)	799	Heat transfer coefficient pipe to pipe surface h_F	Btu ft^{-2} s^{-1} $°F^{-1}$
ST(50)	849	Friction model indicator S_T	

APPENDIX A

INPUT DATA FOR SAMPLE PROBLEM

In this problem the flow path from inlet to outlet is as follows:

(a) a constant displacement pump,

(b) a hydraulic damper simulated by a section of large diameter pipe of correct volume,

(c) a preheater,

(d) feeder,

(e) a throttling valve,

(f) an inlet valve,

(g) heated test section,

(h) outlet valve,

(i) riser,

(j) discharge pipe simulated by the Moody choked flow model.

A graph is required of the fraction of the initial mass still in the heated test section (calculated in SOUT and stored in AZ(2)). Some experimental results are read in and also plotted on the graph.

```
//WJT1P    JOB (P1A03280,M1),W.J.TURNER,
//             MSGLEVEL=(2,0),
//             CLASS=B,
//             TIME=2
//RR     EXEC  PROGEXEC,
//             REGION.GO=220K,
//             LIB='PHYS.WJTOWEN1'
//GO.FT02F001  DD  DUMMY,DISP=OLD
//GO.FT04F001 DD DSN=GDT.BTABLE,DISP=SHR
//GO.FT09F001 DD DSN=PHYS.WJTP15,
//      DISP=(,CATLG),
//      SPACE=(TRK,(10,20),RLSE),
//      DCB=(RECFM=VBS,BLKSIZE=1092),UNIT=SYSDA
//GO.FT10F001 DD SYSOUT=A,DCB=(RECFM=FBA,LRECL=133,BLKSIZE=1330)
//GO.SYSIN  DD  *
PREMOLI (1969)  BURST AT RISER OUTLET   59 MW FIXED INLET FLOW
                711.      .01                       8.        14.
   .0001      7.                    -.03             2.        -2.
   .04        2.           .2        .5                        9999999.
               32.         14.       -1.        .0008454        .04
                                     .001        1.
  0.           .11037                                         .189
   1000.       .11037                                         .189
   2.6        3.3         0.         1.
                           .1        1.
   .0007      540.        6.         .03        .108269
  .332         .094        1.82     1.
  .0007       1.           1.        .03        .108269
  .332         .094        1.82     1.
  .0008454    35.67       8.623       .0328
  .2319       .10307      2.71       1.
  .0008454     1.         .05         .0328                   64.21
  .2319       .10307      2.71       1.
  .0008454    3.27         .164       .0328                   2.2
  .2319       .10307      2.71       1.
  .0007        .12        .063      .0299
  .2211      .09379       2.85      1.
  .0007      2.64         2.64      .0299       2.
  .2211      .09379       2.85      1.
  .0007       5.28       5.28       .0299       2.
  .2211      .09379       2.85      1.
  .0007       5.28       5.28       .0299       2.
  .2211      .09379       2.85      1.
  .0007        .12        .064      .0299        2.
  .2211      .09379       2.85      1.
  .0007          21.478     1.345   .0299                     2.2
  .2211      .09379       2.85      1.
  .0008454    5.318       .291       .0328
  .2319       .10307      2.71
  .0008454                           .0328
  .2319       .10307      2.71
P4      2661P1      2652CHASS   3653R/R0    3654ROFF    3652PC      4751
P7      2670P12     2685P9      2676P14     2691W1      2651W4      2660
W7      2669W12     2684
/*
//WJT12P EXEC  RELEASE,COND=EVEN
//
//WJT12P   JOB (P1A03280,M1),W.J.TURNER,
//             MSGLEVEL=(2,0),
//             TYPRUN=HOLD,
```

```
//             CLASS=B,
//             TIME=2
//AE     EXEC  HUFFPROG,PRG=AEPLOT
//TT     EXEC  PROGEXEC,
//             MEM=PLOT,
//             REGION.GO=180K,
//             LIB='PHYS.WJTOWEN1'
//GO.FT09F001 DD DSN=PHYS.WJTP15,DISP=(OLD,DELETE)
//GO.SYSIN  DD  *
            1           4
   0.            1.                 1                       9   1.
   -8.        -5.
          -8 CISA EXPT 12
  0.          1.          .316        .793        .562        .75
   .798        .665     1.048         .566       1.377        .521
  1.746        .488     2.201         .462
           6           1           2           7           8           9
          10

                                                            9   1.
   -8.        -5.
/*
//
```

APPENDIX B

OUTPUT FROM SAMPLE PROBLEM

```
        PREMOLI (1969)  BURST AT RISER OUTLET   59 MW FIXED INLET FLOW

INPUT DATA ARRAY CC
           1  0.0                 2   711.0000            3  0.1000000D-01          4  0.0
           5   8.000000           6   14.0000             7  0.1000000D-03          8   7.000000
           9  0.0                10 -0.3000000D-01       11   2.000000            12  -2.000000
          13  0.4000000D-01      14   2.000000           15  0.2000000           16  0.5000000
          17  0.0                18   9999999.           19  0.0                 20   32.00000
          21   14.00000          22  -1.000000           23  0.8454000D-03       24  0.4000000D-01
          25  0.0                26  0.0                 27  0.0                 28  0.1000000D-02
          29   1.000000
```

```
PREMOLI (1969)  BURST AT RISER OUTLET   59 MW FIXED INLET FLOW                          28 FEB 74

        CHANNEL GEOMETRY AND POWER DISTRIBUTION

POSITION  AREA(FT2)    SEG LENGTH(FT)   HEIGHT(FT)  EQUIV DIAM (FT)  POWER DIST     ORIFICE COEF  TH CAP(BTU/FT2 DC)   PERIM(FT)
   1        2.6000         3.3000        0.0              1.0000       0.0            0.0             0.0             0.0
   2      7.000000D-04     540.00         6.0000       3.000000D-02     12.801         0.0             0.33200         9.400000D-02
   3      7.000000D-04     1.0000         1.0000       3.000000D-02     12.801         0.0             0.33200         9.400000D-02
   4      8.454000D-04     35.670         8.6230       3.280000D-02    0.0             0.0             0.23190         0.10307
   5      8.454000D-04     1.0000        5.000000D-02  3.280000D-02    0.0              64.210         0.23190         0.10307
   6      8.454000D-04     3.2700        0.16400       3.280000D-02    0.0              2.2000         0.23190         0.10307
   7      7.000000D-04     0.12000       6.300000D-02  2.990000D-02    0.0             0.0             0.22110         9.379000D-02
   8      7.000000D-04     2.6400         2.6400       2.990000D-02     236.47         0.0             0.22110         9.379000D-02
   9      7.000000D-04     5.2800         5.2800       2.990000D-02     236.47         0.0             0.22110         9.379000D-02
  10      7.000000D-04     5.2800         5.2800       2.990000D-02     236.47         0.0             0.22110         9.379000D-02
  11      7.000000D-04     0.12000       6.400000D-02  2.990000D-02     235.47         0.0             0.22110         9.379000D-02
  12      7.000000D-04     21.478         1.3450       2.990000D-02    0.0              2.2000         0.22110         9.379000D-02
  13      8.454000D-04     5.3180        0.29100       3.280000D-02    0.0             0.0             0.23190         0.10307
  14      8.454000D-04    0.0            0.0           3.280000D-02    0.0             0.0             0.23190         0.10307

POSITION  FUEL H. T.      SLIP
   1      1.000000D-01    1.0000
   2       1.8200         1.0000
   3       1.8200         1.0000
   4       2.7100         1.0000
   5       2.7100         1.0000
   6       2.7100         1.0000
   7       2.8500         1.0000
   8       2.8500         1.0000
   9       2.8500         1.0000
  10       2.8500         1.0000
  11       2.8500         1.0000
  12       2.8500         1.0000
  13       2.7100        0.0
  14       2.7100        0.0

    P4       2661    P1        2652    CMASS     3653    R/RO      3654    ROFF      3652    PC        4751    P7        2670
    P12      2685    P9        2676    P14       2691    W1        2651    W4        2660    W7        2669    W12       2684

        TIME(SEC)        IN FLOW LB/SEC-FTS  IN PRESSURE PSIA     IN ENTHALPY BTU/LB   OUT PRESSURE PSIA  TOTAL POWER MW
        0.0                 0.11037            898.01                  42.791              618.42             0.18900
        1000.0              0.11037            898.01                  42.791              618.42             0.18900
```

```
        PREMOLI (1969)  BURST AT RISER OUTLET   59 MW FIXED INLET FLOW                     28 FEB 74

TIME=   0.0          SECS          POWER(MW)=   0.189000       POWER TO COOLANT=   0.189000

NODE DENSITY      FLOW           FLOW          PRESSURE      STATIC ENTH    FUEL TEMP     VOID            TEMP          SAT TEMP      HEAT FLUX
       LB/FT3      QUALITY        LB/SEC         PSIA           BTU/LB         DEGF         FRACTION        DEGF          DEGF       BTU/SEC FT
 1    61.417     -0.72169        0.28696        898.01         42.791        71.247      -0.31688         71.247        531.69        0.0
 2    61.379     -0.71946        0.28696        897.39         44.098        76.939      -0.31588         72.529        531.61        0.22743
 3    49.745     -5.11854D-02    0.28696        786.83        472.06        490.01       -3.70961D-02    486.49        516.30        0.22743
 4    49.726     -5.05066D-02    0.28696        786.43        472.45        486.82       -3.66107D-02    486.82        516.24        8.12543D-15
 5    49.722     -4.84518D-02    0.28696        778.77        472.44        486.81       -3.50775D-02    486.81        515.12       -4.06268D-15
 6    49.698     -3.09353D-02    0.28696        714.43        472.44        486.85       -2.23825D-02    486.85        505.36        4.06279D-15
 7    49.697     -3.00000D-02    0.28696        711.00        472.44        486.86       -2.17196D-02    486.86        504.82        0.0
 8    49.654     -2.87492D-02    0.28696        710.75        473.32        543.73       -2.07978D-02    487.60        504.82        4.1918
 9    31.813      2.62735D-02    0.28696        708.80        505.59        543.43        0.35803        504.48        504.48        4.1918
10    15.924      0.13674        0.28696        701.65        539.30        536.50        0.69519        503.34        503.34        4.1918
11    11.133      0.24754        0.28696        690.32        566.38        530.48        0.79664        501.53        501.53        4.1918
12    11.093      0.24882        0.28696        690.03        566.65        501.48        0.79749        501.48        501.48       -9.07103D-14
13    10.267      0.26172        0.28696        624.86        554.93        490.59        0.81467        490.59        490.59        2.49176D-14
14    10.186      0.26302        0.28696        618.42        553.70        489.46        0.81634        489.46        489.46       -7.01180D-15

NODE   DE2             DE3           RM             DM1           DM2            DM3           RP             RH            EITP          RITP
 1   0.0              0.28696      1.34078D-03   9.34468D-03 -4.99222D-09   4.41151D-08   2.28678D-04 -2.02078D-03   0.50000       0.0
 2   0.0              0.28696      1.34162D-03   9.35048D-03 -5.01349D-09   4.71836D-08   2.29368D-04 -2.15866D-03   0.50000       0.54757
 3   0.0              0.28696      1.65540D-03   1.15374D-02 -1.69420D-08   1.55755D-06   5.09105D-04 -4.68041D-02   0.50000       0.53739
 4   0.0              0.28696      1.65603D-03   1.15418D-02 -1.69795D-08   1.56012D-06   5.09842D-04 -4.68456D-02   0.50000       0.0
 5   0.0              0.28696      1.65616D-03   1.15427D-02 -1.69907D-08   1.56081D-06   5.10101D-04 -4.68592D-02   0.50000        1.0000
 6   0.0              0.28696      1.65695D-03   1.15482D-02 -1.70554D-08   1.56546D-06   5.11556D-04 -4.69542D-02   0.50000        1.0000
 7   0.0              0.28696      1.65697D-03   1.15483D-02 -1.70571D-08   1.56563D-06   5.11594D-04 -4.69579D-02   0.50000       0.0
 8   0.0              0.28696      1.65840D-03   1.15584D-02 -1.71440D-08   1.57149D-06   5.13312D-04 -4.70522D-02   0.73816       0.62886
 9 -4.13870D-02       0.49778      2.60043D-03   1.81239D-02 -1.49679D-05   7.49964D-05   0.17857      -0.89500        0.41420       0.57748
10 -0.10670           0.73040      5.57771D-03   3.88742D-02 -2.38574D-05   9.70907D-05   5.54204D-02  -0.22626       0.24943       0.49697
11 -0.13237           0.77269      8.90631D-03   6.20731D-02 -3.57406D-05   1.23678D-04   3.19926D-02  -0.11218       0.0           0.45999
12 -0.13257           0.77253      8.95083D-03   6.23834D-02 -3.59032D-05   1.23995D-04   3.18319D-02  -0.11142       0.52689        1.0000
13 -0.15256           0.80802      1.00084D-02   6.97541D-02 -4.51137D-05   1.43594D-04   3.22994D-02  -0.10416       0.32697       0.41055
14 -0.15477           0.81170      1.01256D-02   7.05713D-02 -4.61954D-05   1.45801D-04   3.23559D-02  -0.10346       0.0           0.0

NODE     E             EK            F            THT           HT              GS           HSL           HSV           RSL           RSV
 1     12.279      1.78215D-07   3.99744D-05  1.75163D-79  1.00000D-01   3.96682D-04    526.38        1196.5        47.118        1.9915
 2     12.654       9143.4        903.32        1.0000       0.54865        5476.0         526.28        1196.5        47.123        1.9901
 3    135.46       13921.         953.35        1.0000       0.68675        6756.7         507.49        1199.7        48.027        1.7267
 4    135.58        7908.5        608.16        1.0000       0.69343        4634.2         507.42        1199.8        48.030        1.7257
 5    135.57        7909.8        608.21        1.0000       0.69343        4634.6         506.06        1200.0        48.095        1.7078
 6    135.57        7917.3        608.48        1.0000       0.69344        4636.8         494.32        1201.5        48.644        1.5585
 7    135.57       13947.         957.81        1.0000       0.79577        6763.1         493.68        1201.6        48.674        1.5507
 8    135.82       13971.         958.32       15.000        0.79616        6769.0         493.67        1201.6        48.674        1.5505
 9    146.89       34536.        2509.4        23.000         1.1474        17851.         493.27        1201.6        48.693        1.5456
10    169.02      1.78271D+05    6221.5       42.000         1.3478        44237.         491.91        1201.8        48.756        1.5292
11    191.14      5.12387D+05   10233.        42.000         1.5435        72698.         489.75        1202.0        48.855        1.5033
12    191.39      5.18698D+05   10283.         4.0000        1.3088        73060.         489.70        1202.1        48.858        1.5026
13    191.39      3.81447D+05    5529.0       42.000         1.4177        47954.         476.83        1203.3        49.443        1.3549
14    191.39      3.91360D+05    5606.8        4.0000        1.1968        48648.         475.51        1203.4        49.503        1.3404

   TIME           P4           P1           CMASS         R/R0          ROFF           PC            P7           P12           P9
0.0              786.427      898.011       97.9976       1.00000      0.0            0.189000      711.000      690.029       708.804
1.000000D-02     786.429      898.011       98.1572       1.00163      3.539017E-14   0.196862      711.004      696.613       708.864
2.000000D-02     786.501      898.011       98.5975       1.00612      1.236764E-13   0.218667      711.176      707.771       709.404
3.000000D-02     787.057      898.011       99.2049       1.01232      8.463429E-14   0.225237      712.359      715.242       711.372

TIME STEP MULTIPLIED BY   0.50000
3.5[illegible]  787.546      898.011       99.5177       1.01551      2.790835E-13   0.231907      713.932      717.032       713.060
```

```
4.000000D-02  786.588      898.010      99.8588      1.01899      4.127511E-14 0.241777      715.510      719.472      715.189
4.500000D-02  789.987      898.009      100.235      1.02283      5.986429E-13 0.252552      717.874      722.517      717.559
5.000000D-02  791.899      898.008      100.614      1.02670      3.082958E-10 0.261034      720.273      722.998      719.994

TIME STEP MULTIPLIED BY   2.0000
5.500000D-02  794.065      898.007      100.956      1.03019      1.734829E-11 0.264728      723.749      721.291      723.227
6.500000D-02  800.010      898.004      101.367      1.03438      1.350335E-12 0.273388      730.936      714.151      729.825
7.500000D-02  805.394      898.001      101.509      1.03583      6.928975E-13 0.279665      736.438      708.496      734.263

TIME STEP MULTIPLIED BY   2.0000
8.500000D-02  803.611      897.999      101.437      1.03510      9.361269E-12 0.278799      739.516      705.299      736.619
0.105000      803.842      898.000      100.929      1.02991      1.571643E-13 0.282553      740.382      703.333      736.934

TIME STEP MULTIPLIED BY   2.0000
0.125000      801.720      898.006      100.177      1.02224      4.315870E-14 0.270052      731.759      697.499      729.125
0.165000      787.054      898.019      97.8531      0.998526     1.015450E-13 0.271941      715.716      678.020      713.038
0.205000      774.565      898.032      95.2363      0.971823     9.405893E-14 0.275693      699.833      659.478      696.969
0.245000      766.000      898.040      92.5667      0.944581     1.698383E-13 0.274153      686.836      644.581      683.692
0.285000      757.116      898.044      90.0933      0.919343     2.072940E-13 0.273557      671.809      630.655      668.658
0.325000      753.640      898.040      87.9251      0.897217     3.334463E-13 0.265731      662.800      620.522      659.291

TIME STEP MULTIPLIED BY   2.0000
0.365000      746.496      898.031      86.1973      0.879586     1.499197E-13 0.251537      648.411      608.019      645.008
0.445000      742.400      897.975      83.5606      0.852690     3.938378E-13 0.241988      635.063      591.507      631.138
0.525000      732.740      897.883      82.5073      0.841932     2.924748E-11 0.242429      611.861      568.503      607.855

TIME STEP MULTIPLIED BY   2.0000
0.605000      734.925      897.743      81.1374      0.827953     1.501472E-10 0.220161      604.423      558.012      599.853
0.765000      729.732      897.313      80.5925      0.822393     3.701158E-13 0.216691      588.783      539.369      583.563
0.925000      735.044      896.726      79.8238      0.814549     1.526335E-12 0.206693      579.617      528.621      574.063
 1.08500      728.639      895.991      81.2725      0.829332     2.438474E-12 0.207487      568.940      518.498      563.301
 1.24500      733.127      895.128      79.6237      0.812507     6.525237E-12 0.201315      561.742      511.730      556.081
 1.40500      731.493      894.152      80.2029      0.818416     1.247116E-11 0.205401      553.110      503.995      547.581
 1.56500      735.044      893.065      78.2706      0.798699     1.034285E-11 0.201447      548.308      499.454      542.771
 1.72500      730.389      891.874      78.7562      0.803654     9.042400E-12 0.205330      541.728      493.461      536.283
 1.88500      733.921      890.581      77.2142      0.787920     7.329057E-12 0.202229      538.229      489.966      532.757
 2.04500      729.379      889.193      77.7031      0.792909     4.770293E-12 0.205715      533.130      485.188      527.719
```

```
        PREMOLI (1969)  BURST AT RISER OUTLET   59 MW FIXED INLET FLOW                            28 FEB 74

TIME=    2.20500     SECS           POWER(MW)=   0.189000          POWER TO COOLANT=   0.202855

NODE DENSITY        FLOW            FLOW          PRESSURE      STATIC ENTH    FUEL TEMP     VOID            TEMP          SAT TEMP     HEAT FLUX
       LB/FT3       QUALITY          LB/SEC        PSIA           BTU/LB        DEGF          FRACTION        DEGF          DEGF      BTU/SEC FT
  1   61.418      -0.71700        0.28696        887.71         42.791        71.281       -0.31432        71.286        530.33       0.0
  2   61.995      -0.74591        0.29604        887.04         23.154        64.187       -0.32689        52.063        530.24       0.54413
  3   48.730      -7.18061D-03    0.38645        732.71         492.67        501.92       -5.18900D-03    503.94        508.20      -4.64570D-02
  4   48.792      -8.93266D-03    0.38683        732.30         491.36        498.96       -6.44955D-03    502.84        508.13      -0.21162
  5   50.057      -4.38968D-02    0.39417        721.27         464.62        480.60       -3.13148D-02    480.07        506.43       2.85234D-02
  6   41.533       7.05577D-03    0.39471        544.66         463.48        479.46        0.17681        475.91        475.91       0.14089
  7   36.123       1.37400D-02    0.39705        530.74         463.48        475.52        0.28895        473.20        473.20       0.19967
  8   35.427       1.48214D-02    0.39713        530.58         463.92        512.92        0.30312        473.17        473.17        3.4698
  9   22.077       5.63234D-02    0.40430        525.30         477.50        508.96        0.57481        472.12        472.12        4.3027
 10   14.328       0.13206        0.41570        509.24         493.96        498.24        0.73248        468.90        468.90        4.2826
 11   10.572       0.21195        0.41604        483.43         506.06        490.29        0.80852        463.55        463.55        4.2833
 12   10.533       0.21297        0.41606        482.75         506.11        464.69        0.80931        463.40        463.40       9.35239D-02
 13   5.2603       0.31143        0.41768        190.38         412.21        378.93        0.91052        377.69        377.69       0.10255
 14   2.3894       0.35990        0.41764        99.218         353.39        375.32        0.94364        327.25        327.25       0.56482

NODE   DF2              DE3           RM             DM1          DM2            DM3          RP            RH            EITP          RITP
  1   0.0             0.28696       1.34976D-03   9.34455D-03 -4.99052D-09   4.41065D-08  2.29607D-04 -2.02044D-03   0.50000       0.57969
  2   0.0             0.29504       1.41367D-03   9.55054D-03 -4.97599D-09  -1.23827D-09  2.18215D-04  5.43027D-05   0.50000       0.61126
  3   0.0             0.38645       3.06480D-03   1.58612D-02 -3.46445D-08   3.08815D-06  5.50839D-04 -4.91008D-02   0.50000       0.61690
  4   0.0             0.38683       3.06680D-03   1.58561D-02 -3.44577D-08   3.07726D-06  5.48217D-04 -4.89587D-02   0.50000       0.47897
  5   0.0             0.29417       3.10393D-03   1.57490D-02 -3.08914D-08   2.86307D-06  4.98184D-04 -4.61726D-02   0.92208       0.90551
  6 -4.49972D-02      0.59412       3.75421D-03   1.90228D-02 -3.94631D-05   1.75125D-04  0.43345      -1.9236        0.51332       0.51981
  7 -6.35605D-02      0.67007       4.37418D-03   2.20336D-02 -4.28863D-05   1.82849D-04  0.34914      -1.4886        0.50588       0.57679
  8 -6.61918D-02      0.68076       4.46339D-03   2.24780D-02 -4.31400D-05   1.83277D-04  0.33710      -1.4322        0.48128       0.55183
  9 -0.14740          0.98797       7.58964D-03   3.75447D-02 -5.53172D-05   2.11454D-04  0.14687      -0.56110       0.45812       0.54077
 10 -0.24118           1.2654       1.33721D-02   6.43357D-02 -8.79646D-05   2.91296D-04  7.34769D-02 -0.24287       0.42972       0.51995
 11 -0.30064           1.3536       2.02790D-02   9.74946D-02 -1.32987D-04   3.81837D-04  4.81462D-02 -0.13841       0.23479       0.40245
 12 -0.30152           1.3545       2.03894D-02   9.80115D-02 -1.33833D-04   3.83393D-04  4.79551D-02 -0.13756       0.71208       0.75255
 13  -1.0029           1.9768       6.15183D-02   0.29457      -1.13777D-03   1.52691D-03  5.80339D-02 -7.77979D-02   0.64075       0.71752
 14  -2.0758           2.4179       0.12389       0.61725      -4.61188D-03   3.69267D-03  7.19281D-02 -5.74535D-02   0.0           0.0

NODE    E              FK             F             THT            HT             GS           HSL           HSV           RSL·           RSV
  1    12.279        1.78209D-07   3.99704D-05   1.75163D-79   1.00000D-01   3.96675D-04   524.69        1196.8        47.200         1.9666
  2    6.3544         9840.6        954.48        1.0000        0.55129        5770.1       524.58        1196.8        47.206         1.9650
  3    190.39         35431.        1670.4        1.0000        0.79822        12509.       497.72        1201.1        48.486         1.6007
  4    190.07         20120.        1064.9        1.0000        0.83203        8582.0       497.64        1201.1        48.490         1.5997
  5    183.14         20226.        1094.3        1.0000        0.82879        8686.0       495.60        1201.4        49.585         1.5743
  6    183.54         29584.        2057.2        22.000        0.52436        16455.       459.75        1204.3        50.201         1.1762
  7    185.33         70438.        3955.7        22.000        0.79353        29282.       456.63        1204.5        50.337         1.1455
  8    185.73         73410.        4063.3        22.000        0.81633        30079.       456.59        1204.5        50.339         1.1451
  9    201.17        2.16395D+05    7754.7        42.000         1.2749        57541.       455.39        1204.5        50.391         1.1335
 10    229.10        7.47018D+05    15126.        42.000         1.5343       1.12590D+05   451.69        1204.6        50.552         1.0983
 11    252.32        1.95130D+06    24327.        42.000         1.7540       1.80736D+05   445.57        1204.7        50.814         1.0418
 12    252.60        1.97549D+06    24478.        42.000         1.7557       1.81844D+05   445.41        1204.7        50.821         1.0404
 13    256.77        1.34645D+07    40018.        42.000         1.8162       3.70819D+05   351.11        1197.7        54.546         0.41694
 14    257.73        6.39897D+07    83750.        342.00         0.12373      7.87771D+05   297.95        1187.0        56.391         0.22401

   TIME          P4            P1            CMASS         R/R0          RUFF           PC            P7            P12           P9
 2.20500       732.296       887.712       76.3727       0.779332      6.737898E-12  0.202855      530.738       482.751       525.304
 2.36500       723.364       886.144       76.7783       0.783471      1.396902E-11  0.205773      526.756       479.010       521.368
 2.52500       730.951       884.491       75.5143       0.770573      1.655998E-11  0.203089      525.140       477.326       519.730
 2.68500       727.441       882.760       75.7568       0.773048      1.018750E-11  0.207781      521.978       474.365       516.608

TIME STEP MULTIPLIED BY   2.0000
 2.84500       730.008       881.054       74.5466       0.760699      1.580572E-12  0.208341      521.168       473.407       515.768
```

```
TIME STEP MULTIPLIED BY   2.0000
 3.16500       727.130     977.781       73.9227      0.754332      9.024290E-12 0.175764      521.107      472.983      515.719
 3.80500       727.239     870.442       67.5185      0.688981      6.328992E-12 0.190189      518.798      471.137      513.355
 4.44500       723.996     862.924       62.3418      0.636157      1.134656E-11 0.194422      505.479      458.413      500.108
 5.08500       719.260     855.307       57.8129      0.589942      8.829193E-12 0.209311      494.470      447.845      489.129

TIME STEP MULTIPLIED BY   2.0000
 5.72500       714.018     847.859       54.8862      0.560078      7.392280E-12 0.199944      484.929      437.728      479.570

TIME STEP MULTIPLIED BY   2.0000
 7.00500       701.140     833.119       50.4228      0.514531      3.469771E-10 0.200699      473.360      426.210      468.039
```

```
      PREMOLI (1969)  BURST AT RISER OUTLET   59 MW FIXED INLET FLOW                              28 FEB 74

TIME=    9.56500    SECS          POWER(MW)=   0.189900        POWER TO COOLANT=   0.203920

NODE DENSITY        FLOW            FLOW         PRESSURE      STATIC ENTH   FUEL TEMP     VOID         TEMP         SAT TEMP    HEAT FLUX
       LB/FT3        QUALITY         LB/SEC       PSIA          BTU/LB        DEGF          FRACTION     DEGF         DEGF      BTU/SEC FT
  1   61.427       -0.67912        0.28696       804.14         42.791        71.494      -0.29370      71.604       518.80      0.0
  2   62.271       -0.72160        0.29805       803.46         13.322        46.632      -0.31184      42.703       518.70      0.22279
  3   47.786        1.00268D-03    0.27828       677.60        487.85        512.42        2.48833D-02  499.47       499.47      0.27391
  4   46.595        2.08257D-03    0.27822       677.16        488.35        504.01        5.00309D-02  499.39       499.39      3.08082D-02
  5   41.538        7.57226D-03    0.27788       668.65        489.52        499.39        0.15778      498.00       498.00      1.06717D-02
  6   18.386        7.62585D-02    0.27824       464.25        468.00        465.42        0.65238      459.43       459.43      5.14693D-02
  7   17.376        8.34549D-02    0.28031       445.78        464.96        461.59        0.67430      455.33       455.33      4.73393D-02
  8   17.198        8.46800D-02    0.28038       445.61        465.23        498.31        0.67687      455.30       455.30       4.2438
  9   13.285        0.13628        0.28160       440.47        476.39        492.13        0.75483      454.13       454.13       4.2390
 10    9.2805       0.23699        0.28323       424.78        494.46        484.57        0.83441      450.52       450.52       4.2380
 11    6.9627       0.33624        0.28440       400.10        509.17        476.93        0.88002      444.62       444.62       4.2388
 12    6.9371       0.33745        0.28443       399.45        509.24        450.99        0.88051      444.46       444.46      5.03284D-02
 13    3.4808       0.43746        0.28819       155.29        413.53        366.46        0.94277      361.17       361.17      4.69857D-02
 14    2.3519       0.47982        0.28887        88.344       362.85        322.11        0.96191      318.97       318.97      2.79235D-02

NODE   DE2             DE3            RM           DM1          DM2          DM3           RP           RH            EITP           RITP
  1   0.0             0.28696       1.34058D-03  9.34325D-03 -4.97638D-09  4.41244D-08  2.28023D-04 -2.02182D-03  0.50000        0.59784
  2   0.0             0.29805       1.42655D-03  9.57260D-03 -4.87799D-09 -2.57446D-08  2.12932D-04  1.12379D-03  1.0000         0.98891
  3 -1.70475D-02      0.36615       1.62072D-03  1.16480D-02 -1.36121D-05  7.14871D-05  0.40005      -2.1011       0.49580        0.50127
  4 -1.82147D-02      0.37190       1.66153D-03  1.19439D-02 -1.36819D-05  7.15384D-05  0.38225      -1.9988       0.51381        0.54142
  5 -2.46196D-02      0.40215       1.86032D-03  1.33896D-02 -1.42412D-05  7.24474D-05  0.31572      -1.6063       0.63066        0.64232
  6 -0.14325          0.78761       4.41529D-03  3.17372D-02 -3.57134D-05  1.20949D-04  0.12834      -0.43379      0.50812        0.53090
  7 -0.16007          0.82950       4.80280D-03  3.42680D-02 -4.03589D-05  1.31331D-04  0.12300      -0.39923      0.50727        0.50954
  8 -0.16133          0.83293       4.84774D-03  3.45803D-02 -4.06583D-05  1.32003D-04  0.12151      -0.39347      0.45237        0.51810
  9 -0.20241          0.92929       6.76359D-03  4.80367D-02 -5.37171D-05  1.60325D-04  7.97867D-02 -0.23719      0.34788        0.50771
 10 -0.24758          0.97711       1.13864D-02  8.04044D-02 -8.61550D-05  2.19598D-04  4.68150D-02 -0.11951      1.0000         0.50080
 11 -0.26832          0.93066       1.78046D-02  0.12521     -1.28928D-04  2.75888D-04  3.24591D-02 -7.09008D-02  1.0000         0.83079
 12 -0.28872          0.93007       1.79093D-02  0.12593     -1.29728D-04  2.76821D-04  3.23467D-02 -7.04802D-02  0.68715        0.73493
 13 -0.76734           1.2018       5.74817D-02  0.39891     -1.04949D-03  1.01443D-03  4.05133D-02 -4.07724D-02  0.60624        0.67480
 14  -1.3334           1.3644       0.10996      0.76133     -3.35395D-03  2.03919D-03  4.80006D-02 -3.06609D-02  0.0            0.0

NODE    E              FK             F            THT          HT           GS           HSL          HSV          RSL          RSV
  1    12.279       1.78160D-07    3.99378D-05  1.75163D-79  1.00000D-01  3.96621D-04   510.53       1199.3       47.883       1.7674
  2    2.9707        9953.2         966.10       1.0000       0.54999       5822.6      510.41       1199.3       47.888       1.7658
  3    135.81        13761.         1124.8       23.000       0.31887       7974.7      487.30       1202.3       48.968       1.4743
  4    135.97        8212.9         840.48       22.000       0.22775       6405.3      487.22       1202.3       48.971       1.4733
  5    136.44        10317.         1101.3       22.000       0.41345       8385.6      485.57       1202.5       49.047       1.4539
  6    138.88        63251.         3558.7       42.000        1.0540       26660.      440.89       1204.8       51.013       1.0001
  7    140.26       1.33392D+05     6014.5       42.000        1.2313       41751.      436.25       1204.8       51.209       0.96005
  8    140.55       1.36211D+05     6082.5       42.000        1.2365       42223.      436.20       1204.8       51.211       0.95968
  9    152.91       2.93469D+05     9032.4       42.000        1.4051       62720.      434.89       1204.8       51.266       0.94857
 10    173.97       9.59614D+05     15980.       42.000        1.5941     1.10901D+05   430.82       1204.7       51.437       0.91468
 11    195.27       2.47221D+06     24772.       42.000        1.7048     1.71641D+05   424.19       1204.6       51.712       0.86157
 12    195.52       2.50221D+06     24914.       42.000        1.7060     1.72615D+05   424.02       1204.6       51.719       0.86019
 13    204.69       1.62152D+07     32631.       42.000        1.7348     2.98829D+05   333.54       1194.6       55.175       0.34296
 14    207.71       5.97155D+07     60409.       32.000        1.8253     5.60359D+05   289.33       1184.9       56.672       0.20072

   TIME          P4          P1          CMASS        R/RO         ROFF          PC            P7           P12          P9
 9.56500      677.163     804.138      45.7678     0.467030    2.041840E-11  0.203920      445.777      399.453      440.472
```

```
        PREMCLI (1969)  BURST AT RISER OUTLET   59 MW FIXED INLET FLOW                          28 FEB 74

   TIME          P14          W1           W4           W7           W12
0.0            618.419      0.286962     0.286962     0.286962     0.286962
1.000000D-02   565.211      0.286962     0.286962     0.286959     0.251346
2.000000D-02   481.408      0.286962     0.286948     0.286828     0.188991
3.000000D-02   394.918      0.286962     0.286839     0.285976     0.151957
3.500000D-02   337.459      0.286962     0.286743     0.284869     0.146128
4.000000D-02   291.875      0.286962     0.286536     0.283935     0.133355
4.500000D-02   269.856      0.286962     0.286277     0.282538     0.117621
5.000000D-02   257.330      0.286962     0.285888     0.291436     0.116772
5.500000D-02   248.125      0.286962     0.285416     0.279654     0.132037
6.500000D-02   237.270      0.286962     0.283768     0.276721     0.191912
7.500000D-02   227.371      0.286962     0.281716     0.275781     0.248741
8.500000D-02   219.254      0.286962     0.279498     0.275856     0.293699
0.105000       208.907      0.286962     0.275217     0.274803     0.343809
0.125000       201.819      0.286962     0.272965     0.277180     0.364229
0.165000       195.617      0.286962     0.274927     0.279089     0.412682
0.205000       185.284      0.286962     0.282013     0.285825     0.434197
0.245000       175.598      0.286962     0.291684     0.294439     0.446416
0.285000       167.052      0.286962     0.303723     0.306687     0.444416
0.325000       160.097      0.286962     0.315160     0.316509     0.438285
0.365000       154.210      0.286962     0.327860     0.330412     0.425929
0.445000       145.354      0.286962     0.349909     0.350882     0.425100
0.525000       138.400      0.286962     0.371979     0.373915     0.401263
0.605000       133.049      0.286962     0.384258     0.384560     0.406205
0.765000       123.881      0.286962     0.403435     0.405016     0.417009
0.925000       117.122      0.286962     0.402643     0.413831     0.426063
  1.08500      111.540      0.286962     0.409065     0.448033     0.429885
  1.24500      108.921      0.286962     0.397840     0.410656     0.434632
  1.40500      105.623      0.286962     0.400322     0.437367     0.430338
  1.56500      103.868      0.286962     0.393737     0.402092     0.429958
  1.72500      102.272      0.286962     0.396365     0.428536     0.422647
  1.38500      101.185      0.286962     0.390792     0.399868     0.421918
  2.04500      100.103      0.286962     0.392275     0.422173     0.416073
  2.20500      99.2183      0.286962     0.386828     0.397047     0.416062
  2.36500      98.3606      0.286962     0.387381     0.416587     0.411535
  2.52500      97.6529      0.286962     0.381793     0.393755     0.411796
  2.68500      96.9727      0.286962     0.381553     0.410664     0.407791
  2.84500      96.4409      0.286962     0.375802     0.391172     0.408444
  3.16500      95.7276      0.286962     0.369338     0.404827     0.409570
  3.30500      96.6109      0.286962     0.340349     0.377417     0.402225
  4.44500      97.1898      0.286962     0.325716     0.354336     0.373425
  5.18500      96.3743      0.286962     0.314905     0.335015     0.351611
  5.72500      93.9229      0.286962     0.306733     0.322498     0.332986
  7.00500      91.8044      0.286962     0.298619     0.309180     0.317446
  9.56500      88.3437      0.286962     0.278220     0.280308     0.284427
```