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THETAN - A TWO-DIMENSIONAL HEAT TRANSPORT CODE FOR  
ANALYSIS OF POWER TRANSIENTS

by

W.J. GREEN  
W.S.V. JACOBS

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ABSTRACT

A computer code THETRAN has been developed for two-dimensional analysis of heat transfer transients by utilising parts of two available transient heat transfer codes, THETA1-B and HEATRAN. Combination of the one-dimensional coolant energy and heat transfer equations used in THETA1-B with the two-dimensional transient thermal diffusion code HEATRAN was achieved by matching two parameters (surface temperature and heat flux) at the solid/fluid interface. The resultant code is capable of analysing the transient thermal performance of a tube or duct internally or externally cooled by a flow of liquid coolant which may boil. The code was developed to analyse experimental conditions in which an electrically heated tube is subjected to a rapid change in power input while heat is removed by an internal flow of coolant at a constant mass flowrate.

(Continued)

To account for the heat transfer characteristics of the coolant, various options have been included. These are:

- (a) a selection of forced convection heat transfer correlations;
- (b) a selection of two-phase friction correlations;
- (c) a selection of calculation techniques for solving the coolant energy equations; and
- (d) a choice of either water or Freon-12 as the coolant.

The major assumptions made in the code are that:

- (i) the mass flux of coolant is assumed spatially constant along the duct;
- (ii) thermal equilibrium exists within the coolant at each location; and
- (iii) the local conditions hypothesis is valid for application of the heat transfer correlations.

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T. CODES; TRANSIENTS; HEAT TRANSFER; TWO-DIMENSIONAL CALCULATIONS; FLUID FLOW; LOSS OF COOLANT; COOLANTS; REACTOR COOLING SYSTEMS; PWR TYPE REACTORS; BWR TYPE REACTORS

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## 1. INTRODUCTION

The behaviour of the coolant and associated local surface temperature of a fuel pin in a pressurised or boiling water nuclear power reactor during a postulated loss-of-coolant accident (LOCA) has been the subject of considerable experimental and theoretical work over the past two decades. There have been large experimental programs such as FLECHT [Cadek et al. 1971], Semiscale [Zane 1976] and LOFT [Ybarrondo and Nolf 1976], as well as smaller programs [Thomas 1976; Dix and Sozzi 1976] designed to study separate heat transfer effects. In conjunction with many of these experimental programs, computer codes have been developed to calculate fluid flow and heat transfer transients, both to analyse the experimental data and to predict the events that may occur if a PWR or BWR were subjected to a LOCA.

Apart from these elaborate simulated reactor experiments and calculations, there have been several smaller experimental investigations of LOCA phenomena in simple geometries [Friz et al. 1973; Hicken et al. 1972; Morgan et al. 1972] and numerous experimental and theoretical investigations of the heat transfer processes involved in a LOCA. These studies have been reviewed by Collier [1975].

In both the blowdown and rewetting phases of a LOCA there is a need for reliable and accurate information on the rate of heat transfer at the onset of dryout and under post-dryout conditions for rapidly varying power and coolant flow transients. Analysis of the data from even the simplest experiments designed to investigate the heat transfer processes associated with such transients depends, in many cases, on the availability of suitable analytical transient heat transfer techniques or computer codes.

Recent examples [Ott and Hedrick 1977; Cheng et al. 1977] of analytical techniques developed specially to examine experimental data on transients related to dryout (or rewetting) have used measurements of internal temperature transients in high thermal capacity test sections to derive surface heat fluxes and surface temperatures. These methods, however, are one-dimensional and do not consider the thermal properties and response of the coolant fluid.

The code THETRAN was developed from two available codes, THETA1-B [Hocevar and Wineinger 1972] and HEATRAN [Collier 1969], to provide a calculational method which would account for the transient conditions in both

the solid and the coolant and so be suitable for analysing transient heat transfer data from post-dryout experiments being conducted at the AEC Research Establishment.

Although a potential user of THETAN need have no knowledge of THETA1-B, familiarity with HEATRAN and the free format used for specifying input data is necessary. Information on the calculational techniques and general facilities available in HEATRAN has not been reproduced here. However, information is provided on those areas which have been modified and on the manner in which HEATRAN has been combined with the coolant energy and flow equations.

Since subroutines containing many of the heat transfer correlations and steam properties were already available from THETA1-B, these have been incorporated into THETAN; however, since THETA1-B was programmed using British Imperial units, THETAN must also operate in these units. The substantial time and effort required for conversion to metric units was considered to be out of proportion to the improvement that would be achieved.

## 2. DESCRIPTION OF THETAN

### 2.1 Basic Approach

THETA1-B was written to solve the transient thermal response of a nuclear fuel pin subjected to LOCA conditions [Hocevar and Wineinger 1972]. It was developed by coupling a one-dimensional energy equation to describe the coolant flow conditions with a two-dimensional finite difference thermal diffusion code, CINDA [Gaski 1967], capable of determining temperatures and heat transfer within the fuel pin. In its development, however, the general two-dimensional thermal diffusion code was structured so that it modelled only a solid fuel rod, a thin annular cladding region and an interface gas gap separating the fuel rod from the cladding. Direct modelling of other geometrical configurations was not allowed for, thus restricting the use of the resultant code.

HEATRAN [Collier 1969] is a finite element code for two-dimensional analysis of heat transfer transients and requires boundary data as part of the input. It has been extensively used to solve a multitude of problems covering a wide range of physical shapes. It was therefore decided that the coolant energy and heat transfer equations used in THETA1-B should be decoupled from

the diffusion side of the code and linked to the more versatile code, HEATRAN, thus creating a new code, THETRAN, capable of analysing experimental data from power transient tests [Green 1978].

## 2.2 Coolant Energy and Flow Equations

The conservation equations for mass, momentum and energy for flow within a vertical channel of constant cross section may be written (see Section 7 for notation).

$$\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial z} = 0 \quad (1)$$

$$\frac{\partial G}{\partial t} + \frac{\partial [G^2/\rho]}{\partial z} + \frac{\partial p}{\partial z} = - \frac{\Delta p_{fr}}{dz} - \frac{\Delta p_h}{dz} \quad (2)$$

$$\frac{\partial(\rho U)}{\partial t} + \frac{\partial(Gh)}{\partial z} = \beta \quad (3)$$

Introducing the enthalpy relationship

$$h = U + \frac{p}{\rho}$$

Equation (3) becomes

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(Gh)}{\partial z} - \frac{\partial p}{\partial t} = \beta \quad (4)$$

If assumptions are made that

- . the coolant properties can be determined from local bulk coolant conditions,
- . thermodynamic equilibrium exists between liquid and vapour phases,
- . the flow can be considered as homogeneous when determining coolant thermal conditions (i.e. the flow enthalpy and the static enthalpy are equal), whereas when assessing pressure loss effects, the two phases may be considered as travelling at different velocities (i.e.  $S \neq 1$ ), and
- . the coolant mass flux is spatially constant (i.e. the rate of change of coolant density is negligibly small), then Equation (1) reduces to



$$\frac{\partial G}{\partial z} = 0$$

and Equation (4) becomes

$$\rho \frac{\partial h}{\partial t} + G \frac{\partial h}{\partial z} = \beta + \frac{\partial p}{\partial t} \quad (5)$$

$$\text{where } h = h_f + X h_{fg}$$

For a system in which the pressure is also assumed to be spatially constant, Equation (5) can be solved without reference to Equation (2). Alternatively, for a system in which the mass flux is constant with time, Equation (5) may be solved allowing for the rate of change of pressure by estimating the axial variation in pressure from Equation (2) expressed in the simplified form

$$\frac{\partial p}{\partial z} = - \frac{\Delta p_{fr}}{dz} - \frac{\Delta p_h}{dz} - \frac{G^2 \Delta v}{dz} \quad (6)$$

Equation (6) may be expressed in pressure loss terms as

$$\Delta p = \Delta p_{fr} + \Delta p_h + \Delta p_{acc}$$

where  $\Delta p_{fr}$  is the frictional pressure loss over the distance  $dz$  and can be determined from one of the various options available (see Section 2.5),  $\Delta p_h$  is the decrease in static pressure due to the reduction in gravitational head and is given by  $\frac{dz}{v_m} g$  and  $\Delta p_{acc}$  is the decrease in static pressure due to acceleration over the distance  $dz$  and is given by  $G^2 \Delta v$ .

The boundary conditions required to solve the fluid energy and flow equations are the mass flux, the local surface heat flux from the heat dissipating surface, and the fluid pressure and enthalpy at its entry into the heated channel. Of these conditions, all except the surface heat flux need to be supplied as input data. The mass flux and enthalpy at the inlet to the channel are input as the inlet data and the coolant is considered as flowing in one direction only in the channel throughout the transient. Heat fluxes are computed from the heat transfer models (see Section 2.4). Data for determining the coolant conditions are included for two coolants: water and Freon-12. In each case, the thermodynamic properties are in tabular form and an interpolation technique is used to obtain these properties as functions of pressure and enthalpy.

With the transport properties (i.e. specific heat, thermal conductivity and viscosity), these are determined from a combination of tabulated data and equations in the case of water and from equations when considering Freon-12. The sources of information for the properties of the two fluids are

- . Keenan and Keyes [1936] for the thermodynamic properties of steam,
- . Meyer [1967] for the transport properties of steam, and
- . Watson [1975] for all properties of Freon-12.

### 2.3 General Description of Code

Combination of the energy and heat transfer equations from THETA1-B with the heat transfer relations in the code HEATRAN was achieved by matching the interface parameters at the solid-liquid interface, i.e. the surface temperature and heat flux. Different linking procedures are used, however, for the steady state and transient conditions.

In the case of the steady state solution, the heat flux at the surface of the solid is determined from local temperature gradients within the solid. This information is then passed to the coolant side of the calculation which, in turn, calculates surface temperatures. These temperature values are then passed back to the solid as boundary conditions for a further iteration.

With a calculation for transient conditions, no such iteration procedure is used. Instead, surface temperatures are calculated by the HEATRAN side of the code and these values are used in the coolant energy and heat transfer equations which calculate surface heat fluxes. These surface heat flux values are then returned as boundary conditions to the solid for the next time step calculation.

The overall logic and solution sequences for both the steady state and transient conditions are described briefly.

#### Steady state

From a preliminary input estimate of surface temperatures at the coolant boundary, the thermal diffusion code HEATRAN determines the temperature distribution within the solid model and evaluates surface heat fluxes for each

axial region of the channel. These values of surface heat flux are used in the one-dimensional energy equations to determine for each axial fluid node the local enthalpy of the coolant and its associated mass flow fraction (quality) and voidage. Each axial fluid node is then assigned an appropriate heat transfer regime which is dependent upon the fluid properties. An iterative process determines wall temperatures corresponding to the heat fluxes transferred from the solid thermal diffusion part of the code (i.e. HEATRAN) and, if necessary, reassigns heat transfer regimes. When convergence has been achieved, these wall temperature values are returned to the thermal diffusion part of the code where a new temperature distribution and new values of surface heat flux are calculated. The process involving HEATRAN and the coolant energy equations and correlations is repeated until the heat fluxes determined by HEATRAN are within a specified tolerance of those calculated in the previous iteration by the coolant energy and heat transfer equations.

#### Transient

For any particular time step advancement, the temperature distribution in the solid is calculated at the end of the time step by using (a) the surface heat fluxes determined at the end of the previous time step by the energy and heat transfer equations, and (b) the updated power generation rate. The time step for each of these calculations is determined from the printout times specified by the user and an interval subdivision technique coded into HEATRAN. This technique divides the period between two specified printout times by a factor of 20. The first subdivision is then taken as the first time step. Subsequent time steps are increased by an arbitrary factor of 1.8 (as in HEATRAN) provided that inbuilt accuracy tests are satisfied. As the summation of the time steps approaches a specified printout time, the last two time steps are adjusted so that the specified printout time is not exceeded.

After solving the temperature distribution in the solid, the next part of the solution sequence is the determination of the fluid properties, heat transfer coefficients, and surface heat fluxes which correspond to the new wall temperatures. This is performed by solving the energy and heat transfer equations in the following manner.

For any particular time step in the calculation of temperature distribution within the solid, a series of smaller time intervals is determined by further subdivision. New values for coolant properties, heat transfer coefficients, surface heat fluxes and new heat transfer regimes are

determined at the end of each small time interval. Current values of coolant pressure, mass flux and inlet enthalpy are used in each of these calculations. By this process, a good approximation is obtained of the coolant conditions and surface heat fluxes corresponding to the time step for the calculation of solid temperatures. Computation of thermal diffusion within the solid for the next time step is then performed using the computed values of surface heat flux.

## 2.4 Coolant to Surface Heat Transfer

The heat transfer model in THETRAN is capable of selecting the following heat transfer regimes during both steady state and transient conditions: forced convection in a subcooled liquid or superheated vapour; nucleate boiling; forced convection vaporisation; transition boiling; and stable film boiling. Several heat transfer correlations have been included for the nucleate boiling, forced convection vaporisation, and stable film boiling regimes.

The prediction of critical heat flux (CHF) is an important factor [Green 1978] when determining temperature responses under loss-of-coolant conditions; consequently a number of CHF correlations for both water and Freon-12 have been included to allow the effect of choosing different correlations to be investigated.

The heat transfer correlations that are included in the code are given in Appendix A together with information on their applicability.

### 2.4.1 Pre-dryout correlations

Before the onset of dryout, the heat transfer regimes which may exist are forced convection of the subcooled liquid, nucleate boiling, and forced convection vaporisation. Although subcooled nucleate boiling is also a well-known phenomenon which may occur before saturated nucleate boiling begins, it has been omitted from this calculational code because its onset cannot easily be defined. With the existence of two-phase flow conditions and the CHF value not exceeded, either saturated nucleate boiling or forced convection vaporisation obtains. There is some uncertainty as to the delineation between nucleate boiling and forced convection vaporisation; consequently in this code the user needs to nominate the void fraction at which the changeover between regimes occurs. It should be emphasised, however, that heat transfer

coefficients predicted for the two regimes can be significantly different, and a sudden change from one regime to the other can result in a step change in surface temperature. This in turn can have a significant effect on the numerical stability of the code. In an effort to eliminate this type of numerical instability, an intermediate region between the two regimes commencing at one void fraction and terminating at a higher value was considered, based on arithmetic averaging of the surface heat fluxes for the two regimes. This solution was still found to be unsatisfactory since it produced complications in later transition boiling calculations; consequently, it has not been included in the code. Under transient conditions, if there is a large difference between the surface heat fluxes as calculated from the correlations for the two regimes, large, destabilising temperature changes can occur. Moreover, for steady state conditions, it can give rise to difficulties in obtaining a steady state solution between surface heat flux and wall temperature in the transition boiling region.

#### 2.4.2 Post-dryout correlations

After the onset of dryout, transition boiling and film boiling heat transfer regimes will exist. For the film boiling regime, several heat transfer correlations are incorporated in the code. However, Green [1978] formulated modified versions of some of these to correlate experimental data obtained at low flow rates using Freon-12. These versions are also included as user options.

Heat transfer during the transition regime, i.e. the heat transfer regime just after the onset of dryout, is not well understood, hence there are few correlations for this condition.

In post-dryout heat transfer, there are two coolant conditions to be considered, i.e. when (a) stagnation occurs and (b) the coolant is flowing. Since most post-dryout heat transfer correlations developed for flow conditions predict zero heat flux if the flow rate is zero, it is necessary to treat the two cases separately.

Consider first the flow boiling conditions; because of the difficulties in describing the transition boiling regime, two options have been made available to the user for modelling it. In the first option, after the CHF condition, the McDonough, Milich and King [1958] correlation is assumed to apply until the calculated value for the heat flux is exceeded by that

calculated by the relevant film boiling correlation. The point at which these heat fluxes are equal is the minimum film boiling heat flux. A second option has been included based on the work of Green [1978]. This assumes that the McDonough et al. correlation applies until the calculated heat flux is equal to a value calculated from a minimum film boiling correlation. This minimum value correlation is then used until it is exceeded by the surface heat flux calculated by one of the film boiling correlations. These relations are shown in Figure 1. It should be emphasised, however, that Green's minimum film boiling correlation was derived from Freon-12 data and has not been shown to be applicable to water.

Since the code has been written basically to solve problems which involve increases in power with the coolant flowing through the duct, it is assumed that the CHF will be exceeded while flow conditions obtain. Consequently, pool boiling CHF correlations are not required. The pool film boiling model used for very low flow rates is the same as that described by Hocevar and Wineinger [1972], which is based upon the Berenson [1961] correlation for pool film boiling.

## 2.5 Frictional Pressure Loss Equations

In determining the pressure drop over any axial distance, the losses are comprised of several components of which friction is often the largest. For a two-phase fluid a wide variety of correlations have been developed to calculate frictional pressure losses. Consequently, in THETAN the user is given the option of using any one of several correlations for calculating frictional losses when the coolant is in a two-phase state. The correlation options available are given in Appendix B.

## 2.6 Slip Correlations

Although for thermal considerations the coolant is assumed to be homogeneous and in internal thermal equilibrium at any flow section, in ascertaining the pressure distribution along the channel when the coolant is in a two-phase state, the velocities of the vapour and the liquid need not be taken as equal. This facility has been included in the code since the assumption of homogeneity (including slip equal to unity) can cause predictions of frictional pressure losses to be widely at variance with observed data.

Slip has not been included in thermal considerations since it gives rise to the need to differentiate between flow and non-flow qualities. This distinction is unnecessary in thermal analyses since flow quality is the parameter required. The various slip correlations which have been included as options in THETRAN are given in Appendix B.

### 3. DETAILS OF SOLUTION PROCEDURES AND NUMERICAL STABILITY

#### 3.1 General

In the types of problem for which THETRAN could be used, some of the options and procedures included in the basic HEATRAN code would be unnecessary. The source module of HEATRAN [Collier 1969] used in THETRAN has therefore been modified to eliminate some facilities and to include others. These modifications include the removal of (a) the cartesian coordinates option, (b) the option whereby thermal radiation between surfaces separated by a gas is considered, and (c) the one-dimensional option.

Moreover, a heat balance subroutine which operates at steady state conditions (i.e. at initialisation) has been included [E.W. Hesse, AAEC private communication]. This subroutine determines the heat balance between the total heat input to the solid and the heat losses dissipated at the boundaries. However, this subroutine is limited since, apart from the boundaries in contact with the coolant, it is only able to take account of heat losses which occur at boundaries specified by:

- . a heat transfer coefficient and a coolant temperature,
- . radiation to an infinite sink, and
- . a narrow gas gap.

In linking the transient heat transfer code HEATRAN with a one-dimensional energy equation representing the coolant conditions in contact with part of the boundary of the solid, it has been necessary to align axial nodal positions at the surface of and within the solid to those in the coolant. This has been done by assigning 'n' nodes (where 'n' is any number > 3) at the surface of the solid to one axial node in the coolant. The 'n' nodes on the surface of the solid are thus associated with one fluid boundary

condition. However 'n' can be different for each fluid boundary node. To determine surface heat fluxes being dissipated from the solid, each set of surface nodes associated with a fluid boundary node must have 'n' inner nodes at a small radial distance orthogonal to the corresponding nodes on the surface. These inner nodes are referred to in the present work as the proximity nodes. Each coolant node becomes associated, therefore, with a block of nodes within the solid.

### 3.2 Steady State Conditions

Solution for the temperature distribution in the initial steady state is commenced by considering the heat conduction in the solid. For the boundaries that are subjected to the flowing coolant, an initial estimate of the surface temperature is needed. This estimate need not be accurate and is only required to start the calculational process.

After an initial temperature distribution within the solid has been calculated, the surface heat fluxes associated with each coolant node are determined by the equation

$$q = k \cdot \frac{\Delta T}{\Delta r}$$

where k is the conductivity,  $\Delta T$  is the temperature difference between a surface node and its corresponding proximity node, and  $\Delta r$  is the radial distance between these nodes.

For a boundary having an odd number of surface nodes (say five),  $\Delta T$  and  $\Delta r$  are calculated directly from the central surface node (i.e. node 3, the middle node in the length dz) and its corresponding proximity node. This procedure is adhered to irrespective of the axial distance between nodal points. k is taken as the mean value of conductivity for the four finite elements influencing the central node (see Figure 2a).

For a boundary containing an even number of surface nodes (say four),  $\Delta T$  and  $\Delta r$  are interpolated from two innermost surface nodes (i.e. nodes 2 and 3) and the two corresponding proximity nodes. k is taken as the mean value of the two finite elements represented by these nodes (see Figure 2b).

Having ascertained these surface heat fluxes, this information is passed from the heat conduction part of the code to the coolant energy, flow and heat



transfer equations which calculate new surface temperatures and heat fluxes for each coolant node. The new surface temperatures are used to perform a further heat conduction calculation. Surface heat fluxes are then recalculated from the new temperature distribution within the solid and are compared with the heat fluxes obtained during the previous calculations. Provided that these values are within a specified tolerance, initialisation is complete, otherwise the cycle continues until either convergence occurs or 10 cycles have elapsed.

### 3.3 Transient Conditions

The transient phase of the calculation is initiated when the key word TIME of the input data is encountered. On detecting this word, THETAN automatically converts those boundaries of the solid which are associated with the coolant from constant temperature types to variable heat flux types. The first transient calculation commences by using surface heat fluxes that are derived by taking those values determined by the coolant equations at the steady state solution of initialisation and correcting them for any minor overall heat balance discrepancies.

As HEATRAN has been found to be more numerically stable for large incremental time steps than those which can be used to solve the fluid energy problem, the following calculational procedure has been adopted.

For any particular HEATRAN time step, the heat conduction side of the problem is solved using the surface heat fluxes determined by the coolant equations at the end of the previous HEATRAN time step. (The method by which HEATRAN time steps are derived will be discussed later.) This establishes the surface temperatures which will be used in the coolant calculations performed for this particular HEATRAN time step.

The next phase of the calculational procedure is to consider the coolant side of the problem. For this, the HEATRAN time step is subdivided into a series of smaller times of unequal duration. The sequence of events is then as follows.

The first coolant time step is set at the minimum time step supplied by the user. Using the surface temperatures determined from the HEATRAN calculation for the central nodal point (see Section 3.2 for a description of this node), local surface heat fluxes are estimated from the appropriate heat

transfer correlations. The channel inlet values of pressure, mass flux and enthalpy associated with the total accumulated time are then determined and, if required, the pressure distribution along the channel is estimated. Saturation properties of the coolant at these nodal pressures are found and one of the energy equations is called. This equation uses the estimated local surface heat fluxes to calculate new coolant enthalpies. Subsequently, the local fluid properties are recalculated and local surface heat fluxes re-estimated using the appropriate heat transfer correlations. It should be indicated, however, that before the energy equation is called to ascertain the new enthalpies, provided that the input time dependent variables (i.e. inlet enthalpy, pressure, mass flow rate and power) are constant for the time being considered, a check is made to determine whether the surface temperatures and heat fluxes associated with any fluid node are within specified tolerances. Should this be so, the energy equation is bypassed and the coolant enthalpies for these nodes are determined, assuming that there is thermal equilibrium.

After the energy equation has been called, the next coolant time step to be considered is determined by three possible courses: (a) it can be made double the coolant time step; (b) it can be made half the current coolant time step with provision for the accumulated coolant time step becoming exactly equal to the HEATRAN time step if the accumulated coolant time step approaches the HEATRAN time step; and (c) it may be reduced to the minimum coolant time step. (This occurs if the local enthalpies have changed by more than a small percentage (specified by the user) during the current coolant time step.) All of the methods for determining the coolant time steps have been designed to eliminate oscillatory instabilities when evaluating coolant enthalpy.

For subsequent coolant time steps this whole calculational procedure is repeated except that when the energy equation is called, it uses the local surface heat fluxes estimated at the end of the previous coolant time step and the surface temperatures operative at the end of the HEATRAN time step. Finally, when the total accumulated time of the coolant calculations is equal to the current HEATRAN time step, the new surface heat fluxes are passed to HEATRAN for the solution of the next HEATRAN timestep. At this point, should the heat sources acting within the solid be variable with time, the sources required by HEATRAN are updated.

Determination of the HEATRAN time steps is made by first taking one twentieth of the difference between any two specified print times on the TIME card. Subsequent time steps are then either increased by a factor of 1.8 or

halved if HEATRAN determines that its previous solution was not within accuracy limits. When the accumulated HEATRAN time is near a print time, the remaining time interval is adjusted to reach the print time in two finite time steps.

A flow chart showing how the procedure for calculating transient conditions in the fluid is interfaced with HEATRAN is given in Figure 3, and another flow chart showing the calculational logic and principal iterative loops for determining the transient response of the coolant is given in Figure 4.

The user should be aware that the times specified on the TIME card play a significant role in defining calculational time intervals and can influence numerical stability. Consequently, to ensure that the results obtained are correct, it is advised that all calculations should be repeated for two different TIME cards. The user should also closely examine the enthalpy output data for any signs of instability.

#### 4. CODE REQUIREMENTS

##### 4.1 Data Input

Input data for the THETRAN code can be classified into two main areas - one relates to the solid (i.e. suitable for the HEATRAN part of the code) and the other to the coolant. The solid may be modelled using both axial and radial nodes, up to a total of 1000 nodes, whereas the coolant channel is modelled by 20 or less axial regions. In formulating a model, specification of the physical geometry is the same as that required for HEATRAN, with the proviso that blocks of nodes within the solid are associated with each coolant node (see Section 3.1).

Combination of the HEATRAN source module with the coolant energy equations is achieved via the BOUNDARY card required in the HEATRAN data specification. If the keyword FLUID is specified on the boundary conditions card (i.e. BC card) then coolant input data for THETRAN are required and the coolant property, energy and heat transfer equations are automatically called during execution time. Exclusion of the FLUID keyword from the boundary conditions card causes the THETRAN module to execute as a HEATRAN module modified in the manner described in Section 3.1. Since the procedure within

the HEATRAN load module is not to read the input data in bulk but as required during execution (i.e. the load module of HEATRAN only has to ready one input card in advance of itself at any particular execution stage), the input data required by the fluid portion of the code was assigned a different FORTRAN dataset reference number. Similarly, the output from the calculations relating to the solid and the fluid are sent to different FORTRAN dataset reference numbers.

Hence, the HEATRAN section requires:

```
//FT01F001    input data (card reader)
//FT03F001    output data (printer)
```

and the fluid section requires:

```
//FT05F001    input data (card reader)
//FT06F001    output data (printer).
```

The keyword FLUID needs the same input requirements as the keyword T (constant temperature boundary) in the HEATRAN input data [Collier 1969]. Another minor restriction which the user must observe when formulating the input data is that when specifying the SOURCE data (provided that this SOURCE number is requested in the fluid section as a time variant SOURCE number), then this should only be done in the standard form and not by 'nodes' or 'function'. (See Section 5 for sample input of data.)

A detailed description of input data for the fluid sections is given in Appendix C.

#### 4.2 Computer Size Requirements and Approximate Running Times

The sample test case supplied with THETRAN (see Section 5) was run on an IBM3031 computer operating under MVS and required 348 K bytes of memory using an overlaid module, and 484 K bytes of memory using a module without an overlay structure. The sample test case is a simple model using 68 nodes to represent the solid tube. A larger number of nodes may force the HEATRAN segment of THETRAN to use a temporary work dataset during the matrix solution which will increase the core requirements for the code by approximately 2 K bytes.

The time card for the sample test case requested 23 time steps which is equivalent to 161 HEATRAN transient calculations provided that HEATRAN's inbuilt accuracy checks do not reduce a time step. For this case, the running time was approximately 30 seconds for the steady state solution (initialisation) and 9.5 minutes for the transient solution. In general about 95 per cent of the computer core processing time is required by the calculation of thermal diffusion within the solid (HEATRAN).

## 5. SAMPLE TEST CASE

### 5.1 General

THETRAN was developed for determining the transient response of an electrically heated tube having a power input varying with time and being internally cooled by a fluid flowing at constant mass flux, inlet pressure and inlet enthalpy (see Figure 5). The input data for the test case are for a stainless steel tube 10.215 ft long x 0.654 in. i.d. x 0.75 in. o.d. heated with direct electrical resistance heating over two axial sections (one 9.465 ft long and the other 0.75 ft long) and cooled internally by Freon-12.

The mass flux is specified as constant at a value of  $3.47472 \times 10^5$  lb  $h^{-1}$   $ft^{-2}$ , while the inlet pressure is constant at 132.78 psia and the inlet enthalpy constant at 25.4 Btu  $lb^{-1}$ .

Electrical power variations need to be specified as an array corresponding to linear changes in power between time intervals and have to be expressed in power density terms relative to the power density at the time zero. In the test case described here this has been done in the following manner for the 9.465 ft section:

time	$\frac{\text{power density at time } t}{\text{power density at time } 0}$
0	1.00
2.7 s	1.00
5.76 s	1.300
50 s	1.300

Similarly, the electrical power to the 0.75 ft section is specified in the following manner:

time	$\frac{\text{power density at time } t}{\text{power density at time } 0}$
0	1.000
1.8 s	4.000
50 s	4.000

The code interprets this type of information by linearly interpolating between specified times to determine the power density at any specific point in time.

## 5.2 Data Input and Output

Data for the physical modelling and solid conduction part of the code are specified in the same manner as required by HEATRAN [Collier 1969] except for the BC cards (see Section 4). Figure 6 depicts the nodal array used to model the test case. The user is directed to Collier [1969] for further details on the formats to be used. Specification and formats for the fluid section of the code are as given in Section 4. A listing of the data input for the sample test case is given in Appendix D. A listing of the corresponding data output is given in Appendix E.

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7. NOMENCLATURE

A	cross section area
c	specific heat
D	diameter
dp/dz	pressure gradient
f	friction factor
g	local acceleration due to gravity
$g_0$	gravitational constant
G	mass flux
h,H	coolant enthalpy
ht	heat transfer coefficient
k	thermal conductivity
L	length
p	pressure
$\Delta p$	pressure loss over distance dz
Pr	Prandtl number
q	surface heat flux
$q''$	heat conduction per unit area
$q'''$	heat generation per unit volume
Q	volume flow rate
R	radial distance
Re	Reynolds number
S	slip ratio
t	time
T	temperature
$\Delta T_{sat}$	$T_w - T_{sat}$
U	internal energy
V	velocity
v	specific volume
$\Delta v$	change in specific volume over dz
X	mass fraction of vapour (quality)
z	length
dz	incremental length
$\alpha$	void fraction
$\beta$	surface heat flux $\times \frac{\text{wetted perimeter of surface}}{\text{cross section flow area of coil}}$
$\sigma$	surface tension
$\mu$	viscosity
$\rho$	density
$X_{tt}$	Lockhart and Martinelli correlation parameter

$\phi$  two-phase multiplier

Subscripts

acc	acceleration
CHF	critical heat flux
cr	critical point
e	equivalent
f	liquid
fg	associated with change from liquid to vapour
flow	flow
fo	liquid-only case
fr	friction
g	vapour or gas
go	gas-only case
h	associated with difference in head
hom	homogeneous
HE	heated equivalent
HY	hydraulic equivalent
in	inlet
m	mean
NU	non-uniform heat flux
out	outlet
sat	saturation
U	uniform heat flux
v	vapour
w	wall

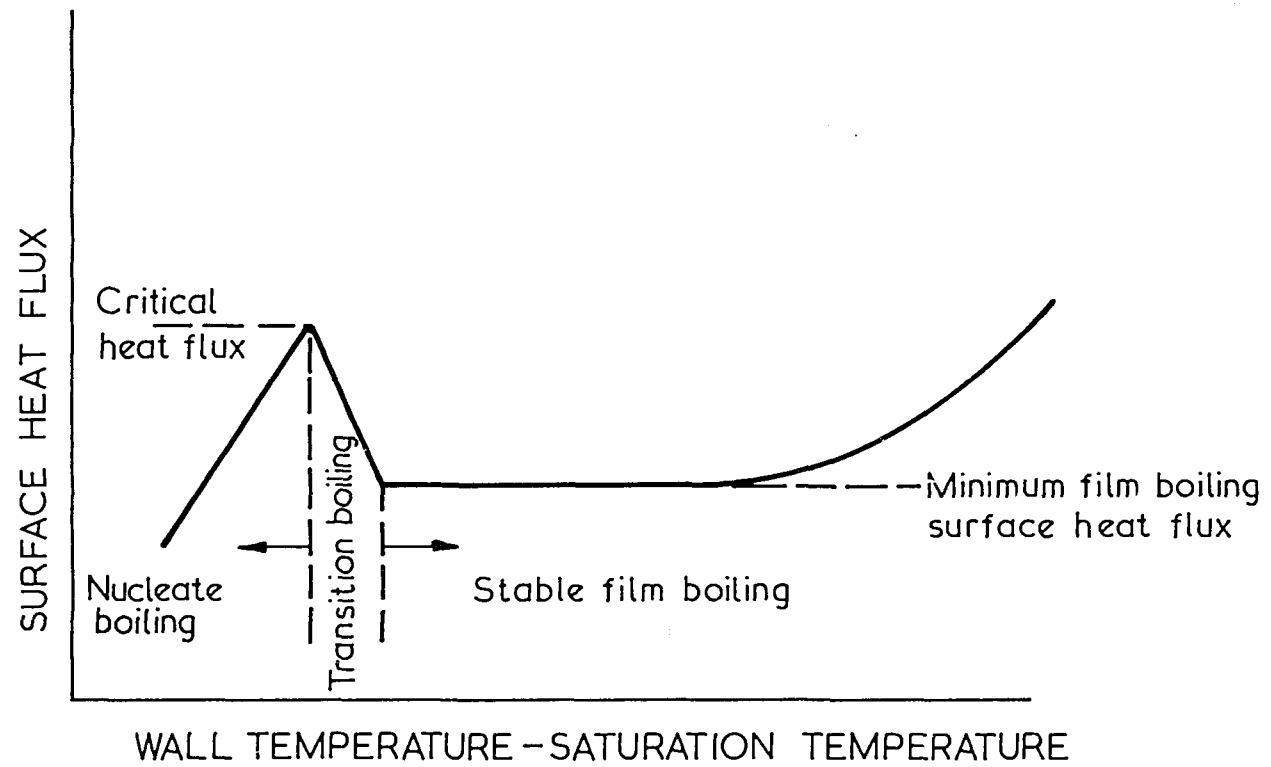


FIGURE 1. FLOW BOILING REGIONS

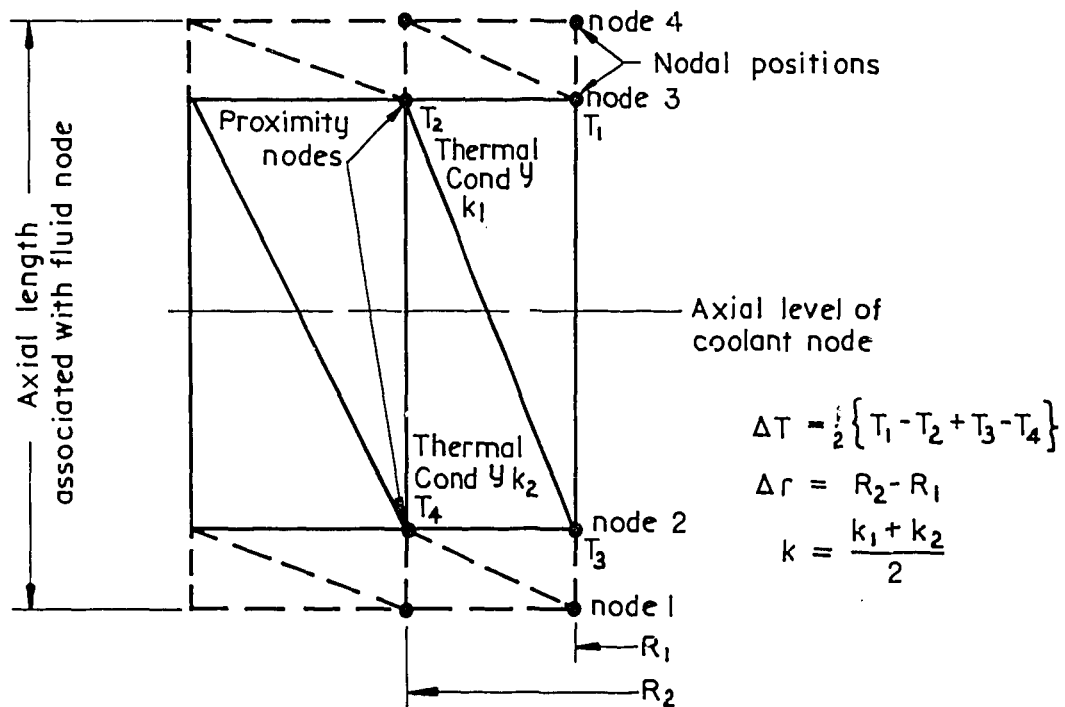
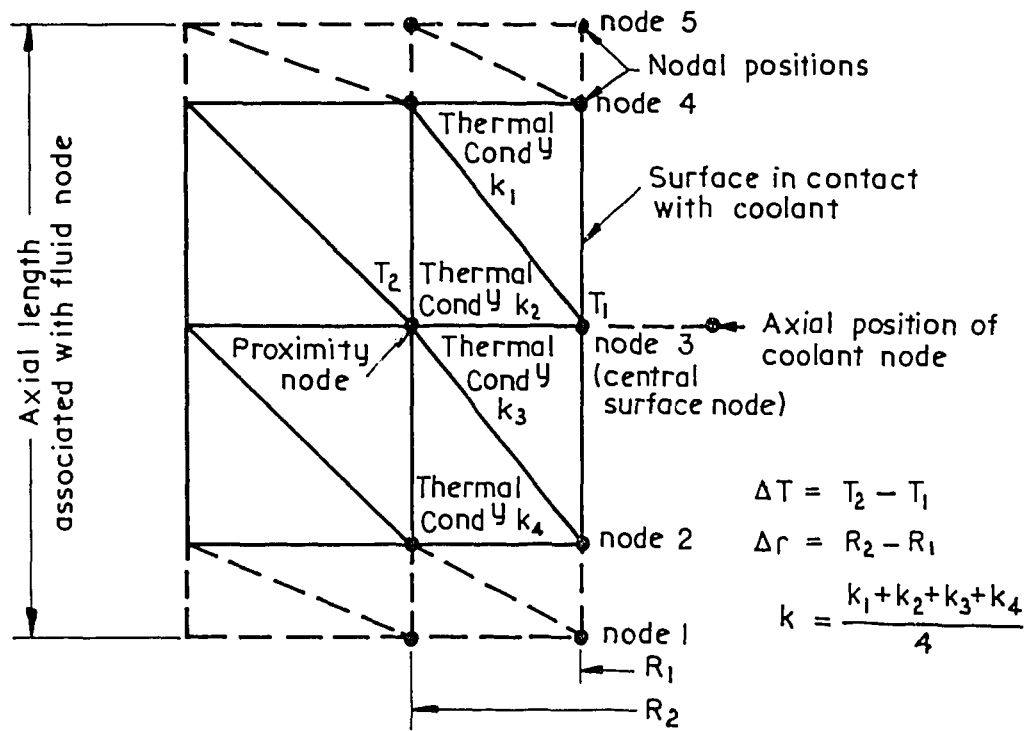


FIGURE 2. DETERMINATION OF THERMAL CONDUCTIVITIES AND TEMPERATURE DIFFERENTIALS OF FINITE ELEMENTS ASSOCIATED WITH A COOLANT NODE

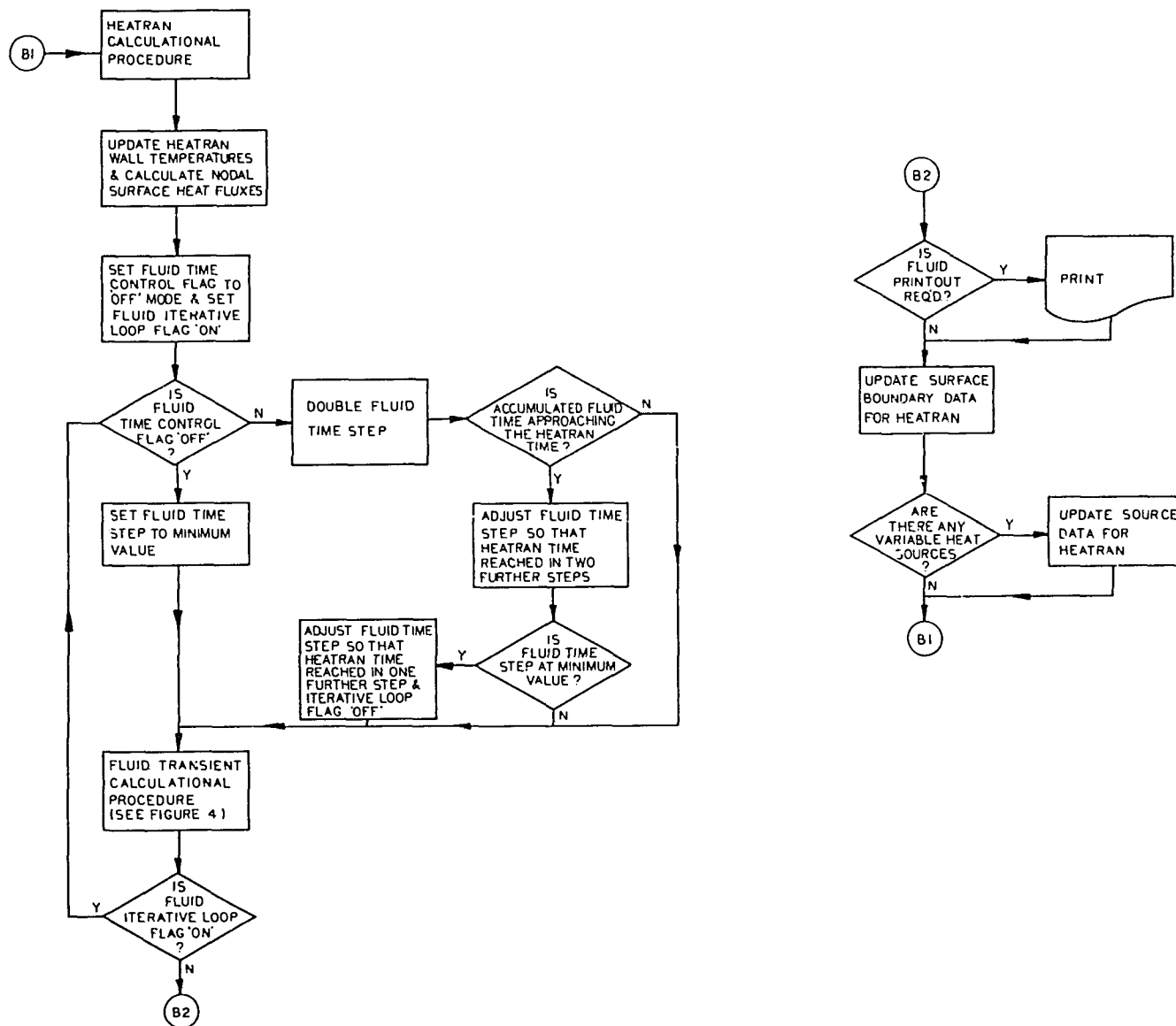


FIGURE 3. FLOWCHART OF LNKFLD, THE INTERFACING SUBROUTINE BETWEEN HEATRAN AND THE FLUID TRANSIENT CALCULATIONAL PROCEDURE

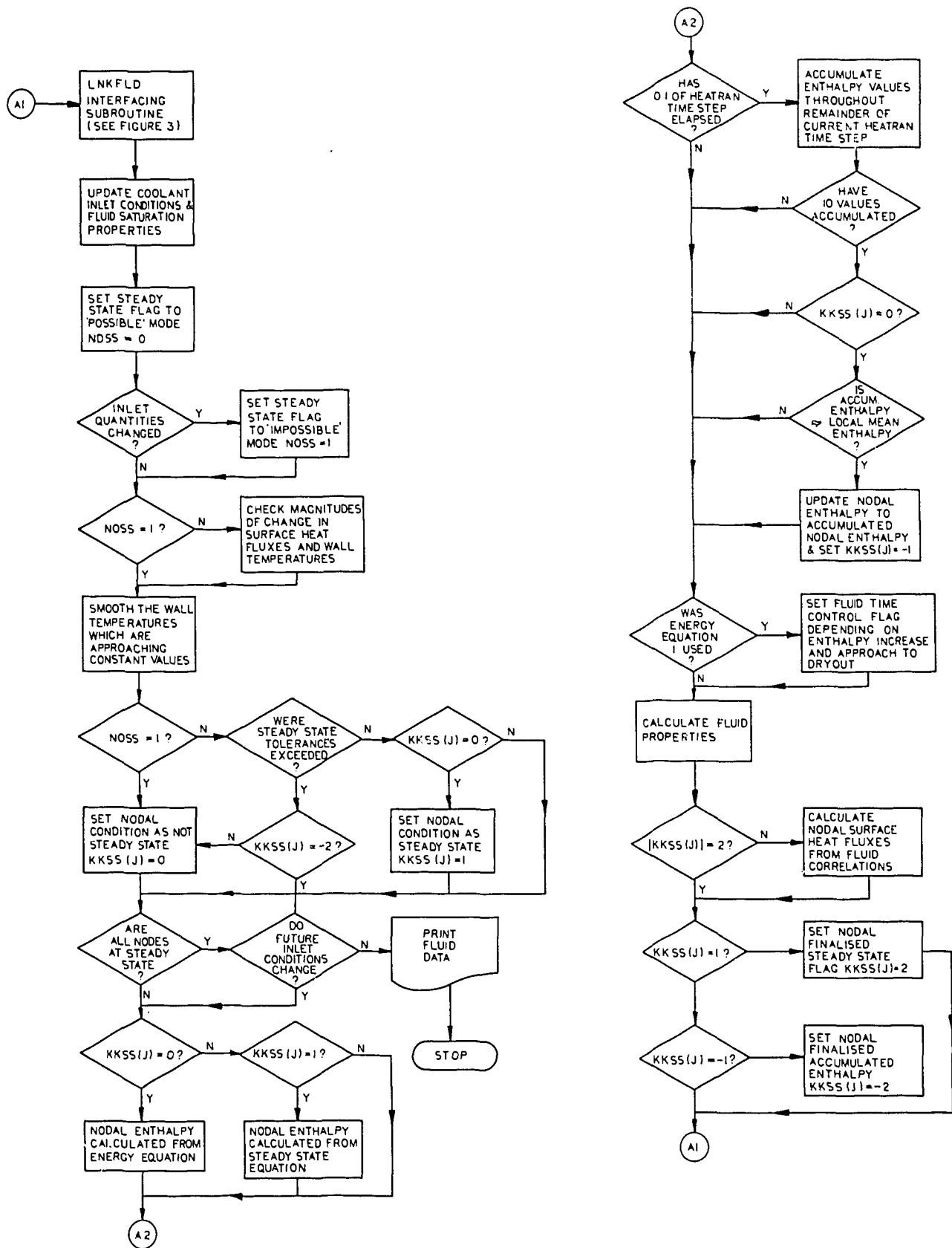


FIGURE 4. FLOWCHART OF FLUID TRANSIENT CALCULATIONAL PROCEDURE



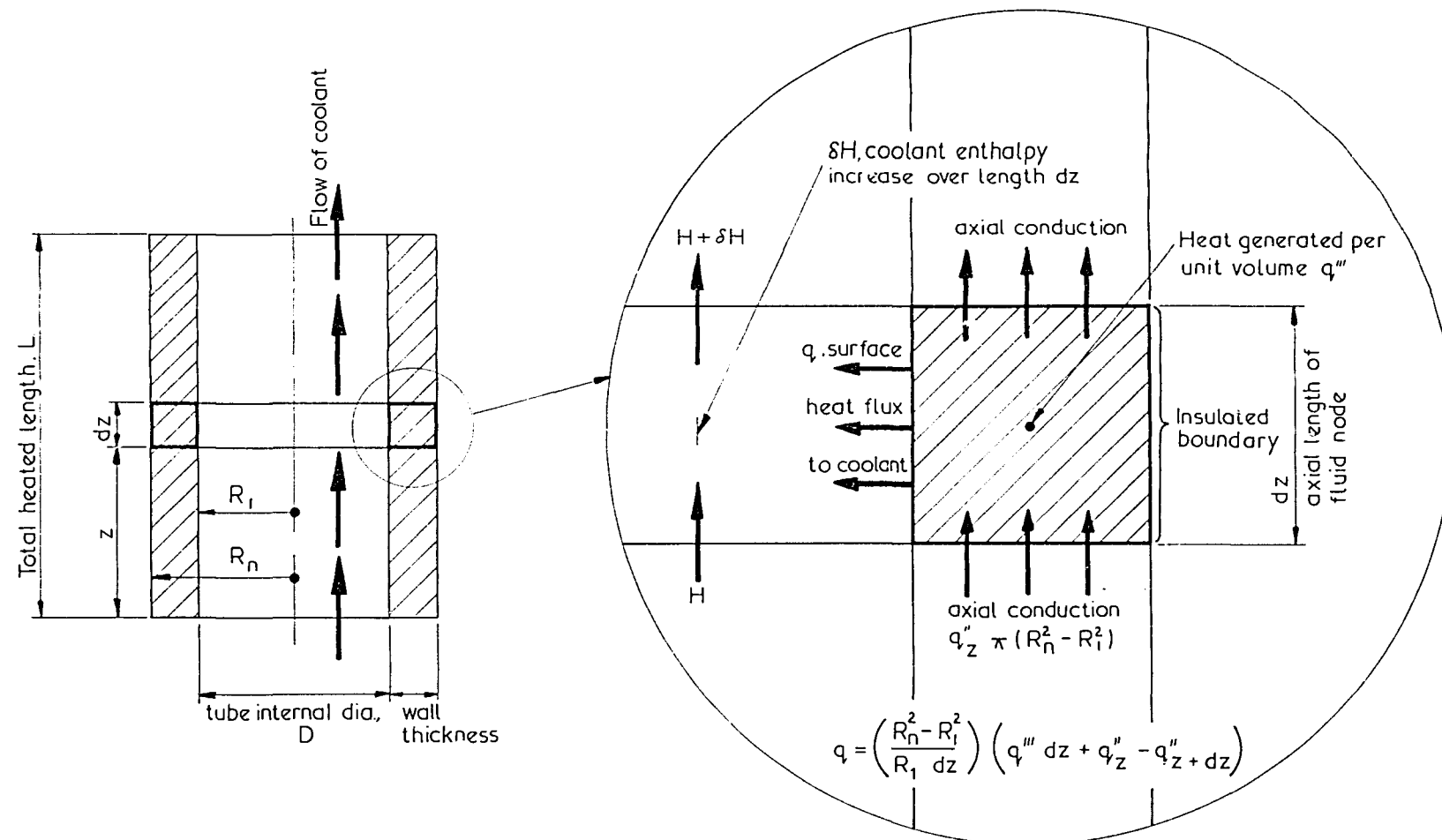


FIGURE 5. GEOMETRY OF TEST CASE AND DIAGRAMMATIC REPRESENTATION OF HEAT FLOWS

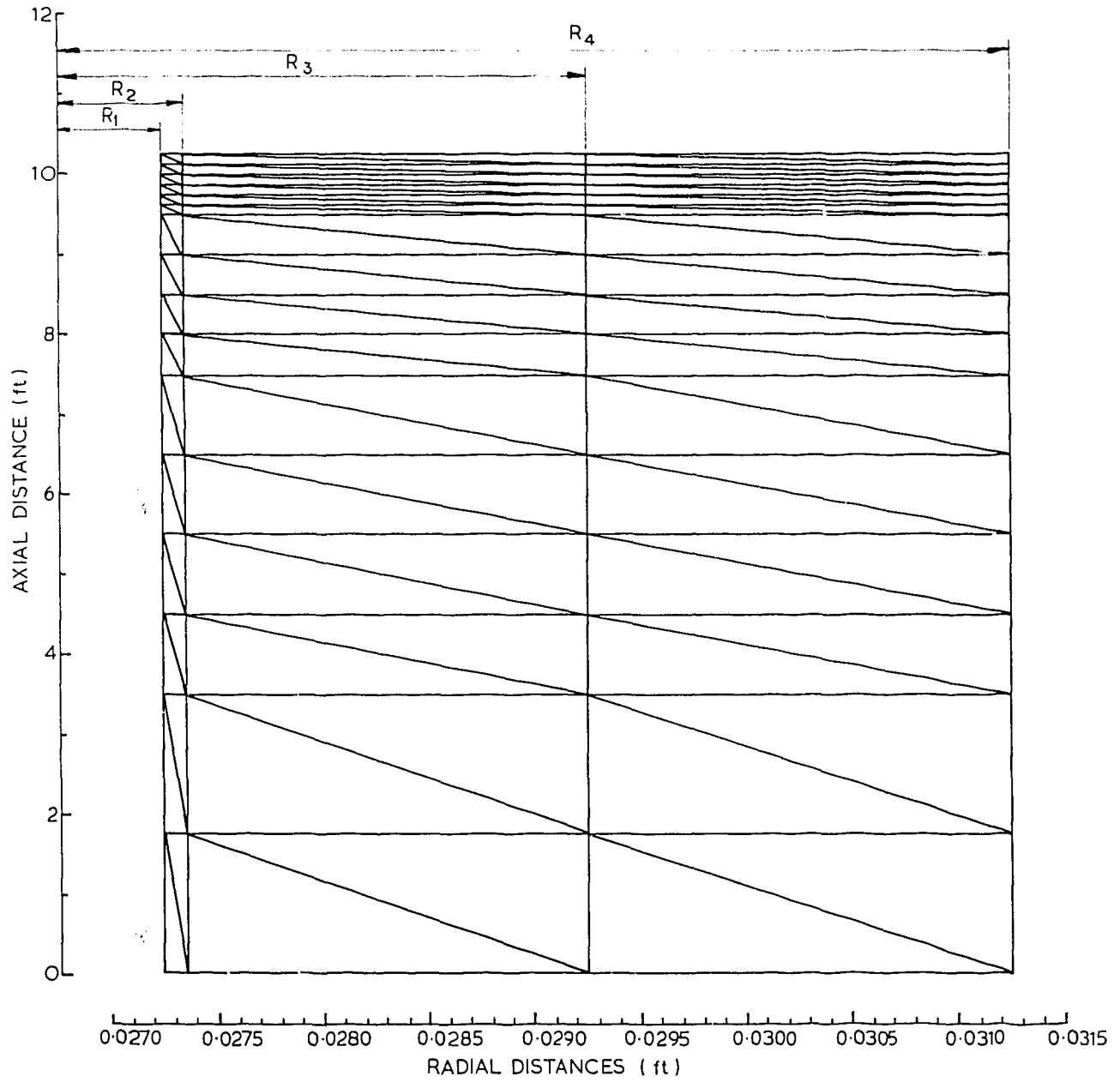


FIGURE 6. SAMPLE CASE NODAL ARRAY

APPENDIX A  
HEAT TRANSFER CORRELATIONS

A1. Pre-dryout Correlations

Forced convection in subcooled liquid and superheated vapour

(a) Dittus and Boelter [Jakob 1957]

$$ht = 0.023 \left\{ \frac{k}{D} \right\} (Pr)^{0.4} \left\{ \left( \frac{GD}{\mu} \right)^{0.8} \right\}$$

Suitable for both water and Freon-12.

Nucleate boiling

For units of T in °F, q in Btu ft<sup>-2</sup> h<sup>-1</sup> and p in psia:

(a) Jens and Lottes [1951]

$$T_w - T_{sat} = 60 (q/10^6)^{\frac{1}{4}} / [\exp(p/900)]$$

Developed from water data at pressures between 500 and 2000 psia.

(b) Thom et al. [1966]

$$T_w - T_{sat} = 0.072 (q)^{\frac{1}{2}} / [\exp(p/1260)]$$

Suitable only for water at pressures between 750 and 2000 psia.

(c) McAdams [1949]

$$q = 0.074 (T_w - T_{sat})^{3.86}$$

Developed from water data at pressure between 30 and 90 psia.

Forced convection vaporisation(a) Schrock and Grossman [1959]

$$ht = (2.50)(0.023) \left(\frac{k_f}{D}\right) (Pr_f)^{0.4} \left[\frac{GD(1-X)}{\mu_f}\right]^{0.8} \left[\frac{1}{x_{tt}}\right]^{0.75}$$

$$\frac{1}{x_{tt}} = \left(\frac{x}{1-x}\right)^{0.9} \left\{\frac{\rho_f}{\rho_g}\right\}^{0.5} \left\{\frac{\mu_g}{\mu_f}\right\}^{0.1}$$

Developed from water data at pressures between 40 and 500 psia.

(b) Chen [1966]

$$ht = ht_{nuc} + ht_{con}$$

where, for British Imperial units,

$$ht_{nuc} = \left\{ \frac{0.00122 k_f^{0.79} C_f^{0.45} \rho_f^{0.49} g^{0.25} B}{\sigma^{0.5} \mu_f^{0.29} (H_{fg} \rho_g)^{0.24}} \right\}$$

$$(T_w - T_{sat})^{0.24} (p_{sat,w} - p_{sat})^{0.75}$$

$$B = 1. / (1. + 2.53 \times 10^{-6} Re_f^{1.17} F^{1.4625})$$

$$F = 1. \text{ for } \frac{1}{x_{tt}} \leq 0.1$$

$$= 2.35 \left(\frac{1}{x_{tt}} + 0.213\right)^{0.736} \text{ for } \frac{1}{x_{tt}} > 0.1 \text{ and}$$

$$ht_{con} = F \cdot 0.023 \left(\frac{k_f}{D}\right) (Re_f)^{0.8} (Pr_f)^{0.4}$$

A2. CHF Correlations(a) Westinghouse W-3 correlation [Tong 1969]

$$q_{CHF,U} = (10^6) \left\{ (2.022 - 0.0004302 p) + (0.1722 - 0.0000984 p) * \right.$$

$$\left. \exp [(18.177 - 0.004129 p) x_{CHF}] \right\} * [1.157 - 0.869 x_{CHF}] *$$

$$\begin{aligned} & [(0.1484 - 1.596 X_{CHF} + 0.1729 X_{CHF} | X_{CHF} |)(G/10^6) + 1.037] * \\ & [0.2664 + 0.8357 * \exp(-3.151 D_E)] * \\ & [0.8258 + 0.000794 (h_{fsat} - h_{in})] F_s \end{aligned}$$

where  $F_s = 1.0 + 0.03 (G/10^6) (TDC/0.019)^{0.35}$ , and TDC is an empirical mixing factor.

$$F = \frac{q_{CHF,U}}{q_{CHF,NU}}$$

$$F = \frac{c \int_{L_{incipient}}^{L_{CHF}} q(z) \exp[-C(L_{CHF}-z)] dz}{q_{local} [1 - \exp(-CL_{CHF,U})]} \quad \text{and}$$

$$C = \frac{(12) (0.44) (1 - X_{CHF})^{7.9}}{(G/10^6)^{1.72}}$$

Since the flux factor (F) was developed only for steady state conditions, it is not used for transient conditions.

Developed from data obtained using high pressure water in circular and rectangular tubes and within a narrow range of quality.

(b) General Electric correlation [Janssen and Levy 1962]

$$\begin{aligned} q_{CHF, p=1000} &= 10^6 [0.705 + 0.237 (G/10^6)] & X_{CHF} < X_1 \\ &= 10^6 [1.634 - 0.270 (G/10^6) - 4.71 X_{CHF}] & X_1 < X_{CHF} < X_2 \\ &= 10^6 [0.605 - 0.164 (G/10^6) - 0.653 X_{CHF}] & X_2 < X_{CHF} \\ X_1 &= 0.197 - 0.108 (G/10^6) \\ X_2 &= 0.254 - 0.026 (G/10^6) \end{aligned}$$

For pressures other than 1000 psia.

$$q_{CHF,p} = q_{CHF, p=1000} + 440 (1000 - p)$$

Developed from data obtained using high pressure water in tubes.

(c) Macbeth [1964]

$$q_{CHF} = 10^6 \left[ \frac{A + 0.25 D (G/10^6) (h_{fsat} - h_{in})}{B + L} \right]$$

$$A = 67.6 D^{0.83} (G/10^6)^{0.57}$$

$$B = 47.3 D^{0.57} (G/10^6)^{0.27}$$

Developed from data obtained from using water at 1000 psia in rod bundles.

(d) Babcock and Wilcox B and W-2 correlation [Gellerstedt et al. 1969]

$$q_{CHF} = \left\{ \frac{1.15509 - 0.40703 D_e}{(12.710) [3.0545 (G/10^6)]^A} \right\} \left\{ (0.3702 \times 10^8) [0.59137 (G/10^6)]^B - 0.15208 X_{CHF} h_{fg} (G) \right\}$$

$$A = 0.71186 + (0.20729 \times 10^{-3}) (p - 2000)$$

$$B = 0.8340 + (0.68479 \times 10^{-3}) (p - 2000)$$

$$F = \frac{q_{CHF,U}}{q_{CHF,NU}}$$

$$F = \frac{1.025C \int_0^{L_{CHF}} q(z) \exp[-C(L_{CHF}-z)] dz}{q_{local} [1 - \exp(-CL_{CHF,U})]} \quad \text{and}$$

$$C = \frac{(12) (0.249) (1 - X_{CHF})^{7.8}}{(G/10^6)^{0.457}}$$

Since the flux factor (F) was developed only for steady state conditions, it is not used for transient conditions.

Developed from data obtained using high pressure water in rod bundles.

(e) Modified Barnett [Hughes 1970]

$$q = 10^6 \left[ \frac{A + B (h_{fsat} - h_{in})}{C + L} \right]$$

$$A = 73.71 D_{HE}^{0.052} (G/10^6)^{0.663} \left( \frac{888.6}{h_{fg}} \right)$$

$$\left\{ 1 - 0.315 \exp[- 11.34 D_{HY} (G/10^6)] \right\}$$

$$B = 0.104 D_{HE}^{1.445} (G/10^6)^{0.691}$$

$$C = 45.55 D_{HY}^{0.0817} (G/10^6)^{0.5866}$$

Developed from data obtained using low pressure water in rod bundles.

(f) Barnett [1966]

$$q_{CHF} = (10^6) \left[ \frac{A + B (h_{fsat} - h_{in})}{C + L} \right]$$

$$A = 67.45 D_{HE}^{0.68} (G/10^6)^{0.192}$$

$$[1 - 0.744 \exp(- 6.512 D_{HY} (G/10^6))]$$

$$B = 0.2587 D_{HE}^{1.261} (G/10^6)^{0.817}$$

$$C = 185.0 D_{HY}^{1.415} (G/10^6)^{0.212}$$

$$D_{HY} = D_o - D_I$$

$$D_{HE} = \frac{D_o^2 - D_I^2}{D_I}$$

$$D_I = D_{rod}$$

$$D_o = \left[ D_{rod} + (D_{rod} + D_{HE}^*) \right]^{1/2}$$

$$D_{HE}^* = \frac{4 (\text{flow area})}{\pi S D_{rod}} \quad S = \sum_{\text{rods}} \frac{q_{rod}}{q_{max}}$$

Developed from data obtained from using water at 1000 psia in annuli.

(g) Becker [1967]

$$q_{CHF} = \left( \frac{G}{4L/D} \right) [(h_{fsat} - h_{in}) + x_{CHF} h_{fg}]$$

$$x_{CHF} = 0.68 \eta_1 \eta x_{RD}$$

$\eta$  is the ratio of heated to wetted perimeter,  $\eta_1$  is a correction factor that is a function of  $q$ ,  $x_{RD}$  is the burnout steam quality in a round duct at corresponding flow conditions. Both  $\eta_1$  and  $x_{RD}$  are presented in graphical form in Becker [1967].

Developed from data obtained using water at pressures  $< 1000$  psia in rod bundles.

(h) Combination of Westinghouse W-3 and General Electric correlations

$x$	$\leq$	0.0	W-3
$x$	$>$	0.15	GE
$0.0 < x$	$\leq$	0.15	Smaller of the two values predicted by the W-3 and GE correlations

(i) Combination of Westinghouse W-3 and Barnett correlations

$p \geq 1500$  psia          W-3

$p < 1500$  psia          Barnett

(j) Combination of Babcock and Wilcox B and W-2, Barnett and Modified Barnett correlations

$p \geq 1500$  psia          B and W-2

$1500 > p > 1300$  psia    Interpolation between B and W-2 and Barnett

$1300 \geq p \geq 1000$  psia    Barnett



1000 > p > 725 psia	Interpolation between Barnett and modified Barnett
725 psia $\geq$ p	Modified Barnett

In the latter option, the CHF value is based directly on the correlations when the mass flux is above 200 000 lb ft<sup>-2</sup> h<sup>-1</sup>. This mass flux was chosen as a lower limit to the validity of the correlations because these correlations only predict the available experimental data to within approximately 15 per cent down to this value. Since the capability of the correlations to predict the data below a mass flux of 200 000 lb ft<sup>-2</sup> h<sup>-1</sup> is in doubt, the following technique is employed to approximate a CHF value for the lower mass fluxes. The correlation for the particular pressure range is evaluated at the current pressure and at a mass flux of 200 000 lb ft<sup>-2</sup> h<sup>-1</sup>. Then an interpolation is performed between this value and the minimum allowable CHF value of 90 000 Btu ft<sup>-2</sup> h<sup>-1</sup>.

(k) Bertoletti et al. [1964]

$$q = \frac{0.417 H_{fg}}{\left[\frac{p_{cr}}{p} - 1\right]^{0.4} D^{0.4}} \left\{ \frac{\left(1 - \frac{p}{p_{cr}}\right)}{(G/100)^{1/3}} - x_{OUT} \right\}$$

(expressed in c.g.s. units).

Developed for Freon-12.

(l) Modified Bertoletti [Green 1978]

$$q = \frac{0.417 H_{fg}}{\left[\frac{p_{cr}}{p} - 1\right]^{0.4} D^{0.5}} \left\{ \frac{\left[1 - \frac{p}{p_{cr}}\right]}{(G/100)^{1/3}} - 0.9 x_{OUT} \right\}$$

(expressed in c.g.s. units).

Developed from Freon-12 data from round tubes.

(m) Groeneveld [1969b]

$$q = A D^b f(L/D) f(G) f(X_{OUT})$$

where for British Imperial units

$$A = (12)^{-0.362713}$$

$$b = -0.362713$$

$$f(L/D) = 9.71043 \times 10^6 - 2.174 \times 10^4 (L/D) + 42.2492 (L/D)^2$$

$$f(G) = 1.16244 \times 10^{-2} - 1.15061 \times 10^{-2} (G/10^6) + 6.28448 \times 10^{-3} (G/10^6)^2 \\ - 1/17288 \times 10^{-3} (G/10^6)^3$$

$$f(X_{OUT}) = 1.36368 - 2.88422 (X_{OUT}) + 3.5288 (X_{OUT})^2 - 2.23072 (X_{OUT})^3$$

Developed for Freon-12 data from round tubes.

(n) Modified Groeneveld [Green 1978]

As shown above excepting that for  $L/D > 200$

$$f(L/D) = 10^6 (7.762663 - 0.00352533 (L/D))$$

and for  $X_{OUT} > 0.6$

$$f(X_{OUT}) = 0.7242012 - 0.5042012 X_{OUT}$$

Developed from Freon-12 data from round tubes.

A3. Post-dryout CorrelationsTransition boiling(a) McDonough, Milich and King [1958]

$$q = q_{CHF} - CC (T_w - T_{w,CHF})$$

<u>p in psia</u>	<u>CC</u>
2000	0.306
1200	0.328
800	0.417

Developed from water data obtained from round tubes.

Stable film boiling(a) Dougall and Rohsenow [1963]

$$ht_{DG} = 0.023 \left\{ \frac{k_g}{D} \right\} (Pr_g)^{0.4} \left[ \left( \frac{\rho_g D}{\mu_g} \right) \left( \frac{Q_g + Q_f}{A_{flow}} \right) \right]^{0.8}$$

Developed from Freon-113 data obtained from round tubes.

(b) Modified Dougall and Rohsenow [Green 1978]

$$ht = ht_{DG} * 7.04 \left\{ \frac{D}{L_{sat}} \right\}^{0.4} \left\{ 1 + 3.65 e^{-0.0347 (T_w - T_{sat}) \left( \frac{L_{sat}}{L} \right)} \right\}$$

where  $T_w - T_{sat}$  is in °C.

Developed from Freon-12 data from round tubes.

(c) Miropol'skii [1963]

$$ht_M = 0.023 \left\{ \frac{k_g}{D} \right\} (Pr_{v,w})^{0.8} \left[ (GD/\mu_g) \left\{ x + \frac{\rho_g}{\rho_f} (1 - x) \right\} \right]^{0.8y}$$

$$Y = 1 - 0.1 (1 - X)^{0.4} \left( \frac{\rho_f}{\rho_g} - 1 \right)^{0.4}$$

Developed from data obtained using high pressure water in round tubes.

(d) Modified Miropol'skii [Green 1978]

$$ht = ht_M * 10.6 \left\{ D/L_{sat} \right\}^{0.4} \left\{ 1 + 3.65 e^{-0.0347 (T_w - T_{sat}) (L_{sat}/L)} \right\}$$

where  $T_w - T_{sat}$  is in °C.

Developed from Freon-12 data from round tubes.

(e) Groeneveld [1969a]

$$ht = 3.27 * 10^{-3} \left\{ \frac{K_g}{D} \right\} (Pr_{v,w})^{1.32} \left[ (GD/\mu_g) \left( X + \frac{\rho_g}{\rho_f} (1-X) \right) \right]^{0.901} Y^{-1.5}$$

$$Y = 1 - 0.1 (1-X)^{0.4} \left( \frac{\rho_f}{\rho_g} - 1 \right)^{0.4}$$

Developed from data obtained using high pressure water in round tubes and annuli.

#### Pool film boiling

(a) Berenson [1961]

$$ht = 0.425 \left[ \frac{k_g^3 \rho_g (\rho_f - \rho_g) g h_{fg}}{\mu_g \Delta T_{sat} \left( \frac{\lambda_c}{2\pi} \right)} \right]^{1/4}$$

$$\frac{\lambda_c}{2\pi} = \left[ \frac{g_0 \sigma}{g (\rho_f - \rho_g)} \right]^{1/2}$$

Developed in British Imperial units from data obtained using carbon tetrachloride and n-pentane at atmospheric pressure, and horizontal flat plates.

APPENDIX B  
TWO-PHASE FRICTION AND SLIP CORRELATIONS

B1. Two-Phase Friction Correlations

(a) Homogeneous theory [Engineering Sciences Data Unit 1976]

$$\frac{dp}{dz} = - \frac{2 G^2}{D \rho_{\text{hom}}} f_{\text{hom}}$$

where

$$\frac{1}{\rho_{\text{hom}}} = \frac{X}{\rho_g} + \frac{1-X}{\rho_f}$$

$$f_{\text{hom}} = 0.046 \text{Re}_{\text{hom}}^{-0.2}$$

$$\text{Re}_{\text{hom}} = \frac{GD}{\mu_{\text{hom}}}$$

and

$$\frac{1}{\mu_{\text{hom}}} = \frac{X}{\mu_g} + \frac{1-X}{\mu_f}$$

(b) Lockhart and Martinelli [Engineering Science Data Unit 1976]

$$\frac{dp}{dz} = \phi_g^2 \left( \frac{dp}{dz} \right)_g$$

where

$$\left( \frac{dp}{dz} \right)_g = - \frac{2 X^2 G^2 f_g}{\rho_g D}$$

$$f_g = 0.046 \text{Re}_g^{-0.2}$$

$$\text{Re}_g = \frac{XGD}{\mu_g}$$

and

$$x = \sqrt{\left(\frac{dp}{dz}\right)_f / \left(\frac{dp}{dz}\right)_g}$$

$$\left(\frac{dp}{dz}\right)_f = - \frac{2 (1 - x)^2 G^2 f_f}{\rho_f D}$$

$$f_f = 0.046 \text{Re}_f^{-0.2}$$

$$\text{Re}_f = (1 - x) \frac{GD}{\mu_f}$$

$\phi_g$  is determined from various relationships between  $\phi_g$  and  $x$  depending upon the Reynolds numbers  $\text{Re}_f$  and  $\text{Re}_g$ .

(c) Modified Martinelli and Nelson [Collier 1972]

$$\frac{dp}{dz} = \left\{ 1 + \frac{11}{6} \left(\frac{1}{x} - 1\right) x^{5/6} \right\} \left(\frac{dp}{dz}\right)_{fo}$$

where

$$x = \frac{\rho_g}{\rho_f} / \left(\frac{\mu_g}{\mu_f}\right)^{0.2}$$

$$\left(\frac{dp}{dz}\right)_{fo} = - \frac{2 G^2 f_{fo}}{D \rho_f}$$

$$f_{fo} = 0.046 \text{Re}_{fo}^{-0.2}$$

$$\text{Re}_{fo} = GD/\mu_f$$

(d) Thom et al. [1966]

$$\frac{dp}{dz} = \phi_{fo}^2 \left(\frac{dp}{dz}\right)_{fo}$$

$$\phi_{fo}^2 = 1 + (\Gamma^2 - 1) x$$

$$\Gamma^2 = \left(\frac{dp}{dz}\right)_{go} / \left(\frac{dp}{dz}\right)_{fo}$$

$$\left(\frac{dp}{dz}\right)_{go} = - \frac{2 G^2 f_{go}}{D \rho_g}$$

$$f_{go} = 0.046 \operatorname{Re}_{go}^{-0.2}$$

$$\operatorname{Re}_{go} = \frac{GD}{\mu_g}$$

B2. Slip Correlations

(a) Homogeneous [Collier 1972]

$$S = 1.0$$

(b) Bankoff-Jones [Jones 1961]

$$S = \frac{1 - \alpha}{\operatorname{CCC} - \alpha + (1 - \operatorname{CCC})\alpha^R}$$

$$\operatorname{CCC} = 0.71 + \frac{0.29}{0.32062} \left( \frac{p}{10\,000} \right)$$

$$R = 3.53125 - 0.1875 \left( \frac{p}{1000} \right) + 0.58594 \left( \frac{p}{1000} \right)^2$$

where p is in psia.

(c) Fauske [1962]

$$S = \sqrt{\rho_f / \rho_g}$$

APPENDIX C  
INPUT DATA FOR FLUID SECTIONS

Data Group	Format	Field	Option	General Description
1	(20A4)			Alphanumeric title
2	(16I5)	1		Nuclear boiling correlations
			1	Jens and Lottes
			2	Thom
			3	McAdams
		2		Forced convection vaporisation correlations
			1	Schrock and Grossman
			2	Chen
		3		Transition boiling correlations
			1	McDonough et al.
			2	Modified McDonough et al.
		4		Stable film boiling correlations
			1	Dougall and Rohsenow
			2	Modified Dougall and Rohsenow
			3	Miropol'skii
			4	Modified Miropol'skii
			5	Groeneveld
		5		Critical heat flux correlations
			1	Westinghouse W-3 (W*)
			2	General Electric design limit (W)
			3	Westinghouse W-3 and General Electric design limit (W)
			4	Macbeth rod bundle (W)
			6	Becker rod bundle (W)
			5	Barnett rod bundle (W)
			7	Westinghouse W-3 and Barnett (W)
			8	Gellerstedt et al. (W)
			9	(Hughes) modified Barnett (W)
			10	Gellerstedt et al. and (Hughes) modified Barnett (W)
			11	Bertoletti (F**)
			12	Modified Bertoletti (F)
			13	Groeneveld (F)
			14	Modified Groeneveld (F)



		6		Coolant
			0	Water
			1	Freon
		7		Output options
			0	Exclude interface data
			1	Include interface data
			2	Output reduced to match HEATRAN TIME card
3	(16I5)	1		Slip velocity ratio correlations
			1	User input value
			2	Homogeneous
			3	(Jones) modified Bankoff
			4	Fauske
		2		2-phase frictional pressure drop correlations
			0	No pressure drop <sup>+</sup>
			1	Homogeneous
			2	Lockhart and Martinelli
			3	Thom
			4	Martinelli and Nelson
		3		Energy equations
			1	Explicit numerical scheme
			2	Implicit numerical scheme
			3	Lax-Wendroff numerical scheme
			4	Method of characteristics scheme
4	(16I5)	1		Number of inlet pressure - time pairs (100 maximum)
		2		Number of mass flux - time pairs (100 maximum)
		3		Number of inlet enthalpy - time pairs (100 maximum)
5	(6E12.6)	1-6		Pairs of inlet pressure (psia) and corresponding time (s)
6	(6E12.6)	1-6		Pairs of mass flux ( $\text{lb s}^{-1} \text{ft}^{-2}$ ) and corresponding time (s)
7	(6E12.6)	1-6		Pairs of inlet enthalpy ( $\text{Btu lb}^{-1}$ ) and corresponding time (s)
8	(16I5)	1		Number of time variant sources (20 maximum)

IF DG8F1 = 0

			skip to 10	
9	(16I5)	1-16		Source numbers for time variant sources. (These must match the source numbers specified in the HEATRAN input data.)
9A	(16I5)	1-16		Number of source-time pairs for each time variant source (10 maximum for each source)
9B	(6E12.6)	1-6		Pairs of source factors <sup>++</sup> and corresponding time (s)
10	(6E12.6)	1		Tube inner diameter (in.)
		2		Tube outer diameter (in.)
		3		Hydraulic diameter (in.)
		4		Flow area (in. <sup>2</sup> )
		5		Slip velocity ratio value (only required if data group 3 field 1 option 1 specified)
			IF DG2F5 is not 1,3 or 7, skip to 12	
11	(6E12.6)	1		Thermal diffusion coefficient used in W-3 CHF correlation
12	(8F10.0)	1		Minimum fluid timestep
		2		Tolerance on rate of change of heat flux (Btu ft <sup>-2</sup> s <sup>-2</sup> )
		3		Tolerance on rate of change of wall temperature (°F s <sup>-1</sup> )
		4		Enthalpy tolerance (Btu lb <sup>-1</sup> )
		5		Voidage value to delineate between regimes

---

\* W denotes suitable for water

\*\* F denotes suitable for Freon-12

<sup>+</sup> This option should be used for conditions in which the mass flux is a significant function of time (see Section 2.3.1.)

<sup>++</sup> Any source data given on the HEATRAN input cards which are to be functions of time are varied by the appropriate factors specified in this data block.

APPENDIX D  
DATA INPUT FOR SAMPLE TEST CASE

```

//GO.FT01F001 DD *
*TEST CASE
GEOM RZ
NODE 1 0.03125 0. (-.002 0. -.0039 0. -.004 0.)/0. 1.7325 TO 3
      4 0.03125 4.465(-.002 0. -.0039 0. -.004 0.)/0. 1. TO 7
      8 0.03125 7.965(-.002 0. -.0039 0. -.004 0.)/0. .5 TO 11
      12 0.03125 9.59 (-.002 0. -.0039 0. -.004 0.)/0. .125 TO 17
CONN 1(1-2--4)(1A84)1-2-3
      4(1-2--4)(1A84)4-5--7
      8(1-2--4)(1A84)8-9--11
      12(1-2--4)(1A84)12-13--17
      4,1-3,1-4,2-3,2-4,3-3,3-4,4-3,4
      8,1-7,1-8,2-7,2-8,3-7,3-8,4-7,4
      12,1-11,1-12,2-11,2-12,3-11,3-12,4-11,4
FAHR
MAP
INRE .02725 0. 0. .004 9.465 1 S 1
INRE .02725 9.465 0. .004 10.215 1 S 2
MATE 1 501. 9. .1
SOUR 1 0. 5595120.
      2 0. 2673103.
BOUN 1,4-1,3--17,4 1 1,4-2,4-3,4 2 3,4-4,4-5,4 3 5,4-6,4-7,4 4
      7,4-8,4-9,4 5 9,4-10,4-11,4 6 11,4-12,4-13,4 7 13,4-14,4-15,4 8
      15,4-16,4-17,4 9
BC 1 1. 0. 0.
    2 FLUI 3 300. 300. 300.
    3 FLUI 3 300. 300. 300.
    4 FLUI 3 300. 300. 300.
    5 FLUI 3 300. 300. 300.
    6 FLUI 3 300. 300. 300.
    7 FLUI 3 300. 300. 300.
    8 FLUI 3 300. 300. 300.
    9 FLUI 3 300. 300. 300.
SOLV
OUT PRIN
TIME 0. .0001 .0002 .0004
ROUT PRIN
SOLV
NEXT
/*
//GO.FT05F001 DD *
TEST CASE
      3 1 2 2 14 1 2
      2 1 2
      2 2 2
132.78 0. 132.78 50.
96.52 0. 96.52 50.
25.4 0. 25.4 50.
      2
      1 2
      4 3
1. 0. 1. 2.7 1.3 5.76
1.3 50.
1. 0. 4.0 1.8 4.0 50.
.654 .654 .33593
.002 .001 1. .0001 1.
/*

```

APPENDIX E  
DATA OUTPUT FOR SAMPLE TEST CASE

11:31:07 9JAN80

```

*TFST CASE

GRUM PZ
NODE 1 0.03125 0. (-.002 0. -.0039 0. -.004 0.)/0. 1.7325 TO 3
      4 0.03125 4.465(-.002 0. -.0039 0. -.004 0.)/0. 1. TO 7
      8 0.03125 7.965(-.002 0. -.0039 0. -.004 0.)/0. .5 TO 11
      12 0.03125 9.59 (-.002 0. -.0039 0. -.004 0.)/0. .125 TO 17
CONN 1(1-2--4)(1A84)1-2-3
      4(1-2--4)(1A84)4-5--7
      3(1-2--4)(1A84)8-9--11
      12(1-2--4)(1A84)12-13--17
      4,1-3,1-4,2-3,2-4,3-3,3-4,4-3,4
      8,1-7,1-8,2-7,2-3,3-7,3-8,4-7,4
      12,1-11,1-12,2-11,2-12,3-11,3-12,4-11,4
FAHR
MAP
INRF .02725 0. 0. .004 9.465 1 S 1
INRF .02725 9.465 0. .004 10.215 1 S 2
MATC 1 501. 9. .1
SCLR 1 0. 9595120.
      2 0. 2670103.
BOUN 1,4-1,3--17,4 1 1,4-2,4-3,4 2 3,4-4,4-5,4 3 5,4-6,4-7,4 4
      7,4-8,4-9,4 5 9,4-10,4-11,4 6 11,4-12,4-13,4 7 13,4-14,4-15,4 8
      15,4-16,4-17,4 9
BC 1 1. 0. 0.
    2 FLUI 3 300. 300. 300.
    3 FLUI 3 300. 300. 300.
    4 FLUI 3 300. 300. 300.
    5 FLUI 3 300. 300. 300.
    6 FLUI 3 300. 300. 300.
    7 FLUI 3 300. 300. 300.
    8 FLUI 3 300. 300. 300.
    9 FLUI 3 300. 300. 300.
SILV
BANDWIDTH=5

```

(Continued)

## HEAT BALANCE

INITIAL VERSION ONLY  
 ONLY FIXED SOURCE AND SIMPLE BOUNDARIES AS YET  
 WILL BE EXTENDED AS NEED ARISES ,SEE E.HESSE

## HEAT TRANSFER ACROSS BOUNDARIES

1, 4- 17, 4 REFLECTIVE BOUNDARY  
 1, 4- 3, 4 FLUI TYPE NOT AVAILABLE  
 3, 4- 5, 4 FLUI TYPE NOT AVAILABLE  
 5, 4- 7, 4 FLUI TYPE NOT AVAILABLE  
 7, 4- 9, 4 FLUI TYPE NOT AVAILABLE  
 9, 4-11, 4 FLUI TYPE NOT AVAILABLE  
 11, 4-13, 4 FLUI TYPE NOT AVAILABLE  
 13, 4-15, 4 FLUI TYPE NOT AVAILABLE  
 15, 4-17, 4 FLUI TYPE NOT AVAILABLE

TOTAL FOR ALL BOUNDARIES 0.0

## HEAT INPUT

ELEMENT	SOURCE TYPE	HEAT INPUT	VOLUME
1, 1-	1, 2-	2, 2	1
1, 1-	2, 2-	2, 1	1
1, 2-	2, 2-	2, 3	1
1, 2-	2, 3-	1, 3	1
1, 3-	2, 3-	2, 4	1
1, 3-	2, 4-	1, 4	1
2, 1-	2, 2-	3, 2	1
2, 1-	3, 2-	3, 1	1
2, 2-	2, 3-	3, 3	1
2, 2-	3, 3-	3, 2	1
2, 3-	3, 3-	3, 4	1
2, 3-	3, 4-	2, 4	1
3, 1-	3, 2-	4, 2	1
3, 1-	4, 2-	4, 1	1
3, 2-	3, 3-	4, 3	1
3, 2-	4, 3-	4, 2	1
3, 3-	3, 4-	4, 4	1
3, 3-	4, 4-	4, 3	1
4, 1-	4, 2-	5, 2	1
4, 1-	5, 2-	5, 1	1
4, 2-	4, 3-	5, 3	1
4, 2-	5, 3-	5, 2	1
4, 3-	4, 4-	5, 4	1
4, 3-	5, 4-	5, 3	1
5, 1-	5, 2-	6, 2	1
5, 1-	6, 2-	6, 1	1
5, 2-	5, 3-	6, 3	1
5, 2-	6, 3-	6, 2	1
5, 3-	5, 4-	6, 4	1
5, 3-	6, 4-	6, 3	1
6, 1-	6, 2-	7, 2	1

(Continued)

6, 1-	7, 2-	7, 1	1	1.0752E+03	1.9216E-04
6, 2-	6, 3-	7, 3	1	9.3457E+C2	1.6703E-04
6, 2-	7, 3-	7, 2	1	9.5572E+02	1.7081E-04
6, 3-	6, 4-	7, 4	1	4.7955E+01	8.5708E-06
6, 3-	7, 4-	7, 3	1	4.8013E+01	8.5813E-06
7, 1-	7, 2-	8, 2	1	5.2586E+02	9.3986E-05
7, 1-	8, 2-	8, 1	1	5.3758E+02	9.6080E-05
7, 2-	7, 3-	8, 3	1	4.6729E+02	8.3517E-05
7, 2-	8, 3-	8, 2	1	4.7786E+02	8.5407E-05
7, 3-	7, 4-	8, 4	1	2.3977E+01	4.2854E-06
7, 3-	8, 4-	8, 3	1	2.4007E+01	4.2906E-06
8, 1-	8, 2-	9, 2	1	5.2586E+02	9.3986E-05
8, 1-	9, 2-	9, 1	1	5.3758E+02	9.6080E-05
8, 2-	8, 3-	9, 3	1	4.6729E+02	8.3517E-05
8, 2-	9, 3-	9, 2	1	4.7786E+02	8.5407E-05
8, 3-	8, 4-	9, 4	1	2.3977E+01	4.2854E-06
8, 3-	9, 4-	9, 3	1	2.4007E+01	4.2906E-06
9, 1-	9, 2-	10, 2	1	5.2586E+02	9.3986E-05
9, 1-	10, 2-	10, 1	1	5.3758E+02	9.6080E-05
9, 2-	9, 3-	10, 3	1	4.6729E+02	8.3516E-05
9, 2-	10, 3-	10, 2	1	4.7786E+02	8.5406E-05
9, 3-	9, 4-	10, 4	1	2.3977E+01	4.2854E-06
9, 3-	10, 4-	10, 3	1	2.4007E+01	4.2906E-06
10, 1-	10, 2-	11, 2	1	5.2586E+02	9.3986E-05
10, 1-	11, 2-	11, 1	1	5.3758E+02	9.6080E-05
10, 2-	10, 3-	11, 3	1	4.6729E+02	8.3517E-05
10, 2-	11, 3-	11, 2	1	4.7786E+02	8.5407E-05
10, 3-	10, 4-	11, 4	1	2.3977E+01	4.2854E-06
10, 3-	11, 4-	11, 3	1	2.4007E+01	4.2906E-06
11, 1-	11, 2-	12, 2	2	6.2737E+01	2.3497E-05
11, 1-	12, 2-	12, 1	2	6.4137E+01	2.4020E-05
11, 2-	11, 3-	12, 3	2	5.5751E+01	2.0880E-05
11, 2-	12, 3-	12, 2	2	5.7013E+01	2.1352E-05
11, 3-	11, 4-	12, 4	2	2.8607E+00	1.0714E-06
11, 3-	12, 4-	12, 3	2	2.8642E+00	1.0727E-06
12, 1-	12, 2-	13, 2	2	6.2737E+01	2.3496E-05
12, 1-	13, 2-	13, 1	2	6.4135E+01	2.4020E-05
12, 2-	12, 3-	13, 3	2	5.5749E+01	2.0879E-05
12, 2-	13, 3-	13, 2	2	5.7011E+01	2.1352E-05
12, 3-	12, 4-	13, 4	2	2.8606E+00	1.0713E-06
12, 3-	13, 4-	13, 3	2	2.8641E+00	1.0726E-06
13, 1-	13, 2-	14, 2	2	6.2738E+01	2.3496E-05
13, 1-	14, 2-	14, 1	2	6.4136E+01	2.4020E-05
13, 2-	13, 3-	14, 3	2	5.5749E+01	2.0879E-05
13, 2-	14, 3-	14, 2	2	5.7011E+01	2.1352E-05
13, 3-	13, 4-	14, 4	2	2.8606E+00	1.0714E-06
13, 3-	14, 4-	14, 3	2	2.8641E+00	1.0727E-06
14, 1-	14, 2-	15, 2	2	6.2737E+01	2.3496E-05
14, 1-	15, 2-	15, 1	2	6.4135E+01	2.4020E-05
14, 2-	14, 3-	15, 3	2	5.5749E+01	2.0879E-05
14, 2-	15, 3-	15, 2	2	5.7011E+01	2.1352E-05
14, 3-	14, 4-	15, 4	2	2.8606E+00	1.0713E-06
14, 3-	15, 4-	15, 3	2	2.8641E+00	1.0726E-06
15, 1-	15, 2-	16, 2	2	6.2737E+01	2.3496E-05
15, 1-	16, 2-	16, 1	2	6.4135E+01	2.4020E-05
15, 2-	15, 3-	16, 3	2	5.5749E+01	2.0879E-05
15, 2-	16, 3-	16, 2	2	5.7011E+01	2.1352E-05
15, 3-	15, 4-	16, 4	2	2.8606E+00	1.0714E-06
15, 3-	16, 4-	16, 3	2	2.8641E+00	1.0727E-06
16, 1-	16, 2-	17, 2	2	6.2738E+01	2.3496E-05
16, 1-	17, 2-	17, 1	2	6.4136E+01	2.4020E-05
16, 2-	16, 3-	17, 3	2	5.5749E+01	2.0879E-05
16, 2-	17, 3-	17, 2	2	5.7011E+01	2.1352E-05
16, 3-	16, 4-	17, 4	2	2.8606E+00	1.0714E-06
16, 3-	17, 4-	17, 3	2	2.8641E+00	1.0727E-06

TOTAL FOR  
 TYPE HEAT INPUT VOLUME  
 1 3.8931E+C4 6.5579E-03  
 2 1.4721E+03 5.5135E-04

TOTAL 4.0403E+C4  
 OUT PRIN  
 TIME 0.0001 .0002 .0004

(Continued)

TEMPERATURES			
ELEMENT	X	Y	TEMPERATURE
1, 1	0.031	0.0	133.23
1, 4	0.027	0.0	127.23
2, 3	0.027	1.732	127.50
3, 2	0.029	3.465	131.06
4, 1	0.031	4.465	132.16
4, 4	0.027	4.465	126.57
5, 3	0.027	5.465	127.19
6, 2	0.029	6.465	130.86
7, 1	0.031	7.465	131.83
7, 4	0.027	7.465	126.90
8, 3	0.027	7.965	127.16
9, 2	0.029	8.465	130.81
10, 1	0.031	8.965	132.07
10, 4	0.027	8.965	126.88
11, 3	0.027	9.465	122.43
12, 2	0.029	9.590	124.67
13, 1	0.031	9.715	124.67
13, 4	0.027	9.715	122.19
14, 3	0.027	9.840	122.31
15, 2	0.029	9.965	124.05
16, 1	0.031	10.090	124.66
16, 4	0.027	10.090	122.18
17, 3	0.027	10.215	122.30

ROUT PR IN  
SOLV

ELEMENT	X	Y	TEMPERATURE
1, 2	0.029	0.0	131.55
2, 1	0.031	1.732	132.43
2, 4	0.027	1.732	127.23
3, 3	0.027	3.465	127.50
4, 2	0.029	4.465	130.90
5, 1	0.031	5.465	132.12
5, 4	0.027	5.465	126.93
6, 3	0.027	6.465	127.19
7, 2	0.029	7.465	130.70
8, 1	0.031	7.965	132.07
8, 4	0.027	7.965	126.90
9, 3	0.027	8.465	127.14
10, 2	0.029	8.965	130.81
11, 1	0.031	9.465	126.28
11, 4	0.027	9.465	122.20
12, 3	0.027	9.590	122.32
13, 2	0.029	9.715	124.06
14, 1	0.031	9.840	124.67
14, 4	0.027	9.840	122.19
15, 3	0.027	9.965	122.30
16, 2	0.029	10.090	124.05
17, 1	0.031	10.215	124.27
17, 4	0.027	10.215	122.18

ELEMENT	X	Y	TEMPERATURE
1, 3	0.027	0.0	127.50
2, 2	0.029	1.732	131.16
3, 1	0.031	3.465	132.21
3, 4	0.027	3.465	127.23
4, 3	0.027	4.465	127.23
5, 2	0.029	5.465	130.86
6, 1	0.031	6.465	132.12
6, 4	0.027	6.465	126.93
7, 3	0.027	7.465	127.16
8, 2	0.029	7.965	130.83
9, 1	0.031	8.465	132.07
9, 4	0.027	8.465	126.88
10, 3	0.027	8.965	127.14
11, 2	0.029	9.465	125.45
12, 1	0.031	9.590	124.68
12, 4	0.027	9.590	122.20
13, 3	0.027	9.715	122.31
14, 2	0.029	9.840	124.06
15, 1	0.031	9.965	124.66
15, 4	0.027	9.965	122.18
16, 3	0.027	10.090	122.30
17, 2	0.029	10.215	123.87

TEMPERATURES			
ELEMENT	X	Y	TEMPERATURE
1, 1	0.031	0.0	133.25
1, 4	0.027	0.0	127.27
2, 3	0.027	1.732	127.50
3, 2	0.029	3.465	131.06
4, 1	0.031	4.465	132.17
4, 4	0.027	4.465	126.98
5, 3	0.027	5.465	127.20
6, 2	0.029	6.465	130.87
7, 1	0.031	7.465	131.83
7, 4	0.027	7.465	126.90
8, 3	0.027	7.965	127.18
9, 2	0.029	8.465	130.82
10, 1	0.031	8.965	132.08
10, 4	0.027	8.965	126.89
11, 3	0.027	9.465	122.59
12, 2	0.029	9.590	125.18
13, 1	0.031	9.715	125.82
13, 4	0.027	9.715	123.13
14, 3	0.027	9.840	123.27
15, 2	0.029	9.965	125.16
16, 1	0.031	10.090	125.81
16, 4	0.027	10.090	123.12
17, 3	0.027	10.215	123.27

TIME= 0.0001000			
ELEMENT	X	Y	TEMPERATURE
1, 2	0.029	0.0	131.57
2, 1	0.031	1.732	132.43
2, 4	0.027	1.732	127.24
3, 3	0.027	3.465	127.49
4, 2	0.029	4.465	130.91
5, 1	0.031	5.465	132.13
5, 4	0.027	5.465	126.94
6, 3	0.027	6.465	127.20
7, 2	0.029	7.465	130.71
8, 1	0.031	7.965	132.10
8, 4	0.027	7.965	126.91
9, 3	0.027	8.465	127.16
10, 2	0.029	8.965	130.82
11, 1	0.031	9.465	126.53
11, 4	0.027	9.465	122.35
12, 3	0.027	9.590	123.28
13, 2	0.029	9.715	125.17
14, 1	0.031	9.840	125.82
14, 4	0.027	9.840	123.13
15, 3	0.027	9.965	123.26
16, 2	0.029	10.090	125.16
17, 1	0.031	10.215	125.41
17, 4	0.027	10.215	123.13

ELEMENT	X	Y	TEMPERATURE
1, 3	0.027	0.0	127.53
2, 2	0.029	1.732	131.17
3, 1	0.031	3.465	132.21
3, 4	0.027	3.465	127.23
4, 3	0.027	4.465	127.25
5, 2	0.029	5.465	130.87
6, 1	0.031	6.465	132.13
6, 4	0.027	6.465	126.94
7, 3	0.027	7.465	127.17
8, 2	0.029	7.965	130.84
9, 1	0.031	8.465	132.08
9, 4	0.027	8.465	126.89
10, 3	0.027	8.965	127.16
11, 2	0.029	9.465	125.66
12, 1	0.031	9.590	125.83
12, 4	0.027	9.590	123.14
13, 3	0.027	9.715	123.27
14, 2	0.029	9.840	125.17
15, 1	0.031	9.965	125.81
15, 4	0.027	9.965	123.12
16, 3	0.027	10.090	123.26
17, 2	0.029	10.215	124.98

(Continued)

TEMPERATURES				TIME= 0.000200							
ELEMENT	X	Y	TEMPERATURE	ELEMENT	X	Y	TEMPERATURE	ELEMENT	X	Y	TEMPERATURE
1, 1	0.031	0.0	133.28	1, 2	0.029	0.0	131.60	1, 3	0.027	0.0	127.56
1, 4	0.027	0.0	127.29	2, 1	0.031	1.732	132.43	2, 2	0.029	1.732	131.17
2, 3	0.027	1.732	127.50	2, 4	0.027	1.732	127.24	3, 1	0.031	3.465	132.20
3, 2	0.029	3.465	131.05	3, 3	0.027	3.465	127.48	3, 4	0.027	3.465	127.22
4, 1	0.031	4.465	132.18	4, 2	0.029	4.465	130.91	4, 3	0.027	4.465	127.25
4, 4	0.027	4.465	126.99	5, 1	0.031	5.465	132.13	5, 2	0.029	5.465	130.87
5, 3	0.027	5.465	127.20	5, 4	0.027	5.465	126.94	6, 1	0.031	6.465	132.13
6, 2	0.029	6.465	130.87	6, 3	0.027	6.465	127.20	6, 4	0.027	6.465	126.94
7, 1	0.031	7.465	131.83	7, 2	0.029	7.465	130.70	7, 3	0.027	7.465	127.16
7, 4	0.027	7.465	126.90	8, 1	0.031	7.965	132.11	8, 2	0.029	7.965	130.84
8, 3	0.027	7.965	127.18	8, 4	0.027	7.965	126.92	9, 1	0.031	8.465	132.09
9, 2	0.029	8.465	130.82	9, 3	0.027	8.465	127.16	9, 4	0.027	8.465	126.89
10, 1	0.031	8.965	132.09	10, 2	0.029	8.965	130.82	10, 3	0.027	8.965	127.16
10, 4	0.027	8.965	126.89	11, 1	0.031	9.465	127.16	11, 2	0.029	9.465	126.22
11, 3	0.027	9.465	122.98	11, 4	0.027	9.465	122.74	12, 1	0.031	9.590	128.84
12, 2	0.029	9.590	127.97	12, 3	0.027	9.590	125.33	12, 4	0.027	9.590	125.20
13, 1	0.031	9.715	128.83	13, 2	0.029	9.715	127.96	13, 3	0.027	9.715	125.38
13, 4	0.027	9.715	125.19	14, 1	0.031	9.840	128.83	14, 2	0.029	9.840	127.96
14, 3	0.027	9.840	125.38	14, 4	0.027	9.840	125.19	15, 1	0.031	9.965	128.82
15, 2	0.029	9.965	127.95	15, 3	0.027	9.965	125.37	15, 4	0.027	9.965	125.18
16, 1	0.031	10.090	128.82	16, 2	0.029	10.090	127.95	16, 3	0.027	10.090	125.37
16, 4	0.027	10.090	125.18	17, 1	0.031	10.215	128.39	17, 2	0.029	10.215	127.80
17, 3	0.027	10.215	125.49	17, 4	0.027	10.215	125.30				

TEMPERATURES				TIME= 0.000400							
ELEMENT	X	Y	TEMPERATURE	ELEMENT	X	Y	TEMPERATURE	ELEMENT	X	Y	TEMPERATURE
1, 1	0.031	0.0	133.32	1, 2	0.029	0.0	131.65	1, 3	0.027	0.0	127.61
1, 4	0.027	0.0	127.34	2, 1	0.031	1.732	132.43	2, 2	0.029	1.732	131.17
2, 3	0.027	1.732	127.50	2, 4	0.027	1.732	127.24	3, 1	0.031	3.465	132.18
3, 2	0.029	3.465	131.03	3, 3	0.027	3.465	127.46	3, 4	0.027	3.465	127.20
4, 1	0.031	4.465	132.18	4, 2	0.029	4.465	130.91	4, 3	0.027	4.465	127.25
4, 4	0.027	4.465	126.98	5, 1	0.031	5.465	132.13	5, 2	0.029	5.465	130.87
5, 3	0.027	5.465	127.20	5, 4	0.027	5.465	126.94	6, 1	0.031	6.465	132.14
6, 2	0.029	6.465	130.87	6, 3	0.027	6.465	127.21	6, 4	0.027	6.465	126.94
7, 1	0.031	7.465	131.81	7, 2	0.029	7.465	130.68	7, 3	0.027	7.465	127.14
7, 4	0.027	7.465	126.88	8, 1	0.031	7.965	132.11	8, 2	0.029	7.965	130.85
8, 3	0.027	7.965	127.18	8, 4	0.027	7.965	126.92	9, 1	0.031	8.465	132.09
9, 2	0.029	8.465	130.83	9, 3	0.027	8.465	127.16	9, 4	0.027	8.465	126.90
10, 1	0.031	8.965	132.09	10, 2	0.029	8.965	130.83	10, 3	0.027	8.965	127.16
10, 4	0.027	8.965	126.90	11, 1	0.031	9.465	129.11	11, 2	0.029	9.465	128.07
11, 3	0.027	9.465	124.74	11, 4	0.027	9.465	124.49	12, 1	0.031	9.590	138.27
12, 2	0.029	9.590	137.20	12, 3	0.027	9.590	134.50	12, 4	0.027	9.590	134.31
13, 1	0.031	9.715	138.50	13, 2	0.029	9.715	137.55	13, 3	0.027	9.715	134.88
13, 4	0.027	9.715	134.70	14, 1	0.031	9.840	138.71	14, 2	0.029	9.840	137.80
14, 3	0.027	9.840	135.25	14, 4	0.027	9.840	135.08	15, 1	0.031	9.965	139.05
15, 2	0.029	9.965	138.16	15, 3	0.027	9.965	135.66	15, 4	0.027	9.965	135.49
16, 1	0.031	10.090	139.39	16, 2	0.029	10.090	138.52	16, 3	0.027	10.090	136.08
16, 4	0.027	10.090	135.92	17, 1	0.031	10.215	138.90	17, 2	0.029	10.215	138.32
17, 3	0.027	10.215	136.11	17, 4	0.027	10.215	135.95				

NEXT

END OF FILE ENCOUNTERED ON UNIT 1

TIME = 1.5 MINS

(Continued)



GENERAL PROBLEM DATA

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TEST CASE

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NUMBER OF AXIAL LEVELS = 8  
 WETTED DIAMETER (IN) = 0.654000E+00  
 FUEL PIN LENGTH (FT) = 0.102150E+02  
 HYDRAULIC DIAMETER (IN) = 0.654000E+00  
 FLOW AREA (IN\*\*2) = 0.335930E+00

HEAT TRANSFER REGION 2 - NUCLEATE BOILING  
 OPTIONS  
 ( 1) JENS-LOTTES  
 ( 2) THOM  
 ( 3) MCADAMS  
 OPTION USED : 3

HEAT TRANSFER REGION 3 - FORCED CONVECTION VAPORISATION  
 OPTIONS  
 ( 1) SCHROCK & GROSSMAN  
 ( 2) CHEN  
 OPTION USED : 1

HEAT TRANSFER REGION 4 - TRANSITION BOILING  
 OPTIONS (OPTION 2 UNAVAILABLE AT STEADY STATES)  
 ( 1) MCDONOUGH ET AL  
 ( 2) MODIFIED MCDONOUGH ET AL  
 OPTION USED : 2

HEAT TRANSFER REGION 5 - STABLE FILM BOILING  
 OPTIONS (OPTIONS 2 AND 4 UNAVAILABLE AT STEADY STATES)  
 ( 1) DOUGALL-ROHSENOW  
 ( 2) MODIFIED DOUGALL-ROHSENOW  
 ( 3) MIROPOLSKI  
 ( 4) MODIFIED MIROPOLSKI  
 ( 5) GROENEVELD  
 OPTION USED : 2

CRITICAL HEAT FLUX  
 OPTIONS (W) SUITABLE FOR WATER (F) SUITABLE FOR FREON  
 ( 1) WESTINGHOUSE W-3 (W)  
 ( 2) GENERAL ELECTRIC DESIGN LIMIT (W)  
 ( 3) WESTINGHOUSE W-3 & GENERAL ELECTRIC DESIGN LIMIT (W)  
 ( 4) MCBETH ROD BUNDLE (W)  
 ( 5) BARNETT ROD BUNDLE (W)  
 ( 6) BECKER ROD BUNDLE (W)  
 ( 7) WESTINGHOUSE W-3 & BARNETT (W)  
 ( 8) GELLERSTEDT (W)  
 ( 9) (HUGHES) MODIFIED BARNETT (W)  
 (10) GELLERSTEDT & (HUGHES) MODIFIED BARNETT (W)  
 (11) CISE (F)  
 (12) MODIFIED CISE (F)  
 (13) GROENEVELD (F)  
 (14) MODIFIED GROENEVELD (F)  
 OPTION USED : 14  
 COOLANT USED : FREON

SLIP VELOCITY RATIO  
 OPTIONS  
 ( 1) USER'S INPUT VALUE  
 ( 2) HOMOGENEOUS  
 ( 3) (JONES) MODIFIED BANKOFF  
 ( 4) FALSKE  
 OPTION USED : 2

2 PHASE FRICTIONAL PRESSURE DROP  
 OPTIONS  
 ( 0) NO PRESSURE DROP  
 ( 1) HOMOGENEOUS  
 ( 2) LOCKHART & MARTINELLI  
 ( 3) THOM  
 ( 4) MARTINELLI & NELSON  
 OPTION USED : 1

ENERGY EQUATIONS  
 OPTIONS  
 ( 1) EXPLICIT NUMERICAL SCHEME  
 ( 2) IMPLICIT NUMERICAL SCHEME  
 ( 3) LAX-WENDROFF NUMERICAL SCHEME  
 ( 4) METHOD OF CHARACTERISTICS SCHEME  
 OPTION USED : 2

AXIAL NODE	NODE LENGTH (FT)	SURFACE AREA (FT**2)
1	0.346500E+01	0.593266E+00
2	0.200000E+01	0.342434E+00
3	0.200000E+01	0.342433E+00
4	0.999999E+00	0.171217E+00
5	0.999999E+00	0.171216E+00
6	0.250002E+00	0.428045E-01
7	0.249998E+00	0.428039E-01
8	0.249998E+00	0.428039E-01

DATA POINT	TIME (SEC)	PRESSURE (PSIA)	TIME (SEC)	MASS FLUX (LBM/HR-FT**2)
1	0.0	0.132780E+03	0.0	0.347472E+06
2	0.500000E+02	0.132780E+03	0.500000E+02	0.347472E+06

DATA POINT	TIME (SEC)	INLET ENTHALPY (BTU/LBM)
1	0.0	0.254000E+02
2	0.500000E+02	0.254000E+02

SOURCE NUMBER	DATA POINT	TIME (SEC)	AXIAL POWER FACTOR (-)
1	1	0.0	0.100000E+01
1	2	0.270000E+01	0.100000E+01
1	3	0.576000E+01	0.130000E+01
1	4	0.500000E+02	0.130000E+01
2	1	0.0	0.100000E+01
2	2	0.180000E+01	0.400000E+01
2	3	0.500000E+02	0.400000E+01

MINIMUM FLUID TIME STEP 2.0000E-03  
 STEADY STATE HEAT FLUX TOLERANCE 1.0000E-03  
 STEADY STATE TEMPERATURE TOLERANCE 1.0000E+00  
 ENTHALPY TOLERANCE 1.0000E-04  
 VOIDAGE DELINEATING BETWEEN REGIMES 1.0000E+00

INITIALISATION ITERATIONS = 2 HEAT BALANCE ERROR = 0.012%

(Continued)

THE TRAN 8/6/79 WJG/WJSJ  
TEST CASE

DATE = 9 JAN 80

INITIALIZATION

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*****
PRESSURE (PSIA) = 0.132780E+03
MASS FLUX (LBM/HR-FT**2) = 0.347472E+06
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SATURATION PROPERTIES

LOWER JUNCTION		UPPER JUNCTION	
PRESSURE (PSIA)	= 0.132349E+03	PRESSURE (PSIA)	= 0.131645E+03
TEMPERATURE (F)	= 0.100450E+03	TEMPERATURE (F)	= 0.100068E+03
LIQUID ENTHALPY (BTU/LBM)	= 0.316774E+02	LIQUID ENTHALPY (BTU/LBM)	= 0.315779E+02
VAPOUR ENTHALPY (BTU/LBM)	= 0.378645E+02	VAPOUR ENTHALPY (BTU/LBM)	= 0.878315E+02
LIQUID DENSITY (LBM/FT**3)	= 0.787496E+02	LIQUID DENSITY (LBM/FT**3)	= 0.788017E+02
VAPOUR DENSITY (LBM/FT**3)	= 0.323010E+01	VAPOUR DENSITY (LBM/FT**3)	= 0.321260E+01

LOWER JUNCTION		UPPER JUNCTION	
TEMPERATURE (F)	= 0.740493E+02	TEMPERATURE (F)	= 0.100063E+03
ENTHALPY (BTU/LBM)	= 0.254000E+02	ENTHALPY (BTU/LBM)	= 0.752433E+02
QUALITY (-)	= 0.0	QUALITY (-)	= 0.776229E+00
DENSITY (LBM/FT**3)	= 0.787177E+02	DENSITY (LBM/FT**3)	= 0.409039E+01
FLOW ENTHALPY (BTU/LBM)	= 0.254000E+02	FLOW ENTHALPY (BTU/LBM)	= 0.752433E+02
MASS FLOW FRACTION (-)	= 0.0	MASS FLOW FRACTION (-)	= 0.776229E+00

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NODE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.100450E+03	0.341925D+02	0.448821E-01	0.384269E+02	0.316704E+02	0.878645E+02	0.132349E+03
2	0.100190E+03	0.430584D+02	0.292538E+00	0.100120E+02	0.316076E+02	0.878421E+02	0.131871E+03
3	0.100146E+03	0.582053D+02	0.473109E+00	0.650238E+01	0.315969E+02	0.878383E+02	0.131789E+03
4	0.100118E+03	0.658158D+02	0.606500E+00	0.514316E+01	0.315901E+02	0.878359E+02	0.131737E+03
5	0.100099E+03	0.708898D+02	0.698756E+00	0.452016E+01	0.315855E+02	0.878343E+02	0.131703E+03
6	0.100085E+03	0.737297D+02	0.749274E+00	0.423094E+01	0.315822E+02	0.878331E+02	0.131677E+03
7	0.100076E+03	0.743352D+02	0.760057E+00	0.417358E+01	0.315800E+02	0.878323E+02	0.131661E+03
8	0.100068E+03	0.749406D+02	0.770838E+00	0.411775E+01	0.315779E+02	0.878315E+02	0.131645E+03

(Continued)

AXIAL LEVEL	SURFACE TEMPERATURE (F)	SUR. TEMP. - SAT. TEMP. (F)	SURFACE HEAT FLUX (BTU/HR-FT**2)	CHF RATIO (-)	HEAT TRANSFER REGIME	FLUID STATE	HEAT TRANSFER COEFFICIENT (BTU/HR-F-FT**2)	VOID FRACTION (-)	SLIP VELOCITY RATIO (-)
1	0.127233E+03	0.267828E+02	0.240271E+05	0.362751E+01	2	2	0.885054E+03	0.533939E+00	0.100000E+01
2	0.126971E+03	0.267804E+02	0.240188E+05	0.223978E+01	2	2	0.884844E+03	0.910096E+00	0.100000E+01
3	0.126927E+03	0.267806E+02	0.240202E+05	0.161592E+01	2	2	0.884935E+03	0.956517E+00	0.100000E+01
4	0.126899E+03	0.267812E+02	0.240215E+05	0.122004E+01	2	2	0.885030E+03	0.974421E+00	0.100000E+01
5	0.126881E+03	0.267816E+02	0.240229E+05	0.108692E+01	2	2	0.885104E+03	0.982719E+00	0.100000E+01
6	0.122190E+03	0.221124E+02	0.114677E+05	0.212080E+01	2	2	0.511776E+03	0.986538E+00	0.100000E+01
7	0.122187E+03	0.221111E+02	0.114649E+05	0.208796E+01	2	2	0.511698E+03	0.987292E+00	0.100000E+01
8	0.122179E+03	0.221111E+02	0.114649E+05	0.205465E+01	2	2	0.511704E+03	0.988025E+00	0.100000E+01

INTERFACE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.740498E+02	0.254000E+02	0.0	0.787177E+02	0.317271E+02	0.878847E+02	0.132780E+03
2	0.100216E+03	0.429851E+02	0.202226E+00	0.137096E+02	0.316138E+02	0.878443E+02	0.131918E+03
3	0.100165E+03	0.531317E+02	0.382838E+00	0.788421E+01	0.316014E+02	0.878399E+02	0.131824E+03
4	0.100127E+03	0.632789E+02	0.563371E+00	0.553231E+01	0.315923E+02	0.878367E+02	0.131755E+03
5	0.100109E+03	0.683527E+02	0.653623E+00	0.481383E+01	0.315878E+02	0.878351E+02	0.131721E+03
6	0.100090E+03	0.734269E+02	0.743882E+00	0.426021E+01	0.315832E+02	0.878334E+02	0.131685E+03
7	0.100081E+03	0.740325E+02	0.754666E+00	0.420207E+01	0.315811E+02	0.878327E+02	0.131669E+03
8	0.100072E+03	0.746379E+02	0.765448E+00	0.414549E+01	0.315790E+02	0.878319E+02	0.131653E+03
9	0.100063E+03	0.752433E+02	0.776229E+00	0.409039E+01	0.315769E+02	0.878312E+02	0.131637E+03

(Continued)

THETRAN 3/6/79 WJG/WSJ  
TEST CASE

DATE = 9 JAN 80

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PRESSURE (PSIA) 0.132780E+C3 TIME (SEC) 0.3600  
 MASS FLUX (LBM/HR-FT\*\*2) 0.347472E+06 MAX TIME STEP (SEC) 0.0216  
 ITERATION NO. 48

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SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR
1	0.100000E+01	2	0.160000E+C1				

SATURATION PROPERTIES

LOWER JUNCTION

PRESSURE (PSIA) = 0.132361E+C3  
 TEMPERATURE (F) = 0.100043E+03  
 LIQUID ENTHALPY (BTU/LBM) = 0.316721E+C2  
 VAPOUR ENTHALPY (BTU/LBM) = 0.878651E+02  
 LIQUID DENSITY (LBM/FT\*\*3) = 0.787487E+02  
 VAPOUR DENSITY (LBM/FT\*\*3) = 0.321329E+01

UPPER JUNCTION

PRESSURE (PSIA) = 0.131673E+03  
 TEMPERATURE (F) = 0.100043E+03  
 LIQUID ENTHALPY (BTU/LBM) = 0.315816E+02  
 VAPOUR ENTHALPY (BTU/LBM) = 0.878328E+02  
 LIQUID DENSITY (LBM/FT\*\*3) = 0.787997E+02  
 VAPOUR DENSITY (LBM/FT\*\*3) = 0.321329E+01

LOWER JUNCTION

TEMPERATURE (F) = 0.740493E+C2  
 ENTHALPY (BTU/LBM) = 0.254000E+C2  
 QUALITY (-) = 0.0  
 DENSITY (LBM/FT\*\*3) = 0.787177E+C2  
 FLOW ENTHALPY (BTU/LBM) = 0.254000E+C2  
 MASS FLOW FRACTION (-) = 0.0

UPPER JUNCTION

TEMPERATURE (F) = 0.100079E+03  
 ENTHALPY (BTU/LBM) = 0.746186E+02  
 QUALITY (-) = 0.765094E+00  
 DENSITY (LBM/FT\*\*3) = 0.414770E+01  
 FLOW ENTHALPY (BTU/LBM) = 0.746186E+02  
 MASS FLOW FRACTION (-) = 0.765094E+00

NODE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.100043E+03	0.341921D+C2	0.448466E-01	0.384442E+02	0.316721E+C2	0.878651E+02	0.132361E+03
2	0.100205E+03	0.480550D+C2	0.292439E+00	0.100168E+02	0.316111E+C2	0.878434E+02	0.131898E+03
3	0.100162E+03	0.581983D+C2	0.472937E+00	0.650000E+01	0.316008E+C2	0.878397E+02	0.131819E+03
4	0.100135E+03	0.658050D+C2	0.608276E+00	0.515119E+01	0.315943E+C2	0.878374E+02	0.131770E+03
5	0.100114E+03	0.708775D+C2	0.698504E+00	0.452268E+01	0.315892E+C2	0.878356E+02	0.131731E+03
6	0.100099E+03	0.728372D+C2	0.733380E+00	0.431844E+01	0.315854E+C2	0.878342E+02	0.131702E+03
7	0.100091E+03	0.735706D+C2	0.746417E+00	0.424650E+01	0.315835E+C2	0.878335E+02	0.131687E+03
8	0.100083E+03	0.742693D+C2	0.756875E+00	0.418012E+01	0.315816E+C2	0.878328E+02	0.131673E+03

(Continued)

AXIAL LEVEL	SURFACE TEMPERATURE (F)	SUR. TEMP. - SAT. TEMP. (F)	SURFACE HEAT FLUX (BTU/HR-FT**2)	CHF RATIO (-)	HEAT TRANSFER REGIME	FLUID STATE	HEAT TRANSFER COEFFICIENT (BTU/HR-F-FT**2)	VOID FRACTION (-)	SLIP VELOCITY RATIO (-)
1	0.127233E+03	0.267828E+C2	0.240271E+C5	0.362751E+C1	2	2	0.885054E+03	0.533939E+00	0.100000E+01
2	0.126971E+03	0.267804E+02	0.240188E+05	0.223978E+01	2	2	0.884844E+03	0.910096E+00	0.100000E+01
3	0.126927E+03	0.267808E+C2	0.240202E+05	0.161592E+01	2	2	0.884935E+03	0.956517E+00	0.100000E+01
4	0.126899E+03	0.267812E+02	0.240215E+05	0.122004E+01	2	2	0.885030E+03	0.974421E+00	0.100000E+01
5	0.126881E+03	0.267816E+02	0.240229E+05	0.108692E+01	2	2	0.885104E+03	0.982719E+00	0.100000E+01
6	0.122198E+03	0.221124E+02	0.114677E+05	0.212080E+01	2	2	0.511776E+03	0.986538E+00	0.100000E+01
7	0.122187E+03	0.221111E+02	0.114649E+05	0.208796E+01	2	2	0.511698E+03	0.987292E+00	0.100000E+01
8	0.122179E+03	0.221111E+02	0.114649E+05	0.205465E+01	2	2	0.511704E+03	0.988025E+00	0.100000E+01

INTERFACE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.740498E+02	0.254000E+02	0.0	0.787177E+02	0.317271E+02	0.878847E+02	0.132780E+03
2	0.100216E+03	0.429851E+02	0.202226E+00	0.137096E+02	0.316138E+02	0.878443E+02	0.131918E+03
3	0.100165E+03	0.531317E+02	0.382838E+00	0.788421E+01	0.316014E+02	0.878399E+02	0.131824E+03
4	0.100127E+03	0.632789E+02	0.563371E+00	0.553231E+01	0.315923E+02	0.878367E+02	0.131755E+03
5	0.100109E+03	0.683527E+02	0.653628E+00	0.481383E+01	0.315878E+02	0.878351E+02	0.131721E+03
6	0.100090E+03	0.734269E+02	0.743882E+00	0.426021E+01	0.315832E+02	0.878334E+02	0.131685E+03
7	0.100081E+03	0.740325E+02	0.754666E+00	0.420207E+01	0.315811E+02	0.878327E+02	0.131669E+03
8	0.100072E+03	0.746379E+02	0.765448E+00	0.414549E+01	0.315790E+02	0.878319E+02	0.131653E+03
9	0.100063E+03	0.752433E+02	0.776229E+00	0.409039E+01	0.315769E+02	0.878312E+02	0.131637E+03

(Continued)

AXIAL LEVEL	SURFACE TEMPERATURE (F)	SUR. TEMP. - SAT. TEMP. (F)	SURFACE HEAT FLUX (BTU/HR-FT**2)	CHF RATIO (-)	HEAT TRANSFER REGIME	FLUID STATE	HEAT TRANSFER COEFFICIENT (BTU/HR-F-FT**2)	VOID FRACTION (-)	SLIP VELOCITY RATIO (-)
1	0.127239E+03	0.267817E+02	0.240261E+05	0.357999E+01	2	2	0.397108E+03	0.533706E+00	0.100000E+01
2	0.126932E+03	0.267767E+02	0.240094E+05	0.221083E+01	2	2	0.396349E+03	0.910038E+00	0.100000E+01
3	0.126933E+03	0.267767E+02	0.240093E+05	0.159539E+01	2	2	0.396644E+03	0.956478E+00	0.100000E+01
4	0.126913E+03	0.267779E+02	0.240133E+05	0.120444E+01	2	2	0.396757E+03	0.974391E+00	0.100000E+01
5	0.126891E+03	0.267770E+02	0.240111E+05	0.107327E+01	2	2	0.396695E+03	0.982695E+00	0.100000E+01
6	0.123131E+03	0.230390E+02	0.134381E+05	0.182729E+01	2	2	0.333278E+03	0.985389E+00	0.100000E+01
7	0.123129E+03	0.230380E+02	0.134353E+05	0.179366E+01	2	2	0.333203E+03	0.986336E+00	0.100000E+01
8	0.123123E+03	0.230374E+02	0.134346E+05	0.176149E+01	2	2	0.333103E+03	0.987209E+00	0.100000E+01

INTERFACE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.740490E+02	0.294000E+02	0.0	0.787177E+02	0.317271E+02	0.478847E+02	0.132780E+03
2	0.100230E+03	0.425821E+02	0.202122E+00	0.137177E+02	0.316171E+02	0.473455E+02	0.131943E+03
3	0.100180E+03	0.531269E+02	0.382703E+00	0.788933E+01	0.316052E+02	0.378413E+02	0.131853E+03
4	0.100144E+03	0.652698E+02	0.563165E+00	0.553551E+01	0.315965E+02	0.478331E+02	0.131786E+03
5	0.100126E+03	0.833416E+02	0.653337E+00	0.481570E+01	0.315921E+02	0.478360E+02	0.131753E+03
6	0.100102E+03	0.724452E+02	0.726404E+00	0.435785E+01	0.315863E+02	0.478345E+02	0.131709E+03
7	0.100095E+03	0.732039E+02	0.739094E+00	0.424218E+01	0.315845E+02	0.478339E+02	0.131695E+03
8	0.100087E+03	0.739159E+02	0.752656E+00	0.421335E+01	0.315825E+02	0.478332E+02	0.131680E+03
9	0.100079E+03	0.746166E+02	0.765094E+00	0.414770E+01	0.315806E+02	0.478325E+02	0.131665E+03

AXIAL LEVEL(S) WITHIN THERMAL TOLERANCES 1 2 3 4 5

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(Continued)

THETRAN 8/6/79 WJG/WJSJ  
TEST CASE

DATE = 9 JAN 80

\*\*\*\*\*  
 PRESSURE (PSIA) 0.132780E+C3 TIME (SEC) 0.7200  
 MASS FLUX (LBM/HR-FT\*\*2) 0.347472E+C6 MAX TIME STEP (SEC) 0.0216  
 ITERATION NO. 96  
 \*\*\*\*\*

SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR
1	0.100000E+01	2	0.220000E+01				

SATURATION PROPERTIES

LOWER JUNCTION

PRESSURE (PSIA) = 0.132361E+03  
 TEMPERATURE (F) = 0.100457E+03  
 LIQUID ENTHALPY (BTU/LBM) = 0.316721E+02  
 VAPOUR ENTHALPY (BTU/LBM) = 0.878651E+02  
 LIQUID DENSITY (LBM/FT\*\*3) = 0.787487E+02  
 VAPOUR DENSITY (LBM/FT\*\*3) = 0.323042E+01

UPPER JUNCTION

PRESSURE (PSIA) = 0.131685E+03  
 TEMPERATURE (F) = 0.100089E+03  
 LIQUID ENTHALPY (BTU/LBM) = 0.315831E+02  
 VAPOUR ENTHALPY (BTU/LBM) = 0.878334E+02  
 LIQUID DENSITY (LBM/FT\*\*3) = 0.787988E+02  
 VAPOUR DENSITY (LBM/FT\*\*3) = 0.321359E+01

LOWER JUNCTION

TEMPERATURE (F) = 0.740498E+02  
 ENTHALPY (BTU/LBM) = 0.254000E+02  
 QUALITY (-) = 0.0  
 DENSITY (LBM/FT\*\*3) = 0.787177E+02  
 FLOW ENTHALPY (BTU/LBM) = 0.254000E+02  
 MASS FLOW FRACTION (-) = 0.0

UPPER JUNCTION

TEMPERATURE (F) = 0.100089E+03  
 ENTHALPY (BTU/LBM) = 0.759030E+02  
 QUALITY (-) = 0.787912E+00  
 DENSITY (LBM/FT\*\*3) = 0.403415E+01  
 FLOW ENTHALPY (BTU/LBM) = 0.759030E+02  
 MASS FLOW FRACTION (-) = 0.787912E+00

NODE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.100457E+03	0.341931D+02	0.448640E-01	0.384365E+02	0.316721E+02	0.878651E+02	0.132361E+03
2	0.100205E+03	0.480595D+C2	0.292507E+00	0.100148E+02	0.316112E+02	0.878434E+02	0.131898E+03
3	0.100162E+03	0.582050D+02	0.473057E+00	0.650450E+01	0.316009E+02	0.878397E+02	0.131819E+03
4	0.100135E+03	0.658140D+02	0.606425E+00	0.515003E+01	0.315943E+02	0.878374E+02	0.131770E+03
5	0.100116E+03	0.708867D+02	0.698664E+00	0.452180E+01	0.315896E+02	0.878357E+02	0.131734E+03
6	0.100102E+03	0.734382D+C2	0.744058E+00	0.420003E+01	0.315862E+02	0.878345E+02	0.131708E+03
7	0.100096E+03	0.744403D+02	0.761888E+00	0.416523E+01	0.315847E+02	0.878340E+02	0.131697E+03
8	0.100089E+03	0.754155D+C2	0.779237E+00	0.407692E+01	0.315831E+02	0.878334E+02	0.131685E+03

(Continued)



AXIAL LEVEL	SURFACE TEMPERATURE (F)	SUR. TEMP. - SAT. TEMP. (F)	SURFACE HEAT FLUX (BTU/HR-FT**2)	CHF RATIO (-)	HEAT TRANSFER REGIME	FLUID STATE	HEAT TRANSFER COEFFICIENT (BTU/HR-F-FT**2)	VOID FRACTION (-)	SLIP VELOCITY RATIO (-)
1	0.127240E+03	0.267824E+02	0.240287E+05	0.357864E+01	2	2	0.897182E+03	0.533806E+00	0.100000E+01
2	0.126935E+03	0.267794E+02	0.240184E+05	0.220982E+01	2	2	0.896898E+03	0.410065E+00	0.100000E+01
3	0.126941E+03	0.267782E+02	0.240141E+05	0.159482E+01	2	2	0.896778E+03	0.956498E+00	0.100000E+01
4	0.126915E+03	0.267796E+02	0.240168E+05	0.120403E+01	2	2	0.896908E+03	0.974406E+00	0.100000E+01
5	0.126894E+03	0.267776E+02	0.240133E+05	0.107302E+01	2	2	0.896757E+03	0.982798E+00	0.100000E+01
6	0.125195E+03	0.250929E+02	0.186852E+05	0.129420E+01	2	2	0.744641E+03	0.986164E+00	0.100000E+01
7	0.125138E+03	0.250925E+02	0.186840E+05	0.126095E+01	2	2	0.744604E+03	0.987414E+00	0.100000E+01
8	0.125181E+03	0.250915E+02	0.186811E+05	0.122870E+01	2	2	0.744519E+03	0.988578E+00	0.100000E+01

INTERFACE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.740490E+02	0.254000E+02	0.0	0.787177E+02	0.317271E+02	0.878847E+02	0.132780E+03
2	0.130230E+03	0.424849E+02	0.202171E+00	0.137149E+02	0.316171E+02	0.878455E+02	0.131943E+03
3	0.100181E+03	0.531322E+02	0.382747E+00	0.788660E+01	0.316052E+02	0.878413E+02	0.131853E+03
4	0.100144E+03	0.632777E+02	0.563305E+00	0.553425E+01	0.315965E+02	0.878382E+02	0.131786E+03
5	0.100127E+03	0.663504E+02	0.653543E+00	0.481563E+01	0.315922E+02	0.878366E+02	0.131753E+03
6	0.100105E+03	0.724279E+02	0.734978E+00	0.430997E+01	0.315870E+02	0.878348E+02	0.131714E+03
7	0.100099E+03	0.739393E+02	0.752973E+00	0.421210E+01	0.315855E+02	0.878342E+02	0.131703E+03
8	0.100093E+03	0.749279E+02	0.770562E+00	0.412061E+01	0.315840E+02	0.878337E+02	0.131691E+03
9	0.100086E+03	0.754036E+02	0.787912E+00	0.403415E+01	0.315824E+02	0.878331E+02	0.131679E+03

AXIAL LEVEL(S) WITHIN THERMAL TOLERANCES 1 2 3 4 5

(Continued)

THE TRAN 8/6/79 WJG/WJSJ  
TEST CASE

DATE = 9 JAN 80

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*****
PRESSURE (PSIA)          0.132780E+C3          TIME (SEC)          1.4400
MASS FLUX (LBM/HR-FT**2) 0.347472E+06          MAX TIME STEP (SEC) 0.0422
                                           ITERATION N'       156
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SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR	SOURCE NUMBER	AXIAL POWER FACTOR
1	0.100000E+01	2	0.340000E+C1				

SATURATION PROPERTIES

LOWER JUNCTION		UPPER JUNCTION	
PRESSURE (PSIA)	= 0.132361E+C3	PRESSURE (PSIA)	= 0.131678E+03
TEMPERATURE (F)	= 0.100457E+03	TEMPERATURE (F)	= 0.100086E+03
LIQUID ENTHALPY (BTU/LBM)	= 0.316720E+02	LIQUID ENTHALPY (BTU/LBM)	= 0.315823E+02
VAPOUR ENTHALPY (BTU/LBM)	= 0.878651E+02	VAPOUR ENTHALPY (BTU/LBM)	= 0.878331E+02
LIQUID DENSITY (LBM/FT**3)	= 0.787487E+02	LIQUID DENSITY (LBM/FT**3)	= 0.787993E+02
VAPOUR DENSITY (LBM/FT**3)	= 0.323041E+01	VAPOUR DENSITY (LBM/FT**3)	= 0.321343E+01

LOWER JUNCTION		UPPER JUNCTION	
TEMPERATURE (F)	= 0.740498E+C2	TEMPERATURE (F)	= 0.100082E+03
ENTHALPY (BTU/LBM)	= 0.254000E+02	ENTHALPY (BTU/LBM)	= 0.752611E+02
QUALITY (-)	= 0.0	QUALITY (-)	= 0.776509E+00
DENSITY (LBM/FT**3)	= 0.787177E+02	DENSITY (LBM/FT**3)	= 0.409008E+01
FLOW ENTHALPY (BTU/LBM)	= 0.254000E+02	FLOW ENTHALPY (BTU/LBM)	= 0.752611E+02
MASS FLOW FRACTION (-)	= 0.0	MASS FLOW FRACTION (-)	= 0.776509E+00

NODE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.100457E+03	0.341889D+02	0.447855E-01	0.384692E+02	0.316720E+02	0.878651E+02	0.132361E+03
2	0.100205E+03	0.480511D+02	0.292360E+00	0.100191E+02	0.316111E+02	0.878434E+02	0.131897E+03
3	0.100162E+03	0.581980D+02	0.472933E+00	0.650602E+01	0.316008E+02	0.878397E+02	0.131819E+03
4	0.100135E+03	0.658085D+02	0.608329E+00	0.515075E+01	0.315942E+02	0.878373E+02	0.131769E+03
5	0.100115E+03	0.708825D+02	0.698591E+00	0.452217E+01	0.315893E+02	0.878356E+02	0.131732E+03
6	0.100100E+03	0.731056D+02	0.738149E+00	0.429214E+01	0.315857E+02	0.878343E+02	0.131704E+03
7	0.100093E+03	0.740001D+02	0.754067E+00	0.420595E+01	0.315840E+02	0.878337E+02	0.131691E+03
8	0.100086E+03	0.748408D+02	0.769029E+00	0.412799E+01	0.315823E+02	0.878331E+02	0.131678E+03

(Continued)

AXIAL LEVEL	SURFACE TEMPERATURE (F)	SUR. TEMP. - SAT. TEMP. (F)	SURFACE HEAT FLUX (BTU/HR-FT**2)	CHF RATIO (-)	HEAT TRANSFER REGIME	FLUID STATE	HEAT TRANSFER COEFFICIENT (BTU/HR-F-FT**2)	VOID FRACTION (-)	SLIP VELOCITY RATIO (-)
1	0.127236E+03	0.267791E+02	0.240171E+05	0.358103E+01	2	2	0.896862E+03	0.533375E+00	0.100000E+01
2	0.126984E+03	0.267796E+02	0.240190E+05	0.221051E+01	2	2	0.896914E+03	0.910007E+00	0.100000E+01
3	0.126942E+03	0.267799E+02	0.240199E+05	0.159494E+01	2	2	0.896938E+03	0.956478E+00	0.100000E+01
4	0.126916E+03	0.267805E+02	0.240219E+05	0.120409E+01	2	2	0.896994E+03	0.974396E+00	0.100000E+01
5	0.126896E+03	0.267812E+02	0.240219E+05	0.107284E+01	2	2	0.896994E+03	0.982702E+00	0.100000E+01
6	0.134309E+03	0.342093E+02	0.152535E+05	0.159890E+01	4	2	0.445887E+03	0.985737E+00	0.100000E+01
7	0.135079E+03	0.345858E+02	0.152536E+05	0.156243E+01	4	2	0.435996E+03	0.986874E+00	0.100000E+01
8	0.135916E+03	0.356299E+02	0.152538E+05	0.152815E+01	4	2	0.425729E+03	0.987901E+00	0.100000E+01

INTERFACE DATA

AXIAL LEVEL	FLUID TEMPERATURE (F)	ENTHALPY (BTU/LBM)	QUALITY (-)	DENSITY (LBM/FT**3)	SATURATED LIQUID ENTHALPY (BTU/LBM)	SATURATED VAPOUR ENTHALPY (BTU/LBM)	PRESSURE (PSIA)
1	0.740498E+02	0.234000E+02	0.0	0.787177E+02	0.317271E+02	0.878847E+02	0.132780E+03
2	0.100229E+03	0.425780E+02	0.202052E+00	0.137216E+02	0.316170E+02	0.878455E+02	0.131942E+03
3	0.100180E+03	0.531246E+02	0.382663E+00	0.788905E+01	0.316051E+02	0.878412E+02	0.131852E+03
4	0.100144E+03	0.632717E+02	0.563199E+00	0.553518E+01	0.315964E+02	0.878381E+02	0.131785E+03
5	0.100126E+03	0.683455E+02	0.653458E+00	0.481619E+01	0.315921E+02	0.878366E+02	0.131753E+03
6	0.100103E+03	0.726604E+02	0.730236E+00	0.433630E+01	0.315866E+02	0.878346E+02	0.131711E+03
7	0.100090E+03	0.735528E+02	0.746108E+00	0.424862E+01	0.315849E+02	0.878340E+02	0.131693E+03
8	0.100089E+03	0.744204E+02	0.761548E+00	0.416662E+01	0.315832E+02	0.878334E+02	0.131685E+03
9	0.100082E+03	0.752611E+02	0.776509E+00	0.409008E+01	0.315814E+02	0.878328E+02	0.131671E+03

AXIAL LEVEL(S) WITHIN THERMAL COLFRANCES 1 2 3 4 5

